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Towards Regenerative Quantum Computing *with proven positive sustainability impact*

[White paper]

COP28 UAE

Towards Regenerative Quantum Computing
with proven positive sustainability impact

CONTENTS

GOAL OF THE DOCUMENT

Quantum computing promises to exploit quantum superposition and entanglement to efficiently address complex problems that are usually inaccessible or significantly resource-consuming to classical computing. This gain in performance can manifest itself in various ways, such as acceleration in terms of execution speed, enhancement in terms of the accuracy and the quality of the solution. However, one may look at this increased efficiency from a completely different angle: ***the energy/ sustainability advantage perspective.*** Indeed, for specific use cases, the gain is expected to emerge in the form of *lesser energy requirements* (hence, lesser carbon emissions) for existing computational tasks or for *solving previously* intractable tasks.

This point of view is a less traveled road for now, as we do not know yet which of the many potential quantum technologies and use cases would bring a true energy/ carbon emission advantage. Therefore, the goal of this document is to establish a joint statement of interest and raise awareness in the academic, research and development, industrial, and end-user communities to call for action, to encourage experimentation and investigation of this emerging technology, its impact, and its potential use cases from an energy footprint perspective.

PASQAL co-founded with Blaise Pascal Advisors and a consortium of partners, including Genci/HQI, QEI, EDF R&D and Jülich Forschungszentrum, an international initiative to *seed proofs for the impact of quantum computing* as well as to foster that the industry takes its share in complying with the United Nations sustainable development goals. This initiative included a hackathon launched in the summer of 2023—*the Blaise Pascal [re]generative quantum challenge*—followed by the present whitepaper and numerous associated actions meant to promote meaningful and sustainable uses of quantum computing. We pursue a deliberate attempt to bring forward positive contributions in the context of a sometimes controversial debate on the impact of technology, including but not restricted to climate change. These endeavors require clear criteria, accountable figures of life-cycle analyses of a Quantum Processing Unit (QPU), and a sound comparative basis to classical computing.

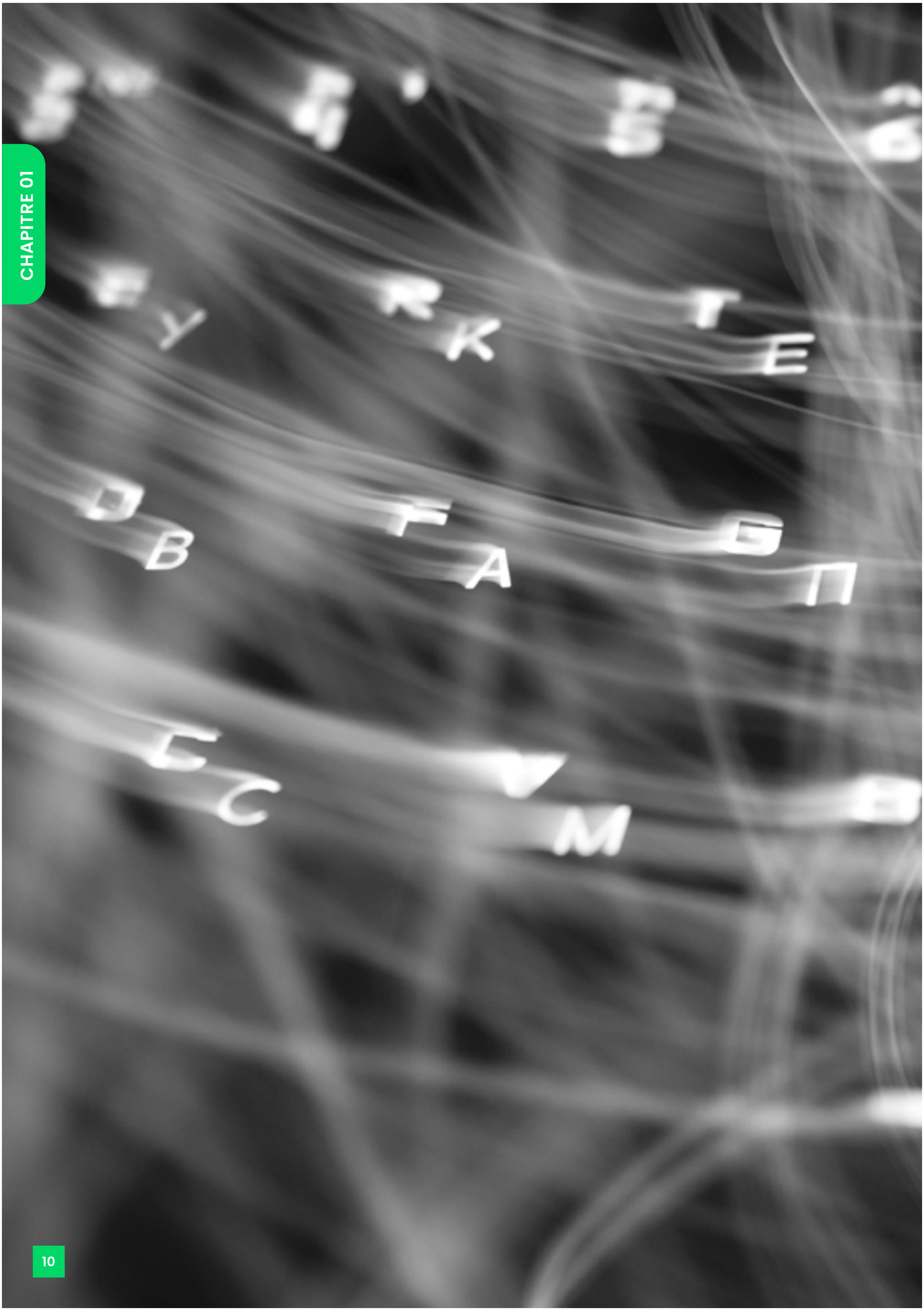
THE PRESENT DOCUMENT AIMS AT :

Setting reference elements for a life-cycle and use-case-based approach of sustainable quantum advantage.

Documenting the hackathon experience as an avant-garde experiment to investigate the potential of sustainable quantum computing.

Preparing future standards for regenerative and impactful quantum computing using neutral atoms technology.

Outlining later research and communication's agenda.



THE GENERAL CONTEXT : IT, SCIENTIFIC COMPUTING AND SUSTAINABILITYCHALLENGES

[*Written by Alexandra de Castro, science and technology communicator at PASQAL*]

In 2017, The United Nations General Assembly adopted the 2030 Agenda for Sustainable Development Goals (SDG). This agenda is the result of many decades of global efforts to promote human rights and sustainable development for all countries and to find common ground to create an effective plan of action to strengthen universal peace and freedom and eradicate poverty in all its forms, balanced in three main dimensions: economic, social, and environmental (UN Resolution, 2017).

Comprised of 17 goals, each plan of action has a specific target that should be achieved by 2030, such as zero hunger, achieving affordable healthcare and medicine for all, limiting global warming to 1.5 °C above pre-industrial levels, and reducing the greenhouse emissions in 43%, aiming at net zero by 2050 (Dpi campaign, 2017). But to be successful and accomplish these goals requires the attention and compromise of all actors: society, governments, and enterprises. We are in 2023, the clock is ticking and we are still facing enormous challenges worldwide, while some improvements suffered a setback due to the COVID-19 pandemic. In fact, the UN SDG 2023 report states that "slow and uneven progress on poverty reduction may leave hundreds of millions in extreme poverty by 2030." (UN-DESA, 2023).

Here, we extract some figures from the UN's latest report as examples that show the dimension of humanity's sustainability challenges.

SDG2 target: zero hunger. In 2022, between 691 and 783 million people faced hunger worldwide (UN News, 2023b, July 13), and around 2.3 billion people suffered from moderately or severely food insecurity (WHO, 2022, July 6).

SDG3 target: access to safe, effective, quality, and affordable essential healthcare, medicines, and vaccines for all. Although effective HIV treatment has cut global AIDS-related deaths by 52% since 2010 and at least one neglected tropical disease has been eliminated in 47 countries. AIDS, tuberculosis, and malaria still have epidemic proportions in developing countries. Around 2 billion people globally have no access

Fig.1. United Nations' Sustainable Development Goals (SDG) - Source https://sdgs.un.org/goals

to essential medicines, particularly in lower- and middle-income countries (Chattu et al., 2023).

SDG13 target : zero emissions and limit the global warming to 1.5 °C : The impact of climate change is increasing in intensity and frequency. Since the last decade, most regions have experienced more and more extreme weather events than in the past such as floods, wildfires, and storms. The global sea level rise is accelerating : it has more than doubled, from 1.4 millimeters per year throughout most of the twentieth century to 3.6 millimeters per year from 2006–2015. In 2022, the global average sea level set a new record high—101.2 mm above 1993 levels, 24 centimeters since 1880. Currently, 2.15 billion people live in the near-coastal zone and 898 million in the low-elevation coastal zone globally (Reimann et al., 2023).

Being SDG 13 only one in 17 goals, climate action is key to help improve in all other sustainability targets. Climate change can undo the progress made over the years. For these reasons, society, governments, and enterprises must ensure limiting global temperature rise to well below 2°C, and according to the US National and Atmospheric Administration we are facing the warmest years in the historical record since 2010 (Climate Change : Global Temperature, 2023b).

During the hackathon— *The Blaise Pascal [re]generative quantum challenge*—launched this year in October, PASQAL proposed six sustainability challenges related to ten SDGs that have the best chance to be addressed using neutral atom technology, effectively reducing the carbon footprint in comparison with classical methods. They are:

- Sustainable Agriculture (included in zero hunger – SDG2).
- Drug Discovery (included in access to safe, effective, quality, and affordable essential healthcare, medicines, and vaccines for all – SDG3).
- Smart cities (included in clean water and sanitation - SDG 6 & 11).
- Smart grids and Affordable/Clean Energy (SDG 7).
- Sustainable transport, industry and circular economy. (SDG 9 & 12).
- Environment, Climate, and Biodiversity (SDG 13, 14 & 15).

1.1 Information Technologies role in help meet SDG

The UN also recognizes the crucial role that Information Technologies (IT) play in achieving SD goals. For instance, digital documents with digital signatures to enhance the good use of natural resources or online meetings to decrease the transportation carbon footprint. Within IT is essential the access and smart use of supercomputers, also called data centers or high performance computers (HPC). Scientists have been using powerful supercomputers to store and process data related to the sustainability challenges. For example,

- Addressing food security (SDG2) through effective models in food supply optimization (Angarita-Zapata et al., 2021). These computational approaches hold enormous potential to help manage supply chains more efficiently and sustainably.
- For healthcare and medicines security, related to SDG3, we have that computer-aid drug discovery has significantly reduced the time and expenditure of drug development (Ece, 2023). Although these methods face some limitations, in some cases, computational techniques can provide a better view of the structure and molecular dynamics of the biological system than experimental setups (D'Arcangelo et al., 2023) .
- Addressing climate impact and targets (SDG13), scientists have been collecting enormous amounts of data from many sources, such as atmospheric, geochemistry, and ecology, and simulating the intricate patterns and modeling the future implications of climate change. However, the data collection, storage, and process have a drawback: supercomputing centers consume vast amounts of energy!

Since the last century, high-performance computers have been growing, offering more precise and faster calculations, and today, they accommodate thousands of processor cores requiring entire buildings with costly cooling systems. Rethinking energy consumption and reducing greenhouse emissions has become an essential mission for enterprises offering computational and data storage services. However, despite the efforts to lower energy consumption it is still extremely high. Therefore, real, transformative strategies and actions are crucial, beyond mere plans and promises.

1.2 Classical supercomputers' footprint

In 2020, IT represented 11% of the global electricity consumption (Puebla et al., 2020). An analysis by Huawei Technologies shows that it can increase to 51% in 2050 (Andrae & Edler, 2015), that this electricity usage could contribute up to 23% of the globally released greenhouse gas emissions in 2030, including, but not limited, to data center computation and storage (also called HPC centers or supercomputers). Supercomputers can consume the same amount of electricity as a town. For instance, the Frontier supercomputer, fabricated by Hewlett Packard and hosted at the DoE Oak Ridge Laboratory in Tennessee, USA, uses 504 MWh on average daily, summing up the energy consumed by around 17 thousand average homes in the U.S. daily (EIA, 2023). And this is only one data center.

Regardless of these numbers being too high, they are actually a success in efficiency (Koomey, 2023). Digital engineers have created smaller and more efficient transistors, improved the circuits, the software, and the power-management schemes. But despite these tremendous improvements, the workload has also increased so that more enterprises need more and larger data centers with an annual energy consumption growth of 20- 40% (Data centres & networks, 2023).

1.3 Addressing SDG challenges and lowering the energy footprint with quantum computers

Quantum computing is rapidly emerging to play a key role in the next generation of high performance computing to address complex problems, inaccessible to traditional devices (see Figure 1 by Ezratty, 2023). They are called inaccessible or intractable because their computation time increases exponentially with their size (Ezratty, 2023). The good news is that most of these problems, that have industrial and scientific relevance, exhibit a natural encoding onto quantum physics, which is the basics of quantum computing. Common examples are optimization problems, such as food chain supply optimization (FSO), which encompasses all activities, organizations, actors, technologies, information, resources, a nd services involved in producing agri-food products for consumer markets.

The upstream and downstream of FSO comprises sectors from the supply of agricultural inputs, such as seeds, fertilizers, feed, medicine, or equipment, to production, post-harvest handling, processing, transportation, marketing, distribution, and retailing (Angarita-Zapata et al., 2021). The Food Supply Optimization represents a complex challenge in finding the balance between productive efficiency and sustainability of food supply systems.

Other typical examples of intractable problems are chemistry simulations at the molecular level, which are particularly crucial in healthcare, such as drug design (Varsamopoulos et al., 2022) or toxicity prediction (Albrecht et al., 2023).

The promise of quantum technologies to tackle such intractable problems in a "human scale" time period is called quantum advantage (Ezratty, 2023). With its promising ability to solve complex problems, quantum computing can provide innovative solutions to address the most pressing humanity and environmental challenges.

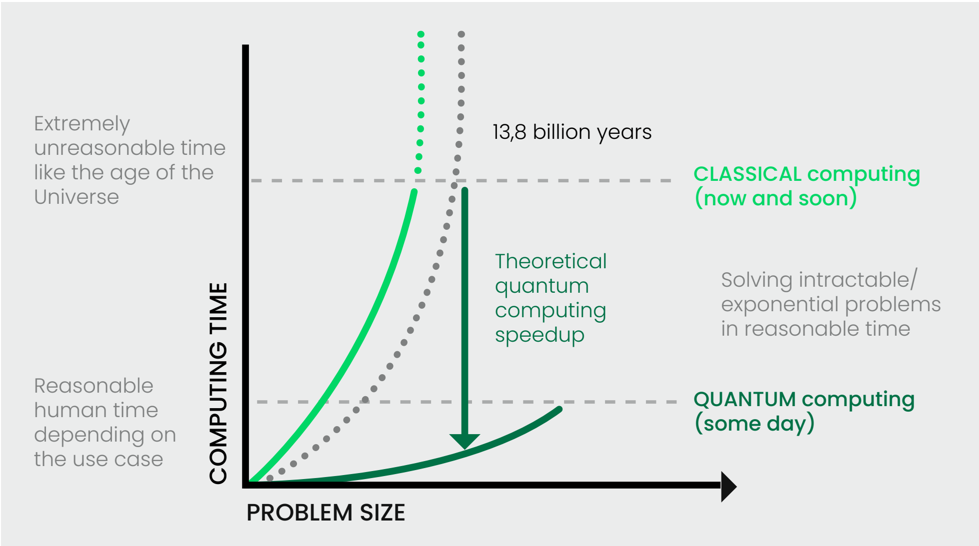


Fig.2. Illustrating the quantum advantage - (CC) Olivier Ezratty, 2023

By combining quantum computing with artificial intelligence and big data analytics, quantum technologies can exploit potential synergies to accelerate environmental innovation. This will identify integrated solutions, such as smart grids, sustainable agricultural practices, and circular economic mechanisms, to maximize positive environmental impact. Will quantum advantage arrive with energy consumption advantage? We still don't know, but what we can say today is that current quantum computers' electricity usage is orders of magnitude much less than any supercomputer, counting all the different quantum architectures available. Being superconducting qubits the most expensive architecture, they only consume about 25 kW (Ezratty, 2023). That amounts to 600 kWh daily, a thousand times less than the Frontier supercomputer. Much less is the consumption of neutral atom quantum devices, such as PASQAL's, which amount up to 3 kW. But again, no current quantum computing can address all the problems that Frontiers is able to tackle.

Although quantum computers have proven superiority over classical computers in tackling particular scientific problems (See Scholl et al., 2021; Chen et al., 2023), they are not yet ready to solve real-world complex problems, since current quantum computers are noisy, and fault-tolerant quantum computers won't be available for a while. However, because some quantum algorithms are designed to successfully work within the so-called Noisy Intermediate Scale Quantum (NISQ) era, certain architectures, such as PASQAL neutral atom devices hold the potential to tackle many industry-level use cases before the fault tolerance era. In this short term scenario, there is room for real energy quantum advantage. Another point to be considered is that quantum technologies are not meant to replace classical CPUs or GPUs but to be in synergy with them. Therefore, the hope is that quantum computers effectively lower the carbon footprint for hybrid workflows.

There are still many questions that need to be addressed, for example, if this potential energy advantage of quantum computing will hold for all kinds of algorithms and applications? Is the fabrication process green enough for computers in both cases, classical supercomputers and quantum computers?

Scientists and engineers need supercomputers for data collection, storage, and computations to create more knowledge, manufacture better products, and solve the most pressing problems of our times, such as food security, drugs discovery and accessibility, and the climate crisis. But to tackle the sustainability problems, enterprises offering computing services, whether classical or quantum, should assume the compromise to lower their carbon footprint, and if possible to reach zero emission, while helping humanity to reach our global sustainable development goals.


DELL

THE BLAISE PASCAL QUANTUM CHALLENGE APPROACH FOR ASSESSING THE QUANTUM SUSTAINABILITY ADVANTAGE

[*Written by Etienne de Rocquigny, CEO Blaise Pascal Advisors, cofounder of the Blaise Pascal [Re]generative Quantum challenge*]

To celebrate the 400th birth anniversary of the renowned French mathematician, engineer, philosopher, physicist, and philanthropic entrepreneur Blaise Pascal, we have launched the hackathon *"Blaise Pascal [Re]generative Quantum challenge"* to underscore the benefits of quantum computing for sustainable development. This endeavor aims to serve in an accountable manner the UN SDGs outlined in the previous section, as well as ensuring a more sustainable energy use of computing resources. To achieve these objectives, we called for SDG-impact use cases evaluating the classical/quantum computing ratio of power consumption.

However, for a meaningful evaluation, first, we need to consider the distinction inherited from Green IT vs. IT for Green:

- *Sustainable QPUs (Green quantum IT)*: an approach whereby quantum computing can solve tasks traditionally performed by classical HPC with a significantly lower energy/carbon footprint.
- *QPU for sustainability (quantum IT for Green)*: an approach whereby quantum computing can solve tasks that are core to applications with a positive impact on sustainability, such as better battery storage, lower car consumption, or food supply optimization), hard or impossible to tackle through classical HPC.

For the purpose of the hackathon, however, use cases without SDG impact[1] are meaningless, as well as those impactful use cases whereby quantum computing has no present (or at least future) advantage over classical computing. A better distinction would be between:

- *Relative sustainability advantage of QPU*: Use cases for sustainability whereby quantum computing shows a better energy/carbon footprint over classical HPC.

[1] Hereinafter,. Impact will stand for impact on SDGs, as subsumed in for instance impact finance, impact funds, etc.

- *Absolute sustainability advantage of QPU*: Use cases for sustainability that are impractical (impossible or far too costly) to tackle with classical HPC.

Under this criteria, we proposed two main requirements to evaluate the projects contenders of the hackathon:

- It must address a use case with sustainability impact, clearly framed in at least one of a selection of SDG challenges (see Appendix for details).
- The projects must provide evidence showing that their solution has a relative footprint quantum computing advantage over classical computing that is higher than 1, ideally infinite (a use case intractable with classical methods).

Those requirements filter out projects judged irrelevant enough at the early stages and rank them until the final phase of the evaluation and selection process.

The proposed solution's quantum feasibility / technical credibility is considered an important part of the score: projects should lead to code that can run on existing quantum technology.

2.1 What is a use case with impact?

The **Blaise Pascal [re]generative quantum challeng**e is meant to promote meaningful and sustainable uses of quantum computing, as a deliberate attempt to bring forward positive contributions including but not restricted to climate change. As advocated in a number of papers (for example in Berger et al., 2021), impactful use cases involve potentially:

- Quantum simulation of classically-intractable quantum chemistry for drug design or material science applied to innovations in solar panels and battery design.
- Quantum optimization: solving hard (incl. NP-complex) problems that are involved in operations research and graph theory that can be applied to transportation or energy network layout.
- Quantum based hybrid solvers for nonlinear partial differential equations, or machine learning used in environmental technology, climate modeling, or resource allocation.

It is helpful to link to existing international standards on common good objectives and ethics of tech, particularly the European, UN, and UNESCO pieces (cf infra). However, honoring Blaise Pascal's philosophy and entrepreneurial spirit, somewhat skeptical of the perfection of law and justice, but fully committed to exploring the public 's attempt to contribute to the common good, it was suggested to take a rather open-minded attitude than to strictly follow a list. Hence, the criteria was open to a variety of statements of purpose, freely argued by the competing teams. The teams also had to discuss how they eschewed potential negative impacts or even excluded use cases. Within the context of the present hackathon, the following general categories were outlined:

- Drug Discovery
- Sustainable Transport, Industry, and Circular Economy
- Smart Cities
- Smart Grids, and Affordable, Clean Energy
- Environment, Climate, and Biodiversity
- Sustainable Agriculture

Beyond the choice of the category, the expected positive impact contribution must avoid too general proposals. For instance, energy-efficient AI is not enough to qualify for a fully-positive impact if nothing is said about the applications of such AI. In this sense, the teams should provide:

A. A statement of purpose
Teams had to argue in their own terms the purpose of the use case they chose: how does it illustrate a contribution of quantum computing to the sustainable development challenges, such as transport, energy, or health within the UNESCO recommendation on the ethics of AI or the UN sustainable development goals.

B. Trustworthiness / limitation of negative impacts
Teams had also to check how the proposed use case builds a trustworthy use of computing as defined for instance by, but not limited to, the European upcoming AI-Act or the UNESCO recommendation on the ethics of AI. They may have had to discuss the mitigation of potential negative impacts, such as lack of intelligibility/transparency, unfairness or endangering of vulnerable people, addictiveness of IT uses, lack of consent or breach of autonomy of human beings, lack of responsibility or human oversight, unwanted safety or security risks, and disrespect of privacy.

Use cases prohibited by the European upcoming AI-Act were excluded from the contest: subliminal or purposefully manipulative techniques, exploiting people's vulnerabilities, social scoring, remote biometric identification systems. Military applications are also excluded.

2.2 A lifecycle approach to assess the energy/carbon footprint of quantum vs. classical computing

It is crucial to go beyond the pure "core run" comparison between CPU and QPU in terms of number of cycles or power requirements. For instance, the list of low energy data centers Green500 distinguishes the highest energy efficiency in Gflops/W (currently led by the Henri system at the Flatiron Institute in New York City, United States, with an energy efficiency of 65.40 Gflops/W). However, the entire energy/carbon load of fabrication, as well as the sustainability goal of the use cases running on them, are not mentioned. Equally, the emerging trend in AI to compute the CO2 emission of machine learning training relies mostly of direct power consumption converted according to the carbon content of the server location (see for instance https://mlco2.github.io/impact/#compute) A life-cycle analysis (LCA) with due overheads associated with the fabrication of the computing machines (generally considered as amounting to more than half of the footprint of IT, depending also on the carbon content of electricity), as well as the entire cycle (pre, post, hybrid architecture) must be subject to constant review and regulation. See for instance the French 2021 REEN Act[2], or MIT's LCA methodology adopted by DELL[3].

Fabricating a supercomputer (be it classical or quantum) indeed involves a complex process with numerous components and considerations, each contributing to an overall carbon footprint:

- Design: The design of a supercomputer involves a large amount of engineering and computational cost, as well as hardware prototyping, which add to the carbon emissions during the manufacturing period.
- Manufacturing Materials: The production of a supercomputer involves a wide range of materials, including metals, semiconductors, lasers, cameras, and plastics. The extraction, processing, and transportation of these materials contribute to carbon emissions. For instance, producing semiconductors, which are at the core of supercomputer components, is energy-intensive.
- Energy Consumption: Fabricating and assembling a supercomputer requires significant energy, especially in manufacturing semiconductor components, plus optoelectronics for quantum. The electricity used in clean rooms, where microchips are fabricated, often comes from fossil fuels or energy-intensive processes, which can substantially increase the carbon footprint.
- Transportation: Supercomputer components are manufactured in different locations worldwide, and they are often transported across long distances. The shipping of components, including server racks, cooling systems, and networking equipment, contributes to emissions due to transportation fuels.
- Manufacturing Processes: The manufacturing process itself involves various stages, including etching, lithography, and assembly. These processes can release greenhouse gasses, depending on the energy sources used and the efficiency of the manufacturing facilities.
- Cooling Systems: Supercomputers generate a significant amount of heat, and efficient cooling systems are essential. The energy used for cooling can be substantial and may involve refrigerants that have a high global warming potential.
- End-of-Life Disposal: The carbon footprint also includes considering the disposal of supercomputers at the end of their life cycle. Proper recycling and disposal methods can mitigate environmental impact.

In brief, a comprehensive analysis should consider the entire **life-cycle assessment** of a supercomputer, from the extraction of raw materials to manufacturing, operation, and disposal. This includes both:

- The direct emissions associated with the **hardware** life-cycle.
- The indirect emissions from the energy required to **operate** the supercomputer.

The entire computation cycle should be considered, given that many HPC tasks include hybrid architectures involving CPU + GPU and QPU in the quantum cases, as well as pre- and post- analysis often involving ordinary computers, cloud servers, databases, and IT networks.

Sustainability is here considered, then, as an energy balance, putting apart the issue of heterogeneous carbonation of energy according to places, as well as other sustainability issues, such as biodiversity, and pollution, less amenable to scoring the differential impact of quantum computing.

Ratios on PASQAL's machines were provided to the candidates in order to have a basis of comparison:

- A figure for the kgCO^2-equivalent per hour of use of the PASQAL quantum stack in a run.
- A figure for the kgCO^2-equivalent per hour of use of the PASQAL quantum stack accounting for the life-cycle footprint of the hardware.
- Corresponding figures for at least one reference HPC classical computer, including reference to number of codes and memory size.

2.3 Energy/carbon footprint of classical HPC centers

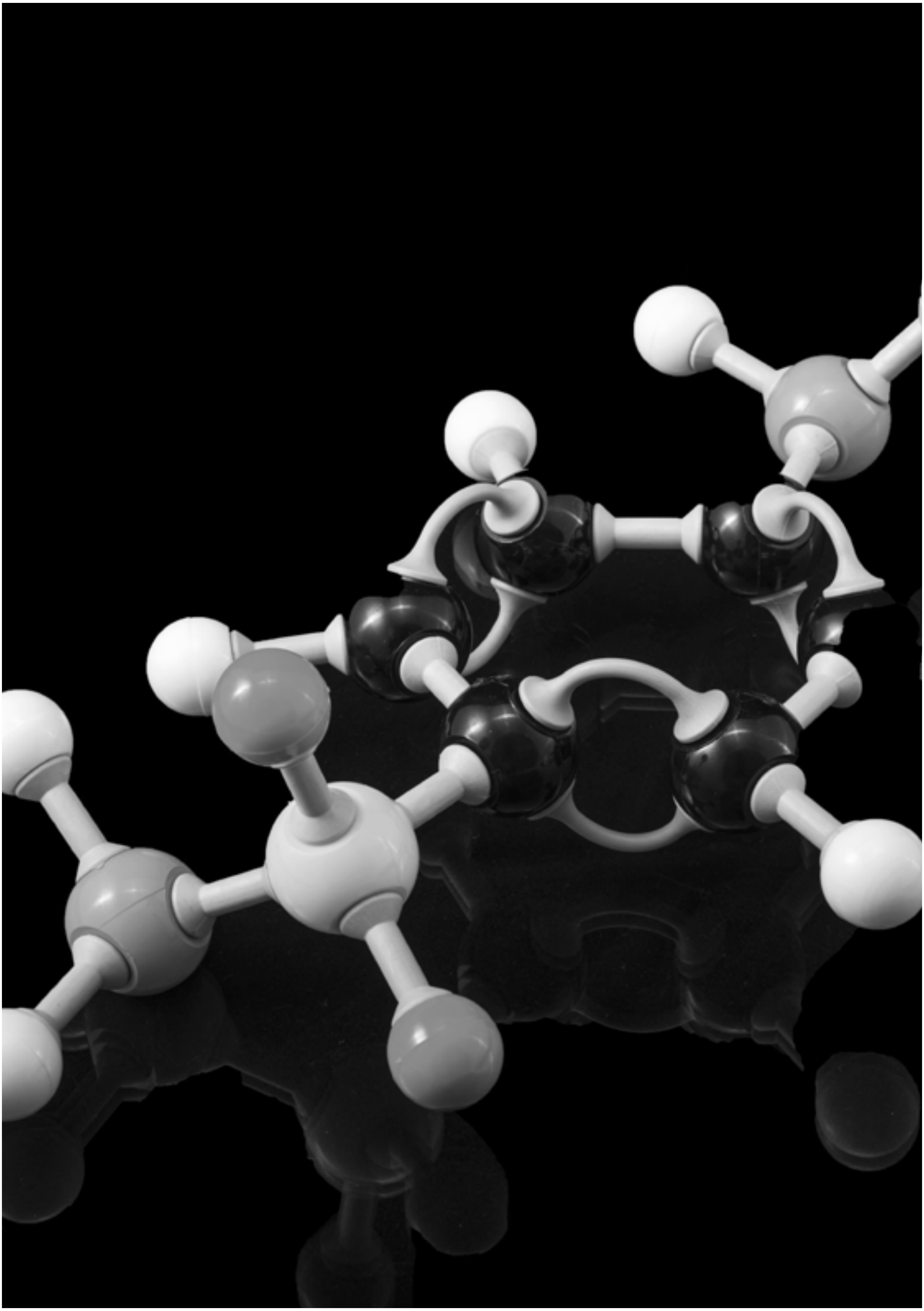
Computers, in general, have a carbon footprint typically coming from:
- Building the computer. Memory (SSD solid-state drives) now weighs the highest, followed by chips within CPU/GPU
- Running programs direct power consumption by the CPU/GPU complemented by cooling power for large machines. Though sometimes the heat extracted is partially reused, its carbon footprint remains high (as heat use is of lesser carbon offset that the carbonation of electricity supplied)

HPC supercomputers vary largely in terms of size, performance, and power needs, and we could not find any life-cycle analysis of carbon footprint. As a starting point, here are a few orders of magnitude[4] from the greenest according to Green500 score (limited to energy efficiency only) to the quickest in flops :
- The winner of Green500, Henri, with ar. 8200 cores consumes 44kW of power for 2,9 Pflops/s. Hard to figure precisely the tCO2eq. fabrication emissions, around 624 tCO2eq. This is around 200 times more power

[2] https://www.vie-publique.fr/loi/278056-loi-15-novembre2021-reen-reduire-empreinte-environnementale-du-numerique
[3] MIT developed a life-cycle analysis methodology for IT products http://msl.mit.edu/projects/paia/main.html , adopted for instance by a Dell whitepaper evidencing 80% of the carbon footprint relevant to manufacturing.
[4] Those orders of magnitude are derived from ratios on the published number of CPUs, GPUs, the amount of RAM, SSD and the power consumption

and 300 times more CO^2 emissions than a standard GPU server (200W to run and some 2t CO^2 eq. to manufacture).

- The winner of TOP500, Frontier with millions of cores consumes 22 MW of electricity power for 1194 Pflops/s. Manufacturing carbon emissions could be around 160 000 tons of CO^2.
- Joliot-Curie Rome, benchmark machine for GENCI with 7Pflops/s involved around 2,2kt CO^2eq of carbon footprint for manufacturing as well as 1.5MW of computing power, meaning with French carbon content ~0,1tCO^2/kwh as much in run emissions as manufacturing emissions in order of magnitude.



LESSONS DRAWN FROM THE BLAISE PASCAL QUANTUM CHALLENGE : USE CASES AND MATURITY

[Written by Krisztian BENYO, PASQAL team and chief mentor of the Blaise Pascal [Re] generative Quantum challenge]

For a neutral atom quantum computer, such as PASQAL's, problems or methods connected to graphs are the best fit due to its relatively native implementability. This is due to the fact that the atomic register of cold neutral atoms can be naturally interpreted as a graph-like structure from a mathematical point of view; indeed by identifying individual trapped atoms as vertices and truncated electric dipole-dipole (van der Waals) forces in between them as edges (Thabet et al., 2023).

Graphs (or more generally speaking, networks) can appear in many shapes or forms for a large variety of problems, and the candidates managed to exploit this particular feature in various ways. The complexity of the Hackathon came from the fact that the participants were required to identify and precise a fitting problem and propose a solution that is implementable in the NISQ-regime.

Problematics of the sustainable transport, smart-grid and smart-city management sectors give rise to many complex network-based optimization tasks, and, as most graph-based optimization problems are connected to combinatorial optimization problems, this yields to large-scale, complex challenges that rarely have exact solutions. Scheduling or planning type problems, resource allocation related issues, object placement and control type problems are typical examples in this field, and most of them are addressed with heuristic methods, providing a time-efficient but only approximate solution.

Due to the heuristic nature of existing classical solutions, there is room for improvement in the quality of the obtainable solution, which gives relevance to quantum-enhanced optimization. However, as the participants tackling problems of this domain were quick to discover, industrially relevant problem sizes far surpass the encoding capabilities of currently existing QPUs. It is indeed a question of the number of qubits after all. Typically, a telecommunications network of varying frequencies tackles a couple thousand nodes simultaneously for a current classical simulation, just as a modeled electricity, gas, or water distribution system contains 2000-5000 junctions, nodes, and entry and exit points. Since the network structure has to be captured on the quantum register, amplitude-based efficient quantum information encoding methods are not applicable. Moreover, because of the many constraints on such systems, ancilla qubits are also necessary, making a typical problem encoding many-to-one in terms of qubits-to-node ratio. Designing intelligent embedding methods that focus more on the structure of the constraints is a valid strategy; however, it is only relevant to certain types of problem classes (planning and scheduling typically).

Quantum chemistry simulation-related problems face similar issues since describing molecular dynamics requires working on the orbital level (so on the scale of the electrons) rather than on the atomic level. Proteins that the pharmaceutical industry deals with typically have more than a thousand atoms (the smallest known protein, the TRP-cage, consists of 154 atoms), implying that the corresponding amino acid chains would need more than 10.000 orbitals for an actual quantum embedding. This makes ab *initio* chemistry-related applications infeasible to the current generation of QPUs, requiring quantum-enhanced applications to divert their gaze towards more structural approaches, focusing on the geometry of molecules rather than their molecular dynamics. Such methods, combined with classical Machine Learning techniques (Henry, et al., 2021), can lead to exploitable algorithms in the domain.

The Hackathon has inspired candidates to investigate in various directions in the drug discovery field, leading to original embedding techniques transforming a molecular dynamics-related problem into an adapted optimization problem instead. Exploiting the binding interaction graph in a ligand-receptor interaction, such as the **Molecular Docking project** (3rd place in the Hackathon), or even encoding crystalline structures on unit-disk graphs, has led to very promising exploratory projects that, given some time for quantum technologies to mature to a larger scale, will lead to exploitable applications in the near future.

A special mention needs to be made for the **NeutroGen project** (2nd place in the Hackathon) for taking a more theoretical approach and reinforcing the data pre-processing method for hybrid algorithms in general. As they have reasoned, neutral atom quantum computing provides a promising framework for addressing a wide variety of data-driven sampling problems that can be adapted to combinatorial optimization that can leverage any previously-found solutions from a conventional optimizer. Incoming data can be automatically translated to high-quality neutral atom positions via techniques from spectral graph theory. The resulting atom embedding gives rise to generated data with similar correlation patterns as the original data using current-day adiabatic protocols.

Interestingly enough, the most promising use cases from the Hackathon have arisen from the renewable, clean energy sector. Not only did the previously mentioned NeutroGen team successfully apply their data-driven approach to benchmark a wind farm optimal placement solution, but the winning **NAREF team** (1st place in the Hackathon) have managed to propose a novel method based on quantum reservoir computing to describe a complex system of renewable energy resource management. A "reservoir" is itself a physical system that exhibits complex behavior. As a metaphor, its mathematical dynamics are used to replicate the behavior of underlying time series. It is an alternative to deep recurrent neural networks, linear regression being the only training step implicated, and is done after all data has been fed successively through the reservoir, therefore has a very low training cost. As it was demonstrated by the team, a free arrangement of neutral atoms makes reservoir computing particularly well suited for analog frameworks such as PASQAL's machines.

ENERGY/CARBON FOOTPRINT OF PASQAL TECHNOLOGY

[*Written by Alexandra de Castro, science and technology communicator at PASQAL, Etienne de Rocquigny, Blaise Pascal Advisors and Matthieu Courtière 500ppm advisory and PASQAL's hardware team.*]

4.1 PASQAL neutral atom quantum processing unit energy cost

In neutral atom quantum computing architecture, a sort of vapor of atoms, typically rubidium or strontium, is created inside an ultra-high vacuum chamber. These atoms are trapped and manipulated within the vacuum chamber using highly focused lasers, so-called optical tweezers, to create 2D and 3D arbitrary shapes. The quantum information is encoded by manipulating the atoms' electronic states. Each qubit is represented by a two-level energy state in an atom, usually a ground state and a Rydberg state. The current generation of PASQAL devices uses around 100 ^{87}Rb (rubidium) atoms for computations. Rubidium is an easy-to-mine alkali metal that benefits from well-established laser technology that brings its electrons to various energy levels, including the Rydberg states. In the Rydberg state, atoms physically grow and get polarized, facilitating van der Waals' interactions and entanglement. The fact that in PASQAL devices, each qubit is created out of a single atom makes this technology less prone to errors since the qubits are identical, not fabricated but provided by nature (see Henriet et al., 2020 for technical details).

Various components are needed to set up and complete the calculations in a neutral atom processing unit and each of them sum up to the energy consumption of the device. Since current PASQAL devices function at room temperature, no power consuming refrigeration component needs to be considered. In the worst case scenario the total Fresnel's energy consumption amounts to 2-3 kW. .

4.2 PASQAL quantum processing unit carbon footprint and benchmark with classical HPC

In this subsection we use the carbon dioxide equivalent (CO2eq) standard unit, a standard metric unit defined to compare emissions from various greenhouse gasses on the basis of their global-warming potential (GWP), to evaluate PASQAL QPU's carbon footprint and compare with classical architectures.

At the present stage a starting estimate for PASQAL's Fresnel would involve :

- In order of magnitude, a few tens of tons of CO_2eq are related to manufacturing the typical hardware equipment (including lasers, control, and opto-electronics).
- In order of magnitude, a few kW of electricity are used to run. In September 2023, the hardware team estimated approximately 3kW, meaning that, under favorable low-carbon French electricity, a few tens of tons of CO_2eq would be released over an operational lifetime of 7 years.

The following table summarizes the benchmark basis between HPC (Joliot Curie supercomputer of GENCI at TGCC/CEA) and PASQAL's technology used for the hackathon.

Key remaining sources of uncertainty for later research :

- The scalability factor :
  - Those orders of magnitude hold for the current 100+ qubits QPU and up to the next generation until 1000 qubits (Rubi). Preliminary PASQAL studies suggest a likely slow increase in power requirements up to 10 000 qubits, to be confirmed.
- The complete time needed to perform a quantum computational task benchmarked with the equivalent classical run, including preparation, repetition of noisy cycles, etc.
- The present-day clock rate is around 1Hz and it is estimated to increase up to 100Hz with good likelihood by 24 months with no increase of power consumption.
- The effective ratio of use including technical uptime + saturation of use.
- Quantum computing is still noisy and a universal fault-tolerant QPU will need to implement error corrections. To implement error corrections we need to encode quantum information into larger Hilbert spaces, which physically might translate into adding more qubits. We will also need to check on the use of classical devices involved in the error correction process (Auffèves, 2022).
- The power cost related to the classical CPU/GPU needed to prepare and/or coprocess the computation.

In a follow-up white paper, we will provide a complete analysis benchmarking quantum/classical power consumption associated with two SDG relevant use cases that are currently being implemented on Fresnel and are candidates to reach quantum advantage. We will analyze the implementation of the same problems addressed with different state-of-the-art classical numerical techniques used for quantum simulations benchmarked with hybrid quantum/classical workflows and discuss the energy consumption and its impact on the environment.

Reference computation					
	Joliot-Curie Rome 12 Pflops/s	Fresnel under 140 Qubits	Rubi500 to 1000 Qubits	Basic GPU server	Impact unit in kgCO2eq. /u
CPU (units)	4 584			0	**20**
GPU (units)	128			3	**20**
RAM (TB)	573			0,128	**3 600**
SDD (PB)	0			0,015	**51 000**
HDD (PB)	5			0,15	**3 750**
Total hardware manufacturing (tCO2 eq)	2 176	25	25	2	**Total emissions for HW manufacturing, transport and disposal over lifetime**
Conservative lifetime hours amortizing hardware emissions	49 056	20 440	20 440	28 032	**Reference number of running hours over lifetime taken as the amortizing basis for the hardware emissions per run**
Equivalent manufacturing emissions (kgCO2 eq/ run hour)	**44**	**1,2**	**1,2**	**0,07**	
Nominal Power requirement (kW)	1 436	3	10	0,2	
Overhead provision for run power equiv (incl. add. net cooling, maintenance, etc.)	1,04	3,5	3,5	1,25	
Carbonation of electricity (kgCO2 eq/MWh)	85	85	85	85	French electricity is taken as reference
Equivalent run emissions (kgCO2 eq/ run hour)	127	0,9	3,0	0,02	
Total emissions (kgCO2 eq/run hour)	**171**	**2,1**	**4,2**	**0,09**	

PERSPECTIVES ON SUSTAINABLE QUANTUM ADVANTAGE BY THE RESEARCH AND INSTITUTIONAL COMMUNITIES

5.1 A Perspective by the quantum energy research community

[*Written by Stéphane Requena, CTO and Sabine Mehr, Chief Quantum Officer of GENCI.*]

The Quantum Energy Initiative (QEI) argues that quantum technologies will only be scalable in a world of finite resources if we make them as energy-efficient as possible.

The Quantum Energy Initiative is a worldwide network of researchers created last year (2022) to encourage and support research on the energy costs of quantum technologies. As founders of this initiative, we believe that we need high-quality research to minimize the costs of quantum technologies, in parallel to the ongoing worldwide research to maximize their benefits. If not, we risk arriving at a situation where a quantum technology will outperform an existing technology, but at a cost and environmental footprint that is too large to be acceptable for many applications.

To avoid this undesirable outcome, it is crucial that researchers develop quantitative methods to minimize energy consumption (and other resource consumptions) in manners that do not impact the benefits brought by quantum technology. This requires a system-level view, sometimes called the full-stack view of quantum technology, in which the full-stack is made of layers that contain everything in the quantum technology from the quantum devices up to the end-user. In this full-stack picture, there is a layer containing the quantum devices (qubits, etc), another layer containing quantum software (algorithms and protocols), and another layer containing all the enabling technologies (cryogenics, lasers, control electronics, etc). We argue that there are often complicated interrelations between different layers. This makes the energy optimization of the full stack a challenging research problem, requiring more than just the optimization of each layer individually. As each layer is typically the domain of a different discipline (Software being quantum information science. Quantum hardware being quantum physics. Enabling technologies being engineering), such research is necessarily interdisciplinary and

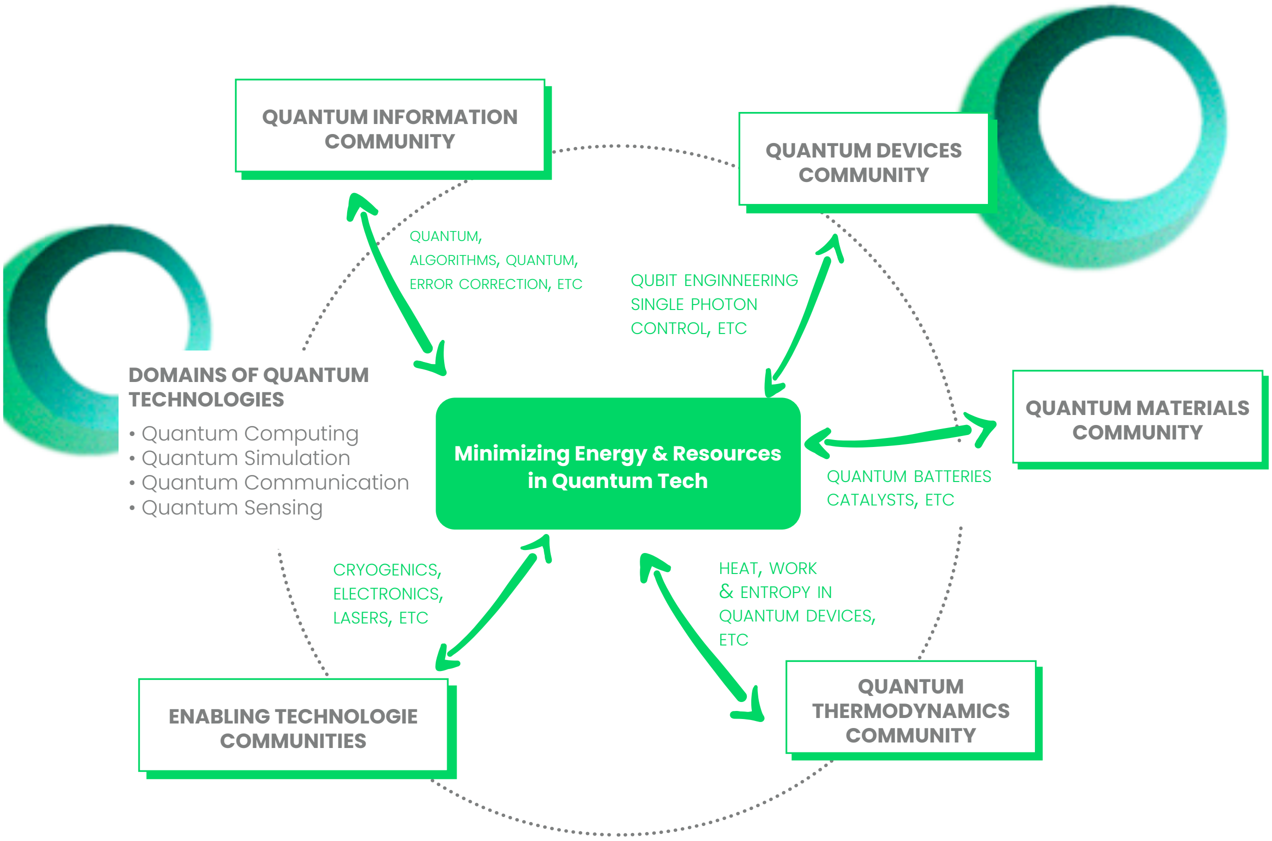


Fig.3. The context of quantum energy advantage - Source: Quantum Energy Initiative 2022

requires the development of a common language (and common tools) between disciplines.

As an example, consider a noisy quantum computer with two potential methods of achieving the desired precision for a given calculation with that quantum computer. The first method would be to cool the qubits further to reduce the thermal noise, while the second method consists of performing more quantum error correction or mitigation. Both of these come with an energy cost; adding more cooling requires more cryogenics or more powerful laser-cooling (consuming more electrical power), and adding more error correction requires more complicated correction protocols (also consuming more electrical power). A quantitative analysis of the costs and benefits of these methods (with costs being power consumption and benefits being improved precision) is required to find the amount of cooling versus error correction that achieves the minimal power consumption under the constraint of the desired precision.

However, we emphasize that this is only one example. This optimum will depend crucially on the type of qubits, the type of cryogenics, and the type of error correction. Improvements in the energy efficiency of either of them will require a re-evaluation of the optimum, so the methods used to determine the optimum should be robust enough for constant re-use. Each implementation of each quantum technology (quantum computing and simulation, quantum communication, and quantum sensing) will bring up other similar examples, each of which requires optimization. It is thus crucial to share methodologies and results as openly as possible.

There is also the open research question of whether quantum technologies are able to consume less resources while performing tasks that conventional technologies can already do, a so-called quantum energy advantage. This differs from better-known quantum advantages, such as quantum computational advantage, which correspond to the perspective that quantum technology could perform a task faster than existing technology. We at the Quantum Energy Initiative ask whether a quantum energy advantage may become the motivating factor for a significant proportion of use cases of quantum technologies. However, it is clear that this will only occur if there are serious research efforts to minimize the energy consumption of all aspects of each quantum technology.

5.2 Fostering key sustainable use cases : the approach of the Open Quantum Institute

[Written by Catherine Lefebvre, Senior Advisor OQI at GESDA and VP Global Policy and Partnerships at PASQAL; and Marieke Hood, Executive Director Impact Translator at GESDA.]

The Open Quantum Institute (OQI) is a multilateral governance initiative that promotes quantum computing for the benefit of humanity. The launch of OQI was announced in October 2023, in partnership with the Geneva Science and Diplomacy Anticipator (GESDA) Foundation, the Swiss Federal Department of Foreign Affairs (FDFA), CERN and UBS.

The OQI was designed and incubated over the period of 2020-2023 by GESDA– an independent non-profit foundation under Swiss law and a private-public partnership with the Swiss and Geneva authorities created in 2019 to strengthen the impact and innovation capacity of the international community through science and diplomacy anticipation – and with the participation of 130 partners from all over the world, including PASQAL. CERN will host the OQI during a three-year pilot implementation phase from 2024-2026, while GESDA will remain involved, ensuring the further growth of the organization.

This ambitious mission of the OQI in pioneering quantum computing for the benefit of all is structured around four core objectives :

- **Accelerating applications for humanity :** Realizing the full potential of quantum computing by accelerating the use cases geared towards achieving the UN's Sustainable Development Goals (SDGs), thanks to the combined forces of researchers and developers, entrepreneurs, the United Nations, and large NGOs.
- Access for all : Providing global, inclusive, and equitable access to a pool of public and private quantum computers and simulators available via the cloud.
- **Advancing Capacity Building :** Developing educational tools to enable everyone around the world to contribute to the development of quantum computing and make the most of the technology.

- **Activating multilateral governance for the SDGs**: Providing a neutral forum to help shape multilateral governance of quantum computing for the SDGs.

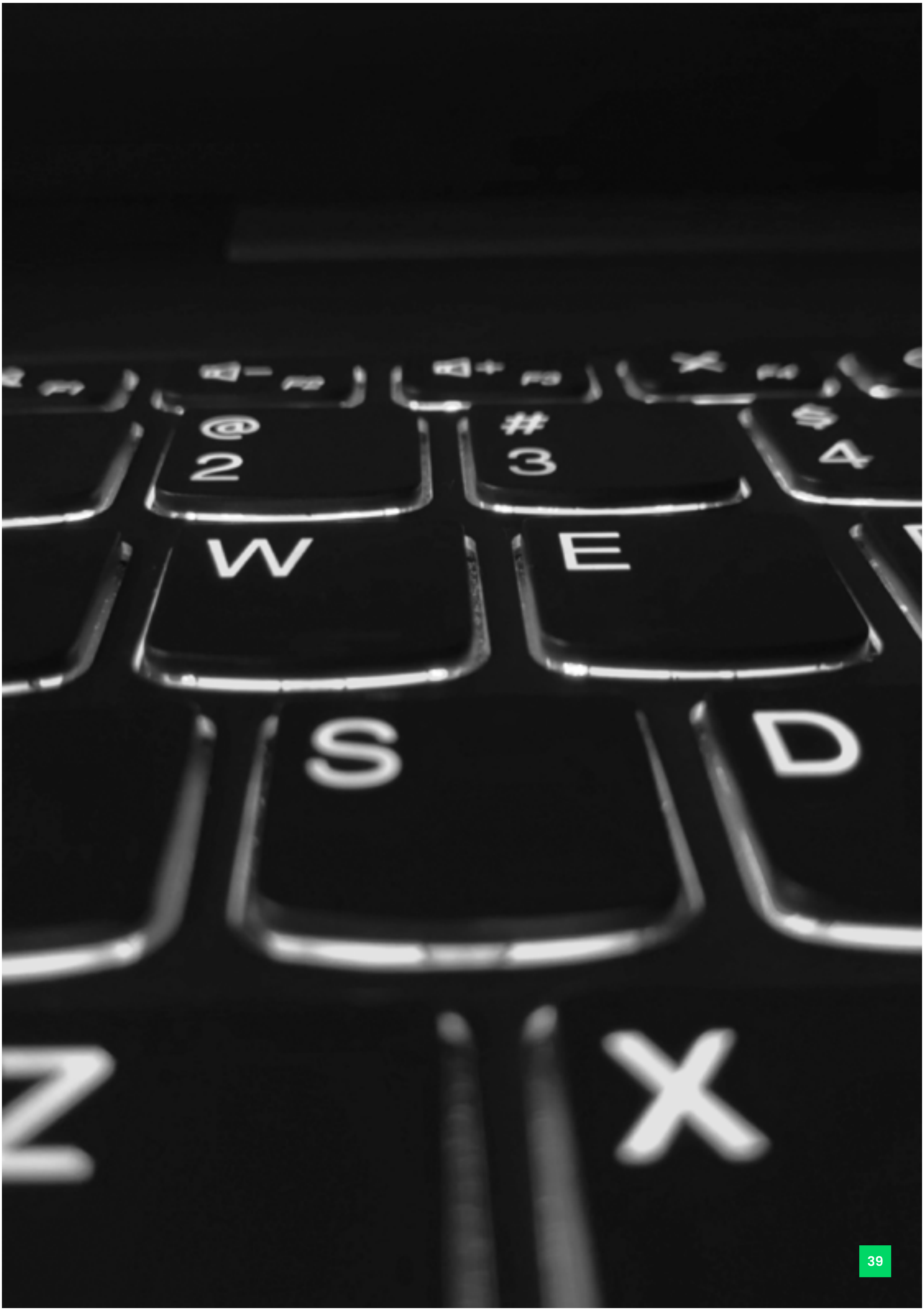
Today, quantum computing is still in its early stage of development and computational resources remain limited. For the few applications that can be implemented on current quantum computers, the focus is on applications presenting an immediately graspable commercial or geostrategic advantage, sponsored by organizations with the means to bet on a return-on-investment in the distant future. As a result, too few resources - in terms of computing and expertise - have been allocated to investigating how quantum computing could be harnessed to achieve the SDGs.

Understanding the importance of accelerating the implementation of the SDGs, the OQI has mobilized stakeholders to participate in re-balancing the focus and resources towards applications beneficial to the SDGs and global challenges. In the past two years, OQI teams from academia, industry, NGOs and International Organizations worked collaboratively to further explore use cases related to Food (SDG2), Health (SDG3) and Climate Change (SDG13). Below are some examples of the SDG use cases (please refer the OQI White Papers 2022 and 2023 for more details):

A. Carbon Reduction (SDG 13): Quantum Computing simulation to reduce carbon dioxide (CO2) in the atmosphere by improving catalysis process responsible for the fixation of carbon on the surface of materials –by a team of experts from Swiss Federal Institute of Technology Zürich, Ecole Polytechnique Fédérale Lausanne and United Nations Framework Convention on Climate Change.

The window is rapidly narrowing to achieve the goal set by the Paris Agreement of limiting global temperature increase to well below 2 degrees Celsius, while pursuing efforts to limit the increase to 1.5 degrees Celsius. Carbon Dioxide Removal could play a key role in achieving and sustaining net negative greenhouse gas emission in the long-term. One of such key challenges is to find effective solutions to store and valorize the CO2 once captured.

One approach to recycling carbon dioxide is to sequester it and then to transform it into other compounds, such as formic acid, methane, methanol, ethanol, or ethene. This chemical transformation can be accelerated by the interaction of carbon dioxide molecules with copper surfaces, through the process so-called heterogeneous catalysis (Nitopi et al., 2019). Although the catalysis process is relatively well adopted, it is still unclear how these chemical reactions are accomplished locally on a copper surface. Quantum computing is a natural tool to simulate chemical systems (Von Burg et al., 2021) to collect sufficiently accurate energy estimates. This is key to deriving a correct mechanism of the chemical processes that will support efficient carbon dioxide reduction solutions.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B. Mitigating Antimicrobial Resistance (SDG 3): Addressing global public health challenges, by developing a quantum computing solution to improve current AI models, predict more quickly and accurately patterns of resistance and identifying new chemical compounds with low resistance on more targeted bacteria – by a team of experts University of Copenhagen, Alphanosos and Global Antibiotic Research & Development Partnership

WHO declared antimicrobial resistance (AMR) as one of the top ten threats to global public health (WHO-GLASS, 2021; EClinicalMedicine, 2021). Furthermore, the World Bank estimates that if AMR is unchecked, by 2030, an additional 24.1 million people could be forced into extreme poverty (World Bank, 2017). Despite the significant economic, environmental, and societal costs, the development of new antimicrobials has not kept pace with the emergence of resistance, leaving healthcare providers with fewer options for treating infections. No new classes of antibiotics have been discovered in the past decades.

An approach to AMR research is to identify new drugs that have more targeted action to specific diseases and that are efficient against any known resistance mechanism. Machine learning methods are used to find new and efficient combination of compounds and prediction of patterns of resistance (Alphanosos, 2021). A quantum machine learning (QML) algorithm (Cerezo et al., 2022) could replace the standard machine learning algorithms to lead to improved mixes that can be tested experimentally, resulting in an iterative quantum computing/biological experiment workflow with faster convergence and higher-qualitative final samples.

C. Sustainable Food Systems & Global Food Security (SDG 2): Improving sustainability of global food systems by making them more resilient to climate change through a quantum optimization solution to produce more nutritious food locally in less land, and by lowering costs and emissions of food transport - by two teams of experts from Ecole Polytechnique Fédérale Lausanne, National Institute for Theoretical and Computational Sciences and Global Alliance for Improved Nutrition; and from ForeQast, Ernst & Young and University of Oxford.

Conflict and insecurity, economic shocks, and extreme weather events are the main drivers of acute food insecurity. To achieve SDG 2, the Food and Agriculture Organization (FAO) affirms that a better understanding of food systems requires a local-to-global perspective. Food systems are complex networks of activities, actors, resources, and environments encompassing the production, processing, distribution, consumption, and disposal of food products. Comprehending these networks is arduous as they are constantly evolving, and are interconnected with broader social, economic and policy systems.

Current projections indicate a necessary increase of food production per hectare by almost 60 percent by 2050 to meet the needs of the projected global population of 10 billion (GESDA Radar Breakthrough, 2023). As populations continue to grow, innovative solutions are much needed to devise sustainable agricultural practices that provide for more affordable nutritious diets, while respecting planetary limits.

Furthermore, climate change has a very strong impact on food systems, exacerbating hunger and malnutrition issues, especially in regions that are already vulnerable. It triggers extreme weather events, the emergence and spread of pests and diseases, and it compromises the adaptation of traditionally grown foods, resulting in reduced crop yields (IPCC: Mbow C., Rosenzweig, C., Barioni, L.G., et al., 2019). On the other hand, food systems also contribute significantly to climate change. While the production of food is a large contributor, greenhouse gas emissions associated with food transport also keep increasing (Pradhan, 2022).

Accurate modeling of food systems will help provide the basis for improving our ability to produce nutritious food sustainably and foster resilience and respond to unforeseeable food systems disruptions due to climate change. This is a class of optimization problems known as mixed-integer linear programming. Classical algorithms to find approximate solutions (heuristics) exist. However, this class of problems is in general computationally hard, making large-scale optimization challenging with classical computers and algorithms, as they would require exceedingly long computational time to reach a good approximate solution. Quantum algorithms hold promise to significantly enhance the quality of the solution to these optimization problems and represent therefore an ideal use case.

The OQI is building a large repository of quantum computing for the SDGs with the objective of inspiring greater participation in this ambitious endeavor to impact humanity. Throughout the process of developing use cases to their implementation on quantum computing devices, the OQI values adopting a responsible approach to quantum computing. This encompasses assessing both societal and environmental impacts (including energy/carbon footprint). In doing so, the OQI collaborates with experts to assess such impacts, anticipate negative externalities, and prioritize use cases.

THE PERSPECTIVE OF KEY HIGH-PERFORMANCE COMPUTING CENTERS ON QUANTUM CONTRIBUTION TO DECARBONIZING HPC

6.1 A French perspective by GENCI : France hybrid HPC quantum initiative (HQI)

[*Written by Stéphane Requena, CTO and Sabine Mehr, Chief Quantum Officer de GENCI of GENCI*]

Created in 2007 by the French Ministry of Higher Education and Research, CEA, CNRS, France Universités and Inria, GENCI (Grand Equipement National de Calcul) has the mission to provide French and European researchers (from academia and industry) access to leading-edge supercomputing facilities and services for their workloads in numerical simulation, high performance analytics and artificial intelligence.

To date, GENCI is giving free access to its facilities to more than 1500 projects per year based on Open Research (with the publication of the results at the end of the grand period). Such projects encompass a wide range of scientific and industrial domains, including climate research, material sciences, life sciences and biology, renewable energies, use of artificial intelligence at scale, fundamental sciences, astrophysics, or seismology, to name a few. In order to address such a variety of heterogeneous needs GENCI is deploying 3 different and complementary HPC architectures, representing a cumulated performance of more than 130 PFlops, hosted and operated by 3 national centers : TGCC for CEA, IDRIS for CNRS, and CINES for France Universités.

In order to continue this dynamics GENCI is also engaged into 2 majors actions :

- As the Hosting Entity together with CEA (as Hosting Site) and SURF (The Netherlands, as a partner) of the Jules Verne consortium for the co-funding and the hosting/operation of the 2nd Exascale system in Europe owned by EuroHPC. Such a system will provide end of 2025 HPC/AI resources as well as exploratory quantum computing accelerators for European researchers;

- French (HQI) and European (HPCQS, EuroQCS-France) hybrid HPC/quantum computing initiatives.

HQI (France Hybrid HPC-Quantum Initiative) stems from the French National Quantum Strategy, announced in January 2021 by Emmanuel Macron, the French President, and other initiatives related to quantum communications, sensors, and enabling technologies. It is led by CEA, GENCI, and Inria to tackle the hybridization between traditional HPC and Quantum computing and simulation technologies. It's a threefold project consisting in:

- A HPC-QCS platform exhibits various QPU technologies (to date, a device based on neutral atoms from PASQAL and soon another owned by EuroHPC based on photonics), coupled with GENCI' Joliot Curie supercomputer hosted at CEA-TGCC and later with the future EuroHPC exascale system hosted by France. The underlying idea is to allow French and European researchers to assess various QPU architectures, even in the NISQ noisy era, in order to find (or not) a possible match between these hybrid HPC+QC architectures and their algorithms and develop/prepare their workloads using scalable emulators (EVIDEN QaptivaTM, PASQAL Pulser or Quandela Perceval) and real physical systems.
- This coupling leverages other advanced features of the EVIDEN QaptivaTM solution. This will allow a seamless integration with the HPC resource management, as well as the provision of a portable programming environment, alongside with full-stack approaches provided by QPU vendors.
- A broad academic and industrial research program, targeting the actual HPC-QCS coupling from a holistic point of view, spanning from system integration up to hybrid end-user applications, as well as more exploratory topics such as noise characterization and mitigation, or leveraging quantum links to scale up.
- A dynamic dissemination (including hackathons) and end-user support program, to ensure French and European researchers from Academia and Industry can assess and benefit from these new

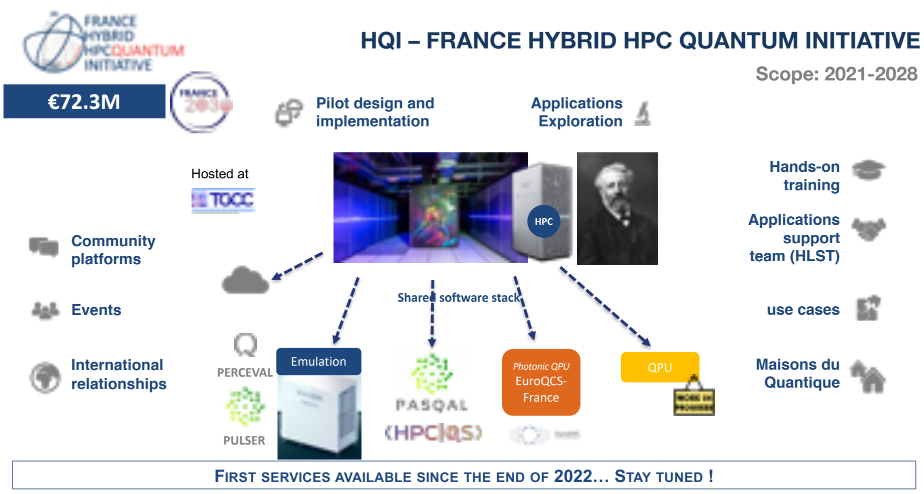


Fig.4. Overall view of the French HQI initiative

hybrid technologies. As an example at date HQI with the Paris Region, Le Lab Quantique and Teratec supported more than 10 proofs of concept of hybrid quantum computing exploration by industrial users (large groups, SMEs) in the field of optimisation, quantum chemistry, energy, CFD or finance/insurance to name a few.

To allow the coverage of a maximum of QPU architectures in Europe, share best practices, improve users engagement, and foster joint R&I actions, HQI is fully integrated inside European initiatives including HPCQS (aiming to couple 2 analogue QPUs from PASQAL to supercomputers in France (GENCI/CEA) and Germany (FZJ), see Fig. 5 and to build a common software stack), and EuroQCS-France (aiming to couple a photonic QPU to Joliot Curie), and collaborating with other EuroHPC JU Hosting Entities through a common integration program.

While these actions will engage users in the assessment of the potential of hybrid HPC/quantum computing for accelerating some workloads (in quantum chemistry, optimisation or quantum machine learning) leading to possibly demonstrating quantum advantage in performance in the future, there is also another kind of quantum advantage that could come earlier in the field of power consumption.

Today, typical power consumption of multi petascale supercomputers is in the range of 1 to 2 MW while next generation systems (so called Exascale) will be in the range of 15 to 20 MW (the #1 top500 supercomputer Frontier owned by DoE at ORNL is requiring 22.7MW for 1.2 Exflops HPL sustained performance). Power consumption is nowadays representing the biggest expenditure in operational expenses of HPC infrastructures and energy efficiency in a systemic approach (from single components, to infrastructure, middleware and end user applications) is a key challenge to address.

In that field, a lot of actions are already implemented by HPC centers/agencies in moving to GPUs (more efficient in term of performance per Watt but requiring code porting efforts), using hot water direct liquid (DLC) cooling techniques, profiling/monitoring end users applications for adapting on-the-fly the level of HPC resources, reusing fatal heat for cooling external building or using low-carbon or decarbonized energy sources.

The use of hybrid HPC/quantum computing i.e QPUs coupled as accelerators to other classical compute nodes (CPU, GPU), if successful, could lead first for some specific workloads to an energy quantum advantage by perhaps running algorithms 10x slower at the beginning but requiring 100 to 1000x less energy. It's important to mention that some scientific fields like quantum chemistry (applied either for materials science, medecine/health or biology) are one of the biggest consumers of HPC cycles of current supercomputers (¼ to 1/3 of the yearly cycles).

Fig.5. Integration of the PASQAL computers with the JURECA DC and the Joliot Curie supercomputers at FZJ and GENCI/CEA, respectively, as part of the HPCQS project
* referred to as quantum simulators according to quantum flagship terminology

The hybrid HPC/quantum computing journey has just started and its important to be cautious but initiatives like HQI, HPCQS, the ones started by EuroHPC and Member States in the field of hybrid quantum computing as well as QEI (Quantum Energy Initiative) could pave the path to concretely reach in some cases energy and performance quantum advantage before the end of the decade.

6.2 Jülich perspective on HPC integrating quantum computing and energy advantage

[Written by Kristel Michielsen, Jülich Supercomputing Centre (JSC), Forschungszentrum Jülich (FZJ), Germany]

Although the Jülich Supercomputing Centre (JSC) first became known by this name in 2007, its predecessor has a long history that goes back to 1961. In autumn 1961, the Central Institute for Applied Mathematics (ZAM) was founded at Forschungszentrum Jülich (FZJ) as a combination of a mathematical institute and a computing center. In 1984, the institute entered the field of supercomputing with the installation of the Cray X-MP supercomputer, which at that time was the fastest supercomputer in Europe. ZAM played a pivotal role in founding the first German national supercomputing center (HLRZ) in 1987. The Cray supercomputer complex installed in 1996 was another milestone in

ZAM's history : for the first time, a supercomputer at FZJ was among the top 10 in the TOP500 list of the fastest supercomputers worldwide.

After 2004, the institute expanded to a leading supercomputing center not only in Germany but also in Europe. In 2007, JSC joined forces with the High Performance Computing Centre Stuttgart (HLRS) and the Leibniz Supercomputing Centre (LRZ) in Garching near Munich to form the Gauss Centre for Supercomputing (GCS), which unites the three most powerful German computing centers under one roof. In 2010, GCS was one of the four founding members of the European HPC infrastructure PRACE – Partnership for Advanced Computing in Europe.

Since 2004, in an increasingly competitive research landscape, funds could be secured to continue to procure and install leadership-class supercomputers. In 2004, the massively parallel supercomputer IBM p690 cluster JUMP was installed and JSC started working with IBM on the IBM Blue Gene series of supercomputers. Utilizing the effect that using lower frequencies for computing cores leads to quadratically decreasing energy consumption, these machines used a very large number of nodes, but the CPU in each node was relatively slow. The energy efficiency increases when the frequency is lowered, and the communication network and main memory can be utilized far more effectively. This paradigm shift in frequency marked the JSC's transition to highly scalable systems. In this way, factors of up to over three in energy efficiency could be achieved compared to all other known technologies. The Blue Gene systems have frequently topped the Green500 ranking of the most energy-efficient supercomputers.

In 2006, JSC installed its first IBM Blue Gene system called JUBL, an IBM BlueGene/L supercomputer. Its successor JUGENE, based on IBM's BlueGene/P architecture, went into operation in 2008. In 2009, two supercomputers JUROPA, built by Sun and successor of JUMP, and HPC-FF, built by Bull, were installed. Both computers could be connected for specific tasks and together they achieved a performance of 274.8 teraflop/s. It was the first computer to be co-designed by JSC and realized by a multinational collaboration of several companies. With an upgrade of JUGENE in 2009, JSC became the first computing center having petaflop capability and in 2010 the first center delivering computing time to the European PRACE community. Since then, Tier-0 supercomputing resources and services – including leadership-class supercomputing systems and state-of-the-art operation and high-level support services – are provided to national and international users. To keep pace with the rapidly growing demand for supercomputing resources and the fast development of new hardware the 1 petaflop/s IBM Blue Gene/P system JUGENE was replaced by the next-generation 5.9 petaflop/s IBM Blue Gene/Q system JUQUEEN in 2012. JUQUEEN was the first HPC system in Europe to pass the 5 petaflop/s barrier. With the succession of various IBM Blue Gene systems, JSC has been operating one of the most energy-efficient computers in the world for some time.

In the summer of 2015, the JURECA system, the successor of JUROPA, went into operation. At first, it only consisted of the JURECA cluster module, serving as a general-purpose supercomputing resource. In 2017, the system was augmented with a many-core processor based booster module to enable highly scalable applications to leverage the system more efficiently. Both modules were tightly integrated and operated as a single system with a modular system architecture (MSA) (see Fig. XX), following the modular supercomputing paradigm, pioneered by JSC in the context of the DEEP series of EU-funded projects. The JURECA cluster module, designed by JSC and T-Platforms, had a peak performance of 1.7 petaflop/s. The JURECA booster module, designed by JSC and Intel, had a peak performance of 5 petaflop/s. JURECA was the first modular supercomputer to be included on the Top500 list. In 2020, the JURECA cluster module was replaced by JURECA DC, a flexible Data Centric (DC) module supplied by Atos to process large volumes of data. In its current configuration JURECA DC has a peak performance of 18.5 petaflop/s. In 2022, the JURECA booster module was decommissioned.

In spring 2018, JUQUEEN was shut down and its successor JUWELS, built by Atos, was installed. JUWELS is constructed as a modular supercomputer (see Fig. 6), an architectural paradigm developed at JSC over the past years (Suarez et al., 2019), (Suarez et al., 2022). JUWELS consists of multiple, architecturally diverse but fully integrated, Tier-0 modules designed for specific simulation, data science and AI tasks. The first module, replacing JUQUEEN, is a versatile cluster architecture based on commodity multi-core CPUs. The JUWELS cluster module has a peak performance of 10.6 (CPU) + 1.7 (GPU) petaflop/s consuming 1.2 megawatts of power. For the second module JSC has focused heavily on energy-efficient GPUs as the main elements of parallel computing, so that the system receives a large performance boost with the lowest possible energy consumption. This GPU-based booster module was installed in 2020. The JUWELS booster module has a peak performance of 73 petaflop/s consuming about 1.1 megawatts of power. The JUWELS booster module was the most energy-efficient system of the hundred most powerful computers in the world when it was introduced. The combined cluster and booster modules have a peak performance of 85 petaflop/s, which made JUWELS the most powerful supercomputer in Europe.

In 2024, JSC will install and operate the first European exascale computer JUPITER, also based on the MSA. The JUPITER booster module will comprise close to 24,000 Nvidia GH200 chips. Being the world's most powerful AI system, JUPITER can deliver 93 exaflop/s of peak performance for AI training — 45x more than JUWELS booster — and 1 exaflop/s for HPC applications, while consuming only 18.2 megawatts of power. In normal operation, the power consumption is expected to be about 12 megawatts.

To maintain its position at the forefront in the field of high-performance computing JSC pursues active research and technological development.

For this purpose, several cooperations with leading hardware vendors, software companies and system integrators were established. This research effort is complemented by JSC's participation in different national and international research projects. In addition, at JSC there is a deep involvement in research and development on key components for advanced computer technologies such as quantum computing and neuromorphic computing. The search is on for a technology that offers more computing power at a comparably lower energy cost. The advent of MSAs with for example quantum computing architectures might be a first step to reach this goal as it will enable hybrid quantum-HPC applications at reduced energy costs, but it will not solve the fundamental problems of digital HPC.

The quantum computing strategy of JSC (Lippert et al., 2022) consists of four pillars. The first pillar is the modelling and emulation of quantum computing devices. The JSC began this work back in 2004. The activities in this pillar consist of developing software for validating designs of quantum processors and researching performance expectations for quantum algorithms. To this end, the emulator JUQCS (Jülich Universal Quantum Computer Simulator) emulator was developed (De Raedt et al., 2007) (De Raedt et al., 2019). With JUQCS several world records have been achieved in emulating the largest quantum computer, a 48-qubit quantum computer, on an HPC system. JUQCS was also used in a collaboration with Google and others to benchmark the Google quantum processor Sycamore and to demonstrate quantum supremacy (Arute et al., 2019), marking the moment when a quantum computer outperforms state-of-the-art conventional computers for a given task for the first time.

In the second pillar, the provision strategy, JSC has been installing and operating a quantum annealer (since 2021), an analog quantum computer with superconducting qubits, from the Canadian company D-Wave Systems. The hosting of a second analog quantum computer is planned for mid-2024 as part of the European project HPCQS, namely a quantum simulator with neutral atom qubits from the French start-up PASQAL. Also in 2024, the first digital quantum computer will be installed, an ion trap quantum computer from the German start-up eleQtron, as part of a project funded by Nort-Rhine Westphalia (NRW). This complements the remote access that JSC will provide to the digital quantum computers with superconducting qubits that are being developed in the German and European research projects Qsolid and OpenSuperQPlus.

In pillar three, HPC systems and quantum computers are integrated. The MSA (see Fig. 6) of the HPC systems at JSC is ideal for integrating quantum computing functions into an HPC workflow.

After a preparatory phase that started in 2015, JSC founded the Jülich UNified Infrastructure for Quantum computing (JUNIQ) (see Fig. 7) in the context of the fourth pillar of its quantum computing strategy. JUNIQ is jointly funded by the Government (BMBF), NRW and the HELMHOLTZ Association. JUNIQ launched user operation in 2019. JUNIQ's mission is to provide German and European science and industry with cloud-access to various types of quantum computers and to run software emulators of ideal and real quantum computers on JSC's Exascale-class supercomputers. Right from its start, JUNIQ is at the vanguard of deeply integrating HPC, and quantum computers and simulators at system level with lowest latency and highest data throughput taking advantage of the MSA. Today, JUNIQ can already integrate its quantum computing systems into JSC's modular HPC environment. With its unified development platform, JUNIQ will include NISQ systems like OpenSuperQplus/QSolid (2024) or eleQtron (2024), quantum simulators like PASQAL / HPCQS (2024), and quantum annealers like the D-Wave Advantage system (2022). All these systems have a power consumption of less than 25 kilowatts, much less than a conventional supercomputer. JUNIQ offers a continuously running call for projects (peer reviewed) together with pertinent support through its Simulation Lab for Quantum Computing to realize hybrid quantum-HPC applications on the integrated systems.

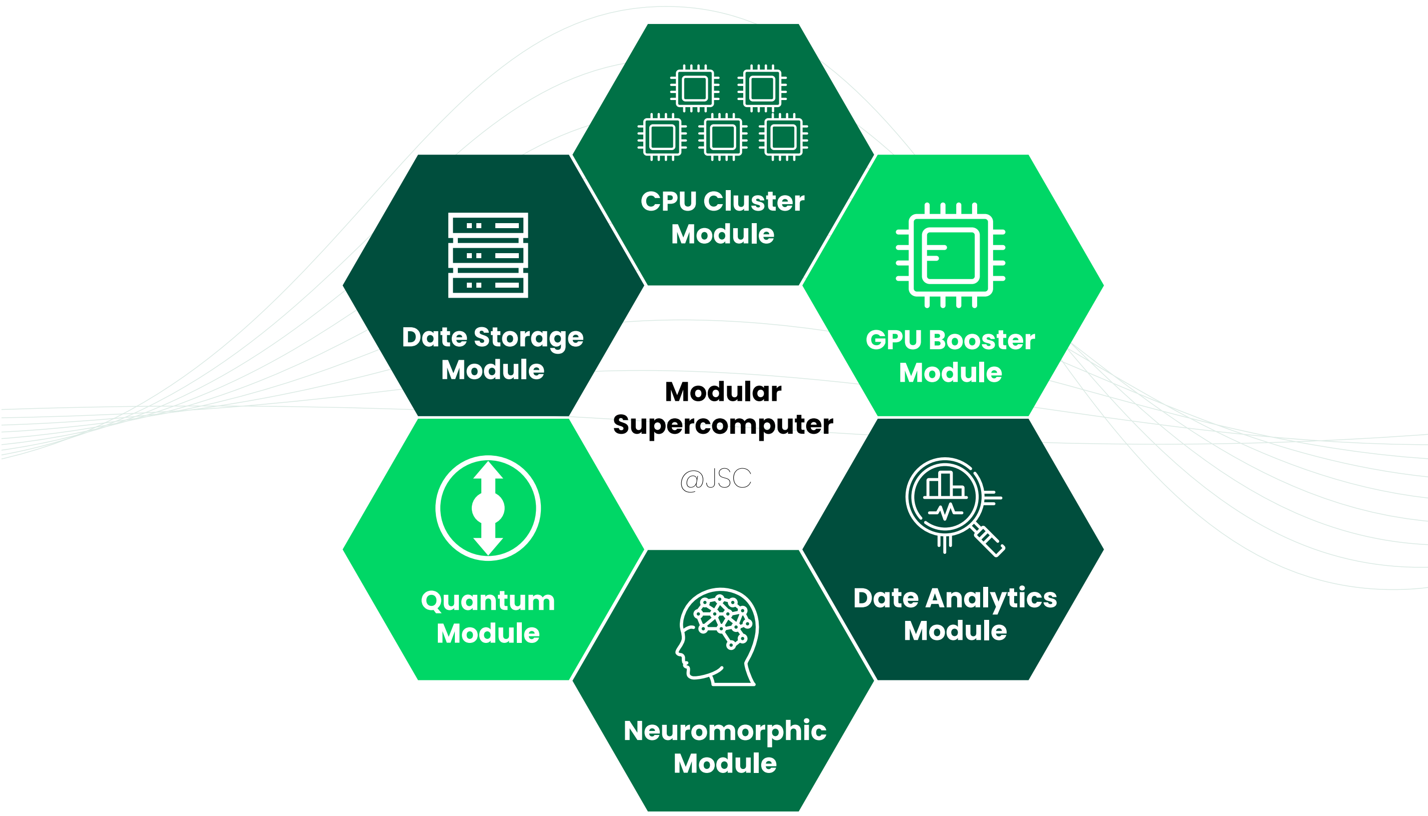


Fig.6. JSC's Modular Supercomputer Architecture

In conclusion, it is clear that the highest efficiency gains can be achieved by reducing primary energy consumption (hardware technology solutions). Further reductions can be obtained by efficient computer room infrastructures and green coding (software solutions).

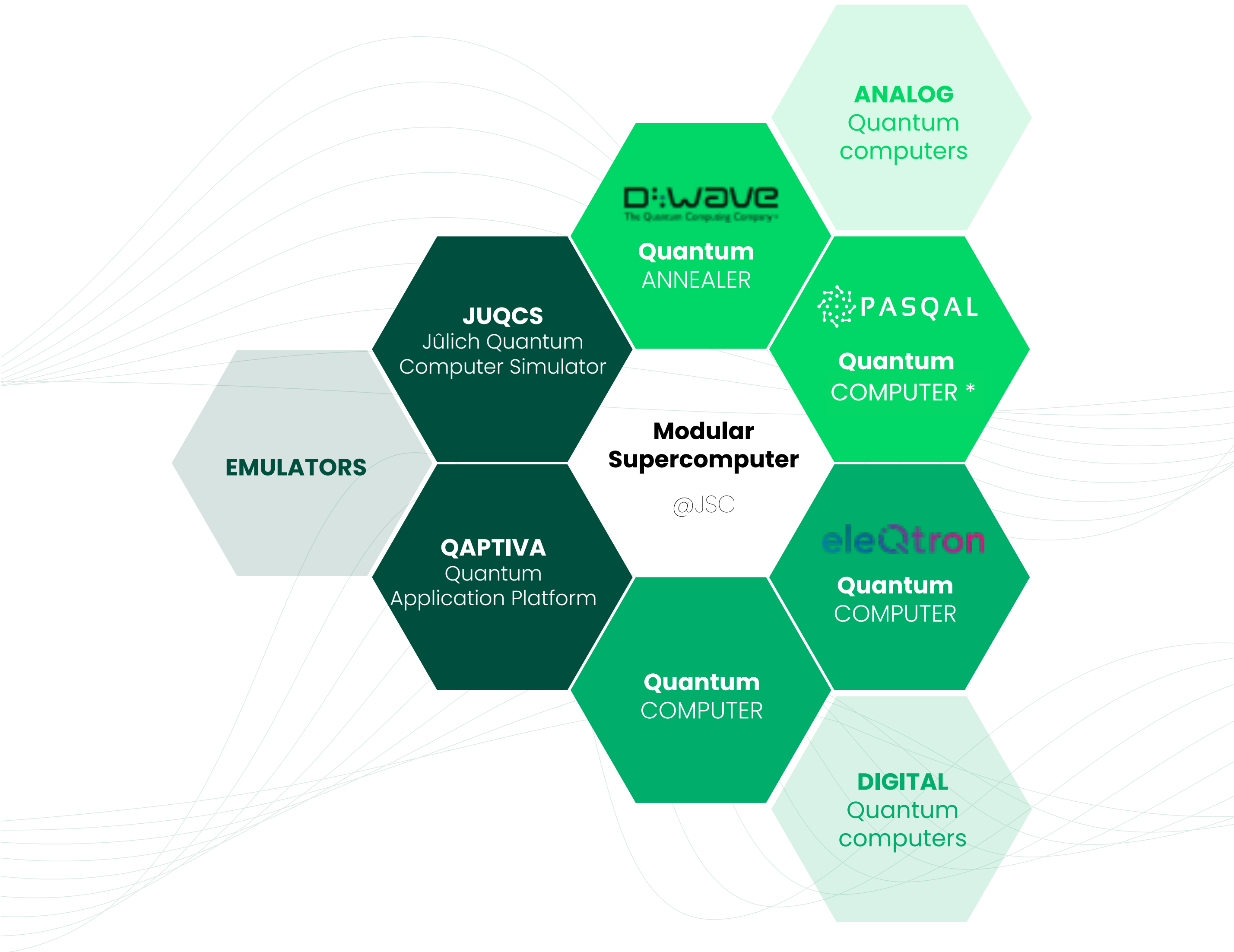


Fig.7. Emulators and quantum computers hosted and operated by JUNIQ
* referred to as quantum simulators according to quantum flagship terminology

THE PERSPECTIVE OF A KEY INDUSTRIAL END-USER : EDF, THE LEADING FRENCH ENERGY UTILITY

[*Written by Joseph Mikael, Head of Quantum Computing, EDF R&D*]

For a major player in the energy sector, such as EDF, the use of High Performance Computing (HPC) resources should constantly grow. In the early 1980s, EDF's research and development department started to carry out model implementations and simulations *in silico* on a Cray, a state-of-the-art supercomputer in terms of performance at the time. Since then, EDF has been replacing one of the two supercomputers every two and a half years, with technologies consistently ranking in the top 100 in the world at the time of the purchase.

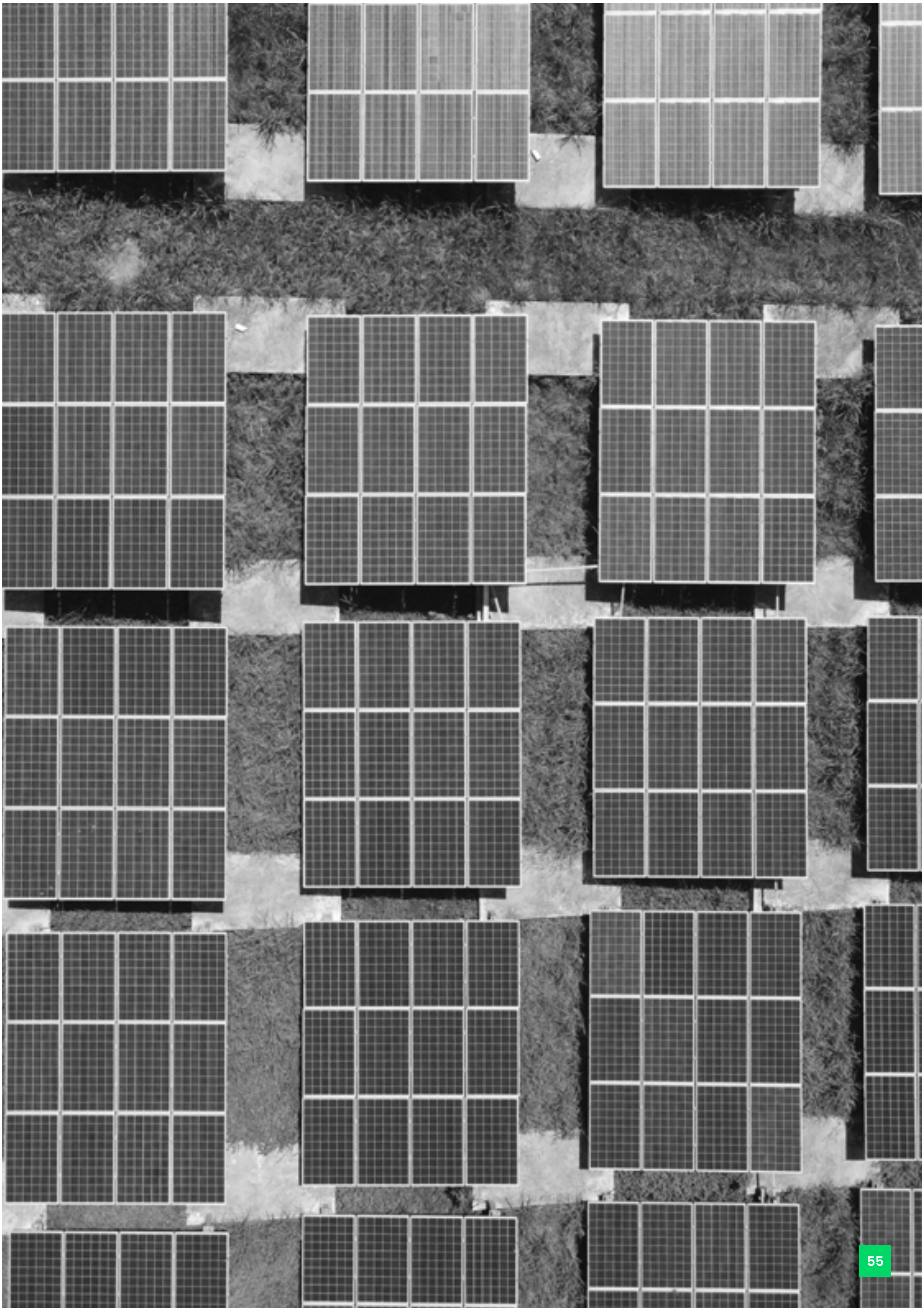
EDF's simulations were initially focused on physics and have been evolving towards diverse applications, such as machine learning and solving combinatorial problems. Moreover, the energy transition makes most of the computational problems that energy companies face even harder to solve. For this reason, EDF turned its attention to quantum computing as it has the potential to become not only an ally at every stage of the EDF Group's value chain but also a potential asset to accompany the transition to sustainable energies. Indeed, quantum computing holds the potential to help tackle crucial problems for EDF, such as supporting the electrification of vehicles, forecasting production and demand, and simulating the aging of equipment.

The first example concerns the smart charging of vehicles. It typically encompasses a range of issues, from the routing of electric vehicles (EVs) to what is known as Vehicles to Grid (V2G). The first case aims to direct EVs to the least congested charging stations, ensuring that priority vehicles, such as ambulances, are charged before others. In the second case, the aim is to use the mobile batteries of EVs to relieve the grid during peak periods. In both cases, complex combinatorial problems arise : exact solutions become difficult beyond a few hundred EVs, and even approximate methods struggle beyond a few thousand vehicles. When considering fleets of several million EVs, quantum computing emerges as a potential solution; see for example, our paper in collaboration with PASQAL and Loria (Daylac et al., 2021).

Another example might be one of the historic challenges for utilities: forecasting production and demand. Until recently, electricity production mainly relied on decisions made by the operator, resulting in relatively low volatility. On the consumption side, fluctuations were also comparatively less volatile. Today, we witness increased consumption volatility due to the electrification of usages and renewable energy sources that further complicate production forecasting. A gust of wind, for instance, can lead to a significant variability in production. The techniques employed to address these new phenomena need to be updated, and again, quantum computing might be an asset to handle them (see outputs of the Blaise Pascal Quantum Challenge).

The third example refers to the microscopic simulation of the aging of materials, another subject linked to the energy transition, where quantum physics may have a role to play. Extending the operation of certain facilities and studying the aging of static batteries, nuclear internals, or photovoltaic panels all rely on atomic-scale simulations of the behavior of materials. Today, these simulations are carried out conventionally using a set of assumptions we would like to eliminate. Doing these computations more precisely would allow us to identify swelling in the structures, understand how batteries age with intensive cycles of charging/discharging periods, and have a detailed understanding of the long-term performance of photovoltaic farms. Together with PASQAL, IOGS, and EVIDEN, EDF has made an effort in this direction (Michel et al., 2022).

For EDF, the advantage of quantum computing can be associated with the quality and precision of a solution (Machine Learning, optimization), the size of the problems that are doable (optimization), be able to avoid assumptions (material simulation), and, last but not least, it might be the energetical cost of running an algorithm. At EDF, one of the two HPCs has a power of 1.4MW, whereas Frontier has 22MW. Reducing this C02 bill might be key if we want this technology to be adopted.



AN AGENDA TO MOVE FORWARD IN SEARCH OF SUSTAINABLE QUANTUM ADVANTAGE

At the end of this whitepaper, the following conclusions can be drawn:

- The **potential** of **quantum computing** to contribute to **sustainability** could be **significan**t. We have seen that researchers can implement use cases specified in the international standard of **United Nations Sustainable Development Goals** on a quantum processor. These could include computing for drug discovery (included in SDG3, instrumental in accessing essential healthcare, medicines, and vaccines), renewable energies (included in SDG13, essential for climate change mitigation and biodiversity), smart cities and transport systems (included in SDG 6 & 11, necessary to sanitation and circular economy).

- Challenges associated with sustainable transport, smart grid, or smart city management are associated with **optimization tasks** that yield large-scale, complex calculations that rarely have exact solutions within classical methods. These combinatorial optimization problems that are best tackled using **graph methods** and **molecular chemistry simulations** are natively implementable on the PASQAL quantum processor and effectively addressed in synergy with artificial intelligence as exemplified by the Hackathon winner.

- Establishing a demonstration of a clear **energy/carbon emission advantage** with quantum/classical HPC benchmarks is a challenging ongoing research. However, it may be at hand before quantum computing delivers a fault tolerance performance advantage. It will be essential to provide a solid analysis benchmarking quantum/classical power consumption associated with relevant use cases and an estimation of the **life-cycle analysis** accounting for all emissions associated with design, manufacturing, maintenance, and end-of-life **beyond the pure electrical power to run** the algorithms on the CPU, GPU or QPU.

- Current PASQAL neutral atoms technology may be better placed than many other quantum technologies to deliver decarbonizing, due to **low energy requirements** to run the algorithms in hybrid workflows and **limited manufacturing emissions** concerning QPU and GPUs. The issue of scalability will be further investigated. PASQAL will issue a complementary publication with a solid analysis benchmarking quantum with classical computing associated with two relevant use cases.

The following vital stakes remain for further analysis and discussion:

1. **Broaden the committed community** by working with partners with similar values as the present white paper advocates, particularly with the Quantum Energy Initiative and Open Quantum Institute as facilitators.

2. Foster **sustainable quantum meetings/events,** such as PASQAL's presence at COP28, workshops organized by the Quantum Energy Initiative (QEI 2023), Australia's International Conference on Quantum Energy (ICQE 2023), or the Blaise Pascal [Re]Generative Quantum Challenge hackathon.

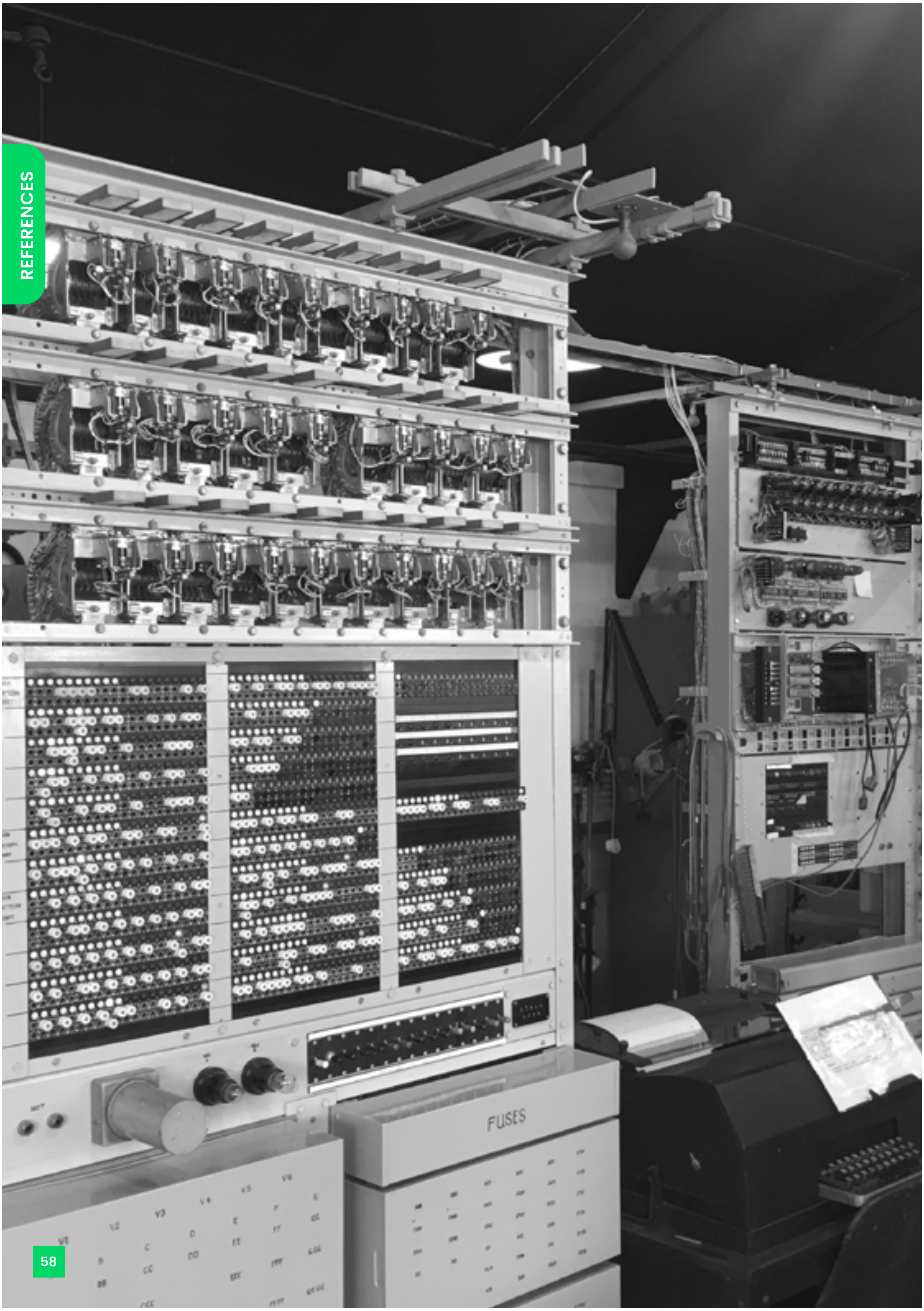
3. Build on current **frameworks** outlined in this manifesto to **assess hardware-linked** emissions and promote **eco-design practices** for hardware efficiency concerning energy consumption.

4. Propose **use cases** with the most favorable sustainability advantage.

5. Deeply analyze the quantum-classical computing performances to **ascertain quantum energy advantage.**

6. Investigate the **computational life-cycle** from the materials used to construct the computers to their end-of-life disposal.

From a more general perspective, comparing quantum and classical computing can be virtuous, leading to improvements in both, or synergy between them. However, we encourage those involved to consider use-cases related to sustainability, and to aim for the most energy-efficient and sustainable computing possible. This would only be possible with capacity-building, including a new generation of talented professionals and scientists : in that respect also, maybe the quest for sustainability could become an attractive motivation.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THE BLAISE PASCAL REGENERATIVE QUANTUM CHALLENGE

The hackathon scoring process as an effort to standardize sustainable quantum advantage

The hackathon candidates were scored according to the following process

First stage involves filtering on the use case for sustainability assessment

- **Dates and Process :**
  - Submission by October 17th,
  - By October 20th validated maximum 50 projects that can advance

- **Deliverable**: text or slideshow detailing the use case in a sustainability statement of purpose, methodology and general computational approach (including relevance to the challenge & common good, potential, and quantum project relevance)

- **Scoring is built with as following subscores:**
  - Exclusion criterion for some use cases: those prohibited by the upcoming European AI-act as well as military applications
  - Sustainability of the statement of purpose
    - Inspiration can be found in the UN sustainable development goals, or the, or the Corporate Dreams (climate / circular economy / health / fulfilling jobs),
    - Each project should contribute at least to one of the 6 following domains :
      - sustainable transport, industry and circular economy (SDG9 et 12; corp dream “circular”)
      - smart city (incl clean water and sanitation - SDG 6 et 11),
      - smart grids and affordable/clean energy (SDG 7),
      - Environment, climate and biodiversity (SDG 13, 14 et 15; corp dream “climate”);
      - drug discovery (SDG3; corp dream “health”)
      - sustainable agriculture (incl. Zero hunger - SDG2),

- Important notice: any of those challenge being open to using quantum computation, including energy-efficient quantum AI
- Argue against potential adverse effects of the use-case, such as listed of UNESCO recommendation on the ethics of AI

Second stage is rated on feasibility/credibility assessment of the proposed quantum program

- **Dates and Process:**
  - Submission by October 25th,
  - By October 27th validated maximum 20 projects can advance

- **Deliverable:** description of the algorithm with arguments suggesting implementability on 2023-2024 PASQAL machines and later scalability
  - analog (with potentially partial addressability functionalities)

- **Scoring was based on**
  - Quality of the argument why the proposed method solves the claimed use-case,
  - Quality of the proposed technical framework as well as feasibility as opposed to present technical capacities, including evidence that the hypotheses are satisfied for analog (near term) implementation; in case of heuristics, arguments to claim why it should perform (similar results in others domains etc.)

Third (final) implementation stage is rated on the basis of the (life-cycle + credible) quantum energy advantage

- **Dates and Process:**
  - Submission by November 8th
  - By November 15th curated 10 projects could participate the final demonstration day

- **Deliverable:** *final version of the algorithm and the code*, report with details graphs, data, simulations, interpretation as well as on the energy consumption of the chosen methodology

- **Score is built with the following subscores**
  - (already rated in stage 2) on the feasibility / credibility of the proposed quantum program
  - On the potential quantum energy advantage, a ratio to a classical HPC equivalent:
    - Required resources both in processors and memory (ancillary CPU/GPU) for the classical HPC runtimes should be clearly stated
    - Required resources for the QPU (nb of atoms) as well as pre/post-coprocessing classical CPU runtimes should be stated

Hence, compute the life-cycle energy required in ratio hybrid quantum to classical

- Candidates should state any additional hypotheses that they need to put a convincing case, e.g. arguments regarding qubit scalability of energy, scalability of energy costs on future classical HPC etc.
- On the excellence / innovation of the code

- Argue from the point of view of either a brand new algorithm or a novel application of an existing algorithm

The final demonstration day took place on the 15th of November, virtually in front of an expert jury in order for them to select the 3 finalist projects out of the 10 participating ones

- **Deliverables:** video demonstration of the use case as well as the final prototype solution, presentation of arguments on the SDG pertinence, as well as the energy impact on the use case and solution as well as its industrial scale roadmap

- **Evaluation was based on:**
  - Sustainability value of the use case (including relevance and potential for the common good)
  - Technical quality of the implementation, quality of the proposed technical framework, implementation on present technical capacities, as well as the excellence / originality of the approach
  - CO2 footprint and energy considerations, carbon footprint advantage resulting from energy savings as compared to existing classical/HPC solutions

Welcome to our hackathon initiative: as the CEO of PASQAL, I am enthusiastic and honored to welcome you in our Regenerative quantum challenge. You are more than 350 from all over the world to have registered in the challenge. The very best is yet to come!

Overview of the spirit of the regenerative quantum challenge

[*Welcome address by Georges-Olivier Reymond, CEO of PASQAL, to the candidates on September 5, 2023*]

Quantum computing promises a disruptive approach with high impact HPC: exploit quantum coherence and entanglement to achieve massive gains of complexity. Hence, computation could go faster, tackle even harder problems than the ongoing ones, which are already impressive. Think of regenerative AI or large-scale climate modeling.

Faster, harder ... Why not dare to imagine greener? As scientists, engineers, tech experts, we are all excited about new frontiers of science and technology. But we also remember that the environment in which we live and which allows us to produce jewels of mankind's creativity is also fragile. Needless to recall, the climate is under threat: as a matter of fact, science and HPC helped quantify the extent of climate change, thanks to large-scale multi-physical modeling and computation. However, IT in general is a fastly-rising net contributor of greenhouse gasses as well as a massive user of non-renewable materials.

At PASQAL, in partnership with Blaise Pascal Advisors, we do not want a quantum adventure standing simply as a "tech for tech" endeavor. We want quantum to definitely prove its sound contribution to the truly meaningful challenges of our world. This has something to do with the iconic figure of Blaise Pascal by which we named our companies and of which we celebrate this year the 400-year birthday. People have heard of that XVIIth century polymath genius: he invented the first all-time computing machine (a mechanical arithmetic machine), but also probability theory as well as recurring algorithms that prove so foundational in numerical modeling and modern AI for instance. Lesser known, Pascal was also a renowned philosopher and even more an engineer-entrepreneur vitally preoccupied with the benefits of tech to mankind. He ended his life inventing and practically running the all-time first public transportation system, with incredible sustainability advantages. Pascal did that with the proof-discipline of a mathematician and the field mastery of an impact-obsessed engineer.

This is exactly what we want to do, 400 years later, in launching the international Blaise Pascal regenerative quantum challenge: well beyond a mere tech-for-tech challenge or self-proclaiming hypothetical climate benefits, prove numerically that quantum computing can pragmatically contribute to impact. This is what you will have to do to win the challenge.

Indeed, massive gains of complexity can be expected to turn into lesser energy requirements for a given computing task, or in some cases open up the solving of previously-intractable tasks. Whenever applied to use cases with impact, it is therefore expected to give rise to a quantum sustainability advantage. Hence our hackathon involves two requirements/scores

1. Argue a use-case with impact.
2. Prove a relative energy footprint advantage to classical HPC that is higher than 1, if not infinite (an impact use-case intractable with classical HPC)

Let me be a bit more specific regarding the two requirements. Within this hackathon, impact should fall within one or many of the following categories: Drug Discovery - Safe & Sustainable Transport - Sustainable Cities - Smart Grids - Low-Consumption / Energy-Efficient AI. Beyond the choice of a category, you should advocate the expected positive impact contribution avoiding too general a meaning.

Regarding the footprint advantage to classical HPC, one should go beyond the pure "core run" comparison between CPU and QPU in terms of number of cycles or power requirements. For instance, the Green500 distinguishes the highest energy efficiency in Gflops/W (currently led by the Henri system at the Flatiron Institute in New York City, United States, with an energy efficiency of 65.40 Gflops/W), however this neglects entirely the energy/carbon load of fabrication (as well as the sustainability of the use-cases). A life-cycle and systemic approach with due overheads associated with the fabrication of the computing machines (generally considered as amounting to more than half of the footprint of IT, depending also on the carbon content of electricity) as well as the entire cycle (pre, post, hybrid architecture). For the purpose of the hackathon we will think about energy footprint, keeping the conversion to carbon footprint as a side calculator to be provided by PASQAL, as the carbon footprint depends among others on the carbon content of electricity production.

Of course, real cases should rather be viewed as associating quantum to classical inside hybrid architectures: hence, the relative energy footprint should be advocated through due accounting of the embedded classical vs. quantum part.

The hackathon will take place exclusively within PASQAL's technology of cold atoms. You will contribute to our Pulser interface and language in order to emulate computing on our quantum machines. Part of the prize should include the eventual possibility to access real quantum computation as a follow-up effort with our teams and partners.

You will be guided throughout the challenge by a timeline, a methodology and objectives within the webpage. You will be helped by expert mentors. At the end of the day, you will need to persuade our multidisciplinary jury. Challenge starts on October 5th until November 10th, with a virtual demo day on November 15th and an award ceremony in an international colloquium in Clermont-Ferrand, birthplace of Blaise Pascal on November 28th.

It is time for me to wish you good luck, deep inspiration and the best of your effort.

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