Contributions Towards a Norwegian Quantum Computing Strategy

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QCNorway

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Preface

The world is approaching a quantum revolution — a 40-year-old dream about computers gaining superpowers by clever utilisation of phenomena from quantum mechanics seems to be rapidly materialising. This change is due to recent advances across several facets of quantum technology. It is still uncertain when, where and in what form a quantum revolution would appear, but it seems quite clear that major and impactful changes will come. Potentially, these changes can supersede the recent wave of triumphs of artificial intelligence and machine learning.

Given the enormous momentum world-wide, and even in our neighbouring countries, it is imperative that Norway starts developing its own *national quantum strategy*, in which quantum computing should be a principal part. This position paper, inspired by the QCNorway workshop in November 2022, conveys our contributions to the debate on which such a strategy should be built.

Quantum technology is often said to span four pillars: quantum simulation, quantum sensing, quantum communication and quantum computing. The authors of this paper have different scientific backgrounds, but our meeting point is that of computing and computer science. We have therefore crafted our input to the debate about a national quantum strategy in the context of quantum computing, which also seems to be the most powerful engine for the current international quantum development. However, a strong and forward-looking Norwegian quantum strategy should be built on a wide understanding of current quantum technologies, and thus *we encourage the Norwegian quantum-interested community at large to bring their ideas and viewpoints to the table*. In this way, politicians and those implementing established policies will be able to educate themselves efficiently and be in a good position to take well-informed and wise decisions for the future.

The process. This position paper is based on presentations and discussions at and after the open workshop *QCNorway: Towards a Norwegian Quantum Computing Strategy* held in Oslo on November 7–8, 2022. The event was organised by Simula Research Laboratory, Oslo Metropolitan University (OsloMet), SINTEF and Sigma2. It was co-funded by the Research Council of Norway (grant 341168), Simula Research Laboratory, and the OsloMet Quantum Hub. The program committee consisted of the authors of this paper and Franz Fuchs (SINTEF). The complete workshop program, as well as recordings of most presentations, are available on the QCNorway web site, www.qcnorway.no.

The writing of this paper started mid-January 2023 as a collaborative effort and was completed early June 2023. On March 27, 2023, a complete draft of the paper was shared with a small group of Norwegian organisers, presenters and panelists at the event *Northern Prospects on Quantum*, held in Brussels on March 30. The purpose of this event was to bring researchers, research management, national funding agencies and decision makers from the Nordic and Baltic countries together with representatives from the European Commission to discuss quantum initiatives. During the weeks prior to this event, similar documents referred to as quantum agendas were published by the Finnish and Swedish quantum communities.

On April 21, an updated draft of this paper was released for an informal hearing among a wide selection of representatives of the Norwegian, Nordic and European quantum communities, including all contributors to the QCNorway event last November. We received a substantial number of responses to this hearing, providing a good mix of applause, constructive feedback, suggestions for improvement, and a few concerns. All responses have been carefully analysed and used actively to improve the paper.

The final version of the paper is made publicly available on the QCNorway website and in other channels.

Acknowledgements. During the writing of this paper, we have enjoyed numerous discussions with colleagues, locally as well as internationally. The contributors to these discussions have been too many to list completely, but they have certainly impacted the end result.

As stated above, we received constructive feedback from several key actors in the quantum community during the open hearing. This has been a tremendous help for achieving a high quality and striking a good balance between being open-minded to other viewpoints and still providing strong arguments for the recommendations offered in the paper. In particular, we would like to extend a special "thank you" to Robert Axmann (DLR), Matthias Christiandl (University of Copenhagen), Carlos Cid (Simula UiB), Himadri Majumdar (SemiQon), and Øyvind Ytrehus (Simula UiB) for their valuable comments and advice.

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Executive Summary

Norway lacks a national strategy and corresponding investments for the development of its own expertise on quantum computing through educational programmes, active research, business creation, and support from technical infrastructures.

Given the enormous momentum in quantum technology and quantum computing R&D world-wide and in our neighbouring countries, there is an immediate threat that Norway will arrive too late at a technology race that has the potential of redefining the digital society and digital business development.

This position paper presents the most important takeaway messages from the open workshop *QCNorway: Towards a Norwegian Quantum Computing Strategy*, which took place in Oslo on November 7–8, 2022 with more than 150 participants. The discussion herein is limited to quantum computing and does not claim to address quantum technology in general. Hopefully, this paper and complementary inputs from other stakeholders can inspire the development of a national quantum strategy, in which quantum computing is a principal part.

Setting the scene. Modern society depends on large quantities of data being continuously collected and processed by advanced algorithms. Currently, the demand for computational power grows millions of times faster than the performance of traditional computers.

The idea of quantum computing was formulated already 40 years ago. Utilising phenomena from quantum mechanics, quantum computers were predicted to solve certain problems in a tiny fraction of the time used by traditional computers, allowing the complexity of manageable problems to go far beyond the reach of conventional technologies. Today, that 40-year-old idea seems to be rapidly approaching reality.

Quantum computers are expected to be particularly effective for solving certain types of computational challenges, such as optimisation problems found across a wide range of demanding applications, including the use of machine learning and artificial intelligence. They can also simulate the behaviour of quantum systems more efficiently than classical computers. This has applications in materials science, chemistry, and numerous other fields. Since there are also important problems that will be better solved by conventional computers, we already see the development of hybrid approaches combining quantum devices with conventional computer systems.

If the power of quantum computing is fully realised, society will face a computational revolution. This revolution could pave the way for new levels of scientific insight and business opportunities, including fundamentally new approaches to diagnosis and treatment of life-threatening diseases. Quantum processing units will consume only a marginal fraction of the power needed for similar calculations by conventional technology, which means that quantum computers might become important for environmentally responsible and eco-friendly data processing, that is, green computing.

While expected to have profound positive effects, the development of quantum computers also poses threats to our modern digital society. It is known that sufficiently large quantum computers will be able to break the cryptographic algorithms most commonly used today to protect privacy, secrets and integrity. As a result, *post-quantum cryptography* is currently a very active field dedicated to the design, analysis and deployment of cryptographic algorithms and protocols that can withstand the power of future, large quantum computers.

Projected to become a 1 trillion USD industry, potentially causing groundbreaking changes to the digital society, quantum computing cannot be ignored by any modern, technology-dependent nation. Today, the USA is leading the technology race, with China and Canada as challengers. Several European countries have already established their national quantum strategies and announced substantial national funding, which in many cases have been matched or superseded by private investments. According to the European Policy Centre, the growing quantum ecosystem is now at a critical stage where it can develop into an internationally competitive European industry.

On March 15, 2023, the UK announced its national strategy that includes a 2.5 billion GBP investment over the next 10 years. By the end of 2022, the total investments in quantum technology in the Netherlands, France and Germany were 765 million, 1.8 billion and 2.6 billion EUR, respectively. Moreover, the German government announced mid-April 2023 a 3 billion EUR investment in the development of a universal quantum computer by 2026. The corresponding numbers for other Nordic countries are smaller but also substantial: Denmark (228 million EUR), Sweden (143 million EUR) and Finland (24 million EUR). These three Nordic countries are among the 11 countries world-wide that have been selected for bilateral quantum R&D agreements with the USA. The investments in Denmark and Sweden include large privately funded initiatives for building high-end quantum computers. Moreover, Denmark has recently been chosen as the host for the new NATO Center for Quantum Technologies.

In these three Nordic countries, there is strong momentum towards developing national quantum strategies. The announcement of the Danish strategy is awaited, while the Finnish and Swedish quantum communities have very recently (February–March 2023) presented their *quantum agendas* as advice to their respective governments.

So far, Norway has no official quantum policy or quantum strategy, nor any dedicated investments — public, nor private. This is a strongly unbalanced situation relative to the momentum shown by our neighbours and the rest of the world. The bibliographical analysis of quantum research in the Nordic region presented in the Finnish quantum agenda[1] shows rather bluntly how Norway is lagging behind at the national level. Consequently, firm actions from the Norwegian government are called for — actions that need to materialise now, before the time window offering valuable positions has closed.

Recently, the Norwegian Government mandated the Research Council of Norway to survey the ongoing research on quantum technology in Norway. The resulting report confirms that there is a need for a national strategy and long-term investments of substantial volume. The report also states that the development of a national quantum strategy should include the research community — a process to which this position paper and similar inputs from other stakeholders can contribute.

Education and workforce. Quantum computing, like its origin in quantum mechanics, has so far been curriculum only for the particularly interested, and usually at advanced levels of physics and chemistry. This needs to, and is about to, change. World-wide, universities are developing new courses at undergraduate and graduate levels to educate young students. This is desperately asked for by a very rapidly growing quantum industry, which cannot afford waiting for the five years it takes to train a high school graduate to a master's degree.

At the same time, as higher education changes to meet the new demand, it is imperative that actions are taken to increase the public knowledge about quantum computing – what it is and what it can do, for better and worse. This *quantum literacy* is essential in order to democratise quantum computing, and quantum technology at large. During the last decade, in the context of AI, the world has experienced a similar imbalance between those in the know and those not. Quantum computing holds an even higher potential for societal impact, and thus for further increased imbalance, partly as an accelerator of AI's capability and footprint.

Norway needs to take these educational aspects seriously by both educating its national quantum workforce and raising the general knowledge and awareness of quantum computing in its population. To this end, investments are needed at both universities and public schools.

Research. Today, billions of dollars are put into the research needed to unleash the expected potential of quantum computing. This research takes place in the USA,

[1] *The Finnish Quantum Agenda* (2023, Table 1), see https://instituteq.fi/finnish-quantum-agenda/

China and several European countries, including other Nordic countries. The vast majority of these research investments are put into the development of the hardware components needed to realise efficient quantum computers, which by its nature is very expensive. While it is natural that the initial strides address hardware, it is striking that there remains a large gap in the needed evolution of software. More research is required in the development of new algorithms, as well as in the assessment of which application areas that are suitable for quantum computing. During the 70+ years of development towards modern computing, most principles and tools for how to make great, useful software have grown out of trial and error. Learning from history, the software engineering aspects of quantum computing should be developed continuously in tandem with the hardware development.

Norway has a unique starting point for becoming a driver in the quantum computing software area. Ever since object-oriented programming, *the* foundation for modern software development, was invented in the 1960s by the computer science pioneers Ole-Johan Dahl and Kristen Nygaard, Norway has had a strong foothold in computer science. As a nation, we are probably too late to take leading positions in the development of quantum computing hardware, at least for solutions based on the technologies that are investigated by major players internationally. Observing that such positions would also carry a prohibitively high financial cost, it can be extremely rewarding to direct national efforts towards the available openings for strong positions in quantum computing software, including supporting areas like quantum information theory, quantum error correction, quantum error mitigation, and fault-tolerant structures. This also includes the opportunity of taking the lead in methodologies for how to develop robust and efficient quantum software that can be trusted to solve relevant problems the right way. Such a software-centred view on quantum computing is fully aligned with ongoing discussions in EuroHPC, as a primary funding body for European research investments in this area. By becoming a leading nation in quantum software engineering, Norway would carry on the torch from the invention of object-oriented programming.

Perfectly aligned with the existing Norwegian research on the quantum computing applications and software engineering, there are strong Norwegian research groups in information security working in post-quantum cryptography. Moreover, Norway has a rich research environment in communication technology, again with emphasis on the software side. This is an excellent foothold for development of research on quantum networking, yet another dimension of ensuring reliable and trustworthy quantum computing ecosystems in the future.

Norwegian quantum computing research should be performed in close collaboration with international partners. Active participation in EU's research funding instruments, including a commitment to the financial investments expected from other participating countries, is fundamental to success. For quantum computing, this applies particularly to Norwegian participation in the EuroHPC Joint Undertaking, Digital Europe, QuantERA, Horizon Europe and future framework programmes.

Innovation. To unleash the full value of education and research, the acquired competence and results need to be translated to value in society and business through innovation processes. Still, in line with the low national level of quantum literacy, there are a few, mainly large, companies that currently make serious attempts at understanding what quantum computing can bring them in the future. The prime examples of quantum-curious businesses can be found in the energy, maritime, logistical, and financial sectors. But they are few and distant from each other.

For Norway to take advantage of the expected opportunities resulting from quantum computing, there is a need for increased knowledge and awareness – not only about quantum computing at large, but about the potential for disruption of existing and creation of new businesses. Likewise, there is a need for a deeper understanding of how this technology can enable totally new levels of important societal commitments, for instance, in the health sector. Additionally, it is equally important to understand the limitations of this new computing paradigm. A Norwegian initiative should therefore encourage a broad and deep interaction with the international scene, for instance, through participation in the European Quantum Industry Consortium (QuIC) and similar forums supporting both private and public sectors. This should be further accelerated by incorporating quantum computing as a prioritised area in existing instruments supporting strong innovation, such as the national funding scheme for Centres for Research-based Innovation (SFIs). Moreover, in line with the disruptive nature of quantum computing, Norway should develop structured means for supporting entrepreneurs in building new, quantum-fuelled business ventures.

Infrastructure. Norway is surrounded by Nordic partners in Sweden, Finland and Denmark that are making substantial strides in quantum computing, even by international metrics. The Nordic region has a long-standing and successful history of collaboration in research and innovation, including technical infrastructures. The leading institutions in these countries express a strong willingness to develop close collaboration with Norwegian colleagues, and together lift the whole region as an international actor. Acknowledging the fact that computational infrastructures consist not only of the needed hardware, but also of the full spectrum of software and human expertise, Norway can position itself as an attractive complement to the largely hardware-dominated efforts in other Nordic countries. Thus, Norway can contribute significantly to the vision of the Nordic region as one strong international contender. This, however, requires a dedicated investment in building the necessary components for such infrastructures in close integration with strides in national education, research and innovation in quantum computing.

Recently, EuroHPC announced the funding of the first six initiatives towards building European quantum computers in connection to existing high performance computing centres across Europe. Norway is deeply involved in one of these initiatives, LUMI-Q, with three partners (Sigma2, Simula Research Laboratory, and SINTEF). This project is a strong example of how Norway can benefit from European competence building and infrastructure access for research and innovation in quantum computing. Still, it is concerning that Norway as a nation currently fails to meet the international expectation of co-funding this and coming EuroHPC projects, in the spirit of a joint undertaking. Unless such commitments are not only accepted but used actively as a force for pushing national efforts in quantum computing, Norway will quickly lose terrain in the field. Given the immense momentum in this development internationally, it is then a matter of a short time before the distance to our natural partners increases beyond what is repairable.

Recommendations

Education

The Norwegian strategy for quantum computing should

- **prioritise quantum-literacy in the workforce across a variety of sectors;**
- **increase public awareness of the implications of quantum technology;**
- **ensure that secondary school curriculum includes basic knowledge of quantum technology, with more advanced subjects at tertiary level;**
- **ensure the development of leading educational programmes in quantum computing through dedicated actions.**

Research

The Norwegian strategy for quantum computing should

- **take advantage of the large quantum computing momentum already present world-wide, including the Nordic region and Europe, and support international research collaboration;**
- **support the development of dependable real-world quantum computing applications by prioritising software-related research, including quantum software engineering, quantum algorithms, quantum information theory, and quantum error correction and mitigation;**
- **accelerate the uptake of quantum computing by prioritising research that allows efficient use of NISQ computers for real-world problems;**
- **support basic research for the development of quantum computers based on other technologies than those already covered by collaborating countries;**
- **develop a strong national competence and technology base for preserving security and privacy in the quantum computing era;**
- **support interdisciplinary R&D that address ethical and societal aspects of quantum computing.**

Innovation

The Norwegian strategy for quantum computing should

- map the Norwegian business areas that are most likely to benefit from quantum computing and identify front runners;
- map the Norwegian companies and research institutions with world-class expertise for the quantum computing stack and supply chain;
- increase collaboration between academia, research institutions, industry and the public sector to strengthen innovation based on quantum computing;
- prioritise continued education within quantum technology to enable the existing workforce to take advantage of quantum computing;
- increase the competitiveness of Norwegian companies through support of innovative development of products and services in the quantum space;
- enable protection of Norwegian interests, in both private and public sectors, from quantum attacks on security.

Infrastructure

The Norwegian strategy for quantum computing should

- secure access to quantum hardware through participation in international consortia such as EuroHPC;
- prioritise competence and securing advanced skill levels needed for development of quantum algorithms, software and applications.

1
Setting the Scene

In order to put the discussion of a national quantum computing strategy on the agenda, the authors of this position paper arranged the open workshop *QCNorway: Towards a Norwegian Quantum Computing Strategy* in Oslo on November 7–8, 2022. This event featured 23 experts from Norway and abroad, and was realised as a collaborative effort between Simula Research Laboratory, Oslo Metropolitan University (OsloMet), Sigma2 and SINTEF. It was financially supported by the Research Council of Norway (project 341168), the OsloMet Quantum Hub, and Simula. The presentations and a summarising panel session addressed experiences, needs and opportunities for education, research and innovation, as well as infrastructure and strategic perspectives. The speakers were from the European Commission, Norway, Sweden, Denmark, Finland, Germany, the Netherlands, and the USA, spanning government, academia, and industry. The two-day event was very well visited with 83 participants at the actual venue and at least 76 participants online. All details concerning the programme of the event and recordings of most presentations are available on the QCNorway website, www.qcnorway.no.

Disclaimer. *It should be emphasised that the QCNorway event and thereby this position paper have been restricted to the context of quantum computing. There are several other relevant research topics within the wider context of quantum technology where Norway can contribute at top international level. These topics are, however, beyond the scope of this position paper and should rather be addressed by other groups in the Norwegian quantum research community.*

Hopefully, this paper and complementary inputs from other stakeholders can inspire the development of a national quantum strategy, in which quantum computing is a principal part.

The need for quantum computing. Modern society and its citizens depend on large quantities of data being continuously collected and processed by advanced algorithms — from the automated tax return to computer-assisted driving, from patient-specific cancer therapy to finding the next favourite series on Netflix. Computing is all around us, at all times, spanning from life-critical assessments to entertainment. Today, the demand for computational power grows millions of times faster than the performance of traditional computers.[1]

Already 40 years ago, the idea of quantum computing, a totally new paradigm for how to design computers and algorithms, was formulated [2]. This idea predicted the construction of a new class of computers capable of utilising phenomena from quantum mechanics. Such an approach would allow the creation of algorithms that can solve mathematical and statistical problems by efficiently exploring an enormous number of potential solutions. That is, a quantum computer would solve certain problems in a tiny fraction of the time used by a traditional computer, and by its enormous computational power it would solve problems of a complexity far beyond the reach of conventional technologies then, today, and in the future. Today, that 40-year-old idea seems to be rapidly approaching reality.

The potential of quantum computing. The fast-growing potential of quantum computing stems from quite recent experimental and technological advancements in quantum mechanics that allow a certain level of control and manipulation of individual, two-level quantum systems, typically realised as single atoms or light particles. These advancements represent a technical revolution, referred to as the *second quantum revolution*, taking place about 100 years after quantum theory was first developed. From this *first quantum revolution* several by now well-established technological applications emerged, applications such as lasers, magnetic resonance imaging and scanning tunneling microscopy — not to mention transistors and integrated circuits that enabled the construction of the *classical computer*.

> “Society will most likely be facing a computational revolution

Quantum computers are expected to be particularly effective for solving certain types of computational challenges. Optimisation problems constitute a particularly relevant target, due to the quantum computer's inherent capability of evaluating all potential solutions in one, single step. As it happens, optimisation problems are at the heart of a very wide range of important applications, from weather forecasting to data-driven models based on machine learning and AI techniques. There are several other computational challenges for which quantum computers hold a tremendous potential, but there are also problems that will be better solved by conventional computers. Consequently, we already see the development of efficient hybrid approaches combining quantum devices with

[1] Based on a conservative extrapolation of the reasoning presented in “AI and Compute” [1].

conventional computer systems. Society will most likely be facing a computational revolution if one is able to fully realise the power of quantum computing. This disruptive development could pave the way for totally new levels of scientific insight and business opportunities, including fundamentally new approaches to diagnosis and treatment of life-threatening diseases.

While quantum computing has for long been an unfulfilled dream, the last decade has accelerated the development of quantum technology dramatically. Motivated by the data deluge and driven by huge financial investments, quantum computing has entered high-risk, high-gain business. According to Qureca Ltd., about 33 billion EUR have been invested in quantum technology world-wide by the end of 2022 [3], and they quote an analysis by Research and Markets that projects the global quantum technology market to reach 40 billion EUR by 2027 at a compound annual growth rate close to 40% [4]. Recently, Honeywell has stated that quantum solutions will become a 1 trillion USD industry [5].

The green perspective. For calculations where quantum computers provide a substantial speed-up compared to classical computers, quantum computers are expected to require a fraction of the electrical power needed by classical computers. Joint research by NASA, Google and Oak Ridge National Lab has demonstrated a case where the quantum computer used as little as 1/50,000 of the power required by the conventional supercomputer Summit [6]. Typically, the main consumption of energy in a quantum computer installation will be the cooling of the equipment rather than the computing devices themselves, especially for superconducting quantum computers that require cryogenic enclosures of the processing units. Although quantum computers will not replace classical ones, but come as additional accelerators or off-load engines, future use of quantum computers can become very important for reducing energy consumption in HPC centres. It is important to note that quantum computing can be advantageous in areas such as simulating chemical reactions, materials, or optimising complex scenarios, which could make a significant contribution to the green shift.

> “The computational power will also pose threats to modern digital society

The security threat. While quantum computing is expected to have profound positive effects, its computational power will also pose threats to modern digital society. This is particularly true for information security since sufficiently large future quantum computers may be able to break the most commonly used cryptographic algorithms used today to protect privacy and secrets, even at governmental levels. As a result, *post-quantum cryptography* is currently a very active field dedicated to the design, analysis and deployment of cryptographic algorithms and protocols that can withstand the power of future, large quantum computers.

The international scene. While the quantum computing revolution is led by the USA, holding about 60% of the private investments and more than 40% of the start-ups world-wide, the European Union is a major actor and invested 7.2 billion EUR of public funding from 2020 to 2021 — about three times the public investments in China and the USA [7]. This ratio is about to change with coming massive public investments announced by China and the rapidly increasing privately funded initiatives in the USA [8]. Globally, China and Canada stand out as challengers to the USA's leading position [9, 10].

Regardless of which level the quantum computing dream is realised at, it is clear that it cannot be ignored by any modern, technology-dependent nation. Even today, when only small quantum computers suffering from limitations imposed by early generations of technology are available, the quantum computing paradigm has already impacted the way we think about algorithm design and computations.

Several European countries have already established their national quantum strategies and announced substantial national funding, which in many cases have been matched or superseded by private investments. For instance, on March 15, 2023, the UK announced its national strategy that includes a 2.5 billion GBP investment over the next 10 years[11]. By the end of 2022, the total investments in quantum technology in the Netherlands, France and Germany were 765 million, 1.8 billion and 2.6 billion EUR, respectively. Moreover, the German government announced mid-April 2023 a 3 billion EUR investment in the development of a universal quantum computer by 2026 [12]. According to the European Policy Centre, "In contrast with the US, where Big Tech actors dominate, Europe's strengths lie in a vibrant ecosystem of research organisations and start-ups. This growing ecosystem is now at a *critical juncture* to develop into an *internationally competitive European industry*." [13].

The corresponding investments in the Nordic countries are smaller but also substantial: Denmark (228 million EUR), Sweden (143 million EUR) and Finland (24 million EUR) [3]. These three Nordic countries are among the 11 countries world-wide that have been selected for bilateral quantum R&D agreements with the USA. The investments in Denmark and Sweden include large privately funded initiatives for building high-end quantum computers. It should also be added that Denmark, due to its significant activity in quantum technology, has recently been chosen as the host for the new NATO Center for Quantum Technologies [14]. In these three Nordic countries, there is strong momentum towards developing national quantum strategies. The announcement of the Danish strategy is awaited, while in Finland and Sweden the local quantum communities have very recently (February–March 2023) presented their *quantum agendas* as advice to their respective governments [15, 16].

The need for a national strategy. Today, Norway has no official quantum strategy or policy, nor any dedicated investments — public, nor private. This is a strongly unbalanced situation relative to the momentum shown by our neighbours and the rest of the world. The bibliographical analysis of quantum research in the Nordic region presented in the Finnish quantum agenda [15, Table 1] shows rather bluntly how Norway is lagging behind at the national level. To reduce this gap, firm actions from the Norwegian government are called for. These need to materialise now, before the time window offering valuable positions has closed.

> “Today, Norway has no official quantum strategy or policy, nor any dedicated investments

Recently, the Norwegian Government mandated the Research Council of Norway to survey the ongoing research on quantum technology in Norway [17]. The resulting report [18] gives a good overview of current activities and confirms that there is a need for a national strategy and long-term investments of substantial volume. The report also states that the development of a national quantum strategy should include the research community — a process to which this position paper and similar inputs from other stakeholders can contribute.

The four axes. When addressing a national strategy for quantum computing, it seems reasonable to organise the discussion along four axes: education, research, innovation, and infrastructure. These axes represent areas of importance that are tightly coupled, but still have distinct features and priorities. In the making of a national strategy, it is important to align the initiatives and incentives in these areas in a holistic way. We have also used these four axes to organise the material in this position paper.

2 Education and Workforce

Recommendations

The Norwegian strategy for quantum computing should

- **prioritise quantum-literacy in the workforce across a variety of sectors;**
- **increase public awareness of the implications of quantum technology;**
- **ensure that secondary school curriculum includes basic knowledge of quantum technology, with more advanced subjects at tertiary level;**
- **ensure the development of leading educational programmes in quantum computing through dedicated actions.**

There is a fundamental need for preparing a *quantum-aware* and *quantum-literate* workforce as the use of quantum information technology will continue to grow among knowledge workers. While quantum physics and quantum technology traditionally have been taught in an academic context to physics students, this alone will not meet the needs of the quantum industry. In particular, aspiring computer scientists need to be introduced to the quantum realm.

Time is of the essence for such an enterprise. It takes years to educate students to a bachelor's degree, master's degree or beyond, or to extend the qualifications of an existing workforce by means of continued education. Therefore, there is no time to lose in order to meet the escalating demands of a rapidly growing quantum industry, its surrounding ecosystem and societal stakeholders. Such concerns have motivated the development of several educational initiatives world-wide, addressing different aspects of quantum technology [19].

Quantum computing education. The United States is the front runner in quantum technology, thus it is highly relevant to use the US quantum job market as a benchmark for estimating the near-future job market in Europe. Several recent surveys have assessed the needs of the US quantum industry, and some of these were presented at the QCNorway workshop by associate professor Benjamin Zwickl, Rochester Institute of Technology [20]. From these surveys, two interrelated aspects of quantum education stand out:

The quantum workforce is more diverse than just PhD graduates.

The quantum workforce goes beyond quantum-specific technologies.

Both these aspects are related to the interdisciplinary nature of quantum information technology. Developing and improving this technology involves efforts from people with varied backgrounds, such as engineers, physicists, material scientists, mathematicians and computer scientists. In this regard, the ability to communicate efficiently with interdisciplinary team members is crucial, even for those who are not quantum experts. That is, there is need for a quantum-literate workforce. Moreover, developing quantum technology involves several aspects outside quantum technology itself, such as electromagnetics, cryogenics, microfabrication and computer science. The ability to communicate with colleagues working on specialised quantum aspects, typically persons holding a PhD in a quantum-related topic, is crucial. Also, a certain familiarity with quantum technology is also a prerequisite, or at least a door opener, for future learning of more specialised subjects. The urgent need for upskilling the existing workforce is discussed in more detail in Chapter 4.

Already today, in the infancy of the quantum industry, we see a job market developing for quantum-literate workers who do not hold a PhD.

> “There is need for a quantum-literate workforce

Correspondingly, we observe a knowledge gap within Norwegian higher education concerning quantum information technology that needs to be filled both quantitatively and qualitatively: There is an urgent need for developing the necessary volume and diversity of courses to be offered. These courses need to be of high quality and continuously evolve to mirror the rapid progress in the field. Moreover, development and execution of successful courses require deeper knowledge and experience about *how* to teach quantum computing and related topics.

Currently, the access to relevant courses in Norwegian universities is very limited. While some quantum computing courses are offered at the Oslo Metropolitan University and the University of Oslo, there is still a long way to go. Fortunately, the number of master’s and PhD projects addressing quantum-realted topics is increasing, and it is encouraging to observe a growing quantum-oriented interest among students in general. To meet this interest — as well as the demands of the industry — there is a need for more research on and development of how to introduce students with highly varying academic backgrounds to the quantum world.

> It is encouraging to observe a growing quantum-oriented interest among students

Educational research for quantum computing. The teaching of traditional computer science topics, as well as the computational aspects of natural sciences and mathematics, has been formed and honed over decades. With the explosive development of quantum technology over the last few years, the educational challenges associated with teaching quantum computing topics are still handled in a rudimentary way. In order to establish a firm basis for this type of education and build strong portfolios of relevant courses at all levels, there is a need for educational research in the quantum computing direction. Such educational research should aim at developing and benchmarking novel teaching methods adapted to cohorts with diverse backgrounds, including students from physics, mathematics, computer science, cyber security, software engineering and beyond. To develop best practices on how to make such cohorts quantum literate, we need answers to several questions:

- To what extent does a computer science student learning quantum computing have to know about *quantum physics*?
- Which type of intuition needs to be built in order to come up with novel quantum algorithms capable of providing a quantum advantage to real-life problems?
- How do we develop the necessary understanding and skill sets to incorporate quantum-resistant security measures in the digital society?
- How should the software engineering curriculum be changed in order to educate students capable of engineering quantum software? Do we need an entirely new curriculum, or is it sufficient to modify existing curricula?
- How do we build relevant courses in quantum computing suitable for students with diverse educational backgrounds?
- Which skills should be built in secondary school and high school in order to support the transition to quantum computing education at the university level?

The experiences we are currently accumulating in ongoing quantum teaching provide a valuable starting point for answering such questions, but there is a need for dedicated efforts orchestrated through a national strategy. To ensure the relevance of such a programme, it is very important to include the full range of stakeholders across academia, research institutions, industry and the public sector rather than exclusively addressing the universities. In particular, a national strategy should carefully consider the experiences from the two existing schemes of Centres for Excellence in Education (SFU) and Centres for Research-based Innovation (SFI), see also the discussion in Chapter 4.

Quantum literacy in society. The notion of quantum literacy is not limited to people seeking a career in the quantum industry. While most of us do not reflect upon it, we already make extensive use of existing quantum technologies in our everyday lives. We do so when using classical information technology, as well as when applying other kinds of semiconductor technologies, such as solar cells. The laser, which first was coined as "a solution looking for a problem", has certainly found several problems to solve, and medical imaging techniques such as magnetic resonance imaging (MRI) have since long become a household tool at hospitals.

These aspects alone should motivate efforts to increase the public awareness of quantum phenomena, and how such phenomena can be brought to practical use. The onset of the second quantum revolution amplifies this motivation, or even need, considerably. As quantum computers are likely to have a large impact on several aspects of society, everyone — not only professionals within the quantum fields — should have some level of understanding of the possibilities and challenges to come. This emerging and potentially disruptive technology might affect us all, and everyone should be able to influence how it will form society. This is an important democratic challenge.

> “The impact of quantum computing is an important democratic challenge

Having said this, we should also point out that the notion of quantum physics and quantum technology is not absent in society. Sometimes it is promoted as something advanced and mysterious, beyond comprehension. Those familiar with quantum technology carry a particular responsibility for disseminating insight into what quantum computing is and what it is *not*, what is hype and what is genuine. Broader education programmes and increased quantum literacy would be the most effective antidote to this hype, one that levels out unreasonable expectations without reducing the natural curiosity and fascination that people often experience when introduced to the quantum world.

3 Research and Development

Recommendations

The Norwegian strategy for quantum computing should

- take advantage of the large quantum computing momentum already present world-wide, including the Nordic region and Europe, and support international research collaboration;
- support the development of dependable real-world quantum computing applications by prioritising software-related research, including quantum software engineering, quantum algorithms, quantum information theory, and quantum error correction and mitigation;
- accelerate the uptake of quantum computing by prioritising research that allows efficient use of NISQ computers for real-world problems;
- support basic research for the development of quantum computers based on other technologies than those already covered by collaborating countries;
- develop a strong national competence and technology base for preserving security and privacy in the quantum computing era;
- support interdisciplinary R&D that address ethical and societal aspects of quantum computing.

According to the analysis conducted by Qureca Ltd., at least 33 billion EUR have been invested in quantum technology world-wide by the end of 2022 [3]. The large majority of these investments have been directed towards the development of quantum hardware, necessary to realise the vision of the quantum computer and all intermediate steps in this endeavour. Norway is far behind in the international hardware race, and it seems unlikely that we as a nation will play a major role in that race in the foreseeable future. This is not only about timing, but also about the enormous cost levels of breaking totally new ground in hardware R&D.

> “Norway is far behind in the international hardware race

From a strategic perspective, Norway would be best served by making sure that future investments in quantum computing research add value to the hardware solutions primarily under development elsewhere (e.g., through Nordic partnerships, Quantum Delta NL, German Quantum Computing Initiative (QCI), etc.), and that access to these systems is secured through well-funded world-wide R&D collaboration. Independently, most respondents to the open hearing on this position paper have strongly supported this view.

In Europe, the EuroHPC Joint Undertaking and the Digital Europe programme stand out as important and relevant instruments where Norway is already involved. Continued involvement in these and future relevant programmes, including fulfilling the expectations of national contributions on which such collaborative efforts are based, is a fundamental requirement for Norway’s participation in the quantum computing revolution. Yet, Norway should consider supporting basic research needed to develop quantum computers based on other technologies than those being investigated by international collaborators, especially in cases where Norwegian research groups or companies have a leading position. For instance, there are strong research groups with expertise in hardware theory at the University of Oslo (UiO), the Norwegian University of Science and Technology (NTNU), and the University of South-Eastern Norway (USN).

Considered research areas. Research on quantum computing spans science, technology and social aspects, as well as the educational research aspects addressed in Chapter 2. Based on the presentations and discussions at the QCNorway workshop, we think that the scientific, technological and societal research areas discussed below deserve special attention. Moreover, based on our knowledge of the Norwegian research landscape, we are convinced the Norwegian research community can contribute substantially to these areas.

It should be emphasised that our analysis is restricted to the context of quantum computing. There are certainly several other relevant research topics within the wider context of quantum technology where Norwegian research groups can contribute at top international level. These topics, which should be part of a national quantum strategy, are beyond the scope of this position paper and would be better addressed by other groups in the Norwegian quantum research community.

The Quantum Software Opportunity

Following several years of hardware-dominated research, the international quantum computing community is increasingly concerned that the software side of the technology development is falling behind. This discussion is also very present in Europe, and it is expected that coming work programmes for relevant European research initiatives will specifically address this gap. In particular, the recently published Finnish quantum agenda states explicitly, "the role of software is crucial in quantum computing, as the hardware alone computes nothing." [15, p. 7].

Increased emphasis on quantum software resonates well with the fact that Norway already has a track record of doing impactful *software research*. The prime example is the invention and development of the programming language Simula by Ole-Johan Dahl and Kristen Nygaard at the Norwegian Computing Center in the 1960s. This language established the foundations of object-oriented programming (OOP) [21]. Today, OOP is the dominating programming paradigm in modern software development and several modern programming languages have a clear lineage back to Simula, 60 years after its conception. Inspired by this pioneering effort, Norway has fostered several strong research groups in computer science and scientific computing. For instance, in addition to conducting internationally leading research in software engineering, Simula Research Laboratory has strong competence in the software aspects of heterogeneous computing. This includes several years of experience with hosting the national infrastructure for experimental HPC research, eX3, which offers an eclectic collection of processors (CPUs, GPUs, FPGAs, processors designed specifically for deep learning, as well as neumorphic processors), interconnect technologies, memory systems, etc. This competence is complemented by SINTEF, which has done groundbreaking work on how to use graphics processing units (GPUs) for general purpose computations, exploiting massive parallelism, before such programming models became a commodity. There are also strong research groups in these domains at several Norwegian universities. In summary, Norway has an excellent basis for taking a leading position in the development of new types of algorithms and software solutions for quantum computers. With such a position, Norway can offer expertise in algorithms and software to international partners building and offering quantum hardware solutions, and thereby enable a strong mutual collaboration.

> “Norway can take a leading position in the development of new algorithms and software solutions for quantum computers

The quantum software stack. In contrast to the high-level abstractions used in classical computing, the current programming paradigms for quantum computers revolve around different ways of describing low-level circuits that can instruct a quantum computer what to do. Conceptually, this is at an abstraction level comparable to the programming of the very first electronic, general-purpose digital computers in the late 1940s, where one physically constructed electric circuits by connecting wires to plugboards [22]. In order to develop a powerful quantum software stack that can enable the creation of dependable applications in an industrial context, leaps are needed in quantum software research.

Research for the development of an industry-strength quantum software stack is expected to target scientific breakthroughs at different technology abstraction layers, such as quantum algorithm development, high-level programming languages, compilers, transpilers, debuggers, quantum computer simulators, and quantum operating systems, as well as other areas supporting quantum software. Such areas are quantum information theory, quantum error correction, quantum error mitigation, fault-tolerant structures, etc. At all layers of the quantum software stack, Norway has relevant competence for making valuable contributions to international research. One example is creating efficient quantum compilers, while another area for Norwegian contribution could be the construction of quantum operating systems designed to utilise quantum computing resources efficiently. Nonetheless, research at the lower level of the quantum software stack, such as building an operating system or a compiler, would require tight cooperation with research groups working on quantum computing hardware.
Norway is well positioned to explore such collaborations in the Nordic region, Europe and beyond. For instance, there are remarkable efforts ongoing in neighboring countries towards building quantum computers with capabilities at the frontier of research and business, in particular at IQM and VTT in Finland [23], Chalmers University of Technology in Sweden [24], the University of Copenhagen and the Niels Bohr Institute in Denmark [25, 26], and within these organisations' corresponding ecosystems.

> “Norway is well positioned to explore collaborations in the Nordic region, Europe and beyond

As a participating state in EuroHPC, Norway is also well positioned for contributing to leading European initiatives. One such example is the LUMI-Q project, which will build one of the first six European quantum computers [27]. LUMI-Q has a substantial Norwegian footprint through the participation of Simula, SINTEF and Sigma2 as consortium partners. To realise such international R&D collaboration, there is need for dedicated funding, both targeting Nordic collaboration and fulfilling the expectations of national contributions to EuroHPC and Digital Europe.

Quantum software engineering. Within information technology, software engineering is one of the areas where Norwegian scientists have showed international excellence. From this classical foundation, Norwegian researchers have been instrumental in establishing Quantum Software Engineering internationally as a new research field. Norway is therefore well positioned to conduct excellent research leading to novel methods, theories, paradigms, and tools for how to engineer correct and reliable quantum computing applications. This research covers many aspects, such as (1) modelling and analysis, e.g., code generation and verification; (2) quantum programming paradigms, e.g., theories and abstractions; (3) foundations for quantum software quality assurance, including testing, debugging, and repairing quantum applications.

An area within software engineering where Norway has made significant progress is *software dependability*, which aims to ensure an application's correctness, robustness, safety, and other dependability features that allow the user to trust the software. The previous Center for Research-based Innovation (SFI), Certus[1], addressed software verification and validation in an industrial context. Certus made tremendous progress in software dependability, both scientifically and innovation-wise. Continuing along the same lines, the research on software dependability for quantum computing applications must start now in order to prepare for successful industrial take-up of quantum computing in the future. Historically, bad software quality has repeatedly compromised the dependability of critical software systems, causing huge financial losses and physical damages such as the administration of wrong doses of drugs, the destruction of space crafts, and security compromises [29]. Quantum computing is expected to help solve even more complex problems of critical importance to business and society. This calls for extreme requirements on dependability, which will be very challenging to achieve due to the non-conventional way quantum computers work. In simple words, even if we had the most powerful quantum computer at hand and we were successful in making a very complex application run on it, this application could not be fully trusted unless we can ensure its dependability. If it cannot be trusted, the application would have very limited value. Therefore, it is crucial that the research on quantum software dependability is prioritised now, before quantum computing gets industrial traction and the consequences of quantum software failure become intolerable.

> “Quantum computing calls for extreme requirements on dependability

Integrating classical and quantum computers. Today, the access to quantum computers is usually provided within specialised laboratories, such as at Chalmers [24] or VTT [23], or via cloud services offered by giants like IBM, Azure, AWS and Google or by dedicated quantum computing companies like D-Wave, QuTech, PASQAL and Rigetti. At the same time, there is fast progress towards incorporating

[1]The Certus Centre for Software Validation and Verification was hosted by Simula Research Laboratory (2011–2019), see [28].

quantum computing hardware in existing high performance computing (HPC) environments. The LUMI-Q project mentioned above and five other EuroHPC-funded projects are about to start the development of six European quantum computers. All of these quantum computers will be integrated into existing European supercomputer facilities, and in some cases, as a federated resource that can be accessed across different HPC centers and country borders.[2]

When integrated into an HPC environment, the quantum computer can be seen both as a stand-alone resource accessed through a conventional computer as front-end, or as an accelerator meant to work together with conventional processors. In the latter configuration, much like using GPUs to offload certain tasks from CPUs in an HPC system, the overall algorithm will use conventional processors for some tasks and the quantum processor for other tasks. The partial results are then combined to form the total solution to the problem. Noticing that quantum computers will perform extremely well for certain types of workloads but be outperformed by conventional hardware for other tasks, such hybrid solutions are expected to be powerful. In a hybrid setup, the quantum processor is not necessarily a full-blown quantum computer but could instead be quantum computing devices, such as *quantum annealer* chips, designed for specific algorithmic tasks like optimisation. In this case, the hybrid concept of a quantum accelerator is even closer to that of GPU or FPGA acceleration.

> “ Hybrid quantum and classical solutions are expected to be powerful

Regardless of how the actual integration between quantum processors and conventional systems is done, the hybrid concept raises several software challenges. How should algorithms be designed or decomposed to take full advantage of the computational resources? Which software abstractions and libraries are needed in order to make such hybrid software development feasible and lead to dependable applications? How can data be transferred between the resources at speeds that keep the quantum processor busy? How can such a hybrid application be debugged without compromising computational results produced by the quantum processor? The list of questions goes on and on, and leads to a corresponding series of research challenges.

[2]As a side note, one of the very first cross-border connections between classical HPC resources and a quantum computer was showcased at the QCNorway workshop by Axel Andersson [30]. In a live demo, Norway's national infrastructure for experimental HPC research, eX3, hosted by Simula in Oslo, Norway was paired with the QAL 9000 quantum computer located at Chalmers University in Gothenburg, Sweden [24].

Using Noisy Intermediate-Scale Quantum Computers

Present-day quantum computers are relatively small in terms of the number of *qubits*[3]. By nature, qubits are error-prone and difficult to control, and quantum computers are therefore unstable, complex systems with much higher error rates than in conventional computers. Due to capacity limitations in current quantum processors, these quantum computers have insufficient resources to support error correction protocols on the needed scale.

Despite a business-driven and media-supported overoptimism, there is a sober realisation that our generation is bound to live in the era of such *noisy intermediate-scale quantum* (NISQ) computers [31]. So far, most existing algorithms have been developed in the context of the ideal, fully coherent quantum computing paradigm. Therefore, it is necessary to advance the development of algorithms — and quantum computing solutions in general — to allow for controllable and scalable implementations on near-term NISQ platforms.

An application-based approach to NISQ computers. For several quantum algorithms, a successful implementation requires quantum hardware with many qubits and virtually no noise, and consequently large efforts are made in these directions. Such efforts, however, are not limited to technical improvements of the quantity and quality of qubits, they also include important theoretical developments within error mitigation and correction. While it is hard to predict the time-scale, it seems fair to say that we will not see large, noiseless quantum computers in the near future. This observation makes it natural to actively explore the scientific and/or commercial viability of present-day and near-term NISQ computers:

> Can present-day NISQ computers do valuable computations?
>
> Is it possible to demonstrate — in substantial detail — that some relevant real-wold problems can be addressed using these computers?

Algorithms that have a certain robustness against noise will be far more interesting and versatile than methods that require many ideal, noiseless qubits. From this perspective, it is rewarding to put emphasis on the development of novel, fault-tolerant quantum schemes, which will have value both in the NISQ context and for potentially error-free quantum computers in the future.

> “ It is rewarding to put emphasis on the development of novel, fault-tolerant quantum schemes

Such development requires theoretical investigations. However, *empirical testing* is also essential — especially given the fact that such approaches are typically

[3] IBM unveiled 433-qubit quantum processor in November, 2022.

heuristic by nature. While we may not always be able to rigorously *prove* any quantum advantage for algorithms designed for NISQ devices in a general context, such algorithms may still turn out to provide more efficient solutions than their classical alternatives. By benchmarking and analysing the performance of such methods on real quantum devices, we would not only be allowed to gauge their efficiency in terms of the computational resources needed, but also in terms of energy consumption.

Quantum annealers, which are quantum processors specialised for optimisation problems, are less prone to errors than the more general gate-based quantum computers. Within the very useful, but limited, scope of optimisation, quantum annealers are an attractive alternative to gate-based NISQ computers. This is due to the improved stability, which allows annealer-based systems to be scaled up to considerable size, such as the 5000+ qubit platform offered by D-wave [32]. However, this approach does not easily extend to other classes of problems.

Still, the usefulness of quantum annealers has recently been demonstrated in OsloMet's collaborative project with the public transport company Ruter. In this project, a quantum AI algorithm (QBoost) [33] has been implemented on the D-Wave Advantage platform [32] and used to predict passenger capacities on different bus lines. The implementation has been trained with a database collected from actual traffic operations and used for benchmarking and comparative analysis relative to Ruter's existing, conventional AI solution. The results show that QBoost gives about 1% increase of the score function value and has better scalability with respect to the size of the database.

Cloud-based NISQ computing platforms as research labs. Rather than contributing to the ongoing fight with noise and decoherence in NISQ computers, we could think of shifting the current paradigm and developing an approach that uses these obstacles as resources. This can be accomplished by reconsidering NISQ processors from the angle of the theory of *open quantum systems*.

In 2022, the first steps in application of the toolbox of the theory of open quantum system to the present-day NISQ processors were made by different research groups in Germany, France, Poland, and Switzerland. We expect that these attempts will result in a new approach to analysing and designing qubit-based NISQ circuits. We think that, along the path to this goal, in a complementary way, a new methodology for simulations of open quantum systems by using existing quantum computer prototypes could be developed. This, in turn, could establish a new direction in experimental studies of open quantum systems. From this perspective, the present-day NISQ

> “ Present-day NISQ computers should not only be viewed as imperfect predecessors of future quantum computers

computers should not only be viewed as imperfect predecessors of future quantum computers but as already established, flexible platforms capable of exploring, simulating and modelling complex systems and phenomena. OsloMet contributes to realising this idea by participating in the European project *QUANT: A Dissipative Quantum Chaos perspective on Near-Term Quantum Computing* funded through the QuantERA programme [34].

Security and Privacy

The computational power of future quantum computers does not only enable valuable advances in important applications — it also poses a challenge to digital security and privacy. Access to such a computational power will make it possible to break the cryptographic algorithms and protocols that are currently keeping secrets safe, for individuals and governments alike. As a modern citizen, we are surrounded by cryptographically protected communications, whether when shopping online, looking up health records, dealing with public agencies like NAV or the tax office, checking the account balance on the mobile phone, or "vippsing" money to a friend. Cryptography is a fundamental tool for the privacy and security of the digital society.

Securing information by encryption. Secure data communication relies on the use of digital keys, often in an asymmetric fashion. Using a publicly available key, anyone (a person or a computer algorithm) can send encrypted secrets to the owner of that public key. Only the recipient in possession of the corresponding private key will be able to decrypt the messages, thus protecting the privacy of communications from eavesdroppers. A natural attack would be to attempt to determine the private key based on the public key. In current cryptosystems (for example RSA), this is a problem which is much too hard to solve using conventional supercomputers. However, a future, sufficiently large quantum computer running dedicated quantum algorithms will be able to break these asymmetric cryptosystems widely used today.

As discussed by Research Director Øyvind Ytrehus, Simula UiB at the QCNorway workshop [35], rough estimates suggest that a large enough quantum computer capable of compromising current algorithms used for secure communication may be available around 2040, less than two decades from now. This threat is however even more urgent: the so-called Store Now, Decrypt Later (SNDL) attacks [36], where an adversary harvest encrypted information today for later unauthorised decryption when the quantum computational resources become available, means that quantum-resistant cryptographic solutions are already in need.

> “Future quantum computers pose a challenge to digital security and privacy

To ensure security and privacy in the quantum society, there is currently a massive amount of research world-wide on *post-quantum cryptography*. These cryptographic constructions are expected to remain secure even with the eventual advent of large-scale and reliable quantum computers.

Post-quantum cryptography. The way forward in post-quantum cryptography entails the design and analysis of cryptographic algorithms whose underlying mathematical problems are difficult to solve on both classical and quantum computers. Important avenues of research include the use of high-dimensional lattices, error-correcting codes, or isogeny-based schemes as new mathematical engines. The standardisation process run by the US government agency NIST is central to this development. In this process, researchers all around the world have been challenged to propose new mathematical foundations for public-key encryption and digital signatures. Algorithms submitted as candidates for a new standard are then analysed by the cryptographic community, who try actively to break them. NIST aims at publishing a new standard in about two years.

There are several research groups in data security in Norway, and some of these address in particular post-quantum cryptography. Simula UiB, which is Simula's organisational unit dedicated to cryptography and information security, is actively involved in this work. In particular, they are part of the submission team of a code-based cryptographic algorithm being considered as a fourth-round candidate for the NIST standardisation. Simula UiB runs several research activities addressing different aspects of quantum-safe cryptography, partly funded by the Research Council of Norway.

Most of the work in post-quantum cryptography is performed in an open and transparent way, both to challenge the robustness of the new algorithms as early as possible and to make sure that democratic principles are protected as best possible. The forthcoming standardisation of post-quantum cryptographic algorithms will be followed by enormous efforts to upgrade current cryptographic infrastructure to use the newly selected algorithms. This world-wide migration endeavour will itself be beset with substantial challenges, and is likely to take several years. In order to protect the interests of the country and its citizens, it is very important that Norway builds the needed competence and technology assets for the assessment, use and deployment of quantum-resistant cryptographic mechanisms.

Ethical and Societal Impacts of Quantum Computing

Research on the ethical and societal impacts of quantum computing certainly deserves attention, in parallel with the scientific and technological R&D. As discussed above, an important part of this is how the power of quantum computing will influence security and privacy. It should also be noticed that several of the application areas that drive the development of quantum computing, especially in the business context, have a potential critical influence on society and even on individual lives.

Such applications include detailed DNA analysis, drug design and discovery, finance, and artificial intelligence. The world has already seen that legislation and ethical assessments are struggling to keep abreast with the development and deployment of advanced machine learning and artificial intelligence algorithms. Taking into account the unprecedented computational power of future quantum computers, and that some applications break totally new ground and will create ethical dilemmas not encountered before, there is clearly no time to lose.

> “Some applications will create ethical dilemmas not encountered before

Today, the large-scale data exploration enabled by machine learning and the development of increasingly autonomous systems have fueled rapidly growing concerns about who controls such technologies and algorithms. Since these technologies can potentially have an enormous effect on society and individuals, the citizens of the world must be able to understand the possibilities and consequences — good and bad — and make their own decisions. This aspect of democratisation, which should be directly translated to the context of quantum computing, is intimately connected to ethics, security, privacy and legislation. As it is highlighted in [37], the ongoing efforts in this direction are not sufficient.

Norway has the tradition and the expertise for conducting high-quality social science research and for being a front runner for democratisation. This, combined with the scientific basis for high-quality quantum research, strongly indicates that a Norwegian strategy for quantum computing should include interdisciplinary actions to bring scientific research, technology development and social science together.

4

Innovation and Business

Recommendations

The Norwegian strategy for quantum computing should

- map the Norwegian business areas that are most likely to benefit from quantum computing and identify front runners;
- map the Norwegian companies and research institutions with world-class expertise for the quantum computing stack and supply chain;
- increase collaboration between academia, research institutions, industry and the public sector to strengthen innovation based on quantum computing;
- prioritise continued education within quantum technology to enable the existing workforce to take advantage of quantum computing;
- increase the competitiveness of Norwegian companies through support of innovative development of products and services in the quantum space;
- enable protection of Norwegian interests, in both private and public sectors, from quantum attacks on security.

The expectations for what quantum computing can actually do, and for how soon powerful real-world quantum solutions will hit the market, tend to be overoptimistic and even hyped when in the hands of marketeers. That said, with some patience and sobriety, one should indeed expect technological improvements and changes that can have a tremendous effect on industry and business.

Internationally, some business areas are recurringly referred to as prime candidates for efficient use of quantum computing. Such examples include pharmaceutics and life science, design and construction, manufacturing, energy, finance, and logistics. In most cases, the applications in question rely on the solution of complicated or very repetitive optimisation problems that can be offloaded to a quantum device, or they embed other core problems suitable for reformulation as optimisation challenges.

For instance, in the pharmaceutical industry, drug discovery is a complex process that requires the analysis of huge amounts of data. Quantum computing has the potential to significantly speed up this process, for instance, by simulating the behavior of molecules and predicting their interactions with other molecules, thereby accelerating basic operations in drug design.

Financial institutions deal with enormous amounts of data, for which fast and accurate analysis is required to make informed decisions. Quantum computing can provide the computational power needed to quickly analyse large data sets and detect patterns and trends that are difficult to discern using classical methods. This could lead to better investment strategies, risk management, and fraud detection.

In manufacturing and logistics, quantum algorithms could, for instance, be used to optimise supply chain management and improve traffic flow. In the energy domain, which is of particular relevance for Norway, quantum computing could be used to optimise resource exploitation under technical, legal and market-driven constraints, for instance, in production rates for oil wells, hydropower stations and wind farms. It could also be possible to take advantage of detailed modeling of physical and chemical processes, such as in hydrocarbon refineries or when designing new generations of high-capacity batteries.

Norwegian uptake of quantum computing. Today, important parts of the Norwegian industry rely on technologies that will benefit from quantum computing, across sectors such as oil and gas, maritime, and aquaculture. There are already early examples of collaborations between research groups and industry, as well as the public sector, that explore the potential of quantum algorithms. To give some examples: The public transportation company Ruter collaborates with OsloMet, applying quantum computing approaches to dynamic prediction of bus passenger capacity [38]. SINTEF coordinates a collaborative project with several leading Norwegian companies, Kongsberg Maritime, DNB and Equinor, with the aim of building industrial-scale quantum optimisation algorithms [39, 40]. Researchers from OsloMet and UiO are trying to evaluate the potential of quantum computing for op-

> “ Important parts of the Norwegian industry rely on technologies that will benefit from quantum computing

timisation of personalised cancer therapy, while Simula and the Cancer Registry of Norway are jointly exploring quantum artificial intelligence (QAI) algorithms for precisely detecting breast cancer from mammography images.

A very important step in drawing up a national strategy will be to identify which business areas in Norway that are most likely to benefit from quantum computing, taking into account both the computational problems to be solved and the access to relevant personnel and equipment. Based on the experience from the industrial front runners, more business areas and companies would be expected to become involved over time.

It will be very important for a successful Norwegian uptake of quantum computing, and quantum technology at large, to get the potential users interested and invested as early as possible. Their involvement should not be limited to high-level feedback, they should rather be encouraged to get really involved with the technology. While the development of quantum hardware is important in the context of European sovereignty, the most important economic leverage will be driven by the *use* of quantum computing.

> “ Get the potential users interested and invested as early as possible

Accessing and developing interdisciplinary expertise. Quantum computing is a significantly different technology compared to classical computing, and it requires a different approach to problem-solving. To achieve an effective uptake of quantum computing, the industry needs to combine its domain-specific know-how with relevant expertise through partnerships with academia, research institutions, and technology providers. Additionally, the industry will have to invest in building in-house knowledge by upskilling the existing workforce, as well as strategic recruitment.

Continuous learning, including attendance at industrial events and conferences to stay updated, should be complemented by a working environment that fosters experimentation and innovation by allocating resources to R&D activities. This can involve setting up a dedicated quantum computing team or partnering with external experts to collaborate on projects. By taking these steps, organisations can ensure that they are well-positioned to capitalise on the potential of quantum computing and avoid the enormous cost of falling behind at an early stage. That is, establishing a comprehensive, research-based innovation programme allowing Norwegian industry, public sector, academia and research institutions build novel quantum computing applications together should be one of the targets for a national quantum computing strategy. This is necessary in order to facilitate a sufficient volume and momentum in the sector-cutting, interdisciplinary R&D. The already existing scheme of Centres for Research-based Innovation (SFI) has proven to be an effective tool for such collaborative efforts, and should be considered as a potential instrument for establishing national powerhouses dedicated to efficient uptake of quantum computing.

Upskilling the workforce. As discussed in Chapter 2, quantum computing is still an emerging field and there is already a shortage of qualified professionals in this area. Since quantum computing is a highly complex technology, it takes time to become proficient, even at more conceptual levels. Therefore, one cannot rely solely on recruiting competent people from the outside — it is equally important to develop programmes for targeted upskilling of the talents already present in the workforce. Training programmes offered to employees should develop a broad understanding of quantum computing, covering both theory and practical applications. The necessary educational actions in industry and the public sector should be well balanced with the progress of quantum computing programmes provided by universities and the general development of quantum literacy in society. On-the-job training should be seen in connection to the interdisciplinary collaboration between sectors discussed above, and one should in particular draw on the experiences from universities and research institutions that are heavily involved in education at bachelor's, master's and doctoral levels.

> “Training programmes should develop a broad understanding of quantum computing

Dedicated funding schemes for developing strong educational and upskilling programmes in quantum computing will be needed and should be addressed by a national strategy. It would be natural to scope such an initiative on the basis of selected experiences with the existing scheme of Centres for Excellence in Education (SFU). However, it is very important that a quantum computing initiative in this direction includes the full range of stakeholders across academia, research institutions, industry and the public sector and is not exclusively addressing the universities. To ensure the necessary integration with the organisations in need of competence, the design of an educational programme should carefully combine relevant experiences from both the SFU and SFI schemes.

Securing sensitive data against attacks via quantum computers. As discussed in Chapter 3, quantum computing poses a significant security threat to organisations that rely on encryption to protect sensitive data. Future quantum computers will have the ability to break some of the most important encryption protocols that are currently in use, which could lead to the compromise of sensitive information. Even if these encryption schemes cannot be compromised today, it is possible to capture transmitted or stored ciphertext (that is, encrypted data) and store this ciphertext until the computational resources are powerful enough to decrypt this information. This is obviously dangerous, especially when the sensitivity of the data does not degrade over time, such as for health records and certain types of government secrets. Therefore, it is essential that organisations in possession of critical data take proactive measures already today to ensure their security in the quantum computing era.

Public investment in R&D of post-quantum cryptography will be necessary, as advocated in Chapter 3, but such an initiative needs also to be complemented by investments in rapid deployment of post-quantum security measures as widely as possible in both private and public sectors. Such actions will complement existing best practices for data security, such as ensuring that data is encrypted both in transit and at rest, restricting access to sensitive data, and implementing multi-factor authentication. Only by taking a multi-faceted approach to data security that includes both technical measures and best practices, organisations can ensure that their data remains secure in the quantum computing era.

International industrial collaboration. SINTEF, Simula, and Equinor are partners in the European Quantum Industry Consortium (QuIC). QuIC's mission is *"to boost the European quantum-technology industry's competitiveness and economic growth, and bolster value creation across the continent."* [41]. In 2022, a Norwegian Chapter of QuIC was co-founded by SINTEF, Simula, and Equinor. The aim of this chapter is to facilitate communication between the association and other interested organisations within Norway. Participation in such associations could help the Norwegian industry and researchers to build strong networks within the EU, and thereby contribute to building quantum computing technologies. Such networks might also help building the necessary capacity to lead or participate in European calls for funding related to quantum computing. Therefore, dedicated schemes are needed to support Norwegian organisations to network with relevant associations and communities working with quantum computing within the EU.

5
Quantum Computing Infrastructures

Recommendations

The Norwegian strategy for quantum computing should

- **secure access to quantum hardware through participation in international consortia such as EuroHPC;**
- **prioritise competence and securing advanced skill levels needed for development of quantum algorithms, software and applications.**

From the perspective of providing production-quality infrastructures for research and public services, it is not recommended to invest in large-scale quantum hardware in Norway in the near future given the current state of quantum computing technologies. For such purposes, access to relevant hardware should rather be secured through participation in international consortia. It might, however, be useful to consider smaller, experimental installations of hardware if these complement the technologies and systems that can be accessed through collaborative schemes.

Acknowledging that competence and software are intrinsic components of any successful computational infrastructure, the national focus on the shorter term should primarily be on building competence and securing advanced skills in quantum software development. In the longer term, when superior quantum computing technologies have proven themselves, investments in national systems can be considered to secure national needs, still taking international collaboration into consideration.

The current state of play. At present, the field of quantum computing appears as immature when considered in the context of delivering a computational infrastructure for a wide group of users. In other terms, quantum computers are still at the lower Technology Readiness Levels [42]. Several technical implementations of quantum computers on the very basic level are competing to become the most viable solutions for scaling up and becoming the basis for industrial products. There is not yet any technology or architecture that stands out as the preferred choice. Because of this uncertainty, and because of the high degree of research and development efforts needed, the costs associated with investments in large-scale infrastructures for quantum computing are very high at this stage. At the same time, Norway needs to be ready when quantum computing enters a more mature and production-capable state. As a consequence, Norway's initial approach should be to partake in international collaborative efforts to build infrastructures, in an orchestrated way that spans all the other pillars discussed in the preceding chapters. Large investments in national quantum computing infrastructures should be deferred until the timing is right.

> “ Norway needs to be ready when quantum computing enters a more mature and production-capable state

Need for international and national collaboration. As discussed in the preceding chapters, quantum computing has the potential to impact many important fields, including finance, healthcare, and energy. As such, many countries are investing in quantum computing R&D. However, the development of quantum computing infrastructures requires significant investments, and an individual country, like Norway, may not have the resources nor the expertise to build and maintain a *comprehensive* infrastructure on its own. Therefore, a national strategy must include an emphasis on and the ability to participate in international partnerships, particularly in Europe. This is needed to ensure that Norway has deep knowledge of the quantum computing infrastructures that will be built, as well as of how they are developed and maintained, in order to harness these tools for use in areas of national importance. In this context, it should be added that investments in quantum computer systems for critical functions like national security, or for purely commercial purposes, might be subject to a different reasoning and are beyond the discussion in this paper.

International collaboration will allow for sharing of resources and expertise, as well as standardisation of technology and protocols. This will enable the development of a network of quantum computing centres and users, making it easier for researchers to access and use quantum computing resources. Likewise, national collaboration and resource sharing are important for the development of a comprehensive infrastructure for quantum computing, such as addressing the needs within research and education of national priority. Norwegian funding agencies, research institutions, and industry must work together on the establishment of shared resources for quantum computing, including building and maintaining the “right level” of national infrastructures for quantum computing in the context of international collaboration.

There is currently a strong drive in the EU for pooling of resources and investments, and this continues to be part of the EuroHPC strategy. EU calls funded by the Digital Europe Programme (DEP) will in many cases require a national contribution, typically 50%. A process for influencing and monitoring work programmes leading to such calls must be established. This process should adhere to a national quantum computing strategy and roadmap, and result in budgeting of funds that allow active Norwegian participation in such European calls.

While collaboration with EU countries is important, Norway should also be open for world-wide collaboration if that gives access to quantum computing technologies that are superior to the European alternatives. One example could be the opportunity for testing how algorithms scale on computers with more qubits than those available in the EU.

The relation to HPC. Classical HPC systems are critical and intrinsic components of infrastructures for quantum computing. There are many practical challenges to overcome in order to make quantum computers run as separate appliances, such as user access (authentication, accessibility, environment, etc.), data access (input/output), workflow management, orchestration/allocation (batch scheduler), quantum resource management [43]. While these challenges need to be addressed also when connecting and properly integrating quantum systems and classical supercomputers, the expertise and experience acquired in the HPC domain during the last 40+ years will ease this integration. Connecting quantum simulators and quantum computers with classical supercomputers through a unified cloud-mode access will allow a large part of the scientific community to become familiar with quantum computing, thereby accelerating its adoption.

As discussed in Chapter 3, current quantum computing technologies do not have sufficient error correction mechanisms to provide stable systems. In order to mitigate some of these issues, classical HPC resources play currently an important role in the post-processing and verification of computational results from quantum computers.

To some extent, classical HPC systems also provide computing power and resources to simulate and test quantum algorithms outside the quantum computer. In this way, these systems support the development of quantum software. As such, HPC must be integrated with quantum computing in order to maximise the potential of this emerging technology.

Glossary of Terms

- *Classical computing*:
  Computing which is not quantum; the use of ordinary computers, in other words
- *Decoherence*:
  When waves meet, they may reinforce each other to produce a larger wave, or they may add destructively, resulting in a smaller wave — or complete cancellation. Quantum objects also have this wave property. However, if a quantum system cannot be fully isolated from its surroundings, this capacity is gradually lost.
- *The first/second quantum revolution*:
  When quantum theory was developed about a century ago, it did not only change science. It brought about novel technologies, such as lasers, transistors and magnetic resonance imaging. This has been coined *the first quantum revolution*. It is a common conception that we are now on the verge of a second revolution within quantum technology — one that will revolutionise information technology by exploiting quantum phenomena in computing, meteorology and information processing.
- *Gate-based quantum computer*:
  A quantum computer which, in principle, can run any quantum program consisting of a sequence of logical *gates* applied to specific qubits. A gate is a specific action imposed on one or a few *qubits*. Many such gates, such as the NOT gate, coincide with logical gates applied in conventional, classical computing. The notion of a *quantum annealer* represents a more contingent alternative to this general approach to quantum computing.
- *Noisy intermediate scale quantum (NISQ) computers*:
  Present day quantum computers are far from ideal in many respects. The number of quantum bits is still somewhat limited. But, more importantly, they are suffering from noise and *decoherence*; the wave-like nature of a quantum system is lost as the system gets entangled up with its environment. To some extent, this is unavoidable in physical implementations. But efforts are made to minimise and mitigate such issues.

- *Open quantum system*:
  An open quantum system is a quantum system that interacts with a much larger system (in general, also quantum). The latter constitutes an "environment" to which the original system is "open". This interaction significantly changes the state and the evolution of the open system. This typically results in destruction — full or partial — of such important quantum features as, e.g., coherence, purity, and entanglement. Because no quantum system is completely isolated from its environment (it is rather a helpful abstraction which might still be valid in some cases), it is important to develop a theoretical framework to model and describe effects induced by the system-environment interaction as well to understand their contribution to the evolution of the open system. This is the main objective of the *theory of open quantum systems*.

- *Post-quantum cryptography*:
  The design and analysis of cryptographic algorithms and schemes whose security is based on mathematical problems for which there are no (known) quantum algorithms offering an exponential speed-up compared to classical computers. Post-quantum cryptographic constructions are expected to remain secure with the advent of large-scale and reliable quantum computers. Often also referred as *quantum-resistant cryptography*.

- *Quantum annealer*:
  A specific class of quantum processors, specifically designed to tackle optimisation problems by letting the qubits find the minmum energy configuration. Such processors are less error-prone than the more general gate-based processors, which makes it possible to build larger computers, currently with 5000+ qubits.

- *Quantum literacy/awareness*:
  The ability to recognise quantum phenomena and how they may be applied in technology. Here, we will not take this to imply proficiency in technical and mathematical aspects of quantum physics, but rather a more general awareness of the quantum nature and applications.

- *Quantum physics*:
  The theoretical framework that describes the micro world, i.e., atoms, molecules, nano-structures and particles — and their interactions. This description is fundamentally different from the classical Newtonian mechanics which describes the macro world.

- *Quantum simulation*:
  Simulating a quantum system on a quantum computer.

- *Qubit*:
  Abbreviation of *quantum bit*, which is a two-state quantum-mechanical sys-

tem that constitutes the basic information unit in a quantum computer. While its counterpart in a conventional computer, a bit, is a binary digit taking on either the value 0 or 1, the qubit can have the value 0, 1 or any quantum superposition of 0 and 1.

References

All web links listed in the references were visited on May 29, 2023

[1] OpenAI. AI and Compute, 2018. https://openai.com/research/ai-and-compute.

[2] 40 years of quantum computing. *Nature Reviews Physics*, 4(1):1, 2022. Editorial, https://www.nature.com/articles/s42254-021-00410-6/.

[3] Qureca. Quantum Initiatives Worldwide – Update 2023, 2023. https://qureca.com/quantum-initiatives-worldwide-update-2023/.

[4] Research and Markets. Quantum Technology Market by Computing, Communications, Imaging, Security, Sensing, Modeling and Simulation 2022–2027, 2023. https://www.researchandmarkets.com/reports/5317365/quantum-technology-market-by-computing/.

[5] Honeywell. Honeywell Quantum Solutions And Cambridge Quantum Computing Will Combine To Form World's Largest, Most Advanced Quantum Business, 2021. https://www.honeywell.com/us/en/press/2021/06/honeywell-quantum-solutions-and-cambridge-quantum-computing-will-combine-to-form-worlds-largest-most-advanced-quantum-business/.

[6] Physics World. Quantum Computers Vastly Outperform Supercomputers When It Comes to Energy Efficiency, 2020. https://physicsworld.com/a/quantum-computers-vastly-outperform-supercomputers-when-it-comes-to-energy-efficiency/.

[7] Anika Pflanzer, Wolf Richter, and Henning Soller. A Quantum Wake-up Call for European CEOs. *McKinsey Digital*, 2021. https://www.mckinsey.com/capabilities/mckinsey-digital/our-insights/a-quantum-wake-up-call-for-european-ceos/.

[8] Matteo Biondi, Anna Heid, Nicolaus Henke, Niko Mohr, Lorenzo Pautasso, Ivan Ostojic, Linde Wester, and Rodney Zemme. Quantum Computing Use Cases are Getting Real – What You Need to Know. *McKinsey Digital*, 2021. https://www.mckinsey.com/capabilities/mckinsey-digital/our-insights/quantum-computing-use-cases-are-getting-real-what-you-need-to-know/.

[9] Thomas Corbett and Peter W. Singer. National Quantum Strategy, 2022. https://www.defenseone.com/ideas/2022/04/china-may-have-just-taken-lead-quantum

-computing-race/365707/.
[10] Matt Swayne. China's Origin Quantum Ships First Quantum Computer, 2023. https://thequantuminsider.com/2023/02/03/chinas-origin-quantum-ships-first-quantum-computer/.
[11] Government of the United Kingdom. National Quantum Strategy, 2023. https://www.gov.uk/government/publications/national-quantum-strategy/national-quantum-strategy-accessible-webpage.
[12] Matt Swayne. Germany Announces 3 Billion Euro Action Plan For a Universal Quantum Computer, 2023. https://thequantuminsider.com/2023/05/03/germany-announces-3-billion-euro-action-plan-for-a-universal-quantum-computer/.
[13] Georg Riekeles. Quantum technologies and value chains: Why and how Europe must act now, 2023. https://www.epc.eu/en/Publications/Quantum-technologies-and-value-chains-Why-and-how-Europe-must-act-now~4f3940a.
[14] Ministry of Foreign Affairs of Denmark. New Danish NATO Center for Quantum Technology, 2022. https://investindk.com/insights/new-danish-nato-center-for-quantum-technology.
[15] The Finnish Quantum Agenda, 2023. https://instituteq.fi/finnish-quantum-agenda/.
[16] En svensk kvantagenda, 2023. https://www.vinnova.se/publikationer/en-svensk-kvantagenda/.
[17] Jan Willie Olsen. Skal kartlegge kvanteteknologi i Norge. *Khrono*, 2022. https://khrono.no/skal-kartlegge-kvanteteknologi-i-norge/707401/.
[18] Research Council of Norway. Gjennomgang av norsk forskning på kvanteteknologi, 2022. Memo on assignment from the Norwegian Ministry of Education and Research.
[19] Maninder Kaur and Araceli Venegas-Gomez. Defining the quantum workforce landscape: a review of global quantum education initiatives. *Optical Engineering*, 61(8):081806, 2022.
[20] Benjamin Zwickl. Developing a "quantum aware" workforce: trends in North America and Europe, 2022. Presentation at the QC-Norway workshop. https://www.qcnorway.no/videos#Zwickl.
[21] Wikipedia. Simula, 2022. https://en.wikipedia.org/wiki/Simula.
[22] Computer History Museum. ENIAC, 2023. https://www.computerhistory.org/revolution/birth-of-the-computer/4/78.
[23] Himadri Majumdar. Finnish perspectives on Quantum Computing and Business, 2022. Presentation at the QCNorway workshop. https://www.qcnorway.no/videos#Majumdar.
[24] Göran Wendin. HPC+QC, NordIQuEst and the Future of Quantum Computing, 2022. Presentation at the QCNorway workshop. https://www.qcnorway.no/videos#Wendin.
[25] Niels Bohr Institute. Microsoft Quantum Computings, 2020. https://nbi.ku.dk/english/industrial-collaboration-at-nbi/cases/microsoft-quantum-lab-copenhagen/.
[26] Niels Bohr Institute. Major investment for developing Denmark's

first fully functional quantum computer, 2022. https://nbi.ku.dk/english/news/news22/major-investment-for-developing-denmarks-first-fully-functional-quantum-computer/.

[27] LUMI. Czechia will host the European LUMI-Q quantum computer, 2022. https://lumi-supercomputer.eu/czechia-will-host-the-european-lumi-q-quantum-computer/.

[28] The Certus Centre for Software Validation and Verification, 2019. http://certus-sfi.no/.

[29] Wikipedia. List of software bugs, 2023. https://en.wikipedia.org/wiki/List_of_software_bugs.

[30] Axel Andersson. eX3 + QAL 9000 connection, 2022. Presentation at the QCNorway workshop. https://www.qcnorway.no/videos#Andersson.

[31] John Preskill. Quantum Computing in the NISQ era and beyond. *Quantum*, 2:79, 2018.

[32] D-Wave Advantage system. https://www.dwavesys.com/solutions-and-products/systems/.

[33] Calogero Zarbo. Take off with Quantum Machine Learning. https://medium.com/@calogerozarbo88/take-off-with-quantum-machine-learning-2d31e95164ea.

[34] DQUANT: Dissipative Quantum Chaos Perspective on Near-Term Quantum Computing. https://quantera.eu/dquant/.

[35] Øyvind Ytrehus. Quantum-safe cryptography, 2022. Presentation at the QCNorway workshop. https://www.qcnorway.no/videos#Ytrehus.

[36] David Joseph et al. Transitioning organizations to post-quantum cryptography. *Nature*, 605(7909):237–243, 2022.

[37] Zeki C Seskir, Steven Umbrello, Christopher Coenen, and Pieter E Vermaas. Democratization of quantum technologies. *Quantum Science and Technology*, 8(2):024005, feb 2023.

[38] Umair M. Imam. How Ruter uses Quantum computing in its machine learning algorithms, 2022. https://youtu.be/_zDMmz4WcOs.

[39] Terje Nilsen. Why should Norwegian companies invest in Quantum Computing knowledge already at this early stage?, 2022. Presentation at the QCNorway workshop. https://www.qcnorway.no/videos#Nilsen.

[40] Tobi Giesgen. Preparing now for the bright unknown in an uncertain future, 2022. Presentation at the QCNorway workshop. https://www.qcnorway.no/videos#Giesgen.

[41] European Quantum Industry Consortium, 2023. https://www.euroquic.org/.

[42] Wikipedia. Technology readiness level, 2023. https://en.wikipedia.org/wiki/Technology_readiness_level.

[43] Partnership for Advanced Computing in Europe. http://www.prace-ri.eu/.

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