En svensk kvantagenda

Bilagor

Appendix 1.

The four areas of quantum technology

In Europe, quantum technology is often grouped into four main areas: quantum computing, quantum simulation, quantum communication, and quantum sensing.

Quantum computing

A quantum computer is a computer which works in a completely different way compared to a conventional computer. As basic building blocks, called qubits, it uses quantum mechanical systems. While the bits in a regular computer can take either the value 0 and 1, the qubits can be both 0 and 1 at once, thanks to the quantum phenomenon of superposition.

Because each qubit can represent two values at once, the total number of possible simultaneous states doubles with each added qubit. Two qubits can represent four values at once, three qubits give eight possible values, and so on. It starts slow but grows faster and faster. Already 300 qubits could represent more values at once than there are particles in the entire universe. And it only takes 50–60 well-functioning qubits to exceed the computing power in today's supercomputers.

There are many possible hardware platforms for quantum computers, for example atoms or ions, superconducting circuits, light particles, molecules with different nuclear spin states, or tiny semiconductor particles called quantum dots. The most promising and developed techniques this far are superconducting circuits and ions. Superconducting circuits are fabricated on a chip, whereas ions are suspended in free space or above a chip using electromagnetic fields, in a so-called ion trap.

At the front

Already a couple of years ago, Google's quantum computer and later the quantum computer of a Chinese research team surpassed the world's best supercomputer in computing a specific task – demonstrating so-called quantum advantage. The flip side is that the task was useless, chosen solely to be easy for a quantum computer and at the same time difficult for a conventional computer. The next step is to surpass a supercomputer in solving a task that is beneficial to someone.

A few other quantum computers, which have not proven quantum advantage, are available for commercial and research activity via the cloud, for example IBM's 127-qubit superconducting quantum processor, Rigetti Computing's 80-qubit superconducting quantum processor, and IonQ's 23-qubit trapped-ion quantum computer. Thanks to funding from Knut and Alice Wallenberg Foundation, Sweden will have its first quantum computer available for industrial use in 2025.

Comparing different quantum computers

News articles often focus on the number of qubits in a quantum computer. However, this number alone tells very little about its performance. There are several other useful metrics to consider:

- the connectivity – the number of other qubits that couple to each qubit,
- the types of quantum-logic gates that can be implemented,
- the reliability, often referred to as fidelity, of the gate operations,
- the number of parallel operations that can be implemented, and
- the circuit depth, that is the number of gates in sequence that can be applied to all the qubits before the fidelity has decayed too much during an algorithm.

How will quantum computers be used?

Quantum computers are predicted to be particularly suitable for solving problems that involve many possibilities, such as optimization problems in logistics or machine learning, and the calculation of properties of large molecules. Breaking today's encryption codes is further away, since running such algorithms requires thousands of well-functioning qubits.

Quantum computers will most likely be part of hybrid computing systems, where a quantum computer operates as a subroutine or co-processor to a conventional supercomputer. The conventional processors will do most of the work, whereas the quantum processor performs the specific calculations that a quantum computer is significantly better at.

Quantum simulation

Properties of molecules, for example their energy levels, are important to know when designing new materials or drugs. However, for larger molecules, the computational problem becomes too large for the computer to handle.

But in 1982, the famous physicist Richard Feynman got an idea about how to overcome the difficulties: A controllable quantum system could be used to study another, less controllable or accessible quantum system. This is called quantum simulation.

Quantum simulation could be implemented using quantum computers but also with simpler devices, so-called analogue simulators, which would be easier to construct. Analogue simulators are specifically designed to simulate a certain system or process and therefore have a limited scope of use, while quantum computers can be programmed to take on many types of problems.

In recent years, the field of quantum simulation has been developing rapidly, and there are now several different platforms in which quantum systems – such as neutral atoms, ions, superconducting circuits, nuclear spins, and photons – can be experimentally probed for quantum simulation.

In addition to helping to identify new materials and drug substances, quantum simulation promises for example to solve routing and scheduling problems, and to be very useful in advancing research in many fields of physics, quantum chemistry, and cosmology.

Quantum communication

Our digital society is highly dependent on secure information, but with the progress of quantum computers that potentially can break today's encryptions, the security risks are rapidly increasing. Quantum communication – based on the laws of physics – provides intercept-proof solutions which are already in use in some places.

How does it work?

Encryption relies on so-called encryption keys – usually strings of ones and zeroes – used to encrypt and decrypt information. If the receiver of an encrypted message has the key, then he or she can decrypt and read the information. The problem is generally to transfer the key without an adversary getting hold of it.

In quantum communication, the encryption key is transferred using quantum particles, so called Quantum Key Distribution (QKD). According to the laws of quantum physics, it is impossible to measure or copy an unknown state of a quantum particle without noticeably changing it. Therefore, one can always be sure to detect interception.

The quantum particles generally used in quantum key distribution are particles of light, photons. The most established scheme for quantum key distribution – the BB84 scheme – relies on the sender and the receiver to measure the polarization of the photons by randomly using different polarization filters.

Already available

Commercial systems using the BB84 scheme are already on the market. The drawback of these systems is that they require an unbroken optical fiber connection channel. This limits the distance to 200–300 km.

The most advanced, known systems for quantum communication are found in China. The first is a long-distance quantum encrypted link between Beijing and Shanghai, based optical fibers connected at relay nodes. The nodes are susceptible to hacking, and therefore only security-classed personnel has access to them. In the second system, satellites act as nodes and the encryption key is sent as faint pulses of light between a ground station and the satellite.

Coping with long distances

The limited range over which it is possible to send quantum keys is a big hurdle. For a global quantum communication network to become true, one must find a way of amplifying and forwarding the signals, without having to decrypt and re-encrypt the data along the way. A so-called quantum repeater could do the job, but these are very complex machines. Developing practically viable quantum repeaters is one of the most important and challenging tasks within current quantum communication research.

At the forefront

A drawback with today's BB84 systems is that they require trusted devices for sending and receiving photons. Therefore, scientists are working on more advanced, device-independent quantum communication schemes. The choice of equipment then becomes less important from a security point of view – one could even buy equipment from an enemy.

Quantum sensing

Human knowledge of the world and our technological progress is limited by what we can measure, and how accurately. By exploiting quantum properties of single particles, measurement capability can be pushed far beyond what has previously been possible.

Quantum states are extremely sensitive to disturbances – this means that sensors which utilize quantum states for measurements have the potential to become extraordinarily sensitive measuring instruments.

Measurement devices which exploit quantum properties have been around for a while, such as atomic clocks, laser distance meters and magnetic resonance imaging used for medical diagnosis. What now is new is that individual quantum systems, such as atoms and photons, are increasingly used as measurement probes, and that entanglement and manipulation of quantum states are used to enhance the sensitivity.

Quantum tricks to reach new levels of accuracy

The so-called uncertainty principle in quantum mechanics limits how precisely measurements can be made. However, the quantum state of the measurement probe can be manipulated so that the uncertainty is shifted to another physical quantity and the physical quantity of interest can then be measured with enhanced precision. Quantum states can also be manipulated to make the measurement immune to the strongest sources of noise.

What to expect in the future

The potential impact of quantum sensors is broad and considerable. From ultra-high-precision microscopy, positioning systems, clocks, gravitational, electrical and magnetic field sensors, to optical resolution beyond the wavelength limit.

Quantum sensing will definitely help advance the research front in many fields of science. They are also predicted to enable detailed mapping of the underground, autonomous driving, medical progress, brain-machine interfaces, detection of minor traces of explosives and poisons, and improved imaging technologies both at short and long distances.

Appendix 2.

SWOT Analysis

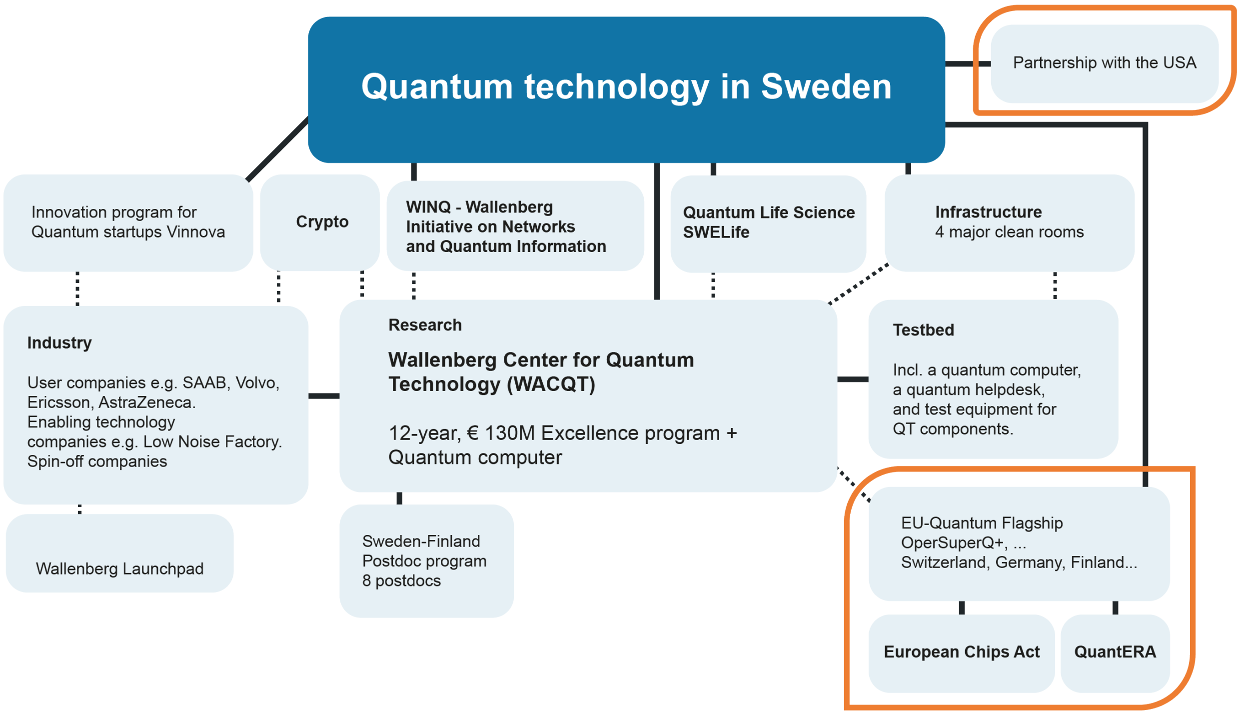
This SWOT analysis was made during December of 2022 to evaluate the status for Quantum Technology in Sweden. The group contributing to this analysis contained people from academia, industry, funding agencies, government authorities and defense. This SWOT analysis is made as a part of the Swedish Quantum Agenda, and it also serves to bench mark the Swedish quantum ecosystem within the Nordic collaboration Nordic Quantum. A SWOT analysis focusing more on the innovation aspects can be found in Appendix 5.

Strengths	Weaknesses
The research centre Wallenberg Centre for Quantum Technology (WACQT), generously funded by Knut and Alice Wallenberg Foundation, which started timely in 2018 and covers all pillars of quantum technology. Additional quantum research initiatives: Wallenberg Initiative on Networks and Quantum Information (WINQ) and Quantum Life Science (QLS). Good infrastructure, for example the excellent micro and nano fabrication lab Myfab and an abundance of dark fibres, i.e. unused optical fibres, which could be used for quantum communication. A large Swedish interest in new high-tech innovation, with both large and small companies engaging in quantum technology. Quantum technology being a "hot" area attracts many strong candidates to PhD positions.	Lack of national coordination, such as a national agenda, and unclear which agency is responsible for different initiatives. Weak governmental engagement, with no responsible agency, at the EU level. Unbalance between private and governmental funding. Weak Swedish involvement in the quantum communication part of the European Quantum flagship. Strong international competition for competent staff in quantum computing, which makes it hard to recruit especially postdocs. Weak focus on commercialisation and applications.
Opportunities	**Threats**
A national agenda would give increased focus and common direction, allowing to coordinate the strong activities in quantum technology. Become part of the European Quantum Communication Infrastructure (EuroQCI) – a nascent quantum internet for intercept-proof communication. Create a Nordic collaboration in quantum technology to strengthen research and become a stronger international player. Create testbeds to accelerate the Swedish competence in quantum technology. Benefit from potential synergies with the opportunities offered by the European Chips Act, such as competence centers and investment in pilot lines. Involve the right companies, both quantum tech user companies and enabling tech companies. Create dedicated MSc programmes in quantum engineering to attract talents worldwide.	The quantum technology hype – failure to meet the expectations fed by the hype could lead to a "quantum winter" with declining interest and funding. Having only one private funding source is a vulnerable situation and is not sustainable in the long run. If quantum technology competence is not strengthened, Sweden will be vulnerable for other nations developing such competence. Financing of infrastructure remains a challenge and risks to fall between chairs. Especially Myfab requires continuous reinvestments to stay at the forefront. Information and internet security can be threatened by quantum computing, as quantum computers develop. Low awareness and knowledge level within many companies in Sweden regarding the possibilities and (future) advantages with quantum technologies. Increasing competition for research funding, VC funding and competence (lack of competent staff due to hard international competition).

Appendix 3.

The Swedish quantum technology landscape

Graphic overview of the actors and initiatives in Sweden related to quantum technology, also showing the links to Nordic, European, and international initiatives.



Appendix 4.

Education and competence in quantum technology

As mentioned, quantum technology builds on the quantum mechanical concepts of superposition and entanglement to deliver technology that supplies a qualitatively new level of computational power, qualitatively new and secure ways of communication and unprecedented measurement sensitivity and accuracy.

The technology readiness level (TRL) varies in the field. Some applications, like quantum key distribution are already commercially available and a few quantum sensing applications are also approaching this stage. Useful quantum computers are currently not commercially available, but a few companies offer cloud access to devices which potentially will reach this stage within a few years. This has spurred an increasing worldwide effort to explore real-world use-cases for these near-future quantum computers.

Since quantum technology is based on quantum phenomena which are contra-intuitive in nature, a strong graduate education is key to ensure competitive levels of research and development, at universities as well as in small and large companies. Probably as important for quantum technology to fulfill its potential to improve society, is also to educate decision makers in companies as well as in the rest of society about the possible applications and use-cases, as well as parallel management of potential risks. It is of the utmost importance that not least politicians and others in the public have sufficient understanding to develop both facilitating and protective adequate control and facilitating regulatory instruments.

Graduate education and research training

In Sweden, the Wallenberg Centre for Quantum Technology (WACQT) has taken on the dual mission of promoting excellent research in the field and providing resources of building a superconducting quantum computer. To this end, the center includes a graduate school currently including approximately 60 PhD students of which 10 are industrial PhD students, employed by companies. Together with the approximately 25 post-docs employed by WACQT, this forms a large part of the quantum technology research training in Sweden.

To develop a long-term and sustainable quantum technology ecosystem, it is crucial that we as a country and our universities can offer attractive conditions to both successfully recruit and retain young talent. This refers to education at all levels, both undergraduate and graduate education and continuous specialist education in the field within various sectors.

Undergraduate education

Training PhD students and post-docs in quantum technology is an excellent way to make sure that we have expertise in Sweden, enabling us to exploit this new technology as more applications are developed. However, there is also a need to increase the undergraduate education, to attract young researchers to quantum technology and to give a larger number of engineers and future decision makers the necessary understanding to be able to see and adopt the new opportunities arising.

Relying on quantum mechanical concepts, quantum technology is typically taught at Engineering Physics or Physics bachelor and master programs. However, certain aspects and concepts in quantum information can be understood also without a full quantum physics background, but e.g., based on linear algebra, which is taught in most engineering bachelor programs. There is thus a possibility to educate students and providing some knowledge on conceptual and fundamental quantum science and technology more broadly than what is currently done.

At the Swedish universities most involved in WACQT, the status for undergraduate education in quantum technology can be summarized as: At KTH, there is since 2019 a quantum technology track in the Engineering Physics master program and at Chalmers such a track started in the Physics and Nano master programs in autumn 2022. At Stockholm University, there is a master track on Quantum Matter, which is somewhat broader than quantum technology, while at Lund several relevant courses are available and discussions are ongoing to propose a quantum technology track to Engineering Physics/Physics students, with possible openings towards Computer Science and Electrical Engineer students. At Linköping University, a master profile in quantum technology and photonics within the "Civilingenjör" program in Electrical Engineering and Applied Physics has been created. Outside of WACQT, Uppsala University has developed a quantum technology master program.

Changes in undergraduate education are often slow, which generally means that such changes are well anchored and thought through. Due to the academic autonomy of universities, it is also hard to force such changes. The different universities have different organization of their respective bachelor and master programs as well as different research specialties within quantum technology. In general, we also see that many engineering physics students choose other master programs than Physics, knowing that industry has a large demand for programming skills. There are also in general fewer female students in the Physics master programs in Sweden.

A national coordination, surveying all relevant quantum technology undergraduate courses in Sweden, spreading good examples of both individual courses as well as tracks and also master programs and potentially even bachelor programs, would increase the quality of the education as well as push the educational systems towards an increase of undergraduate students in quantum technology.

Professional education and lifelong learning

Since 2018, WACQT has delivered many introductory lectures at different companies and other organizations. A few half day courses on quantum algorithms and joint workshops to determine relevant quantum technology use-cases and research topics has also been held. For quantum technology to reach its full societal impact, these activities must increase and be nationally coordinated. It is key that stakeholders from industry and other parts of society take part in developing the formats of these activities, which can range from introductory lectures, overview as well as topical one-day courses, to one-week summer schools and full 7.5 credit courses.

Testbeds in education and cross-fertilization

The testbeds that are now being developed will be offered to industry but also to other sectors. They can also be used for training at different levels of various categories. Here both undergraduate students at different levels, graduates as well as specialists in the industry, can be offered additional or complementary training. The testbeds can also be excellent environments for cross-fertilization between different skills from different sectors. Consequently, testbeds may become an additional tool to develop an advanced and broad quantum technology ecosystem in Sweden.

Community awareness

It is a considerable threshold for a layman to undertake and thereby be able to be part of the quantum technology ecosystem, both to be able to take part in opportunities and at the same time be usefully critical of a high-tech development driven by quantum technologies. Creating awareness and gaining support from an enlightened public requires knowledge dissemination with the help of skilled science communicators, researchers, and journalists. This is particularly important in an initial phase of the use of quantum technology in society and therefore requires adapted, often shorter training opportunities for different professions.

Appendix 5.

Quantum technology innovation

Analysis of the emerging Swedish ecosystem

Executive summary

Introduction

The first quantum revolution contributed to significant technological advances and laid the foundations for widely used technologies including nuclear energy, lasers, and digital imaging devices. We now again stand before a period of rapid technological development in quantum technology, labeled the second quantum revolution, that is expected to create significant disruptions in areas from communication and processing to sensing and imaging – foundations for important and wide-ranging industries such as data security, life sciences, meteorology, cryptography, energy, transportation, and more.

General development

Technological development

Technology areas included in this second wave of quantum technology advancements are often broken down into three major subcategories: quantum communication, quantum sensing, and quantum computing, which includes quantum simulation. Although at an early stage of development, these interconnected technology fields are expected to bring significant advantage in a wide range of applications and industries.

Quantum Communication	Quantum Sensing	Quantum Computing and Quantum Simulation
Involves using the laws of quantum-mechanics to secure transmit data.	Involves using different quantum particles and systems to make measurements.	Involves using quantum mechanical phenomena to perform computations much faster than traditional computers.

The technology readiness for different subcategories of quantum technology varies. Some applications are already in use within quantum communication and quantum sensing, and these areas are expected to mature further over the coming years. For quantum communication, development challenges include scaling to larger networks and communication over larger distances, while challenges in quantum sensing include increased sensitivity and high costs.

While quantum computing over all is at an earlier development stage than quantum communication and sensing, significant milestones have been achieved over recent years. There is an ongoing debate in the scientific community to what degree existing quantum computers has shown advantage over existing computers and to what extent the recent achievement constitutes proof of concept. A number of development hurdles lie ahead, including ability to scale quantum computers, and effective error correction needed before quantum computers can find real applications outside research environments.

Just like traditional computers, the development of quantum computers relies on both hardware and software. Quantum computing relies on the construction of quantum bits (qubits) which is currently taking place using a number of different qubit technologies. Much of ongoing research and development in quantum computing focus on the construction of qubits using different technologies, evaluating their respective pros and cons.

Some of the most commonly used technologies are described below:

Qubit technology	Description	TRL-level
Super-conducting qubits	Achieving a superposition state via an electronic circuit where the charge carriers are electron pairs, and each qubit is a superconducting circuit. Currently, most big tech companies are using superconducting qubits.	4
Trapped ion qubits	The use of magnetic fields/lasers to trap electrically charged atoms (ions) within which qubits are stored.	3

Cold atoms	Similar to ion traps, but in this case the qubits come away from an array of neutral atoms trapping qubits with light and controlling them with lasers.	3
Photonic qubits	Carrying information using light particles/photons in a quantum state (rather than electrons).	3
Electron spin qubits (Silicon-based quantum dots)	These qubits are created from nuclei fixed in solid substrates or spins of electrons.	3

Quantum computers, similar to conventional computers, requires software to run on top of their hardware in order to generate results. Quantum software in this way refers to programs and algorithms that are designed to run on quantum computers to preform various tasks such as simulation, optimization factorization and linear algebra.

Market development

While much of quantum technology activities are focused on early-stage research and development, the past five years have seen continuous growth in quantum technology investments with a number of niche markets starting to develop. This trend is expected to continue in the future as commercial applications inch closer towards becoming a reality. The market development as well as the market potential varies between different sub-technology areas in quantum, largely relying on technological advancements for its realization.

Quantum communication is expected to be an important market and is beginning to see traction, including large amounts of public investment from US, Europe, and China. Some sources estimate that the market will be as big as quantum computing by 2030. The market is driven by the need for secure communication and specific use cases have been proven in cryptography and secure communication, not the least building on quantum key distribution (QKD). There are already companies commercializing QKD devices for secure communications, and national quantum-secured networks are under development across the globe.

The market for quantum sensing currently exists, although it is small, niche, and fragmented. Quantum sensors could find advantage over many existing sensors in a wide range of industries ranging from oil and gas to health care. Quantum sensors are available today for limited production use cases and experts expect their availability and capability to attract great funding and grow rapidly within five to 10 years.

Because there are so many use cases in different industries, quantum computing is expected to have the largest potential market – however, at this stage the technology is in its infancy, so the impact is unknown. Finance and infrastructure needs are large, so this development is taking place mostly in larger companies or bigger startups, besides development carried out within academia. There are increased volumes of private venture capital aimed at startups in quantum computing. However, given the significant technological challenges associated with the development of quantum computers, such investments are taking a long-term perspective and are subject to significant risk.

Role of government

The role of the state in the development of quantum technology varies significantly between countries. In some countries, the government have taken a leading role in funding and supporting research and development efforts, as well as establishing policies to encourage the growth of the industry; this is the case for the United States, China, and Canada, among other countries. In other cases, governments have taken a less active role in funding and supporting quantum technology research and development, leaving the development of quantum technology to research financiers, private sector or research financed by philanthropic sources; examples of the later include Sweden and Denmark.

National governments are increasingly taking a more active role in coordinating efforts in research, development, and ultimately commercialization of quantum technologies. This is done by bringing together actors from government, academia, and industry in dedicated forums outlining national strategies for quantum technology. The growing interest of governments in quantum technology is driven by several factors, including the anticipated economic impact resulting from quantum technology's development, its potential contributions to national competitiveness, as well as concerns regarding national sovereignty. Increased attention is also motivated by national security considerations and dual-use possibilities. Recent years have also seen an increase in international collaboration in quantum technology innovation, in many cases anchored on government level.

In the past five years, major government funding has been announced around the world. Announced global public investment in quantum technology exceeds $30 billion and is continually rising. China is a global leader when it comes to public funding of quantum technology who currently has committed approximately $15 billion to funding quantum technology. While the US can be viewed as the global leader in quantum technology, public investments are relatively sparse, with a $1.2

billion budget for the National Quantum Initiative. Instead, the US is largely relying on private funding for its quantum technology development. The EU-block on the other hand is a front runner when it comes to public investments in quantum technology, with significant research investments on both EU-level as well as on national level. The EU Quantum Flagship amounts to about the $1.1 billion, and national initiatives to roughly $7 billion. Despite significant investments, the region is trailing both China and the US in terms of technological development and commercialization, largely due to lacking coordination between academia, industry, and startups.

The emerging Swedish ecosystem

The Swedish quantum ecosystem is centered around research and university-based initiatives. The structure of the Swedish ecosystem can be described as university-driven, where philanthropic funding from the Wallenberg Foundation through the Wallenberg Centre for Quantum Technology (WACQT) drives basic research that is rooted in universities and research labs. The Swedish quantum ecosystem today is characterized by a strong concentration around the WACQT initiative, and limited activity and coordination outside the philanthropically funded initiative. This is linked to a lack of coordination and investment from the public sector, which is only recently increasing its involvement.

Sweden has a strong research and innovation ecosystem with robust infrastructure for quantum technology research. Overall Swedish research in the quantum field can be described as narrow and with high impact. In a bibliometric comparison between five leading innovations hubs conducted by Amsterdam Data Collective, Sweden ranked the highest in terms of Scientific impact. At the same time, the volume of research output is lower than many comparative countries.

A clear position of strength for Swedish research can be found within the field of quantum computing, as Sweden has established strong research, developing full stack competence from qubit development to software. This can be attributed to the ambitious research conducted with the WACQT initiative aimed at building a 100-qubit quantum computer based on superconducting circuits in ten years. At the same time the strong focus on a single technology platform (semi-superconducting qubits) presents a risk and potential weakness as there is much uncertainty around what technologies will be dominant in the future. Further weaknesses include the limited research activities conducted outside the WACQT initiative.

Besides the ambitious focus on quantum computing, the WACQT initiative has further supported research in quantum sensing and quantum communication. WACQT initiatives in quantum sensing, and quantum communication are coordinated from Lund University and KTH Royal Institute of Technology, respectively. The quantum sensing area is arguably the subcategory where technology maturity has gotten the furthest in the Swedish context with active spinout startups from the WACQT-initiative.

The development of a marked and commercialization-oriented quantum innovation ecosystem is still at an early stage in Sweden. Applications oriented activities are taking place within the WACQT-initiative through an industry partner program. Six incumbent firms are currently taking part in the program together with four enabling technology partners hosting seven industrial PhD Students. Further, an emerging ecosystem of startups in quantum technology exists in Sweden. The ecosystem largely consists of spinout companies from academic research active in specific niches of the ecosystem where solutions have reached a sufficient technology maturity. In addition to startups focused on developing solutions for quantum technology, the ecosystem also includes firms that offers enabling technologies for quantum. Such firms are offering technologies that can support both academic institutions as well as firms that are developing quantum technology solutions. Sweden is still in the early stages of venture capital entering the system. No venture capital activity in Sweden is identified through the startup and investment database Crunchbase (Jan 2023).

Sweden has not yet formulated a national strategy and coordinated efforts to develop Swedish capabilities in quantum technology can mainly be linked to initiatives funded by the Wallenberg Foundation. Public research financiers have historically funded individual research projects within quantum technology and have recently increased their engagement to support the financing and coordination of quantum technology development.

Sweden has during the past five years joined and participated in a number of international collaboration framework around quantum. The joint statement on cooperation in quantum information science and technology between Sweden and the United States particularly deserves to be highlighted. Sweden also participates in several European initiatives and collaborations including European Quantum flagship, OpenSuperQ and Euro QCI. In addition to the previously mentioned collaboration, interviews indicate that emerging Nordic collaboration in the field of quantum technology presents a significant opportunity for long-term development and competitiveness in Sweden. Collaboration between Nordic actors has arisen over recent years through a combination of bottom-up research collaboration and ecosystem-level contacts. The relatively parallel timelines of initiatives to develop a Swedish, Danish, and Finnish national strategy have further highlighted the potential for future collaboration.

Mapping of the Swedish quantum landscape

Based on insights from interviews and desk research a landscape image of the Swedish ecosystem for quantum technology has been developed. The mapping is presented below.

Quantum Technology Ecosystem in Sweden (actors and initiatives)

Research	Start-ups and companies	Industry
Private/Philanthropic The Wallenberg Foundation: The Wallenberg Centre for Quantum Technology, WACQT (12-year, €130 M): **WACQT entails two parts:** 1. The **core project** with the objective to build a 100-qubit quantum computer based on superconducting circuits. The quantum computer is developed in a targeted project at Chalmers. 2. An **excellence program**: Quantum computing coordinated by Chalmers, quantum simulation coordinated by Chalmers, quantum communication coordinated by KTH, and lastly, quantum sensing coordinated by Lunds Universitet. **Efforts within WACQT:** • **WACQT-IP**: holding company that will protect and exploit patents within Quantum Technology. **Other efforts funded by The Wallenberg Foundation:** • **WINQ**: Wallenberg Initiative on Networks and Quantum information • **WALP**: Supports innovation at universities linked to spin-off companies or researchers who want to start spin-off companies.	**5 Spin-off companies from WACQT:** • **Deep Light Vision AB**, Oxygenation measurement instrument • **Atlantic Quantum**: Quantum computing • **Scaling**, Quantum computing, sample holder • **Sweden Quantum AB**, Microwave filters • **quCertify**, Quantum communication • **Quantum Scopes**, Quantum Life Science • **Single Photon Quantum Radiology**, Quantum Life Science **Enabling technology companies:** • Low Noise factory	**Industry partners involved in WACQT:** • **SAAB**: Quantum radar, noise radar • **Volvo**: Quantum machine learning • **Astra Zeneca**: Quantum chemistry • **Ericsson**: Distributed quantum computing • **Jeppesen**: Optimization of flight routes • **Hitachi ABB Power Grids**: Quantum key distribution – Includes 7 industrial PhDs. **Enabling technology partners within WACQT:** • Spectracure AB • Research Institutes of Sweden (RISE) • Intermodulation Products AB • Sahlgrenska

Public
Vetenskapsrådet Funding of numerous research projects in collaboration with partners such as QuantERA. **Vinnova** Providing funding for quantum technology innovation calls (€2 million). 3 ventures, 2 Start-ups and 1 platform **Quantum Life Science Center - Karolinska Institute** Center for Swedish Quantum Life Science research and innovation. **Swedish Foundation for Strategic Research** Various research projects funded focused in quantum technology.

Regional and international collaboration and coordinated efforts
International level • Innovation Partnership in Quantum Technology (U.S.) **European level** • EU Quantum Flagship • QuantERA (European network of public research funding organizations) via Vetenskapsrådet • Open SuperQ+: Open super Qplus100 • European Chip Act • EURO QCI (signatory on the EuroQCI declaration) **Nordic level** • Nordic Quantum • Nordic Quantum Life Science • Nordic Quantum Computing Group

Research

Key trends impacting the development

The report identifies a number of central trends that will affect the development of quantum technology, these are described below:

Overall strategy and coordination

- Governments are increasing their involvement in the field to coordinate and drive development.
- Race between countries to become a leader in quantum technology.

- Countries and clusters compete to attract private and public investment in this area.
- Public investment continues to be a driver, direct and indirect, for the development of the ecosystem.
- The U.S. and China continue to be leaders in the field and Europe continues to chase.
- Bilateral and multilateral cooperation is of great importance for countries' competitiveness in this area.
- More co-operation in the Nordic region with joint coordination and funding.
- Initiatives are taken on a European level to coordinate research and development activities across Europe, but fragmentation persists.

Capabilities and attractiveness

- Lack of competence limits development and competition for existing skills is fierce, both nationally and internationally.
- The defense and security dimension have a major impact on the development of the civilian ecosystem for quantum technology.
- Interdisciplinary competence challenges in building up knowledge in other disciplines outside physics.
- Investments in quantum knowledge can have applications in other fields, even if quantum is not commercialized.

Research and technology development

- Continued rapid technological development in many parallel technology areas.
- Several technology platforms compete for the development of quantum computers, without achieving a "standard".
- Scalability remains a major challenge.
- Competing organizational forms for the development of quantum computers are used in various ecosystems, these involve universities, established companies and startups (supported by VC-firms), among others.
- Technological breakthroughs are achieved in quantum computing without it having a decisive impact on the commercialization of the technology.

- Access to infrastructure and supporting technologies continues to be important for development.
- Academic research drives technology development.
- Technology development is centered around a few globally leading players.

Commercialization and applications

- The commitment of the business community to participate in development is growing rapidly.
- Increased volumes of private venture capital aimed at startups in quantum computing.
- Limited access to long-term financing for startup companies in Sweden, startups are looking for money internationally.
- Startups with a research focus have a central role in the development.
- Early commercialization of technologies in quantum sensors and quantum communication (achieves high TRL).
- Trends pointing to the potential of a few companies dominating the industry in the future.
- Risk of a quantum winter – signs of slowing investments. Consolidation in the market.
- Development is slowed by increasing rates, and investors becoming more short term.

Trends and underlying factors in Sweden

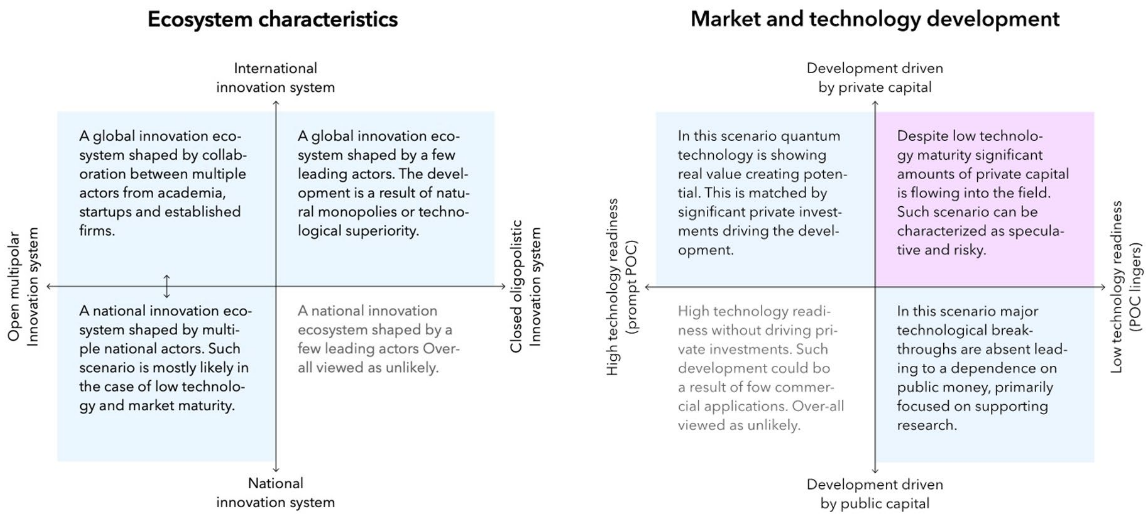
- The development has been concentrated around a single financier and research initiative.
- Government involvement has historically been limited and in some cases uncoordinated.
- Sweden is showing emerging strength in quantum life science.
- All three sub-categories of quantum technology are gaining traction in Sweden, but their readiness levels differ.
- The high barriers to entry and the limited number of players engaged in

development are challenges to development and wider adoption.

- The broader understanding of quantum technology and potential application is growing at a slow pace in Sweden.
- Initiatives are being taken to strengthen Nordic collaboration in quantum technology.
- The commitment of the business community to participate in quantum technology research and development is growing.
- Lack of competence limits development and competition for existing competence is tough.

Scenario analysis

Based on the analysis and the identified trends a scenario analysis has been conducted based on four identified strategic dichotomies. The four dimensions are joined in two scenario matrixes identifying 8 potential outcome scenarios focused on the one hand on ecosystem characteristics as well as on the interplay between resources allocated to development and technological development. These outcomes are presented below, where green highlighting indicating likely scenarios, and red highlighting scenarios with high associated risks.



Three development scenarios

Based on the outcomes of the two matrixes, three joint scenarios are formed. These are presented below.

International focus, closed ecosystem, high TRL, private capital	International/regional focus, open ecosystem, high TRL, private capital	National/regional focus, open ecosystem, low TRL, public capital
Quantum technology has advanced to the point where a small number of tech giants control the majority of the ecosystem. These companies have invested heavily in research and development, and as a result, possess a significant advantage in terms of technology and resources. Individual countries as well as firms have little autonomy to govern their own quantum technology development, as access to leading quantum technology and platforms is essential for success.	Quantum technology development is taking place in an open innovations system on a global level. This system is characterized by rapid technology development. Countries and firms are able to position their own national ecosystems within niches of the global ecosystem, both alone and in collaboration with others. As a result of this open innovations system, it becomes increasingly important for countries to attract global capital for commercialization and research.	Due to the lack of significant technological breakthroughs, private funding for quantum technology is limited. This scenario presents an open innovation system, where actors and countries can position themselves on a national and regional level. In this scenario, it is important for countries and firms to focus on funding research for long-term technology development. To maximize their resources and chances of success, countries and may collaborate with others to pool competences and resources.

SWOT analysis of the Swedish ecosystem for quantum technology innovation

Based on the assessment of the Swedish ecosystem for quantum innovation the below SWOT analysis has been developed. It includes elements from all parts of the ecosystems and aims at identifying overarching trends with importance for current and future development. The SWOT analysis has been developed by Amsterdam Data Collective in dialogue with Vinnova and is based on insights from interviewees as well as extensive document studies.

Strengths:

- Established strong research with high impact.
- Full stack competence in QC
- Strong funding levels in the short run.
- Strong infrastructure for quantum technology research.
- Established international networks.
- Strong over all research and innovation ecosystem.

Weaknesses:

- Lack of breadth in research.
- Limited number of research environments.
- Narrow focus on single technology platforms (QC).
- Limited government coordination and support (historically).
- Weak focus on commercialization and applications.

Opportunities:

- Emerging Nordic collaboration in quantum technology.
- Potential strength in life science.
- Established partnerships and agreements with countries and leading actors.
- Established companies with interest and relevance for the development of quantum technology.

Threats:

- Increasing competition for research funding, VC funding and competence.
- Sweden is not perceived internationally as a leader in the quantum field.
- Lacking strategic positioning in an international innovation ecosystem.
- SMEs seek capital abroad.
- Global Swedish companies are linking to international hubs.

System analysis and development areas for Sweden in quantum technology

Overall strategy and coordination

Sweden is currently facing challenges in the coordination of its actors and initiatives in the field of quantum technology. At the same time strong framework conditions and a well-developed research and innovation system provides a solid base for future development of research and innovation in quantum technology. To achieve a strong and effective innovation system for quantum technology, a clear national strategy and stronger government involvement is necessary to ensure coordination among various actors and initiatives in the field. Further opportunities exist in strengthening existing international partnerships in quantum technology and explore synergies together with partners.

Development areas:

- Set an ambition – formulate and implement corresponding strategy
- Foster international collaboration
- Support the formation of a complete and connected ecosystem

Capabilities and attractiveness

A number of underlying capabilities will affect Swedens ability to be competitive and develop a strong ecosystem in quantum technology. Sweden is facing challenges in terms of education and human capital, which is further exacerbated by the lack of dedicated courses and programs in Swedish universities. Further, the overall understanding of quantum technology in society is low, which is hampering the involvement of relevant actors, such as policy makers and private companies, in the development. Finally, Sweden has been unsuccessful in communicating existing strengths in quantum technology and is thus facing challenges in terms of attractiveness.

Development areas:

- Invest in quantum education
- Continue to build knowledge and involve a broader audience
- Communicate Swedish strengths and strive to be an attractive destination for capital, research and competence

Research and technology development

The Swedish research and development ecosystem in quantum technology is largely driven by academic research, financed by the Wallenberg Foundation's research effort WACQT, with a strong focus on developing full stack capabilities in quantum computing. Important achievements have been made through the WACQT initiative and Sweden has developed leading expertise in the field of quantum computing. However, the sole dependence on private philanthropic investment for funding raises concerns about the long-term sustainability of quantum technology development in Sweden, and the absence of a national program hinders the growth of a diverse and inclusive ecosystem. To achieve long-term sustainability and practical applications, there is a need to strike a balance between basic research and applied research, and to develop a more diverse funding model that includes government investment and private sector involvement.

Development areas:

- Build on existing strengths and broaden the research ecosystem
- Ensure long term financial support for quantum research
- Increase support for applied research and increase access to quantum infrastructure

Commercialization and applications

The corporate R&D and startup scene in quantum technology in Sweden is still in its early stages. The research ecosystem has to this day had a limited focus on commercialization and applications. The application focus of quantum technology applications has progressed the most in the area of life sciences. As the technology matures support structures are needed to assist the translation of research results to the economy. Such support could include incubation, technology transfer offices as well as support for startup companies. To achieve a coordinated development of both technology and market should be a priority, and the government has a role in supporting early-stage startups both through financial and non-financial means. Further opportunities exist in engaging established firms in Sweden to take part of and contribute to research on quantum technology.

Development areas:

- Support the emerging startup ecosystem through seed-funding and non-financial support
- Ensure access to capital infrastructure and network
- Identify application and engage with industry

Introduction

The following report presents the results from an analysis of innovation in quantum technology conducted by Amsterdam Data Collective on behalf of Vinnova. The study covers three main areas:

a. External monitoring of global activities in quantum technology
b. Scenarios for future development of quantum technology
c. Forward-looking system analysis of the Swedish national context

The project has been conducted as a part of a larger process aimed at contributing to the definition of an agenda for Sweden in quantum technology. Results from this report will be used in the process to define such agenda as well as material for Vinnovas continued work to support the emerging quantum innovation ecosystem.

The report takes a broad perspective on quantum technology aiming to provide a broad information base for policy makers and ecosystems actors engaged in the development of the Swedish innovation ecosystem for quantum technology. For this reason, the report covers a broad range of areas such as segmentation of development areas in quantum technology, emerging market characteristics and government involvement in global ecosystems. In this way the study introduces the basic dynamics shaping quantum technology,

The study builds on an extensive review of existing literature on quantum technology. Further, interviews have been conducted with stakeholders in Sweden as well as international experts on quantum technology innovation.

To identify important development areas for quantum technology innovation in Sweden two workshops have been conducted. These workshops have contributed to the definition of future development scenarios, the system analysis and the subsequential recommendations for further development of the Swedish ecosystem for quantum technology innovation.

Global development in Quantum technology

Technology

Many of today's existing technologies are based on quantum physics, including nuclear energy, lasers, and digital imaging devices such as thermal imaging cameras. These are considered first-generation quantum technologies. Current conversations surrounding quantum technology refer to next-generation technologies (Quantum 2.0) that are a result of a deeper understanding and application of quantum properties. The emergence of quantum mechanics has resulted in different quantum phenomena that can be used to develop these various technologies; these phenomena include but are not limited to superposition (the ability of quantum systems to exist in multiple states at once), entanglement (the interaction of several particles so that their quantum states become connected, even across long distances) and tunneling (where quantum particles can pass through previously impassable barriers). As research continues to unlock new possibilities, excitement surrounding Quantum 2.0 has intensified as the potential for these technologies to disrupt everything from communication and processing to sensing and imaging – foundations for important and wide-reaching industries such as data security, life sciences, meteorology, cryptography, energy, transportation, and more – is expected.

Quantum technologies can be broken down into three major subcategories: quantum communication, quantum sensing, and quantum computing, which includes quantum simulation.

Quantum Communication

Communication is one of the most developed quantum technologies at this point and is expected to play a big role in the next level of secure communication as the current cryptography framework will be vulnerable to quantum computers. A core element of quantum communication is quantum key distribution (QKD) systems that encrypt by way of quantum particles, which are impossible to copy and sensitive to disturbances. Countries like the U.S. and China are already investing heavily in QKD and other infrastructure to create secure communication networks, and there are already companies commercializing QKD devices for secure communications.

The science for quantum communication hardware exists but for a proof-of-concept to be done to scale, regulatory approval to access a LAN on the scale of a university or city is required. Demos of quantum cryptography have begun taking place in small networks (such as an internal system) or in existing telecom fiber networks. The next step in technological development is to tackle long-distance communication by circulating a quantum message for optical fiber or satellite connections as well as a fully quantum random number generator, which would be an accessible, cheaper chip assisting with security processes in every IoT device.

Quantum Sensing

Solutions based on quantum sensing already exist, although the market is considered small, niche, and fragmented between the different sensors. Quantum systems can help create new kinds of sensors that are more accurate and sensitive than previous technologies when measuring gravity, time, acceleration, magnetic fields, and more.

At a high level, the quantum sensing field comprises multiple technologies that use different quantum particles and systems to make measurements. These technologies, in turn, can be divided into three broad categories; Optical sensors, based on the properties of light (photonic systems), solid-state systems, that use the physical properties of electrons or atoms, and atomic vapor sensor, exploring the properties of atoms.

While quantum sensors are still in the early stages of development, they have shown promising results in some application areas and are expected to find broader applications in the future. For quantum sensing applications to be competitive and attractive they will need to provide higher sensitivity than existing sensors, at a price that are comparative- or lower than alternative technologies. Another challenge relates to the difficulty of functioning outside the protected lab environment, due to being sensitive. Therefore, it is relatively difficult to predict the development.

Quantum Computing and Quantum Simulation

With a normal computer, information is processed as either a 0 or a 1. Qubits can be both 0 and 1 at the same time, meaning that they can simulate possible states more quickly and on a much larger scale than normal computing. Quantum computing relies on the construction of quantum bits, or qubits, which is currently taking place via a variety of different technological processes, each with its own drawbacks and benefits. The scaling of stable qubits creates more powerful systems, but currently, some types of qubits have high error rates due to environmental sensitivity (for example, if they get too warm, they lose their properties and therefore their information) and need to be corrected, which involves shielding them from factors such as temperature, light, and sound. Access to infrastructure and supporting technologies (such as cryogenics and photonics) for quantum computing continues to be important for development for this reason. As quantum computing still requires substantial error-correction, fully fault-tolerant quantum computing will be considered a "key milestone" in use cases and scalability remains a major challenge.

Quantum computing is the quantum technology with the largest potential for use cases and impact, but it is still very early-stage. Generally, experts voice the opinion that the software (algorithm) side of quantum computing is generating intellect that the hardware cannot currently support, so much is still unknown about both the market and use cases, although there are some early indicators.

Quantum computing will not take over all traditional computing tasks nor be suited for application everywhere; rather, it will be used in cases where it can address problems unable to be calculated with traditional processing and/or complete specific functions in a mere fraction of the time that it would otherwise take a traditional computer.

We have not yet seen demonstrated concrete advantages over conventional computers (Quantum Advantage), but the view of many experts is that quantum computers will be able to demonstrate performance better than that of high-performance conventional computers within a decade, but for certain applications. While it is anticipated that Quantum advantage still is some years away it is generally accepted that Quantum Supremacy already is achieved.

Box 1: Comparing Quantum versus Classic computer

Quantum Advantage	Quantum Supremacy	Quantum Value
Demonstrating that a quantum computer can solve a problem (irrespective of the usefulness of the problem) faster or lower cost than a classical computer.	Demonstrating that a quantum computer can solve a problem, again irrespective of the usefulness of the problem, that a classical computer cannot solve in a practical length of time.	Demonstrating quantum advantage or supremacy for a problem that has a real commercial relevance where value (e.g., better solution shorter run time) is created.

Source: World Economic Forum, 2022. NASA Ames Research Center, 2019.

Hardware

However, research in qubit technology is constantly advancing, resulting in even more qubit types such as spin and neutral atom qubits that are currently under development. Qubit technologies can be split into three main-categories: electron-based (which includes the most invested-in superconducting technology), atom-based (which includes cold atom and trapped ion technologies), and photon-based. There is not yet any consensus on which qubit technology that is most likely to be successful nor the time for this to occur.

To assess the potential of the various qubit technologies two features must be considered, as needs to work simultaneously; scalability i.e., the possibility to increase their number without deteriorating the quantum behaviors of the ensemble, and increased quality in of the qubits. Additionally, it is not likely that there will not be a single qubit better than others for all functions. Therefore, evaluating is no easy task.

No matter the qubit type, as quantum hardware is resource and environment-intensive, it is expected that most user access to computing will happen through a cloud service.

In the box below, some of the major qubit technologies are described more in depth to contrast features and possible future possibilities and challenges.

Box 2: Major Qubit Technologies being researched

Super-conducting qubits

Achieving a superposition state via an electronic circuit where the charge carriers are electron pairs, and each qubit is a superconducting circuit. Currently, most big tech companies are using superconducting qubits.

- Pros: speed, potential for scale-up, and familiar technology.
- Drawbacks: physical environment needs (refrigeration to near absolute zero), error-correcting techniques are required for the qubits.
- Maturity: TRL 4: Technology validated in limited form at lab scale.

Trapped ion qubits

The use of magnetic fields/lasers to trap electrically charged atoms (ions) within which qubits are stored.

- Pros: trapped ion qubits are more stable, can store "quantum information with longer coherence times" and can operate at room temperature.
- Cons: trapped ion is considered slower and the technology less mature.
- Maturity: TRL 3: Proof of concept exists.

Cold atoms

Similar to ion traps, but in this case the qubits come away from an array of neutral atoms trapping qubits with light and controlling them with lasers.

- Pros: horizontal scaling from fibre optics and the potential creation of quantum computer memory schemes (e.g. quantum random access memory (qRAM).
- Cons: operation times and gate fidelity. Leading companies using cold atom quantum technologies include Cold Quanta and Pasqal.
- Maturity: TRL 3: Proof of concept exists.

Photonic qubits

Carrying information using light particles/photons in a quantum state (rather than electrons).

- Pros: "long coherence times", can function across a range of temperatures, and can be integrated with fibre-optic communication infrastructure.
- Cons: debatable scaling potential as the computer can currently only execute a single algorithm, cumbersome set-up.
- Maturity: TRL 3: Proof of concept exists.

Electron Spin qubits (Silicon-based quantum dots)

These qubits are created from nuclei fixed in solid substrates or spins of electrons.

- Pros: can leverage silicon chip- making. They lead to longer lifetimes of a qubit, and they are also prone to interferences from low gate fidelities.
- Cons: prone to interferences from low gate fidelities and Manufacturing costs are high.
- Maturity: TRL 3: Proof of concept exists.

Source: Arthur D.Little, 2022. Rand, 2023. HSBC, 2022.

Software

Quantum machines, similar to conventional computers, requires software to run on top of their hardware in order to generate results. Currently, quantum software development involves programming the physical states on a quantum computer. Thereby, quantum computing entails not only new hardware, but also new software stack that controls the hardware.

Quantum algorithms where at least one of the steps involves a quantum principle (e.g., superposition or entanglement) designed to run on quantum computers – have been a topic of research for the past twenty years. But as no general-use, scalable quantum computers currently exist, quantum algorithms are seen as “proofs of principle” and have not yet demonstrated concrete advantages over their classical counterparts. Yet, during the past couple of years some stakeholders have already declared quantum advantage, or supremacy, on specific use cases. One example is Google who in 2019 announced the achievement of “quantum supremacy” after using a computer with 54 qubits (Sycamore) to perform a calculation in 200 seconds that would have taken the world's most powerful supercomputer 10,000 years to complete. Since then, others have managed to solve the same task and with fewer errors using conventional computing methods and the questions regarding quantum advantage and supremacy remains controversial.

Although there are quantum algorithms available today, their application remains practically limited by hardware considerations. In this regard, being able to speed up quantum algorithms to prove that they can solve intractable problems and outperform conventional computers is crucial. It is expected that they will be able to problem-solve significantly faster than classical algorithms when large-scale quantum computers are developed.

Box 3: Most important algorithm types

Simulation
Algorithms that can simulate quantum-mechanical molecules, reactions, or electrons. Current computers cannot accurately simulate quantum systems with larger numbers of particles, so they are not very accurate. Use cases include quantum mechanics, molecular mechanics, and molecular dynamics.

Linear Algebra
Applied mostly in AI and machine learning. Quantum algorithms can replace current ML and shorten the training time of algorithms, or neural networks can be converted to be fully quantum. Yet, it is still an ongoing challenge with many technological lockers, especially to compete massive parallelization existing in current ML.

Optimization
Quantum algorithms can be used to solve optimization problems, conduct efficient searches in large and unstructured data sets, and generally reduce computing time when compared to today's computers and optimization processes.

Factorization
Current online security measures bank on the impossibility of finding prime factors of large sets of integer numbers within a realistic time frame: quantum factorization algorithms such as Shor's algorithm will be able to calculate the prime factors of large numbers at a faster rate than current algorithms. This will have repercussions for cyber security and online financial transactions.

Source: McKinsey, 2021. World Economic Forum, 2022. HSBC, 2022.

Quantum Simulation

The simulation of quantum systems – quantum information processing – on analog and digital platforms is expected to be one of the first promising applications of quantum computing. Quantum simulation can go beyond the current limitations of computers in trying to predict, calculate, and model properties of materials used in, for example, physics and chemistry. Specially applied simulators can already be used today – long before a fully fault-tolerant quantum computer is built – for example, when studying aerodynamics. There are three types of quantum simulators: analog simulators physically built in the lab, digital simulators, and quantum annealers.

Market

The past five years have seen continuous growth in quantum technology investments from both private and public sources, and this trend is expected to continue in the future as commercial applications inch closer towards becoming a reality.

Quantum Communication

Quantum communication is expected to be an important market and is beginning to see traction, including large amounts of public investment from US, Europe, and China; according to BCG, the market will be as big as quantum computing by 2030. Quantum communication has specific use cases, a demonstrated market in cryptography and secure communication and data, (including in IoT devices) and mature technologies. There are already companies commercializing QKD devices for secure communications, and national quantum-secured networks are under development across the globe. Telecom providers will be able to offer quantum-secured communications as a service, and a quantum random number generator embedded in a chip could be in every IoT device in the future. Regulatory approval for further development will be a factor in scaling.

Quantum Sensing

The market for quantum sensing currently exists, although it is small, niche, and fragmented. Interviewees expressed the opinion that the products need to find demand, but that they expect it to be a competitive market, albeit smaller than other technologies. The technology already exists, and it is relatively inexpensive. Quantum sensors could replace many existing sensors within oil, gas, mineral monitoring, constructive sites, and weather.

Emerging application areas include food science, military defense, and automobile. In addition, developments in sensing with help with the development of quantum computing, as sensing assists with reading end-states for computing. As one example, quantum sensor is expected to boost areas such as the transportation sector by improve precise navigation and positioning systems.

Quantum sensors are available today for limited production use cases and experts expect their availability and capability to attract great funding and grow rapidly within five to 10 years. Some of the most promising use cases are bioimaging, spectroscopy, navigation, environmental monitoring, geographic surveying, and fundamental science applications. Quantum sensor systems are not fully mature but are approaching industrial market and are already used in niche applications. One example is for gravitational changes beneath the earth’s surface as a proxy for volcanic activity.

Quantum Computing and Quantum Simulation

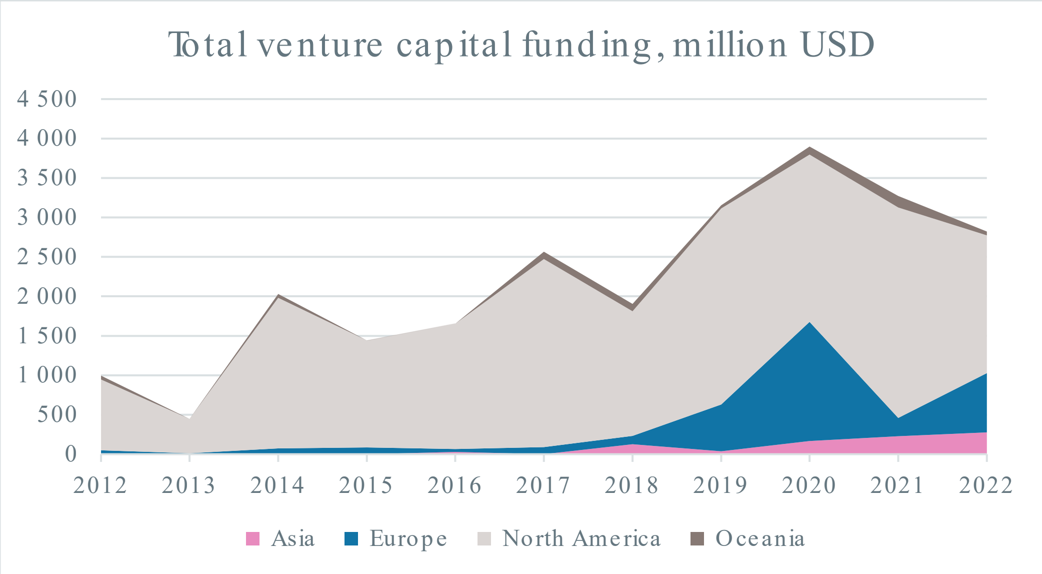
Because there are so many use cases in different industries, quantum computing is expected to have the largest potential market – however, at this stage the technology is in its infancy, so the impact is unknown. Finance and infrastructure needs are large, so this development is taking place mostly in larger companies or bigger startups, besides development carried out within academia. There are increased volumes of private venture capital aimed at startups in quantum computing. However, given the significant technological challenges associated with the development of quantum computers, such investments are taking a long-term perspective and are subject to significant risk.

While a lot of money has poured into quantum computing, there are recent signs of slowing investments and market consolidation; experts mention that to avoid a quantum hype and a 'quantum winter', companies will have to be ambitious but realistic and make sure that they can deliver proof of concept, address actual problems, and work closely with industry. Experts report the need for investors to understand the technologies to validate them in the market, which requires both advising from those with a strong enough academic background as well as research to provide early demonstrations and use cases to engage industries and companies as early as possible. Experts are clear that identifying quantum advantages in specific use cases should be considered the exception rather than the norm. Specific industries such as finance, energy, and infrastructure are then expected to see the most benefits, given the cost. Interviewees mention that currently, no one is investing solely in quantum – rather, VC is funding balanced portfolios (such as spread-out deep tech funds) to help manage risk. It is expected that a second wave of innovation will take place once the market figures out what solutions work and what is relevant or not for the industry.

Hardware manufacturing currently comprises the majority of quantum computing startup funding, but application software and algorithm startups are growing at a faster rate. Due to costs, the hardware market is currently dominated by big tech and some scale-ups. Software is a developing market that is far from saturated and has the largest number of value chain players.

When it comes to number of startup companies no country can compete with the United States. As of 2022 the US had approximately 60 startups in quantum computing, whereas the runner-up Canada had around 30. The US remains ahead in winning patents, setting up startups, and making investments which can be seen as important aspects when it comes to countries abilities to develop a complete value chain. Countries that follow the US in Most Startups, Private Investments, and Patents in Quantum Computing are for example China, Canada and the UK. An overview of total venture capital funding to firms in quantum computing is presented in Graph 1 below.

Graph 1| Total venture capital funding, million USD



Source: Crunchbase

Box 5: Short list of the biggest companies in quantum technology

IBM Q

A subsidiary of IBM that provides quantum computing services and solutions.

Google

The company has been researching quantum computing and has made significant advancements in the field, including the achievement of quantum supremacy.

Microsoft

The company is developing a topological qubit-based quantum computing platform and has also made significant investments in quantum research.

Alibaba Group Holding Ltd

The Chinese technology giant has been making investments in quantum computing and has a research lab dedicated to the field.

Honeywell

The company has developed a quantum computer that it claims can outperform traditional supercomputers for certain tasks.

Rigetti Computing

A full-stack quantum computing company that offers cloud-based quantum computing services.

IonQ

A startup that specializes in trapped ion quantum computing technology.

Xanadu

A startup focused on developing photonic quantum computers.

Case 1: Quantonation – the first VC fund dedicated to Quantum technologies

In 2018 Quantonation was founded in France becoming the first venture capital fund dedicated to Quantum technologies. The fund invents in four areas: Quantum computing (hardware and software), Quantum sensing and Deep physics.

Most startups today are research-based and spin-offs from labs. While it has been fairly easy for startups to secure early-stage funding in the last couple of years, late-stage funding has been, and still is, a big struggle. As interviewees describes, when startup companies start to grow it is often hard for them to switch to scale and what they need is financing and capital to overcome hurdles and to continue their work.

Quantonation aims their investments at startup companies who have academic backgrounds and are in an early stage to support the transition of technologies into commercially available products for industry. Their strategy focuses on areas such as molecular design, high performance calculation, cybersecurity, drug discovery, or ultra precise sensing as these areas are now driven by innovation based on Quantum Technologies. Another important part of the strategy is to create synergies between the companies within their portfolio. As a part of a bigger ecosystem, Quantonation takes part in Quantum Paris-Saclay and Quantum flagship. Also, they are a founding member of Le Lab Quantique, a Quantum Tech Innovation center based in Paris.

In Europe it has historically been challenging to obtain VC funding. One reason might be related to the fact that it is important for venture capital firms to have deep and great knowledge of what they are investing their money in. They need to understand the science behind the technology to be able to link technology with markets, and in the case with quantum technology this can be rather difficult since knowledge is still highly concentrated and exclusive. Strong knowledge and competence within the field is something that Quantonation possesses and can take advantage of.

Commercialization of quantum technology

The transition from research to commercialization in quantum technology is not without challenges. Key challenges include technical difficulties associated with securing funding and investment, as well as the need for trained professionals to support the development and deployment of quantum technologies. Overcoming these challenges will be crucial for realizing the full potential of quantum technology in a commercial setting. A summary of some prevalent challenges associated with transferring research to commercial application is presented in Box 4.

There are some strategies to de-risk the transition and to overcome challenges related to going from research to commercialization, for example through intellectual property (IP) and technology transfer (TT). By securing IP rights and licensing agreements, research institutions can generate revenue and attract investment, which can help to de-risk the commercialization process. TTO's (Technology Transfer Offices) main function is to manage the IP portfolio of research institutions, identifying potential commercial applications of the technology, and facilitating licensing and spin-off company creation. TTOs can also provide funding and resources to support the commercialization process, therefore they are important in the transition process.

Box 4: Challenges associated with the transition from research to commercialization

Lack of knowledge in business/industry

- Many companies and industries lack knowledge about quantum technologies, what they can do, and how they are relevant, especially at the top level.
- Researchers need to inform, educate, and show actual use cases to industry.

Moving from lab to market

- Academic researchers that have worked with technologies do not necessarily have the business knowledge to support a spinout or company.

Funding gaps between basic research and innovation research

- More support is needed for quantum technologies that lie between these categories.

Lack of stable talent pipeline and enough skilled labor to work with quantum technologies, especially in the future.

Access to experimentation and testing with quantum computing hardware is expensive, making it more accessible via cloud access is expected to be the solution.

"Pre-seed" funding is easy to access in Europe – but it is more challenging to obtain VC funding and onwards.

Economic impact from quantum technology

Forecasts of the economic impact from any new technology are intrinsically uncertain, and quantum technology in no exception. For this reason, estimates on future market value should be interpreted with significant caution. However, a large body of recent literature point to significant potential value in a broad range of industries. Some of the sectors where high value applications are identified are:

1) Life sciences
2) Travel/transport/logistics
3) Financial services

Within life sciences, quantum computing is expected to assist in the development of major trends such as precision medicine and small molecule drug design by making possible, for example, the simulation of complex atomic molecules. Transport and logistics will benefit from optimization via logistic and supply-chain management and traffic and delivery optimization, whereas finance is expected to benefit from using quantum algorithms in everything from financial portfolio modeling and risk assessment to fraud detection and credit score improvement.

It is expected that the finance sector will be a first mover in the application of quantum computing, where first use cases include portfolio optimization and risk models, joined by materials science, where complex molecule simulation is projected to replace lab testing and lead to new materials. This is followed by pharmaceuticals, logistics and ultimately industries such as energy (grid optimization and flexibility), advanced materials (including quantum materials that will pave the way for further quantum development).

While identified use cases for quantum exists in several industries, the broad range of potential applications are yet to be identified and verified. Quantum technology may prove to be uncompetitive in relationship to already identified use cases while other unexpected use cases may present significant opportunities for value creation. Despite the uncertainty, the broad body of literature reviewed for this report indicate significant disruptive capacity for quantum technology and expects extensive economic impact from the emerging technology.

Role of Government

The role of the state in the development of quantum technology can vary greatly between countries depending on a variety of factors such as the level of government support, the level of private sector involvement, and the specific priorities and goals of the government. In some cases, the government may take a lead role in funding and supporting research and development efforts, as well as establishing policies to encourage the growth of the industry; this is the case for the United States, China, and Canada, among other countries. In other cases, governments have taken a less active role in funding and supporting quantum technology research and development, leaving the development of quantum technology largely to the private sector or research financed by philanthropic sources; examples of the later include Sweden and Denmark. These countries may still provide some level of support for quantum technology research, but the level of support is generally lower than in countries where the government has taken a more active role in funding and supporting these efforts.

The overall trend seen around the world is that states are increasing their involvement in the field to coordinate and drive development.

Increased focus on developing national strategies for quantum technology

Governments are increasingly taking a more active role in coordinating efforts in research, development, and ultimately commercialization of quantum technologies by bringing together government, academia, and industry in dedicated national strategies. Governments increasing interest in quantum is motivated by a number of factors including the economic impact expected from quantum combined with expected contributions to national competitiveness as well as national sovereignty concerns. Governments worry that a lack of development in quantum technology would leave their countries dependent on other countries for technologies, and vulnerable to potential industry disruption.

National security considerations and dual-use possibilities are motivating increased government coordination in quantum technology

Interest in dual-use application and development of quantum technologies varies from country to country. Countries like China, the US, and Israel have had strong military interest and early involvement in quantum technology R&D, where military interest can spur innovation and provide important initial funding. China, for example, has focused on quantum communications and cryptography in recent years; developments such as a quantum satellite and QKD network are expected to be relevant for Chinese military use. The U.S. has joint research partnerships such as DARPA's ONISQ program dedicated to exploring quantum for military use in collaboration with NASA, USRA, and Rigetti, and defense contractor Lockheed Martin has established a joint computing center with the University of Southern California. The Israeli aerospace industry has been heavily involved with quantum development from the start, with a focus on defense and privacy, and the army is a key actor in the Israeli quantum ecosystem. On the contrary, the EU has not shown much interest in military collaboration; EU's public investments mainly focus on academic institutions and research projects and not state-sponsored initiatives.

International collaboration in quantum technology innovation

More and more governments are either developing and implementing national quantum strategies or initiatives or entering international partnerships. One can sort countries into different stages when it comes to national strategies or agendas formed by the governments within these countries. Firstly, countries with coordinated national quantum strategies such as US, China, France, Germany, Israel and more who have some form of national initiative or strategy to support quantum technology. Secondly, countries without national strategy, but with significant government-led or -endorsed initiatives such as Canada, Sweden, Denmark, and Finland where the government and/or non-profit foundations have devoted significant resources into quantum-related research or technology development. Lastly, there are countries without a national strategy or significant coordinated initiatives.

Approaches to support commercialization of quantum technology development

There are several different approaches that governments around the world have taken to support the development of quantum technology. Some governments have established national strategies and dedicated funding programs to support quantum research and development. Some have also established partnerships with private companies or research institutions to encourage collaboration and transfer of knowledge. This can be seen in for instance France where the government has been actively supporting the development of quantum technology innovation over the past five years through a combination of funding, research institutions, and partnerships with private companies. An important element of the French quantum technology ecosystem is a network of Technology transfer offices (TTO). The case on the next page elaborates on a support initiative for quantum technology development in Sherbrooke, Canada.

Case 2: Developing an all-inclusive innovation ecosystem at the Quantum Sherbrooke Innovation Zone in Québec

In June 2023 the Quantum Sherbrooke Innovation Zone will officially begin operations in Sherbrooke, Québec. Already home to an established quantum ecosystem, Sherbrooke will receive financial support from the government of Québec to realize 13 quantum projects, including installing an IBM quantum computer and develop the area further as a designated "innovation zone". Québec's innovation zones aim to build on synergies between research, industry, education, and entrepreneurship to address challenges found when moving technologies and products to market, attracting foreign investment, and supporting sustainable local economic growth. Sherbrooke will be one of the first two innovation zones in Québec.

Funding of the zone comes from both public and private investments; the Government of Québec is the biggest investor, having committed $131 million of the $435 million in total investments. Private investors include prominent quantum companies such as

1Qbit and Pasqal as well as industry actors such as Bell, a Canadian telecommunications company. Investing in this specific location means that companies will reap the benefits of being part of a strong ecosystem where all relevant actors are in the same physical place, making it easier to collaborate and build synergies.

Supporting applicable research in an industrial and innovative environment

By placing academic, innovation, and research communities in close physical proximity to industrial and entrepreneurial communities, the zone aims to facilitate cooperation by making it easier to develop industry-relevant solutions within quantum. Different actors with various focuses within the quantum value-chain create a complete ecosystem around quantum (established companies, startups, and academic research are represented) and the idea is that all actors can utilize each other, while at the same time providing incentives for further attracting additional talent to Sherbrooke in the form of private, national, and international partnerships as well as a quantum workforce.

The Innovation Zone at Sherbrooke contains the following components:

- Innovative Manufacturing area, including specialized tools, automated equipment design and manufacturing facilities.
- Innovation – ACELP Park, including a technological innovation and circular economy hub as well as University of Sherbrooke's quantum institute and various companies renting space.
- Downtown area, including entrepreneurship headquarters, chamber of commerce, and a cultural digital hub.

Benefits include:

- Creation of a hybrid environment where expertise in hardware, software, and AI are combined through an integrated environment of industry and academia.
- Companies can boost knowledge and best practice-sharing when operating in an emerging industry.
- Facilities provide equipment that most startups are not able to acquire themselves such as dilution refrigerators to support quantum computing and dark fiber halls to support quantum communication.
- Unique hybrid environment entailing quantum computers as well as HPC which

are interconnected at the same location.

- The next generation of quantum talent (students) has direct access to industrial and entrepreneurial opportunities alongside their studies.

Removing the entry barrier for startups

With the aim of trying to remove entry barriers that many startups often face, one of the tasks of Quantum Sherbrooke Innovation Zone is to facilitate and provide starts ups with equipment needed.

One example is equipment related to the use of dilution refrigeration technology (an enabling technology specifically for superconducting qubits for quantum computing). This apparatus is very expensive to operate, consequently it is unlikely that startups have the capital to invest in it. Yet, it is the fundamental tool that they would use in their environment. Often startups companies which formerly were research groups at universities operating at labs and research centers had access to the equipment needed through the universities. Leaving these environments startups are faced with collaboration partners within the industry. This cannot provide with tools and equipment to the same extend, nor have the investment ability needed- which creates enormous barriers for startups. As the innovation zone buys the equipment to provide for the startups, which they then can rent, it supports the continuum of training that needs to happen in quantum innovation.

An ecosystem benefitting the local community

In addition to enabling the overlapping of research (technological readiness) and industry (demand-side) within quantum, another strategic goal of the innovation zone is to contribute to the vitality of the region and build a sustainable community via the attraction of new businesses, resources, and citizens to the area, supporting social, cultural, and economic development.

Emerging typologies of the quantum technology ecosystem

While universities and research stand for much of the development within quantum technology, increasing private investments are becoming a significant driver for the development. Not the least in quantum computers private firms in the technology sector as well as venture capital backed startups are playing an increasingly important role. This has led to a diversity and structure and dynamics shaping global quantum technology innovation systems. One can describe three typical variations in the structure of quantum ecosystems:

- University-driven: Public funding or philanthropic funding drives basic research that is rooted in universities and research labs. Under such structure quantum computers are developed within academic research institutions.
- Integrated firms: On the global arena major technology firms are investing large amounts in developing quantum capabilities. Examples of such initiatives include IBM and Google that are developing quantum computers and a broader stack of quantum capabilities in-house.
- Venture capital-driven: Research focused startups backed by significant venture capital investments are making significant contributions to quantum technology development. Venture capital driven technology development is in interviews described as beneficial because of the stronger incentive structure. However interviewees also caution that too much focus on venture capital-driven development could hamper long term development of the technology.

In addition to the various actors contributing to quantum development described above, various forms of collaboration are taking place between them, including:

- Established company + startup: Collaboration between larger companies and startups helps both actors. Larger companies can give startups the credibility they need as well as contribute with relevant resources, while in return incumbents can get access to knowhow, talent, and dynamic innovation environments.
- Startup + academia: Work together in a variety of settings. In many cases startups are spinout companies tracing their roots to university research environment. The startup + academia combination can provide startups with necessary facilities and equipment, while startups can contribute with additional financial resources as well as application-oriented incentive structures.
- Established company + academia: Collaborations here might follow traditional industry collaboration patters where firms and academy co-finance quantum development projects benefiting from each other's resources and competences.

Public Investments

When it comes to public investments some governments are more committed than others and as previously mentioned it varies between governments on whether there are established national strategies, programs, or agendas in place. In the following table examples of efforts from other countries that can serve as inspiration are shown. The focus is largely on the national strategies or agendas developed. Relevant countries in addition to Sweden that are studied in more detail in this regard are: Canada, China, Denmark, Finland, France, Germany, Israel, and the United States.

Table 1| Public investments by country

	National strategy or agenda	Notable government investments	Public funding characteristics	Key insights
Canada	National Quantum Strategy (NQS) launched in 2023. $360 million over 7 years towards the launch of a National Quantum Strategy (2021).	~ $1 billion in quantum research over the past decade.		The Canadian strategy aims to amplify Canada's significant strength in quantum research, grow their quantum-ready technologies, companies, and talent and lastly, solidify Canada's global leadership in the area.
China	Quantum technology R&D as strategic industry in Five Year Plans and "Made in China 2025" (2021).	~ $15 billion national plan. $10 billion to create a national laboratory for quantum information sciences. These numbers are an estimation of the Chinese governments' investment in quantum technologies; however, this figure has not been officially confirmed.		China is by far the global leader in public investment. Initially they focused on quantum communication but has now made quantum computing a top priority and has invested significant public sums. China's government has invested heavily to build the world's largest quantum research facility.
Denmark	Danish Quantum Agenda (2022), no official national strategy as of yet.	~ $18 million. Innovation Fund Denmark invested: $12 million in the Quantum Innovation Centre – Qubiz involving three universities. $2.6 million FIRE-Q (Field-Ready single-photon Quantum technology) and $ 3.3 million Crypt Q to develop technology for secure quantum communication.	National open calls complemented by international calls.	Research capability is strong but there is a need for a national strategy to support the move to commercial use and industrial application. The research made during the last five years have mainly been supported by private investors, for instance a DKK 1,5 billion invest In QLS made by Novo Nordisk Fonden. There is a lack of an active startup environment and a lack of investors and venture capital.
Finland	National Quantum Agenda which is planned to serve as the basis of a possible national quantum strategy. The first	~ $24 million. The government of Finland has granted a project of €20.7 million funding to VTT	Open, bottom-up national calls.	What separates the development in Finland from many other European countries is the fact that the Finnish

	version of the agenda is anticipated to be ready by December 2022. (As of January 2023, it has not been released.)	and IQM to build its first Quantum Computer. This is in addition to a raise of €3.3 million.		government is the funder of Finland's first 5-qubit quantum computer since it has been developed and build by VTT (Technical Research Centre of Finland), together with the quantum computing hardware startup IQM.
France	National strategy for Quantum Technologies (2021), €1.8 billion plan.	~ €1.8 billion. The €1.8 billion strategy plan includes €1 billion from the French government. €200 million per year over the next 5 years/€1 billion in total. €800 million from industry, European funding, and investors in startup ecosystem.	National open calls complemented by international open calls.	Has a strong research foundation but like many European countries, faces challenges when transferring tech from research to industry. One part of the strategy is to focus on global and integrated technological development throughout the entire value chain (basic research to industrialization). France currently has one fund fully dedicated to quantum (Quantonation) and hopes that at least two more will follow.
Germany	National quantum research agenda presented (2021).	~ €2,6 billion In 2018, €650 million funding to its quantum technologies Program. In July 2020, €2 billion to quantum effort, supplementing EU plans for 2028.	Thematic calls complemented by open calls.	The German ecosystem consists of big corporations and strong research institutions; therefore, it is important for innovation to be at the interplay of these two. Germany’s fundamental research is strong, but there are some difficulties in coordinating research efforts, therefore the government is aiming its efforts on the transition to application and collaborative R&D.
Israel	$ 380 million, National Program for Quantum Science (2019).	~ $380 million over 6 years and is a collaboration between the education, innovation, science, defense, and finance ministries.	Thematic calls/programs.	The Israeli ecosystem is small, yet agile with around 30 startups, 120 research groups and a €350 million national budget and crossovers army, government, industry, and research. Recently there has been a shift

				from R&D as a hobby to a national priority.
Sweden	No national strategy or agenda as of yet.	~ €2 million funding by Vinnova (the innovation Agency). Vetenskapsrådet (the Swedish Research Council) is also funding of numerous research projects. SSF, is founding various research project funded focused in quantum technology.		The Swedish ecosystem is characterized by strong research capability, yet there is need for a national strategy to support the move to commercial use and industrial application. The research made during the last five years have mainly been supported by philanthropic investments made by the Wallenberg Foundation. The Wallenberg Centre for Quantum Technology (WACQT) is a twelve-year, SEK 1 billion research effort aimed at taking Sweden to the forefront of the very rapidly expanding quantum technology field. WACQT's main project is to develop a quantum computer.
United States	The National Quantum Initiative (NQI) Act, $1,2 billion (2018).	~$1.2 billion. The NQI (National Quantum Initiative Act) was introduced in 2018, with a five-year budget of over $1.2 billion. Ending in 2023, another initiative- or a continuation has not yet been announced.		The US established a national program with the founding of a consortium to develop a quantum supply chain. The main objective of the strategy is: Developing the scientific approach to solve the challenges identified for transformative progress. The National Quantum initiative have resulted in 13 research centers, a national education partnership, and collaborations with other nations. The US also has several other initiatives and policy measures.

Table legend:	Has a national strategy	Has a national program	Does not have a national strategy

In the past five years, major government funding has been announced around the world. Global public investment in quantum technology exceeds $30 billion and is continually rising. This is most likely an underestimation, since not all public investment is captured due to national security concerns.

Public investments are led by China, who currently has committed approximately $15 billion to funding quantum technology. The EU is a frontrunner in quantum technology research and talent but has a harder time translating research into commercial benefits compared to the US and China due to weaker coordination between actors. Therefore, the European Commission established the $1.1 billion research and innovation initiative EU Quantum Flagship (2018) to developing and commercializing quantum technologies. Governments in the EU have announced roughly $7 billion in total public funding besides the EU Quantum Flagship. These two actors are followed by the US, who has announced $1.9 billion in public investments as of 2022, which includes the National Quantum Initiative Act.

Within the EU, countries with the highest announced public funding include Germany and France. National efforts take many shapes and forms. While Germany has coordinated approximately €2 billion in funding between research and economic affairs ministries that focus on research/academia and innovation/industry respectively, France's €1.8 billion plan is shared between multiple research institutions who each cover different sub-areas within Quantum Technology.

In Nordic countries such as Sweden and Denmark, efforts related to quantum technology are highly dependent on philanthropic and private investments, which have superseded largely absent public investments. The exception to this is Finland, whose government has been the primary funder and driver of much of the country's quantum activity, including the development of a quantum computer. In the case below, Denmarks development prior to quantum technology and future strategy is explored.

Case 3: Danish effort on quantum technologies for making Denmark a frontrunner in the second quantum revolution

Over the past couple of decades, the Danish research funding system has shown its support for Danish quantum technology research efforts. Major centers at University of Copenhagen, DTU, and Århus University received a total of 80 million DKK from Innovation Fund Denmark back in 2016 to establish a Quantum Innovation Center (Qubitz) to translate quantum physics into practical quantum technologies. The Niels Bohr Institute at the University of Copenhagen has engaged in several notable collaborations, including an academic/startup collaboration tasked with exploring quantum communication (FIRE-Q) and a quantum computing partnership with Microsoft established in 2017. Therefore, the Danish quantum research community is the international forefront, and it recently received a boost in 2022 with the launch of Novo Nordisk Foundation's Quantum Computing Program, which will explore different qubit platforms over a period of seven years to single out a "champion" upon which to build a functional quantum computer aimed at life science use cases. It was also announced that the Niels Bohr Institute will host a NATO Center for Quantum Technologies focusing on bringing tech to market via accelerators, incubators, test facilities, and labs.

Interviewees describe ample funding at the basic research level as important, but that funding is needed to address the gap between basic research and mature tech; state funding could assist with advancing technological readiness and identifying business use cases. The Danish government has not yet formed an official national strategy, however, a working group that is not government-affiliated created a quantum agenda for Denmark in 2022.

One notable governmental ministry that has been active in the Danish quantum ecosystem is the Foreign Affairs Ministry, which has led quantum activities from the government side both internally and internationally. Internally, they've focused on facilitating dialogue between companies, networking, educating business on technological readiness and potential use-cases, and educating scientists and researchers on how to promote a quantum agenda at the political level. Internationally, the ministry attends conferences to promote Danish interests and attract business, monitors development in specific innovation hotspots, and reaches out to various relevant academic environments.

The emerging Swedish ecosystem

The Swedish quantum ecosystem is centered around research and university-based initiatives. The structure of the Swedish ecosystem can be described as university-driven, where philanthropic funding from the Wallenberg Foundation through the Wallenberg Centre for Quantum Technology (WACQT) drives basic research rooted in universities and research labs. The Swedish quantum ecosystem today is characterized by a strong concentration around the WACQT initiative, with limited activity and coordination outside the philanthropically funded initiative.

The Swedish ecosystem has for the five past years been characterized by the absence of the public sector, which is only now starting to get more involved. Likewise, industry and the business community have not been that engaged in the development of quantum technologies but are now starting to turn their attention towards quantum as they realize the role that quantum is expected to play in the future. Even though they may not comprehend concretely what is happening right now, they are interested in understanding their role in the development.

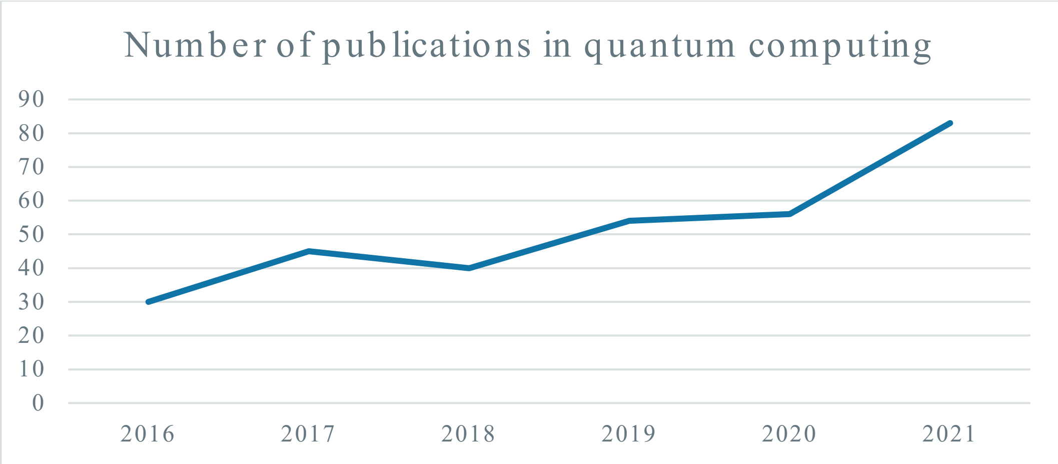
Like other countries with a similar type of ecosystem, the Swedish ecosystem faces challenges when it comes involving a larger set of actors in the development of quantum technology ecosystem. Not the least the strong focus on basic research presents a potential challenge in identifying applications for quantum technology and in the longer run commercialize the technology.

Research activities

Sweden has a strong research and innovation ecosystem with robust infrastructure for quantum technology research. Academic publication focused on quantum computing has increased significantly in Sweden over the last five years, as can be seen in Graph 2. Overall Swedish research in the quantum field can be described as narrow in scope but with high impact. In a bibliometric comparison between five leading innovation hubs conducted by Damvad Analytics, Sweden ranked the highest in terms of Scientific impact. At the same time, the volume of research output is lower than many comparative countries.

A clear position of strength for Swedish research can be found within the field of quantum computing, as Sweden has established strong research, developing full stack competence from qubit development to software. This can be attributed to the ambitious research conducted with the WACQT initiative aimed at building a 100-qubit quantum computer based on superconducting circuits in ten years. At the same time the strong focus on a single technology platform (semi-superconducting qubits) presents a risk and a potential weakness as there is much uncertainty around what technologies will be predominant in the future. Further weaknesses include the limited research activities conducted outside the WACQT initiative.

Graph 2| Development of Swedish publications in quantum computing



Source: Amsterdam Data Collective based on: Scopus, 2022.

Besides the ambitious focus on Quantum Computing the WACQT initiative has further supported research in quantum sensing and quantum communication. WACQT initiatives in quantum sensing, and quantum communication are coordinated from Lund University and KTH Royal Institute of Technology, respectively. The quantum sensing area is arguably the subcategory where technology maturity has gotten the furthest in the Swedish context with active spinout startups from the WACQT-initiative.

Innovation and market development

The development of a marked and commercialization-oriented quantum innovation ecosystem is still at an early stage in Sweden. Application oriented activities are taking place within the WACQT-initiative, through an industry partner program. Six incumbent firms are currently taking part in the program together with four enabling technology partners hosting 7 industrial PhD Students. The collaboration aims to support knowledge building across academia and industry, providing researchers with possibilities to explore real-life applications for quantum technology while firms gain forefront knowledge and competence allowing them to identify business opportunities based on quantum technology.

In a step to further support application-oriented research and development WACQT announced in January 2023 that the quantum computer developed within the initiative would be made available to the industry. Trough funding from the Knut and Alice Wallenberg Foundation a copy of the existing quantum computer at Chalmers is to be built. The computer, accompanied by a helpdesk, is intended to provide a test bed for researchers and companies to run quantum algorithms, and by this contribute to the raise broader competence in quantum technology.

Box 6: Enabling technology companies

SpectraCure AB

The company is developing a treatment system for the elimination of internal solid cancerous tumors. The method is based on a treatment system consisting of a hardware, a laser unit, in combination with a software, a dose planning platform. SpectraCure AB has held the role of industrial partner in the research project that now has spinned out as the company Deep Light Vision AB. SpectraCure will during 2023 become the largest owner of the company.

Low Noise factory (low noise microwave amplifiers)

Low Noise factory is a Swedish company established in 2005 which produces low noise microwave amplifiers. They both develop and manufacture products. The amplifiers are used near absolute zero - cryogenic- temperatures and can be used for quantum computing.

Intermodulation Products AB

The company emerged out of inventions made in the Section of Nanostructure

Physics at the Royal Institute of Technology (KTH). The company is dedicated to the research and development of measurement and analysis techniques for nonlinear physics and quantum technology.

Emerging early-stage startup ecosystem

Despite the early days of quantum, an emerging ecosystem of startups in quantum technology exists in Sweden. The ecosystem largely consists of spinout companies from academic research active in specific niches of the ecosystem where solutions have reached a sufficient technology maturity. These companies are focused on developing products and services that can be used in industries such as healthcare, logistics, and transportation. These are also some of the applications areas where quantum technology is expected to have the most impact. A selection of identified firms are presented in Box 7.

Enabling technology companies contributes to the ecosystem

In addition to startups focused on developing solutions for quantum technology, the ecosystem also includes firms that offers enabling technologies for quantum. Such firms are offering technologies that can support both academic institutions as well as firms that are developing quantum technology solutions. Such firms can play an important role in the further development of the quantum technology ecosystem in Sweden. An example of such company is Low Noise Factory that develops low noise microwave amplifiers with important applications in quantum computing. A selection of identified enabling technology firms are presented in Box 6.

Limited private investments in the ecosystem

Sweden is still in the early stages of venture capital entering the system. No venture capital activity in Sweden is identified through the startup and investment database Crunchbase (Jan 2023). Identified quantum startups are generally small and financed through own means, through direct investments by parent companies, angel investments or public funding programs such as the Quantum Kick-Start run by Vinnova. An exception is the US based firm Atlantic Quantum, with strong ties to the WACQT initiative, that raised a USD 9 million seed fund in 2022 backed by a group of five US based investors.

Box 7: Sample of identified firms

Deep Light Vision AB (Oxygenation measurement instrument)
Was founded to further develop, and in the future commercialize the invention that the research group Lund University (funded by grants from WACQT) has worked on during their research project. The project focuses on a new method for measuring with laser light deep inside the body without having to use optical fibers and needles.

Atlantic Quantum (Quantum Computing)
Is a startup and spin-off from two leading research labs, Chalmers and MIT, and one of the founders is Jonas Bylander, professor at Chalmers and one of the members in WACQT. The aim is to build large-scale quantum computers with superconducting electronics.

Scaling (Quantum computing sample holder)
Is a spin off company from Chalmers research. The company just launched their first product launched its first product, LINQER which is ais a microwave-based packaging solution (or sample holder) for superconducting quantum circuits.

quCertify (Quantum communications)
Started as a project in within the public funded programme Quantum Kick-Start by Vinnova. The aim is to develop and validating secure quantum communication and quantum random number generation.

Emerging areas of strength

The area where commercialization of applications has gotten the furthest in Sweden is related to life science, although still at an early stage. Experts voice the opinion that Sweden already has competences and investments within life science; it has emerged as an area of strength, where Sweden currently could have a competitive advantage. Still, capital is needed to ensure that quantum life science in Sweden can continue to be an area of strength.

Government support

Sweden has not yet formulated a national strategy, coordinated efforts to develop Swedish capabilities in quantum technology can mainly be linked to initiatives funded by the Wallenberg Foundation. Public research financiers have historically funded individual research project within quantum technology, including support from the Swedish Foundation for Strategic Research (SSF) and the Swedish Research Council (Vetenskapsrådet). Swedish research environments have further benefited from EU-funding, including the Horizon program. Recently the public actors in Sweden have increased their engagement to support the financing and coordination of quantum technology development. The Swedish Innovation Agency VINNOVA has as an example provided funding for startups trough the previously mentioned Quantum Kick-Start-program.

International collaboration

During the past five years Sweden has joined and participated in several international collaboration frameworks around quantum. Interviewees point particularly to the importance of the joint statement on cooperation in quantum information science and technology between Sweden and the United States, presented in 2022. The statements identify a number of avenues for future collaboration and makes Sweden one of only a limited number of countries to whom the US has made such a statement.

Sweden also participates in several European initiatives and collaboration frameworks such as the:

- European Quantum flagship, a research and innovation initiative launched by the European Union aiming to ensure Europe's leading position in the emerging quantum technology field.
- OpenSuperQ, a project that has received funding from the European Union's Horizon 2020 research and innovation program.
- Euro QCI, an initiative focusing on quantum communication infrastructure.

As of 2022 Sweden is also a part of the Entanglement Exchange, which is a portal for providing information regarding international exchange opportunities for students, postdocs, and researchers in quantum information science (QIS). The platform is a partnership between 12 countries including Australia, Canada, Denmark, Finland, France, Germany, Japan, the Netherlands, Sweden, Switzerland, the United Kingdom, and the United States.

Opportunity for emerging Nordic collaboration

In addition to the previously mentioned collaborations, interviews indicate that emerging Nordic collaboration in the field of quantum technology presents a significant opportunity for long-term development and competitiveness in Sweden. Collaboration between Nordic actors has arisen over the recent years through a combination of bottom-up research collaboration and ecosystem-level contacts. The relatively parallel timelines of initiatives to develop a Swedish, Danish, and Finnish national strategy have further highlighted the potential for future collaboration. At the time of completing this report, discussions were ongoing about establishing Nordic collaboration platforms such as Nordic Quantum and Quantum Life Science (QLS).

Quantum Ecosystem in Sweden

The most important actors and ongoing initiatives in quantum computing in Sweden is described in the chart below. The chart builds on a combination of interviews with actors in the Swedish ecosystem as well as document studies.

Quantum Technology Ecosystem in Sweden (actors and initiatives)

Research	Start-ups and companies	Industry
Private/Philanthropic The Wallenberg Foundation: The Wallenberg Centre for Quantum Technology, WACQT (12-year, €130 M): **WACQT entails two parts:** 3. The core project with the objective to build a 100-qubit quantum computer based on superconducting circuits. The quantum computer is developed in a targeted project at Chalmers. 4. An excellence programme: Quantum computing coordinated by Chalmers, quantum simulation coordinated by Chalmers, quantum communication coordinated by KTH, and lastly, quantum sensing coordinated by Lunds Universitet. **Efforts within WACQT:** • WACQT-IP: holding company that will protect and exploit patents within Quantum Technology. **Other efforts funded by The Wallenberg Foundation:** • WINQ: Wallenberg Initiative on Networks and Quantum information • WALP: Supports innovation at universities linked to spin-off companies or researchers who want to start spin-off companies.	**5 Spin-off companies from WACQT:** • Deep Light Vision AB, Oxygenation measurement instrument • Atlantic Quantum: Quantum computing • Scaling, Quantum computing, sample holder • Sweden Quantum AB, Microwave filters • quCertify, Quantum communication **Enabling technology partners within WACQT:** • Low Noise factory • Spectracure AB • Research Institutes of Sweden (RISE) • Intermodulation Products AB – Includes 4 industrial PhDs.	**Industry partners involved in WACQT:** • SAAB: Quantum radar, noise radar • Volvo: Quantum machine learning • Astra Zeneca: Quantum chemistry • Ericsson: Distributed quantum computing • Jeppesen: Optimization of flight routes • Hitachi ABB Power Grids: Quantum key distribution – Includes 7 industrial PhDs.

Public
Vetenskapsrådet Funding of numerous research projects in collaboration with partners such as QuantERA.
Vinnova Providing funding for quantum technology innovation calls (€2 million). 3 ventures, 2 Start-ups and 1 platform
SSF Various research project funded focused in quantum technology.

Regional and international collaboration and coordinated efforts
International level • Innovation Partnership in Quantum Technology (U.S.)
European level • EU Quantum Flagship • QuantERA (European network of public research funding organizations) via Vetenskapsrådet • Open SuperQ+: Open super Qplus100 • European Chip Act • EURO QCI (signatory on the EuroQCI declaration)
Nordic level • Nordic Quantum Life Science • Nordic Quantum Computing Group

Long term capabilities

As many other countries Sweden is facing challenges associated with a shortage of skilled workers to support the development of quantum technologies. According to interviewees, the Swedish talent and skill pipeline is narrow and insufficient. To address this, there is a need to develop the capabilities of the workforce in both education and industry, including training experts in quantum technology and increasing quantum competencies in engineering and other fields. This also involves raising awareness and knowledge in sectors that are expected to be impacted by quantum technology. To increase the domestic quantum workforce, international mobility in the quantum field is also necessary.

Globally there are few universities offering advanced degree program in quantum technology. Although many universities recognize the need of the industry for individuals with quantum technology related skills and capabilities, there has been a slow development in establishing corresponding courses and programs. The same issue can be identified in Sweden.

Key trends

The following section describes trends with significance for the development of the quantum technology ecosystem. Trends are based on findings from literature and interviews and have been developed in dialogue with Vinnova. These trends point to central development themes in the current ecosystem and present the foundation for the continued work to develop future scenarios for the quantum technology ecosystem.

Trends in overall strategy and coordination

The U.S. and China continue to be leaders in the field and Europe continues to hunt

The U.S. remains the front-runner in funding (combined private and public) and quantum technology research, followed by China, and European countries continue to hunt with increased funding and research initiatives. The US, on the other hand, is a market leader that benefits from a constellation of strong digital players such as Alphabet, IBM, Amazon, and Microsoft, major investments and dedicated public funding, a focus on coordination and collaboration both nationally and internationally between academia, industry, and government, and a robust innovation ecosystem and private sector that supports commercialization of research developments. What China lacks in private investments (only about 6% of private investments were in China as of 2022) it makes up for in public funding ($15.3 billions) that is double that of the EU ($7.2 billions) and eight times as much as the US. This has been followed by an increasing focus on research (China currently sits second behind the U.S. in number of quantum technology patents produced) and investment in quantum education and development in the academic sphere.

Coopetition: more bilateral and multilateral cooperations established as countries look to boost competitiveness

Individual countries are also looking to the establishment of partnerships to boost their capacities within research and innovation. The majority of national quantum initiatives cite international collaboration as important for knowledge-sharing, R&D, and business activities, and countries are seeking to strategically partner with others to address relevant needs – for example, Finland, who does not currently have a national strategy, signed a MoU with Singapore in 2022 to promote bi-literal research and exchange knowledge regarding national strategy development, Denmark has signed a joint statement on cooperation with the U.S. focused on the role of the private sector in driving innovation and development, and Canada and the U.K. have established joint calls for research proposals.

Efforts to coordinate development in Europe, but fragmentation persists

Although we see efforts to coordinate quantum development within the EU, it is still quite fragmented, and despite significant EU initiatives, national efforts dominate, especially regarding funding amounts. The most significant example of EU-level cooperation is the European Commission's Quantum Flagship program (2018), that committed €1 billion to research and innovation and coordinates efforts across countries, as well as a European Quantum Industry Consortium (QuIC), to boost collaboration opportunities between various industries across the region. The effort has turned into a dynamic mechanism that fosters collaboration between European countries. Yet some European countries are still developing siloed efforts, and several interviewees mentioned poor collaboration and coordination in the region. France and Germany are examples of two countries that are approaching quantum differently (France has a very decentralized strategy while Germany's is highly centralized) but share a highly nationalized focus on technological self-reliance and sovereignty in their strategy.

Public investment continues to be a driver, direct and indirect, for the development of the ecosystem despite increases in private funding

Private funding is increasing across the different stages of technological development, including from later stage/VC sources and philanthropic organizations interested in funding research and exploration in certain sectors. Yet national and regional governments and research initiatives continue to be the primary source of funding, especially as more and more of them formalize dedicated budgets and clear national quantum strategies. The public sector is also a significant source of indirect funding through, for example, the purchase of quantum technology products such as quantum communication technologies for the military. Interviewees voice the importance of public support especially when it comes to agenda-setting, financing, and coordination of national and regional developments. At the same time interviews point to the possibility of diversifying public investment and the importance of designing public investment schemes in quantum technology to develop constructive incentives for firms and researchers.

Trends in capabilities and attractiveness

Increased focus on education and training to support future quantum competences

There is expected to be a shortage of skilled workers to support quantum technologies, which means that talent and education pipelines are currently being developed to avoid stiff competition for existing and future skilled workers. Current projections take existing talent shortages in STEM fields into account, but it remains to be seen exactly where quantum will develop and at what scale. Therefore, it can be hard to pinpoint exactly where the competences will be needed; however, as we gain understanding of which areas will become more relevant, education and upskilling can be more targeted. Developments in quantum-related educations include QTOM, a year add-on master's program sponsored by the EU's Quantum Flagship as well as open-source upscaling initiatives such as global hackathons and quantum computer providers giving access to hardware so that others can try out algorithms. There is a focus on alternatives to simply funding more PhDs, which are considered resource-intensive, which includes development of middle level higher educational degrees, interdisciplinary higher-education programs, engineering programs, and upskilling initiatives within the industry that can deliver a better return on investment. Experts mention the importance of addressing existing inequalities within STEM talent shortages when thinking about quantum pipelines, for example skewed gender and racial/ethnic representation in the field. Greater diversity benefits innovation as it secures a broader base of knowledge from which to develop ideas and results in solutions that are relevant for a wider part of society. This point is for example explicitly mentioned in Canada's national strategy.

Trends in research and technology development

Researchers and investors are battling it out when it comes to qubit-construction

There are different technological approaches to the construction of qubits, each with its own drawbacks and benefits. A few are considered leading types and are more widely used, but because the technology is so early-stage, there is no perfect technology which is strong in all elements, and more qubit technology types are still being developed. As a result, several technology platforms are competing for the development of quantum computers without yet having achieved a standard. Researchers are either focusing on one technology that they may have an advantage with (for example France, which has a history of cold atom research and is therefore focusing on atoms) or focusing on the initial exploration of many technologies at once to see which ones will appear most promising long-term. Investors are investing in diversified "deep-tech" portfolios and/or diverse qubit technologies to spread out the risk.

The primary risk for quantum investments in quantum computing is technical

One characteristic of the quantum computing ecosystem is that the investment risk is primarily technical. There are already several identified use cases where a scalable quantum computer would bring significant economic value. Thus, the risk associated with investing in quantum computing is primarily technical. This implies that technical scrutiny should be important in continued investments in the ecosystem. The distance between a quantum "proof of concept" and "quantum supremacy" is wide; one is a smaller scale experiment that demonstrates potential use cases but can still be addressed with classical computers, and the other is a quantum computer's ability to perform tasks that current computers cannot in a reasonable amount of time without needing error correction. At the same time, the development of classic computer capabilities is also improving, shortening the gap between the two.

Trends in commercialization and applications

Potential risk of a quantum winter – speculation driving the ecosystems

Increasing venture capital investments in quantum technology without corresponding breakthroughs in technology developments have resulted in worries for the long-term sustainability of the ecosystem. Signs of slowing investments and consolidation in the market have increased such fears. This has led to a discussion of how sustained investment in quantum can be conducted without leading to speculation. The potential scenario where initial investments are not able to deliver on investor expectations, leading to significantly slowed investments, has been described as a 'quantum winter', building on historic similarities to the development of AI-technology. Experts interviewed for this study caution against speculative investment in the field and the importance of actors in the ecosystem working towards sustainable funding of the development with realistic expectations on what the technology can deliver. In practice this means that increasing investments should go hand in hand with the establishment of proof of concept for quantum technology.

Trends and underlying factors in Sweden

Concentrated development centered around one financier and one research initiative

The development related to quantum technology innovation in Sweden the last five years can be almost exclusively connected to The Wallenberg Foundation's research effort WACQT, which is the primary innovation effort regarding quantum technology in Sweden. This means that Sweden's "national program" has been a private initiative, something that has been identified as a vulnerability for the long-term development. Prior to 2018, quantum technology development in Sweden was primarily funded through EU programs. Academic research has been the driver of the development as WACQT has primarily financed university activity; there are a few companies sponsoring industrial PhDs in the area. This arrangement, where the development is solely funded by one private philanthropic investment has resulted in a situation where the knowledge base is concentrated within a small circle of people. This has been identified as a challenge as it may slow the development of a broad knowledge base around quantum technology in the research sector as well as in the economy at large. The Swedish development within quantum technology has been characterized by a few actors, which means that research and development in the field tends to become person dependent

Government involvement has historically been limited and in some cases uncoordinated

Interviewees highlight the fact that without the Swedish government playing a stronger role, the actors and initiatives already existing besides WACQT are highly uncoordinated and scattered. An example is when Sweden did not join the first round of applications for EUOR QCI as it was not clear which authority would take responsibility for this effort. Interviewees voice that without a national strategy, it can be difficult to get decision makers involved in research policy. At the same time, interviewees mention previous episodes where Sweden was late in getting involved with technology; for example, Sweden is mentioned as being one of the last European countries to support an EU quantum communications internet collaboration initiative, and as being "underprepared" for artificial intelligence.

More recent involvement from public actors in Sweden includes the Swedish Research Council (Vetenskapsrådet), which has funded numerous research projects in the field, and the Swedish Innovation Agency (Vinnova), which has provided funding for startups working on quantum technology.

Quantum life science and logistics are emerging areas of strength in Sweden

Several experts point to both logistics and life sciences/pharmaceuticals as the most immediately relevant industry segments for Sweden, both because Sweden has competencies in these areas and because they are among the first expected use-case industries for quantum computing; companies that have gotten involved in the WACQT industrial program include Volvo and Astra Zeneca, among others. Quantum computing could optimize logistics, which companies such as Volvo and Stena are interested in. It is expected that the pharmaceutical industry could see early benefits from molecular simulation, and other possibilities for quantum life science in Sweden include precision health, microscopy and radiology, quantum spectroscopy, and quantum sensors. The Nordic region is considered strong in the life sciences, with robust research activity, strong competencies, and solid industry. Therefore, interviewees mention a competitive edge within life sciences for Sweden and the Nordic area in general. The area where commercialization of applications has gotten the furthest in Sweden is related to life science, although still at an early stage.

All three major quantum technologies are gaining traction in Sweden, but are at different readiness levels

Quantum communication

Sweden is currently a member of the EuroQCI (European Quantum Communication Infrastructure) initiative. Interviewees believe that Sweden is strong in this research area; currently, dedicated research groups to quantum communication exist at Stockholm University where the research focuses on multidimensional qubits to improve performance.

Quantum sensing

Quantum sensing is the most developed in terms of commercialization of applications/TRL. The market in Sweden is characterized as existing but niche, and applications could be better communicated to companies as the potential uses are quite widespread. Research on quantum sensing is concentrated in Lund – it is supported by a company working with blood oxygen measurement and focusing on laser models with sound and light wavelengths.

Quantum computing

Aside from a single alternative project at Stockholm University working with ion traps, the concentrated nature of Sweden's quantum computing development means the focus is on a single qubit technology platform: semi-superconducting qubits. WACQT has developed a variant of a solution used by IBM, and currently has a 20-qubit quantum computer which will be functional in two years, with a goal of achieving 40 and ultimately 100 qubits in the future. Experts expect that Sweden's efforts in computing will not necessarily be at the level of solving industrial problems but will be able to contribute to building knowledge.

High barriers to using the technology and only a few can engage in development

One issue identified as a limiting factor to the technical development within the field is that there are high barriers to using quantum technology and therefore only a few can engage in development. This may be seen as an explanatory factor when it comes to Sweden's historical struggle to broaden knowledge outside of already very knowledgeable clusters. Interviewees therefore highlight the importance of initiating efforts that involve more diverse actors with different focuses.

Broader understanding of quantum technology innovation is growing too slowly

A theme in our interviews has focused on the general lack of knowledge about quantum technology innovation in Sweden, as well as in other countries. This risk hampers the development on several levels. The lack of understanding for the potential of the technology might lead to lower engagement from both public and private actors including research financiers, government, and established firms. Furthermore, a specific challenge exists in ensuring the transferal of knowledge from disciplines working actively with technology development to other areas where the eventual applications will be found.

Initiatives to strengthen Nordic collaboration

The Swedish development the past five years does not include a coordinated effort with other Nordic countries that share similar characteristics. On a Nordic level, co-operation in the form of joint coordination and funding would most likely increase the probability of successful development in the coming years, rather than working in silos. As this seem like an attractive future scenario for Nordic countries, it is not certain that collaborations will occur as the Nordic countries have different motives and different national characteristics and therefore will enter potential collaborations with their own national standpoint.

The commitment of the business community to participate in development is growing

Sweden, like many other European countries, has struggled in the past when it comes to the transition from research to commercialization. Recently, a few startups have emerged as spin-off companies from different research projects situated at several Swedish universities. At the same time, the commitment of the business community to participate in development is growing, as larger-scale Swedish companies such as Astra Zeneca, Hitachi ABB Power Grids, Jeppesen, Volvo, Ericsson and Saab are increasingly engaging with quantum.

Lack of competence limits development and competition for existing competence is tough

Like what can be seen globally, Sweden is expected to have a shortage of skilled workers to support the development of quantum technologies. Interviewees define the Swedish talent and skill pipeline as under-dimensioned and encourage increased focus on education and training to support future quantum competences. The challenges can be seen as two-fold: first, in education and competence building, as Swedish universities lack dedicated courses and programs in quantum technology. Rather, the focus has been on quantum physics and quantum chemistry. Second, there are challenges with maintaining the competence that already exists in Sweden, since competition for competences is stiff. Sweden is also facing a challenge when it comes to maintaining PhD students due to Swedish labour migration policy regulations regarding residence permits.

Scenario analysis

The previous analysis of the quantum-technology ecosystem has identified several central trends in the development that Vinnova and other Swedish actors need to take into consideration when developing strategies and support measures. In the section below, the outlook based on these trends is discussed.

Where are we heading?

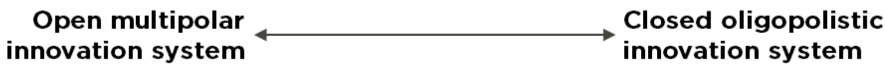
The development of quantum technology is complex, consists of many parallel developments, and is to some degree subject to expectations not necessarily matched by technological development. Across all three dimensions there are influential factors that will affect the development.

The structure on the future ecosystem is uncertain

From the analysis we have identified several emerging typologies within the ecosystem with different stakeholder relations. Based on these identified trends, we can devise strategic dimensions based on the polarity of a future ecosystem, ranging from an open innovation ecosystem with a broad range of stakeholders involved to a closed ecosystem dominated by a small number of actors. Such a dichotomy reflects recent developments in many technology fields where the market dynamics have led to few actors taking a dominating position in the emerging technology field.

In the observation, tendencies towards such development can be identified, especially when looking at firms like IBM and Alphabet that strive to establish a full stack internal ecosystem. At the same time, at current state, the emerging ecosystem is significantly multipolar and developments towards a more closed ecosystem are to be expected as the technology reaches a higher maturity. Furthermore, the development along this dimension might vary for different parts of the ecosystem such as quantum sensing, quantum telecommunication, and quantum computing.

For actors supporting the development of a national ecosystem for quantum technologies, the positioning along this dichotomy has significance as it will affect the level of influence that can be had on the ecosystem. In an open ecosystem scenario, national support organizations have larger freedom in supporting the actors in the ecosystem and its development, whereas a closed ecosystem would limit the possibilities in driving a national agenda for quantum technology. In a closed ecosystem scenario, relationships with central ecosystem actors become more important.



Technology maturity will affect the development of the ecosystem

A key determining factor for the future development of the ecosystem around quantum technology is how fast the technology will mature and find actual applications in the economy. An important step in such a development is the establishment of clear proof of concepts for quantum technology that showcase technological maturity for specific applications. The establishment of proof of concepts is a more important step for the development of the ecosystem than the often-discussed quantum supremacy and is therefore an important threshold for the ecosystem. Based on this trend, a dichotomy for the future development of the ecosystem is proposed, ranging from a scenario with high technological maturity and prompt proof of concept to a lower technological maturity where the proof-of-concept lags.

In the scenario where proof of concepts for important applications can be achieved quickly, this would trigger several developments for the ecosystem, not the least increased investments. The establishment of proof of concepts would effectively lower the risk of development as well as instill a sense of urgency in other aspects (such as legal and market adaptations) relevant to the development of the ecosystem. On the other hand, if the technological readiness remains low and proof of concept lags, this entails a higher risk for investments being made in the field, hampering the speed of investments directed towards the technology. Such dynamics are both true for the quantum ecosystem as well as for individual technologies and applications.

For national actors, the development has significant implications. The establishment of proof of concepts is expected to increase private investments in such applications. As private funds flow in, public funds can find more important uses in other parts of the ecosystem. In the absence of established proof of concept, the role of public funding is expected to play a larger role in supporting development of the technology and translation of technology into feasible use cases.

High technology readiness (prompt POC) ↔ **Low technology readiness (POC lingers)**

The role of private capital is still not clear

Despite increasing private investment in quantum technology, public investments in the sector still comprise most of the resources allocated to quantum technology research and development. The increase of private risk capital in recent years has had a significant impact on the development of the ecosystem. Such development helps further commercialization attempts of the technology as well as introduces a stronger incentive focused on technological applications in the ecosystem. While increased levels of private capital have had many positive effects on the ecosystem development, concerns have been raised that the speculative nature of such investments could lead to a backlash in the case of a delayed commercialization of the technology. If the early investments of recent years fail to show realistic prospects of achieving their goals, there is a risk that further investments will stall, an event that has been depicted as a quantum winter.

Based on the identified trend of increasing private investments, a dichotomy can be formed ranging from an ecosystem primarily driven by private investments to an ecosystem primarily driven by public investments. In the scenario where private money drives the ecosystem, an increased focus on commercialization is expected. However, under such circumstances, public money will play an important role in financing basic research in the field. In the scenario where public money remains the primary source of financing for the sector, there is a risk that applied research and commercialization receives only limited amounts of money.

Development driven by private capital ↔ **Development driven by public capital**

The level of internationalization of the ecosystem will have a significant impact

The quantum technology ecosystem is becoming increasingly international. International leaders, including firms and academic institutions, are establishing networks of actors to support the development of specific technology directions. In addition, the growth of private investments has supported an internationalization of the ecosystem with significant levels of cross-border and cross-region investments. Politically, countries are establishing bilateral and multilateral agreements to jointly pursue quantum technology development. Similarly, on the EU-level, significant initiatives have been taken to increase regional coordination within quantum technology. However, such initiatives have to some degree been overshadowed by the development of national strategies and increased national investments in quantum technologies. Furthermore, in the Nordic context, significant informal networks have emerged over the last few years, laying the foundation for increased regional collaboration in the Nordics.

Based on the developments described above, a dichotomy can be described ranging from a national focused ecosystem to an international ecosystem. This dichotomy describes the relationships between actors in the ecosystem and what geographies that constitute the primary focus of actors in the ecosystem in aspects such as funding, applications, collaboration, and strategy. In the case of a nationally focused ecosystem, Swedish actors would primarily relate to other Swedish stakeholders, leading to a focus on developing full stack capabilities nationally. Such a focus is expected to be resource-intensive but would at the same time ensure capability-building across the entire quantum value chain, supporting national independence. In the other end of the spectrum, an international ecosystem would entail an ecosystem centered around globally leading nodes where actors collaborate based on niche capabilities. Such development is expected to result in a high degree of interdependencies of actors, and for a small country like Sweden, this could lead to a scattered capability profile that might imply high dependence on global leaders for access to leading quantum technologies. Along the dichotomy exist various positions of regionally focused ecosystems, including on a Nordic and EU level.

For national agencies like Vinnova, the national-international dimension is both an endogen and an exogen factor. National actors can promote ecosystem development with different degrees of regional and international focus. At the same time, exogenic factors such as technology development and the influence from international capital in the sector will affect the direction of development. This means that a national strategy needs to set a strategic direction for the internationalization of the ecosystem that is favorable for Sweden, while at the same time be open to external factors that may impact the configuration along this dimension.

National innovation system ⟷ **International innovation system**

Three development scenarios

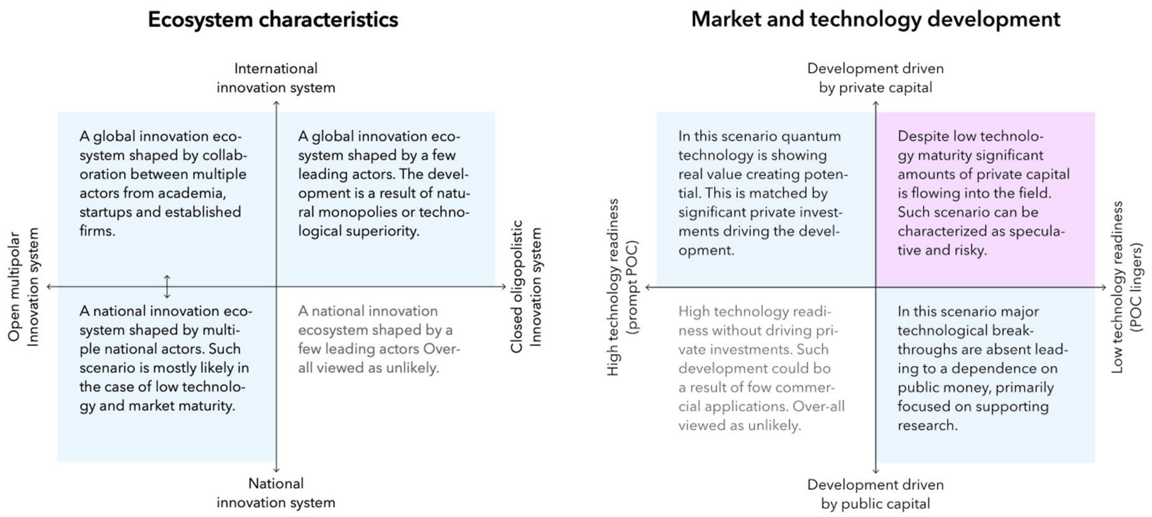
Scenario matrixes can be formed based on the four dimensions presented above. The figure below identifies 8 potential outcome scenarios focused on the one hand on ecosystem characteristics as well as on the interplay between resources allocated to development and technological development. The potential outcomes can be described according to the figure below. In the figure, scenarios that are deemed more likely are highlighted in green while outcomes that are deemed risky are highlighted in red.

In the matrix depicting ecosystem characteristics, the top right corner implies a closed global ecosystem controlled by a small number of major firms. Such development is similar to the dynamics identified in many technology markets today. In such a scenario the ability for countries to shape independent strategies in quantum technology is limited. The left two outcome quadrants on the other hand implies an open innovation ecosystem with a plurality of actors active in a broad range of technology and market niches. Such open systems can exist with various degrees of internationalization. Under such scenario, the ability to set up independent quantum technology strategies is larger, and countries can develop positions of strengths in various market and technology niches.

The matrix describing the relationship between market and technology development identifies two likely scenarios. The top left corner describes an outcome where technology maturity is high and correspondingly significant levels of private investments are made in quantum technology. Such scenario is depending on prompt proof of concepts and proof of value being achieved in quantum technology. Under such scenario public resources towards quantum should focus on long term research needs as well as identified market failures. The lower right quadrant on the other hands outlines a scenario where technology maturity remains on lower levels, and as a result public investments remains the driving force for development in the area. Under such scenario significant public resources might be needed to continue the development of basic technology as well as identification of application areas. Further public resources might also need to play a role in supporting early-stage startups aiming at commercializing niche technologies in the quantum technology field.

The right scenario matrix further describes an outcome where private investments in quantum technology increases sharply despite technology readiness remaining low. Such outcome is deemed risky as investor expectations hardly can be realized. Such outcome is similar to previously discussed worries about a 'quantum winter' where over investments in the short run leads to under financing in the longer period.

Graph 3| Scenario outcome matrixes



Ecosystem development scenarios

Based on the outcomes of the two matrixes, three joint scenarios are formed.

Scenario 1 – International focus, closed ecosystem, High TRL, Private capital
Quantum technology has advanced to the point where a small number of tech giants control the majority of the ecosystem. These companies have invested heavily in research and development, and as a result, possess a significant advantage in terms of technology and resources.

Individual countries as well as firms have little autonomy to govern their own quantum technology development, as access to leading quantum technology and platforms is essential for success.

In this scenario a rapid technological development in quantum technology has led to a point where a small number of leading tech firms control most of the ecosystem. These companies have invested heavily in research and development and internalized large parts of the ecosystem, and as a result, possess a significant advantage in terms of technology and market power. This results in a closed international ecosystem where actors who want to engage in quantum technology must rely on access to the platforms provided by a few actors.

In this scenario, access to quantum technology becomes a key determinant of a firm's success in the fields. Firms focus on identifying and developing applications based on quantum technology provided by dominating firms. Firms that want to stay competitive in the global market must partner with these tech giants or risk being left behind.

Individual countries have little autonomy to govern their own quantum technology development. Countries can support industry and innovation by ensuring good framework conditions as well as supporting and facilitating good access to services provided by dominating firms. Further national innovation system actors can support firms in developing solutions based on established quantum technology backend.

This scenario is more likely for applications of quantum computing and to some degree quantum communication, while a more open innovation ecosystem in quantum sensing is viewed as more likely.

Scenario 2 – International/regional focus, open ecosystem, High TRL, Private capital

Quantum technology development is taking place in an open innovation system on a global level. This system is characterized by rapid technology development. Countries and firms are able to position their own national ecosystems within niches of the global ecosystem, both alone and in collaboration with others. As a result of this open innovation system, it becomes increasingly important for countries to attract global capital for commercialization and research.

In this scenario, quantum technology development is driven by an open innovation system on a global level. This system encourages fast technology development by allowing countries and firms to participate in global ecosystems.

Countries and firms can position their own national ecosystems within niches of the global ecosystem, both alone and in collaboration with others. This allows for a diversity of approaches and specializations, leading to faster and more comprehensive technological advancements.

As a result of this open innovation system, it becomes increasingly important for countries to attract global capital for commercialization and research. Countries that can establish themselves as attractive destinations for investment in quantum technology are able to attract top talent and resources, further accelerating their development.

This open innovation system also leads to greater democratization of access to quantum technology, as more countries and firms can participate in its development and commercialization. This helps to ensure that the benefits of quantum technology are more widely distributed, rather than concentrated in the hands of a few large companies or countries.

In the future, the development of quantum technology is slow and primarily driven by public capital investments. This scenario presents an open innovation system, where actors and countries can position themselves on a national and regional level. Due to the lack of significant technological breakthroughs, private funding for quantum technology is limited.

In this scenario, it is important for countries and firms to focus on funding research for long-term technology development. This means investing in basic research, as well as in the development of the necessary infrastructure and talent to support future advancements.

To maximize their resources and chances of success, countries and firms must collaborate with others, for example, in the Nordic region, to pool competences and resources. This enables them to contribute to the global technology development, in the form of research and development.

With this approach, the slow and steady development of quantum technology is driven by public capital and collaborative efforts, and as a result, the ecosystem becomes more diverse and resilient. Countries and firms can position themselves in niches of the global ecosystem, and this leads to more sustainable and inclusive technological advancements in the long run.

What is a desirable development?

Governments need to take several factors into account when approaching the uncertain development surrounding quantum technology. Governments need to find a balance between ambitious objectives for supporting the development of strong commercial ecosystems and the technological risk and uncertainties relating to achieving proof of concepts in the quantum field.

Small countries face additional resource constraints and need to take a strategic approach in prioritizing initiatives. For a small country like Sweden, investing the vast resources needed to develop an independent quantum technology ecosystem may not be feasible. As such, differentiation of efforts is crucial, particularly in comparison to countries such as the United States and China. Governments face a complex and challenging task in determining the best path for investment in quantum technology, and must consider various factors such as technology maturity, industry demand, and the geopolitical landscape.

The current state of development of quantum technology ranges from very immature to somewhat mature, with some researchers at universities claiming years of readiness and some industry players claiming immediate applicability. However, it can be argued that mainstream adoption of quantum technology may not occur for 5–10 years due to a combination of immature technology and a lack of investment from the industry. For this reason, governments need to strike a balance between nurturing commercial dimensions of the ecosystem without exaggerating expectations and risking over-investments from both private and public investors.

The geopolitical landscape presents both positive and negative perspectives, as most countries see quantum technology as a disruptive technology and wish to engage in its development, while at the same time being wary of sharing proprietary technologies. Governments must consider multiple questions, including what technology to invest in, what the maturity of the technology is, what the industry needs are, and what can be shared internationally. As the assessment has shown, there are clear opportunities for strengthening regional collaboration.

In conclusion, determining the best course of action for investment in quantum technology is a complex and multi-faceted operation, requiring consideration of the technological sphere, nation-state communication, the finance sector, healthcare sector, energy sector, and more.

Set an ambition for position in global innovation chains

Sweden should set a strategic ambition for its position in the global innovation chains in quantum technology. The goal for Sweden should not necessarily be to become a full stack frontrunner in quantum technology, but rather to find specific niches within quantum technology and work broadly with actors in the national innovation system to identify applications relevant for the Swedish context.

This can be achieved by creating unique quantum solutions that cater to various industries in the country. In the long run, quantum technology has the potential to drive innovation and economic growth in a variety of sectors, and it is crucial for Sweden to take advantage of this opportunity. By setting a strategic ambition for its position in the global innovation chains of quantum technology, Sweden can differentiate itself from other countries and carve out a niche for itself in the field. This will enable the country to attract investment, create job opportunities, and drive technological advancement.

Strive for a balanced development between technology development and market development

It is crucial to avoid a situation where expectations from investors and the industry exceed what can be realistically achieved, as this can have a negative impact on the long-term support for investments in the field. There are clear motivations for already beginning to support commercialization and build expertise in the commercialization of quantum. At the same time, initiatives in this field should be undertaken with some caution.

It is important to be aware of technological risks while supporting the growth of startup ecosystems and encouraging established companies to become involved in the field. Approaches to manage this balance include continuous assessment of technology maturity, identification of potential use cases, and knowledge-building. Furthermore, it is important to identify areas with high technology readiness and direct commercialization support to these areas. At the same time, it is equally important to provide the research ecosystem with enough resources to enable a long-term focus on solving key challenges such as scalability.

Support the development of a broad national innovation system.

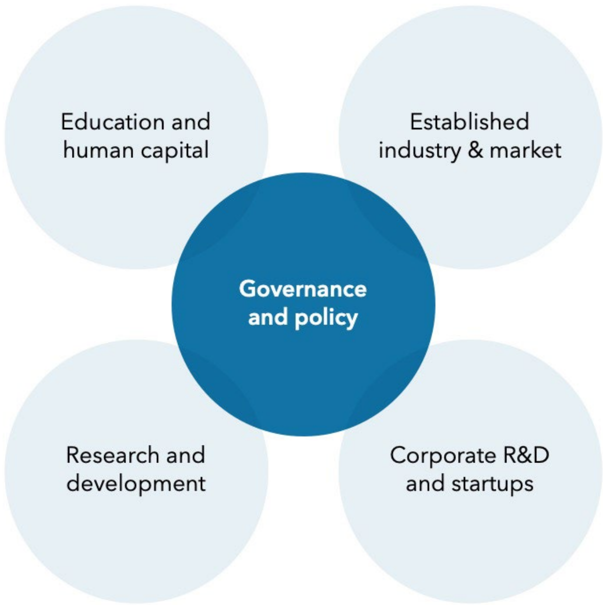
Sweden should aim at developing a broad national innovation system for quantum technology in order to manage the uncertainties and potential risks associated with the field. Focusing on a single technology platform might result in path dependencies that are not favorable for the long-term development, and it could be associated with high risk.

In order to build competence and capability in many different fields, Sweden should strive for a broad innovation system that encompasses different categories of quantum technology such as quantum sensing, quantum communication, and quantum computing, as well as different technology platforms. The ecosystem should also include applied research that is relevant for various industries and supports the identification and development of use cases.

Forward-looking systems analysis

Based on the mapping of the Swedish ecosystem for quantum technology innovation conducted earlier in this report the following segment explores the current state of the Swedish innovation ecosystem for quantum innovation and points to strengths and weaknesses in the current system. The assessment is based on a model for the innovation ecosystem as presented below.

Graph 4| Model for system analyses



System model for mapping and analyzing the quantum technology innovation ecosystem

Source: Amsterdam Data Collective

Governance and policy

Sweden is currently facing challenges in the coordination of its actors and initiatives in the field of quantum technology. Interviews highlight the need for stronger government involvement in the governance of quantum technology development. This lack of coordination has resulted in missed opportunities, such as not participating in the first round of applications for the EU's Quantum Communications Infrastructure initiative.

However, recent involvement from public entities such as the Swedish Research Council and Vinnova have funded research projects and startups working in the field of quantum technology, indicating a move towards stronger support in this area.

Strengths in Sweden's current level of development in quantum technology include strong framework conditions and a well-developed research and innovation system. On the other hand, the scattered and uncoordinated nature of the current initiatives is a weakness that needs to be addressed in order to fully leverage Sweden's potential in this field. A clear national strategy and stronger government involvement in governance and coordination would be necessary to fully support the development of a strong and effective innovation system for quantum technology in Sweden.

Education and human capital

Sweden's quantum technology sector is facing challenges in terms of education and human capital. There is a general lack of knowledge and understanding about the potential of quantum technologies, leading to lower engagement from public and private actors. Additionally, there is a challenge in transferring knowledge from technology development to other areas where the applications will eventually be found.

Several interviewees highlight the importance of getting more diverse actors involved with different focuses engaged to develop a sustainable Swedish quantum ecosystem. New and old actors need to understand and be made aware of existing ecosystems to participate in them. Even more importantly, actors within the ecosystem need to understand their role in the system as well as interact with each other to recognize what role they should assume going forward. The ecosystem needs to be understood correctly by all relevant actors to discern where collaborations are necessary and where they are not relevant.

The Swedish talent and skill pipeline for quantum technology is also lacking, leading to a shortage of skilled workers to support the development of the technology. This shortage is exacerbated by a lack of dedicated courses and programs in quantum technology in Swedish universities, which focuses mostly on quantum physics and quantum chemistry. The competition for existing competences is also stiff, making it difficult for Sweden to maintain its current level of knowledge and expertise. This is particularly challenging as the lack of skilled researchers and professionals is a global phenomenon. To address these issues, it is important for Sweden to focus on education and training to support future quantum competences and retain its existing knowledge and expertise.

Research and development

The Swedish research and development ecosystem in quantum technology has been largely driven by academic research, financed by the Wallenberg Foundation's research effort WACQT. Important achievements have been made through the WACQT initiative and Sweden has developed leading expertise in the field of quantum computing. This concentration of funding has however resulted in a small circle of experts driving the knowledge base in the field, presenting a challenge for the development of a broader ecosystem in both academia and for the translation of technological development to the economy.

WACQT's efforts have produced a 20-qubit quantum computer with the goal of reaching 40 and ultimately 100 qubits. Sweden is strong in quantum communication and has dedicated research groups at Stockholm University focusing on multidimensional qubits. Meanwhile, quantum sensing is the most developed area in terms of commercialization, with the market in Sweden being niche but existing. Research in this area is centered in Lund and supported by a company working on blood oxygen measurement.

However, the sole dependence on private philanthropic investment for funding raises concerns about the long-term sustainability of the development of quantum technology in Sweden. The absence of a national program has also led to a situation where research and development tends to become person dependent, hindering the growth of a diverse and inclusive ecosystem. Addressing these weaknesses and developing a more robust and diverse research ecosystem in quantum technology would help secure Sweden's future in this field.

Corporate R&D and startups

Sweden's corporate R&D and startup scene in the field of quantum technology is still in its early stages, with a weak focus on commercialization and applications. In terms of partnerships, industry-academia collaborations are seen as beneficial as companies provide academia with real-life applications to investigate, while the companies gain forefront knowledge and competence. Companies are also partnering with enabling technology companies, which specialize in the supporting technologies needed for building quantum devices.

The area where commercialization of quantum technology applications has progressed the most in Sweden is related to life science, although it is still in its early stages. Sweden has competencies and investments within life sciences and could have a competitive advantage, but capital is needed to ensure continued growth in this area.

The current state of the ecosystem highlights the need for a stronger focus on commercialization and more investment in startups and

SWOT analysis of the Swedish ecosystem for quantum technology innovation

Based on the assessment of the Swedish ecosystem for quantum innovation the below SWOT analysis has been developed. It includes elements from all parts of the ecosystems and aims at identifying overarching trends with importance for current and future development. The SWOT analysis has been developed by Amsterdam Data Collective in dialogue with Vinnova and is based on insights from interviewees as well as extensive document studies.

Graph 4 | SWOT analysis of the Swedish ecosystem for quantum technology innovation

Strengths	Weaknesses

• Established strong research with high impact
• Full stack competence in QC
• Strong funding levels in the short run
• Strong infrastructure for quantum technology research
• Established international networks
• Strong over all research and innovation ecosystem
	• Lack of breadth in research
	  • Limited number of research environments
	  • Narrow focus on single technology platforms (QC)
	• Limited government coordination and support. (historically)
	• Weak focus on commercialization and applications

Opportunities	**Threats**
• Emerging Nordic collaboration in quantum technology • Potential strength in life science • Established partnerships and agreements with countries and leading actors	• Increasing competition for research funding, VC funding and competence • Sweden is not perceived internationally as a leader in the quantum field Lacking strategic positioning in an international innovation

• Established companies with interest and relevance for the development of quantum technology	ecosystem • SMEs seek capital abroad • Global Swedish companies are linking to international hubs

Development areas for Sweden in quantum technology

Based on the combined insight from the analysis, the scenario analysis, and the system analysis of the Swedish ecosystem, 12 prioritized development areas for Sweden in quantum technology across 4 dimensions were identified. These are presented below.

Overall strategy and coordination

Set an ambition – formulate and implement corresponding strategy

Sweden should formulate its ambition within the quantum technology area and develop a strategy to realize this ambition. Such strategy should outline what position Sweden aims to take in global research and innovation chains, and the needed resources and actions to fulfill these goals.

The strategy should build on existing strength and aim at coordinating Swedish efforts. This also entails a division and clarification of responsibilities between government actors as well as actors in the broader innovation system. Emphasis should be put on building a complete and connected innovation chain.

Vinnova should play an active part in the implementation of the Swedish strategy and ensure that commercialisation and innovation topics are given enough focus and resources, depending on the broader development of quantum technology.

Foster international collaboration

Sweden should actively develop international collaboration in the quantum technology field. Collaboration should be developed in line with the overall strategy and with defined ambitions for collaboration on Nordic, European and global levels. Collaboration should be developed from a national perspective with clear support from the political and national agency level.

Sweden should engage with actors on Nordics and EU level to support initiatives focused on building regional ecosystems for quantum and together with state actors in the Nordics and EU identify and exploit synergies. Such involvement is depending on strong government involvement in international collaboration platforms for quantum, not the least when it comes to EU-level research collaboration.

A particular opportunity for increased Nordic collaboration exists with synergies in both research and innovation domains. Such collaboration can be developed from existing collaborative initiatives.

Support the formation of a complete and connected ecosystem

The assessment of the Swedish ecosystem for quantum innovation identifies a need for increased coordination between different actors. Strategic initiatives should aim at fostering an interconnected ecosystem stretching from academic research to commercialization.

Initiatives supporting this objective include support for developing national platforms for collaboration and knowledge building. Such platforms can be developed both on a general and industry specific level.

Capabilities and attractiveness

Invest in education

The report identifies a potential shortage of relevant competences to support quantum technology development in the long run. To address this Sweden should continue to build competence in quantum technology by investing in education and training programs to develop the talent needed to advance the field.

Educational initiatives should include a broad range of educational programs aimed at building a broad competence profile in society around quantum technology. Programs should not only aim at fostering the next generation of researchers in quantum technology but also contribute to increasing quantum understanding in broader engineering programs. There is further a need to increase understanding in disciplines outside the technical domain to facilitate application of quantum technology in various industries. Educational offers can also be directed at professionals through various forms of upskilling.

Continue to build knowledge and involve a broader audience.

State actors should continue to support knowledge building around quantum technology. There is a need to better understand the evolving ecosystem including mapping of actors (active research groups, incumbents working with quantum and startups), identification of use cases and Sweden's position in global innovation chains. Such information has multiple recipients and will contribute to a more connected ecosystem as well as serving as an important knowledge base for the continued governance of the ecosystem.

In practice these knowledge building activities could be conducted in conjunction with as a part of multi-disciplinary platforms, further contributing to increased collaboration and community building in the ecosystem. Such platforms can contribute to the overall development of the ecosystem by:

- Knowledge building such as collecting use cases, drafting white papers and continually monitoring of the ecosystem.
- Motivating more actors to engage in the ecosystem by knowledge sharing and lowering entry barriers. Building more accessible narratives around quantum.
- Supporting community building in the quantum field.

In the short term, it is essential to prioritize knowledge building activities. If dedicated platforms are not yet available, expert organizations can be commissioned to conduct relevant analyses including landscape mapping and international comparisons.

Communicate Swedish strength and strive to be an attractive destination for capital, research and competence

To stay relevant in an increasingly competitive global quantum technology landscape Sweden needs to work actively to communicate existing and developing strengths. The study has identified that other countries systematically work to attract resources related to quantum technology development. To remain competitive, Sweden should strive to be perceived as an attractive destination for investments in research and quantum startups. Sweden should also strive to be an attractive destination for global competence in quantum.

Research

Build on existing strength and broaden the research ecosystem

While Sweden shows case strong researchers with high scientific impact in the quantum technology field, the research ecosystem is concentrated around a few research groups focused on a limited number of technology platforms. In developing the research ecosystem, Sweden should aim at broadening the research field by expanding the number of involved researchers and building competences around more technology platforms. Such efforts need to be implemented in a balanced way and need to take the existing strengths in the research ecosystem into account. Efforts should not negatively affect the existing strengths in producing high-impact basic research. In particular there still needs to be room for larger concentrated efforts aimed at developing quantum computers.

A broad range of actors in the research supporting landscape could contribute to the broadening of the research ecosystem. Such efforts could both focus on supporting research on other technology platforms as well as a broad range of applications of quantum technology. Efforts could also be coordinated with other actors in regional ecosystems to share the costs of investing in research in new technology areas.

Ensure long term financial support for quantum research

Long term funding opportunities are essential for developing a strong quantum technology research ecosystem. Swedish quantum research has largely been depending on the funding through the WACQT program. State actors should commit long term to ensure enough funding, in line with the stated ambition to support leading quantum research beyond the end of the WACQT program. Funding opportunities should be sufficient enough to cover the broader focus of quantum research including quantum simulation, quantum sensing, and quantum communication.

Increase support for applied research and increase access to quantum infrastructure

The Swedish ecosystem around quantum technology is largely focused on basic research and the development of core quantum technologies. This has had significant benefits, not the least supporting broad knowledge building and full stack competence in quantum. Moving ahead, research funding should in addition focus on applications for quantum technology. Such investments serve several purposes, including supporting commercialization and allowing more actors to engage in the quantum ecosystem.

The development of the broader ecosystem depends on the proving of usable quantum advantage and proof of concepts. By supporting research that can contribute to such development, the ecosystem will attract interest from more actors, furthering its development. Applied research in quantum will also support the broader ambition of developing commercialization track in the ecosystem and enable actors outside academia to engage with research environments supporting a more connected ecosystem.

Commercialization and applications

Support the emerging startup ecosystem through seed-funding and non-financial support

Despite the uncertainty surrounding the timeline for commercialization of quantum technology there are clear motives for developing market-oriented dimensions of the quantum ecosystem. The international outlook identifies a rapidly growing global ecosystem of firms and investors engaging in various aspects of quantum technology development. Furthermore, within the quantum field, there are large variations in the technological maturity for different technologies and already commercially viable solutions on the market. It is therefore important for Sweden to support the emerging startup ecosystem and commercialization of mature quantum solutions.

State actors should actively support startups in the quantum field through relevant financial and non-financial measures; this might include ensuring stable access to early investments as well as organizing regular calls for innovation support. Early-stage startups can further be supported through non-financial measures such as mentoring and business matching.

Ensure access to capital infrastructure and network

Ensuring strong framework conditions for quantum startups will be important for the long-term success of the Swedish quantum ecosystem. Among other things, this includes access to capital, competence, and infrastructure.

Access to capital will be essential for the development of new quantum ventures. So far only limited VC-activity focused on quantum in Sweden can be identified. At the same time, there is an increasing global interest from investors to contribute and take part in the rapidly developing field. Over time, ensuring that startups in Sweden have access to capital will be an important determinant for the success of a Swedish quantum ecosystem. Assessment of the Swedish VC-landscape indicates a lack of funding for deep tech firms. This underlines the importance of actively working to support the development of a strong funding landscape for Swedish firms. Such work could include continued monitoring of the Swedish VC-landscape relevant for quantum startups, as well as connection activities towards international pools of capital.

State actors should support initiatives that remove barriers to access to infrastructure. This includes access to lab environments as well as to quantum hardware. Such initiatives can be organized on a national as well as on a regional and international level.

Identify applications and engage with industry

The government should prioritize the collaboration between industry and academia in the identification of quantum applications and increase industry engagement in quantum technology. This can be achieved by creating awareness and understanding of the potential value and impact of quantum technology on different industries, as well as making quantum technology more accessible for industry actors and startups. By fostering industry-academia collaboration and increasing industry engagement, the government can support the development and commercialization of quantum technology.

Appendix

Interviewee	Organization
Anders Broo	Astra Zeneca
Cassia Naudet-Baulieu.	Boston Consulting Group
Jean-Francois Bobier	Boston Consulting Group
Per Delsing	Chalmers – WACQT
Pontus de Laval	Chalmers – WACQT
Göran Wendin	Chalmers – WACQT
Fabien Déchery	Cognitive Atlas
Emily Meads	Speedinvest
Ebba Carbonnier	Swelife
Ulrik Busk	Technical University of Denmark (DTU)
Pauline Coucher	Quantonation
Richard St Pierre	Zone d'Innovation Quantique

Appendix 6

Quantum Technology Research within Sweden

Executive Summary

This report is a summary of current Swedish research within Quantum technology. The summary is based on a survey sent to and answered by 40 research groups within the field, located at seven different Swedish universities. The respondents were identified through a bibliometric analysis. Additional bibliometric analysis is included to facilitate international comparisons.

The main findings of the report are:

Facilities: National and local cleanrooms need to be upgraded and expanded in order to be able to meet current and future needs to develop devices and systems for Quantum Information Processing.

Facilities: Access to computational power needs to be strengthened in Sweden, as well as to EuroHPC computational resources (e.g. LUMI in Finland).

Staffing: More funding is needed to increase the number of PhDs, Postdocs and Assistant Professors.

Education: More Master's programs (MSc) are needed in quantum engineering.

Collaboration/competence: National and international collaborations are seen as essential for current and future research activities and important links to complementary competence in a rapidly developing area.

Gaps: More support is needed for Quantum Information Processing activities, in particular quantum simulation which is less well represented in Sweden compared to internationally.

Methods

The survey

The survey was sent to and answered by 40 research groups within the field, located at seven different Swedish universities. The respondents were identified through a bibliometric analysis and the list of respondents was verified by experts in the field. The survey covered: group composition, research activities divided into subfields, important collaborations (national and international), necessary infrastructure (current and near-future), and training & education planned in the near future.

Bibliometric analysis

The search for Swedish researchers currently active in quantum technology research was performed using the Swedish Research Council's publication database (which is based on data from Clarivate Analytics and contains the same information as Web of Science). The search terms were identified with the help of field experts. The final analysis also included search terms used in the Finnish quantum technology strategy report. Relevant publications were identified by these specific keywords included in their title or abstract.

The publications included *articles* and *reviews* published in 2017-2021. No conference publications, preprints or similar were included.

Figure 1 shows how the Swedish share of the total international Quantum Technology publications is in accordance with the size of countries of comparable size. The high Swedish share of top 10 publications clearly indicates the visibility of Swedish research within the Quantum technology area.

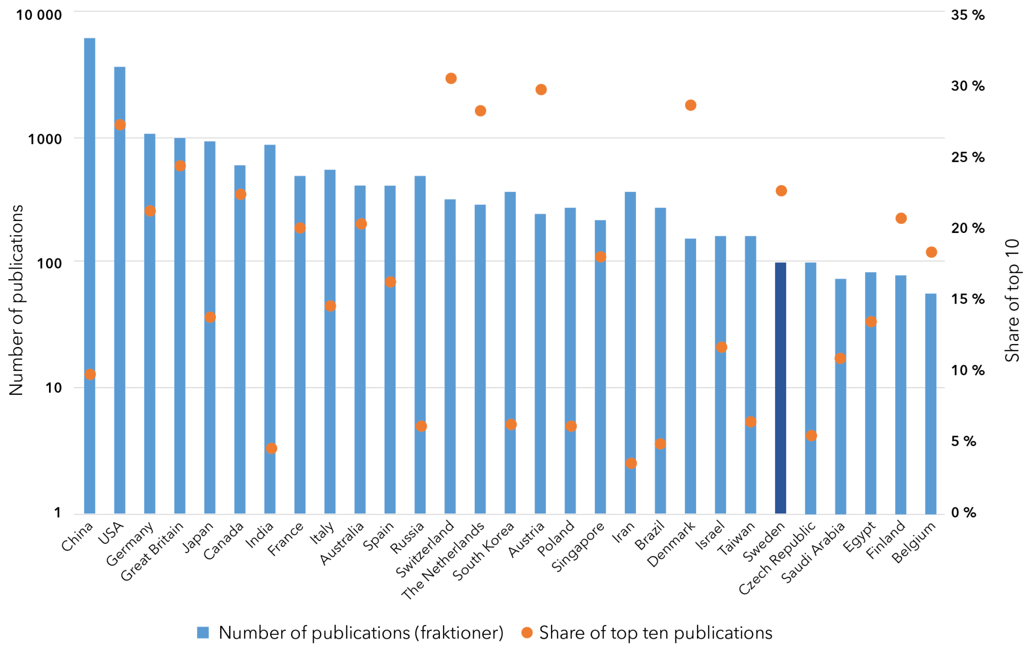


Figure 1. The 30 largest countries sorted by publication volume (fractioned). Number of publications and share of top 10 publications. By Andreas Krigh using Data from Web of Science, Clarivate Analytics.

Research group size and composition

The summary of survey responses on group size and composition can be found in Table 1. Please note that some responses are missing for LiU and KTH due to incomplete survey responses, so fewer researchers are listed for them.

Table 1: Number of senior researchers, postdocs, PhD students and other staff within the field of Quantum technology at Swedish University, as reported in the survey.

University	Senior researchers	Postdocs	PhD students	Other staff
CTH	25	20	48	5
GU	1	0	1	0
KTH	10	7	16	2
LiU	5	1	5	0
LU	12	16	24	3
SU	6	5	16	2
SU/Nordita	4	3	0	0
UU	1	1	1	4

Total	64	53	111	16

Many survey respondents find it difficult to recruit new staff with the right competence and background, especially postdocs, due to intense competition from international universities and industry.

Collaborations are key

Access to collaborators with complementary expertise, both national and international, is seen as essential by many respondents. Figure 2 shows a network map over which countries Swedish researchers within Quantum technology collaborates with. The figure is built from analysis of bibliometric material.

Collaborations could be facilitated by national and/or international research programs (such as QuantERA). Swedish strategy could be to support large-scale thematic projects involving a number of complementary groups. This could include e.g. organising a yearly Swedish conference gathering groups from all subfields of Quantum Technology, as well as workshops for the subfields.

Germany is somewhat of a role model here, with "Sonderforschungsbereiche" and recent huge national programs funding groups of academia and industry focusing on building quantum computers and creating algorithms for useful industry applications.

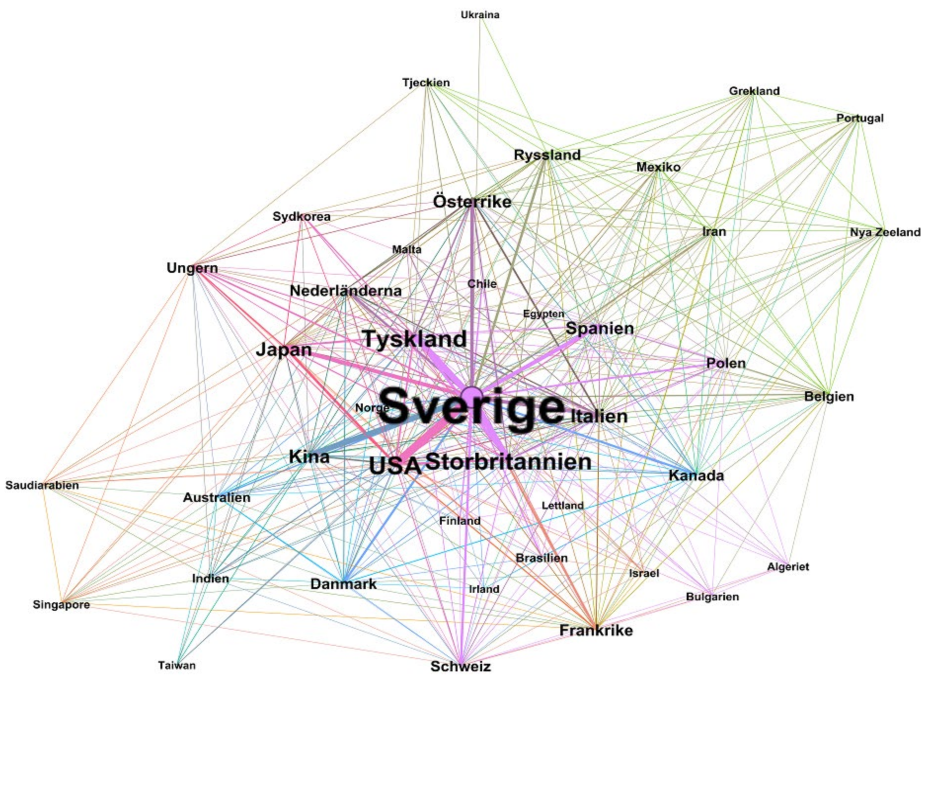


Figure 2. Collaboration network map for Swedish quantum researchers, based on publications from 2017- 2021. Node size scales with the number of publications. Distance and edge thickness indicate the degree of collaboration (authors). Data from Web of Science, Clarivate Analytics.

Descriptions of current activity for each subfield

In the survey and his report, for simplicity, the division into the four core application areas from the quantum manifesto is used. It should be noted that in a Swedish perspective, the division into four core application areas leads to fragmentation and misses many opportunities to promote constructive collaborations between the core areas. The present division of fields and topics is often artificial: quantum computation and simulation are closely related and should be treated as one field. The quantum advantage of near-future quantum computers might in fact be to simulate physical processes rather than performing digital algorithms. Quantum communication is based on interfaces using devices common with computing and simulation, and the role of quantum networks is to connect devices and platforms for information processing. Moreover, quantum devices for sensing and metrology are similar to the ones (qubits) used for computing, simulation and interfaces, and will be integrated in future with quantum processors for real quantum advantage. On top of this, the future of quantum information science depends on advanced materials science and semiconductor technology.

Table 2. Sweden: Organisations with more than 20 publications for the years 2017 – 2021. In numbers and fractions, Share of highest cited (top10) and indicator for international collaborations (field normalised indicator where 1 corresponds to the global average). The table also include number of publications divided by core. By Andreas Krigh using Data from Web of Science, Clarivate Analytics.

Organisation (Sweden)	Number of publications	Number frac-tiones	Number top10	Share in International Collaboration	Quantum Computing	Quantum Communi-cations	Quantum Sensing	Quantum simulation
CTH	66	27,8	31%	2,18	46	10	7	3
KTH	42	16,6	39%	1,91	16	22	2	2
SU	35	9,9	15%	3,39	16	11	5	3

LiU	31	11,6	17%	1,99	11	16	4	0
LU	24	11,3	12%	1,92	22	2	0	0
UU	23	9,8	7%	3,05	21	1	0	1

Quantum Communication (19/40 groups)

The work on quantum communication aims at creating local and global quantum networks for connecting quantum information processors, quantum memories and quantum sensors. It involves cryptography and secure digital transfers, and it requires technological development also of classical methods. It could have significant technological impact. It is also tightly connected to our understanding of the foundations of quantum mechanics.

Summary:

All of the group leaders in this survey are experts in the field and working in the international forefront. There is a very strong activity on quantum device technologies and cryptography among individual groups, but there seems to be a lack of a quantum communication community with overarching common goals. Such a common goal would be developing a national Swedish quantum internet as a testbed for research in quantum communication. Although Sweden formally joined EuroQCI in 2019, only recently could an active Swedish node be formed by Katia Gallo, KTH/WACQT to participate in the 2023-2025 EuroQCI project to build a European quantum internet. This collaboration needs stronger long-term Swedish support. In this context, strong support for quantum interfaces and repeaters is needed.

Strengths and weaknesses:

All of the groups in this survey are experts in the field and working in the international forefront.

Strengths:

- Quantum device technologies
- Cryptography

Weaknesses:

- Quantum networks
- Quantum interfaces
- The Swedish effort seems fragmented. Might profit from creating a common action plan or roadmap (not necessarily implying collaborations). This includes quantum cryptograhy.

Quantum Computing (29/40 groups)

Quantum computing has become a frontier of research. The prospects of developing quantum computing and taking it beyond its current limits has a manifold of possible applications. It contains both theoretical work, ranging from efficient algorithms to broadening the scope of applications, to technical and engineering aspects of building a quantum computer. Several different quantum systems constitute possible candidates for a quantum computer: superconducting platforms, ion traps, atom traps, semiconductor spins, photonic networks.

Moreover, several auxiliary topics are being developed in parallel to the mainstream efforts towards realizing a large-scale (multi-qubit) programmable device, aiming to reduce the required quantum communication resources, including the use of quantum machine learning for optimization of resources.

Summary:

Several of the group leaders in this survey are experts in the field and are working in the international forefront. There is very strong, well-supported, activities on superconducting quantum computers and ion traps within WACQT. There is also work on enabling technologies for photonic quantum processors, but, as it seems, no work so far on processing quantum information for computing. The photonics topic is strong internationally, at the focus of a Japanese "moonshot" program, as well as US-based SMEs like Xanadu and PsiQuantum. Regarding atom traps with optical lattices or tweezers, the survey mentions no experimental activity in Sweden. However, internationally this is a very important field, with potential for analogue-digital quantum computing.

Strengths and weaknesses:

All of the groups in this survey are experts in the field and working in the international forefront.

Strengths:

- Superconducting quantum computing
- Ion trap quantum computing
- Photonic devices

Weaknesses:

- Photonic quantum computing
- Atom traps (optical lattices, tweezers) for computing

Quantum Simulation (9/40 groups)

Closely related to quantum computing, quantum simulation is aimed at the successful use of quantum systems and quantum processor platforms for efficient simulation of other systems.

Summary:

The group leaders in this survey are experts working in the international forefront. There is no work so far by Swedish groups on photonic platforms (in contrast to photonic devices) for quantum simulation. Regarding atom traps with optical lattices or tweezers, the survey mentions no experimental activity in Sweden. However, internationally this is a very important field, expected to produce useful quantum advantage in the near term as quantum simulators, with potential also for analogue-digital computing. The French SME Pasqal is already providing prototype atom-trap simulators to customers. There is strong theoretical expertise at KTH, but no visible experimental activity at KTH or elsewhere in Sweden. It therefore seems that a Swedish strategy should be to support additional work on simulators based on photonics and atom traps.

Strengths and weaknesses:

All of the group leaders in this survey are experts working in the international forefront.

Strengths:

- Superconducting platforms for simulation
- Ion trap platform for simulation

- Photonic devices
- Strong atom-trap physics researcher at KTH

Weaknesses:

- Photonic platforms for quantum simulation
- Atom trap platforms (optical lattices, tweezers) for simulation
- There seems to be no experimental group working on atom traps, in contrast to high-priority international efforts.

Quantum Sensing & Metrology (20/40 groups)

The use of quantum systems for measurements is an important part under the umbrella of quantum technologies. The extreme sensitivity of qubits to noise is here an advantage. Quantum metrology aims at pushing the boundaries for our measurement capabilities.

The very special properties of ultra-cold atomic quantum gases, ranging from designable superfluidity to the highly controllable quantum states of Rydberg atoms, open unprecedented prospects for new quantum technology applications.

Summary:

The group leaders in this survey are experimental and theoretical experts working in the international forefront. The work on devices for quantum communication, computing and simulation is directly relevant for supersensitive measurement technologies, even beyond quantum limited (e.g. via squeezing). This field is closest to being able to turn quantum devices into commercial tools. Such activities exist or are under way.

Strengths and weaknesses:

All of the groups in this survey are experts working in the international forefront.

Strengths:

- A broad variety of experimental devices and tools
- Strong theoretical groups

- Existing industrial commercial applications
- Strong potential for commercial applications

Weaknesses:

- Possibly lack of exploitation of potential for commercial applications.

Other Quantum relevant research (24/40 groups)

There are other fields that fall under the umbrella of quantum technologies, closely connected to the areas previously mentioned: Foundations of quantum mechanics; Quantum transport; Quantum/ nano thermodynamics: energy conversion at the nanoscale. Special and general relativistic effects in quantum systems. Semiconductor device technology. Laser technology. Materials science.

Summary:

The group leaders in this survey are experimental and theoretical experts working in the international forefront. There is a wide variety of basic science underlying the basic topics of computing etc., often providing an essential foundation for further progress.

Strengths and weaknesses:

All of the groups in this survey are experts working in the international forefront. Predominantly theory groups.

Strengths:

- Strong theoretical and experimental groups
- Strong background for more applied work.

Future needs

Future facility needs

A central message emerging from the present survey is that national and local cleanrooms need to be upgraded and expanded in order to be able to meet current and future needs and competition to develop devices and systems for quantum information science and technology.

The development of Myfab during the last 20 years, from a collection of local nanofabrication cleanrooms to a national facility, has been groundbreaking and decisive for Sweden's present great expertise and performance in a global perspective. However, despite constant upgrading of tools and facilities, the extremely rapid development of quantum technologies (QT) is currently putting great demands on procuring new state-of-the-art tools and upgrading old tools.

The requests for upgrading cleanrooms and local labs span over the entire QT field. In preparation for a Swedish national QT strategy and funding, it might be useful to extend the present survey to investigating the concrete needs/requests of Swedish groups for tools and facilities.

The access to computational power needs to be strengthened in Sweden, as well as to EuroHPC computational resources (e.g. LUMI in Finland).

Discussion

For the purpose of getting an overview of the field of quantum technologies within the Swedish research landscape, Swedish Research Council has performed a bibliometric study in conjunction with a survey to the relevant Swedish research community. For the latter purpose, a questionnaire was sent to 40 groups in the field, of which 40 responded. Sweden has a strong and active research base in the field of quantum technologies, and it can be expected to further growth over the coming years. The current data show that the fields engage researchers from a wide geographical and topical spread, and their international collaborative ties are highly active, contributing to Swedish research in a competitive international context. The collected material gives a base from which conclusions can be drawn, with possible strategic consequences.

When it comes to facilities, it was found that in order to consolidate the field, and to see further progress in an international context, local and national cleanrooms need to be upgraded and expanded to meet the needs in the field. Such investments could benefit users also outside the field of quantum technologies. This is also true for computational facilities, where efforts are already on the way, but further focus may be needed (e.g. through EuroHPC resources).

If the field of quantum technology is to be put on a solid footing within the Swedish research community, further investments into young researchers' careers would be an important part of such strategies. Closely tied to this is further need for educational efforts in the field, in order to build a base for recruitment both at universities and for industry.

The need to foster strong collaborative ties within the community of quantum technologies can be identified. This includes collaboration between research groups at universities, industry partners, and international actors.

Quantum simulation is a field which is projected to increase in importance, but where the Swedish efforts are few in an international comparison. It would be strategic to strengthen this field to keep a sound basis for future research.

Summary

The main findings of the report are:

- Facilities: National and local cleanrooms need to be upgraded and expanded in order to be able to meet current and future needs to develop devices and systems for QIP.
- Facilities: Access to computational power needs to be strengthened in Sweden, as well as to EuroHPC computational resources (e.g. LUMI in Finland).
- Staffing: More funding is needed to increase the number of PhDs, Postdocs and Assistant Professors.
- Education: More Master's programs (MSc) are needed in quantum engineering.
- Collaboration/competence: National and international collaborations are seen as essential for current and future research activities and important links to complementary competence in a rapidly developing area.
- Gaps: More support is needed for Quantum Information Processing activities, in particular quantum simulation which is less well represented in Sweden compared to internationally.

Appendix 7

Agenda working group

This agenda is a joint effort between a broad network of experts and stakeholders in the quantum technology field. Ten workshops have been held as a preparation for writing the agenda.

Participants and main contributors:

Name	Organisation
Tove Jaensson	Vinnova
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Göran L Johansson	WACQT
Lena Gustafsson	WACQT
Johan Veiga Benesch	WACQT
Ingela Roos	WACQT
Tomas Andersson	VR
Mattias Marklund	VR
Elizabeth Sandström Greenfield	PTS
Göran Wendin	WACQT
Hanifeh Khayyeri	RISE
Daniel Ekström	ADC
Malin Sandström	VR
Magnus Friberg	VR
Pontus de Laval	WACQT/KAW
Raoul Stubbe	
Katia Gallo	WACQT
Johanna Dahlin	Vinnova
Lars Hammarström	Vinnova
Cristian Jonsson	Vinnova