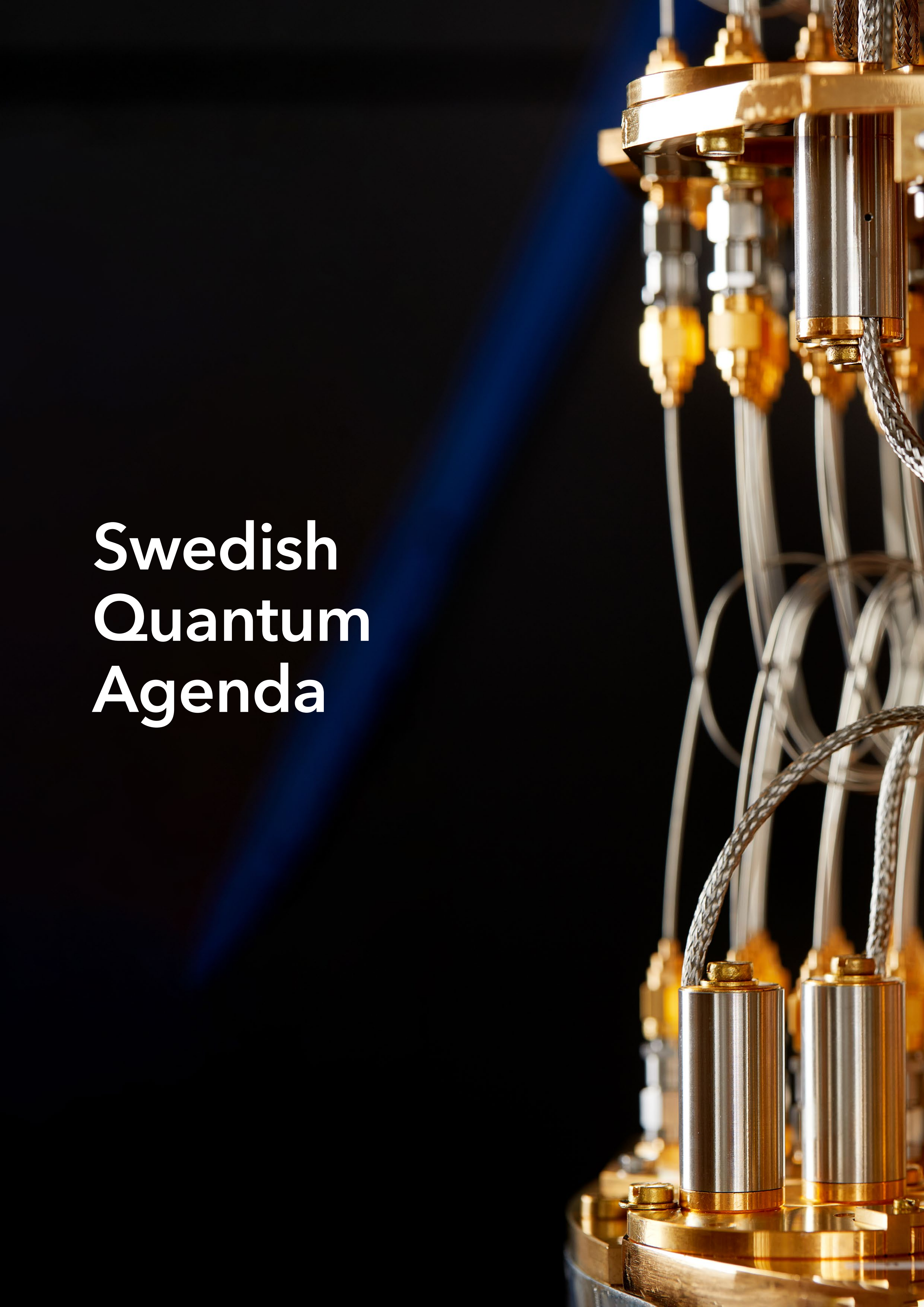
# Swedish Quantum Agenda



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# Content



# Appendices



All appendices are available at www.vinnova.se.

# 1 Executive summary

A technological revolution – the second quantum revolution – is underway, with quantum computers, intercept-proof communication, and ultra-sensitive measurements. In countries all over the world, quantum technology is seen as a key technology for future security, computing power, and sensors, affecting large parts of society. Sweden has strong research in quantum technology, much thanks to private funding, but now national coordination and investments are needed to maximize the benefits of this emerging area of technology.

Quantum technology is based on quantum mechanics – the physics that describes the world at its smallest scale. The revolutionary novelty lies in the relatively new ability to control and manipulate individual quantum systems, such as single atoms and particles of light. This ability opens the door to brand new technology with extraordinary capabilities.

Quantum technology is a new and disruptive technology that both creates new and improves existing applications. It aims to harness quantum mechanical phenomena, such as superposition, squeezing, and entanglement to do things that are otherwise impossible. Quantum technology has the potential to affect many areas of society, such as information technology, health, energy systems, finance, and defense. Generally, it is divided into four subfields: quantum computers, quantum simulators, quantum communication, and quantum sensors.

The quantum computer is a good example of the new technology. A sufficiently large quantum computer can solve problems that are out of reach for conventional computers. The development of quantum computers is fast, and we are currently at a stage where it becomes difficult and soon impossible to simulate quantum computers on existing supercomputers. In Sweden we will in 2025 get access to a testbed for quantum computing, where algorithms can be run on a real quantum computer, financed by Knut and Alice Wallenberg foundation (KAW). This will allow Swedish researchers and industry to examine a wide range of applications, which makes it possible to start realizing the potential of this new technology.

To stay at the forefront of this new emerging technology, Sweden needs to secure competence in quantum technology, through high-quality undergraduate and graduate education as well as training and skills development within both industry and society. The benefits of quantum technology could potentially have a significant impact on economy and society, which is why Sweden must become an active player in this rapid international development. Today, KAW finances the only major quantum technology venture in Sweden, though other funding agencies have recently launched a few smaller programs.

To take advantage of the opportunities that quantum technology brings in Sweden, coherent national objectives and a well-funded national quantum strategy are needed.

## 1.1 Quantum technology research investments internationally and in Sweden

There are presently large investments in quantum technology all over the world. The EU's ten-year €1 billion flagship investment started in October 2018. Several European countries including Germany (€2.6 billion), France (€1.8 billion), the Netherlands (€0.76 billion), and the United Kingdom (1 billion €), have made extensive national investments that are substantially larger than the EU investment. Similar large research programs exist in North America, Asia, and Australia. IT companies such as Google, IBM, Intel, and Microsoft are also making significant investments into quantum computing.

Within Sweden, there is strong research in quantum technology. The quality of the research is confirmed by the fact that the US has selected Sweden as one of eleven partner countries in quantum technology. The KAW Foundation has allocated approximately SEK 1.2 billion in the Wallenberg Centre for Quantum Technology (WACQT), Swedish universities (mainly Chalmers, KTH, Stockholm University and Lund University) and industry partners contribute another approximately SEK 300 million. About ten Swedish companies are involved in the research via industrial doctoral students. WACQT is a 12-year venture that started in January 2018 and has two main goals: i) To raise both the general knowledge and the more specialized level of competence in quantum technology in Sweden and ii) to build a Swedish quantum computer. Other initiatives include the Wallenberg Initiative on Networks and Quantum Information (WINQ) at Nordita, the Nordic Institute for Theoretical Physics and the Quantum Life Science Centre, based at Karolinska Institutet.

In addition, KAW and other funding agencies also support several quantum technology researchers via their individual grants. Swedish research in quantum technology is therefore strong, however the funding is mainly private and for a limited time. The equivalent billion-SEK investment does not exist when it comes to education and innovation.

## 1.2 Conclusions

This report has identified nine areas that are necessary to develop to strengthen Sweden's position within quantum technology:

- Need for a Swedish national objective and strategy for quantum technology
- Coordination of quantum technology activities is necessary
- Increased support for education in quantum technology
- Need for support to research infrastructures
- Ensured long-term financial support for quantum research
- Need for strengthened quantum innovation
- Identification of applications and engagement with industry
- Quantum standards at the international level
- Fostering of Nordic, EU, and international collaboration

These conclusions are further elaborated in Section 10.

# 2 Introduction – Why quantum technology?

Currently, global warming forces us to change how we produce and use energy. We have just come out of a pandemic, to find ourselves in a geopolitical situation, more unstable than in decades. At the same time, digitalization is continuing to change the way we organize our society and how we live our lives. In this context, why should we put quantum technology (QT) on the agenda?

One reason is that quantum technology has the potential to significantly influence our society, through qualitatively new computational capabilities. This could in the long run e.g., facilitate the transition to a smart energy grid, as well as reduce the energy needed in the transport sector through logistics optimization, and lead to novel energy efficient ways to produce fertilizers. However, these computational capabilities will also have impact on security since they threaten currently used protocols for secure communication.

In life science, we can foresee better models and understanding of complex biologically active molecules and protein folding as well as improved medical image recognition and metagenomic analysis. The technology, that as mentioned has the potential to give us qualitatively new computational resources, will also enable improved measurement and sensing applications in the near future. This includes less invasive medical diagnostics tools, but also detection of minerals underground through small changes in gravity, as well as improved systems for navigation where GPS is unavailable.

Since quantum technology has the potential to significantly influence many aspects of society, many countries have recently launched significant national initiatives, including Germany (2.6 b€), France (1.8 b€), the Netherlands (0.76 b€), Great Britain (1 b€) and EU has launched a quantum technology flagship program (1 b€). Similar programs have started in North America, Asia, and Australia. Companies like IBM, Google, Microsoft, Intel, Alibaba, Tencent, and Honeywell are investing considerable resources in R&D and there are also several fast-growing start-up companies in the US, but also in Europe, mentioning e.g., IQM in Finland, founded in 2018 and now employing 150+ staff. In Sweden, Knut and Alice Wallenberg foundation took the initiative to the Wallenberg Center for Quantum Technology (WACQT), a SEK 1.5 billion 12-year effort which also started in 2018. In 2022, the Novo Nordisk foundation in Denmark launched their Quantum Computing Program with a funding of DKK 1.5 billion for the first seven years. NATO also announced an innovation accelerator for quantum technology to be placed in Copenhagen.

WACQT has enabled Sweden to be an active player in the global quantum technology community. For example, Sweden is (together with Denmark and Finland) among the eleven countries which has signed a bilateral agreement with the US on research and development in quantum technology. From this very positive starting point, we see a clear need for a national Swedish strategy on quantum technology, not the least for the long-term goal of creating a sustainable society.

# 3 What is quantum technology?

The quantum world – at the scale of atoms and below – is paradoxical and bizarre. Particles appear to simultaneously be both here and there, or mysteriously entangled at a distance. Quantum technology is about harnessing these strange phenomena to create brand new technology with extraordinary capabilities.

Quantum mechanics emerged in the early 1900s to describe nature at the smallest scales. In the 1930s, the mathematical formulation of quantum mechanics was essentially complete and the new understanding of quantum properties of light and materials led to the invention of the laser and the transistor – inventions that form the basis of today's information technology. Computers, the internet, and smartphones have drastically changed our lives. Today, we refer to this as he first quantum revolution.

However, it was long regarded as impossible to control individual quantum systems such as single atoms, electrons, or light particles (photons). But in the 1980s, scientists managed to develop methods for measuring and controlling individual atoms and photons, work which was awarded the Nobel Prize in 2012. In parallel, other researchers developed electrical components in which they could manipulate single electrons.

The abilities to exploit the properties of individual quantum systems open the door to brand new technology. It is not about incremental change but really a game changer – a second quantum revolution.

## 3.1 Phenomena at the heart of quantum technology

The extraordinary capabilities of emerging quantum technologies are all based on the counter-intuitive phenomena of quantum mechanics. The most important are:

### Superposition

In the world of quantum mechanics, it is fully possible for particles to be in many different places at once, or to simultaneously be in states that for example have different energy or different polarization. These ambiguous states are called superpositions.

### Entanglement

Superpositions can extend between several particles, a special type is called entanglement. A manipulation of one particle affects its entangled partner immediately – even if they are vastly far apart, and without any transfer of information.

### Squeezed states

In quantum physics, there is a limit to how accurately you can simultaneously know coupled (conjugated) variables, such as frequency and time, for an object. But by manipulating the object into a so-called squeezed state, one can have the uncertainty to primarily affect just one of the variables. The other variable can then be measured more accurately.

## 3.2 The four areas of quantum technology

Quantum technology is often grouped into four main areas: quantum computing, quantum simulation, quantum communication, and quantum sensing. Read more about them in Appendix 1.

### What is quantum technology good for? – based on the technology:

i. Quantum computers have the potential to perform calculations that a classical computer cannot, including solving difficult optimization problems, for example in logistics, DNA sequencing and machine learning. A large quantum computer can also crack encryption codes that a classical computer cannot.

ii. Quantum simulations of complex molecules could help us develop new drugs, or catalysts. It could also help us design new materials. A concrete example where quantum simulations are used is to improve the production process of fertilizers, which today consumes enormous amounts of energy.

iii. Quantum communication uses entangled states to send messages that cannot be eavesdropped. In the longer perspective, a new internet built for quantum information, a quantum internet, is being discussed. But in the shorter term, the technology is interesting for secure sharing of data in for example health and security sectors.

iv. Quantum sensors can enable significantly more accurate measurements. Better atomic clocks used in GPS are one example, sensors for medical diagnostics are another.

## 3.3 Relation to machine learning and AI

Machine learning could be defined as algorithms that improve the more data they get access to. Artificial intelligence (AI) includes algorithms performing tasks as varied as driving cars, facial and speech recognition, beating human players in chess or creating long texts or images from simple text input. The recent success of these algorithms, often based on mathematical modelling of neural networks which have been known for decades, is based on the access to huge datasets as well as unpreceded computational power.

One question is how a quantum computer, with its qualitatively new computational power, can improve machine learning and AI. There are quantum algorithms that can solve linear algebra calculations, being at the heart of machine learning, exponentially faster than classical algorithms. However, they rely on the data already being present in the quantum computer. This is a very serious limitation since no one presently knows how to input large amounts of data into a quantum computer. This gravely limits the potential impact of also a future large fault tolerant quantum computer on machine learning. There are interesting ideas of how to use a quantum computer for specific tasks in e.g., pattern recognition using so-called quantum kernels, but there is currently no hope that a quantum computer would significantly reduce the classical computations needed in this field

# 4 What can quantum technology do for society and industry

Quantum technologies have the potential to benefit society and almost all industries. Some of the most promising application areas are health and life sciences, energy, finance, and cybersecurity. These industries stand to benefit from quantum technologies due to the exponential increase in computational power and secure communication capabilities. Below we give concrete examples of what we could hope for in the future.

In healthcare and life sciences, quantum technologies can play a transformative role in advancing precision health and precision medicine. Applications such as quantum microscopy, quantum spectroscopy, and quantum computing can improve disease prediction, prevention, diagnosis, and treatment. For example, quantum microscopy can enhance eye imaging, quantum spectroscopy can monitor tissue oxygenation in the heart and brain, and quantum computing can aid in understanding diseases such as Alzheimer's, Parkinson's, and ALS, as well as accelerate drug development.

> “We have eight projects within quantum life science, ranging from quantum computing in metagenomics, protein folding and chemistry, to quantum microscopy and spectroscopy for higher resolution in the eye and brain. Healthcare and life sciences cannot miss out on the opportunities that quantum technologies can give us and therefore we have started a Swedish Quantum Life Science Centre to accelerate the development and create an attractive ecosystem for our research, innovation, and our companies.”
>
> Ann-Marie Wennberg Larkö
> Professor and Hospital Director Sahlgrenska University Hospital

## 4.1 Examples of applications

### Oxygenation in the heart and brain

A research team in Lund investigates how quantum structures that reduce the speed of light to a few tens of kilometers per second can be used for enabling optical imaging deep inside the body. Specifically, they aim at measuring oxygenation in the front cardiac wall and in the brain, which would be very helpful when diagnosing stroke. If the project turns out well, every accident and emergency department would benefit from having such an instrument. Therefore, the researchers have founded a start-up company – Deep Light Vision AB – with the goal of developing a commercial oxygenation measurement instrument.

### Live imaging of biological processes

Quantum microscopy holds the potential for better performance than traditional microscopy techniques, as it can achieve higher spatial resolution, enhanced imaging depth, and wider wavelength operation. The Royal Institute of Technology (KTH) has developed a quantum microscope that can perform in-vivo imaging at the single-photon level, using innovative infrared biomarkers. This technology will be available to the market through the spinoff company, Quantum Scopes. Karolinska Institutet (KI) has developed a platform for using the eye as a body window to study the function of implanted tissues, non-invasively. Quantum microscopy, by KTH and KI together, will permit imaging deeper in the tissue and therefore provide more detailed information to fill important knowledge gaps.

## Simulating pharmaceuticals

In pharmaceutical research, quantum chemical calculations on classical high-performance computers (HPC) are used to predict reactivity and properties of drug molecules to inform the design of new molecules, and in the selection of drug candidates. To be able to simulate chemical reactions and to accurately predict properties, the molecule of interest needs to experience the influence of the surrounding environment in solution or in the solid state. This is a difficult computational problem which is hard and time consuming for classical HPC. The screening process of drugs can therefore be very time consuming and expensive, and here is a chance for quantum computers to make substantial difference.

> "AstraZeneca is closely following the development of AI, machine learning, and quantum computing to understand how it affects our abilities to discover and develop new medicines and treatments. We investigate the possibilities of quantum computing, for example, through collaboration with IBM and the Hartree Center in the UK, but above all through our industrial PhD project and partnership with WACQT, which we plan to expand with an industrial postdoc."
>
> Anders Broo, PhD
> Executive Director, Head of Data Science and Modelling, Pharmaceutical Sciences, R&D
> Astra Zeneca

## Protein folding and metagenomics

DNA sequencing has revolutionized our understanding of biology and medicine and is paving the way towards future precision medicine. There are many computational challenges involved in transforming this ever-increasing amount of data into improved health in our society. Understanding how mutations affect protein folding in our cells is a genuinely hard computational problem. The machine learning based AlphaFold gives part of the answer, but we still need to understand more about folding dynamics in living cells, which is important e.g., for Alzheimer's disease. Here, quantum computers have the potential to qualitatively change the simulation capabilities in the future. In metagenomics, DNA sequences should be matched to identify different bacteria and viruses in e.g., blood samples. Here, read errors both in the sample sequences as well as in the database implies that this matching has a fuzzy nature. This could be an area where a quantum computer would be able to give better performance than classical computers.

## Energy savings

Once really large molecules can be simulated, one can imagine solving the nitrogen fixation problem in a much more energy efficient way. Today, large amounts of energy (several percent of the world's energy production) are used to make ammonia, which in turn is used to make fertilizers. This is done using the so-called Haber Bosch process which is very energy inefficient since it uses high pressure and high temperatures. At the same time, we know that bacteria can do the same thing at room temperature using an enzyme. If we can simulate and imitate the active part of this enzyme, we could potentially develop a much more efficient process and save a lot of energy.

## Cybersecurity

The currently used encryption algorithms rely on the inefficiency of classical computers to solve the functions required to decrypt the secure data. While they are astronomically hard to solve in classical implementations, a quantum computer equipped with the right algorithm can break the encryption with relative ease. This has motivated multiple European initiatives to quickly assemble quantum cryptographic communication channels where fiber-optic networks will be used to securely communicate sensitive information between and inside of national borders. Additionally, satellite networks will be put in place to connect local fiber networks to the global web - something that requires considerable national effort to initiate.

## Quantum key distribution

Encryption relies on so-called encryption keys used to encrypt and decrypt information. The problem is generally to transfer the key without an adversary getting hold of it. In quantum communication, this is solved by transferring the encryption key using quantum particles. This is called Quantum Key Distribution (QKD). According to the laws of quantum physics, it is impossible to measure or copy a state of a quantum particle without noticeably changing it. Therefore, one can always be sure to detect interception. Commercial systems for QKD are already available on the market.

## Supply chain and logistics

In logistics, finding the most efficient solution for routing e.g., airplanes or electric/hybrid trucks, simultaneously fulfilling all constraints of finite loading capacity and finite distance before recharging, leads to hard optimization problems. The number of possible solutions grows extremely fast with the number of vehicles and destinations. These so-called combinatorial optimization problems are straightforward to map to quantum computers and if the quantum computer can find more optimal solutions, we will use less resources and experience less delay and congestion in both air and road traffic. Supply chain optimization leads to similar types of combinatorial optimization problems and finding better solutions could significantly improve the production efficiency in many companies.

> "Jeppesen finds it extremely important to closely follow the developments within quantum computing worldwide and in particular those for optimization. Since in Sweden our core business is logistics optimization, it is essential for us to know if and when a quantum computer can contribute to significantly better solutions. To this end, our partnership and industrial PhD project together with WACQT is a key component and we will certainly benefit from the upcoming Swedish testbed for quantum computing."
>
> Dr Peter Sutton,
> Director for Software Development, Jeppesen Sweden

## Quantum meteorology

Accurate models of weather or climate systems, and predictions based on them, require large vast of classical computational power. Especially for making those predictions accurate in the long-term. This is because weather phenomena are chaotic and non-linear in nature – their current state determines their future, but the approximately current state does not approximately determine the future. The models used typically involve many input variables, and it is a big challenge to find extreme points in a space of such large dimensionality – a space where quantum computers can provide a benefit. A relatively small set of qubits can be used to represent information of large dimensionality, whereas the classical counterpart is limited.

# 4.2 Quantum technology– humanities and society

As discussed above, quantum technology has a very large development potential in many areas of big importance for business and public activities, such as healthcare.

The emerging technologies thus have the potential to change people's everyday lives and society at large.

Consequently, we cannot even imagine today what kind of technological and societal developments and challenges that lie ahead. At the same time as we see fantastic opportunities, we cannot ignore possible negative consequences that quantum technology enables. We therefore have a responsibility to learn about potential risks in parallel with the development we seek within all possible areas. Although there are already functioning laws and regulations today, which of course also include handling various issues in the quantum technology area, we certainly also need to further develop the regulations. To be able to do that, a growing level of knowledge and competence is needed not only among scientists and students, but also among the public, public authorities as well as todays and tomorrow's politicians.

One of the sharpest tools for managing risks, including ethical issues, is increased levels of knowledge. From this follows that we need supplementary education on all levels. It includes education in quantum technology in schools, from primary school upwards, but also as part of lifelong learning and tailored education in both the public sector and business. It should also include ethical, legal, social sustainability and cultural issues. To be a country at the forefront of taking advantage of the opportunities offered and at the same time managing risks, a high level of knowledge is a necessity. This is achieved through research hand in hand with education at all levels, as well as implementation in various sectors.

# 5 The state of Swedish research in quantum technology

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 – Figure 1 shows how Sweden compares to other countries regarding scientific publications – that is 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.

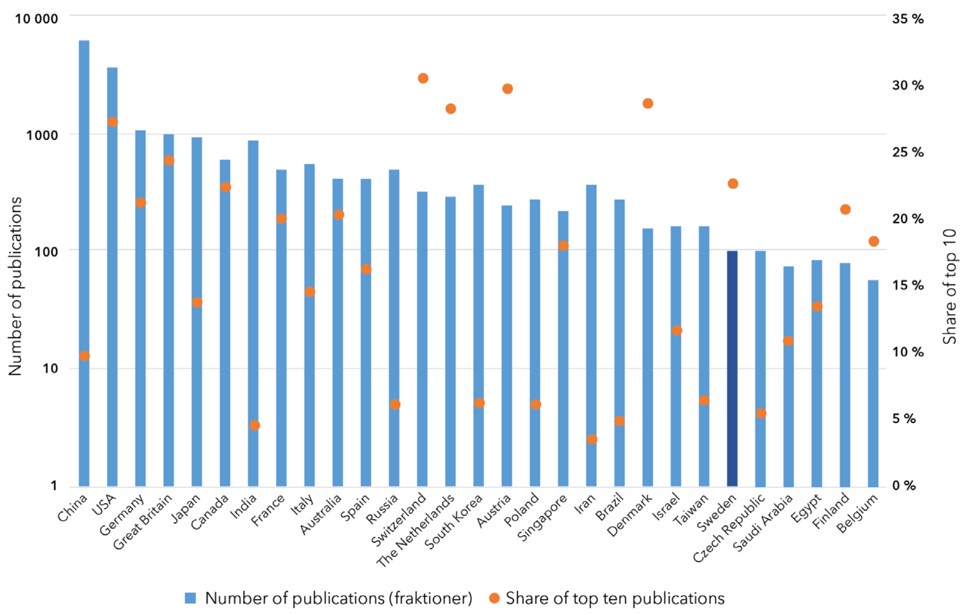
When it comes to facilities, it was found that in order to consolidate the field, and to see further progress in an international context, local and national cleanrooms need to be upgraded and expanded to meet the needs in the field. Such investments could benefit users also outside the field of quantum 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.

**Figure 1. Quantum technology 2017–2021**




The

30 largest countries in quantum technology, sorted after the number of scientific publications (blue bars). The orange dots show the share of top-ten publications for each country. Data from Web of Science, Clarivate Analytics.

# 6 Education and competence in quantum technology

If Sweden is to be able to take advantage of the opportunities in the quantum area, but also parry the risks that may arise, then an increased level of competence for several different groups of people in society is necessary. Many countries have become painfully aware of the fierce competition for skilled labor in the quantum technology area. If Sweden is to succeed in developing a viable ecosystem in the field, a targeted investment in education in the field is absolutely necessary.

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. But to achieve this, we as a country and our universities must offer attractive conditions to both succeed in recruiting and retaining young talents.

Training PhD students and postdocs 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 give a larger number of engineers and not the least future decision makers the necessary understanding to be able to see and adopt the new opportunities arising.

To pave the way for a good and healthy reception of quantum technology by the public and thereby increase the possibilities for a powerful and sustainable development of society, the general understanding of quantum technology needs to be promoted. Once the interest is aroused, the introduction of new findings in various fields is facilitated, as well as healthy criticism and suspicion from a more enlightened public can promote a positive development in the quantum technology field.

Different tools can be developed to achieve this, but here, of course, the media plays an important role. In turn, this points to the need for an increased level of competence within quantum technology also within the journalistic profession.

# 7 What are other countries doing?

Figure 2 shows the global investments in quantum technology, reflecting the increasing interest and funding from governments in the world. With quantum computing, quantum sensing, and quantum communication expected to bring transformative impacts on various fields, countries are positioning themselves to be leaders in the second quantum revolution. The investments demonstrate the growing importance of quantum technologies in shaping the future of innovation and competitiveness.

The countries' different objectives testify to the breadth of the quantum technology area, which is expected to yield returns in a broad area of applications. This also indicates the expected breadth of the impact on different sectors of society. To give a hint of already ongoing initiatives, we highlight here a few examples from various national approaches.

Among our Nordic neighbors, both Finland and Denmark are strong nations in the field of quantum technology. Finland considers itself to have developed a strong quantum ecosystem that is internationally recognized and competitive. From Finland, it is emphasized that the potential strength of the second quantum revolution is so powerful that it thus constitutes important elements in national security and self-sufficiency. Consequently, there is an identified need for systematic and coordinated collaboration.

Even Denmark acts from the standpoint that quantum technology will permeate society. Denmark has for many years made significant investments in basic research and research infrastructure in the field. However, as the field is now rapidly moving from fundamental aspects to applications, further investment in innovation is now considered necessary.

France, Germany, and the Netherlands are investing government money into quantum technologies because they recognize the potential for these technologies to transform various industries, such as finance, healthcare, and telecommunications. For example, Germany aims to use quantum technologies to enhance security and privacy in communication networks, while France is investing in quantum computing to develop new materials and optimize supply chains.

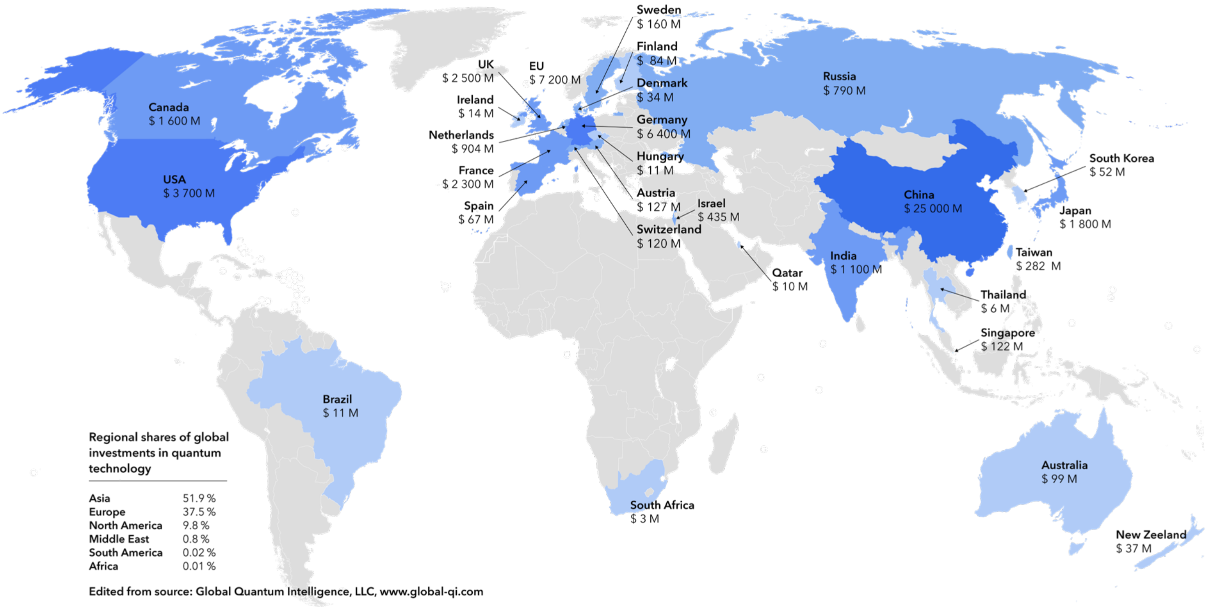
The Netherlands is investing in quantum technologies to create new applications for quantum sensors in fields such as healthcare and agriculture. Overall, these countries hope to gain a competitive advantage in the global race towards quantum technologies and to position themselves as leaders in the field.

If we move across the Atlantic, we find major investments and prominent countries within the field of quantum technology. The investments in quantum technology and research in Canada over several decades makes the country a global leader in the field. But Canada identifies in its national strategy that it must continue to invest and innovate to stay ahead.

USA is, as always, a major power in this type of development and there are large investments both from the government and industry. The government has launched a National Quantum Initiative with five major research centers. On the corporate side, large companies such as Google, IBM, and others are investing heavily in developing quantum computers. The USA has also taken the initiative for bilateral agreements with eleven other countries (including Sweden) and thus created a consortium of like-minded states with strong research in the field.

## 7.1 Quantum initiatives all over the world

**Figure 2. Map of investments in quantum technology until 2022 in millions USD**




# 8 Innovation and commercialization

Quantum technology holds immense potential in several fields, including communication, cryptography, health and life science, and materials science. However, for its technical achievements to benefit society and the economy, a strong focus on commercialization and innovation is required.

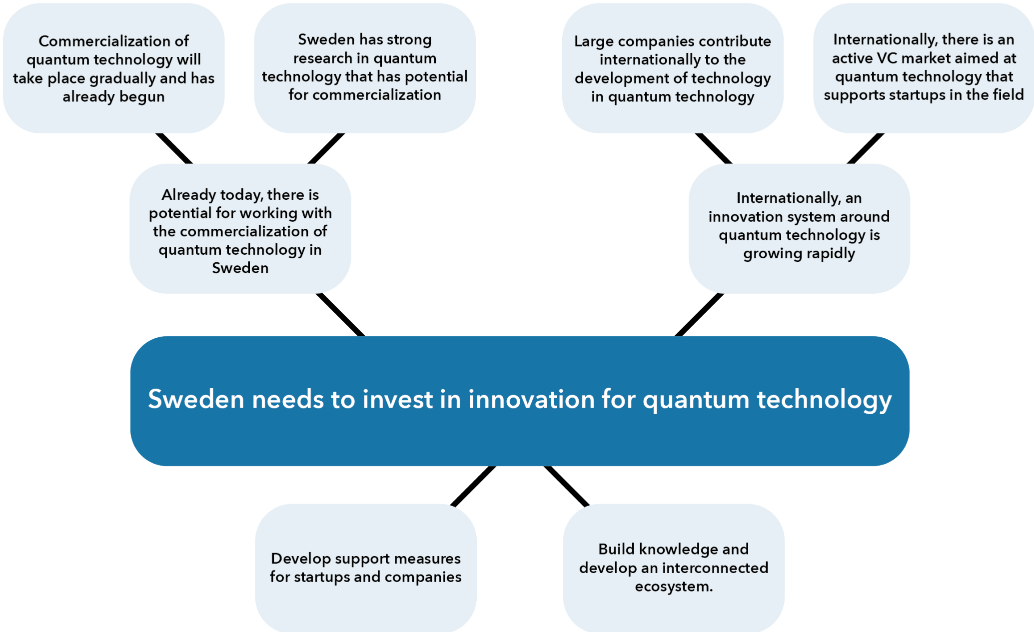
Although quantum technology is still in its early stages of development, there are compelling reasons for establishing a national ecosystem for innovation and commercialization of the technology. Established companies and start-ups are already playing a significant role in the development of quantum technology, alongside academia, and international technology giants are investing heavily.

Sweden has a strong research base in quantum technology and shows distinct areas of strength, not the least linked to the available competence in quantum computers. However, to translate this strong research into societal and economic benefits, it is crucial that the ecosystem is developed with a focus on innovation. This requires support for start-ups and established companies, as well as researchers who wish to commercialize their technologies or ideas, enabling technology transfers from basic research to commercialization. Sweden must develop an innovation ecosystem that includes a wide range of actors to capitalize on its strengths in quantum technology. Commercialization of the technology will be gradual, and although major breakthroughs are yet to come, technical solutions that have reached a high level of technology maturity and have been successfully commercialized already exist.

In conclusion, developing an innovation ecosystem that focuses on commercialization and innovation is crucial for Sweden's long-term competitiveness in the field of quantum technology. Sweden has the potential to become a leader in this field with support for start-ups, established companies, and researchers. Figure 3 describes Sweden's conditions for quantum innovation. The following measures are of the highest priority:

- Support to start-ups in the form of financial as well as non-financial support.
- Support for established companies to identify, together with universities, applications for quantum technology.
- Support for researchers who want to commercialize a technology or idea.
- Continuous knowledge building for increased understanding and development of an interconnected innovation ecosystem.

Figure 3. Why Sweden needs to invest in innovation for quantum technology




# 9 Standardization

Sweden should participate in the standardization and policy- and regulation activities in the area. Quantum technology is young but would already benefit from standardization. Standards and frameworks enable actors to use and join a common way of development in the field, and can provide large benefits for the success of various companies. It is a way of increasing interoperability that can also lead to cost-effectiveness in the implementation itself. A high degree of international cooperation and joint projects are other ways of creating a kind of informal standardization.

Many standardization forums and regulations are relevant to quantum technology, depending on the application and perspective. However, it is important to also consider the overarching initiatives that exist within the EU regarding a common approach to knowledge security so that we work for continued free research in areas such as quantum technology regarding products, technology, and solutions that can come to both civil and military use, the so-called dual use perspective.

# 10 Conclusions

To harness the potential of quantum technology and to bring Sweden to the forefront of quantum technology, the following development areas are identified.

## Need for a Swedish national objective and strategy for quantum technology

Sweden needs to formulate its ambition within the quantum technology area and develop a national 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.

## Coordination of quantum technology activities is necessary

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

## Increased support for education in quantum technology

Today, quantum physics is taught at most Swedish universities, while there is little education in quantum technology. The engineering aspect is largely missing. 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.

## Need for support to research infrastructure

Components for quantum computers are manufactured by nano and microfabrication, typically in cleanrooms that host advanced process and analysis equipment. Sweden has several high-class cleanrooms in the Myfab network. Maintaining and improving these cleanrooms would support both the emerging quantum technologies and Sweden's ability to develop and produce semiconductor chips. In recent years the funding for new equipment in Swedish cleanrooms has declined and there is a risk that Sweden loses its leading position. Long term funding for the quantum computing testbed is also of high priority.

While Sweden showcases 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.

## Ensured 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. It is important to guarantee a long-term and sufficient funding, in line with the stated ambition to support leading quantum research beyond the end of the WACQT program (2029). Funding opportunities should be sufficient to cover the broader focus of quantum research including all four areas: quantum computing, quantum simulation, quantum sensing, and quantum communication.

## Need for strengthened quantum innovation

To exploit the research results and convert them into innovations, products, and companies there is a need for a coordinated innovation program in quantum technology. Vinnova has recently launched a few programs to support innovation, however these are small programs which are very limited compared to the research efforts. KAW can only support research at the universities. Moving ahead, research funding should to a higher degree focus on applications for quantum technology. Such investments serve several purposes including supporting commercialization and allowing more actors to engage in the quantum ecosystem.

## Identification of applications and engagement with industry

Sweden needs to prioritize the collaboration between industry and academia in the identification of quantum applications and increase industry engagement in quantum technology. By fostering industry-academia collaboration and increasing industry engagement, the development and commercialization of quantum technology can be supported.

## Quantum standards at the international level

Quantum technology is still young but would already now benefit from standardization. Sweden should join other countries to agree on standards for quantum technologies. For example, standardized protocols for quantum communication and benchmarking standards for quantum computers.

## Fostering of Nordic, EU and international collaboration

Sweden should actively develop international collaboration in the quantum technology field while also developing cooperation with ambitions on Nordic, European, as well as global levels.

The Nordic countries, in particular Denmark, Finland, and Sweden have a strong research tradition in quantum technology. Presently there are two important Nordic organizations in this area: "Nordic Quantum" and "Nordic Quantum Life Science". Together the Nordic countries become a strong international player.

Sweden should also strengthen and coordinate its involvement in quantum technology activities at the EU level, such as the EU Quantum Flagship, EuroQCI, EuroHPC, QuantERA, and the European Chips Act. This could for example be improved by strengthening the Brussels office with competence in this area.

Sweden is among the eleven countries (including Denmark and Finland) which have a bilateral agreement with the US to collaborate on quantum technologies. Sweden should take advantage of this bilateral agreement and the network of other countries who have similar agreements.

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