INDUSTRIENS FOND FREMMER DANSK KONKURRENCEEVNE
The Danish Industry Foundation

KPMG

IT-Branchen

Quantum technology in Denmark

The case for Danish investment in quantum technology

November 2020

Forord

"Hvis kvantemekanikken ikke gør dig svimmel, har du ikke forstået noget som helst", er Niels Bohr citeret for at sige.

Kvanteverdenen er abstrakt og strider på mange måder mod gængs fornuft. Men en lang række konkrete teknologier, som vi omgiver os med i det daglige, gør allerede brug af kvantemekanikkens love: fra lasere og MR-skannere, til mikroprocessorer og GPS.

Verden står imidlertid på dørtærsklen til en ny kvanterevolution. En revolution, der indvarsler udnyttelsen af atomare egenskaber til realiseringen af et astronomisk stort potentiale. Det er nye kommunikationsteknologier, ultrapræcise måleinstrumenter, ubrydelige krypteringer og kvantebaserede supercomputere.

Danmark var et arnested for kvantevidenskaben og huser den dag i dag en række af verdens førende forskningsmiljøer og virksomheder, der arbejder med feltet. Det betyder også, at Danmark på netop dette teknologiområde har et helt særligt afsæt for at udnytte de vækstmuligheder, der ligger i teknologien.

I processen omkring udpegning af Danmarks styrkepositioner og fremtidige klynger er kvanteteknologien blevet betegnet som klart det mest umodne af de spirende erhvervsområder. Vi oplever imidlertid i disse år, at nogle af de helt store nationer investerer gigantiske beløb i udviklingen af teknologien, og andre mere sammenlignelige lande følger trop, også i Europa. Udover at mange lande handler på denne dagsorden, kan vi se, at kvanteteknologi i stigende grad kommer i konkret anvendelse i produktudvikling; at etablerede danske industrivirksomheder som NKT Photonics og Foss arbejder med feltet; og at mindre virksomheder med udgangspunkt i deres styrker inden for kryptografi, laserteknologi og nanoteknologi tager favntag med teknologien.

Har Danmark overhovedet en chance som lille nation i giganternes kamp? Hvordan udnytter vi fortidens styrker, og har vi nogle særlige udfordringer ift. udnyttelsen af kvanteteknologien? Hvem er de afgørende aktører, der skal sætte os i gang - og få os i mål? Er kvanteteknologien bare det seneste skud på stammen af nye fremadvoksende teknologier? Og hvornår er det rigtige tidspunkt at rykke?

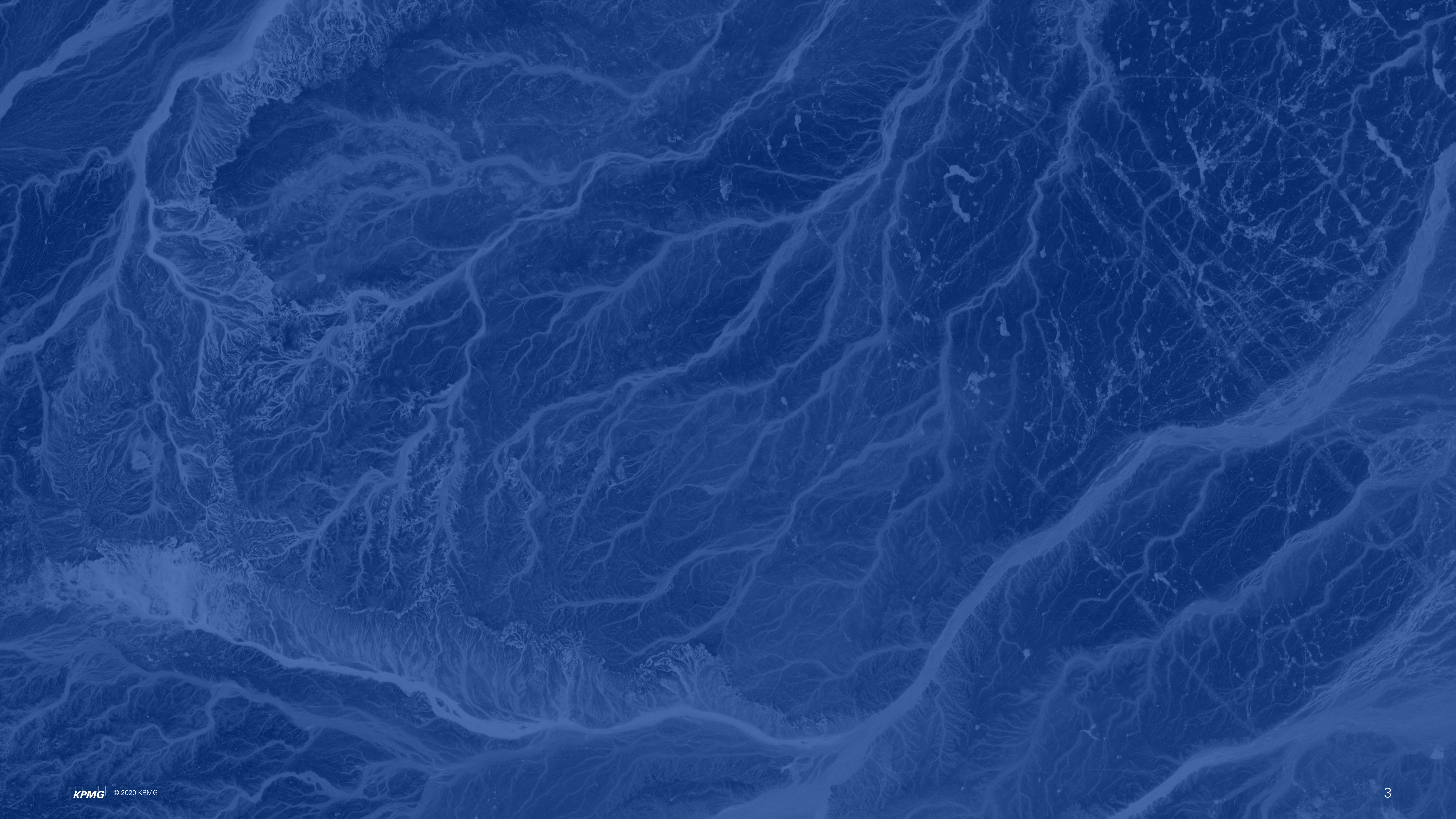
Dette er nogle af de spørgsmål, som vi i Industriens Fond gerne ville have svar på og baggrunden for, at vi satte denne kortlægning, "Danish Quantum tech drive", i gang. Kortlægningen er udarbejdet af KPMG, og bag arbejdet har stået en gruppe bestående af IT-Branchen og Industriens Fond

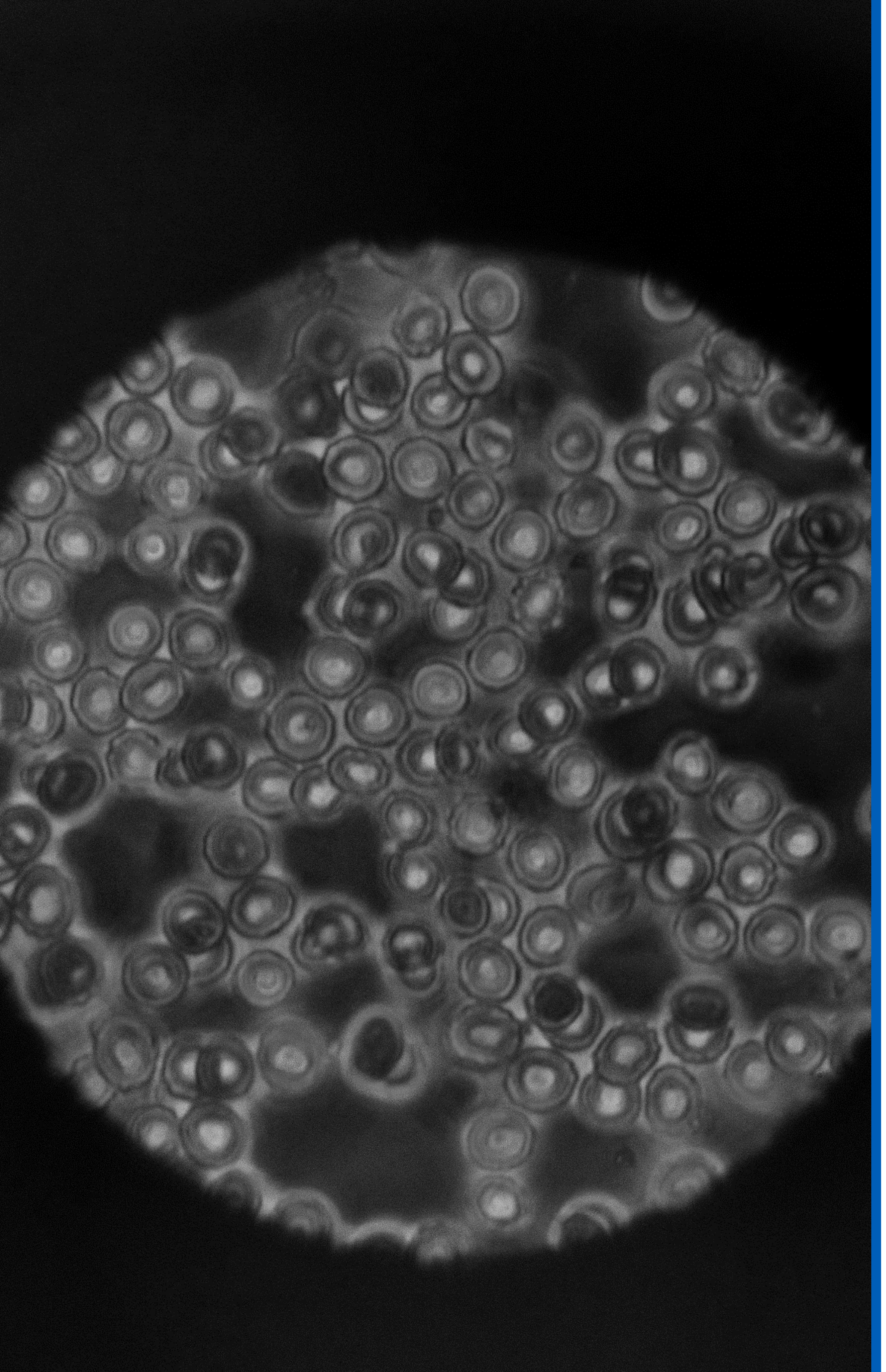
Kortlægningen er blot en første byggesten til et arbejde, der kan vokse sig meget større. En afgørende forudsætning er, at miljøet står sammen i en koordineret, engageret og vedholdende indsats, der går på tværs af de meget forskellige aktører, der er væsentlige for, at Danmark og dansk erhvervsliv kan udnytte de mange muligheder inden for kvanteteknologien.

Vi har en imponerende arv at stå på inden for kvanteteknologien. Vi skal også gerne se ind i en blomstrende fremtid.

God læselyst.

Thomas Hofman-Bang
Administrerende direktør, Industriens Fond





Index

The Case

Supporting the case

READERS GUIDE

This report outlines the reasons for Denmark to invest in quantum technology

The report consists of five parts:

1. **The case for Danish investments in quantum tech**
   Part one is a general introduction to the report
2. **Why quantum technology is important**
   Part two explains what quantum technology is and why it is a transforming technology that will drive technological innovation in the 21st century and beyond.
3. **The Danish potential**
   Part three explains how a strong quantum research tradition and strongholds in life sciences and green tech give Denmark a head start in the race to reap the benefits of quantum technology.
4. **Now is the time to act**
   Part four shows that we are in the beginning stages of the second quantum revolution and uses lessons from the past to illustrate that this is the time to act and invest if Denmark wants to claim a stake in the emerging quantum technology market.
5. **Next steps**
   Part five outlines the possible next steps towards a strong and prospering Danish quantum ecosystem.

The report is supported by three appendixes containing the facts used throughout the report.

THE CASE

The case for Danish investment in quantum technology

01

THE CASE FOR DANISH INVESTMENT IN QUANTUM TECHNOLOGY

Introduction

Starting in the 1950s and 1960s, the first quantum revolution brought us a number of technologies that radically transformed the world, but which we take for granted today. Think of the computer, the smartphone and the Global Positioning System (GPS) to mention a few.

Today, we are at the verge of the second quantum revolution, which promises a number a similar revolutionary technologies, fx extremely sensitive sensors, quantum computers and extremely secure digital communication protocols.

Second generation quantum technologies mature at a fast pace and the first products are on the market. If a small country like Denmark wants to benefit from this development, this is the time to assess Danish strongholds and opportunities.

With this report we provide a first view on the opportunities, that the second quantum revolution presents for Danish industry. We hope to ignite a debate on how to support the development of a strong Danish quantum ecosystem by asking: “Why should Danish stakeholders act now?” and “What should they do?”

Background

KPMG prepared the report with the backing of Industriens Fond and IT-Branchen.

Findings and conclusions arise from desk research and 14 interviews with key stakeholders, e.g. researchers, private enterprises, foundations, trade associations and government agencies.

KPMG is sole responsible for summarizing and conveying the views, thoughts, and opinions expressed in the text.

02

WHY QUANTUM TECHNOLOGY IS IMPORTANT

Quantum technology, explained

Quantum technology is an umbrella term for technologies which rely on or exploit quantum mechanical effects (physical effects on the subatomic level), including quantum entanglement and superposition.

It sounds complicated – and it is. But you do not need to understand quantum technology in scientific detail to use it and appreciate the transformative potential.

The theoretical foundation was established in the early 20th century and led to the first quantum technology revolution in the 1950s and 1960s. This first quantum revolution enabled passive exploitation of quantum effects and resulted in technologies such as transistors, magnetic resonance imaging and lasers. In other words, we take first generation quantum technology for granted and use the resulting products, for example smart phones, on a daily basis.

Today, we are at the onset of the second quantum revolution, where both scientists and companies not only used the insights from quantum theory, but actively control quantum effects. That opens for new possibilities and it is these new possibilities we talk about in this report.

Quantum technology is truly revolutionary

It is hard for us to apprehend the truly transformative character of quantum technology.

Every day, we use smartphones, laptops, internet, it-enabled banking services etc., but we do not think of them as applications enabled by the first quantum revolution. And we have a very hard time imagining a life without them.

The second quantum revolution holds equal or perhaps even greater potential for societal transformation.

On a high level, active control and manipulation of quantum effects enable three groups of quantum technologies: quantum computing, quantum sensors and quantum communication.

Quantum sensors exploit quantum effects to accurately detect slight changes in time, speed, gravity and electric or magnetic fields.

Precise measurement of minuscule physical phenomena opens new and exciting possibilities**.** For example, quantum radars may make current fighter plane stealth technology obsolete. Or quantum sensors may allow neurologists to measure nerve impulses and aid the treatment of nerve diseases such as sclerosis and Alzheimer's.

Quantum computing has the ability to solve problems that classical computers are incapable of.

For example, quantum computing can enable quick and precise simulation of chemical reactions. As such, it has the potential to speed up the discovery of new drugs, develop new (and perhaps, more sustainable) materials and bring down the energy consumption when producing fertilisers which today accounts for 2-3 percent of global CO_2 emissions.

There is more to quantum computing than hardware and the actual computer. E.g. quantum computing also requires specialised software to run the simulations.

Quantum communication allows for relaying highly complex information and enables new levels of security in digital communication.

On one hand, quantum computing promises the computing power to disrupt our current methods of protecting information. On the other, quantum communication heralds new and more sophisticated security solutions that also protect information from decryption by quantum computers.

For example, a quantum communication technology like quantum key distribution (QKD) secures information sent between smartphones or digital infrastructure such as the NemID solution, without being compromised by the use of either current or future technologies.

Although the above examples of second generation quantum technology are transformative in themselves, they are only examples of what we may imagine today.

The commercial potential is significant

Revolutionary and transformative technologies like second generation quantum technology hold a significant commercial potential.

At present, the first products based on second generation technology are on the market, and the current global revenue exceeds 2 billion DKK annually.

Though, this represents only a fraction of the expected potential. Market analysts predict that the total market value will increase rapidly to reach around 400 billion DKK annually by 2040 and continue to grow afterwards.

CURRENT STATE

Quantum technology already makes an impact

Quantum sensors
Quantum sensors are already available at the market. For example gravimeters, which are developed using quantum technology and provides a clear image of the underground landscape to support in construction projects.

Quantum computing
Quantum computers are in its early stages, but have performed the first quantum-enabled chemical simulations, which promise to reduce time and cost of drug development.

Quantum communication
Many quantum technologies are currently in development and some technologies are on the market. Samsung, for example, launched a smartphone in 2020 in which they applied quantum technology to ensure higher levels of security.

SEE APPENDIX A – "What are the relevant use cases?"

CASE

Quantum technology will transform secure communication

Today, the majority of digital communication is encrypted to ensure that only the intended recipient(s) receive the messages. This holds true whether it is private voice calls or confidential exchanges of information between states or companies.

Classical computers encrypt information by systematically scrambling the content in a way which can only be unlocked by a key (a mathematical algorithm). It would take nearly an infinite amount of time for a classical computer to identify the current encryption keys and access the information.

Quantum computers are superior to classical computers in identifying encryption keys and will be able to break traditional encryptions in a short amount of time. As such, they will compromise both the security of current communication channels, as well as the security of stored information.

This will have major consequences on our security. For example:

- Intelligence services and other institutions handling classified information will no longer be able to communicate securely on digital platforms.
- National digital infrastructure such as Danish NemID will be vulnerable to hostile outsiders accessing data.
- Real-time bank transactions will be vulnerable to hacking and theft, although banks are required to protect sensitive client and proprietary information Full scale quantum computers do not exist as of yet, but their future emergence already affects our security. Information handlers need to address that sensitive information stored today may be compromised in 5 or 10 years.

That said, quantum communication solutions already exist which have the potential to protect our information from quantum computers. The first quantum-enabled solutions are already available on the market and include Quantum Key Distribution (QKD) and Quantum Random Number Generators (QRNG).

03
THE DANISH POTENTIAL

Denmark has a head start

Denmark has an established quantum research community, built on the legacy of Niels Bohr, a Danish Nobel prize laureate and founding father of quantum theory.

The strength of the research community provides Denmark with a competitive advantage and head start in the race for developing quantum technologies.

University of Copenhagen houses the Niels Bohr Institute, which today ranks seventh globally in terms of number of unique researchers publishing quantum research in renowned journals the past five years.

Danish quantum researchers receive a higher proportion of EU research funds than researchers in other fields.

Denmark has the highest concentration of enrolled graduates attending quantum-related scientific studies globally. Denmark has 635 graduates attending quantum-related studies per million inhabitants. France has the second most graduates with 438 per million inhabitants.

Successful translation of quantum research to business may provide Denmark with a competitive business advantage as well.

Danish key industries will benefit

Quantum technology is a transformative technology which has the potential to change both business models and ways of working in large industries.

Some of the best use cases for quantum technology relate to Danish key industries and can potentially boost Danish competitiveness.

Chemical simulation enabled by quantum computers will lead to reduced time and cost of drug discovery and will fundamentally change the **life sciences industry**. In 2020, Google revealed the first prototype of quantum-enabled chemical simulation, and IBM has also made significant progress.

In the **logistics and transportation industry**, operators will be able to plan routes in real time through the use of sophisticated models built on big data. This enables better planning, dynamic routing and real-time adaption to demand.

Wind power firms, in the **Danish green technology industry**, may benefit from wind flow simulations performed by quantum computers, as well as the increased accuracy in measurements offered by quantum sensors.

Danish companies may pursue different strategies to benefit from second generation quantum technologies. For example they may develop cutting edge technology on their own, incorporate pre-made technologies in products or simply focus on being first movers in adopting and using frontier technologies.

No matter how Danish companies in key industries choose to use quantum technologies it will be vital for them to have access to a highly skilled workforce to strengthen their competitiveness.

Investments in quantum has great upside

It is important to take the positive derived effects of a potential Danish investment in quantum technology into account.

A push towards quantum technology would most likely lead to an increase in foreign investment in Denmark. For instance, in 2018, Microsoft established its quantum materials lab in Lyngby, due to the strength of the Danish quantum research. This resulted in high-paid jobs and further strengthened the Danish research community.

A strong Danish research and business ecosystem may tap into and benefit from the wider European ecosystem. For example, the EU has committed 1 billion EUR over a 10-year period to the European Quantum Flagship programme.

There is a need for European infrastructure

The European Flagship programme is based on an ambition to reduce or remove the dependency on China or USA to meet the fundamental technological needs of European citizens and companies. That entails collaboration across European countries on developing alternatives to critical quantum infrastructure such as quantum communication.

Additionally, EU and several individual European countries commit substantial resources and investments into quantum technology to balance the American and Chinese investments.

Given Denmark's head start, Denmark has the opportunity to become a central player in the development of parts of a European alternative to the quantum based infrastructure, which USA and China pursue the lead on.

Germany, France and the Netherlands already seek European collaboration in their national quantum strategies.

THE DANISH QUANTUM ECOSYSTEM

The Danish ecosystem need further collaboration to realise the Danish potential

The Danish ecosystem

The quantum technology ecosystem consists of three layers.

The core business of producing, supplying and distributing quantum technology.

The extended enterprise of standardising and using the technology etc.

The broader business ecosystem of funding, regulating, researching etc.

Obviously, the Danish quantum ecosystem is in it's infancy.

The core business in Denmark consists of a handful of small start-up companies. Key stakeholders point to the lack of commercialisation and the wide gap between the strong research community and the few start-ups as a key obstacle to a strong Danish quantum ecosystem.

Though, the strong research community attracts international attention, and the core business in Denmark has been strengthened by the establishment of Microsoft's quantum materials labs in Lyngby.

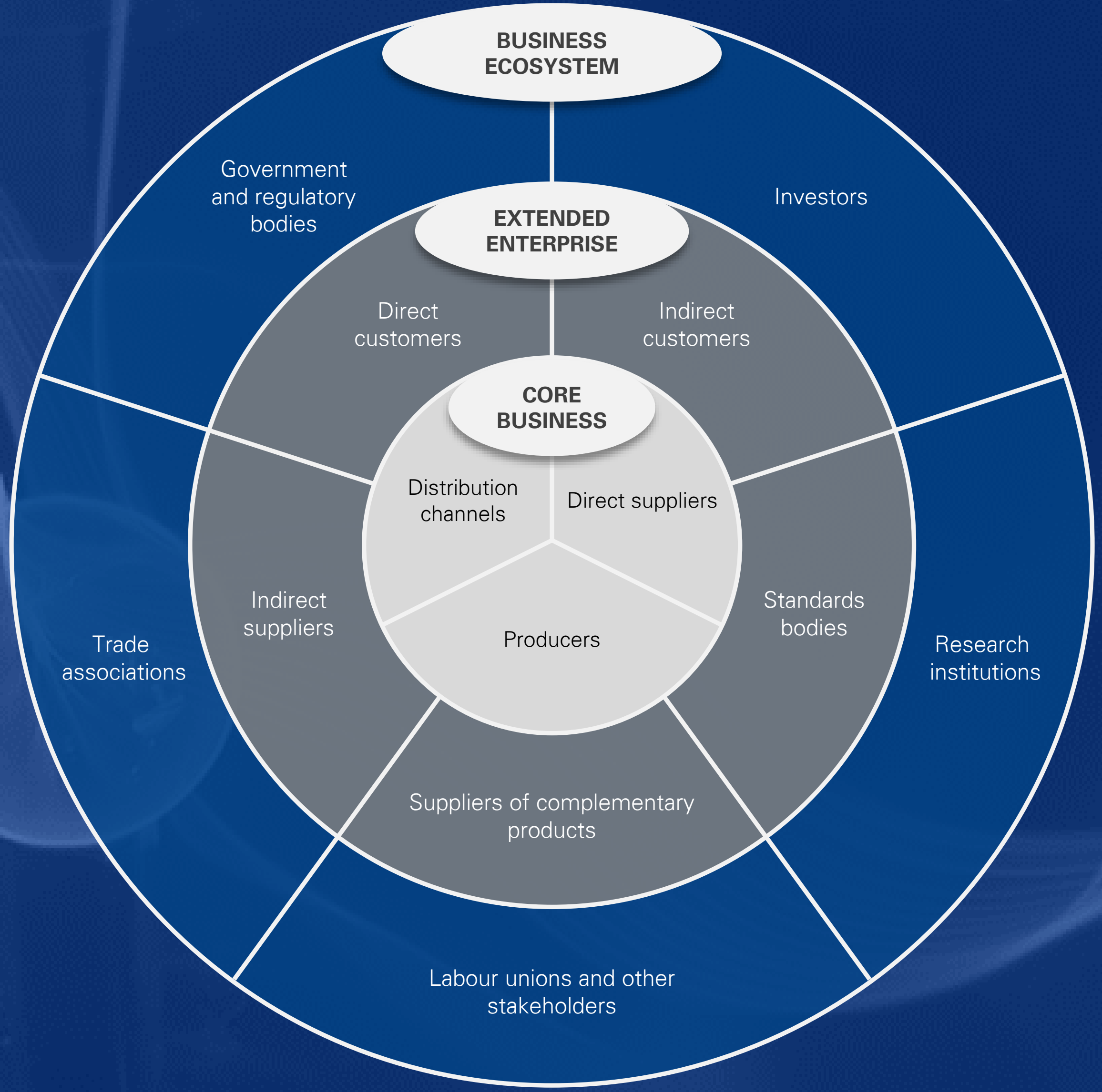
The extended enterprise of the business ecosystem is currently immature, which is natural given the early stage of most quantum technologies. There are, however, some Danish highlights worth noting.

The industries expected to benefit the most from quantum technology – e.g. life sciences and green tech companies – may serve as valuable test beds for developing quantum solutions. Denmark also has notable suppliers to the quantum technology industry, for example NKT photonics, which provide sensitive lasers useful in a number of quantum technologies.

The broader Danish business ecosystem has both strengths and weaknesses.

On the positive side, Denmark has a strong research community producing a skilled workforce for business engaging in quantum technology. And Denmark has engaged trade associations driving the agenda.

On the negative side, stakeholders point to a general lack of investors and venture capital. Government support for basic research in quantum technologies has been strong, but stakeholders consider the government's official stance on quantum technology and support for funding applied research and innovation to be weaker than in neighbouring countries. Though, the stakeholders recognise that a few government actors show dedication to the quantum agenda, most notably Innovation Fund Denmark and the Ministry of Foreign affairs.



04

NOW IS THE TIME TO ACT

The future is shaped today

Looking at the available facts, now seems the right time to invest if the ambition is to become a key player in the future quantum market.

Specifically, this report points to the lesson of the semiconductor industry that early entrants came to dominate the industry. We underscore the growing competition in the quantum space that may make it hard or impossible to enter at a later stage. And we point to the fact that a lot of both large and small countries already see the need and urgency of committing substantial resources to quantum technology.

Lessons from history tell us to invest now

Second generation quantum technologies offer a wide range of transformative uses and are bound to transform society. In that regard, quantum technology share a lot of similarities with the semiconductor industry (see appendix B.2 "Drawing from the lessons of the semiconductor industry"), and the history of the semiconductor industry may indicate the future trajectory of the quantum industry.

The semiconductor industry witnessed long and enduring double-digit growth from the inception in the early 1950s to today.

The majority of today's dominant semiconductor companies were founded around 1970 and a few years ahead, when the first semiconductor hardware products came to market. That is exactly where a lot of second generation quantum technologies are today.

The quantum technology industry may evolve and grow even faster than the approximately 16 percent annual growth the semiconductor industry demonstrated from 1970 to 1990. For example, IBM recently released their quantum computer roadmap. IBM expects qubits to more than double every 12 months, which is significantly faster than Moore's law of the semiconductor industry, which saw the number of transistors in an integrated circuit to double every two years.

It required large amounts of talent, dedication and investments to catch up if you were not part of the foundational phase around 1970. For example, Taiwan Semiconductor Manufacturing Company (TSMC) was founded in 1987 and is today one the world's largest semiconductor companies. Besides an innovative business model, TSMC partly owe their success to extensive government collaboration on research.

The semiconductor revolution sparked the development of a others industries, most notably the software industry, and we may see the same happen with quantum computing specifically and quantum technology in general.

Growing competition requires action

Competition within the quantum technology space is rapidly increasing.

Market consolidation is trending as evidenced by the occurrence of more than 88 acquisitions of quantum technology companies between 2012-2018. The financial details were disclosed on 60 of the deals with a total value of 4.7 billion DKK.

That corresponds to an annual investment of at least 700 million DKK in quantum technology companies, although the technology is still in the early stages.

In addition, quantum talent is highly sought after. Large commercial players are increasing recruitment efforts to attract quantum talent and as a result, small companies and universities have a hard time recruiting the necessary talent to drive research and commercialisation.

Although, the competition increases, there are still time to act as there are plenty of market opportunities. That is obvious in the international start-up sphere, where new quantum-focused companies continue to emerge.

Both large and small countries invest

Several countries see the potential in quantum technology and understand the importance of investing now.

The superpowers, the USA and China, invest heavily in quantum technologies to establish leadership.

China's investments in quantum technology include the launch of the world's first quantum satellite in 2018 and allocation of 65 billion DKK in 2017 to build an extensive quantum research facility. China also singled out development of quantum technology as one of six major science and technology projects it will prioritise towards 2030.

From 2017 and onwards, the USA has formulated an offensive national quantum strategy, putting up 15 billion DKK in public funding. In addition, government agencies and American technology giants such as IBM, Google and Microsoft have substantial budgets dedicated to quantum R&D.

The dedication of the superpowers does not discourage other countries, both small and large, from investing and trying to carve out a niche for themselves in the quantum space.

Germany dedicated 20 billion DKK to quantum technologies as part of their 2020 Covid stimulus package, almost matching the investments in AI and supercomputers.

The Netherlands invested over 1 billion DKK solely in research and innovation in selected quantum technologies over a ten-year period. In 2014, QuTech (Dutch quantum research network) was named one of four national innovation icons promoted and prioritised by the Netherlands.

Israel, a country about the size of Denmark, invests more than 2 billion DKK over a six-year period in quantum technology, and also managed to attract investments from companies like Google.

That was just a few notable examples. Several other countries including South Korea, the UK, France and Japan also invest in quantum technologies.

Other countries' investments put pressure on Denmark to follow suit realise the full potential of the privileged starting position and remain relevant in the competition for talent and investment.

KEY OBSTACLES FOR A DANISH QUANTUM ECOSYSTEM

Denmark is a small nation and traditionally relies on collaboration and partnerships to overcome key barriers

Collaboration

Key stakeholders in the Danish ecosystem do not regard the current level of collaboration as sufficient, if we want to benefit fully from the emergence of quantum technologies.

The key stakeholders point to the fact that Denmark is a small country and that the players in the Danish ecosystem need to work closely together if Denmark wants to succeed in an emerging global industry or at least exploit the new opportunities presented by quantum technologies. For example, researchers ask for insights in business challenges to guide their efforts, and big companies are unaware of the potential benefits of quantum technology.

This is particularly important in the quantum technology industry because political superpowers and large international corporations make significant investments and challenge Danish strongholds.

Awareness

Key stakeholders among both researchers and core businesses stress the need to increase awareness of the quantum agenda.

Danish industry needs to be aware of the commercial opportunities for manufacturers as well as users of quantum technology. At best, lack of awareness make Danish companies miss out on substantial commercial opportunities. At worst, they become disrupted by more aggressive and forward-looking competitors.

Political decision-makers need to be aware of the current Danish strongholds and how they can help Danish industry to capitalise on past public research investments.

Commercialization

In general and especially in quantum technology, Danish universities produce very few commercial spin-outs compared to the size and impact of the research community.

Denmark has ten research centres working within the quantum field, but that has only led to the foundation of a handful companies in the last five years. In contrast countries like Canada, the UK, Israel and to some degree The Netherlands see many spin-outs and start-ups emerge in the quantum field.

Key stakeholders underscore a renewed Danish take on how to promote commercialisation. For example, they point to Israel as an example of a small country that succeeds in the discipline of turning research into commercial success. Not by chance, but by making a coordinated effort.

Funding

Denmark invests significantly in basic research, and that is one of the reasons why Denmark is home to a world-renowned Danish quantum research community. Furthermore, Danish researchers are good at leveraging international collaboration and EU research funds to increase scope and impact.

However, the competition in the quantum space is increasing, and long-term funding commitment is essential to attract talent and investors. This is particularly the case for funding of innovation and applied research. Today Denmark is not committing funding in the same scale relative to its size as other countries with strong research bases, even though Innovation Fund Denmark has been providing some high risk capital to quantum cases.

Engaged government

Key stakeholders often point to government involvement as a deciding factor for promoting a Danish quantum ecosystem. They also point to the fact that only a few dedicated Danish government agencies are active on the quantum agenda. Their assessment is that the Danish government is less involved in the quantum agenda than governments in countries with similar strong research bases such as the Netherlands, UK and Germany.

Explicit government commitment is a strong signal to partners, talents, investors and companies that Denmark is in for the long haul.

Government agencies also hold a unique position to support the ecosystem form and prosper. Government agencies can commit dedicated resources and they may act as a neutral mediator and facilitator, as they do not hold commercial interests on their own.

05

NEXT STEPS

Seize the unique opportunity

Second generation quantum technology is a transformative technology that promises to shape society and everyday life in the 21st century and beyond.

Denmark is in a strong position to begin to develop and commercialise quantum technology. There are, of course, limitations to what Denmark can achieve. For example, Denmark will likely not become a leader in the capital-intensive manufacturing of quantum computers. However, there are several areas within quantum technology where Danish researchers and industries have the ability to stand out and become key players.

In order to build on the great starting point and capitalise on the investments already put into Danish research, Denmark needs a coordinated effort to address key obstacles, see the previous side.

Build a community

Denmark is a small country, and like the Netherlands, Denmark needs a joint effort by research organisations, commercial industries, government and other stakeholders to achieve sufficient scale and make an impact in the quantum space. One solution is to establish a quantum community comprising key stakeholders to promote collaboration and coordination.

A primary task for the quantum community is to bridge the gap between Danish industry and research and secure collaboration amongst the stakeholders. Currently, Danish expertise within quantum research does not translate into commercial opportunity.

If the community can increase the level of coordination and knowledge sharing it would be beneficial for Denmark. For example private enterprises need to learn about the technological opportunities and how to adopt them, researchers need input on which challenges to focus on, government institutions need to know who and how to support the ecosystem and start-ups need access to venture capital.

The community could be build around a network structure with a coordinating body, perhaps with clear government support. It could look like the Quantum Delta in The Netherlands where universities established a coordinating body with government support, or the UK National Quantum Technologies Programme, where government agencies drive the agenda with a programme board.

Key stakeholders believe that establishing a community – especially with government support – will send a clear signal to potential partners and investors that Denmark is committed to quantum technology and to transforming the strong Danish research community into a fully fledged business ecosystem.

Create a roadmap for quantum technology

In the short term, a Danish quantum roadmap could enable rapid action and bold choices. Though, there is a need for further knowledge to be able to answer the key questions, for example which technologies to focus on and how to gain commitment to a common agenda focused on developing and promoting a competitive Danish quantum technology ecosystem.

It is an obvious task for the community and key stakeholders to create the roadmap.

Promote commercialisation

How to translate a strong research community into commercial success is a key issue, the roadmap needs to address. Compared to other countries with the same level of quantum research activity, Denmark has fewer investments in start-ups and spin-outs. Israeli quantum start-ups has for example raised 215M DKK in disclosed investments and UK start-ups around 400M DKK whereas Danish companies have raised far less (e.g. only 8M DKK in venture capital).

Key stakeholders underscore the importance of proper incentives for researchers or skilled graduates to start businesses. Furthermore, there is a need to strengthen the connection between the researchers *exploring* quantum technologies, the start-ups *producing* quantum technologies and companies (eventually) *using* quantum technologies.

Inspired by other countries (e.g. Israel or The Netherlands), possible initiatives could be to create an incubator environment to make it easier for start-up prospects to test and mature their ideas as well as for investors to know where to find targets.

It is also possible to create mission-driven hubs focusing on developing specific technologies and secure funding for all stages of the start-up journey, for example by government matching private investments

Secure funding

The quantum technology roadmap could also address how to secure funding for applied research, innovation and research infrastructure, which key stakeholders regard as underfunded. Having long term funding commitments is vital to sustain a strong research environment and attract talent and investments.

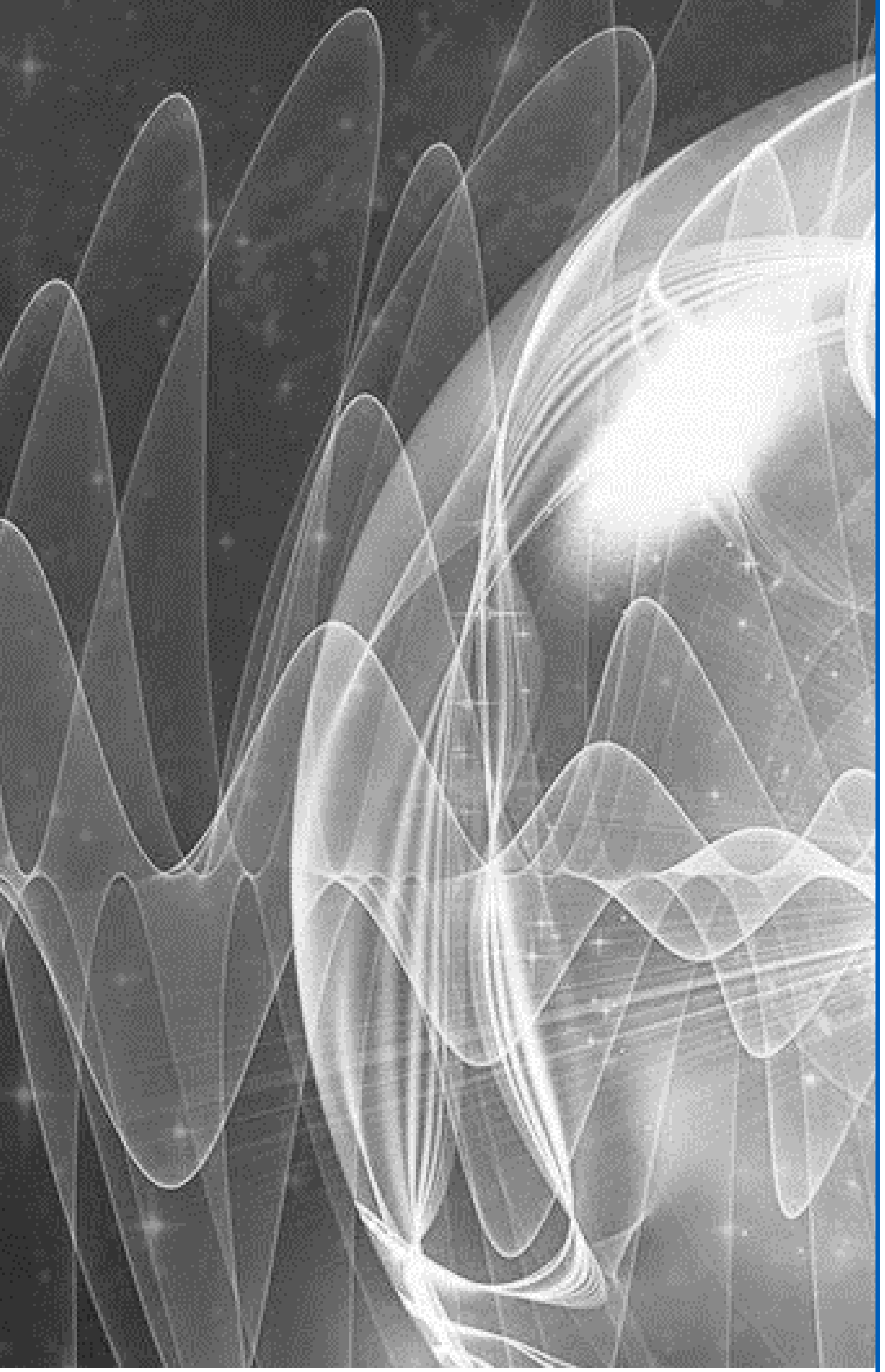
To get the most out of a long term funding commitment Denmark could benefit from an in depth analysis of which quantum technologies that carries the largest commercial potential as well as the best opportunities to attract investments and talents.

As a small country with limited resources, Denmark must act effectively to make an impact. EU and public/private partnerships have proven effective for Denmark in the past and could be useful in supporting the quantum ecosystem too.

Long-term funding commitments are another way to nurture the ecosystem and create fertile ground for commercialisation.

Appendices

What is quantum technology?



Appendix content

The appendix section contains three sections, each answering a range of questions, supporting the main argument conveyed in the report.

A MAPPING THE **TECHNOLOGY**

Appendix A introduces the three groups of quantum technologies providing both a general description and use cases for each group.

A.1 What is quantum technology?

A.2 Current use cases

B MAPPING THE **MARKET**

Appendix B provides insights into the market for quantum technologies. In the appendix, we assess the global market from different angles to provide an insight into who is currently market leading and who are striving to become future market leaders.

B.1 Estimates of the future market size

B.2 Drawing from the lessons of the semiconductor industry

B.3 Other countries' push for quantum technology

B.4 Private equity investments

C MAPPING THE **DANISH ECOSYSTEM**

Appendix C sheds light on the Danish ecosystem for quantum technologies. We assess the current strengths and hurdles of the Danish ecosystem.

C.1 What does the Danish ecosystem look like?

C.2 Key enablers and strengths of the ecosystem

C.3 Key obstacles for the ecosystem

C.4 What do Danish stakeholders suggest as next steps?

A.1 What is quantum technology?

We are at the onset of the second quantum revolution, where we are not only able to passively exploit quantum effects at the subatomic level, but to actively control them.

What is Quantum technology?
Quantum technology is an umbrella term for technologies that rely on or exploit quantum mechanical effects that are physical effects on the subatomic level.

The theoretical foundations for the study of quantum mechanical effects were laid in the beginning of the 20th century by prominent physicists like Max Planck, Albert Einstein, Niels Bohr and Erwin Schrödinger. The offset was a number of observations on the subatomic level that could not be explained by classical physics.

Quantum physics and quantum theory gradually matured during the first half of the 20th century culminating in the first quantum revolution, which took off in the 1940s and 1950s. The first quantum revolution was about passively exploiting quantum effects and ushered in technologies like transistors, magnetic resonance imaging and lasers.

Today, we are at the threshold of the second quantum revolution, where scientists and companies are actively controlling and using quantum effects. The second quantum revolution consists of three main areas: quantum computing, quantum communication and quantum sensing.

Quantum computers attract the most attention in quantum tech and hold incredible promises. But the development of quantum computers are in the early stages, and it may take 10 or 20 years before we reach the goal of reliable, large-scale, error-tolerant quantum computers that can solve a wide range of useful problems.

On the other hand, the first quantum sensors and communication devices have already left the research labs and entered the market. For example, you can now buy a Samsung smartphone equipped with second quantum revolution technology.

QUANTUM SENSORS

In a nutshell
Quantum sensors exploit quantum effects to accurately detect very small changes in, for example, speed, gravity and electric or magnetic fields.

Potential
Accurate detection and sensing of minuscule changes in time, speed, magnetic fields, etc. open up a lot of potential use cases.

Quantum sensing is particularly promising for the healthcare sector. Quantum sensors may help detect very small bodily variations, like the heartbeat of a foetus.

Quantum sensing will enable satellite free navigation by using accelerometers to measure movement with an extreme precision.

In the military field, quantum sensing may enable stealth radars that cannot be detected and sensors that can scan the entire radio spectrum with one device.

Current state
Some quantum sensing technologies, like quantum clocks and accelerometers, are available in the market. But most of the activities in the quantum sensing field are still taking place in the research labs.

QUANTUM COMPUTING

In a nutshell
Quantum computing exploits quantum effects to tackle computational problems intractable by the classical computer.

Potentials
Universal gate-based quantum computers can in principle handle every type of computational problem and will be superior to the classical computers if the problem at hand is very complex.

Quantum algorithms are an important part of the quantum computing tech stack as they enable the application of quantum computers to specific challenges.

Current state
Today, the first basic quantum computers are operational.

Specialised quantum computers like quantum annealers are showing promising results in handling specific kinds of optimisation problems. For example, quantum annealers can be used to accelerate drug discovery processes, allocate capital and optimise transport and logistics.

However, the consensus is that we have yet to mature the technology that will enable reliable, large-scale, error-tolerant quantum computers which can solve a wide range of useful problems.

QUANTUM COMMUNICATION

In a nutshell
Quantum technology provides new communication forms and methods for encrypting messages and information.

Potential
Secure communications is a cornerstone of modern, digitised economies, but increases in computational power and not least the emergence of the quantum computer make existing encryption methods vulnerable. Quantum technology holds the promise of increasing communication security tremendously and keeping essential data and systems safe from theft, hostage-taking and sabotage.

Additionally, quantum communication is an enabler of quantum computing, as you need a quantum-based communication network to share qubits and quantum gates, the smallest data unit in quantum computers. Over the next decades, we will be witnessing the gradual forming of the quantum internet.

Current state
There is a plethora of potential quantum communication technologies in development, for example quantum repeaters, post-quantum cryptography and quantum random number generators. Commercialisation is taking place, but especially security applications need standards and the process of standardisation is long and meticulous.

Quantum key distribution (QKD) is a specific quantum security application that is used on the market with vendors and networks promoting it. QKD pre-empts that information stored today can be decrypted later.

SEE THE NEXT PAGES FOR EXAMPLES ON USE CASES!

A.2 Current use cases

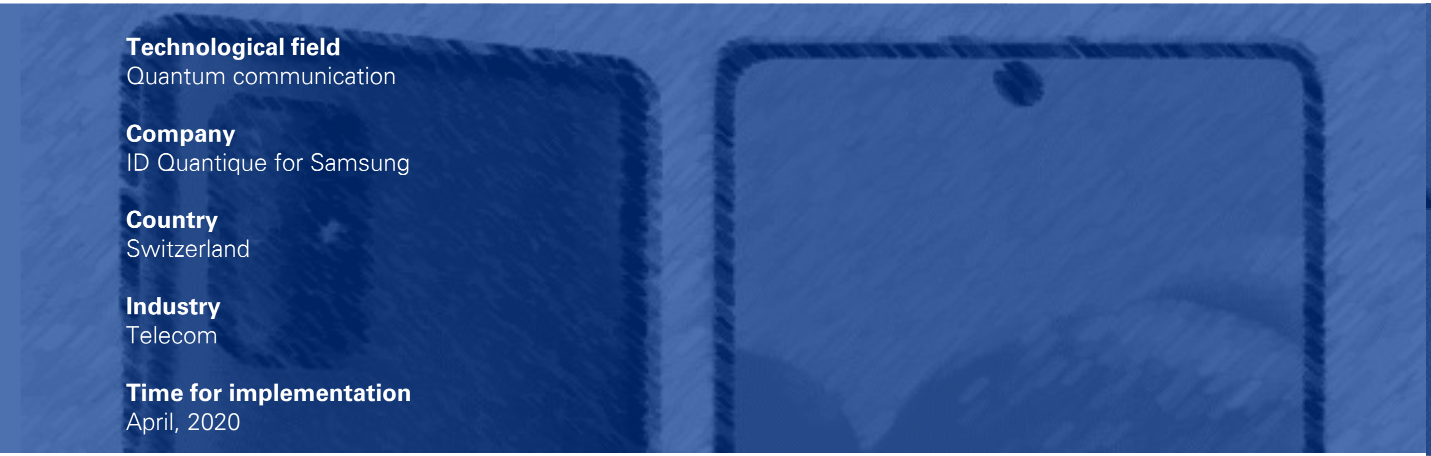
SMARTPHONE ENCRYPTION

Samsung has launched a new smartphone that contains second generation quantum technology

Challenge
Whenever we share a text, a picture or other information with our smartphones, we use cryptography to make sure that only the receiver can read the message. In order to achieve a secure encryption, we need randomness so eavesdroppers cannot guess or calculate the encryption key. But true randomness is not easy to create with classical computers, because they are deterministic by nature. Therefore, our current encryption technologies are inherently insecure and our communication is subject to unauthorised access.

Solution
Quantum effects are probabilistic and not deterministic. Therefore, quantum effects may be used to generate true random numbers. Samsung has recently brought a new smartphone to the market with a quantum random number generator to boost security. The phone has a chip that can feed random numbers when requested by applications or security protocols using the probabilistic behaviour of quantum objects.

Benefits
The chip enables Samsung to achieve a level of security that would not be achievable by classical computer protocols without lowering the overall performance and user experience of the phone.



Technological field
Quantum communication

Company
ID Quantique for Samsung

Country
Switzerland

Industry
Telecom

Time for implementation
April, 2020

Source: https://www.forbes.com/sites/daveywinder/2020/05/15/samsungs-surprising-new-5g-smartphone-is-worlds-first-with-quantum-technology/#2bdd197b30e0

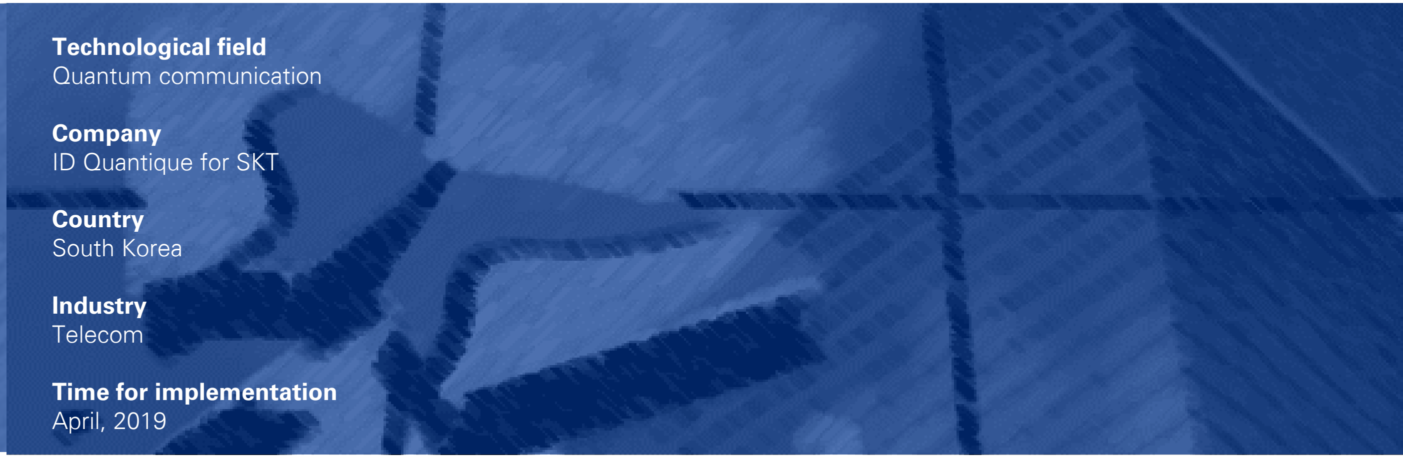
5G ENCRYPTION

SK-Telecom is planning on using quantum technology to secure the 5G network

Challenge
5G networks will bring new speeds and interconnectedness to wireless communication. The amount of data that will flow in 5G-networks will be massive. Classic cryptography will help maintain privacy of the data flow, but the emergence of quantum computers presents a liability. Quantum computers may still be a thing of the future, but when they emerge, they may be able to decrypt not only present but also stored communication. In other words, the telecom operators of today must prepare for the security situation of tomorrow to protect the privacy and data of their customers.

Solution
Interestingly, quantum communication technology can be used to mitigate the future security threat from quantum computers. Quantum key distribution (QKD) is a prominent present day application that enables hyper secure communication and helps the telecom operators of today to protect data against future threats. As an example, SK Telecom plans to use quantum key distribution to secure the core network of its 5G infrastructure.

Benefits
QKD helps SK Telecom to secure their 5G infrastructure. QKD is not the only countermeasure, and it is still not standardised, i.e. it needs to be assessed by international entities such as ISO. Nevertheless, it promises a very high level of security and mitigates the threats brought by supercomputers and quantum computers.



Technological field
Quantum communication

Company
ID Quantique for SKT

Country
South Korea

Industry
Telecom

Time for implementation
April, 2019

Source: https://www.idquantique.com/sk-telecom-continues-to-protect-its-5g-network-with-quantum-cryptography-technologies/

CHEMICAL SIMULATION IN LIFE SCIENCES

Google is pushing its early stage quantum computer to solve chemical simulation in life sciences

Challenge

In the life science industry, companies often need to test chemical reactions at the atomic level, for example when pharmaceutical companies develop medicine or chemical plants produce fertilisers. Currently, the companies do the testing by trial and error or through very inefficient simulations. It is a laborious process, which requires a lot of time in the laboratory and drives cost.

Solution

Google recently assembled a team to simulate a – fairly simple – chemical challenge on their early stage quantum computer consisting of 54 qubits (The Sycamore). The simulation process can narrow the amount of possible chemical compositions significantly and decreases the development time and cost of new medicine. Companies like IBM and Microsoft are also exploring quantum simulation.

Benefits

When quantum computers can perform large scale simulations, the time and cost spent on development processes for medicine and other life science products could be decreased dramatically, which will benefit both companies and patients/consumers. Although promising, it is still highly uncertain when quantum computers have matured to the level where they will revolutionise development cycles in the life sciences industry.

Technological field
Quantum Computing

Company
Google

Country
USA

Industry
Life Sciences, Farming, etc.

Time for implementation
First test 2020 – implementation 5-10 years

https://phys.org/news/2020-08-google-largest-chemical-simulation-quantum.html

OPTIMISATION OF CITY TRAFFIC

Volkswagen is exploring the potential of D-Wave quantum annealer to optimise city traffic

Challenge

Managing public transportation and taxis is a hard challenge for classical computers. It has to take many parameters into account when planning the best possible routes. The algorithms must be efficient, fast and reliable, but the amount of computation needed to achieve good results is often too high.

Solution

Quantum annealers are good at solving certain categories of optimisation problems. D-wave and VW set out to develop an algorithm for traffic management which can be used for example to optimise taxi rides in order to minimise the amount of time the taxis are empty. They do this by using anonymised movement data from persons or cars to perform real-time predictions of the demand for transportation.

Benefits

In this case, the quantum annealer can optimise the productivity of bus and taxi services and optimise the cost of operation through a fast and reliable algorithm.

There are already promising performances for low-scale problems, and there is a potential to increase the advantage once the hardware becomes better. Quantum annealers have an advantage in actual application and are used in various ways today, even though they are only able to tackle a very limited set of problems compared to other types of quantum computers.

Technological field
Quantum computing

Company
D-Wave for Volkswagen

Country
Canada

Industry
Automotive

Time for implementation
In production for small cases – wider implementation 1-2 years

Source: https://media.vw.com/en-us/releases/1098

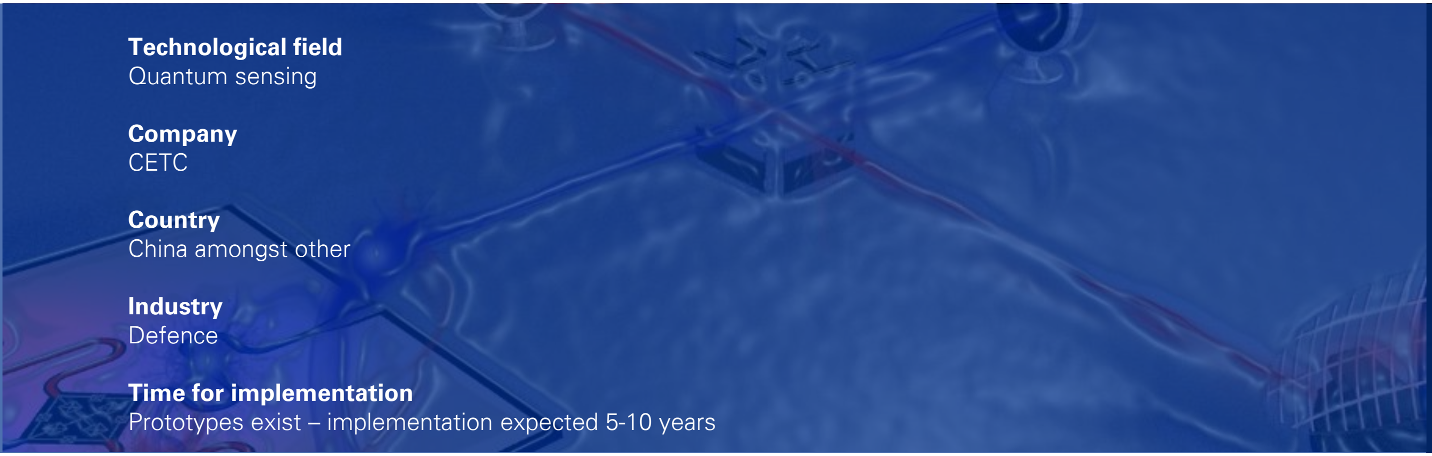
QUANTUM RADAR

The quantum radar promises high resolution stealth radar which cannot be detected.

Challenge
Radars are a central part of warfare as they are used to identify objects in a certain area. It is equally important for a pilot to know whether someone is tracking your position with a radar. Classical radars need to use a very strong signal to detect objects and are therefore easy to identify for airplanes which can jam the radar signal when detected.

Solution
Quantum radars promise to bring better resolution and are also harder to detect. The main reason for this advantage is that you do not need to send a strong signal thanks to the quantum phenomenon of entanglement.

Benefits
The quantum radar will give several strategic advantages in modern warfare and give new insights into the amount of foreign objects in a country's airspace making it more transparent when sovereignty is violated.
In 2016, the Chinese company CETC claimed to have developed a prototype with a range of approximately 100 km. At this stage, there exist only prototypes with limitations, but researchers are getting closer to a more mature product.



Technological field
Quantum sensing

Company
CETC

Country
China amongst other

Industry
Defence

Time for implementation
Prototypes exist – implementation expected 5-10 years

Source: https://phys.org/news/2020-05-scientists-quantum-radar-prototype.html

GRAVIMETERS

Quantum gravimeters support construction projects

Challenge
When doing construction work, it is important to have as good a picture of the landscape underneath the earth's surface as possible to know where to dig and to avoid for example voids and cavities. Existing methods can be costly and are unable to detect all cavities.

Solution
Quantum gravimeters can bring a better overview of what is in the underground without actually digging. A precise measurement of the gravitational field on a certain spot can provide the needed information of the underground and save both time, money and enhance safety. The first gravimeters are already commercialised and can be purchased.

Benefits
In construction, using gravimeters can help avoid holes in the road, needless digging, etc. They can be used in many other fields such as checking for underground magma in geophysical research, scouting for oil or give a more accurate measurement of the groundwater table. Having insights of the underground structure of an area can save both money and time.

Technological field
Quantum sensing

Company
MuQuans

Country
UK, France

Industry
Construction, Energy

Time for implementation
First commercial products are available now

Source: https://iopscience.iop.org/article/10.1088/1742-6596/723/1/012050

B.1 Estimates of the future market size

The market for quantum technologies have already exceeded 2bn DKK and is expected to reach 400 billion DKK in 2040.

Market size

The estimates on a global market size range from 365 billion DKK to 408 billion DKK in 2040 – almost the same size as the global market for wind turbines today. The estimate is based on an assessment of eight different market estimates – the most sophisticated being from Australian and Dutch reports on quantum technology. In 2018, BCG had also made estimates on the market size of quantum computing emphasizing that the market lift-off will depend on the technological development. The BCG cases project a market size between 40bn DKK and 850bn DKK in 2040. This gap in projections illustrates well the uncertainty in the market estimates. As quantum technology is developing at a rapid pace (illustrated by IBM's roadmap for scaling quantum technologies) we would expect the market will lift off sooner rather than later.

All estimates of the market for quantum technologies expect a significant growth which will most likely be seen in 2030s.

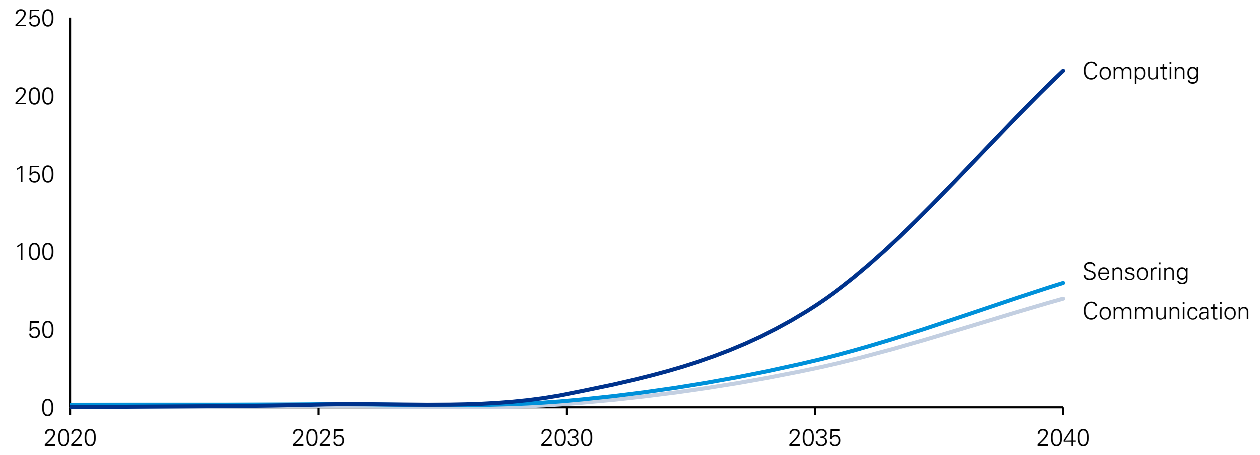
Quantum computing is expected to be the largest market of the three technological areas in 2040, but today the market for quantum sensors is the biggest driven by products like atomic clocks or sensing and imaging such as gravimeters.

Interviews show that companies are already experiencing a rising demand for quantum technologies, for example for atomic clocks or components for quantum technologies. Players in the Danish ecosystem are also experiencing a demand for people who can work with quantum technologies. These tendencies underline the fact that the market for quantum technologies is growing and that we can expect significant growth rates over the coming years.

Estimates from other strategies

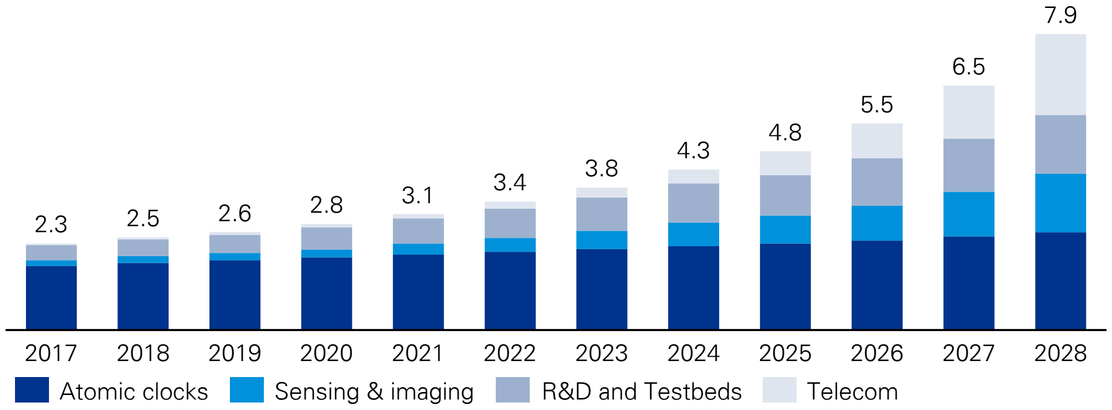
Source	Technology	Year of estimate	Market size estimate (billion DKK)
"Growing Australia's QT Industry"/BCC research	computing	2040	215bn DKK
"Growing Australia's QT Industry"/BCC research	sensoring	2040	80bn DKK
"Growing Australia's QT Industry"/BCC research	communication	2040	70bn DKK
"Natinonal Agenda for Quantum Technologies" Qunatum Delta, NL	All quantum tech	2040	410bn DKK

Estimates of the market size for each technology, billion DKK



Source:"Growing Australia's QT Industry"/BCC research

Market estimates for selected quantum communication and sensing, billion DKK



Source: Market Research Study in Nanoscale quantum optics', COST Action MP1403, Tematys, 2019

B.2 Drawing from the lessons of the semiconductor industry

Quantum technology may exceed the explosive growth trajectory of the trillion-dollar semiconductor industry

Second generation quantum technologies share a lot of features with semiconductors, one of the central first generation quantum technologies.

Firstly, both second generation quantum technologies and semiconductors are considered enablers of other technologies. For example, semiconductors enabled the emergence of the personal computer, the internet and computer-assisted design.

Secondly, the development of both semiconductor and second generation quantum technologies are research and capital intensive.

Thirdly, it is equally difficult to truly grasp the possibilities of second generation quantum technologies as it was to understand the potential of the internet when the first transistor was built in 1950.

For these reasons, it is valuable to revisit and explore the lessons learned during the transition of the semiconductor industry from its early days in 1950 to the 2.5 trillion DKK industry it is today.

Measured on market volume and technological maturity, second generation quantum technology is currently at a similar stage in its evolution as the semiconductor industry just prior to 1970.

Prior to 1970, the global semiconductor market was valued at less than 10 billion DKK, and the first products were entering the market. For example, Texas Instruments released their break-through transistor-based desktop calculator ‘Cal Tech’ in 1967.

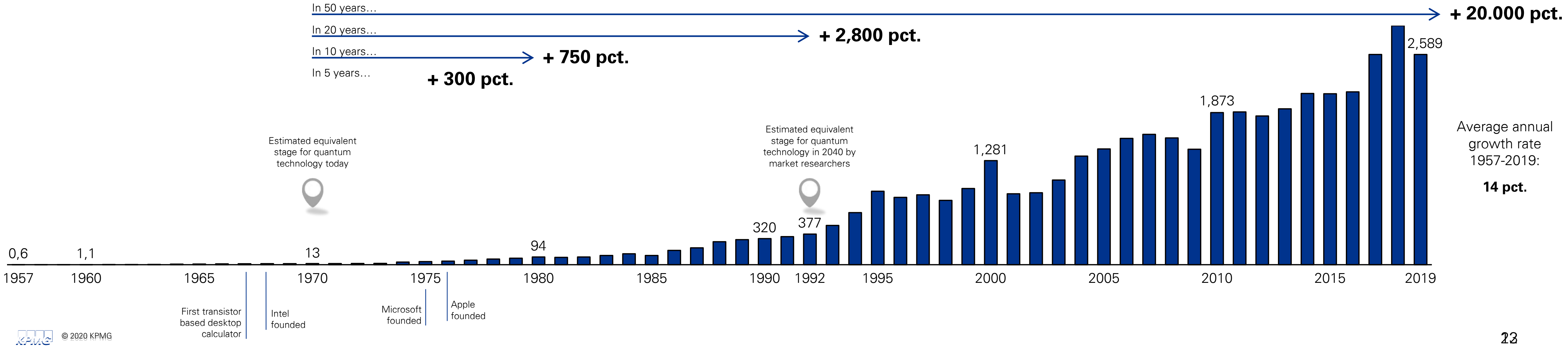
Many of today’s dominant players in the semiconductor and associated industries were founded at this stage. Intel was founded in 1968, Samsung in 1969, Microsoft in 1975 and Apple in 1976. Also specialised companies like Burr-Brown, which was founded in 1956, had commercial success during the 70s and 80s and was eventually sold for 7.6 bn. USD in 2000. For second generation quantum technology, this implies that we may expect to see the future dominant players emerge around now.

The market growth rate depends on the pace of the technological development , which appears to be even faster for quantum technology than for semiconductors.

IBM recently released its quantum computing roadmap, where IBM states the expectation of more than doubling the number of qubits every year. That is significantly faster than Moore’s law of the semiconductor industry, which saw the number of transistors in an integrated circuit to double every two years.

Furthermore, technological advances seem to spread at a greater pace on a global scale than in the 1970s. In ten years from 2007 to 2017, smartphone sales went from 122 million units to 1.5 billion. In contrast, it took PCs 36 years from 1975 to 2011 to reach the same number.

Growth trajectory of semiconductor industry



B.3 Other countries' push for quantum technology

Several countries put resources and political weight behind developing quantum technology. Especially, the US and China are battling for dominance but other countries are also investing in quantum (see following page for detailed overview).

The major players
China and the US are considered to be the most influential countries in quantum in the world.

China's government has invested heavily in quantum technologies especially within the field of quantum communication. This constitutes a potential security threat to other countries such as the US and other NATO countries.

The US has in its strategy a focus on security – but being home to some of the largest companies within quantum computing, the American strategic focus is also on securing a strong research base, having a talented workforce and securing the link between academia and research.

In Europe, Germany has pledged heavy investments in quantum technologies, the UK has been moving early on the agenda and France has recently pledged large financial contributions to develop quantum technologies in France.

The European strategies have not narrowed the technological focus, although the UK roadmap has a focus on 7 groups of technologies.

The European countries have different models for driving the agenda forward such as heavy governmental investment in research (Germany), focus on a strong research hub (The Netherlands) and public funding to attract private investment (France). Some countries are primarily driven by private initiatives such as Sweden and Switzerland

The EU is in 2021 launching the quantum flagship programme committing €1bn which will fuel further development.

Inspiration for Denmark
Recently, countries like the Netherlands and Australia have shed light on the quantum agenda. The Netherlands has a national strategy and has ramped up the funding, whereas Australia has made a thorough analysis calling for a national strategy.

These initiatives could serve as inspiration for Denmark. Like Denmark, both countries have a solid research base and are smaller in size. The focus of their strategies is to establish cooperation and ecosystems, investing in their research base and developing talents in the workforce.

Innovation the Israeli way – start-ups open innovation

Israel has a high number of successful start-ups with over 100 of them making exit deals every year. Israel might serve as an example to follow in at least five factors:

Government support – Israel has an innovation authority working with incentives in start-ups for both academia, corporations, venture capital, government and media

Mature technology transfer – All major Israeli research institutions have technology transfer offices focusing on licensing new technologies.

A strong tie to industry – Strong industry ties expand the pool of potential entrepreneurs, e.g. in cyber start-ups most entrepreneurs are hatched from the armed forces.

Easy access to venture capital – Large venture capital funds (e.g. from the US) are attracted to Israel.

Incubators in attractive markets – Incubators driven by venture funds build the foundation for start-ups. They are set up to have hubs in attractive foreign markets to ease the access for start-ups to those markets.

Overview of investments in the quantum agenda, by country

Country	Resources committed	Other comments
Denmark	80m DKK committed from Innovation fund Denmark 2017-2019.	• Strong universities (e.g. Copenhagen University and DTU) • High degree of talented workforce in quantum
Switzerland	260m DKK from 2010 – 2017 on the National Centre of Competence in Research for Quantum Science and Technology	• The Swiss Science Council released a white paper on quantum technology in October 2020 • Strong universities (e.g. ETH Zürich) • Home to ID Quantique, one of the largest quantum- driven companies in Europe
Japan	1.8bn DKK over the last 15 years	• Aims at having a 100 qubit quantum computer by 2029 focusing on fields like manufacturing and financial services
Russia	4bn DKK over the next five years from government	• Intensifying investments and focusing on national security
Republic of Korea	300m DKK over the next five years in government funding	• Aims at demonstrating a practical five qubit quantum computer by 2023 • Has companies like SK telecom and Samsung investing in quantum technology
Canada	6bn DKK spend in the past 10 years	• Has been running the Quantum Canada programme since 2016 • Hosts D-wave as one of the current commercial leaders in quantum computing (annealing).
Israel	More than 2bn DKK invested primarily in defence-relevant technologies	• Has a mature model for creating spinouts
Austria	No government pledge identified, but has invested 75m DKK in a start-up	• Has received a large amount of funding from the EU-programmes relative to its size
Sweden	No government pledge identified but 650m DKK from a large private investment	• Building a Centre for Quantum Technologies based in Chalmers University

Country	Central documents	Strategies in brief	Key activities	Substantial investments
China	• Megaproject for quantum communications and computing (2016)	No official Chinese strategy has been located, but it is evident that China is investing heavily in quantum technologies – especially in the areas of computing and communication where China announced a "megaproject" for in the five-year budget in 2016.	• Launched a quantum communication satellite to enable secure communication (2016). • State-owned company CETC announced it had tested a quantum radar enabling them to sense stealth airplanes (2016).	Funds are in general undisclosed • 65bn DKK for one quantum research centre
USA	• National strategic overview for quantum information science (2018) • National quantum initiative act (2018)	The National strategy has six general headlines focusing on securing an excellent and coordinated research base and infrastructure, a workforce able to work with quantum both through education and attracting talent, engagement between industry and research, national security and international cooperation.	• Large American corporations are battling for "quantum supremacy" (having a quantum computer do operations a classical computer is not capable of) with first instance proclaimed in 2019. • National quantum initiative initiated by the congress to advance quantum computing (2018).	• 8bn DKK in the US National Quantum initiative for 2018-2023 • 6.3bn DKK for 12 new research institutions in 2020 On top of these governmental investments, the USA is also expected to use large undisclosed amount of resources in governmental security agencies. Large private companies are also expected to invest heavily in this.
Australia	• Growing Australia's Quantum Technology Industry (2020)	Australia is still in the early stages of developing the quantum technology ecosystem and do not have an official strategy, but a key document in form of a report by CSIRO – an Australian Quango working with innovation, science and technology. The report focuses on coordinating Australia's quantum industry through a national strategy, investing in talent and research infrastructure, international cooperation with focus on the "Five Eyes Alliance" and enhancing readiness in government and businesses to use quantum technology.	• A roadmap for growing the quantum industry towards 2040.	• 0.6bn DKK in federal government funding invested in recent years
Germany	• Quantum technologies – From basic research to market (2018)	The German federal ministry of education published the federal strategy. The strategy has six main themes including creating research networks, initiating lighthouse projects in communication and computing, ensuring national security, taking lead on international cooperation, especially in Europe and getting Germany's population to understand quantum technology. The German government is amongst those who have committed most resources to support their strategy.	• A heavily funded programme put up by the federal government to build quantum computers (2020). • Some of the largest research institutions (e.g. Fraunhofer Gersellschaft) have quantum computing and communication as a key strategic area.	• 15bn DKK in a federal government programme for 2020-2028 • 5bn DKK in a federal government programme for 2018-2022 • Quantum technologies are also expected to get more funding following the German coronavirus stimulus package
France	• Quantique: Le virage technologique que la Frenace ne ratera pas (2020) (Quantum technologies: the technological revolution France fully intends to embrace)	The French parliament wrote the strategic document which was adopted by the government. The strategy sets out to support research and application of technology, establish research infrastructure and three quantum hubs focusing on innovation. The strategy also focusses on international cooperation and on establishing a good governance to handle uncertainties and long-time horizons.	• The SIRTEQ project is creating a hub for quantum, bringing together more than 100 research groups working in quantum, funded by France's largest region (2017). • A plan for development and innovation within quantum has been set up by the federal government.	• 10.5bn DKK in both public and private investments from 2020-2025
United Kingdom	• National strategy for quantum technologies (2015) • A roadmap for quantum technologies in the UK (2015)	The UK was the first European country to develop an actual strategy for quantum technologies. The strategy is five years old, and some priorities can have changed. It focusses on a strong research base and infrastructure, stimulating market opportunities and application and growing a skilled workforce focusing on industry needs and free flow of people between sectors. It also focusses on effective regulation and international engagement securing UK as a global supplier of quantum devices, components, systems and expertise. The strategy is supported by a roadmap for different technologies.	• UK National Quantum Technologies programme accelerating the translation of quantum technology to market for UK businesses (2013). • The Quantum Computing and Simulation Hub ensuring collaboration across 17 universities within quantum (2019). • Most start-ups within quantum technologies in Europe are situated in the UK.	• 8.5bn DKK in both government and industry spending from 2014-2019 • 0.75bn DKK investment in four hubs over the next five years pledged through UK national quantum technologies programme
Netherlands	• National agenda for quantum technology (2019)	Quantum delta Netherlands (an organisation uniting the Dutch ecosystem of researchers, start-ups, talents, etc.) made the strategy upon request from the government. The strategy calls for realising research and innovation in both hardware and software in quantum computing, sensing and communication. It also focusses on developing a full ecosystem with research infrastructure, local hubs, international cooperation and by developing human capital through education. The strategy also emphasises the importance of creating broader awareness of the technologies potentials.	• The research centre QuTech situated in TU Delfts bringing together scientists, engineers and industry (2014). • Quantum delta founded to drive the Dutch quantum agenda bringing together five universities in a hub for quantum development (2019).	• 1.1bn DKK in government funding in a quantum research centre over the next 10 years. • 0.25bn DKK the next five years to benefit the photonics sector

B.4 Private equity investments

The private equity investments in quantum companies the past years have been concentrated in Canada, the USA, China, the UK and Switzerland. The centre for computing and software investments is in North America, while China and Europe are the centres for communication.

Investments in quantum companies

88 major deals from 2012-2018 show that investments in companies are primarily in few countries. The data does not show many examples of cross-border investment.

Computing investments are primarily in North America, with D-wave being the primary investment object in Canada.

In software, Canada has most investments and most companies working in the field.

Communication investments are focused in China and in Switzerland with ID Quantique being the company attracting the largest investments in Europe.

Both sensor and instrumentation, tools and services have not attracted large amounts of investments yet. One Danish company did, however, receive a private investment in 2016; Sparrow Quantum got an early stage investment of 1 million € (7,5 million DKK) from Seier Capital, a Danish/Swiss-based investment fund. Sparrow was a spin-out company from Copenhagen University and is still part of the Danish quantum ecosystem.

In total, more than 4bn DKK has been invested over a period of six years showing that quantum technologies have a commercial potential, and this is not counting the investments larger companies are putting into R&D.

Major investments in quantum companies 2012-2018

Country of company	Sum of investment, disclosed deals (million DKK)					Number of deals	
	Computing	Communication	Sensors	Software	Instrumentation, tools and services	Disclosed deals	Undisclosed deal
USA	1,344	75		201	42	23	6
Canada	1,151			374		12	1
Australia	408	104			94	6	
Switzerland		468	1			4	1
UK	13	77	-	135		9	6
China		93*				1	9
Israel		-			35	1	1
Italy	19					1	
Japan	11			5		2	
Denmark					8	1	
Belarus				-			1
Norway				-			1
Singapore				-			2
Total	**2,946**	**818**	**1**	**715**	**179**	60	28

Total number of deals: 88

* The 9 undisclosed deals in Chinese companies are all within communication and are expected to be significant

Source: Supplementary information for News Feature 'Quantum gold rush: the private funding pouring into quantum start-ups' (Nature 574, 22–24; 2019)

The USA and China are the hotspots of development at the moment. The USA is dominant in quantum computing, whereas China is a superpower in quantum communication.

Patents

The number of active patents serve as an indicator of which companies are on the forefront of the development of current technologies.

The current leading companies in quantum computing are mainly situated in the USA, China and Japan with the weight in the USA. Only one European company is present in the top 15.

China is the epicentre of quantum communication and has 13 of the top 15 patent holders.

We could expect these companies to play a significant part in the technological development in the coming years. A positive story for Denmark is that Microsoft has invested in a development centre in the Copenhagen area.

The number of patents do not necessarily tell the entire story. In Europe, a company like ID Quantique based in Switzerland holds valuable active patents, for example for random number distribution. Some companies will also publish new discoveries instead of patenting them. An example of this is IBM's Qis-kit where quantum-relevant software is posted.

Patent holders in quantum computing

Company	HQ country	No. of patent families
IBM	USA	96
D-Wave Systems	Canada	70
Nippon Telegraph & Telephone	Japan	67
Microsoft	USA	66
Beijing University of Post & Telecom	China	64
South China Normal University	China	61
Intel	USA	55
Group Electronics	UK	53
Toshiba	Japan	51
MagiQ Technologies	USA	49
Google	USA	46
Quantumctek	China	45
Anhui Qasky Quantum S&T	China	41
University of S&T of China	China	41
Nec	Japan	39

Source: "Economic impact of Quantum in The Netherlands", Qunatum Delta NL, 2020

Patent holders in quantum communication

Company	HQ country	No. of patent families
Toshiba	Japan	36
Ruban Quantum Technology	China	22
Chinese Academy of Sciences	China	15
Quantumctek	China	12
Huawei Investment & Holding	China	10
Chengdu University of IT	China	9
Pioneer Technology	USA	9
Southeast University	China	9
Zhejian Shenzhou Quantum NT	China	9
University of S&T of China	China	8
Harbin Institute of Technology	China	7
Zhejian Shenzhou Liangzi Network S&T	China	7
Zhejiang Qusenjoy Network Technology	China	6
Anhui Power Jiyuan Software	China	5
Guangxi University for Nationalities	China	5

C.1 What does the Danish ecosystem look like?

The Danish ecosystem for quantum technology is still operating separately from each other and needs central players who engage in order to build a strong foundation for the ecosystem

The Danish ecosystem

The quantum technology ecosystem consists of three layers:

- The core business in quantum technology producing, supplying and distributing the technology.
- The extended enterprise of quantum technology using the technology, supplying products to the core businesses and setting up standards for the products.
- The broader business ecosystem of quantum technology laying the foundation for the industry to grow by providing funding, knowledge and good conditions for businesses.

When assessing the layers of the Danish ecosystem, it becomes obvious that there is still some development to be done.

The core business in Denmark consists of a handful of small start-up companies. The players in the quantum society in general regard this as too little commercial activity, as there is much development happening in the universities today.

The core business in Denmark also consists of Microsoft's quantum materials labs which contribute to Microsoft's ambition of building a scalable quantum computer. This gives the Danish ecosystem access to funding and is creating highly skilled jobs.

The extended enterprise for businesses is currently not at a mature state given the nature of the technologies. There are, however, some advantages in Denmark worth noting.

Industries which can benefit from quantum technologies – such as life sciences and green tech companies – can serve as valuable test beds when developing the technologies. Denmark also has notable suppliers to the quantum technology industry, e.g. NKT photonics who provide sensitive lasers useful for various quantum technologies

It is important that tight links between all the layers of the ecosystem are established.

The broader Danish business ecosystem has both strengths and weaknesses.

On the positive side, Denmark has a strong research community producing a skilled workforce for quantum technologies as well as engaged trade associations driving the agenda. These strengths make it possible for businesses to use cutting-edge technologies and connect with other relevant stakeholders in the industry.

On the less positive side, it seems that investors and venture capital are scarce resources. Government support for basic research in quantum technologies has been strong. In contrast, few players* drive the government support for applying the technologies, which stakeholders considers to be weaker than in our neighbouring countries, both in terms of funding for applied research and innovation and in terms of official support for the agenda.

It is important for Denmark to get the broader business ecosystem to function well to create a solid foundation for quantum technology to be produced and/or developed in Denmark.

*most notably Innovation Fund Denmark and the Ministry of Foreign affairs

Level	Element	Danish situation	Notable Danish players
CORE BUSINESS	Producers	Globally, a lot of companies are working on quantum technologies and some companies have products selling widely. In Denmark, only few companies exist and none of them are established in the market.	Microsoft Quantum Materials Lab, Sparrow Quantum, Quantum Wise, Beamfox, Qdevil, Siphotonics,
	Distribution channels	With few marketed quantum technologies, the distribution channels are still underdeveloped globally and in Denmark.	-
	Direct suppliers	With few marketed quantum technologies, no suppliers of quantum technologies have emerged.	
EXTENDED ENTERPRISE	Indirect suppliers	Denmark has indirect suppliers for producers of quantum technology, the most notable being NKT photonics supplying lasers to the quantum industry globally.	NKT Photonics supplying lasers, Foss
	Direct customers	The Danish economy is highly digitised and will benefit from secure communication enabled by quantum technology. Furthermore, Denmark has a number of key industries that would benefit from computing and sensing, for example life sciences, green tech and transportation.	Danish life sciences companies (Novo Nordisk, Novozymes, Lundbeck, etc.), green tech companies both emerging and established (Vestas, Grundfos) and transportation (Mærsk, DSV)
	Indirect customers	The indirect customers will eventually comprise the majority of Danish consumers and business. But as of now, there are few indirect customers and none worth noting.	-
	Standard bodies	Initial work is done in the EU to establish standards for quantum technology – but none have been established so far. Danish Standardisation Foundation has in 2020 established a Danish committee on quantum standardisation to secure Danish influence on the European work.	Danish Standards Foundation (Dansk Standard)
	Suppliers of complementary products	Danish researchers are working on quantum key distribution that in a few years may be supplied and used with a lot of different products. A few Danish companies are active in this field such as Aarhus-based Cryptomathic making key distribution systems or Zybersafe working with hardware encryption.	Cryptomathic, Zybersafe
BUSINESS ECOSYSTEM	Research and educational institutions	Denmark has a very strong position across a wide range of disciplines within quantum research building on the legacy of Niels Bohr. Danish universities educate a large number of graduates in quantum-related research fields.	The Niels Bohr Institute, DTU, Aarhus University, University of Southern Denmark, Aalborg University
	Trade associations	Denmark has several trade associations heavily engaged in promoting Danish competiveness, not least by supporting the technological agenda including quantum technology.	IT-Branchen, Dansk Industri, Dansk Erhverv
	Government and regulatory bodies	Denmark has a long tradition for public private collaboration supporting Danish innovation and industry development. The Danish government's investments into basic research in the quantum agenda has secured a strong position for the Danish research community. Aside from being engaged in the European quantum agenda, the support from governmental institutions for the quantum agenda is centred around a few proactive institutions.	Innovation Fund Denmark, Invest in Denmark, DFM
	Investors	The Danish venture capital market is generally weak in quantum technologies.	Private investors
	Other stakeholders	Denmark has a number of large foundations which support research, innovation and industry development. A few are already engaged in supporting the quantum technology agenda.	The Danish Industry Foundation, Novo Nordisk Foundation

C.2 Key enablers and strengths of the ecosystem

Interviews show that our strong research institutions and universities are considered to be a Danish stronghold and that some of the leading industries in Denmark can gain significantly from using quantum technology.

Strong research and universities
Danish researchers and universities are top class and famous worldwide, building on the legacy of Niels Bohr within the quantum disciplines. The researchers in the universities are on the forefront of the development across a wide spectre of quantum technologies. Both small and large companies are benefitting from that today in the field of quantum technologies. The strong research society is generally considered to be a key part in releasing Denmark's potential in becoming a leading nation in quantum technology.

Strong life sciences and green energy industries
Denmark has a strong background in life sciences and green energy where quantum technology potentially can revolutionise these sectors. In principle, quantum technologies can improve performances of complicated processes in life sciences (drug discovery, chemical simulation, etc.) and the energy sector (fluid dynamics simulation and energy storage). Cooperation between researchers and these industries could be mutually beneficial moving both into a leading position.

Coveted talent
Denmark has a strong education in quantum science. Universities are working to create quantum science masters. In recent years, many of the players in the Danish ecosystem have experienced it is harder to recruit relevant candidates both in industry and in research as they are increasingly recruited by large international companies when they are still in universities.

Attracting talent through welfare
Players in the industry and in research generally experience an interest in living and working in Denmark due to a good welfare system and work life balance. There are, however, framework conditions making it harder to attract the talents such as bad conditions for spouses and a maximum number of students allowed in universities.

Technological strengths and enablers

On the forefront of photonics research
Denmark is a stronghold for photonics; there are several research groups working both on computing, communication and sensing, as well as companies which are supplying optical components at an international level. Photonics is a key discipline for the second generation quantum computers, quantum secure communication (quantum key distribution) and quantum sensors.

Strong position in quantum materials research and development
Quantum technology needs top quality quantum material in order obtain its full potential, and Denmark already has a strong position in this field. An example of this is the joint work between Microsoft and NBI in Lyngby, where Danish scientists are working to create the underlying material for the creation of topological qubits (which when working would need less qubits to solve large challenges).

Deep dive: Strong research, universities and talents

Denmark has a privileged position to leverage the quantum agenda due to a large concentration of graduates with relevant educations and University of Copenhagen amongst the top universities in Europe and the world.

Talents

In order to attract investments and develop the industry, an attractive talent pool among researchers and graduates is crucial.

Denmark has a strong foundation to build from, which can be leveraged to give Denmark a key position in the second quantum revolution.

In research, University of Copenhagen is amongst the top universities in Europe both when looking at unique authors publishing in large journals and in terms of number of articles and citations. University of Copenhagen is ranked on level with the largest universities in the USA. On top of that, Denmark also has research environments on quantum-relevant issues at other strong universities.

Denmark has the world's highest concentration of graduates enrolled in quantum-relevant educations across physics, mathematics, IT and other related sciences. This indicates that these sciences are a stronghold for Denmark and that Denmark can have a very qualified workforce in quantum-related jobs.

Authors publishing on Quantum (2015-2020)

University	Country	No. unique first authors
University of S&T of China	China	71
Delft University	Netherlands	64
MIT	USA	55
Harvard University	USA	37
University of Maryland	USA	35
University of California (Berkeley)	USA	35
University of Copenhagen	Denmark	35
California Institute of Technology	USA	32
Stanford University	USA	31
Yale University	USA	29
Tsinghua University	China	29
University of Oxford	UK	29
Princeton University	USA	28
University of Waterloo	Canada	28
ETH	Switzerland	26

Graduates (master level) enrolled in quantum-relevant studies (2017)

Country	Number of students per million inhabitants	Number of graduates
Denmark	645	3,753
France	438	29,433
UK	392	26,236
Germany	356	29,491
Australia	280	7,075
Switzerland	280	2,406
Netherlands	263	4,539
Poland	249	9,427
USA	242	79,794
India	217	296,601
Italy	175	10,540
Spain	158	7,364
China	157	218,981
Russia	137	19,787
Korea	116	5,988

Denmark is getting twice as much funding from EU research programmes for quantum projects compared to the general funding level indicating that quantum is a stronghold in Danish research.

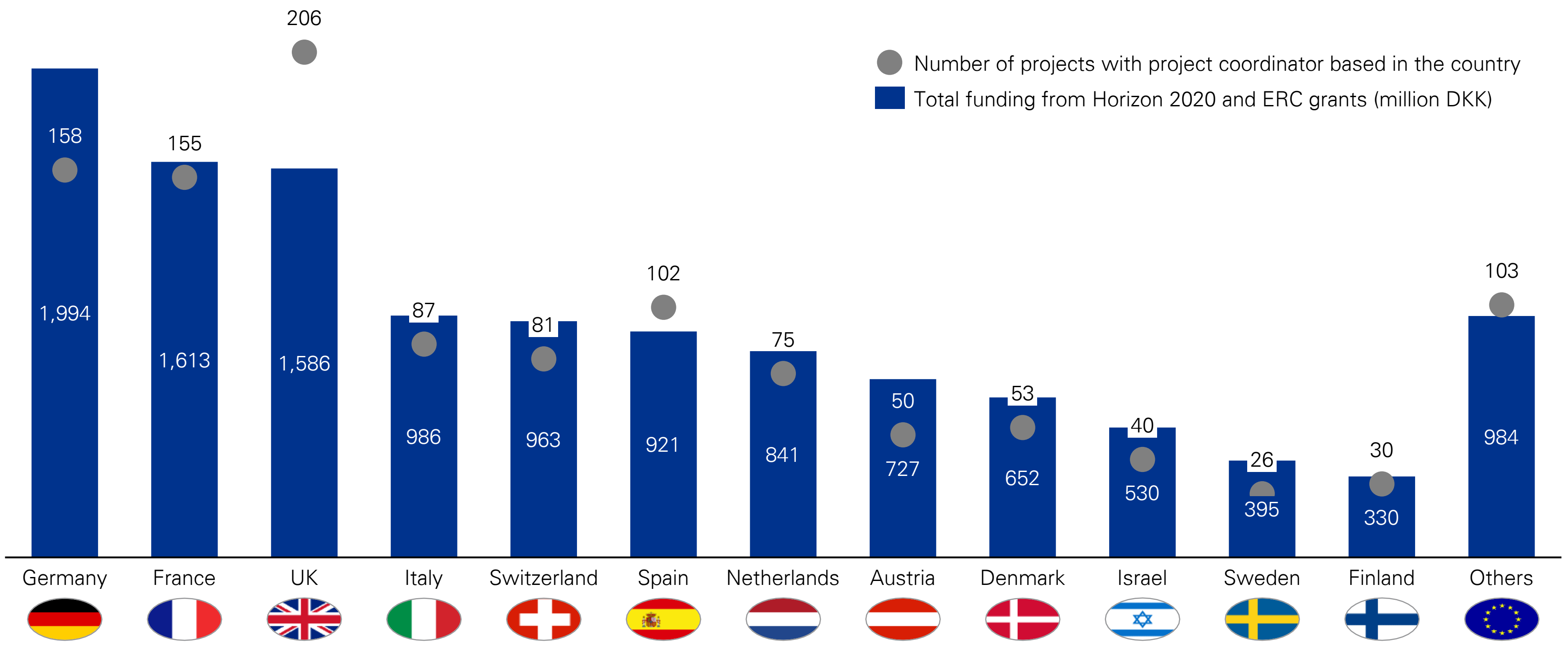
EU research funding

A preliminary analysis of funding for quantum projects shows that projects with Danish coordinators get 5.2 percent of all funding for quantum-relevant projects. The general level for Denmark is 2.6 percent, indicating that quantum technologies are a stronghold in Danish research.

Germany, France and the UK have had coordinating responsibility for approximately 40 percent of the project funding in the latest period, which shows that these countries in general have been driving research and development.

Countries like Denmark, Switzerland and Austria are overperforming on the quantum agenda, which indicates that these countries have a strong research base in this field compared to other research themes.

Funding for quantum projects from EU research programmes (2014-2020), country of project coordinator, million DKK



	Germany	France	UK	Italy	Switzerland	Spain	Netherlands	Austria	Denmark	Israel	Sweden	Finland	Others
Share of quantum funding	16%	13%	13%	8%	8%	7%	7%	6%	5%	4%	3%	3%	8%
Share of general funding	14%	12%	11%	8%	4%	11%	8%	3%	3%	2%	3%	2%	18%

Source: Cordis and own preliminary sorting on quantum technology projects of Horizon 2020 project and ERC grants, 2014-2020.

C.3 Key obstacles for the ecosystem?

Interviews show that the key obstacles for the emergence of a Danish ecosystem are a lack of funding to keep up with our neighbouring countries, an inability to commercialise products, a lack of awareness and government engagement in the agenda.

Inability to commercialise products
Even though Denmark has a large talent pool in the universities and a lot of exciting technologies are being developed, very few start-ups and spin-outs see the light of day. Players in the quantum community explain this fact with several reasons, including lack of a good model in the universities for spin-out and lack of incentives for researchers to quit their exiting job with a high level of security for a risky position they are not trained for. Today, only few collaborations between research and industry are successful which inhibits the researchers to come up with solutions to current challenges in the industry. The strong link between research and industry is especially relevant in quantum technology as the knowledge in the industry about the possibilities these technologies give are lower than the knowledge about the possibilities for applying other technologies.

Lack of awareness
Quantum technology is considered science fiction, and the hype around quantum computers has lowered the expectation of many people seeing this technology as a far away tech. The players in the Danish quantum community see a need to raise awareness about present technologies, their actual potential and the risk associated with them both in the industry and in the broader population.

Lack of coherence among Danish players
The research community is currently focused on basic research in a broad range of quantum-related issues, but there is little focus on exploiting the synergies and applying the research. Moreover, the Danish ecosystem is lacking coherence and coordination in order to exploit synergies, for example between the life science industry and the possibilities of applying quantum technologies.

Lack of funding
There is a general understanding that funding for basic research has been sufficient in Denmark. However, there is also an understanding that funding is missing for important quantum activities in Denmark which is accelerated by the large investments made by other countries. The general assessment is that it is key to fund:

- Cutting-edge research infrastructure to support further development in basic research but also engineering of quantum technologies, for example to exploit the potential of a new Niels Bohr building to its fullest.
- Applied research to reap the benefits of the strong basic research conducted in Denmark.
- Innovation to secure venture capital for Danish companies in the quantum technologies and an environment for start-ups. Innovation Fund Denmark sponsored Qubiz from 2016-2019, which was to help commercialising products, and is still sponsoring innovation projects, but the demand from the quantum community seems to be higher.

Government engagement smaller than in neighbouring countries
The Danish government has to this day funded basic research in quantum technologies to a large extent. Some government actors such as Invest in Denmark and Innovation Fund Denmark are very committed to the quantum agenda. The Danish government is, however, not as engaged as governments in countries like The Netherlands, the UK, France and Germany, which all have prioritised to make official policies on quantum technologies and are all supporting quantum hubs in different forms. Government involvement is generally seen as important in order to attract investments and keep talents in Denmark.

Technological barriers and challenges

Only little software development happening for quantum technologies
Even though software is a fundamental part of all the modern technologies, Denmark does not have a strong research effort in this field. There are strong scattered groups amongst the universities but no start-ups in this field. Software development is in general considered to be immature, and Denmark still has an opportunity to get a good position in the field.

Too small to compete with superpowers on developing full stack quantum computer
Competing with the US, China or Germany for the creation of a quantum computer would require an investment too large for Denmark. Even though some research groups are working on light base quantum computers (DTU) or material for quantum computers (NBI) a full stack quantum computer is generally regarded as too ambitious for Denmark. Denmark is, however, expected to have an opportunity in providing vital components for computers.

C.4 What do Danish stakeholders suggest as next steps?

Interviews with players in the Danish ecosystem show that we have some opportunities to strengthen the collaboration across key stakeholders in the community and that there are both short-term and long-term business opportunities in different technologies.

Strategy for Denmark
Some players are calling for a general national strategy driven by the government as we have seen in our neighbouring countries. The strategy would serve the purpose of prioritising and targeting investments into technologies and applications as well as sending the signal to international investors and potential partners that Denmark is at the forefront of quantum technology. It is seen as equally important that a strategy will help Denmark to take fast action and not make us loose ground in developing new technologies.

A healthy start-up environment
In general, more start-ups are wanted in Denmark. Creating a start-up is not an easy task, and creating one that works with emerging tech is even harder. Establishing a model similar to the Netherlands (with a strong start-up hub in Delft University already attracting a handful of new quantum companies), the UK (with a strong tradition of creating start-ups and spin-outs) or Israel (with a model of start-up based open innovation has proven successful) can improve the success of start-ups in Denmark.

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Collaboration between industry and academia
Academia has know-how and industry has needs. There is a gap between the two, as companies do not know thoroughly what the applications of quantum technologies can bring them, and academia does not have a clear picture of the applications that are actually needed. A framework for mutual beneficial collaboration is needed to release the immanent potential for quantum technologies in Denmark.

Technological opportunities

Quantum key distribution (QKD) could soon be an off-the-shelf product
Europe is working to standardise QKD and there are at the moment no mature European supplier for the technology. Denmark has all the components scattered among start-ups and universities and it is just a matter of creating an off-the-shelf reliable product that can be considered for European critical infrastructure.

The quantum sensor market is mature and could be a short-term opportunity
Quantum sensors are a fair mature product, and most of them are based on optical systems. The commercialisation of quantum sensor can be an opportunity for the Danish and international market.

Quantum software and algorithms are an open playing field
The world is racing to obtain quantum advantage with the present technology. For that to happen, strong algorithms and software are needed and there are currently no clear leader within software development. This serves as an opportunity for Denmark due to a strong tradition in coding and software development.

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