THE QUANTUM SCIENCE AND TECHNOLOGY WORKFORCE IN FINLAND

2035

Institute Q

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FOREWORD

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Quantum mechanics is a century old theory in science; after all these years it is finding its way into technology. One of the achievements has been the demonstration and development of “almost” macroscopic devices, made in a laboratory, which obey the laws of quantum mechanics. Still there is an ongoing struggle to make this mission complete, to make them quantum coherent for long enough periods of time to perform useful tasks.

Finland has pioneered in research areas that have now become the basis of certain quantum technologies, in particular low temperature techniques and superconducting devices. Low Temperature Laboratory on Aalto University campus, founded 60 years ago by Olli V. Lounasmaa, has been the stepping stone for world leading refrigeration technology and industry, and for the development of superconducting interference devices (SQUIDs) that originally served as ultrasensitive detectors of magnetic fields of human brain, but have since been developed into superconducting quantum bits, qubits.

Global competition in quantum technologies is intense, both in research and in industrial applications: quantum computer is the spearhead objective to realize, but lots of potential lies, e.g., in quantum sensing and communication. Progress needs competence in quantum science and technology, which can be achieved by education and training. Therefore, now is the time to consider how we should get quantum-ready as a society. This report is about this challenge with a time perspective of five to ten years. Concretely, this report analyzes how the workforce needs are developing in various sectors of quantum technology, and how this development affects the needs and training on different levels of education, and in retraining on all levels to work in this emerging field.

InstituteQ as a trustee and national representative of quantum science and technology in Finland wants that different stakeholders in the country would be aware of the opportunities that quantum technology can offer and that they operate in line with this growing field of research and industry. InstituteQ also wants to be ready to face its role in realizing and facilitating the competence actions in the forthcoming national quantum technology strategy.

I hope that you find this report useful for you and for the community that you may represent, and that you enjoy reading it.

InstituteQ – The Finnish Quantum Institute is a joint initiative founded by Aalto University, the University of Helsinki, and VTT Technical Research Centre of Finland Ltd. in 2021.

The goal of InstituteQ is to raise the readiness of Finnish society for the disruptive potential and implications quantum technologies will have for society and the economy at large. By teaming up expertise and resources, InstituteQ aims to carry, implement and mutually benefit from front line research, education, innovations, and infrastructures, that form the competitive edge for the Finnish community in the quantum era.

instituteq.fi

Cygnus Quantum Oy is a management consultancy based in Finland. Founded in 2024, the company specializes on strategy, funding, and analytics in deep tech & education and has a special focus on quantum technology in the Nordic region. The company serves both public and private sector organizations.

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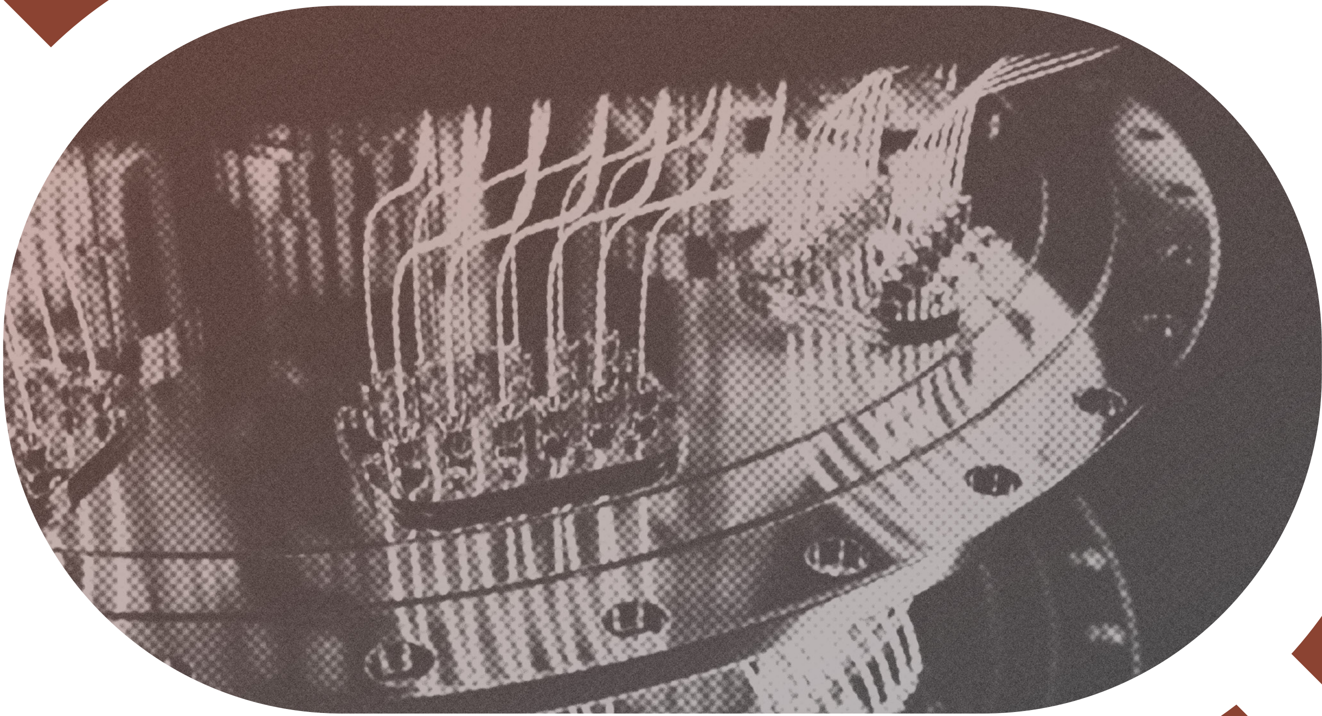


EXECUTIVE SUMMARY

In just a short period of time, Finland has succeeded in creating an exceptionally diverse, high-quality, and well-connected quantum science and technology ecosystem on an international scale. The ecosystem has members from the research and education sector to companies that develop and apply quantum technologies to service sector companies that focus on supporting quantum technology companies in developing their operations and scaling their business.

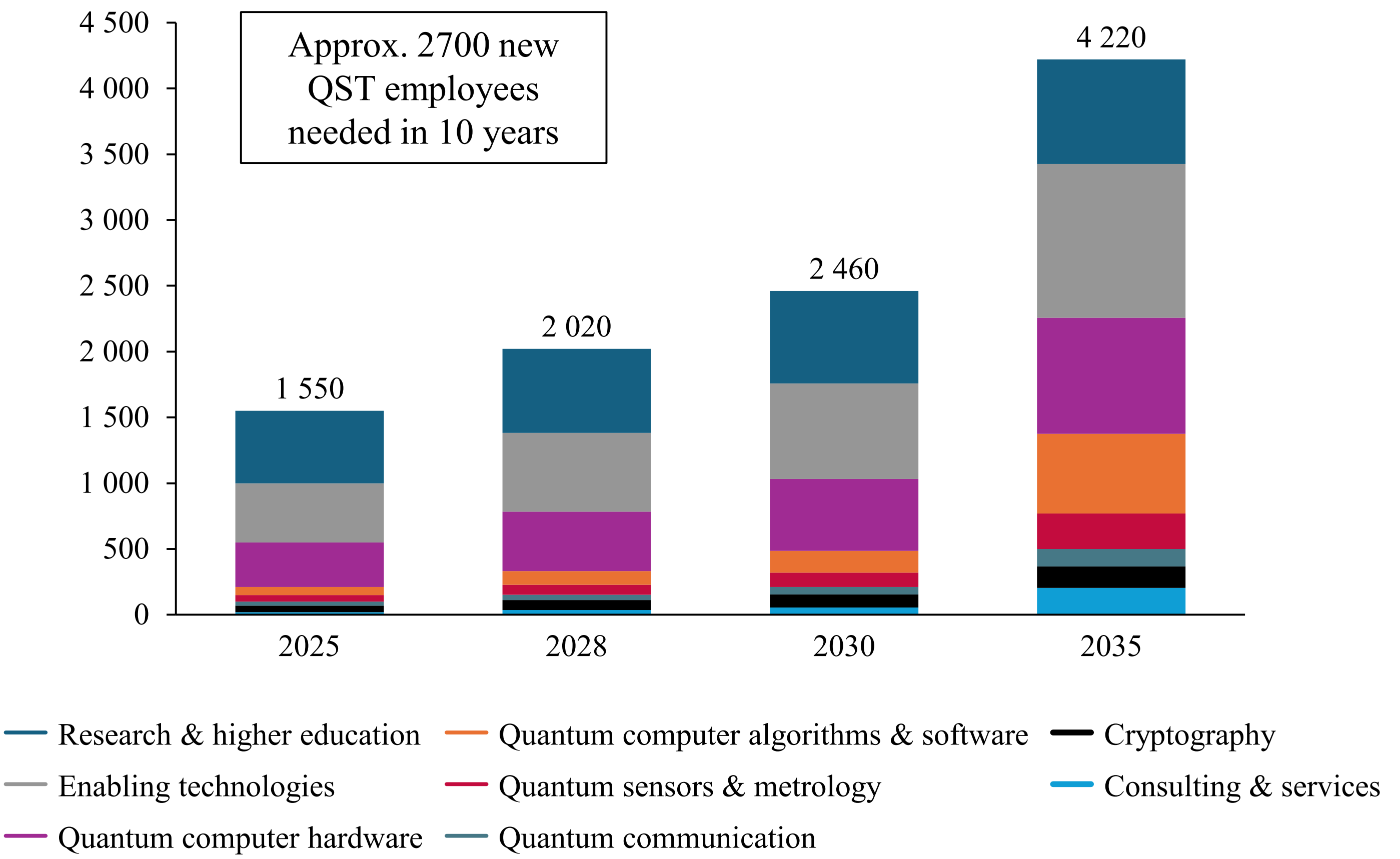
The quantum science and technology sector is estimated to currently employ directly approximately 1,550 people in Finland. Approximately 550 of the workforce is employed in the research and higher education subsector and the rest in companies in various other subsectors. The broader Finnish quantum ecosystem also includes a large number of current and potential future end users of quantum technologies, who are currently testing the different technologies under development, as well as funders, service providers, and other key stakeholders.

If quantum technologies continue to develop as expected and quantum computing in particular begins to yield significant new and commercially valuable applications by the end of the decade, the field has potential to directly employ approx. 2,500 people in Finland in 2030 and more than 4,200 people in 2035. In addition to creating new jobs in the field, the sector has potential to create a significant number of new jobs in other fields, especially in end user companies and organizations connected to the sector's supply chains.

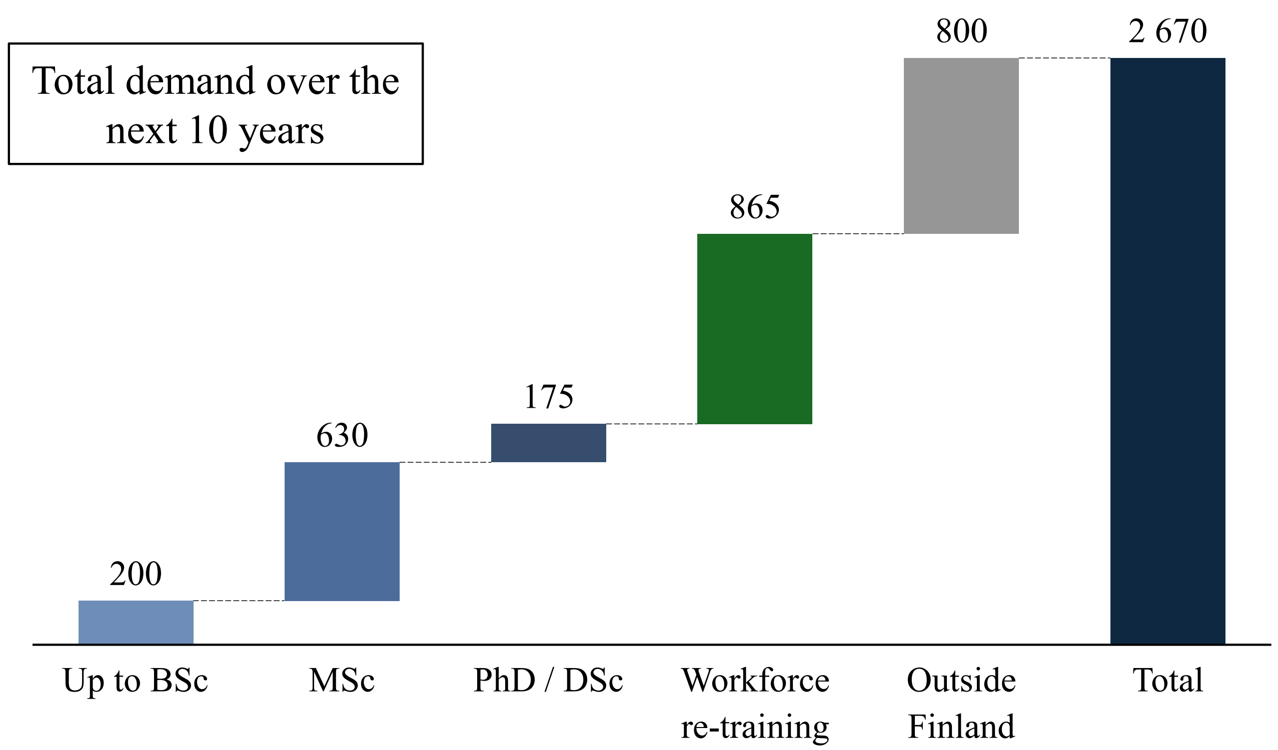
The number of people directly employed in the field is predicted to grow in a controlled manner and, for this purpose, significant increases in the number of students attending higher education or doctoral education will not necessarily be needed in the next five years, assuming that the field attracts students as it has done so far. However, by 2030 and onwards the annual need for workforce re-training is estimated to at least double compared to the current level. We estimate that as also end users will need and benefit from focused training in quantum science and technology topics, the total training need is at least 700 – 1300 people per year.

In order to reach such numbers, preparations for increasing and scaling re-training activities must begin within the next 2-3 years. This means that the re-training focus areas, target groups, objectives, methods, and organizing responsibilities must be developed and agreed upon at the national level as soon as possible. It is also recommended to further streamline the quantum science and technology degree education, as well as harmonize education by offering students joint training modules and cross-institutional study opportunities between different universities and other actors.

Key chart: Estimated quantum science & technology (QST) employee number development in Finland during 2025–35.



Key chart: Estimated new quantum science & technology employees' required training levels or background and their total need in Finland during 2025–35.



INTRODUCTION

How Quantum science and technology will change the world

Quantum technology is based on utilizing quantum phenomena

Quantum science and technology refer to the study and utilization of phenomena in which quantum physics plays a key role. Quantum physics is the science of the most fundamental phenomena in nature and the theory framework that describes them mathematically. The term “quantum” refers to the smallest indivisible properties of nature, such as in the exchange of small, discrete energy packets, i.e. quanta of energy, between atoms.

Often, the study and utilization of quantum physics phenomena require either diving into the nanoscale or extremely low temperatures. In doing so, quantum technologies that utilize quantum phenomena can enable unprecedented precision measurements, the ability to create completely new kinds of materials, and an exponentially faster way to process information and solve different types of computational problems which are otherwise intractable.

Although the key areas of quantum theory were formulated already a hundred years ago and several phenomena based on quantum physics have been successfully utilized for a long time, for example, in smartphones, GPS navigation, lasers, LED lights, and solar panels, it has only been during the recent decades that researchers have learned to effectively manage individual quantum phenomena. The progress has been so rapid and remarkable that the current development has come to be called the “second quantum revolution”. To recognize the importance of quantum science and celebrate the first centennial of quantum physics, the UN has designated 2025 as the International Year of Quantum Science and Technology[1].

Quantum science and technology can be categorized by three main areas:

Quantum computing is a new way of processing information with quantum bits, or qubits, instead of the bits of a classical computer. In the future, the quantum physical nature of qubits is expected to enable an exponentially faster way to process information and solve different types of computational problems much more efficiently than any supercomputer that processes classical, i.e. non-quantum, bits. Quantum computers can utilize various technologies, such as superconductivity or photonics, but they are all still in the development stage. A quantum computer that solves useful problems has not yet been built, however, it is believed that it will happen within the next few years.

Quantum sensing and metrology refer to high-precision measuring devices and measurement methods based on quantum phenomena. They enable significantly higher accuracy than many current technologies in measuring various physical quantities, such as weak magnetic and electric fields or temperature. Various quantum sensors and detectors have already been built, and their properties are being utilized in several different sectors. These applications are discussed below.

Quantum communication is a new type of communication technology based on the laws of quantum physics. Quantum communication is believed to be exceptionally secure, as the so-called Quantum Key Distribution (QKD) enables the detection of eavesdropping attempts on the communication channel. Quantum communication is a technology under development that may one day enable the construction of a global communication network of quantum computers and quantum sensors, i.e. the so-called quantum internet.

Quantum technology has multiple use cases

In the future, quantum computers are expected to work together with artificial intelligence (AI) and classical supercomputers to enable new ways to detect suitable molecules for drug discovery or battery development, model climate change and aerodynamics, and enhance AI training and reduce its emissions. Quantum computers are also believed to be well suited for solving many optimization problems, which may have significant and commercially valuable applications, especially in industry and logistics[2].

On the other hand, quantum computers are believed to soon have the ability to crack many of the traditional methods used for encryption of data storage and transmission, which would enable malicious actors to break into systems that contain or transmit critical information. This has created the need to prepare by updating encryption methods to become quantum-safe and by developing new cryptographic methods[3].

However, quantum technology can also be used to secure data transmission. Quantum communication is believed to be able to protect not only personal data but also financial transactions and diplomatic and military communications in the future. It is also hoped that quantum communication will one day enable parallel quantum computing and, by doing so, solve even trickier computational problems than individual quantum computers are capable of[4].

Already today, quantum sensors and metrology have a wide range of applications from manufacturing to aerospace and defense, and from the microelectronics and semiconductor industries to environmental monitoring[5]. These include many sensitive thermometers, atomic clocks, chemical sensors, and various medical imaging devices that can be used to study, monitor, and develop a wide range of phenomena and applications with unprecedented accuracy. Quantum measurements also play a significant role in the definition of the base units of the international SI system of units, through which they have a remarkable importance for the society across sectors.

Quantum technology has potential to change the world

As technology has developed, society has become increasingly dependent on the semiconductor and materials industries, which are the basis of many modern technologies. In the future, a similar dependence is likely to develop on quantum technology: the ability to understand, manufacture, and apply solutions that benefit the society at large.

At the moment, the biggest bottlenecks to the commoditization of quantum technologies globally are the pace of technological development, the number and price of commercial solutions that attract end users, and the availability of skilled labor. Globally it is estimated that the sector will create as many as 840,000 jobs by 2035[6], but this requires not only the development and commercialization of technology but also training of the necessary workforce. The typically long time span of growing the highly skilled workforce is a challenge that must be quickly resolved in the sector.

In the Finnish context, it is particularly important to ask what kind of effects the expected growth and availability of labor in the sector will have on Finland. How many experts in quantum science and technology will Finland need to educate in the coming years? How many of them will join the workforce right after graduation? How many are expected to find employment in the quantum technology sector from adjacent fields, such as the semiconductor industry? In addition to these questions, it is necessary to ask what kind of training at different levels of qualifications will best serve future experts in this field that is strategically important for both Finland and the European Union.

This report presents the key results of a survey done to answer these questions, as well as a call for action to all quantum science and technology stakeholders in Finland.

Part 1 of the report presents briefly the current Finnish quantum science and technology ecosystem, whereas Part 2 presents an estimate of its expected growth over the next 10 years (until 2035) in different subsectors of the quantum science and technology field. Part 3 presents an overview of the estimated implications for higher education and workforce re-training. After that, we summarize the findings in Conclusions and present our recommendations in the final chapter (Recommendations for key stakeholders). The research methodology is explained in Appendices 1 and 2.

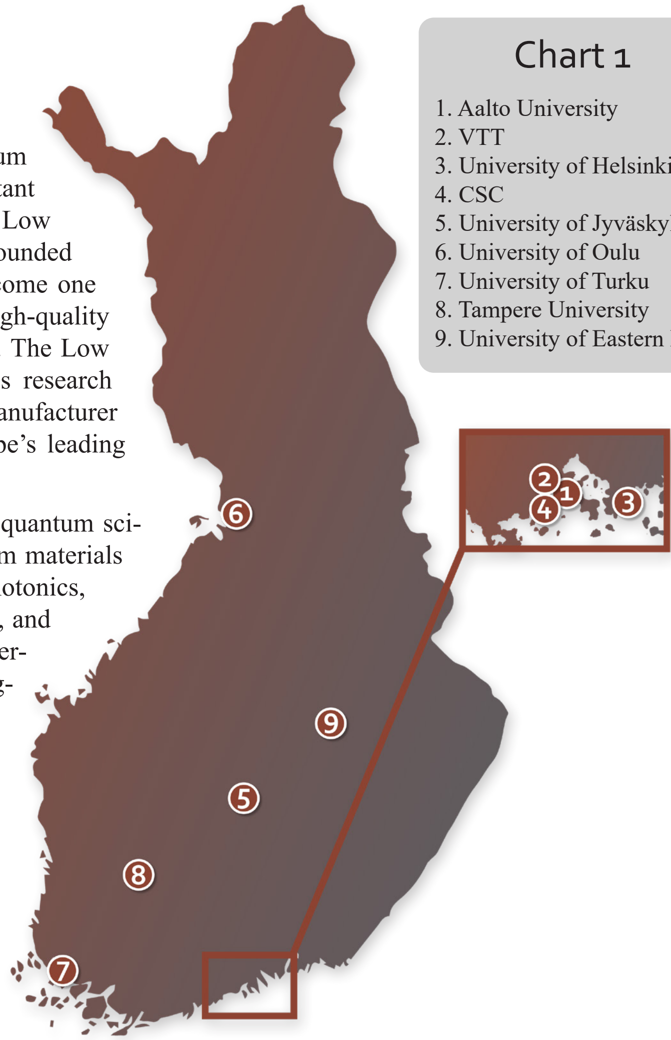
PART 1

The Finnish Quantum Ecosystem

Finland has a world-class Quantum Science & Technology ecosystem

Chart 1

1. Aalto University
2. VTT
3. University of Helsinki
4. CSC
5. University of Jyväskylä
6. University of Oulu
7. University of Turku
8. Tampere University
9. University of Eastern Finland



Since the 1990s, Finland has been investing significantly in quantum science and technology. Yet, the field's roots are deeper: an important part of the research done across the country today dates back to the Low Temperature Laboratory of the Helsinki University of Technology founded in the 1960s[7]. Over the decades the Laboratory has grown to become one of the world's leading research centers in the field, conducting high-quality research in topics such as superconductivity and quantum sensors. The Low Temperature Laboratory has also given rise to many world-class research teams and companies, including Bluefors, the world's leading manufacturer of ultra-low temperature refrigerators, and IQM, known as Europe's leading developer of quantum computers.

Overall, Finland has significant expertise in several subsectors of quantum science and technology. Finland has notable expertise in e.g., quantum materials and devices, superconducting and semiconducting technologies, photonics, quantum sensors and metrology, quantum software and algorithms, and quantum information theory[8]. In addition to these, Finland has expertise in both quantum communication and quantum-related cryptography.

Today, quantum science and technology are researched and developed in almost all Finnish universities. A particularly significant hub in the field is the Helsinki Metropolitan Area, where the ecosystem includes Aalto University, the University of Helsinki, VTT Technical Research Centre of Finland, CSC – IT Center for Science, and a large number of quantum technology companies. The research institutions with direct affiliation to InstituteQ are depicted in Chart 1.

The Finnish ecosystem is brought together by three parties: the InstituteQ established by Aalto University, the University of Helsinki, and VTT Technical Research Centre of Finland; the Finnish Quantum Flagship (FQF)[9] as an integral part of InstituteQ, and the PREIN flagship in photonics[10], funded by the Research Council of Finland. Together these actors bring together the universities and research institutes in Finland, as well as a large number of companies operating in subsectors of quantum technology and the related fields, such as photonics. A large part of these connections dates back to the Quantum Technology Finland[11] (QTF), which operated as one of the Finland's National Centres of Excellence from 2018 to 2025.

In total, quantum physics research and early-stage technological development have attained more than EUR 250 million in public funding in Finland for the years 2020–27[12]. In addition to the Research Council of Finland, notable public sector funders include Business Finland and the State of Finland. The former has funded the field especially through its Quantum Computing campaign which runs during 2023–25, and the latter has granted funding for the acquisition and development of Finland's first own quantum computers.

The state has also allocated EUR 79 million of funding for the acquisition and deployment of shared devices for the new Kvanttinova piloting and development centre in Espoo, which will be completed in 2027[13]. In the future, Kvanttinova will complement the existing OtaNano infrastructure[14] which operates as the national research infrastructure for micro-, nano-, and quantum technologies and which has been on the national research infrastructure roadmap[15] since 2013.

In addition to Finnish funders, research and business development in the field have also been significantly supported by the European Union, especially through its ten-year Quantum Flagship program[16], a large-scale European initiative funded at the EUR 1 billion level on a 10-year timescale since 2018.

The funding has allowed the sector to achieve many significant milestones, such as the completion of Finland's first quantum computer Helmi at Micronova in Otaniemi, Espoo, in 2021. Helmi was built jointly by VTT and IQM and, the parties have subsequently upgraded it to 20 qubits in 2023 and finally to 50 qubits in March 2025[17].

In addition to building and developing its own quantum computers, Finland is also involved in a European project called OpenSuperQPlus, which is building a 1,000-qubit quantum computer for Europe[18]. Finland is also involved in several other significant international networks and collaborations, such as the EuroQCI project. The project, which will be implemented in all European Union member states at the same time, targets at developing and building national test networks in each country to enable a new kind of quantum communication[19]. In Finland, the initiative is being implemented by the NaQCI.fi project[20].

At the moment, Finland is also preparing a national quantum technology strategy, which aims to harness quantum science and technology to an engine creating a sustainable future and economic growth[21]. The strategy is scheduled to be published in spring 2025.

Finland has a sizeable and diverse Quantum technology value chain

Investments in world-class research and infrastructures have enabled quantum science to rise from the laboratory to an increasingly business-driven technology. The growth of the sector has accelerated in the 2020s, and a comprehensive value chain in quantum technologies has emerged in Finland in just a short period of time. The value chain includes companies from the enabling technologies subsector (e.g., Bluefors) to quantum computer components and hardware (e.g. IQM, SemiQon, Modulight), and from algorithms and software (Algorithmiq, QMill, Quanscient, QuantrolOx) to companies focusing on quantum communication and cryptography (e.g. Cinia, Erillisverkot, SSH, Xiphera). An overview of the value chain is presented in Chart 2.

In total, the Finnish quantum start-up companies have raised a significant amount of growth funding, approx. EUR 240 million, during 2019–24[22]. At the same time, the growth of the industry has created a large number of jobs, and also changed the skills sets required from employees. Because quantum technologies are based on the laws of quantum physics which differ in many ways from classical physics and its traditional applications, the development of technologies that utilize quantum phenomena often requires highly developed special skills. However, as quantum technologies become more common, there is need for talent on a wide range. In the future, the required expertise is not limited to just design, manufacturing, or development of applications in quantum technologies, as discussed in more detail in Part 3. An overview of some of the most common jobs in the field and their placement in the quantum value chain is presented in Chart 3.

In total, the field is estimated to currently employ about 1,550 experts in Finland (see Chart 4). A significant part of the experts (approx. 550 people) work in the research & higher education subsector at universities, VTT, or CSC, which is natural due to the early stage of development of quantum technologies. In this report, with the research and higher education subsector we refer specifically to employees working in the public sector, VTT or CSC, not to research and product development done in the private sector.

Currently the second and third largest quantum science and technology subsectors are the enabling technologies and the development and manufacture of quantum computers' components and hardware. The associated numbers, 450 and 340 employees, respectively, are largely due to the industry's largest domestic employers, Bluefors and IQM, which together employ more than 600 people in Finland. In addition to these companies, several companies focusing on quantum computer algorithm and software development have already been established in Finland, but they are currently small in terms of the number of employees. Together they are estimated to currently employ approx. 60 people in Finland.

It is estimated that approx. 130 people in Finland are currently working on quantum technologies other than those related to the development of quantum computers or their applications. Such fields include quantum sensors and metrology, as well as quantum communication and quantum-relevant cryptography. However, it is estimated that currently the majority of experts in these subsectors, especially those working with various encryption methods, do not focus full-time on quantum technologies but carry out related research, product development, and customer service work as part of their main duties.

In addition to the above-mentioned subsectors, a small service sector has already emerged to serve companies developing quantum technologies in Finland. This subsector mainly consists of consultants and analysts familiar with the field. It is estimated that a total of approx. 20 people currently work in the sector, some full-time and others part-time.

As the technologies develop further, and especially as quantum computing applications become more common, the number of employees in the field overall is likely to increase in the future. The following sections focus on how the number of employees and the qualitative skills and training needs in the field are expected to change over the next ten years (2025–2035).

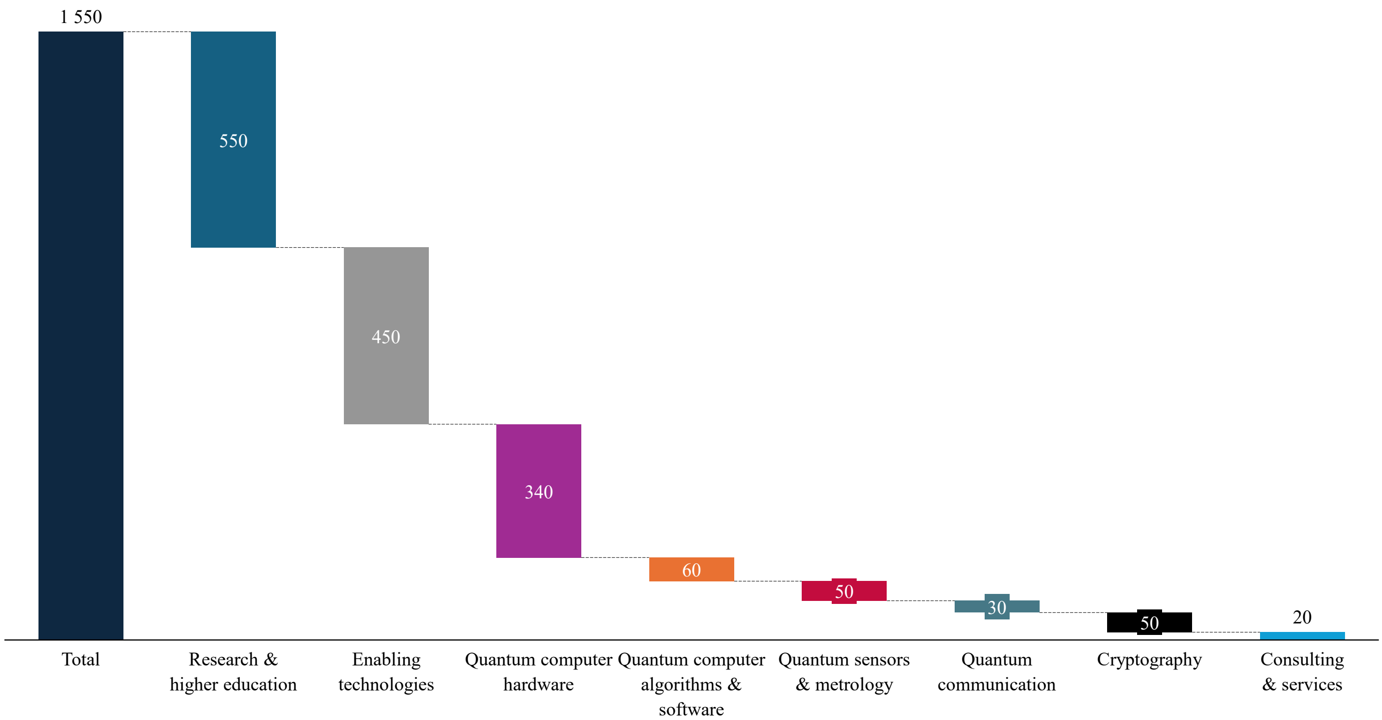
Chart 2: Overview of the quantum science & technology sector in Finland in 2025

Quantum science & technology sector	Description	Example companies in Finland
Research & higher education	Universities and other public research institutes (VTT, CSC)	Aalto University, VTT, Helsingin yliopisto, CSC
Enabling technologies	Critical technology providers for other quantum technologies, e.g., cryogenics	Bluefors
Quantum computer hardware	Full stack QC and component manufacturers	IQM, SemiQon, modulight
Quantum computer algorithms & software	Quantum algorithm & QC software developers	Quanscient, QMill, algorithmiq
Quantum sensors and metrology	2nd gen. quantum sensor developers and quantum metrology service (e.g., atomic clocks) providers	VTT, MEGIN, aivon
Quantum communications	Communications (e.g., QKD) network and device manufacturers	Cinia, CSC, Erillisverkot
Quantum-relevant cryptography	PQC and quantum cryptography developers and service providers	ssh, Xiphera, F-Secure
Consulting & services	Technical & management consultancies directly serving quantum technology market actors	Cygnus Quantum, Unitary Zero Space, August

Chart 3: Examples of quantum science & technology experts across value chain (2025)

Research & education	Enabling technologies	Hardware development	Software development	Business operations
Professor	Laboratory engineer	Quantum engineer	Quantum algorithm engineer	Technical consultant
University lecturer	Cryogenic engineer	RF engineer	Quantum software engineer	Technical sales specialist
Postdoctoral researcher	R&D Scientist	IC Designer	Quantum chemist	Management consultant
Doctoral researcher	Application specialist	Fabrication engineer	Full stack developer	Chief Technology Officer
Research assistant	Assembly technician	Metrology engineer	Back-/Front-end engineer	Technical team lead
Technician	Electrical engineer	System delivery engineer	Quantum information scientist	Product designer
Coordinator				Procurement specialist
				Business analyst

Chart 4: The quantum science and technology sector currently employs 1550 experts in Finland (2025). Data source: Interviews with 30+ representatives from Finnish research & technology institutes and companies.



PART 2

The future of quantum science and technology in Finland: Years 2025-2035

Most quantum technologies are emerging, but some are already here

Quantum technologies have developed rapidly over the past 20 years. Some technologies are still experimental or in transition from research to product development and commercialization, while in certain subsectors of the field, the utilization of quantum phenomena is already an existing practice with significant commercial applications.

Examples of the former class are quantum computers and quantum communication. For the time being, they are mainly considered experimental technologies, the large-scale commercial benefits of which are estimated to be another 5–10 years away[23]. Correspondingly, the development of quantum algorithms and software, as well as the growth of supply of consulting and other services in the field, strongly depend on the developments seen in the hardware side of quantum computers. On the other hand, the development of useful quantum algorithms for quantum computers today or in the near future can accelerate the development of the field on a large scale, including on the hardware side of quantum computers, as the resources allocated to it will likely increase.

The uncertainties listed above also apply to quantum-associated cryptography. The growth of the industry will largely depend on how quickly quantum computers develop in the future and how quickly they are believed to break traditional encryption methods such as the RSA algorithm[24].

On the other hand, the development of quantum sensors and metrology services and products that utilize quantum physics, such as high-precision atomic clocks, brain imaging devices, or satellite-independent navigation systems, is at a much more mature stage. However, at the moment there are only few companies operating in Finland, such as VTT, Aivon, and Megin. It is possible that due to the mature level of technological development and the demand generated by both the medical imaging and defense industries, more companies specializing in the utilization of quantum properties will emerge in the field. Such development can significantly increase the number of employees in the sector in the future.

Quantum technologies are estimated to create 2,700 new jobs in Finland by 2035

In this section, we present an estimate of the number of new jobs created in the field in Finland and their distribution in different quantum science and technology subsectors over the next ten years, i.e. until 2035. The estimates are based on expert interviews, company websites, and forecasts for the development of technologies and the related market growth as presented in various industry reports, adapted to the situation in Finland today.

The following analysis is based on a base scenario, the main assumptions of which are presented in Table 1.

Table 1: Benchmark scenario for the analysis

The analysis is based on the following assumptions:

1. The QST[25] employee numbers will grow at a steady rate until 2030 – With some QST subsectors such as Quantum algorithms & software development, Quantum sensors & metrology seeing accelerating growth in employee numbers already before the year 2030.

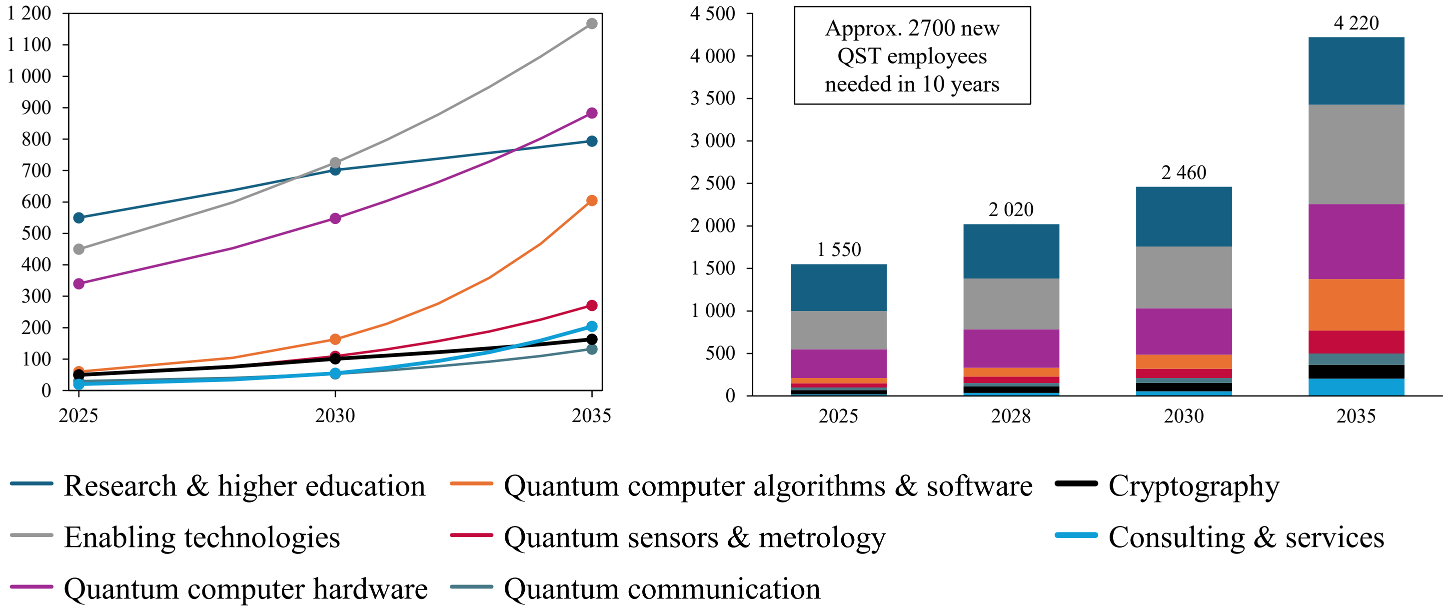
2. Emergence of quantum computing utility applications will take place by 2030, leading to a surge of new applications and use cases in the 2030s and to an accelerating employee number growth in most QST subsectors.

3. The numbers are scenario-agnostic – Organic growth, establishment of new QST companies, possible merger & acquisition scenarios, major quantum companies moving operations to or from Finland etc. are all implicitly covered by the QST subsector-specific growth rates. As a base scenario, it is assumed that across all subsectors and years 30% of the new employees will come outside Finland. Deviations from this scenario and its implications for education & workforce re-training are presented in Part 3.

More detailed descriptions of the benchmark scenario and the research methodology are given in Appendices 1 & 2.

Estimates of the workforce growth and job placement across QST subsectors based on these assumptions are presented in Chart 5.

Chart 5: Estimated quantum science and technology (QST) workforce growth in Finland between 2025–2035.



In total, the number of direct jobs in quantum research and technology field is estimated to increase by a total of about 2,700 people by 2035. At that time, it is estimated that slightly more than 4,200 people work in the field. This means that the size of the field will almost triple from the present scale during the next ten years. The sector would then be slightly smaller than the Finnish photonics or semiconductor sectors are today, as these similar but distinct sectors have been estimated to currently employ directly approx. 6,000 and 7,000 professionals, respectively[26].

The most significant part of the QST sector growth is likely to take place in the 2030s when quantum technologies and their applications, accelerated in particular by quantum computing, become more common and the companies developing them increase their number of employees with the increase of demand for their products and services. However, it is estimated that the total number of jobs will increase by almost a thousand already by 2030. At that point, approx. 2,500 people are estimated to work in the field in Finland. During 2030-2035, the estimated increase is approx. 1,800 employees – roughly double compared to the growth between 2025 and 2030.

Below, we present in more detail how the jobs are estimated to be distributed across quantum science and technology subsectors.

Research & higher education: Number of jobs in public sector research & higher education is estimated to grow at a small but steady 5% annual rate until 2030, and after that at a slightly lower rate of 2.5% a year as technology moves from lab to market and fundamental research re-focuses on new topics. However, as most of the quantum technologies of the future are still in the research phase or otherwise at early stages of development, a strong emphasis on fundamental research and investments in it can be seen as a prerequisite for the growth of the sector as a whole. In total, this subsector is estimated to grow to about 700 people by 2030 and to approx. 800 people by 2035.

Enabling technologies: Number of jobs in enabling technologies is estimated to grow at a steady 10% rate a year until 2035. In general, the growth of the subsector largely depends on the development of quantum computer hardware, but considering Bluefors' position as the world's leading manufacturer of cryostats and cryogenic measurement systems, the growth of this subsector in Finland is less dependent on, for example, success of individual hardware manufacturers or even type of quantum computer technologies. It is estimated that approximately 700 people will work in this subsector in Finland in 2030 and nearly 1,200 in 2035.

Quantum computer hardware: Number of jobs in quantum computer hardware is estimated to grow at a steady 10% rate a year until 2035. Although the demand for quantum computers may grow much faster than this, especially in the early 2030s, the industrialization of production and the possibility of process automatization and component sourcing outside Finland are likely to keep the growth of jobs in Finland fairly stable. This subsector is still estimated to see strong growth: the number of jobs is estimated to grow to 550 people by 2030 and to almost 900 people by 2035.

Quantum computer algorithms & software: Number of jobs in quantum computing algorithms and software is estimated to grow at an increasing rate: we estimate 20% annual growth until 2028, then a 25% annual growth until 2030, and finally a 30% annual growth until 2035. The high growth rates are based on the assumption that significant and commercially valuable applications for quantum computers will be developed by the early 2030s at the latest. Thus, this subsector could grow in Finland from the current 60 people to approx. 160 employees by 2030 and up to 600 employees by 2035. This would mean a tenfold increase compared to the current number.

It is noteworthy that although the development of quantum algorithms and software is likely to become globally a larger industry than the component and hardware manufacturing subsector, the starting point in Finland differs from the global situation. At present, Finland is a global leader in the manufacture of cryostats and the provision of cryogenic measurement systems (Bluefors), and among the leading countries in Europe in the development of superconducting quantum computers (IQM). The growth of both of these subsectors is expected to remain particularly strong in the future.

Therefore, even though multiple start-up companies focusing on quantum algorithm and software development have already emerged in Finland, it will be difficult for them to reach the number of employees in the hardware sector in the near future. The quantum algorithm and software companies should grow or increase in number so that their combined amount of employees would grow annually at an average rate higher than 40% for them to reach the estimated numbers presented here for the jobs in the quantum hardware subsector.

Such growth is probably neither realistic nor necessary, as algorithm and software development is a highly scalable business. Even a small number of employees can generate significant revenue, up to hundreds of millions or, at best, billions a year, with a successfully developed and scaled algorithm or software. Therefore, being successful does not necessarily require a significant increase in the number of employees.

Quantum sensors & metrology: As these technologies are already at a relatively mature stage of development compared to other modern quantum technologies and there are existing products in the field, this subsector is expected to grow fairly strongly in the future. The number of jobs is expected to grow by 15% year-on-year until 2030, and then by 20% year-on-year until 2035. Thus, approx. 110 people are projected to work directly in this subsector in Finland in 2030. For the year 2035 we estimate a number slightly less than 280 in this subsector.

Quantum communication: Quantum communication is likely to remain a small subsector in terms of the number of jobs: it is estimated that the number of jobs in this subsector in Finland will grow annually at a level of 10% until 2028 and thereafter at a level of 15–20% by 2035, provided expected success is seen in quantum communication hardware development and testing. Thus, according to our forecast, approx. 50 people will work in this subsector in 2030 and roughly 130 people in 2035.

However, this estimate includes notable uncertainties, as the quantum key distribution technologies are still largely in the research phase and expectations of their usefulness and commercial viability vary among experts. The quantitative estimate presented here assumes that the technology will develop in a positive direction in the near future and that more and more test and end users are found. As a result, the subsector would need more employees, but a big jump in the number of jobs is unlikely to be seen in this sector at least in the next ten years. However, an exception to this could be, for example, a situation in which a global company that builds QKD devices or offers related services is established in Finland. This would be a very positive scenario that would likely result in a higher number of jobs in the subsector within the next 5–10 years.

Quantum-relevant cryptography: In this report, cryptography refers to two areas: on one hand, so-called post-quantum cryptography (PQC), which is just classical algorithms that are used to overcome the threats posed by quantum computers regarding the cracking of many traditional encryption methods, and on the other hand, potential future encryption methods that utilize the laws of quantum information. The latter is a fairly small sector on a global scale and we do not expect significant development in the number of employees in that area until the 2030s at the earliest.

However, the former, i.e. PQC, is an area that is likely to see a significant increase in the number of employees in the near future. A notable part of this is related to the development of various PQC products developed for consumers and companies, and to the so-called PQC migration of systems used by companies and other organizations. This refers to a scenario in which various digital systems and equipment are upgraded to become quantum-safe. Since the US-based National Institute of Standards and Technology (NIST) has already published the first quantum-safe (PQC) encryption algorithm standards[27], this kind of development is likely to be rapid in the next few years and result in the subsector employing a large number of different IT and cryptography experts and consultants for the migration process.

In total, the growth of employees in this subsector is estimated to increase at an annual rate of about 15% until 2030, after which the growth in the number of experts is estimated to continue but slow down to about 10% rate for annual growth. Thus, according to the forecast, this subsector will employ about 100 people in Finland in 2030 and just over 160 people in 2035.

However, the increase in the number of jobs depends strongly on the time frame in which quantum computers are believed to be able to crack many of the encryption methods currently in use and how quickly companies outside the quantum sector react to the threat. A significant additional growth in the number of employees in this subsector could also arise in a situation where Finnish companies would succeed in developing products or services related to valuable new quantum-related encryption technologies (e.g., software or certificates) for which there would be significant global demand.

Consulting & services: In this report, consultants and other service providers, such as analysts who serve private funders or banks, refer to employees directly working in quantum technology fields or serving the wider quantum ecosystem. Some consultants and other service providers are generalists who primarily focus on business development, while others focus on issues that require more technical expertise, such as hardware integration or design of software products for consumers.

The demand for services provided by this subsector is expected to increase significantly in the future. In terms of employee numbers, we expect growth which is first at a 20–25% annual level by 2030 and then at a 30% annual level until 2035. Thus, it is estimated that slightly more than 50 people will work in this subsector in Finland in 2030 and slightly over 200 people in 2035.

The estimated growth is realistic but depends on two important factors

In general, the above estimates can be considered conservative despite the relatively high annual growth rates for the number of employees assumed for different subsectors. Overall, the quantum science and technology sector is associated with high growth expectations and is currently attaining broad support from both the public and private sectors. As the industry takes a leap forward, especially in regards to quantum computing applications, the total number of employees in the sector could become even higher than what is estimated here for the year 2035.

On the other hand, the development of quantum computing and most other quantum technologies is also associated with considerable uncertainties, especially regarding the pace of technological development, commercialization channels, and the willingness of potential end-user companies to adopt new technologies. A particular risk for the growth is the so-called quantum winter which, if realized, would reduce investments in the sector and, consequently, also slow down technological development and the growth in the number of employees working in the field. Even then, an exception to this could still be the quantum sensors and metrology services subsector due to the high maturity of the related technologies.

In total, the quantum science and technology sector is projected to grow to 4,200 employees, i.e. slightly less than three times its current size, by 2035. The forecast is in line with the growth expectations for the industry's overall annual turnover in Finland[28], assuming that over the next ten years the technologies and their commercialization will develop and scale so that the sector's turnover per employee will triple from the 2023 level[29]. The expectation can be considered plausible, considering the early stage of the industry at present.

The projected growth also matches with the expectations set for the semiconductor industry in the recent semiconductor strategy for Finland. The sector is projected to grow from the present, approx. 7,000 employees, to approx. 20,000 employees by 2035[30], i.e. slightly less than tripling in total employee number. As the quantum industry is subject to greater uncertainties than the mature semiconductor industry and the overall growth can in the end be either higher or lower compared to the estimate presented in this report, we regard the same growth rate as found for the semiconductor industry to be a good midway benchmark.

At the end of this section, it is worth noting two important points:

1. The projected increase in the number of employees in the quantum science and technology sector only applies to those who are directly employed in the field. In addition to the more than 4,200 employees working in the sector in 2035, the number of employees who utilize quantum technologies and gain a competitive advantage indirectly from them, as well as those working in companies connected to the sector's supply chains, may be many times higher than the number of employees directly employed in the sector. In this report, we have not estimated the magnitude of these fields.

2. The quantum science and technology sector will only see the predicted increase in the number of employees if the number of domestic university graduates and workforce undergoing re-training, as well as the total number of workforce arriving from abroad, matches to the forecasted need. We will discuss these needs and their implications for education and workforce re-training in more detail in the next section.

Together, points 1–2 also raise the question of what kind of training should be given to the future experts working in this field so that quantum technologies develop and mature as expected and eventually find end users who understand the added value of quantum and know how to make use of it. We will focus on this question in more detail in the next section.

PART 3

Implications for higher education and workforce re-training

Present efforts are likely to suffice until 2030, but need to grow after that

As quantum science and technology sector develops and grows, the field requires diverse expertise from the bachelor to doctoral level and, in certain situations, also from the vocational level. The growth of the sector will also require additional training for the workforce (called re-training in this report) and a large amount of foreign labor. The distribution of projected workforce growth at different levels is shown in Chart 6.

Chart 6 assumes the base scenario, i.e. across sectors 30% of all new employees will come outside Finland, the additional training of the workforce currently employed in adjacent fields to the quantum sector will cover 5–40% of the growth in the number of employees in the quantum sector (the share depending on the subsector – assumed to be the smallest in research and higher education, highest in enabling technologies, quantum communication, quantum sensors and metrology, and in consulting and services), and the rest of the future employees will come from vocational education or as recent graduates with a university degree.

The numbers at different degree levels have been estimated based on the semiconductor strategy for Finland[31] so that from 2030 onwards, the distribution of degrees will correspond to the semiconductor industry: 20% of the new employees will hold up to bachelor's degree, 70% have a master's degree and 10% have a doctoral degree. However, as the quantum science and technology sector is still in a less mature stage of development and currently requires more doctoral expertise than the more mature semiconductor sector, the required number of doctoral degree holders is estimated to be 30% and the number of master's degree holders 50% of all new graduates before the year 2030.

Similar degree figures have also been assumed for the scenario where the share of people employed from abroad accounts for 50% of the total number of new employees. The effect of this on the number of employees at different degree levels is presented in Table 2.

Chart 6: Total number of graduates and other workforce needed in Finland by 2035 to accommodate the need of companies and public sector organizations directly employing in the quantum science and technology sector.

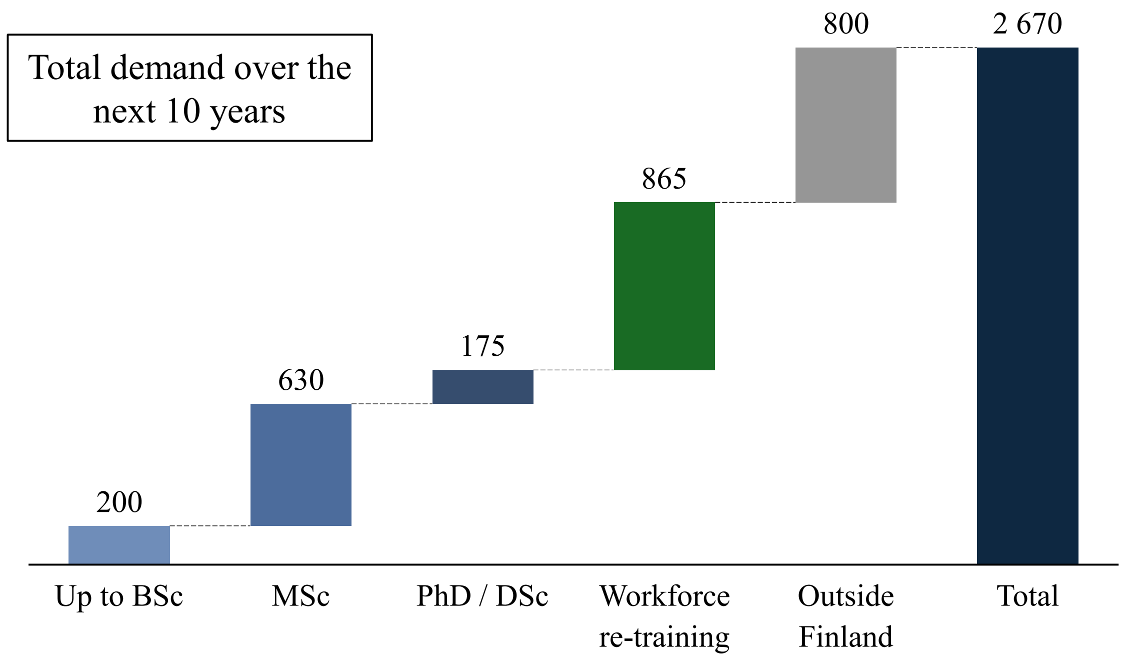
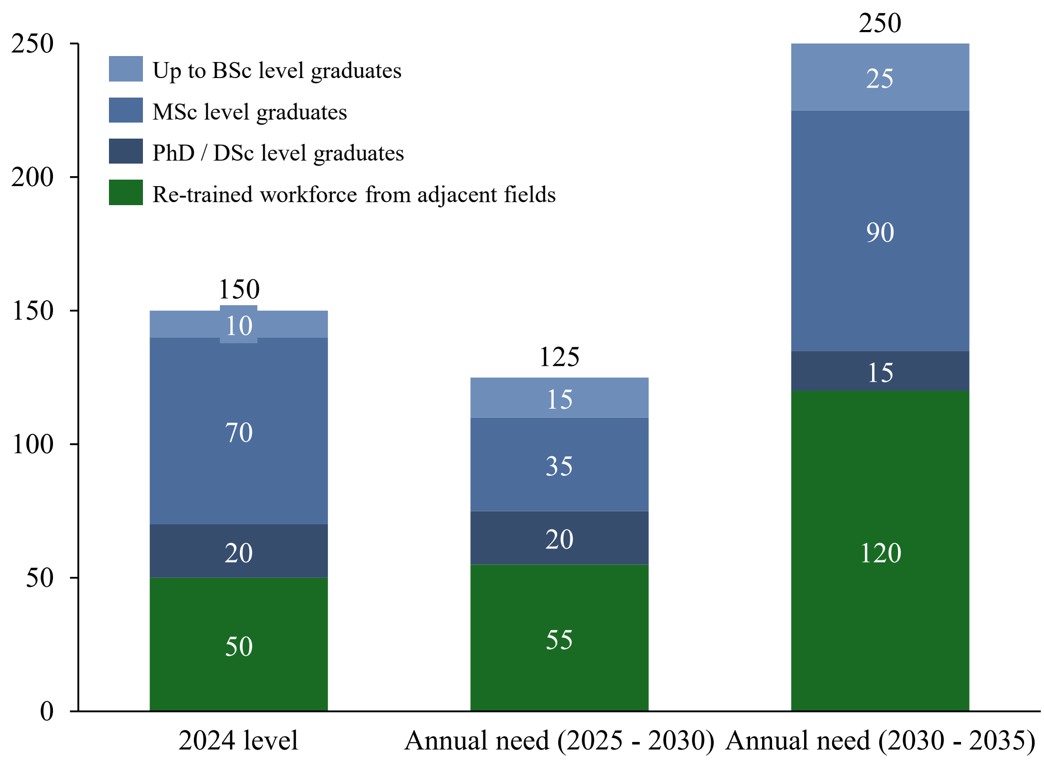


Table 2: Total number of required graduates & re-trained workforce during 2025 – 2035 depending on the share of workforce coming outside Finland.

Share of employees coming outside Finland (% of all)	**30%**	**50%**
Outside Finland (absolute number)	800	1335
Up to BSc degree graduates	200	140
MSc graduates	630	450
PhD / DSc graduates	175	125
Re-trained workforce from adjacent fields	865	620
Total	**2670**	**2670**

It is useful to compare these numbers to the current annual training volumes. The training volumes for 2024 and the projected annual training need for 2025–2030 and 2030–2035 are presented in Chart 7. Note that the projected training need does not account for current employees' change of field, retirement, or other factors that could result in a potential decrease in the overall employee number (4,200 employees by the year 2035).

Chart 7: Present and required annual quantum science and technology education & workforce re-training levels in Finland during 2025–35. Note that the projected numbers only concern those employed directly in the field.



The current number of graduates at different degree levels have been estimated based on the number of master degree students in quantum science and technology fields in Finnish universities in 2024. The current level of annual workforce re-training is based on the total number of participants attending the quantum computing trainings organized by CSC every year.

It should be noted that although it is already possible to learn about quantum computing and its potential future applications through, for example, various lectures and webinars, the actual application of quantum technology requires more advanced skills. For this reason, the number of people who have actually been re-trained is currently low in the field.

Based on this estimate, it seems that unless there are significant changes to the estimated development of the field, the current annual training volumes are already sufficient for the research and product development needs of the quantum science and technology sector during the years 2025–2030. In terms of doctoral education, there seems to be a slight additional need for the number of doctoral graduates during 2025–30 compared to the 2024 level but this will be compensated for by researchers currently in the Quantum Doctoral Programme QDOC[32], as the number of graduates from that program will greatly exceed the level of 2024 in the next few years.

As we move to the 2030s, the annual need is estimated to grow to about 90 master level graduates a year and to about 25 graduates with up to a bachelor's degree a year. In terms of the annual number of doctoral graduates, it is sufficient to remain at about 10–20 graduates a year also from the year 2030 onwards. These numbers may seem small but the relative decline in the share of doctors can be seen as a natural consequence of technological development in the field and the commoditization of commercial applications.

We reiterate that the estimated growth in this report only concerns those directly employed in the quantum science and technology sector. In addition to these employees, also quantum technology end users as well as other sectors are likely to benefit from employees having expertise in quantum science and technology. The total training need at all graduate levels may thus be higher than that estimated in this report.

The annual need for workforce re-training is estimated to increase from the current approx. 50 employees a year to approx. 120 people a year by 2030 to accommodate the growing needs of industry. In addition to those directly employed in the field, quantum technology end users and others benefitting indirectly from it will need re-training in the future. Since there is no direct point of comparison from other fields and there are many different needs among future employees — one may only need to learn about the applications of quantum computers, another about the physics behind quantum communication — it is difficult to estimate the number of such additional trainees. However, it can be roughly estimated that in the end user category the number is at least 5–10 times higher than the number of people who will be directly employed in the quantum technology sector after re-training. In that case, the annual training need of at least 600–1,200 people a year would be forecast by 2030. Together with the professionals directly employed in the field the training need would thus be approx. 700–1,300 people a year by 2030.

Education and re-training should be tailored for different focus groups

In addition to quantitative estimates, it is important to assess the qualitative requirements for the training of students, the current workforce in adjacent fields, and the end users.

As the majority of experts in Finland are estimated to work with enabling technologies and quantum computer hardware in the future, a lot of key skills of an experimental physicist and engineers will be needed in the future. For example, currently important skills such as quantum chip design and manufacturing, as well as e.g., radio frequency, electrical, and mechanical engineering are all important skills in the future too.

Until now, the quantum industry has preferred experienced and highly educated employees who can do different things flexibly but it is likely that in the future increased specialization will be needed. This change makes it easier for engineers who are not familiar with quantum physics to find employment in the sector through only light additional training, especially in the component and hardware development sector.

In the future, working on quantum computing in particular is likely to become less dependent on understanding the underlying laws of quantum physics as the hardware and software hierarchy grow. This is likely to be reflected in the education and re-training requirements of those employed in the field already in the mid-term, so that not everyone who uses a quantum computer or classical-quantum hybrid computing, or develops software for them, needs to have a deep understanding of quantum physics or quantum information theory. In the future, end-to-end software development and, for example, product support will become more common so that in the near future, the quantum computing industry may need more traditional software engineers than those who also have expertise in quantum algorithms or software.

In the longer term, the same type of change is likely to happen with end users. While quantum computing is expected to create significant new applications and enable exponentially more efficient problem-solving in certain fields such as drug discovery or logistics, quantum computing is unlikely to significantly transform the jobs of most end users or create entirely new professions in this sector. In this sense, the development of quantum computing is reminiscent of the prevalence of AI in the early 2020s: the more common the applications become, the smaller the proportion of users who know how the applications have been designed. As a result, most training should focus on application areas and factors such as the pace of technological development, its opportunities and challenges, as well as, for example, the price point development of different technologies.

In the future, a significant proportion of those directly employed in the field will have a degree other than that of a physicist, engineer or, for example, computer scientist. These employees include, for example, salespeople and business management, as well as product design and development. However, it is beneficial for all directly employed in the QST sector as well as those working in companies that use quantum technologies to understand what the technology can be used for and how to combine and integrate various AI and quantum computing tools, for example.

This means that those employed in the field will usually have very different needs in terms of the required skills and education. Therefore, it is necessary to define in more detail what kind of training different groups will need in the future. In this report, the training needs are approached with a classification based on Table 3. The table also presents examples of the categories of this classification, and the objectives and different types of training aimed at different focus groups. All these factors are discussed in more detail below the table.

Table 3: Examples of training activities for different categories and focus groups.

Training category	Focus group(s)	Type of training	Target outcome(s)
1. Workforce re-training	Specialists in other technology sectors	• Advanced quantum computing schools & MOOCs • Formal specialization training • R&D project collaboration with industry • R&D infrastructure provision	• Quantum use case adoption and development in industry • Trained workforce for QST companies • New IP developed in joint projects
2. Quantum awareness raising	End users, decision-makers	• Tailored lectures on QST basics & use cases • Beginner- & intermediate level MOOCs (also in Finnish & Swedish) • Outreach campaigns for the general public	• Knowledge of quantum physics basics • Understand technology's possibilities & limits • Understand quantum use cases and risks • Impact for own organization, ways to utilize
	School teachers	• Tailored re-training programs for teachers • Lectures at schools, MOOCs • Outreach campaigns for students & teachers	• Quantum physics & technology basics and use cases taught at schools • Skilled students pursue a career in QST
3. Higher education	Physics & engineering students	• Advanced QST substance knowledge • QST use case training and development • Training-focused infrastructure provision • Industry collaboration	• Strong QST substance knowledge • Good understanding of QST use cases in industry • Skilled students pursue a career in QST
	Computer science students	• Quantum information and software theory and application development • QST use case training	• Good quantum information & software knowledge • Good understanding of quantum software use cases and ways to utilize them
	Other students (incl. universities of applied sciences)	• Quantum information and software • Quantum hardware manufacturing • Domain-specific training on QST use cases	• Understanding of QST possibilities and ways to utilize them in own domain • Capability to develop QST HW components or SW
	Doctoral researchers	• Academic research • R&D project collaboration with industry	• Very strong QST substance knowledge • New IP and use cases developed

1. Workforce re-training

The first category, i.e., additional training provided for experts to be directly employed in different subsectors of quantum science and technology, is divided into two groups: on the one hand, the training of technical experts working in adjacent fields (e.g., semiconductor technology, information and communication technology, electronics, process technology, or chemical engineering) and, on the other hand, the training of generalists who understand the market and business logic of the QST field and focus on them as part of their job.

Technical experts will need significantly more advanced additional training in quantum physics, information, and technology than generalists. For example, advanced MOOCs (Massive Open Online Courses) from different providers as well as the quantum computing training provided by CSC are already quite well suited for the additional training of technical experts in terms of their content. They teach technologies and methods commonly known in the field and can thus familiarize those to be employed in the field, for example, with problems that remain currently unanswered. Such advanced MOOCs and online training modules based on them are offered globally by, for example, the Finnish IQM and the US-based IBM company, both of which are developing their own training offering in addition to manufacturing quantum computers[33].

However, the most essential re-training channels for technical experts in adjacent fields who later find employment in the quantum sector are still likely to be on-the-job learning and joint research and product development projects of companies in which new quantum technology is developed and applied to use cases. In addition to technological progress, initiating and supporting them also builds up the talent pool of the field.

As the need for workforce re-training increases by 2030 and beyond, the field will also need more formal re-training channels. These could be organized and coordinated through e.g., the various channels of the open university in Finland, new types of specialization training offered by Finnish universities[34], the Digivisio 2030 programme[35], the Finnish Institute of Technology[36] (FiTech), and the Finnish Service Centre for Continuous Learning and Employment[37].

By utilizing these channels, it is possible to give the required re-training in a longer format while still keeping the schedule flexible. This should make it easier to acquire additional training while working full- or part-time. Longer-term re-training also offers the trainees a broader opportunity to delve deeper into the topic, as well as reflect on and apply their learning already during the training.

In the future, universities and research institutes such as VTT and CSC could also create more tailored training for employees hired by companies developing quantum technologies, for individual workers seeking additional training and aspiring to work in the QST field in the future, and for end-user companies. If necessary, the education could be domain-specific, focusing not only on the basic principles of quantum science and technology, but also on the applications in the fields of chemistry, drug development or other life sciences, or in the fields of finance or logistics, for example.

Universities and other actors could implement training independently or in cooperation with other research institutes such as VTT and CSC, as well as with companies. If seen as beneficial, these actors could also certify courses and training modules in such a way that they enable crediting learners as well as making a comparison of trainings of different providers. To support the definition of more detailed goals and the desired expert profiles for such training, the Quantum Technology Competence Framework created by the European Union's Quantum Flagship[38], which aims to standardize the training goals and job requirements in the field, can be used.

Generalists employed in the fields of quantum science and technology should continue to focus on application areas of quantum technologies, rather than quantum physics, information, or hardware. However, knowledge of these still helps to understand the pace of technological development and the limits of possible, as well as the resources required by different application areas.

Training in these topics can be organized in the form of high-quality webinars, lectures, and other events organized by reputable operators, as well as MOOCs focusing on the application areas of quantum science and technology. So far, the role of universities, research institutes, and commercial actors has been fairly minor in Finland in this regard (with the exception of the ABCs of Quantum Computing[39], the IQM Academy[40], and QPlayLearn[41]), but their wider activation in providing quantum education and re-training to different domains in Finland and in the local context could accelerate especially the growth of the local ecosystem in Finland.

2. Quantum awareness raising

There is significant need for quantum science and technology training also in that part of the society which will use quantum technology, be involved in making legislation or other decisions that affect the technologies' development and adoption rate or volume, or which otherwise finds the topic interesting. The amount of people that can benefit from the related "quantum awareness raising" or otherwise broader training can easily be many times higher than the re-trained workforce directly employed in the field during the next ten years.

At the moment, there is reasonable training offering available in the field, especially in the form of various MOOCs and webinars, but the industry suffers from a mismatch problem. Although there is already ample training available in English, outside the QST sector there is little awareness of the existing courses and other training opportunities in quantum. That being the case, even the provision of high-quality training is not always reaching the right audience. In the future, training should be offered and marketed to its target groups much more actively than at present.

In terms of quantity, the most effective way to increase awareness of the field, its technological applications, and their impact on society would be to create a MOOC-type course that reaches a wide audience with a relatively small effort. When successful, a single course can enable the training of tens of thousands of people in Finland alone, and even millions across the globe, as the online Elements of AI course developed by the University of Helsinki and Reaktor has shown[42]. In particular, there may be significant demand for high-quality content produced in Finnish and Swedish. The development of such course would also fill a void in terms of large-scale training given in languages other than English or other major European languages.

Similar training content would also benefit teachers and students in undergraduate and upper secondary education. Also, it is particularly important to target more extensive outreach campaigns to them in the future, as the knowledge of the field within upper secondary school students and their interest in it are a prerequisite for Finland to be able to train enough skilled workforce for quantum science and technology sector in the future.

A similar requirement also applies to the knowledge and skills of upper secondary school teachers. It may be necessary to provide them with targeted re-training in the form of tailored courses and seminars given by universities. In the long term, it would also be useful to consider reforming the curricula of upper secondary education so that the basic principles and applications of quantum physics and information would be studied already as part of upper secondary education.

3. Higher education

The last category mainly deals with education provided in Finnish higher education institutions. Instead of individual disciplines, this subsection focuses on different degree levels and broader skills that will be needed in the quantum science and technology field in the future.

Degree education in physics and engineering emphasizes strong understanding of the foundations of quantum technology

For the majority of degree and postgraduate education in quantum technology, strong understanding of the physics and engineering foundations should continue to be emphasized. Strong general skills enable flexibility and ability to quickly learn and process new information in a rapidly developing field.

However, strong basic skills should not be limited to having knowledge of the theory behind. In the future, graduates who will either do component and device design and manufacturing or develop quantum algorithms and software as part of their job are required to have experience with a real quantum computer or other quantum technologies already during their studies, and to have the ability to apply their learnings. In universities across Finland, it would be good to align the educational content accordingly. In general, courses and modules should also build up a more coherent path from basics to advanced topics and the field would benefit from greater harmonization of education nationally.

As a special feature of components and equipment manufacturing, laboratory and cleanroom expertise will be further emphasized in the future, as hardware manufacturing is likely to continue to have a strong position in the Finnish ecosystem. This is supported not only by the projected increase in the number of employees in the manufacturing industry to nearly 2,500 people by 2035[43], but also by Finland's recent investments in world-class infrastructure such as the Kvanttinova centre. The new centre will focus especially on the development, testing, piloting, and manufacturing of components and hardware solutions.

At the moment, there are currently no facilities in Finland suitable for teaching cleanroom skills to students. There are also no concrete plans for including such facilities in future projects. In the future it would be beneficial to consider the construction of new types of teaching laboratories and even cleanrooms, although a significant part of the education in this area can also be implemented through joint research and product development projects between universities and companies.

Investing in infrastructure supporting not only industrial R&D but also training can be worthwhile because the need would not depend solely on quantum technologies. Similar facilities and equipment are also used in the semiconductor industry, not only today but also in the future and at an even larger scale than today, as the EU seeks to reduce the dependence of the semiconductor sector on manufacturing in Asia[44].

Another special area important in the future is programming. In the future, higher education should include carrying out practical exercises with a real quantum computer, preferably in a use case focused manner and, if possible, also as part of joint projects with companies or research partners. The need will be more prominent in the future as the quality and capability of quantum computers will increase, in particular when similar exercises can no longer be carried out efficiently with simulators. For developing strong competence in the field, it is important that students have access to computing infrastructures that are at the forefront of global development. It would also be good to create more cross-institutional study opportunities for students in order to make use of the complementary curricula and infrastructures in use in different higher education institutes.

In addition to programming quantum computers, employers hiring workers with a physics or engineering background will continue to value traditional data processing skills and good code and software development practices. The ability to learn new things and to document and communicate one's work to others is often valued more than highly developed technical skills.

On the other hand, it should not be forgotten that even though the hardware and software hierarchy of quantum computers will increase in the future, it will still be good for certain groups to have a deep understanding of the operating principles of quantum computers and, for example, different qubit modalities. This is essential to enable not only the construction of more powerful quantum computers but also to gain a competitive advantage by developing algorithms and software for quantum computers that utilize hardware more efficiently than competing software solutions. In recent years, similar development has been seen especially with various AI solutions[45].

At a more theoretical level, it may be worthwhile to develop the way quantum physics is taught in universities. The traditional way which emphasizes atomic physics should move towards the theory of quantum information and information processing, as well as to quantum phenomena in condensed matter systems. Such a shift in the focus of teaching would not only modernize the teaching of quantum physics but also improve the ability of students and graduates to apply quantum information theory especially to algorithm and software development.

Learning quantum science & technology is important in other domains, too

While physics and engineering will likely continue to be the most important focus areas for education and re-training of the future workforce directly employed in the quantum sector, other fields can also benefit from quantum science and technology training.

The clearest benefit would be achieved by including teaching of quantum information and algorithms as well as quantum computer programming in the master's and doctoral education in computer science. So far, quantum software and applications training has mainly focused on beginner-level courses in Finland but in the future there will be need for more advanced and cross-disciplinary competence. For example, creating a joint quantum information training module for physicists and computer scientists or a master's or doctoral degree programme in quantum software development would be a solution worth considering in the future.

In the future, it would also be useful to offer specialization courses or training modules that familiarize students with quantum technologies and their application areas or, for example, the special characteristics of the quantum technology market. Students of disciplines such as industrial engineering, law or management could benefit from such training, and so would students of potential end-user domains such as chemistry, biosciencies, and materials sciences.

In the future, characteristics of end-user domains could also be taught for physicists. As part of their training, quantum technology students could be provided with substance-level information of the domains in which quantum computing and other quantum technologies can be utilized in the future and in what ways. This would further improve the skills of the quantum industry workforce to apply quantum technologies in different domains.

In the future, the basic principles of quantum physics and the current and future application areas of quantum technologies should also be emphasized in teacher education in physics and related fields. This goal and the training of domain experts could be supported, for example, by the universities' own or jointly developed MOOCs in Finnish and Swedish presenting the basics of the field, the completion of which would be rewarded in the form of credits included in the teacher's degree.

Universities of applied sciences can have an important role in QST workforce education

Although quantum technology has traditionally been associated with high, even doctoral-level skills, there are already employees with a vocational or a bachelor level degree working in the field. Especially in subsectors such as enabling technologies and quantum computer component and hardware development, there are several practical tasks for which a bachelor's degree or vocational education is largely sufficient. Various machining or assembly tasks are examples of these, and the number of similar tasks is likely to increase in the future.

As quantum computing develops in the future, there may also be increasing demand for workforce with up to a bachelor's degree who apply quantum computing in their job or develop quantum software at the higher levels of software hierarchy. However, this requires that also universities of applied sciences start teaching the applications of quantum information and quantum software development.

So far, training in quantum technologies has not been provided in vocational schools or universities of applied sciences, but the practice may change in the future. In this case, there needs to be clear benefit for companies to offer suitable internships and on-the-job learning opportunities for students with different backgrounds to a greater extent than at present.

Also, in the short and medium term, the bottleneck in organizing training may be the number of skilled teaching staff and the long time span for degree education. Since quantum science and technology have not traditionally been taught outside universities, universities of applied sciences need to increase their efforts in finding suitable teaching resources, as well as in planning and organizing suitable training. If quantum technologies or quantum computing are taught only to new students, the first graduates with an equivalent of a bachelor's degree in the field will enter working life around 2030. However, as there unarguably is demand also for those with up to a bachelor's degree, it is recommended to start preparing for these changes in universities of applied sciences as soon as possible.

Doctoral education would benefit from stronger industrial collaboration

Finally, we make a brief comment on doctoral education. The Finnish education in the field is of high-quality and globally valued, and there is no reason to make changes to doctoral education in this regard.

However, in the future it may be good to invest more extensively in joint industry-academia research projects, both with companies developing quantum technologies and, where relevant, also with quantum technology end-users. In this way, awareness of the maturity level of quantum technologies and their suitability for solving various end-user-specific problems increases, and allows finding interesting new research problems that are close to end-users.

Even if the annual number of doctoral graduates in different fields of quantum technology does not need to increase significantly from the current level to accommodate the direct needs of the growing industry, research and doctoral education will continue to play a key role in attracting talent to Finland. Strong international collaboration in research and high quality of work demonstrated through scientific publications and world-class research infrastructures in the field attracts experts to become part of the Finnish ecosystem and find employment in Finland.

In the future Finland should invest more strongly in integrating these experts into the Finnish society and quantum workforce. The need is particularly prominent in doctoral education where a significant proportion of researchers originally comes outside Finland. Without these experts and their networks, the quantum science and technology industry will not see the predicted growth in employee numbers nor commercial profit.

CONCLUSIONS

Over the past few decades, Finland has succeeded in creating an exceptionally diverse, high-quality and well-connected quantum science and technology ecosystem. The ecosystem includes members from the research and education sectors to companies that develop and apply quantum technology, as well as service sector companies that focus on supporting quantum technology companies in developing their operations and scaling their business.

The sector currently employs directly approx. 1,550 people in Finland, of whom approx. 550 work in the research and higher education subsector and the rest in companies distributed across various other subsectors. In addition to these actors, the Finnish quantum ecosystem as a whole includes a large number of current and potential future end users of quantum technologies who are currently testing the different technologies under development, as well as funders, service providers, and other key stakeholders.

If quantum technologies continue to develop as expected and quantum computing in particular begins to yield significant new and commercially valuable applications by the end of the decade, the field has the potential to directly employ at least 2,500 people in Finland in 2030 and more than 4,200 people in 2035. In addition to these jobs, the sector has potential to create a significant number of new jobs especially in end-user companies as well as in companies connected to the sector's supply chains.

A significant part of the total growth in the number of employees is estimated to come from the enabling technologies and the quantum computer component and hardware manufacture subsectors. Together they are estimated to become the largest quantum science and technology subsectors in Finland, surpassing research & education subsector during the early 2030s. Together, these two subsectors are estimated to employ more than 2,000 people in Finland in 2035.

The largest relative growth is likely to be seen in the quantum algorithms and software subsector, and the second largest relative growth in quantum sensors and metrology subsector. The former, in particular, is likely to globally represent the commercially most valuable part of the quantum technology value chain by 2035, assuming that significant and commercially valuable applications for quantum computers are developed by the early 2030s at the latest. However, as the number of employees in this subsector is currently very small in Finland, this subsector is forecasted to remain behind equipment manufacturers in employee numbers at least until 2035.

Overall the number of people directly employed in the field is predicted to grow in a controlled manner and, for this purpose, significant increases in the number of students attending higher education or doctoral education will not necessarily be needed in the next five years, assuming that the field attracts students as it has done so far. However, by the year 2030 and onwards the annual need for workforce re-training is estimated to at least double compared to the current level: from 50 to 120 people per year. We estimate that as also end users will need and benefit from focused training in quantum science and technology topics, the total re-training need is at least 700 – 1300 people per year.

The estimated growth of re-training need means that the content, target groups, objectives, methods, and organizing responsibilities of workforce re-training must be developed and agreed upon at a national level as soon as possible. Although the most essential re-training channels for technical experts in fields adjacent to quantum who later find employment in the quantum sector may still be on-the-job learning and companies' own research and product development projects in the near future, formal re-training channels should also be created by the year 2030. In creating them, it is possible to utilize, for example, the channels of the open university, new types of specialization training, the Digivisio 2030 programme, the Finnish Institute of Technology (FiTech), the Service Centre for Continuous Learning and Employment, as well as tailor-made training provided by universities and other actors. Such training should be targeted at employees hired by companies developing quantum technologies, workforce seeking other additional training and aspiring to enter the field in the future, as well as end-user companies of quantum technologies.

It is also recommended to further align the content of university education in the next few years, and to harmonize education at a national level by offering students joint training modules and cross-institutional study opportunities between different universities and other actors.

In the future, it would also be beneficial to outline more broadly how extensively quantum technologies should be taught not only in different fields of higher education but also as part of upper secondary qualifications and whether there is need for prioritizing, for example, stronger hardware manufacturing techniques or algorithms and software training. In any case, it is important to ensure that the training offered as part degree education reflects the career opportunities in the field and attracts students to the field at an early stage.

Concrete measures for developing quantum education and re-training were presented in more detail in Part 3. A summary of the proposed measures, including the suggested focus groups and objectives, is presented in Table 3. Below we also show our specific recommendations for different key stakeholders.

RECOMMENDATIONS FOR KEY STAKEHOLDERS

For policy-makers

1. Enable coordinated cooperation in quantum science and technology education and broad cross-institutional study opportunities at the national level.
2. Enable creating a comprehensive workforce re-training programme with clear objectives and sufficient resources to expand the training opportunities at a national level.
3. Invest in attracting and integrating foreign labor, especially with regard to doctoral education and industry collaboration.
4. Include quantum science and technology topics in the upper secondary education curricula.
5. Promote the training offered in Finnish and Swedish and support and resource broad awareness campaigns for the general public.

For quantum technology developers

1. Intensify cooperation with higher education institutions by participating in work done as part of doctoral and undergraduate education, as well as by offering internships and on-the-job learning opportunities for students.
2. Actively bring up suggestions on what kind of additional training needs companies have and what kind of cooperation between universities and companies would benefit the growth of the industry.

For end users of quantum technology

1. Map the impact of quantum technology on your company, especially in terms of the competitive advantage to be achieved and potential risk factors.
2. Develop a roadmap on how you will use quantum technology in the future and how you will acquire the necessary resources.
3. Instruct employees to get to know the industry, taking advantage of the existing trainings such as free webinars and MOOCs.
4. Actively bring up suggestions on what kind of additional training needs companies have and what kind of cooperation between universities and companies should exist.

For higher education institutions

1. Intensify educational cooperation between higher education institutions by harmonizing education and creating more cross-institutional study opportunities for students at a national level.
2. Increase the dialogue between universities and universities of applied sciences to expand quantum technology education offering in suitable fields.
3. Intensify cooperation with companies to launch and expand workforce re-training, joint doctorates, and student internship programs.
4. Launch educational cooperation with other research and technology institutes in the field, such as VTT and CSC, focusing especially on workforce re-training.
5. Create high-quality training material in Finnish and Swedish to reach large audiences, for example through online MOOCs, and organize awareness campaigns for the general public and schools.

Appendix 1: Details about the benchmark scenario

Sector	Assumed scenario	Uncertainty	Most important dependencies	Est. annual growth-%
Research & education	Low but steady growth as new research questions emerge and technology develops	Low	Public sector funding, annual number of QST graduates	2.5-5%
Enabling technologies	Medium growth due to high maturity but global demand especially in QC hardware	Medium	QC hardware development, workforce supply	10%
Quantum computer hardware	Steady, medium-level growth in employee numbers through '35	High	QC hardware development, global competition, private funding, workforce supply	10%
Quantum computer algorithms & software	High growth due to founding of new companies and emergence of utility applications around '28, surge of new applications and use cases in 2030s	High	QC hardware & software development, QC end user adoption rate, private funding, workforce supply	20-30%
Quantum sensors & metrology	High but mostly steady growth due to high tech maturity and emergence of new use cases	Medium	Customer demand, some enabling technologies, workforce supply	15-20%
Quantum communication	Medium to high growth to enable growing number of Proof-of-Concept (PoC) projects	Very high	Success of PoC projects, QKD device & network technology and cost development	10-20%
Cryptography	Relatively high growth with PQC migration until '30, after which growth decreases a little	Medium	QC hardware & crypto algorithm development, PQC migration timeline and related regulation	10-15%
Consulting & services	High growth through the QC adoption stage and emergence of new utility applications through 2030s	Medium	QC utility application emergence timeline, private funding levels	20-30%

Appendix 2: How the study was done

This report is based on a study that was conducted during January–February 2025.

The main source of information were 30+ interviews with Finnish quantum science and technology, artificial intelligence (AI), semiconductor, and education experts in industry and academia, as well as interviews with other key stakeholders who comprised of experts in e.g., public sector funding and government policies.

In addition to interviews with Finnish experts, the report is based on several interviews with quantum science and technology experts who reside outside Finland. These interviews were used to benchmark the analysis' starting point and main assumptions of the base scenario, as well as the early results and recommendations. Also these experts represented both academia and industry.

The work also included a desk study. The most important literature, industry and policy reports, company and media websites, and other publicly available sources that were used for this study are listed below in References section.

The study and the resulting report were done as a collaboration between InstituteQ and Cygnus Quantum Oy. The work was led by Dr. Tommi Tenkanen (Cygnus Quantum) and done in collaboration with the InstituteQ project working group (Prof. Kimmo Tuominen, Elina Palmgren, Kaisa Michelsson, Juho Pirinen). The layout of this report was designed by Gavin Pugh.

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