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Mid-term evaluation QuTech 2019-2021
Delft University of Technology
Netherlands Organisation for Applied Scientific Research (TNO)

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1. Foreword by the committee chair

The QuTech research institute specializes in probably the most challenging, innovative and exciting field of science at the moment quantum technology. Much is expected from this key enabling technology; scientifically, but also for breakthroughs in materials science, medicine or (cyber) security. It is a privilege to judge such an institution on its merits in terms of scientific quality, social relevance and viability.

In addition, by Dutch standards, the institute occupies a special position. The institute does not fall under a specific faculty, but directly under the Executive Board of the participating partners, TU Delft and TNO. The institute also enjoys great support from the government, which entails a great deal of responsibility.

It was a great pleasure to delve into QuTech and see that the enthusiasm among the research leaders, management team, support staff, postdoc's and PhDs was still just as great as noted by the previous review committee. The quality of the research remains excellent. In addition, the organization has again taken an important step forward in the field of professional management.

Next to acquiring fundamental knowledge, QuTech is also dedicated to generating societal and economic impact in quantum technology, and is one of the key players in Europe in this regard. As a committee, we are happy to make a number of recommendations that endorse this ambition. This requires the vision and courage that the entire QuTech team radiates to a great extent.

Prof. dr. ing. Dave Blank
Emeritus Distinguished Professor at Twente University

June 2022

2. Procedure

2.1 Scope of the review

The Executive Board of Delft University of Technology, in close coordination with the Executive Board of TNO and with the consent of the (other) Partners of the Partner Covenant QuTech, asked a review committee of external peers to evaluate QuTech over the period 2019-2021.

In the Partner Covenant QuTech of June 10, 2015 the ministries of Economic Affairs and Climate (EZK) and Education, Culture and Science (OCW), Delft University of Technology (TU Delft), the Netherlands Organisation for Applied Scientific Research (TNO), the Netherlands Organisation for Scientific Research (NWO) and Dutch Top Sector High Tech Systems and Materials (HTSM, Holland High Tech) have agreed to support QuTech financially as Strategic Partnership over the period 2015 - 2025. The QuTech Partner Covenant, in which this commitment was formalized, specified two mid-term reviews by an international committee within this ten-year period. The first review was conducted by an international assessment committee in January 2019 (over the period 2015-2018). This review is the second of these mid-term reviews and covers the period between 2019 and 2021.

Assessment criteria

This review is based on the Standard Evaluation Protocol (SEP) 2021-2027 for research reviews in the Netherlands, and the Protocol for the evaluation and monitoring of the Applied Research Organisations in the Netherlands (EMTO). In this evaluation, the SEP is used as the guideline for the evaluation, supplemented with aspects and indicators from EMTO. The main assessment criteria, which are similar for both SEP and EMTO, are:

- Research quality
- Societal relevance
- Viability

Within the main assessment criteria, the committee is requested to pay attention to the following specific aspects:

1. The quality of the research and engineering activities conducted by each of the three divisions (Qubit Research, Quantum Computing and Quantum Internet), and their mutual coherence, interaction and added value;
2. QuTech's policy and actions to realize open science, education of talent, and academic culture;
3. The scientific and economic impact of the research and engineering activities in each of the divisions, and QuTech's policies and actions to realize knowledge utilization, including technology transfer (e.g., spin-offs, licenses, and sponsored research collaboration);
4. QuTech's contributions to innovation agendas, such as the NWA and the NAQT, to societal themes as well as contributions to national and EU policy agendas;
5. The extent to which QuTech is equipped for the future, both in the short term (2022-2025) and the longer term (2025 and beyond), in terms of governance, strategy, technology road mapping, funding, attracting and retaining talent, housing, facilities, and equipment.

In addition to these criteria and aspects specified in the SEP 2021-2027, the committee is requested to offer its assessment and recommendations on

- QuTech's proposed role and positioning as a public research actor amidst the international race for quantum computing;
- The scope of QuTech's research and engineering portfolio, and whether topics are missing or rather more focus should be achieved.

Finally, the committee is requested to assess to what extent and how QuTech has followed up on the recommendations of the midterm evaluation committee 2015-2018.

The committee is asked to provide its written conclusions and recommendations based on considerations and arguments.

2.2 Composition of the committee

The composition of the committee is as follows:

- Prof. dr. ing. Dave Blank, Emeritus Distinguished Professor at Twente University (chair);
- Dr. ir. Maud Vinet, Quantum hardware program manager at CEA Leti, Grenoble;
- Prof. dr. Daniel Loss, Director of the Basel Center for Quantum Computing and Quantum Coherence (QC2);
- Prof. Mag. Dr. Barbara Kraus, Head of the Institute for Theoretical Physics and the research group Entanglement Theory & Quantum Information Theory at the University of Innsbruck;
- Dr. ir. Jos Benschop, Senior Vice President Technology ASML;
- Ir. Daniel Karrenberg, Chief Scientist RIPE NCC;
- Dr. Philippe Chomaz, Scientific Director of CEA fundamental research division and Chair EU Quantum Flagship project on international cooperation (InCoQFlag).

The committee was supported by Peter Hildering MSc, who acted as secretary on behalf of evaluation bureau Academion.

2.3 Independence

All committee members have signed the Statement of Impartiality and Confidentiality. In this statement, the committee members have declared to have no direct relationships or connections with the institute and its departments, currently as well as during the assessment period.

Any affiliations or relationships that could lead to (the semblance of) a biased assessment was discussed with the committee chair and the partners of QuTech. The following issues were discussed:

- The role of Maud Vinet as project leader of the large-scale EU project QLSI, in which QuTech researchers participate;
- The position of Daniel Karrenberg in the Advisory Board of the European Quantum Internet Alliance;
- The co-publication of three review articles of Daniel Loss with QuTech researchers in the 2019-2021 period.

In all cases, it was concluded that the affiliations and relationships did not form a direct or indirect conflict of interest, and do not hinder an independent assessment of QuTech.

2.4 Data provided to the committee

The committee received the self-evaluation report from QuTech, including all the information required by the SEP and the EMTO protocol, and with several links to online sources with background information. The committee also received the following documents:

- The Terms of Reference;
- Partner Convenant QuTech;
- Topsectors information;
- QANU Report Mid-Term Review QuTech 2015-2018;
- Cooperation agreement QuTech;
- QuTech Internal Operational Framework;
- Tenure Track Policy QuTech;
- QuTech - TU Delft Employee Monitor 2020;
- Diversity & Inclusion Policy QuTech;
- QuTech Research Data Policy;
- TU Delft Research Data Framework Policy;
- Doctoral Education Programme Course Guide;
- Guide for Doctoral Candidates and Supervisors;
- QuTech Foresight Study 2025 – 2035;
- TU Delft Code of Conduct;
- TNO Code of Conduct.

2.5 Procedures followed by the committee

The committee proceeded according to the SEP 2021-2027. In its preliminary online meeting on 1 April 2022, the committee was briefed by Academion about research reviews according to the SEP 2021-2027, the Terms of Reference and the specifics of the QuTech review. Prior to the site visit, all committee members independently formulated a preliminary evaluation of the units under review based on the written information that was provided before the site visit.

At the start of the site visit, the committee discussed the preliminary evaluations and identified questions to be raised during the site visit. It agreed upon procedural matters and aspects of the review. The site visit took place on 20-22 April 2022 (see the schedule in Appendix 1). After the interviews the committee discussed its findings and comments in order to allow the chair to present the preliminary findings and to provide the secretary with argumentation to draft a first version of the review report. The final review is based on both the documentation provided by QuTech and the information gathered during the interviews with management and representatives of QuTech.

The draft report by the committee and secretary was presented to QuTech for factual corrections and comments. In close consultation with the chair and other committee members, the secretary drafted the final report based on these corrections and comments. The final report was presented to the Executive Board of Delft University of Technology, as well as to the management of QuTech.

3. Review of QuTech 2019-2021

3.1 Mission, vision and organization

Mission and vision

QuTech was founded in 2014 as a mission-driven research centre for quantum computing and quantum internet that aims to develop scalable prototypes of a quantum computer and inherently safe quantum internet based on superposition and entanglement, by bringing world-class scientists, engineers and industry together in an inspiring environment.

QuTech views quantum technology as having a world-changing potential, and as a game changer for many societal and economic sectors such as health, agriculture, climate and safety. *Quantum computing* offers the promise of solving computational problems that are far beyond the reach of the most powerful supercomputers, with applications in a broad range of fields where computational power can realize breakthroughs. Small-scale quantum computers have already been demonstrated on a variety of platforms and over the past decade, global IT companies have increasingly become interested in this 'holy grail' technology. The *quantum internet* aims to use quantum communication to connect any two points on Earth, unlocking new features such as inherently secure communication and near-perfect synchronization. Now that the basic principles have been demonstrated, creating a quantum internet requires the development of a full range of basic elements, including communication channels, repeaters, end nodes and switches.

According to the committee, the mission and vision of QuTech stand strong since its inception. The goal to not only study quantum technologies, but also develop actual prototypes for quantum computers and the quantum internet, is clear and ambitious, and is as relevant now as it was in 2014. QuTech has created an environment through partnerships and collaborations that equips it very well to realize its mission. The institute continues to be recognized as a world-class research institute for quantum computing as well as the quantum internet.

Organizational structure

QuTech was founded as a collaboration between TU Delft and TNO. It is not a legal entity: its staff is either employed at TU Delft or at TNO. Originally, QuTech was hosted by the Faculty of Applied Sciences of TU Delft. Since 2014, the institute has quickly grown into a major research centre with over 300 staff members working on realizing this mission. This considerable growth in personnel and facilities led to a need for a more independent position and steering power. In 2019, QuTech became a separate organizational entity within TU Delft under the responsibility of the TU Delft Executive Board, which consults the TNO Executive Board when appropriate. QuTech is governed by its Board of Directors (BoD), consisting of a Director Research (TU Delft) responsible for the scientific and engineering process, a Director Business Development (TNO) responsible for business development strategy and planning, and a Director Operations (TU Delft) responsible for internal business and organization. The Director Research chairs the BoD and is the first point of contact for the TU Delft Executive Board.

The internal governance structure of QuTech was changed in 2020 from a matrix organization with research (TU Delft) and engineering (TNO) "roadmaps" to three divisions in which researchers and engineers work together. The current divisions are Qubit Research, Quantum Computing and Quantum Internet. This change was introduced to better integrate research, engineering and business development activities within QuTech, partially in response to the recommendations made in the previous mid-term evaluation. Each division is headed by a management team that consist of at least a TU Delft research lead and a TNO

engineering lead. Next to the three divisions, QuTech consists of the support staff, headed by the Director Operations, and the QuTech Academy.

Based on the documentation and discussions during the site visit, the committee concludes that QuTech forms a fruitful collaboration between TU Delft and TNO. Both Executive Boards support the institute and its mission. The new internal governance structure has created a better synergy between research and engineering (including software engineering), uniting research, engineering and business development efforts in coherent research & development aims with regard to various quantum technologies and demonstrators within the divisions. Moreover, the committee noticed in many of the interviews that staff members consider the cross-fertilization between research and engineering to be one of the main strengths of QuTech. According to the committee, the synergy between research and engineering that QuTech has been able to achieve in such a pioneering research domain is exemplary. It has been envisioned many times by different institutions world-wide, but has rarely been executed so successfully as in QuTech.

Although the organizational context of QuTech with two collaborating institutions is complex, the management of QuTech has been able to successfully run an effective and decisive organization within the current structure. Working with two different institutions is however not completely seamless. During the site visit, a number of issues were discussed where the embedding of QuTech within TU Delft and TNO lead to more complex procedures. For instance, the project-based mode of operations at TNO with a dynamical allocation of human resources does not fully match the long-term research projects at QuTech, which requires continuity in the commitment of key personnel. This makes it difficult to make an engineer formally responsible on the long-term for part of a QuTech research project. Furthermore, several crucial research positions are formally embedded within the Faculties of Applied Sciences (AS) or Electrical Engineering, Mathematics and Computer Sciences (EEMCS), which sometimes leads to more complex procedures regarding for instance selection and supervision. On a smaller scale, there are often inconsistencies in policies and procedures resulting from employees being embedded in two different organizations.

The committee understood that even though the collaborations are very constructive and both institutions are willing to work towards solutions, QuTech's organizational structure sometimes leads to discussions and delays in decision-making that distract from the main mission of QuTech. According to the committee, it is essential for the long-term success and decisiveness of QuTech that it can be governed as if it were one organization. For the short term, the committee recommends a bigger mandate for the QuTech management to achieve this; on the longer term QuTech should work towards a decision about what kind of organization QuTech will be (see Chapter 3.4). In addition, QuTech should keep working on achieving a unified 'look and feel' throughout the organization regarding policies and procedures to further promote QuTech as a united institute.

Response to recommendations previous mid-term evaluation

Next to the changes in the governance of the institute, QuTech has also worked energetically on implementing the other recommendations made by the previous mid-term evaluation committee. Among others, the institute has worked to upgrade its facilities to accommodate its growth, expanding its IP activities, and has worked on a national programme on quantum technology. This has resulted in a National Agenda on Quantum Technology, and subsequently in an awarded National Growth fund proposal (M€ 615) coordinated by a new national foundation, Quantum Delta NL. The committee considers the responsiveness to the previous recommendations to be very good, and praises QuTech for its active work on using these recommendations to further the growth and development of the institute.

3.2 Research Quality

To assess the research and engineering quality of QuTech, the committee considered the performance indicators formulated by QuTech in the self-assessment report. These included research output as well as marks of recognition from peers such as research grants, prizes and awards, and publications with other research organizations. The committee considered the research and engineering quality of the Qubit Research, Quantum Computing and Quantum Internet divisions, as well as the synergy between the three divisions and the scope of the total research and engineering portfolio.

In general, the committee considers the quality of QuTech's research and engineering activities in the past three years to be excellent beyond doubt. The institute has generated several breakthrough results and continues to be world-leading in several of the fields it is active in. As discussed above, the institute has a unique set-up where research and engineering go hand in hand to not only generate innovative theoretical concepts, but also translate these into tangible demonstrators and prototypes. QuTech is a world-leading institute in quantum technology, both in research and in engineering activities.

Division Qubit Research
The Qubit Research division studies the development of robust protected qubits that are intrinsically protected by the underlying physical properties. The current focus lies on semi/superconducting hybrid systems and on protected superconducting circuits. In the past years, the division suffered setbacks in its research, as research results demonstrating the supposed observation of Majorana bound states had to be retracted due inappropriate data processing that invalidated the experimental results (see also Chapter 4.5). This development accelerated the shift in research focus towards hybrid nanowire/circuit systems and the fabrication of the associated nanowire devices. In 2021, a new PI was hired to strengthen the team. Another reason for expanding the activities of the division was the choice of Microsoft Research, a major research partner with its own lab facilities in Delft, to scale down worldwide its interactions with university groups on topological quantum computing. To reduce the risk of critical dependence, the division is increasing its research efforts in areas where it can better collaborate with other QuTech divisions as well as external partners.

The committee applauds the shift that the Qubit Research division has undertaken when earlier directions to develop topological qubits fell short of expectations. The topic of topological quantum computing has always been a high-risk, high-gain endeavour, and staying flexible and adapting to new insights mitigates the inherent risk in this approach. It understands that the team will need time to complete this shift, as well as recover from the stir caused by the retracted research papers, and needs time to further develop and grow. The division still produced high quality results, such as the in-situ fabrication of nanodevices in vacuum, the systematic study of the physical properties of nanowire devices, the study of two-dimensional electron gases coupled to superconductors as a platform for Majorana physics and setting a world record by reaching an electron temperature of less than 0.5 mK in a nanodevice. Furthermore, the division is already showing promising results in hybrid systems, for instance on circuit quantum electrodynamics. The work of the division is published in high-quality papers, and rewarded with multiple grants and prizes, such as ENW Open Competition - Large (Wimmer, 2019, coordinated by Eindhoven University of Technology. The committee encourages the division to continue its efforts to broaden the research portfolio.

Division Quantum Computing
The Quantum Computing division investigates the various hardware and software components of the future quantum computer. These research efforts are mainly based on two types of qubits: electron spins in

quantum dots and superconducting quantum circuits. Furthermore, the division investigates qubit control and readout as well as the interface between quantum hardware and software.

According to the committee, the Quantum Computing division delivers excellent research results. It shapes the world-wide state of the art in quantum computing, in particular with its ground-breaking work on spin qubits. Notable results include exceeding the 99% error threshold for fault-tolerant electron spin qubits, improving spin readout time by two orders of magnitude, controlling six qubits at the same time, creating single and two-bit gates at temperatures above 1 Kelvin, making major advancements on strained germanium structures, and many more. For superconducting quantum circuits, the division has produced significant results on two-qubit controlled-phase (CZ) gates, and on surface code for stabilization of logical qubits. In addition, the division has extended its work on noisy intermediate-scale quantum (NISQ), as recommended by the previous committee, as well as quantum error correction, and uses this work for instance in its demonstrators. Researchers work closely together with engineers who produce the materials used to create qubits, as well as the hardware and software building blocks for controlling qubits. The work of the division has resulted in many high-quality research papers, major individual research grants such as the Spinoza Prize (Vandersypen 2021), and ERC Starting (Veldhorst 2019) and Advanced (Vandersypen 2020) Grants. The committee thinks that the division can take pride in its accomplishments over the past years and is very well equipped for the future.

Division Quantum Internet
The Quantum Internet division works on developing the technologies which enable a quantum internet that can connect quantum computers worldwide. The division is currently investigating quantum networks connecting multiple quantum nodes based on nitrogen vacancy centres in diamond and rare earth-ions in crystals. It develops hardware as well as software for the complete network architecture of a quantum internet, as well as for distributed quantum computing.

The committee concludes that the Quantum Internet division has an excellent track record of innovative and leading research in the past years. It focuses on many aspects of the quantum internet and has a very hands-on approach where researchers and engineers collaborate to translate research results into innovative working prototypes. This integrated research and engineering effort allows the division to develop prototypes for the network itself as well as operating systems, the network nodes, repeaters and processors. The division was successful in generating quantum entanglement between two network nodes connected by a direct physical link in a ground-breaking experiment. Other highlights include the development of long-distance communication protocols for long quantum networks, realizing a multi-node entanglement-based quantum network, development of quantum repeaters based on rare-earth ions, a diamond-based multi-qubit processor and experimentally observing a discrete time crystal, an until then only theoretically known phase of matter in which particles are periodically arranged in time as well as space. The division is also very active in setting up international collaborations: it is a founding member and the coordinator of the Quantum Internet Alliance that coordinates efforts between various research groups and companies working on the quantum internet throughout Europe. Over the past years, members of the division published impressive results in many research papers, and saw their work recognized through multiple grants and prizes, including the Spinoza Prize (Hanson 2019), an ERC Starting Grant (Taminiau 2019) and the KNAW Ammodo Science Award (Wehner 2019). According to the committee, the division has produced excellent results in the past years and has everything in place to continue doing so in the near future.

Synergy between the three divisions
During the site visit, the committee investigated the synergy between the research and engineering activities within QuTech. It notes that the restructuring of the institute to integrate research and engineering has had a

very beneficial effect on the effectiveness of the collaboration. This has led to many impressive projects on instruments, materials, demonstrators and prototypes that have only been possible through close collaboration. Regarding collaborations between the divisions, the committee saw clear examples of joint efforts between the Quantum Computing and Quantum Internet divisions, for instance on diamond-based qubits and distributed quantum computing. Also, interactions between the Quantum Computing and Qubit Research divisions are growing on the topic of superconducting qubits.

The committee encourages the divisions to foster and expand these collaborations. Next to enlarging the critical mass of QuTech's research, it also offers flexibility when working on such novel research fields to shift focus when needed. In order to achieve this, QuTech could keep working on creating opportunities for interaction between researchers of different divisions, for instance through research-related events or informal activities aimed at connecting the QuTech staff.

Scope of research and engineering portfolio
According to the committee, QuTech has demonstrated to focus on selected key research areas in quantum computing and the quantum internet. The committee considers this to be a good strategy to prevent spreading the research focus too thin. QuTech will not be able to compete with the large industrial players that can invest significant amounts of money and resources, and does not aim to do so. The choice of research areas aligns with the strengths of the institute, in particular the application- and demonstration-oriented approach in which the researchers and engineers at QuTech excel.

One particular research area that the committee felt should be strengthened at QuTech is the sustainability and the social and ethical aspects of quantum technology. If the quantum computer and the quantum internet become a reality, issues regarding the social acceptance of this new technology, its safety and its sustainability will arise. According to the committee, QuTech as a public actor has a responsibility to participate in such discussions. Relevant issues include the sustainable production and use of quantum devices, safety by design and the potential impact of quantum technology on society. Next to participating in actions related to ethical, legal and social aspects of quantum technologies (for instance those that are initiated through Quantum Delta NL), this also include raising awareness within QuTech for these issues, and integrating these aspects in internal research activities.

3.3 Societal Relevance

Since the previous mid-term evaluation, the field of quantum technology has changed significantly from a research area dominated by a few leading research institutes to a field where many companies and governments are doing major investments with the expectation of economic impact of quantum technology. New companies specialized in quantum technology are starting to emerge, often as spin-off companies from research institutes. Contributing to economic impact for the Delft region, the Netherlands, and Europe has always been one of QuTech's aims. The institute pursues a business development and innovation management strategy aimed at stimulating and supporting entrepreneurship, developing Intellectual Property (IP), as well as building strategic partnerships with private and public partners.

Technology transfer
Developing demonstrators is an important component of QuTech's business development strategy. Demonstrators show potential users what quantum devices can do, and can generate interest in quantum technologies. QuTech currently maintains the demonstrators Quantum Inspire (a simulated and small-scale qubit-based quantum computer accessible to anyone) and Quantum Network Explorer (a website with a simulated quantum network). These demonstrators are the first of their kind within the EU, and already

attract external users (3,000 registered users for Quantum Inspire that was launched in April 2020, and 120 researchers and software developers for the Quantum Network Explorer, that was launched at the end of 2021). Furthermore, QuTech has launched NetSquid, a tool that is used worldwide in quantum network simulation. It is capable of exploring and validating future quantum network architectures – ranging from the physical layer, over the control plane, to an understanding of application requirement. QuTech has invested in software engineers that are embedded in the divisions, and work on developing and maintaining software for the demonstrators. Furthermore, the underlying technologies are increasingly being marketed by QuTech spin-off companies. The committee thinks that the demonstrators are unique and important focus points for QuTech's research and engineering efforts, and are already showing to have economic impact through the spin-off companies emerging from these activities.

Following the recommendations of the previous committee, QuTech has invested in developing, protecting and harvesting IP. TU Delft and TNO jointly developed an IP policy, which is supported by specialists from both institutions. This has resulted in an increase in patent applications to 13 per year in both 2020 and 2021. The committee praises this positive trend, encouraging QuTech to keep working on a further increase. The number of patent applications by private players in the field is rapidly increasing, underlining the important role patenting plays in the current field of quantum technology. According to the committee, the target should be the protection of IP in high-quality patent applications, rather than working towards a specific number of applications.

Collaboration with private partners
Another aspect of the business development strategy of QuTech is to build a quantum ecosystem in which the institute connects to private and public partners working on quantum technologies, and engages in the launch of spin-off companies. For several years, QuTech has worked with Microsoft (topological qubits) and Intel (superconducting and spin qubits). The role of both partners is decreasing, as both are increasingly investing in their own internal engineering activities. Fujitsu has partnered with QuTech per 2020 in a joint research project to create a blueprint for a modular quantum computer based on diamond spin qubits. In the field of the quantum internet, QuTech works with for instance KPN, ABN AMRO and SURF to develop technologies and applications for a future quantum internet.

The committee recognizes the importance of the current strategy of QuTech to focus on strategic partnerships with private partners, as these companies have the means to offer facilities at a scale an academic institution will not be able to build. However, the phasing out of the industrial partners from the early years of QuTech has shown that the dependence on commercial partners should not be too big to fail. They do not play the same role in the quantum ecosystem as QuTech, and can decide unilaterally to end collaborations. The institute applies this lesson in new collaborations that are mainly based on long-term, well-specified projects rather than more open collaborations. The committee supports this decision, and thinks that this model better protects QuTech now that the role and interests of private partners in the quantum landscape is changing. The committee expects the landscape to drastically evolve as commercialization of quantum technology comes closer, and recommends QuTech to frequently keep revisiting its partnership strategy to keep up with these changes (see Ch 3.4, Viability)

Spin-off activities
An important role in the quantum ecosystem is reserved for spin-out companies launched from QuTech, TNO and TU Delft activities. These companies are housed at or near the TU Delft Campus and provide a vibrant local quantum ecosystem under the name Quantum Delft. Recent spin-off companies include QBlox (control stacks for quantum computers, 23 employees), Quantware (superconducting quantum hardware, 15 employees), Orange QS (support of quantum R&D activities by offering quantum control software and

quantum systems, 12 employees). In total, the Quantum Delft companies housed 135 employees per 2021. QuTech actively identifies spin-out opportunities, and provides researchers and engineers interested in launching a spin-off company with help and advice.

The committee acknowledges the importance of spin-off activities for realizing economic impact from quantum technology within the Netherlands and Europe. The current Quantum Delft ecosystem is already attracting and retaining talent in the Netherlands, for instance by employing former QuTech PhD students. Especially in the current absence of large Dutch and European industrial partners for quantum technology, spin-off companies might be the driving force of a quantum industry in the Netherlands. The committee advises QuTech to keep supporting its spin-off activities, in particular during the start-up phase of new companies that are expected to be valuable to the quantum ecosystem. This could for instance take the form of arrangements to use QuTech facilities and work with Quantum Delft and Quantum Delta NL in coupling new companies with experienced entrepreneurs that can help the young companies grow and develop in their first years.

National and European programs
On a national and European level, QuTech builds its ecosystem primarily through networks and alliances with other research institutions. The National Agenda on Quantum Technology (NAQT), that was co- initiated by QuTech in line with the recommendations by the previous mid-term evaluation committee, was very successful in formulating a national quantum agenda. It has further developed into Quantum Delta NL, where QuTech works with other hubs in Delft, Eindhoven, Leiden, Amsterdam and Twente to coordinate research efforts. In 2021, Quantum Delta NL was awarded 615 M€ over a seven-year period from the National Growth Fund for the full implementation of the agenda. On a European level, QuTech is one of the founding members and the coordinator of the Quantum Internet Alliance, a collaboration of research institutes working on quantum networks.

The committee considers in particular the national programs to be very successful. Quantum Delta and the National Growth Fund have a lot of opportunities to build on this. On a European level, QuTech is in an excellent position to take a leading role in Europe. The Quantum Internet Alliance is a very good example of this, where research is very well aligned within Europe. Members of the alliance work closely together to align their research agendas, partly funded through the Horizon Europe and Quantum Flagship funds of the EU. For the Quantum Computing and Qubit Research divisions, coordination on a European level is less prominent. There are plenty of collaborations between institutions, but no central coordinated effort. The committee thinks that a more coordinated effort within Europe would be very helpful in pursuing economic impact for Europe, creating critical mass and getting industrial partners involved. It encourages QuTech to investigate opportunities together with other leading European institutions to realize this (see also Viability).

Education of talent
Next to science and innovation, QuTech also contributes to the quantum ecosystem by educating new talent and workforce in quantum technology. The educational activities of QuTech, although not part of the original mission, have emerged in the past years as an investment to train the quantum researchers and engineers of the future, and prepare society for the quantum computer. Educational activities are coordinated through the QuTech Academy and include a BSc minor programme related to quantum technologies at TU Delft, and a master track in Quantum Technologies for the MSc Applied Physics in Delft. Together with Leiden University, TU Delft is currently developing a full master's programme in Quantum Information Science & Technologies, which is expected to start in 2023. QuTech Academy MSc courses will be part of this curriculum. Furthermore, QuTech Academy organizes Massive Online Open Courses (MOOCs) and develops a platform for collecting learning activities related to quantum (Qutube.nl). QuTech participates in

a European effort (QTEdu) to create pan-European pilot programs for quantum education at European universities.

The committee thinks that QuTech Academy is a very good and successful initiative to educate talent in quantum technologies on the longer term. In the global competition for talent, participating in educating talent is an important factor. The committee applauds the developments to offer education in quantum technology on a European level, which it expects to be important for the joint European effort to create long-term societal and economic impact.

Evaluation of societal relevance
In general, the committee is impressed by the activities deployed by QuTech to create societal and economic impact for quantum technologies. The institute is heavily involved in many collaborations, partnerships and activities that will help creating impact when the technology finally emerges as an economically viable activity. Major societal impact can be expected when the quantum computer and the quantum internet become a reality: such massive parallel computing power will probably generate applications with far-reaching effects that cannot yet be imagined at the moment. However, the technology is not yet near this level of technological readiness at the moment, in particular for the fundamental research conducted in for instance the Qubit Research division. The committee therefore deems it too early to judge the societal relevance. However, given the state of the technology at the moment, the investments and activities of QuTech are appropriate to pursue future impact. The institute is dedicated to technology transfer, building a quantum ecosystem with private partners and other research institutions, and educating new talent in quantum technology. The emerging spin-offs on a local level are the first concrete example of economic activity rising from QuTech's research. This can be expected to expand to a national and international level in the coming years. The committee thinks that QuTech should work on keeping in touch with the national and European level efforts in research, innovation as well as education to ensure that impact is created for the Netherlands and Europe.

3.4 Viability

Short-term viability (2022-2025)
Based on the quality of the research and engineering staff, as well as the current funding position, the committee concludes that QuTech is in an excellent position to pursue its mission in the coming years. The institute is successful in attracting and maintaining excellent researchers and engineers throughout all ranks of the institute, including PhDs, postdocs and other junior staff, supported through a professionalized governance and support structure. The Boards of TU Delft as well as TNO are dedicated to QuTech and fully support the mission and current strategy. The institute has shown excellent research results across the divisions, and as a result has a very visible and respected position in quantum research world-wide. Through QuTech Academy, the institute invests in the education of new talent on the short as well as the long term.

QuTech has been able to secure ample funding for its activities. Next to the funding resulting from the partner covenant, it attracts funding from multiple other sources. In particular the National Growth Funding awarded in 2021 provides QuTech with an excellent outlook for the coming years. Other sources include individual research grants (Spinoza Prize, ERC), various funding programs from the EU (Horizon 2020, Flagship) and the Dutch Research Council and collaborations with partners such as Fujitsu, Intel and IARPA. This will allow QuTech to cover the costs of its staff and equipment, as well as pursue further growth. This growth should be supported by an investment in the facilities; the committee understood that in particular housing, power and clean-room facilities are critical for the near future. It supports the plans for a new

building on the TU Delft campus to accommodate the expansion of QuTech, and encourages QuTech and its partners to commit to this.

Long-term viability (beyond 2025)
During the site visit, the committee discussed the longer-term outlook with various representatives of QuTech, as well as with the Boards of TNO and TU Delft. According to the committee, the coming years will be critical to determine what type of institute QuTech should become. It expects rapid developments in the field, in particular through the investments made by larger industrial partners and the increased commercialization of quantum technologies. The committee noted with approval that QuTech has already developed four broad scenarios for the future, with various levels of success for quantum technologies and roles for research institutes such as QuTech. It recommends starting active preparations for these scenarios, deciding what type of institute QuTech will be in each of these scenarios, what the consequences of each scenario are, and how QuTech can keep the flexibility to shift from one scenario to the other, and possibly to new, unexpected scenarios. In this dynamic forcefield, QuTech should continuously monitor the achievement of its goals, and adapt these to external developments in a continuous strategic process. For instance, being a frontrunner in developing working prototypes for quantum computers might be less realistic in a scenario when major industrial partners are working on the same topic with much larger budgets, or the dominance of a particular platform for quantum computing might make research into other platforms unsustainable. This requires flexibility, and the ability to adapt and refocus the organization when necessary.

The committee thinks that the coming years should also be used to decide on the organizational structure of QuTech on the long term. Although the collaboration between TU Delft and TNO is very fruitful, an institute with the size and budget of QuTech probably cannot remain a joint project between two organizations forever. QuTech and its mother organizations should therefore reflect on a form in which QuTech can function as a more independent entity beyond 2025. Such a reflection should include different scenarios, with related consequences regarding the maximum and minimum size of QuTech, the effect on the involvement of both TU Delft and TNO, the embedding within the Dutch (applied) research landscape, any collaboration with private partners and the associated funding structure.

In any scenario, the institute and its partners should keep working on acquiring long-term funding, since major sources of funding (partner covenant, National Growth Fund) are temporary and have an end date. A more independent position of QuTech will also require a more independent funding structure. Maintaining an institute with the size and facilities of QuTech requires a long-term commitment that allows for strategic investments and long-term financial planning.

International role and positioning
As discussed under Societal Relevance, the global landscape of quantum technology is rapidly changing. The context of technological innovations is increasingly related to the geopolitical landscape, where technological sovereignty and protection of IP by companies and governments in Europe, the USA and China are important factors. This changes the benefit that QuTech can have from collaborations with big tech companies outside Europe. While collaborations on a research level might be very beneficial, it can be expected that these collaborations will not include commercialization of quantum technology within Europe. This geopolitical shift is also apparent within the EU. Early 2022, the European Commission proposed the Chips Act to strengthen Europe's technological leadership and digital sovereignty.

Therefore, the expected economic impact of quantum technology for the Netherlands and Europe will be strongly dependent on the ability of QuTech and its European partner institutions to set up a successful

quantum ecosystem within Europe. This should be a top priority for QuTech as well as the other European stakeholders involved in quantum technology for the coming years. The key question is what this ecosystem should look like given the fact Europe does not have big tech companies like the US. In the longer term, a start-up ecosystem such as the one that is forming in Quantum Delft might play a role in this, but the committee believes that in the shorter term the involvement of multiple European tech companies is instrumental. QuTech is excellently positioned to take a leading role in orchestrating this. Quantum Delta unites the research & engineering efforts in the Netherlands, and QuTech has already shown to be capable of pursuing coordination on a European level in quantum communication. This field is perhaps therefore the first candidate to strengthen ties with European industrial partners. In general, the committee encourages QuTech, its stakeholders and partners to develop a partnership strategy on a European level, and keep working on uniting the European efforts in quantum technology in research as well as in collaborations with industry. The recently proposed European Chips Act that advocates for digital sovereignty might be a good starting point for such a debate. The institutes in quantum technology and their partners cannot do this alone: this endeavour likely requires major investments on a European level, which the committee thinks are necessary if the EU wants to be a major player in a future quantum industry.

3.5 Organizational context

Academic culture
Both TU Delft and TNO adhere to the Netherlands Code of Conduct for Research Integrity. As QuTech is a highly visible institute that wants to excel in science and technology, it also pursues excellence in the way it operates regarding scientific integrity. This means *transparency* (including open research data), a *culture of integrity* (raising awareness for scientific integrity and, avoiding unhealthy expectations/pressures) and *training* (on-the-job and graduate school training on good scientific practices.). Following the recommendations of the previous committee, QuTech developed a data management policy, providing guidelines for storing and sharing raw research data.

In 2021, QuTech was confronted with a retracted research paper on Quantized Majorana conductance published in 2017 in *Nature*. In its investigation, the Research Integrity Committee (RIC) of TU Delft concluded that the paper contained technical errors and inappropriate data selection. Several other papers on the same topic are being investigated by the RIC of TU Delft for similar reasons, with a second paper being retracted in April 2022. After the investigations of the RIC have been completed, the Board of TU Delft will decide on possible measures for the researchers involved.

As the investigations were still ongoing, the committee did not discuss this particular case during the site visit, but spoke with QuTech representatives about the culture of academic integrity at QuTech. It learnt that QuTech took steps to strengthen the academic culture, even before the investigation came to a conclusion. It organized a mandatory meeting for all staff members to inform them of the ongoing investigation, to discuss the pitfalls of scientific integrity, and how to raise and discuss issues regarding scientific integrity. Furthermore, the importance was stressed of reporting not only successes but also failures. The committee concludes that QuTech took the case very seriously, and took it as an opportunity to strengthen its academic culture to prevent future issues. It encourages QuTech to use this momentum to set up a continuous process to monitor the academic culture, and set up a strategy to support research integrity within QuTech. The committee also encourages QuTech to keep collaborating to the fullest extent regarding the Majorana papers case, and use the results of the RIC investigation to further strengthen the academic culture at QuTech.

According to the committee, the retracted papers should function as a wake-up call to the entire field as a reminder of the pitfalls in an emerging field with high expectations and high pressure to deliver results. Having experienced this first-hand, QuTech has the opportunity to set an example to other research institutes by promoting a culture of academic integrity.

In an unrelated issue, the committee noted from the interviews that QuTech does not have a central policy regarding authorship of research papers, and that some researchers perceive different cultures between departments and groups on this aspect. The committee recommends reflecting on this, and determine whether any central policy is necessary.

Open science
QuTech follows the guidelines of TU Delft with regard to open access publishing, which state that all publications should be publicly available. This is usually done by uploading preprint versions to arXiv.org, and pursue publications in open access journals as much as possible. Regarding the sharing of research data, QuTech committed to making data available to the level of numerical data behind published figures. In a new data policy introduced after the retracted papers, QuTech is striving for sharing raw data, as well as analysis and plotting scripts. The open access and open data policy of QuTech is a boundary condition for publishing with external partners, including industrial partners.

The committee values the open access and open data policies of QuTech, and praises the institute for also applying this to publications based on industrial collaborations. It also appreciates the increased attention to making raw and simulation data available in response to the integrity issues reported above. According to the committee, it can be expected that large industrial partners might be hesitant to do so. The committee recommends keeping communicating clearly about this to external research partners.

PhD education
PhD students at QuTech participate in the TU Delft Graduate School, and are associated with either the Faculty of AS or EEMCS through their promotor. They follow a training programme to develop their research and professional skills, and are offered optional career training and workshops to get the most out of their PhD. During the site visit, the committee had the opportunity to speak to a number of QuTech's PhD students. It learnt that they are generally very satisfied and happy to be at QuTech. In particular they valued the unique opportunities at QuTech to work on state-of-the-art research, the direct connections with engineering and the social links between staff members.

Based on the documentation and the interviews, the committee concludes that PhD education at QuTech is well-structured and that there is sufficient attention for the development of talents as well as the well-being of PhD students. Some remarks were made by PhD students regarding the quality of some of the graduate school courses, as well as the internal communication and coherence between groups and divisions. Some felt that there could be more interaction between the different groups and divisions, so that staff members can get to know each other's work and interact socially. The committee recommends investigating the abovementioned issues to see whether actions are necessary. Possibly more opportunities for unstructured interaction between staff members would be appreciated by the staff.

Internal culture and atmosphere
The staff members that the committee interviewed during the site visit were generally content with the atmosphere and internal culture at QuTech. They felt valued and well-supported by the management as well as their colleagues at QuTech. The institute invests in social and team-building, and aims to create and maintain connections between staff members. The lockdowns during the COVID-19 pandemic were

sometimes challenging, but the institute has worked hard to facilitate the continuation of research and monitor the well-being of staff members. The institute has an active personnel committee with representatives from both TNO and TU Delft, formally a subcommittee of the TU Delft Works Council. It represents the interests of staff members, and has various opportunities to provide formal and informal advice to QuTech's management. The committee had the opportunity to speak to the personnel committee during the site visit, and was impressed by the important role that the committee plays in various internal affairs, in particular in safeguarding the well-being of the staff.

From the interviews, the committee noted that the workload at QuTech can be high at times, but that the management as well as the personnel committee take this issue very seriously. The institute for example creates awareness of the various opportunities for support within QuTech, so that staff members know where they can get assistance for several responsibilities, pays attention to onboarding and creates opportunities for social interaction to prevent staff members from feeling isolated.

4. Summary

Conclusion

The period 2019-2021 was very fruitful for QuTech. The institute is very well equipped to realize its mission, and is recognized as a world-class research institute for quantum technology. The quality of its research and engineering activities is excellent beyond doubt, as demonstrated in high-quality output and world-leading work on several fields within quantum computing and the quantum internet. The set-up where researchers and engineers work closely together provides unique opportunities to work on tangible demonstrators and prototypes. QuTech is heavily investing in creating societal and economic impact for quantum technology, including industrial partnerships, setting up spin-off companies and providing education in quantum technology. The institute has been very successful in acquiring funding and support for its activities in the coming years.

According to the committee, the central questions for the coming years should be what type of organization QuTech should become in the long term, and how economic impact can be generated regarding quantum technology within the Netherlands and Europe. This includes a partnership and funding strategy, the further development of a quantum ecosystem and mechanisms to continuously adapt these strategies to the fast-changing global landscape of quantum technology. The committee is confident that QuTech is well-prepared for these discussions and will be able to further develop the institute in the coming years.

Recommendations

1. Setting up a viable quantum ecosystem within Europe is a top priority for the coming years. Work with other leading European institutions in quantum technology to pursue economic impact for Europe, creating critical mass and getting multiple European tech companies involved. This requires efforts to unite the European efforts in quantum technology and a partnership strategy that is frequently revisited and updated with changes in the landscape. The recently proposed European Chips Act might be a good starting point for such a discussion.

2. Devise a continuous strategic process to monitor the achievement of QuTech's goals, and adapt these to fast-changing external developments. This requires strategic flexibility, and the ability to adapt and refocus the organization when necessary.

3. Work towards a governance structure where QuTech can be governed as if it were one organization. A bigger mandate than is currently the case for the QuTech management will be necessary to achieve this.

4. Use the next years to decide on the organizational structure of QuTech on the long term, investigating options for QuTech to function as a more independent entity beyond 2025. Such a reflection should include different scenarios, with related consequences regarding the maximum and minimum size of QuTech, the effect on the involvement of both TU Delft and TNO, the embedding within the Dutch (applied) research landscape, any collaboration with private partners and the associated funding structure.

5. Keep collaborating to the fullest extent regarding the Majorana papers case, and use the results of the investigation to set up a strategy to further promote research integrity at QuTech.

6. Execute the plans for a new building to accommodate the expansion of QuTech, addressing the current needs regarding housing, power and clean-room facilities.

7. Foster and expand collaborations between research divisions wherever possible, aimed at creating critical mass and increasing flexibility to shift research focus when necessary. It might be helpful to initiate more interaction between different groups and divisions to achieve this.

8. Keep investing in spin-off activities, in particular during the start-up phase of new companies that are expected to be valuable to the quantum ecosystem. This could for instance take the form of arrangements to use QuTech facilities and work with Quantum Delft and Quantum Delta NL in coupling new companies with experienced entrepreneurs that can help the young companies grow and develop in their first years.

9. As major sources of funding have an end date, keep working on acquiring long-term funding commitments that allows for strategic investments and long-term financial planning.

10. Participate in discussions research regarding the sustainability and the social and ethical aspects of quantum technology, and raise awareness for these issues within QuTech. Relevant topics include the sustainable production and use of quantum devices, safety by design and the potential impact of quantum technology on society.

Appendix 1: Programme of the site visit

Wednesday 20 April 2022

15.00-15.30	Welcoming of guests
15.30-17.00	Internal preparation panel
17.00-17.45	Tour of the facilities: Quantum Computing and Qubit Research

Thursday 21 April 2022

09.00-09.30	Start site visit, welcome and acquaintance
09.30-10.45	Interview with Board of Directors QuTech
10.45-11.30	Interview with Executive Board TNO and Managing Director TNO Unit Industry
11.30-12.15	Lunch
12.15-13.00	Interview with Executive Board TU Delft (online)
13.00-14.15	Interview with the Quantum Internet division and Demonstrator Board
14.15-14.30	Break
14.30-15.15	Interview with PhD students
15.15-16.00	Tour of the facilities: Quantum Internet
16.00-16.15	Break
16.15-17.00	Interview with the Executive Boards of Quantum Delta NL and Quantum Delft
17.00-18.15	Informal discussion/drinks and bites with stakeholders QuTech

Friday 22 April 2022

9.00-10.00	Interview with Qubit Research division
10.00-10.45	Interview with QuTech Academy
10.45-11.00	Break
11.00-11.30	Interview with OdC (personnel committee) members
11.30-12.30	Lunch
12.30-13.45	Interview with Quantum Computing division and Demonstrator board
13.45-14.30	Concluding interview with Board of Directors
14.30-17.00	Composing of preliminary assessment by panel
17.00-18.00	Oral presentation by panel

Appendix 2: Quantitative data

Overview of QuTech staff

QuTech		2019			2020			2021		
SEP category		SEP #	Avg. FTE	SEP FTE	SEP #	Avg. FTE	SEP FTE	SEP #	Avg. FTE	SEP FTE
Scientific staff	PI	16,7	13,8	11,0	16,8	13,9	11,1	17,0	14,0	11,2
	Postdoc	36,5	36,0	14,4	39,5	38,6	15,4	38,9	37,3	14,9
	PhD	81,7	79,8	63,8	91,8	89,5	71,6	95,4	93,0	74,4
	Researcher	44,0	26,1	18,3	44,8	29,8	20,8	38,4	27,0	18,9
Total Scientific staff		178,8	155,6	107,5	192,9	171,8	119,0	189,8	171,3	119,4
Engineering staff		64,0	52,6		73,1	59,3		96,7	67,2	
General support staff		27,0	19,1		26,1	16,8		31,7	20,6	
Grand Total		**269,8**	**227,3**	**107,5**	**292,1**	**247,9**	**119,0**	**318,1**	**259,1**	**119,4**

Funding (TU Delft part)

	2015		2016		2017		2018		2019		2020		2021	
(x €1.000)	€	%	€	%	€	%	€	%	€	%	€	%	€	%
Funding:														
Direct funding[1]	2.119	91%	1.517	13%	2.567	17%	2.835	16%	3.413	18%	4.381	18%	4.534	18%
Research grants[2]	203	9%	4.517	39%	5.954	39%	5.480	31%	6.992	37%	7.677	32%	6.323	25%
Contract research[3]	-	0%	5.514	48%	6.773	44%	9.310	53%	8.229	44%	11.454	48%	13.798	55%
Other[4]	2	0%	7	0%	8	0%	-	0%	63	0%	339	1%	243	1%
Total funding	**2.324**	**100%**	**11.555**	**100%**	**15.302**	**100%**	**17.625**	**100%**	**18.697**	**100%**	**23.851**	**100%**	**24.899**	**100%**
Expenditure:														
Personnel costs	-1.168	48%	-4.802	42%	-6.799	60%	-9.425	58%	-11.745	67%	-14.107	68%	-15.186	65%
Other costs	-1.245	52%	-6.556	58%	-4.474	40%	-6.769	42%	-5.895	33%	-6.746	32%	-8.178	35%
Total expenditure	**-2.413**	**100%**	**-11.358**	**100%**	**-11.273**	**100%**	**-16.194**	**100%**	**-17.639**	**100%**	**-20.853**	**100%**	**-23.364**	**100%**

Funding (TNO part)

	2015		2016		2017		2018		2019		2020		2021	
(x €1.000)	€	%	€	%	€	%	€	%	€	%	€	%	€	%
Funding:														
Direct funding[1]	2.5	38%	4.025	66%	4.45	58%	4.5	47%	4.5	47%	4.3	54%	4.3	28%
Research grants[2]	-	0%	-	0%	-	0%	-	0%	-	0%	-	0%	-	0%
Contract research[3]	4.113	62%	2.048	34%	1.547	20%	4.278	44%	4.711	49%	3.344	42%	10.939	71%
Other[4]	-	0%	-	0%	1.714	22%	860	9%	250	3%	250	3%	250	2%
Total funding	**6.613**	**100%**	**6.073**	**100%**	**7.71**	**100%**	**9.635**	**100%**	**9.641**	**100%**	**7.894**	**100%**	**15.489**	**100%**
Expenditure:														
Personnel costs	-2.776	91%	-4.759	96%	-6.585	91%	-8.279	80%	-8.230	84%	-8.060	86%	-9247	91%
Other costs	-279	9%	-216	4%	-703	9%	-2.168	20%	-1.584	16%	-1.274	14%	-886	9%
Total expenditure	**-3.055**	**100%**	**-4.975**	**100%**	**-7.56**	**100%**	**-10.597**	**100%**	**-9.814**	**100%**	**-9.334**	**100%**	**-10.133**	**100%**
Delta	**3.558**		**1.098**		**149**		**-962**		**-173**		**-1.440**		**5.356**	
Work in Stock	**3.558**		**4.655**		**4.805**		**3.758**		**3.585**		**2.145**		**7.501**	