RESEARCH REVIEW

QUTECH

DELFT UNIVERSITY OF TECHNOLOGY

NETHERLANDS ORGANISATION FOR APPLIED SCIENTIFIC RESEARCH (TNO)

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REPORT ON THE RESEARCH REVIEW OF QUTECH

1. FOREWORD BY COMMITTEE CHAIR

Regular review of a research institute is an essential instrument to guarantee its scientific quality, societal relevance and viability. A panel of international experts has the challenging task to form a balanced judgement on the basis of a self-evaluation report, site visit and a variety of discussions with research leaders. In the case of the QuTech institute this task is even more challenging, but also exciting, since QuTech deals with the potentially very disruptive and innovative topic of quantum technology. In addition, QuTech does not limit itself to basic research but also has as a mission to implement the technology and bring it to higher so-called Technology Readiness Levels (TRL's).

Both participating partners, TU Delft and TNO, strongly supported by the Dutch government, have had the bold vision bring their organizations together. Guided by four main PI's, QuTech has set up a coherent research and business development program, including collaborations with main information technology companies, that is unique in the world.

It has been our great pleasure and privilege to get informed about the scientific quality, the vibrant energy, the enthusiastic and driven young talented people and ambitious plans of QuTech. Moreover, the panel is very impressed by the enormous progress the relatively young institute has made and professional organization it has established. The challenge for QuTech, being a worldwide leader in developing quantum technologies and bringing them to practical implementation is enormous, but the committee is impressed by the flying start of the institute and very eager to follow the progress of QuTech in the years to come.

Prof. R.H. (Robbert) Dijkgraaf, Chair of the Committee
Director and Leon Levy Professor of the Institute for Advanced Study, Princeton

Prof. A. (Albert) van den Berg, Vice-Chair of the Committee
Professor of Nanotechnology, University of Twente

February 2019

2. THE REVIEW COMMITTEE AND THE PROCEDURES

2.1. Scope of the review

The review committee was asked to perform a mid-term review of research conducted between 2015 and 2018 at the QuTech Institute for Quantum Technology, a collaboration between Delft University of Technology (TU Delft) and the Netherlands Organisation for Applied Research (TNO), located at TU Delft.

In 2015, TU Delft, TNO, the Dutch Ministries of Economic Affairs and Education, Culture and Science, the Netherlands Organisation for Scientific Research (NWO) and the Dutch Top Sector High-Tech Systems and Materials (HTSM) committed themselves to QuTech, to providing a ten-year financing perspective. The QuTech Partner Covenant, in which this commitment was formalized, specified two mid-term reviews by an international committee within this ten-year period. This review is the first of these mid-term reviews and covers the period between 2015 and 2018.

This mid-term review is based on the Standard Evaluation Protocol 2015-2021 (SEP, amended version September 2016) for research reviews in the Netherlands. As specified in the SEP, the committee's tasks were to assess the quality, the relevance to society, and the viability of the scientific research at the research unit as well as the strategic targets and the extent to which the unit is equipped to achieve these targets. A qualitative review of the PhD training programme, research integrity policy and diversity also formed part of the committee's assignment.

The Boards of TU Delft and TNO, in consultation with the other Covenant partners, provided the committee with Terms of Reference concerning the assessment. In this document, the Boards asked the committee to pay special attention to and offer recommendations in the assessment regarding the following questions:

1. QuTech's strategy to develop technology from scientific research towards higher technology readiness levels (TRL) and business applications and the period in which QuTech expects these applications to have an economic impact and impact on society; please specify these impacts at world, EU and Dutch levels.
2. In view of the point above, please advise on the (additional) expertise QuTech needs to develop the roadmaps further.
3. QuTech's extensive collaboration with international companies and the impact of this, for example on the independence of QuTech's science and engineering activities; please advise about the strategy and development of such extensive collaborations for both QuTech and these private partners.
4. The contribution of the Dutch efforts and investments of global companies in QuTech's research and engineering activities to the competitiveness of the Dutch knowledge infrastructure in Europe and possibly globally, both financially (successful in competitive calls such as flagship, attracting private investments) and policy-based (influencing the EU agenda).
5. Please include a qualitative assessment of the four QuTech roadmaps in relation to their strategic targets and ambitions.
    a. Fault-Tolerant Quantum Computing (FTQC);
    b. Quantum Internet and Networked Computing (QINC);
    c. Topological Quantum Computing (TOPO);
    d. Shared Technology Development (STD).

2.2. Composition of the committee

The composition of the committee was as follows:

- Prof. R.H. (Robbert) Dijkgraaf, Director and Leon Levy Professor of the Institute for Advanced Study, Princeton - chair
- Prof. A. (Albert) van den Berg, Professor of Nanotechnology at the University of Twente – vice-chair
- Prof. T. (Tony) Hey, chief data scientist at the UK's Science and Technology Facilities Council in Oxford

- Prof. E. (Evelyn) Hu, Professor of Applied Physics and Electrical Engineering at Harvard University
- Prof. D. (Daniel) Loss, Professor of Theoretical Physics at University of Basel and director of the Basel Center for Quantum Computing and Quantum Coherence
- Dr. N. (Nils) Trautmann, senior manager for innovation at Carl Zeiss AG
- Prof. M. (Maud) Vinet, Manager Advanced CMOS Laboratory at CEA-Leti Grenoble

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

2.3. Independence
All members of the committee signed a statement of independence to ensure that they would assess the quality of QuTech in an unbiased and independent way. Any existing personal or professional relationships between committee members and the research unit(s) under review were reported. The committee concluded that there were no unacceptable relations or dependencies and that there was no specific risk in terms of bias or undue influence.

2.4. Data provided to the committee
The committee received the self-evaluation report from the unit under review, including all the information required by the SEP.

The committee also received the following documents:
- the Terms of Reference;
- the SEP 2015-2021, amended version September 2016;
- appendices to the self-evaluation report.

2.5. Procedures followed by the committee
The committee proceeded according to the SEP. Prior to the first meeting, all committee members independently formulated their preliminary findings of the unit under review and additional questions for clarification based on the written information that was provided prior to the site visit.

The final report is based on the documentation provided by the research unit, and also includes the information gathered during the interviews with management and representatives of QuTech. The interviews took place on 10 and 11 January 2019 at Delft University of Technology. Preceding the interviews, the committee was briefed by QANU about research reviews according to the SEP. It also discussed the preliminary findings and questions, decided upon a number of comments and questions, and agreed upon procedural matters and aspects of the review. After the interviews the committee discussed its findings and comments, allowing the chair to present the preliminary findings and the secretary to draft a first version of the review report.

The draft report was presented to the research unit concerned for factual corrections and comments. In close consultation with the (vice-)chair and other committee members, the comments were reviewed by the secretary and incorporated in the final report. The final report was presented to the management of the research unit.

2.6. Application of the SEP and scores
The committee used the criteria and categories of the Standard Evaluation Protocol 2015-2021 (SEP). For more information see Appendix 1.

3. QUANTITATIVE AND QUALITATIVE ASSESSMENT OF QUTECH

3.1. Mission, vision and organization

Foundation and mission of QuTech

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'.

In contrast to classical computers, which are based on bits that can be either 0 or 1, quantum computers are based on qubits, which can be 0 and 1 at the same time. It is anticipated that qubits can be used to perform an exponentially large number of computations at the same time. Algorithms that exploit this computational power can be used to address problems that are far beyond the reach of classical supercomputers, such as designing new materials, chemical processes or medicines. The quantum internet as envisioned by QuTech enables communication between any two points on earth by transporting qubits. It can operate in parallel to the classical internet, and can for instance be used to provide a secure communication channel that cannot be tapped. The basic principles of a quantum computer and the quantum internet have been demonstrated for various platforms and systems in the past two decades. Current research is aimed towards overcoming the challenges surrounding the reliability, fabrication, implementation and applications of quantum technologies.

As quantum technologies are increasingly viewed as a high-potential breakthrough technology, research within this field has grown rapidly in the past decades. In 2014, TU Delft and TNO joined forces by bringing together four influential researchers in quantum computing and internet from TU Delft and the engineers from TNO with the goal of developing a quantum computer and quantum internet, thus founding QuTech. Funding for the period 2015-2025 was pledged by the Dutch Ministries of Economic Affairs and Education, Culture and Science, the Netherlands Organisation for Scientific Research (NWO) and the Dutch Top Sector High-Tech Systems and Materials (HTSM) through the QuTech Partner Covenant. In recent years, QuTech has increasingly welcomed industry into its environment. As a commercially feasible quantum computer and a prototype quantum internet are expected to be possible within ten to twenty years (or even earlier), quantum technology has started attracting additional interest from global IT companies. QuTech has established partnerships for close collaboration with Intel and Microsoft to work on quantum computing.

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. As of 2018, the QuTech organization consists of three branches: Research, Operations, and Business Development. Each branch is led by a Director, and all three form the QuTech Management Board headed by the Research Director as a *primus inter pares*. This Board reports to the TU Delft Executive Board, which consults the TNO Executive Board regularly.

Research in QuTech is organized in three research roadmaps: Fault-Tolerant Quantum Computing (FTQC), Quantum Internet and Networked Computing (QINC) and Topological Quantum Computing (TOPO). FTQC and TOPO are focused on QuTech's mission to develop a quantum computing prototype, while QINC aims to realize a quantum internet. In addition to the roadmaps, QuTech recognizes three cross-cutting activities to which all three research roadmaps contribute. The first one is Shared Technology Development (STD), which is considered the fourth roadmap, headed by TNO. STD strives for technology push: translating fundamental research into applications and taking them to the market. The other two cross-cutting activities are Quantum Software and Technology and QuTech Academy. Quantum Software and Technology is focused on the development of new theories and methods for quantum technology and the development of quantum algorithms. QuTech Academy consists of all educational and a number of education-related outreach activities of QuTech.

During the site visit, the committee spoke to QuTech's management, the Chairs of the Boards of TU Delft and TNO as well as representatives of all four roadmaps. It encountered a vibrant atmosphere with a powerful shared mission of developing ground-breaking quantum technologies. The institute is strongly supported by the Boards of TU Delft and TNO, which meet with the QuTech management on a monthly basis and closely monitor and discuss the developments within the institute. The QuTech management board works on a collegial basis with the roadmap leaders. According to the committee, the recent addition of a Director of Operations and a Director of Business Development to QuTech's management is appropriate considering the growth of the institute and the increasing focus on applications of quantum technology. The matrix structure guarantees the embedding of shared interests between the roadmaps within the structure of the institute.

There is frequent interaction between the principal investigators (PIs) within and between the roadmaps. According to the committee, this is a strong characteristic of QuTech, which is contributing to the success of the institute as a whole. By successfully combining the expertise and focus points of the researchers, QuTech is more than the sum of its PIs and can successfully generate critical mass to tackle the challenges associated with the institute's mission.

Cooperation between TU Delft and TNO
During the site visit, the committee discussed the cooperation between TU Delft and TNO within QuTech with various representatives of the institute. It views this collaboration as a unique feature of QuTech, reflecting a visionary approach towards developing new technologies. The inclusion of TNO from the very beginning of QuTech shows that the institute was not founded purely as a research institute; it has a clear vision of realizing marketable applications. TNO's expertise of taking scientific research into practice complements the research expertise of TU Delft and makes the institute excellently equipped to realize its mission. The committee deduced from the interviews that, although connecting the two worlds of TU Delft and TNO has taken some time to get used to, the institute is dedicated to making this cooperation a success.

The committee views the balance of responsibilities between TU Delft and TNO within QuTech as currently leaning in the direction of TU Delft. The university houses the institute, employs the majority of the researchers and is directly responsible for the institute in the governance model. According to the committee, this is a fitting structure considering the current technology readiness level of the topics investigated at QuTech, which for a substantial part is still in the pioneering research phase. However, applicable technology in various research areas will come within reach in the near future. It would seem natural to the committee for the balance between TU Delft and TNO to rebalance more towards TNO in the coming years. The newly appointed Business Director (on the payroll of TNO) could take on a leading role in business development. This will be discussed further in section 3.3.

3.2. Research quality
To assess the research quality of QuTech, the committee considered the performance indicators formulated by QuTech in the self-assessment report. These included the research output listed in Appendix 3, as well as marks of recognition from peers such as research grants, awards and membership of prestigious organizations. The committee's qualitative findings were discussed for the Fault-Tolerant Quantum Computing (FTQC), Quantum Internet and Networked Computing (QINC) and Topological Quantum Computing (TOPO) roadmaps, including possibilities for their future development. The Shared Technology Development (STD) roadmap will be discussed in the section on Societal relevance (section 3.3).

Fault-Tolerant Quantum Computing (FTQC)
The FTQC roadmap at QuTech aims to realise a full-stack scalable quantum computer, including qubit circuits, control electronics and software. As qubits, it uses either electron spins confined in semiconductor quantum dots or superconducting transmon qubits. The roadmap applies quantum error correction to detect and correct errors to realize a reliable, fault-tolerant system. It is currently in the process of constructing quantum computer demonstrator systems based on their results. The

FTQC roadmap is divided into two teams: the spin qubit team under the leadership of Prof. Lieven Vandersypen and the superconducting qubit team under the leadership of Prof. Leo DiCarlo.

The spin qubit team has established itself as one of the leaders in the field and has a high international reputation. It has achieved control of spin qubits in Si/Ge quantum dots with a fidelity that has set the standards in the field worldwide. Most recently, it pioneered the coupling of spin qubits to photons in microcavities, which the committee considers to be one of the highlights of QuTech in recent years. The group is extremely successful in attracting the best talents and competitive funds. The collaboration with Intel is producing impressive fruits, especially in the development of scalable structures and cryogenic control technology. The visibility and leadership of the spin qubit team are excellent, and they belong to the pioneers of the field worldwide.

Similarly, the achievements of the superconducting qubits team are most impressive, notably the high level of control electronics which is at the forefront of the field worldwide. This area has one of the highest technology readiness levels of QuTech, thanks to the exemplary collaboration of TNO engineers and FTQC researchers, in collaboration with Intel. The near-term goals of the superconducting team are to demonstrate quantum error detection with 7 qubits, build a useful quantum memory with 17 qubits and demonstrating quantum fault tolerance with 49 qubits. These form the biggest milestones of the entire field of quantum computing at the moment. There seems to be no other group worldwide closer to these breakthroughs than the team at QuTech.

The research output in both teams is at the highest level, with many high-impact publications which have set the standards in the field, for instance for a programmable two-qubit silicon device (Nature 2018), a quantum simulation with quantum dots (Nature 2017), strong spin-photon coupling in silicon (Science, 2018), using germanium to host spin qubits (Nature Communication 2018), long spin lifetimes at elevated temperatures (Physical Review Letters 2018) and many more. Both teams have excellent research facilities and are enjoying the highest funding support, attracted by their outstanding track record and promise of future achievements. Funding currently includes ERC grants (Synergy and Advanced), NWO's talent scheme (Vidi, Vici), the Intel collaboration and funding by US agencies IARPA and ARO.

Both teams are focussing on fault-tolerant quantum computation, which is the ultimate goal and holy grail of the field in the long term. However, the committee encourages both teams to focus part of their attention on noisy intermediate quantum devices for the near-term benefit. Expanding expertise in this direction can demonstrate quantum advantages, and might deliver technological benefits that could contribute to the realization of the long-term goal. In addition, the team would benefit from additional investments in nanofabrication, which is essential for realizing quantum technology in practice. Additional expertise as well as dedicated equipment to this end might speed up the team's progress. The roadmap could look for collaboration with the QINC roadmap in this, as well as investigate possibilities to use facilities of existing or new (industrial) partners.

The FTQC roadmap sets the gold standard for qubit research and technological applications worldwide. It is among the most influential teams, or possibly is the most influential team worldwide to work on this topic. It has an extremely bright outlook for the future and is uniquely positioned together with Intel to reach the next milestones in the development of a scalable quantum computer based on spin or superconducting qubits.

Quantum Internet and Networked Computing (QINC)

The QINC roadmap led by Prof. Stephanie Wehner is developing technologies for communication over quantum networks. These networks can be used either for developing a quantum internet or for providing networked computing between multiple quantum devices. A specific application that QINC is working on is Quantum Key Distribution (QKD), a cryptography method which makes it impossible to eavesdrop on communication without the receiver knowing, using fundamental quantum mechanical properties. The team has already been successful in demonstrating major building-block concepts of quantum communication in practice, including teleportation of data, and is currently working on expanding the reach of its prototype quantum internet.

According to the committee, the QINC roadmap is a world leader in its field. It has had a profound impact in advancing and helping to define the parameters of a quantum internet. The excellence is manifested in the consistent output of highly cited publications in leading journals such as *Nature* and *Science.* The team's most prominent result has been a successful demonstration of entanglement between two nitrogen-vacancy centres in diamond separated by 1.3 km, published in Nature in 2015. This demonstration set the record for the longest distance for heralded entanglement, and the highest quality (fidelity) of remote heralded entanglement. This achievement was recognized as a top-ten breakthrough of the year in *Science* and *Nature,* and recognition was also given in the popular press: for example, the *New York Times* and *Economist* magazine covered this teleportation of data.

The proposed qubits of QINC's quantum internet, NV centres, are widely recognized as an excellent candidate for qubits, and the QINC team has tackled substantial challenges in achieving qubit control in such materials. Realizing such an achievement has built upon a succession of major fundamental scientific achievements, such as the understanding of decoupling the NV qubits from noise induced by the spin bath. At the same time, this demonstration of *loophole-free Bell inequality violation* provided the platform for entanglement distillation (*Science 2017)* and deterministic delivery of entangled states over a quantum network (*Nature 2018).* In addressing the totality of quantum network issues, the QINC team has also demonstrated a complete active quantum error protocol (Nature 2016) and studied the capacity estimation of quantum channels with arbitrarily correlated errors (*Nature Communications 2018).* Anticipating future demands for longer-distance information propagation of their quantum internet, the team has explored quantum frequency conversion to telecom wavelengths (*Physical Review A 2018),* allowing low-loss information propagation through optical fibres. In every respect, the QINC roadmap is helping to set the groundwork, address the challenges and set the guidelines for the creation of new quantum internets and networks, as embodied in the recent article in *Science* on *Quantum Internet: A Vision for the road ahead.*

The prominence of QINC's researchers is evident in the citations of their publications, the number of invited talks they deliver, and the plethora of prizes they have received, such as the *Paul Ehrenfest Award* (Wehner, Taminiau, Elkouss, 2016; also for Hanson, 2016) and the Huibregtsen Award for Excellence in Science and Society (Hanson, 2016). Members of QINC are leaders in the *Quantum Internet Alliance* (2018-21, part of the EU Flagship on Quantum Technologies).

The quality of the research facilities appears to be excellent, and the research environment is a collaborative, synergistic and closely interactive one. According to the committee, the main expertise required for QINC to move forward is toward application rather than research. To realize a large-scale quantum internet beyond the 2020 Demonstrator of connecting four Dutch cities, it will require resources and collaboration of users in the domain of classical networking. The larger complexity of the more sophisticated quantum internet will require a greater participation of engineering staff as well as scientists, and possible coordination with governmental agencies and internet providers. The committee recommends investing in these connections, and exploring possibilities for further collaborations with potential users.

Topological Quantum Computing (TOPO)

The TOPO roadmap led by Dr. Michael Wimmer aims to demonstrate topological protection of quantum information using a topological qubit based on Majorana fermions. This platform promises protection from errors without the need for external error correction. To realize this platform, hybrid semiconducting / superconducting devices harbouring Majorana fermions need to be explored, which is mainly scientifically uncharted territory, requiring encouragement of the development of both new materials and fabrication techniques as well as the fundamental physics of these new devices.

According to the committee, research in the TOPO roadmap is the most fundamental of the three roadmaps, but offers great promise. A prominent partner in this research line is Microsoft, which has recently hired former roadmap leader Prof. Leo Kouwenhoven from QuTech and has made a major investment in a new research lab next door to the QuTech facilities, where Kouwenhoven can continue his work in close collaboration with the TOPO research team at QuTech. The group has done pioneering work in the field with the ground-breaking experiment of Mourik et al. (Science 2012), and has continued to steam ahead. It has performed experiments at the highest possible level of originality and has created an entirely new field of research in the pursuit of building topological qubits based on Majorana fermions. This area has been one of the most topical fields in condensed matter physics over the last years, and its development has largely been driven by the efforts of the outstanding QuTech team. These experiments have attracted the brightest talents worldwide, both experimentally and theoretically, to develop the Majorana physics unravelled by the QuTech team.

The visibility of the research output is high with numerous high-impact publications, including on improving the 2012 Majorana experiment (Nano Letters 2017, Nature Nanotechnology 2018), the superconducting properties of epitaxial aluminium on InSb nanowires (Nature 2017), and quantized conductance due to Majorana bound states (Nature 2018), as well as joint experimental and theoretical efforts to unravel topological superconductivity (Nature Communications 2017). As a result, the researchers' reputation is very high, with some clearly being leaders in the field worldwide. The research facilities are excellent, especially the new lab funded by Microsoft. The research environment is stimulating for young researchers, particularly for graduate students being attracted to work at the forefront of experiments on topological quantum science. The future is highly promising, especially given that Microsoft has established a new centre at Delft under the leadership of Prof. Kouwenhoven which is committed to collaborating closely with the TOPO team of QuTech.

One of the most challenging tasks in the near future will be to establish the existence of Majorana fermions unambiguously and to build topological qubits with long coherence times. The TOPO team is uniquely positioned for this challenge, and there is no doubt that pioneering progress will be made towards this goal. According to the committee, the TOPO roadmap is excellently positioned in terms of expertise. It forms, together with Microsoft, by far the largest focused effort in this field. The committee encourages the TOPO roadmap to continue on its pioneering endeavour.

3.3. Relevance to society

QuTech was founded with clear applications in mind: realizing a quantum computer and quantum internet prototype. When successful, these new technologies are expected to have a major societal and economic impact. The vast computing power of quantum computers is expected to be applicable to grand societal challenges such as climate change (greatly improved climate models and simulations), health (computational medicine) and security (a safe quantum internet). Quantum technologies are also expected to have a substantial economic value. As specified in the QuTech's Self-Assessment Report, an early estimate for the global market for quantum technology in 2030 is €60 billion, with an associated potential 7000 fte in jobs on the local (Dutch) labour market directly associated with QuTech's endeavours.

According to the committee, these promises form the basis for the societal relevance of QuTech. At the moment, it is too early to tell whether quantum technologies will be able to fulfil these promises or possibly exceed them. Based on the recent research results and the interviews held during the site visit, the committee is confident that QuTech is coming closer to the realization of technology that will have a major impact on society and economy, possibly already within a 5 to 10 year time-frame.

To realize these ambitions, QuTech has defined four types of activities in order to transfer its insights to society:

- business and technology development
- developing a quantum community
- developing a quantum campus
- outreach and education.

Technology Development
QuTech aims to increase the technology readiness up to the level that it can be adopted by business partners. Technology development at the institute is a joint effort between the three science & technology roadmaps and the Shared Technology Development (STD) roadmap. The STD roadmap's mission is to increase TRLs of technology needed for quantum computers and quantum internet. Within the Shared Technology Development (STD) roadmap, the engineering skills and technology development expertise of TNO are coupled to the scientific expertise of the TU Delft researchers. The science & technology roadmaps and STD develop quantum computer and quantum internet demonstrators. Current demonstrator projects developed at QuTech include the *Quantum Inspire*, a silicon-based quantum chip available in the cloud and *Quantum Link*, the world's first four-node Quantum Internet, as well as (pre)prototypes for key components such as a vector switch matrix, central controller and quantum frequency convertor to be used for instance in the *Quantum Infinity* demonstrator.

According to the committee, technology development at QuTech can already showcase some impressive results. The choice by QuTech to use demonstrators is impactful. The pragmatic approach chosen to identify relevant demonstrators at a given maturity stage helps provide structure for the research teams and is gaining QuTech an influential global position. Building up demonstrators like *Quantum Inspire* and giving potential users the ability to play with the technology will help to identify relevant applications of quantum computing, and to generate the required market pull for commercialization. By giving users an open platform such as *Quantum Inspire*, QuTech can learn from them what kind of applications are of interest. This is especially important for use cases in the NISQ (Noisy Intermediate-Scale Quantum) regime, as mentioned under the discussion of the FTQC roadmap (Section 3.2). This knowledge can be used to steer hardware development. In addition, the QINC network settlement is a pioneering step for the quantum internet and provides the Netherlands with a strong innovation image.

From an organizational perspective, the contribution of engineering and project management through the STD roadmap makes TNO a valuable partner in QuTech. The assigned TNO staff currently work both on an identified-need basis, providing support where the research roadmaps identify possibilities for technology development, as well in increasing TRL in the demonstrator projects assigned by QuTech's Board of Directors. Until recently, the STD roadmap mainly operated in a supporting role providing applied researchers and demonstrator engineers to the research roadmaps. This was a reasonable arrangement in a pioneering and prototyping phase. However, as a the larger role of innovation management is expected in the near future, the institute decided to increase the role of technology development within the institute's governance. In 2018, it included a Director of Business Development in QuTech's Board of Directors next to the Director Research and Director Operations.

The committee is very positive about this inclusion, and recommends QuTech to empower the new Director of Business Development to take a leading role in innovation management and business development activities. This leading role is a necessary step towards more involvement of TNO in QuTech, as required by the increasing maturity of quantum technology. According to the committee, the TRLs that QuTech aims for require focused investments in business opportunities when they present themselves, which are decisions taken on a management level. Also, when higher TRLs are achieved, the importance of innovation management increase. A closer involvement of TNO will help to provide QuTech with the relevant skills and prepare it for the management decisions which will arise in the future, such as prioritization between technologies and strategies for commercialization.

Another area in which TNO might contribute additional expertise to QuTech is on the topic of Intellectual Property (IP) rights. According to the Self-Assessment Report, QuTech has currently filed 14 patents. The committee thinks that QuTech should consider making an additional effort to turn its impressive scientific output into IP. This does not necessarily apply just to future technologies: there is already potential for IP in the methods being developed now. Building up an IP portfolio will be crucial to commercialize quantum technology, either through start-ups or in collaboration with industry. According to the committee, a rapid rise can already be observed in patent applications in the area of quantum technologies, especially in quantum computing. It can also help to protect QuTech once more industry players become active in the area of quantum technologies, which might pursue a more commercialized and aggressive IP policy. Given that TNO already has extensive experience regarding IP, it could be a valuable partner to enable QuTech to build up an IP portfolio and file IP from QuTech as part of the tasks of the newly appointed Business Director.

Quantum community

QuTech has been a major player in the global quantum community since its foundation in 2015, and its principal researchers did important work even before then. As a young field, the community has had to organize itself to create an impact in society and public awareness. One of its major accomplishments has been to put quantum technologies on the European research map. QuTech was a co-initiator of the EU Quantum Technologies flagship, a major funding initiative of €1 billion spread over 10 years which was launched in 2016. QuTech has representation at all levels of the flagship's governance, including through TNO in the Quantum Support Action, which coordinates and manages this initiative. A major project funded through the EU Quantum Flagship is the Quantum Internet Alliance (QIA), a €10 million project with 12 European research groups and 20 associated companies and institutes, led by Prof. Wehner from QuTech. In addition, QuTech is a player in the Quantum Community Network (QCN), which coordinates the field of quantum technology in Europe, and has strategic alliances in Denmark (Niels Bohr Institute), Japan and Jülich-Aachen.

According to the committee, QuTech is very well positioned in the quantum community, and has been instrumental in making the Netherlands a central player in quantum technology, not only on the European level but also globally. It is also in the process of forming a quantum community of its own. Through attracting and educating top researchers and PhD students in quantum technology, QuTech has an increasingly larger network of researchers in academia and beyond. A fair number of its PhD students and postdocs get employed at one of the industrial partners, suppliers or spin-off companies surrounding QuTech.

Quantum Campus

Generating commercial activities directly around QuTech on a Quantum Campus is a deliberate ambition of QuTech. A cluster of companies and labs is already growing on the so-called Q-Campus. Next to the recently opened Microsoft Quantum Lab Delft, a number of spin-off companies and suppliers opened R&D offices in Delft, including Bluefors (cryogenic technology), Delft Circuits (hardware supplier) and Single Quantum (single photon detectors). The committee thinks that this small cluster has the potential to grow into a larger hub for quantum technology businesses. The current companies in the Q-Campus are involved in technology and instrumentation for quantum researchers, but in the near future, spin-off businesses working on actual quantum computing or networking are to be expected, and the Q-Campus seems like a natural location for these activities. If it continues to be successful, this campus could have a major impact on the regional or even national economic activity.

Outreach and education

QuTech's educational activities are organized in the QuTech Academy. As part of its educational activities, the Academy organizes courses for master and PhD students on quantum technologies at TU Delft, provides BSc and MSc projects, scholarships for talented students interested in quantum computing, and a number of Massive Open Online Courses (MOOCs). The committee thinks that QuTech is very dedicated to education and praises its efforts.

In outreach, QuTech has made considerable efforts to communicate the field of quantum technology to a broader audience. Its researchers are widely recognized in the Netherlands and abroad as thought leaders in the field and thus are often asked to contribute an expert view on quantum technology to media productions, companies and institutions. QuTech has been officially labelled a 'National Icon' by the national government since 2014, which opens up opportunities for meeting with top politicians and industry representatives.

QuTech has featured regularly in news media, most prominently regarding the teleportation experiment in 2015, but also for the announcement of the EU Quantum Flagship and in features on quantum computing and quantum internet in general. QuTech's researchers have also appeared in many popular science shows on television and live, to promote quantum technologies. The committee is impressed by the PR and outreach activities of QuTech, and the effort the institute makes to popularize its field.

The committee notes that the outreach activities of QuTech, although very successful, have mostly been created in response to demand and appear fragmented as a result. QuTech's management acknowledged this and stated to the committee that they are currently working on a coherent communication strategy, and are planning to attract additional communication and PR expertise to QuTech. The committee supports this development. It wants to stress that this communication strategy should not focus too much on inflated promises of future quantum computers. This type of outreach has an associated risk of overselling, as the future applications of a quantum computer are not yet clear. The committee also advises focussing on quantum technology in the broader sense, including other applications than the quantum computer, such as quantum metrology, and on currently available technology.

Overall, the committee thinks that QuTech has an outstanding relevance to society. This is most prominently visible in its overall mission: the promise of developing new quantum technologies and the associated large societal and economic impact. Additionally, the societal relevance of QuTech is already becoming visible by attracting the quantum community and associated economic activities to the Netherlands. The committee thinks that QuTech will be a major player in the quantum transition expected in the near future and has the potential to make the Netherlands, and by extension Europe, a focus point for these innovations.

3.4. Viability

In terms of funding, the committee considers QuTech exceptionally well equipped for the future. In the past years, the institute has expanded on its basic funding through the QuTech partner covenant by successfully setting up partnerships with companies (Microsoft, Intel, Industrial Partnership Programme), attracting project funding (EU Quantum Flagship, Horizon 2020, NWO Gravitational programme) and personal grants (NWO Talent Scheme, ERC). The committee praises QuTech for this success, and encourages it to continue its good work in attracting new partners to the quantum community. To build long-term relationships with external partners, QuTech will need a visionary and compelling narrative that changes over time with the progress of quantum technology. It needs to manage the hype by being both realistic and promising for the future. The committee advises developing and managing such a narrative as part of the communication strategy mentioned above.

As a result of QuTech's success, the institute has grown rapidly and has been able to attract very talented researchers. The committee compliments QuTech for this, as it knows from experience how hard it can be to attract and retain talent in competition with companies and institutes in other countries. It sees this as additional evidence of the attractiveness and high profile that QuTech has in the view of its field.

Future strategic choices

As the realization of QuTech's mission comes closer, the institute is moving towards a point at which important strategic choices have to be made. When successful prototypes of quantum computers and a quantum internet are realized, the associated research lines will become increasingly applied and technology-focused. According to the committee, QuTech should ask itself whether it wants to move with the readiness levels of the technology and become more focused on applied science and applications, or whether it wants to continue to focus on the fundamental research side of quantum technology. The committee recommends that QuTech already start reflecting on this and articulate a vision of how it wants to position itself on the fundamental science-application spectrum when the quantum computer and the quantum internet become a reality.

QuTech is currently working on the realization of a prototype quantum computer based on different technology platforms. It is impossible to tell which platform will become the basis for a breakthrough technology, so the committee thinks that QuTech is right in supporting these various approaches. However, when one of the platforms is successful and becomes the dominant platform for technology development, QuTech will need to rethink its strategy about which platforms to support. The committee advises QuTech to start deciding how to proceed in such a situation, and prepare plans on how to gently downgrade platforms that might turn out to be less successful in the future.

Industrial partnerships
QuTech has a close collaboration with two major IT companies to develop quantum technologies. Microsoft has had a formal collaboration with TU Delft and TNO since 2017 for research on topological quantum computers. This collaboration is led by Prof. Leo Kouwenhoven, who transferred from QuTech to Microsoft but retained his research chair at TU Delft and is still working in close collaboration with QuTech. In Fault-Tolerant Quantum Computing, QuTech has a 10-year research collaboration agreement with Intel Corporation with the purpose of developing reliable qubit chips. The corporation contributes $50 million to QuTech, as well as a team of researchers (currently 12) who work in close cooperation with the QuTech researchers.

During the site visit, the committee discussed with QuTech's management and researchers the nature and impact of these industrial partnerships. The funds and facilities provided by Microsoft and Intel provide a major boost for QuTech, and guarantee a link to valorisation of research results. According to QuTech's management and the researchers involved, the collaboration is academic, and the researchers are given full freedom to pursue their research interests. The companies invest in quantum computing for the long term and are mainly interested in the future prospects of a quantum computer. The recent opening of a Microsoft Quantum Lab on the Q-Campus is proof of this long-term commitment and shows that Microsoft is planning to concentrate its quantum computing efforts in Delft for the foreseeable future.

The committee agrees with QuTech that the partnerships with Intel and Microsoft are currently very beneficial for both parties: QuTech is provided with ample funding, while Microsoft and Intel have the opportunity to be at the forefront of a very promising emerging technology. However, the committee stresses that QuTech should not become too dependent on private companies for its research focus and funding. While the interests of QuTech might align with Microsoft and Intel at the moment, there will almost certainly come a time when they will start to diverge. Either a research line might turn out to be disappointing, causing Microsoft or Intel to withdraw, or a research line might become so successful that commercialization takes the upper hand over research. According to the committee, QuTech should be prepared for such a moment by creating a risk management strategy in case one or both of its business partners should drop out or decides to initiate commercialization of a new technology.

Upgrading facilities
One issue that was regularly brought up during the site visit interviews was that of the limited capacity of QuTech's facilities, as well as the critical role of cleanroom facilities. Due to the large growth of QuTech and the associated rise of high-power installations, the institute has reached the limits of its facilities. This not only includes office and lab space, but also the availability of cleanrooms and core utilities such as electricity and cooling water. As stated in the Self-Assessment Report, if the cooling water infrastructure fails, all experiments in the dilution fridges (which constitute more than half of QuTech's experiments) come to a standstill. QuTech is planning to relocate to a new building in 2025, with the old building being scheduled for divestment.

Given the expected further growth of the institute, the committee thinks that this is a very undesirable situation. Considering the high impact of QuTech's research, this needlessly limits the institute's possibilities. The committee urges TU Delft to upgrade QuTech's facilities earlier than 2025, or at least try to find alternative solutions as soon as possible to address the limitations of the building, and to make sure that the institute has the utilities, space and cleanroom facilities its research requires.

National Quantum Hub
During the site visit, the committee discussed with the management of QuTech the possibility of setting up an inclusive national programme on quantum technologies within the Netherlands. Aside from QuTech, a number of other quantum technology initiatives have sprung up in the Netherlands. Research groups in for instance Amsterdam, Nijmegen, Twente, Leiden and Groningen are working on quantum technologies and devices. As quantum technology is increasingly a focus point of the Netherlands, the committee thinks that maximizing the impact through joining forces in a National Quantum Hub is a fruitful strategy to solidify the position of the Netherlands as a major player in this field. By aligning research agendas through a national programme, the research can be complementary and the endeavours of the individual players optimized.

One of the fields that the committee feels that QuTech, and by extension the Netherlands, can profit from by cooperating with other players is that of quantum software. Although many researchers at QuTech are involved in the development of quantum software through the cross-cutting area Quantum Software and Theory, the institute lacks critical mass and focus in this area compared to its quantum hardware efforts. To make the quantum computer and quantum internet a success, it is essential to keep the development of quantum software parallel to that of quantum hardware. Therefore, the committee thinks it crucial for QuTech to be strongly connected to this. This does not necessarily mean extra investments in this area: a national programme could be an excellent way for QuTech to connect to existing, complementary initiatives in this area within the Netherlands. The Quantum Software Consortium set up in 2017 as part of the NWO Gravitation grant is a good step in this direction, and could be integrated into a National Quantum Hub.

The committee thinks that, as the largest player, QuTech is in a position to take the lead in such an initiative and to coordinate the establishment of an inclusive national programme. It recommends that QuTech explore the possibilities for this, and would enthusiastically endorse such an initiative.

To sum up, the committee considers QuTech to be excellently equipped for the future, both in terms of funding as well as in partnerships, staffing and strategy. It encourages the institute to prepare for changes in the upcoming years as technology matures, and to investigate further cooperation within the Netherlands in a National Quantum Hub.

3.5. PhD programmes
QuTech aims to educate PhD students with a creative and flexible research mind-set, which is of value in many (emerging) positions and careers inside and outside academia. The PhD programme of QuTech is connected to the organization and policy of the TU Delft Doctoral Programme. PhD students follow Doctoral Education (DE) which is aimed at the development of transferable skills, discipline-related skills and research skills, for a total of 45 credits (15 in each category). Depending on their field, PhD students fall under either the Applied Sciences (AS) Graduate School or the Electrical Engineering, Mathematics and Computer Science (EEMCS) Graduate School. For discipline-related skills, QuTech’s PhD students can obtain credits at the Casimir Research School, the joint research school on interdisciplinary physics of the Universities of Delft and Leiden, or QuTech’s own Academy (see Section 3.3).

The PhD programme is monitored by the University Graduate School, which has standardized and formalized protocols for supervision, training and quality assurance. As part of these protocols, each PhD student has a minimum of two supervisors: a daily supervisor (usually an assistant or associate professor) and at least one promotor (full or associate professor). In addition, PhD students have a mentor assigned by the AS or EEMCS Graduate School, who acts as a sounding board, provides support and can connect the PhD student to relevant people in the organization. All PhD students are subject to a PhD Development Cycle, which includes multiple evaluation milestones throughout the duration of the PhD programme.

During the site visit, the committee had the opportunity to speak to a number of QuTech's PhD students. The students indicated that they felt privileged to be part of QuTech. The institute provides them with an excellent research environment, in which they have ample access to state-of-the-art equipment and can build up an international network in academia and industry. This quantum ecosystem surrounding QuTech opens up career opportunities in academia and industry, which helps them to prepare for a career after obtaining their PhD. In general, the PhD students feel well supported by their supervisors and QuTech as a whole, and are content with the technical and skills courses offered by the Graduate Schools.

The committee praises QuTech for realizing this fertile research environment with solid guidance for PhD students. The sense of doing pioneering research in a dynamic organization appeals to young researchers. As QuTech is in a process of rapid growth, the committee advises the institution to keep paying attention to the well-being of its PhD students. An unavoidable consequence of growth is that part of the small-scale, close contact nature of the research groups will disappear. For instance, recently hired PhD students indicated to the committee that they have had a harder time mixing with PhD students of other research groups than their colleagues from earlier years due to group size. In larger groups, it is easier for an individual to lose touch and stay under the radar. Combined with a feeling of having a lot of work to do, which all PhD students recognized, this might impact the sense of well-being of the QuTech PhD students. The committee advises QuTech to invest in the embedding of new PhD students (and by extension all newly hired employees) in the organization, and keep track of the issues they might face throughout their PhD trajectory. The PhD buddy system mentioned in the self-evaluation report, but not yet implemented at QuTech according to the PhD students, might be a good starting point for this.

3.6. Research integrity

Integrity and research ethics are important to QuTech. The institute follows the integrity policies and codes of conduct of both TU Delft and TNO. TU Delft's Vision on Integrity document focuses on academic integrity, social integrity and organizational integrity. It lists rules and regulations on topics such as ancillary activities and reimbursements, and guidelines on how to address suspected wrongdoing or conflict of interests. The TNO Code of Conduct describes the core values of TNO on professionalism, independence, engagement with society and integrity, and lists similar and complementary rules, regulations and guidelines on these topics.

All PhD students follow courses on integrity as part of their Graduate School training and are familiarised with the integrity guidelines of TU Delft mentioned above. This not only includes research integrity, it also covers topics of social and organizational integrity, such as the prevention of bullying, harassment or discrimination. The PhD students the committee interviewed were satisfied with these courses and felt well-informed about these topics. They also mentioned that the university provides an annual survey in which employees can anonymously report scientific or social misconduct (or suspicions) in any form.

The committee is satisfied with the attention paid to issues of research integrity at QuTech, and the implementation of these policies in the workplace. It does point out that the institute does not yet have a policy for dealing with and storing raw and processed data. It recommends to develop such a policy, and to explore to what extent experimental data can be disclosed under the heading of 'open science'.

3.7. Diversity

QuTech values diversity in gender, culture, age and opinion, and aims to have students and staff of all different backgrounds feel at home, who are being treated equally and with respect. This diversity is reflected in the international workforce of QuTech: 56% of the staff is non-Dutch, and 23% is non-European.

The current male-female ratio of QuTech is 83% male and 17% female (2018). This ratio has been fairly constant in recent years. The institute acknowledges that this ratio is far from ideal and that it would prefer a more balanced workforce in terms of gender. However, it sees this imbalance not as a particular feature of QuTech, but of the disciplines involved. It reflects the ratio of female graduates in associated master's programmes at TU Delft, such as Applied Physics (13% female), Computer Engineering (6% female) and Electrical Engineering (19% female). During the interview, QuTech's management indicated that the global market for female talent in quantum computing is very competitive. The institute aims to use its senior female professors to act as role models, and to raise awareness of diversity issues for its staff, for example by training staff involved in hiring to prevent unconscious or implicit bias.

The committee acknowledges that the gender balance at QuTech is comparable to that of other research institutions in quantum computing. However, as QuTech aims to be better than a world leader in all of its undertakings, it encourages the institute to aim high and exhaust all possibilities in order to attract female talent. It endorses the current initiatives to proactively approach female candidates for tenure track positions, and to try and retain female PhDs and postdocs. As discussed during the site visit, a suggestion by the committee that is worth exploring is to expand the role model approach by bringing young female undergraduate and graduate students, PhD students and postdocs in touch with female role models on all levels (junior to senior) to promote a career in academia, comparable to the Rising Stars programme at MIT or the Affinity Groups from the IEEE-initiative Women in Engineering. And conversely, by participating in similar initiatives globally, QuTech could make itself more visible to young female talent worldwide.

3.8. Conclusion

In the period 2015-2018, QuTech has been highly successful in pursuing its mission to develop a prototype quantum computer and quantum internet. In terms of scientific results, the committee sees an institute with world-class-quality research, with influential breakthrough experiments and theory published in leading journals. This extends to all three research roadmaps, which are each at the frontier of their respective fields. QuTech has been successful in attracting many academic, industrial and societal partners to its endeavours, both in terms of funding and in the set-up of a quantum community and quantum campus surrounding its activities.

As QuTech's technology matures, the institute will reach a point at which scientific results will become ready to be transformed into actual products and technology with a high societal and economic impact. The collaboration between the scientific excellence of TU Delft and the business development expertise of TNO places QuTech in an outstanding position to translate its research results into quantum technologies and business, and has the potential to come to full fruition in the coming years. In the next few years, the institute will need to prepare for this and reflect on its strategy and role in regard to this transition. The committee is confident that QuTech is excellently equipped for this.

In conclusion, the committee is unreservedly positive about the success of QuTech in the past, and fully endorses the institute in the years to follow.

Overview of the quantitative assessment

Research quality:	excellent
Relevance to society:	excellent
Viability:	excellent

4. RECOMMENDATIONS

1. Prepare for an increased focus on innovation management and business development within QuTech to match the expected maturation of quantum technology, and empower QuTech's new Business Director to take a leading role in these activities.

2. Focus part of the attention of the FTQC roadmap on noisy intermediate quantum devices. Expanding expertise in this direction can demonstrate quantum advantages, and might deliver technological benefits that contribute to the realization of the long-term goal

3. Invest in nanofabrication, which is essential for realizing quantum technology in practice. Investigate possibilities to use facilities of existing or new (industrial) partners

4. For the QINC roadmap, invest in the expertise, resources and collaboration of potential users of the quantum internet in universities and other organizations

5. Consider making an additional effort through TNO to turn scientific output into IP, as an IP portfolio will be crucial to commercialize quantum technology

6. Construct a coherent communication strategy, providing a good narrative that changes over time with the progress of quantum technology. It needs to manage the hype by being both realistic as well as delivering a promising perspective for the future

7. Reflect and articulate a vision on the future positioning and priorities of the institute, specifically on how QuTech wants to position itself on the fundamental science-application spectrum when the quantum computer and the quantum internet become a reality

8. Prepare a plan on how to proceed when a technological breakthrough occurs on one of the platforms for a quantum computer, including how to gently downgrade technology platforms that might turn out to be less successful

9. Prepare a risk management strategy in case one of the major business partners drops out or moves towards commercialization of a new technology

10. Upgrade QuTech's facilities as quickly as possible, or try to find alternative solutions to address the limitations of the building before the scheduled date of 2025, and to make sure that the institute has the utilities, space and cleanroom facilities its research requires

11. Explore the possibilities of setting up an inclusive national programme on quantum technologies, including quantum hardware, quantum software and associated technologies, in order to align research agendas and solidify the position of the Netherlands in this field

12. Keep track of coherence and communication within the institute, as QuTech expands from a small, close contact organization to a larger research unit. Focus on embedding new personnel in the organization, and keep track of the issues they might face

13. Develop a policy on dealing with, storing and disclosing raw and processed experimental data

14. Keep aiming towards a better gender balance within the institute, and exhaust all possibilities in order to attract female talent

APPENDICES

APPENDIX 1: THE SEP CRITERIA AND CATEGORIES

There are three criteria that have to be assessed:

- Research quality:
  - Level of excellence in the international field;
  - Quality and scientific relevance of research;
  - Contribution to body of scientific knowledge;
  - Academic reputation;
  - Scale of the unit's research results (scientific publications, instruments and infrastructure developed and other contributions).

- Relevance to society:
  - quality, scale and relevance of contributions targeting specific economic, social or cultural target groups;
  - advisory reports for policy;
  - contributions to public debates.

The point is to assess contributions in areas that the research unit has itself designated as target areas.

- Viability:
  - the strategy that the research unit intends to pursue in the years ahead and the extent to which it is capable of meeting its targets in research and society during this period;
  - the governance and leadership skills of the research unit's management.

Category	**Meaning**	**Research quality**	**Relevance to society**	**Viability**
1	World leading/excellent	The unit has been shown to be one of the most influential research groups in the world in its particular field.	The unit makes an outstanding contribution to society	The unit is excellently equipped for the future
2	Very good	The unit conducts very good, internationally recognised research	The unit makes a very good contribution to society	The unit is very well equipped for the future
3	Good	The unit conducts good research	The unit makes a good contribution to society	The unit makes responsible strategic decisions and is therefore wel equipped for the future
4	Unsatisfactory	The unit does not achieve satisfactory results in its field	The unit does not make a satisfactory contribution to society	The unit is not adequately equipped for the future

APPENDIX 2: PROGRAMME OF THE SITE VISIT

Tuesday 10 January 2019

10.30 – 11.00	Arrival, welcome
11.00 – 12.00	General introduction (by QANU)
12.00 – 13.45	Internal panel meeting (including lunch)
13.45 – 14.15	Interview Boards (TU Delft, TNO)
14.15 – 15.15	Interview Management QuTech
15.15 – 15.45	Break/internal session
15.45 – 16:45	Interview Roadmap Fault-Tolerant Quantum Computing (FTQC)
16.45 – 17.00	Break/internal session
17.00 – 17.45	Interview Roadmap Quantum Internet and Networked Computing (QINC)
17.45 – 18.45	Drinks with industrial partners
19.00 - 21:30	Panel dinner

Friday 11 January 2019

09.00 – 09.30	Internal session
09.30 – 10:30	Tour of the facilities (part 1)
10.30 – 11.15	Interview PhD students
11.15 – 11.30	Break
11.30 - 12.30	Tour of the facilities (part 2)
12.30 – 13.15	Lunch
13.15 – 14.00	Interview Roadmap Topological Quantum Computing (TOPO)
14.00 – 14.15	Break/internal session
14.15 – 15.00	Interview Roadmap Shared Technology Development (STD)
15.00 – 15.30	Break/internal session
15.30 – 16.00	Concluding interview with Management QuTech
16.00 – 17.15	Composing final assessment
17.15 – 17.30	Oral presentation
17.30 - 19.00	Buffet dinner with QuTech representatives

APPENDIX 3: QUANTITATIVE DATA ACCORDING TO SEP PROTOCOL

QuTech research staff (#)

	2015	2016	2017	2018 *
Scientific staff	11,0	16,1	19,0	21,8
postdocs	7,9	35,6	42,3	42,4
PhD students	18,9	43,3	59,6	73,7
Total staff	**37,8**	**95,0**	**120,9**	**137,9**

QuTech research staff (fte)

	2015	2016	2017	2018 *
Scientific staff	3,8	5,6	6,5	7,2
postdocs	6,3	26,5	32,7	33,1
PhD students	15,1	34,5	47,2	58,2
Total staff	**25,2**	**66,6**	**86,4**	**98,5**

QuTech total staff (fte)
(including TNO staff and support staff)

	2015	2016	2017	2018*
Scientific staff	9,5	14,1	16,3	18,0
postdocs	7,8	33,1	40,9	41,3
PhD students	18,8	43,3	59,0	72,8
TNO R&D Engineers	10,2	16,7	25,5	30,2
TNO Technical support	0,4	0,5	1,4	1,5
TNO Management	1,3	3,0	2,0	1,9
Technical support	6,2	9,1	11,2	14,6
Administrative support	3,1	6,3	9,0	10,8
Total staff	**57,3**	**126,1**	**165,3**	**191,1**

Research output

*Publication category***	2015	2016	2017	2018 *
Refereed articles	46	63	59	69
Book chapters	1	2	1	1
PhD theses	3	13	11	7
Conference papers	27	24	24	5
Patents	1	2	8	3
Total publications	**78**	**104**	**103**	**85**

* until Oct 22, 2018
** Numbers represent single publications, corrected for joint publications

Research funding

	2015	**2016**	**2017**	**2018 ***
Funding (M€/%)				
Direct funding (TUD)	2.119	1.517	2.567	2.835
Direct funding (TNO)	2.500	4.025	4.450	4.497
Research grants	203	4.517	5.954	5.480
Contract research (TUD)	0	5.514	6.773	9.310
Contract research (TNO)	4.113	2.048	1.547	4.278
Other	2	7	1.722	860
Total funding	**8.937**	**17.628**	**23.016**	**27.260**
Expenditure (M€/%)				
Personnel costs TUD	1.168	4.802	6.799	9.425
Personnel costs TNO	2.776	4.759	6.585	8.429
Other costs TUD	1.245	6.556	4.474	6.769
Other costs TNO	279	216	703	2.168
Total expenditure	**5.468**	**16.333**	**18.561**	**26.791**

* estimate for whole year