

NAVIGATING QUANTUM UNCERTAINTY

*STIMULATING COLLABORATION
TO REMEDY QUANTUM ADOPTION
BARRIERS*

MASTER THESIS
APRIL 2026

Technology is neither good nor
bad; nor is it neutral.

Kranzberg's First Law of Technology

Navigating Quantum Uncertainty

Stimulating collaboration to remedy
quantum adoption barriers

PROGRAM

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Faculty of Industrial Design Engineering
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AUTHOR

Lennart Hessels
4847040

IN COLLABORATION WITH

Dr. Giulia Calabretta - IDE (Chair)
Dr. Rebecca Price - IDE (Mentor)
Dr. Kees Eijkel - QuTech
Dr. Anne Hofmann - QuTech

PREFACE

Dear reader,

I embarked on this journey driven by pure intrinsic motivation and curiosity for quantum technologies. It allowed me to explore a new technology and find ways to add value through my unique background. Throughout my education in Industrial Design Engineering at the TU Delft and other experiences in the last few years, I have found a personal focus on creating meaning, in the broad sense. Pursuing a path, investing time into something, and developing a technology should all be done with intent and to create value. Quantum technologies have great potential and are already becoming indispensable to society. But the development of quantum technologies should also be done with intent. This requires collaboration between stakeholders, as challenging as that can be sometimes.

Quantum technologies are a fascinating new technology that can open the door to many unthinkable applications. We are just at the start of the development, but I am optimistic about what is to come. There is a lot still unknown, but that is part of what makes it exciting.

This thesis is the result of the exploration of a personal curiosity. I am proud of the result and thrilled to share it with you. I would like to start by thanking my supervisory team.

Thank you to Giulia and Rebecca for your guidance and mentoring throughout the project and for joining me in the quantum adventure. I appreciate the confidence I was given with a vaguely formulated research direction driven mainly by motivation. Thank you for the critical feedback, creative inspiration, and for keeping me focused on the strategic designer perspective.

Kees and Anne, thank you for the warm welcome at QuTech. Thank you for the faith that you gave me. I learned a lot from you and your perspectives on quantum development.

Initially, you must have wondered where this project was going, but I hope you are as enthusiastic about the collaboration as I am. I hope the future holds many more collaborations between IDE and QuTech.

I want to thank the people who participated in the interviews and workshops. Without their expertise and provided insights, the report would be significantly less rich.

Lastly, I want to thank my friends and family. Thanks for sticking with me as I found a new project to dive into headfirst, for the coffee breaks, for the listening ear, and for the motivation.

Enjoy reading the report. If you have thoughts about my findings, feel free to reach out! I am always happy to discuss my findings over a cup of coffee.

- Lennart

EXECUTIVE SUMMARY

Quantum technologies hold enormous potential, yet organizations remain hesitant to engage due to several barriers to adoption. This report investigates how collaboration between stakeholders can address those barriers through a literature review and semi-structured expert interviews conducted within the Dutch quantum ecosystem. Given the uncertainty, differing stakeholder values, and communication challenges, Future Value Mapping (FVM) is introduced. This foresight method provides a structured, value-driven path to quantum development and is demonstrated using two showcases.

Quantum technologies are recognized as key enabling technologies by governments, industry, and academia worldwide. The Netherlands, among the leading countries, has prioritized quantum technology development given its potential impact. Spanning computing, communication, and sensing, quantum technologies have prospective applications in healthcare, material design, encryption, and many more.

The first part of this report explores the barriers to adoption through a literature review and a qualitative study. Fifteen experts across startups, academia, industry, and governmental organizations in the Dutch ecosystem participated in semi-structured interviews. Four categories of barriers emerged: technological, organizational, knowledge-based, and environmental. While technological immaturity is the most prominent barrier, the impact of the others is equally large. Current wait-and-see mentalities, a lack of large organizations, perceived complexity, insufficient infrastructure, and limited funding are among the main barriers organizations face in adopting quantum technologies.

Running through most of the barriers is uncertainty. Uncertainty about applications, value, timelines, costs, which problems quantum technology will solve, the required level of knowledge, and which organizations should engage in the development. This is not just a technological issue; solving it requires active participation from all stakeholders. Collaboration is widely recognized as essential for development, but also to overcome many barriers to adoption, which can often be difficult to recognize. Common goals, active orchestration, building trust, and alignment are key enablers for successful collaborations, while conflicting motives, increased complexity, and opportunistic behavior hinder them.

The second part of this report introduces Future Value Mapping as a direct response to these findings. FVM is a strategic foresight method designed to navigate the uncertainty of quantum technologies, bringing stakeholders together and highlighting the value and risks. FVM uses three interconnected phases. The first involves creating normative scenarios that serve as a point on the horizon and show the value a technology can bring for various stakeholders. These do not serve as speculation or prediction, but as a concrete vision that forms the starting point for looking back. The second phase is backcasting: identifying concrete interventions required to realize the future scenario based on what-how-who questions. The third phase involves developing what-if questions to identify the consequences, risks, and opportunities of the scenario. All three phases inform decision-making today.

Together, the three phases form a coherent and iterative method serving multiple purposes: stimulating dialogue between stakeholders with different values, goals, and expertise, highlighting interdependencies, and creating a shared direction. The purpose is not to predict the future, but to prepare stakeholders and stimulate development by transforming uncertainty into a starting point for action. FVM was developed specifically for the conditions of quantum technology development: deep uncertainty, a diversity of stakeholders, and high potential impact. FVM has been applied to two showcases, personalized medicine and secure quantum communications, demonstrating its applicability across domains.

This report argues that quantum technology development should be value-driven and built on collaborations. The choices made today will shape the trajectory of the technology, and with that, the future it creates.

GLOSSARY

FREQUENTLY USED TERMS

QUBIT	Quantum bit - The basic unit of quantum information, similar to a classical bit (0 or 1) in a classical computer.
STRATEGIC AUTONOMY	The ability of a country to make independent decisions and compete globally without depending on foreign powers.
SCENARIOS	Detailed normative descriptions of a plausible future in which quantum technology application has become a reality.
BACKCASTING	A planning method that starts from desired future state and works backward to identify which steps <i>need</i> to be taken.
WHAT-IFS	Future scenarios based on speculative questions exploring implications of a quantum scenario.
DESIGN THINKING	A human-centered approach to innovation and problem-solving that integrates the needs of several stakeholders.
BREDE WELVAART	A Dutch policy concept meaning 'broad prosperity', used to evaluate value creation beyond purely economic indicators.

ABBREVIATIONS

FVM	Future Value Mapping - The strategic foresight method developed in this thesis.
QDNL	Quantum Delta NL - The Dutch national program coordinating quantum technology development and ecosystem building.
NISQ	Noisy Intermediate-Scale Quantum - The current phase of quantum computing development. Limited in its capabilities.
QKD	Quantum Key Distribution - A method of secure communication that uses quantum mechanics to distribute encryption keys.
TRL	Technology readiness level - Method to establish the maturity of a technology on a scale from 1 (basic) to 9 (mature).
PPC	Public-Private collaboration - A structured partnership between public and private organizations with a common goal.
SDGs	Sustainable Development Goals - The global goals set by the United Nations in 2015 to achieve in 2030.

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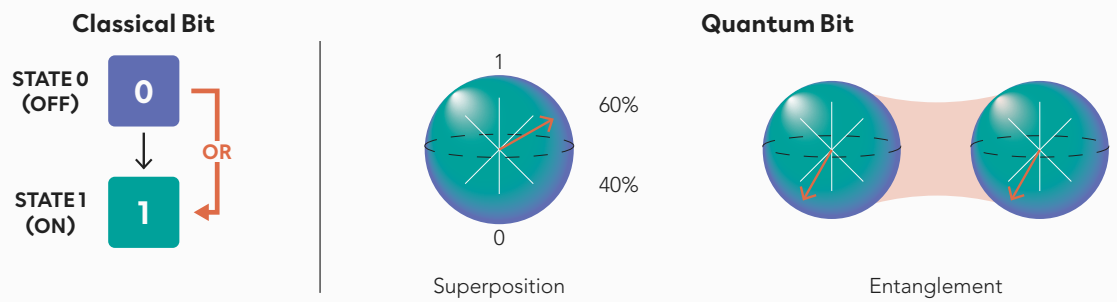
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1. PROJECT INTRODUCTION

1.1 INTRODUCTION

Quantum technologies (QT) have the potential to change the world. What started with a letter from Werner Heisenberg in 1925 has led to the quantum computers hanging from the ceiling today [1]. Classical computers store their information in bits, which can be either 0 or 1, relying on two distinct states. Quantum bits, also known as *qubits*, can exist in multiple states simultaneously, which is known as *superposition*. This property enables quantum applications to store information exponentially dense compared to classical computers. Bits in classical computers are created through transistors, for qubits there are several ways to build one. Qubits can be built using neutral atoms, photons, ions, and other physical systems. Qubits also have the feature of *entanglement*, linking the states of qubits even if they are physically separated. When a qubit is measured, its state collapses to either 0 or 1, and the entangled qubits share the same state.

Figure 1: Bits and Qubits



Quantum applications are often divided into three categories: computing, communication (including the quantum internet), and sensing. Quantum computers leverage the principles of quantum physics, such as *interference*, to process information and execute specific algorithms significantly faster than classical computers. Currently, quantum computers are in the *Noisy Intermediate-Scale Quantum (NISQ)* phase [2]. This phase refers to the size and current limitations of these systems. They typically contain "50 to a few hundred" qubits and are considered noisy due to high error rates and the fragility of qubits. Quantum communication enables communication that promises near-impenetrable security, using concepts such as *Quantum Key Distribution (QKD)* [3]. Finally, there is quantum sensing, which uses quantum phenomena to achieve extremely precise measurements, with applications such as atomic clocks and navigation systems like GPS.

These quantum applications are set to have enormous potential, which is recognized by many organizations and nations. There has been a shift in geopolitical winds with the EU focusing more on strategic autonomy, industrial competitiveness, and technological sovereignty, as stated in the Draghi Report (2024) [4]. The report refers to quantum technology as "the next trailblazing innovation in the computing field, which could open new opportunities for the EU's industrial competitiveness and technological sovereignty". European governments see the potential of QT for technological leadership after losing leadership in technology areas such as artificial intelligence (AI) and photovoltaics (PV). The role quantum technologies can play in national security, through their implications for encryption and secure communication, further increases the willingness to invest. Organizations also see

many potential applications of this enabling technology, including the creation of new materials, drug design, cybersecurity, financial problems, vehicle routing, medical devices, and more [5–8]. The global market size has grown substantially, exceeding 1 billion US dollars in 2025, and total funding has reached upwards of \$10 billion [9]. However, many proposed applications remain highly abstract, and it is uncertain which specific problems quantum technology will ultimately solve.

The uncertainty of quantum applications, alongside other barriers, prevents organizations from engaging in the development of the technology. While the potential is widely regarded as significant, this enthusiasm risks the creation of a *quantum hype* [10]. Different organizations are required to engage in the development of the technology as the potential spans far beyond the direct applications. Collaboration is therefore required to realize the potential value of quantum technology. While the Netherlands is praised for its ecosystem and Quantum Delta NL (QDNL) is regarded as a leading example, there are major steps still to be taken to improve the collaboration between stakeholders [11].

This report explores the barriers to adoption and seeks to understand why organizations are hesitant to engage with the technology. A collaboration within the TU Delft between QuTech and Industrial Design Engineering led to the findings as presented in this thesis. This project aims to bring two worlds together: the deep tech quantum expertise of QuTech and the human-centered design approach of IDE. The result is an inquiry-based study that identifies barriers to adoption and develops a method to stimulate collaboration as a means to address them.

1.2 RESEARCH GAP AND AIM

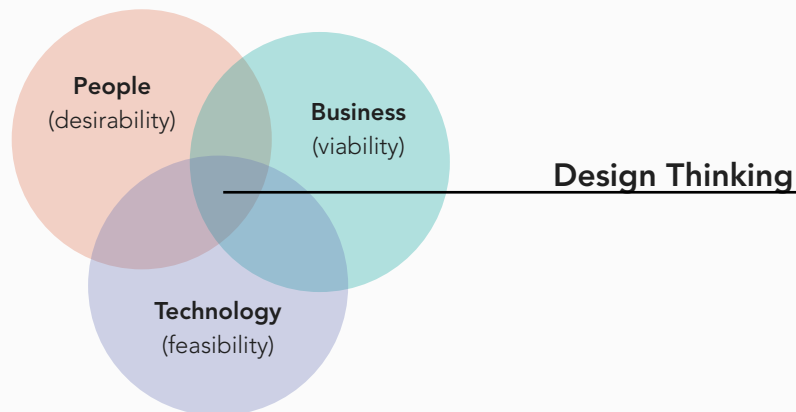
Numerous studies have examined the applications and commercialization of quantum technologies, even though many applications are far away, with a low *Technology Readiness Level* (TRL) [5–7,12]. Currently, the development of quantum technologies faces hurdles to fully come to fruition, a topic that has been researched often by several researchers [5,13]. The most prominent barrier is the technological barrier. QT requires further research and development to mature the technology and deal with the fragility of qubits to improve the transition from laboratory settings to real-world applications [14]. Other barriers could be categorized as organizational, knowledge-based, and environmental. Possible remedies for specific barriers have been researched, with stakeholder collaboration often mentioned as an important step to overcome certain barriers [15–17].

Similar to other emerging technologies of the past, collaboration between stakeholders should influence the shaping of the technology [18,19]. Currently, barriers still prevent seamless collaboration for quantum technologies. In the Netherlands, QuTech notes that “...barriers to intensive public-private cooperation often prove high.” [20]. Martens et al. [15] identified that researchers recognize the importance of collaboration among stakeholders, but struggle to understand the perspectives and characteristics of different stakeholders. Their qualitative study examined the barriers to the acceptance and development of quantum computing, discussing the challenges of knowledge transfer and communication between stakeholders, along with possible remedies. However, the study fails to thoroughly consider the different aspired values of various stakeholders, which are central to a successful collaboration. This has been explored in contexts beyond quantum computing [21]. There is limited insight into specific challenges for quantum-related collaborations in the context of value creation through quantum technologies.

Stakeholder values in the development of quantum technologies have been studied, albeit inadequately. Umbrello et al. [22] used the *Value Sensitive Design* (VSD) method to map the complex landscape of QT stakeholders. They discussed the various roles of stakeholders in the development of quantum technologies. The aspired values of stakeholders can conflict, for example, through tensions between broader societal values and commercial viability.

Stakeholders often have different underlying motives for entering a collaboration to support the development of quantum technologies. Understanding these differing motives and values is important to stimulate collaboration. To bridge this research gap, a qualitative study has been conducted to understand the value various stakeholders aim to create, the current barriers in QT adoption, and how stakeholder collaborations can remedy these barriers, and a method has been proposed to stimulate these collaborations. This study begins with a literature review exploring existing research on value creation through quantum technologies, barriers in quantum development, and the implications of public-private collaborations. To verify the findings from the literature and contribute to the research domain, semi-structured interviews were conducted with key stakeholders in the Dutch quantum ecosystem. The Netherlands was chosen given the available network of the researcher and its position among the leading countries in quantum computing [23]. Beyond understanding the value and barriers to adoption, this study aims to provide tools to address the uncertainty and barriers. Existing methods, such as strategic foresight, backcasting, or scenario planning, fail to meet the challenges specific to quantum technologies. Many methods do not make value creation explicit or mainly deal with environmental uncertainty. QT possesses uncertainty beyond the environmental factors.

Figure 2: Design Thinking



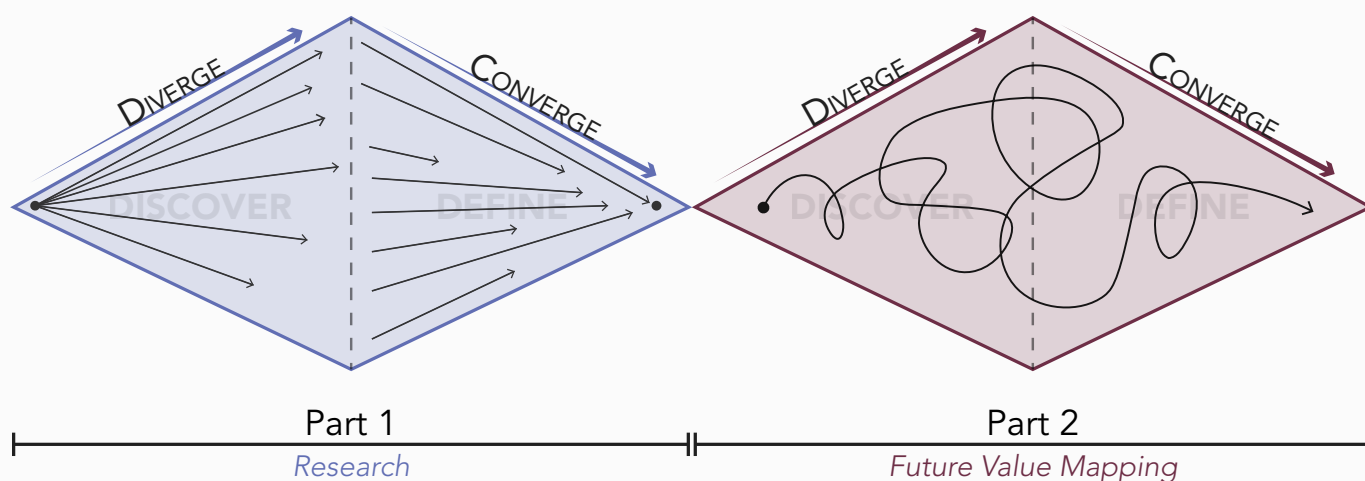
1.3 APPROACH

The core of this research is grounded in design thinking [24], which aims to bring technology, business, and people together. This human-centered approach ensures meaningful development and provides an outside-in perspective on the development process. While design is mainly associated with product design, it provides a unique perspective on societal and business problems as well. The double-diamond approach [25], a commonly used method in design and innovation processes, was utilized throughout the study. The research phase consisted of exploring the existing barriers to adoption and converging on the most dominant ones. Throughout the development of the method, several iterations were made to improve the quality, and several parts were tested with potential stakeholders. Unlike most strategic design-driven processes, powered by the double-diamond approach and design thinking, this research does not claim to solve a problem. This meant adapting the methods to suit the purposes of this project. Just like this research functions as a tool, so do the methods that were used. During the development of the method as presented later in this report, several other existing methodologies were employed, such as roadmapping, backcasting, scenario building, and workshops. Detailed explanations are provided in the corresponding chapters.

Given the complexity of quantum technologies, this study embodies an inquiry-based approach. Unlike most design-driven challenges, there is no single problem to be solved, or at least not one within the scope of this research. Rather, the mapping of existing challenges, while aiding in addressing them, provides tools to tackle those problems. To illustrate, a lack of collaboration is not specific to quantum technology development; however, understanding what factors hinder collaboration for QT development does create a foundation upon which collaboration can be built.

Throughout the project, continuous reflection guided the process. As the cornerstone of this research is creating value, the question *'So what?'* was asked weekly to reflect on the findings and their impact. Clear goal setting, reflection on the progress, and the pursuit of as many different insights as possible stimulated an agile development approach.

Figure 3: Double Diamond process



1.4 STRUCTURE OF REPORT

The first part of this report explores the barriers to adoption for quantum technologies. By exploring the literature on value creation through quantum technologies, barriers to adoption, and collaborations between public and private actors, a foundation is established in the second chapter: **2. Literature review**. The third chapter, **3. Research method**, explains the methodology for the qualitative study, followed by the results in **4. Results**. The results of the study are placed in context and compared to the literature in the fifth chapter: **5. Research discussion**. Limitations and reflection on the findings complete the first part of the report.

The second part presents a methodology developed to map value creation through quantum technologies. Following two showcases, Future Value Mapping is explained and put into practice. The sixth chapter, **6. Method introduction**, introduces the developed method and the reasoning behind it. In the seventh chapter, **7. Future Value Mapping**, this method and its steps are explained in detail. Chapters 8 through 10 walk through the several steps of Future Value Mapping, using the two showcases. **8. Scenarios** covers the development of the scenarios, **9. Backcasting** explains the backcasting and roadmapping process, and **10. What-ifs** presents the what-ifs process and reflects on the findings. The eleventh chapter, **11. FVM in practice**, discusses the practical implications of the method. The report is concluded with a discussion (**12. Discussion**), a conclusion (**13. Conclusion**), and an ethical essay (**14. Ethical essay**), followed by the bibliography and appendices.

The report can be treated as two separate parts, but they are very much intertwined. The second part is the result of the first part, but both parts could also be useful as standalone sections. The breadth of the target audience necessitates adjusting the style to suit different readers. Therefore, the choice was made to target the first part more towards academics and the second part to practitioners. This is reflected in differences in wording, structure, and professional language across both parts.

Figure 4: Report structure



PART 1

Research into value creation through quantum technologies, barriers to adoption of quantum technologies, and public-private collaborations.

"Our vision is that society must be ready before or at the same time as the technology is ready"

Participant 5

LITERATURE RESEARCH

The background features a series of white, wavy lines that create a sense of movement and depth. These lines are set against a dark blue background that transitions into a lighter blue at the bottom, where a pattern of small, light blue dots is visible. The overall aesthetic is modern and academic.

2. LITERATURE REVIEW

The following chapters provide a theoretical foundation for the complex relationship between values, barriers to adoption, and collaboration. Through research based on general innovation practices, quantum-specific studies, and comparisons to AI, a thorough base is created.

2.1 VALUES OF DIFFERENT STAKEHOLDERS IN QT

Innovation has seen many definitions. Schumpeter (1939) is often seen as one of the first to define innovation. He described it as the process of “*setting up a new production function*” [26]. Rogers (2003) defined it as “*an innovation is an idea, practice, or project that is perceived as new by an individual or other unit of adoption*” [27,28]. Taylor (2017) described it as “*the creative process whereby new or improved ideas are successfully developed and applied to produce outcomes that are practical and of value*” [29]. The latter definition is especially interesting, as it involves the creation of value. However, the type of value created depends on the innovator and their goal [30].

Quantum technologies have the potential to generate different types of value. Applications such as quantum computers, quantum clocks, or the quantum internet create new opportunities. To illustrate, quantum computers could offer unique solutions to tackle climate change, such as carbon capture, energy optimization, and environmental modeling [31]. They could also advance drug discovery, personalized medicine, medical imaging, or DNA sequencing, to improve healthcare [32]. Quantum computing could optimize financial portfolios and assess financial risk [33]. In general, given the breadth of possible applications, the potential to generate value is extremely high, through market value, public value, and more. On a macro level, quantum technologies could offer countries strategic autonomy, enhance national security applications, provide economic advantages, help achieve the SDGs, and more [34]. At the meso level, organizations could derive operational and commercial advantages. By optimizing processes, they could generate higher profits and new products, such as medicines or energy solutions, which in turn help organizations add value to society [5]. At a micro level, quantum technologies will most likely create indirect value for individuals because they are expected to be primarily B2B [35]. These QT applications have the potential to enhance well-being, impact security and privacy, and transform everyday navigation.

The opportunities to create value through the development of quantum technologies seem substantial. However, challenges arise when aspired values come into conflict. Purohit et al. note that “*Different stakeholders have different value sets and even within the stakeholder groups with similar value sets, there are differences in prioritization of these.*” [8]. Understanding diverse stakeholders, their roles, and interests is crucial for quantum technology advancement. For the industry, value is often defined as creating competitive advantage, (new) profitable business models, or improved efficiency [5,7]. Their primary drive for commercial viability might conflict with societal values [22]. Meanwhile, governments and regulators might link their goals to ethical development, ecosystem development, workforce readiness, and balancing technological growth with societal safety and equity [22]. Academia focuses on creating knowledge and conducting scientific research, pushing the boundaries of what is possible. These conflicting values can prevent collaboration and hinder the development of quantum technologies. Understanding and acknowledging these diverse stakeholders is therefore essential. Based on the *WEF Quantum Computing Governance Principles* [36], Binder et al. [37] and Umbrello et al. [22], the following stakeholders have been identified: governments and public

“Different stakeholders have different value sets...”

- Purohit et al.

institutions (including policy makers), academics and universities, investors and funders, quantum startups, industry partners and suppliers, and the general public.

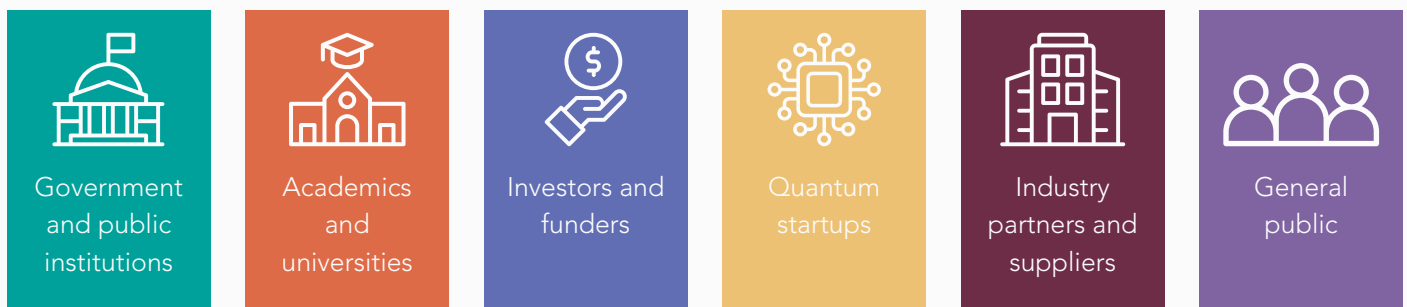


Figure 5: Stakeholder overview¹

Stakeholder identification depends strongly on the context and perceived goal, as noted by Umbrello et al. [22]. Given the goal of utilizing collaboration between active stakeholders to address barriers to adoption, only stakeholders playing an active role are taken into account. Other potential stakeholders, like the media, journalists, or international organizations, will most likely act on the initiative of the listed stakeholders, leading to their exclusion from the list. Each stakeholder has its own role in the ecosystem and aims to create specific value. Below is an overview of the stakeholders, their roles, and aspired values. Different values and goals have the potential to create more inclusive development, but could also hinder collaboration. Similarly, inequality in access might prevent certain (smaller) organizations from participating at all. Understanding these inequalities and different objectives is important, as a lack of knowledge can act as a barrier to QT development [15].

The current atmosphere around quantum technology development is described as a *'gold rush'* by several researchers [10,18]. Governments are investing in QT to achieve quantum supremacy first, creating an *arms race* for dominance. This is due to the dual-use nature of the technology and economic competitiveness. Experience with technologies such as AI and PV has shown that maintaining a competitive economic position is crucial for strategic autonomy [4]. However, this battle for quantum dominance also shapes geopolitics. Coenen et al. [18] quoted the French president Emmanuel Macron from 2021:

"We are aware of the Chinese and American competition but—given the disciplines that are key to the quantum, given what has already been done by our scientific community, given the involvement of our fundamental research and industrial stakeholders—today we have the recipes for success and for being among the top players in this battle."

It shows the perception that global leaders have towards quantum technologies, wanting to win the "battle". The Wennink Report [38] highlights its role in geopolitics as well:

"The proposals in quantum technology, photonics, and neuromorphic computing are examples of the market potential in emerging digital technologies. ... By taking leading positions in new markets, we can contribute to Europe's digital autonomy, and this avoid becoming dependent on economic superpowers such as the US and China."

¹ Icons by the Noun project

The focus on quantum supremacy and winning the race can risk prioritizing development for its own sake and overlooking the importance of value creation. Similarly, a premature *imaginary lock-in* on certain visions of applications can shape the trajectory of quantum technologies [35]. For instance, potential applications for military use cases lead to protectionism and make collaboration more difficult, which fuels the race and encourages competition between nations [39].

Advancing quantum technologies requires collaboration. While multiple actors might pursue different values, acknowledging these and bringing them closer together is important. The current focus on geopolitical competition overshadows the importance of value creation and identification, risking a fragmented ecosystem. As Purohit et al. [8] noted, recognizing values and stimulating collaboration are important for an effective ecosystem. Successful collaboration and adoption of quantum technologies require stakeholders to transcend conflicting values and pursue shared goals. This integrated approach is critical not only for development but also for ethical and value-driven development, creating shared value.

Table 1: Stakeholders in the quantum ecosystem with role, responsibilities, and aspired values

Stakeholder	Role and responsibility	Aspired value
<i>Government and public institutions (incl. policy makers)</i>	Set national strategies, fund research, set regulations, balance innovation and protecting society, and support infrastructure development.	Long-term public good through, e.g., national security, economic growth and competitiveness, public welfare, and risk mitigation.
<i>Academics and universities</i>	Advance scientific research, educate a quantum-literate workforce, and act as experts to inform policy, ethics, and public debate on quantum development.	Scientific progress, creation of public knowledge, and ethical development.
<i>Investors and funders</i>	Provide capital for quantum development and influence priorities.	Financial return and sustainable market development.
<i>Quantum startups</i>	Scale technology, advance QT development and research, define use-cases, help create ecosystems, and make technology accessible.	Competitive advantage, grow the company, and QT development.
<i>Industry partners and suppliers</i>	Integrate QT into existing systems, build supply chains, identify problems, and identify high-value use cases and applications.	Business impact, efficiency, market development, solve (business) problems.
<i>General public</i>	Engage in discussion, articulate societal values, and participate in education.	Societal values, well-being, and public good.

2.2 BARRIERS TO QUANTUM ADOPTION

The United Nations marked 2025 as the ‘Year of Quantum’ [40], aiming to highlight developments since the groundwork of quantum mechanics was laid 100 years ago. But in those 100 years, the technology has yet to reach many people and organizations. Many new technologies face adoption problems, a topic explored across multiple domains, such as digital health technologies [41], construction [42], AI [43], and others. Studies often examine barriers that limit the adoption of technologies, such as technological, communication, organizational, financial, knowledge, or regulatory factors. However, each technology also faces its own challenges. This section explores the barriers to adoption of quantum technologies through *A) Technological barriers, B) Organizational barriers, C) Knowledge barriers, and D) Environmental barriers.*

Table 2: Barriers to the adoption of quantum technology

Type	Category	Sub-category
Technological	Qubit challenges	Scalability
		Error-correction
		Coherence
	Engineering challenges	Material science challenges
		Quantum repeaters
	Architecture challenges	Cooling
Controlling challenges		
Organizational	Commercial uncertainty	Application uncertainty
		Lack of use cases
		Long horizons
	Monetary challenges	Long-term commitment required
		High costs and long run times
		Lack of private capital
		Lack of interest in new processes
	Business challenges	Organization structure
		Organization culture
Mapping business problems is hard		
Knowledge	Lack of knowledge	Quality of knowledge
		Vision for applications
		Lack of stimulated conversations
	Communication challenges	Communication challenges experts
		Perceived complexity
		Pitching paradox
		Hype
	Skill gap and talent	Skill gap
Shortage of talent		
Environmental	Ecosystem and collaboration	Lack of actively involved stakeholders
		Lack of ecosystems
		Divide academia and industry
		Lack of government support commercialization
	Regulation	Regulatory
	Infrastructure	Specialized equipment and space
		Energy costs
Supply chain	Supply chain challenges	

A) TECHNOLOGY

Currently, the biggest challenge lies in the maturity of the technology. Preskill [44] highlights that moving from today's quantum devices with a few hundred qubits, to fault-tolerant machines with hundreds of thousands or millions of qubits "*is likely to take a while*" and that the truly transformative impact of quantum computing "*might still be a few decades away*".

Quantum technology, particularly quantum computing, must scale to a substantially larger number of qubits to create large computational power [45]. For example, Google's Willow chip features 105 physical superconducting qubits [46]. However, running Shor's Algorithm to break RSA-2048 encryption would require over a million physical qubits according to a preliminary report by Gidney (2025) [47]. But the usefulness of physical qubits is determined by how well they combine to form fault-tolerant logical qubits. Error correction and coherence remain the main obstacles in realizing quantum computers [48]. The vulnerable nature of qubits and their sensitivity to environmental interference, which makes them lose their data extremely quickly, are inherent limitations that need to be tackled. Correcting operational errors and reducing measurement errors pose a major challenge to obtaining reliable and useful quantum data [45]. Challenges in material science and fabrication for qubit platforms (e.g., qubits, optics, electronics, control systems, etc.) need to be overcome for quantum technology to reach its potential [14]. Scaling up will bring additional fabrication and architectural challenges. Controlling and calibrating thousands, if not millions, of qubits and creating internal wiring for such sophisticated quantum computers imposes a severe engineering constraint [14]. In addition to the complications mentioned regarding quantum computing, another technological challenge for quantum communication is the creation of true quantum repeaters [3]. In order to realize long-distance communication, the signal needs to be refreshed to maintain its integrity. But currently, the repeaters are at TRL 3, still needing proof of feasibility [34].

Uncertainty exists about which exact problems quantum technology can solve better. Although plenty of high-level use cases have been identified, such as new material development, molecular simulation, or the traveling salesman problem [5], they remain abstract. Adoption and organizational readiness do not come from technological maturity alone. It requires organizations to actively pursue integration of the technology and strategize for when the technology matures [33].

B) ORGANIZATIONAL

The uncertainty that the technology and its development bring is accompanied by uncertainty about commercialization. Organizations' management typically evaluates a technology's impact before investing in or adopting the technology [49]. Current uncertainty regarding the impact could make quantum technologies unattractive to explore. Furthermore, the impact of QT is expected to occur mainly in the long-term instead of the short-term [50], making it less attractive to invest in today. However, this has not deterred organizations from exploring quantum technologies, most likely due to the perceived long-term value and strategic positioning [51]. Successful development requires high continuous investments and long run times [52]. It needs long-term commitment for research and development initiatives, something that is currently lacking [53]. Impact uncertainty, longer-term value creation, and perceived high costs make the investment thesis challenging for quantum technologies. Stakeholders might delay

1 million

Physical qubits
required to run
Shor's Algorithm

Need for a “killer application”

- Bhasin & Tripathi

their participation until the technology's performance becomes predictable and the business case is more defined. This indirectly results in the vast majority of funding for quantum R&D being a consequence of public investment. Especially within the EU, there is a dearth of private venture capital, making scaling up the technology a challenge [4,54].

For adoption, organizations (public or private) need to start using the technology to solve problems or assist in their tasks. But currently, there is a lack of organizational interest in adopting new processes [53], a lack of comparable use cases [15], an unsupportive organizational structure, and a need for a “killer application” if quantum technologies want to succeed [55]. Kwon et al. [51] expand on this by highlighting the importance of *quantum supremacy* and *quantum advantage* in driving adoption. Organizations need to see a clear advantage over current applications, which are currently perceived as very limited. This is partly due to the uncertainty regarding applications from a technological point of view, but also from a lack of true knowledge about possible advantages. They furthermore stress that organizational culture, such as risk aversion or internal change resistance to potential implementation problems, can impede adoption. For investors, developers, but also public institutions, understanding the market demand is very critical, a feat that has been proven to be very difficult [53]. At the same time, organizations find it difficult to map their problems to quantum solutions [6,15]. Due to the abstraction of possible solutions, the difficulty of mapping business problems to computational problems, and the lack of experts who understand and recognize the opportunities, it is difficult to adopt new technologies.

Not just the demand for new technologies, but the way new quantum technologies will enter the market is also yet to be decided. Technology and innovation create opportunities for new business models [55,56]. Besides the development of the technology, business models might need to be innovated and changed.

C) KNOWLEDGE

If organizations want to adopt new technology and integrate it into their businesses, they need to have a level of understanding. However, the quality of knowledge remains too low across stakeholders. For example, the Wennink Report [38] highlighted the importance of investing in quantum technologies to create strategic autonomy for the Netherlands, but lacked the vision on applications of these technologies. Creating this understanding is difficult unless conversations are stimulated between various stakeholders to grasp the potential and works of quantum technologies, something which is currently not stimulated enough [57]. In general, a lack of understanding of technology will decrease the likelihood that stakeholders want to engage in the subject and decrease adoption [58], which makes working on that understanding a vital task. Quantum technologies are a challenging subject to properly communicate. The abstraction, unintuitive nature, and complexity of quantum physics make it hard to fully comprehend. However, it is mainly the intimidation of the subject that prevents non-experts from engaging the topic [15]. They feel underqualified to converse on the topic due to a lack of knowledge. Experts, often physicists, struggle with the right tone of communication. But the question is how much you need to understand about the inner workings of quantum technology to adopt it, as many people also have little understanding of the exact workings of a classical computer.

Quantum technologies have an ever-growing technology skill gap, making

Quantum technologies is an intimidating subject

it harder for organizations to understand due to the increase in difficulty and shortage of experts [15,55]. This gap will only increase as quantum becomes more sophisticated [33]. IBM [33] even goes as far as to state that inadequate skills are the biggest barrier to quantum adoption. The amount of quantum-skilled talent is scarce, and too few universities have QT-related degrees to meet the future workforce demand [59]. Proper adoption requires expertise across several steps of the integration, meaning organizations would need several experts [15]. The lack of available talent would force organizations to plan on how to train their own workforce, a difficult task given the unintuitive nature of quantum physics and the limited resources available [55].

The knowledge gap provides difficulties in acquiring funding. The EU has a dearth of knowledge within financial institutions, such as VCs, about the potential of quantum technologies [54]. The value of deep tech is often found in the nuance, which loses its value when turning a complex topic into a narrative. Startups face the challenge of finding a balance between simplistic pitches for understanding against oversimplification, which risks discounting their technology. This leads to the '*pitching-paradox*' for quantum. Startups must sell a narrative to attract funding, but this narrative might hurt them in the long run if they fail to deliver results. Pitching the science and nuance risks sounding like a "*research project*" [60], while pitching the hype risks backlash. The uncertainty about applications and the realization of QT, combined with the inherent difficulty of understanding quantum technologies, can lead to misinformation and create hype [15]. This hype helps realize funding, attention, and prioritization in national strategies, but it will lead to a major drawback when quantum technology does not provide the esteemed value in the short term. This also occurred with the development of AI. Which shows several parallels to the development of quantum technologies. More specifically, the IBM computer *Watson*, an automated question-answering system developed in the early 2000s. This natural language processing machine aimed to search its internally stored documents and answer questions posed by individuals. The victory of *Watson* at gameshow *Jeopardy!* showed the potential of the computer and led to a lot of public excitement [61,62]. In search of commercial applications, IBM decided to focus on health care, more specifically cancer treatment, as its first commercial application for *Watson*. But the powerful technology did not lead to the digital doctor that IBM had hoped for. Their "*marketing first, product second*" approach caught up to them when the technology was not able to meet expectations [63] – a fear present in the QT domain too.

A big difference between the promise of AI and the current expectations around quantum is the level of applications. With many AI promises, like with *Watson*, the application was clear, but the technology did not meet those expectations. With quantum technologies, the applications are uncertain. People investing in quantum often invest for the potential of the technology rather than a specific application [5]. There also seems to be a wide understanding that the technology needs to be developed first.

D) ENVIRONMENTAL

To develop technology, the environment must be supportive. Demand to drive and develop the technology towards commercialization is required. A role that needs to be filled by industry and government. Currently, there is a lack of government support for commercialization, limiting the development and working as a barrier towards adoption [53]. Quantum technologies' complexity

requires synchronized efforts of various stakeholders to succeed [8]. From hardware developers to policymakers, many actors will be involved in the realization of quantum technology and bear a responsibility. Oftentimes, stakeholders are involved in the ecosystem, but not on an active level. Organizations might, e.g., be involved for PR purposes or just to stay in touch with developments [15]. A lack of true ecosystems and uncertainty about potential stakeholders hinders the adoption [55] – albeit that the Netherlands and QDNL are renowned for the orchestration of the Dutch quantum ecosystem [9,11].

“Wicked policy problem”

- Al-Kuwari

New technologies require new regulations. Quantum technologies pose risks like decryption, imbalance in accessibility, and national security concerns, requiring proper regulatory frameworks. However, the current missing frameworks lead to more uncertainty, risk aversion (e.g., export regulations), and a lack of collaboration opportunities due to varying regulations per location. This absence of legal clarity and integration obstructs the adoption of quantum technologies [55]. Government leadership and willingness to support innovation from a financial and policy perspective are crucial for the adoption. The current mechanisms and structures for creating these policy frameworks or providing input are uncoordinated [57]. As a result, valuable input, potentially bridging the gap between science and policy, is lost. Moloney and Al-Kuwari [64] call the current challenge a ‘*wicked policy problem*’ due to its complexity, uncertainty, and disagreement, highlighting the need for a proper regulatory framework. They endorse the notion that there is a need for regulation, especially to prevent the potential risks. Next to the distance between policymakers and quantum experts, there is a divide between academia and industry, as stressed by Zappin et al. [65]. Factors such as secrecy, the siloed nature of startups, and strategic competition all have contributed to this gap. Lack of proper communication leads to the industry being unaware of developments in research, and academia being unaware of practical problems and real-world needs. This absence of collaboration slows the development of technology, application creation, and their adoption.

Developing and adopting quantum technologies requires extensive infrastructure. Quantum computers need cleanrooms, cryogenic environments, high power, and supporting devices. For example, superconducting qubits currently operate at temperatures around 10 – 20 mK, and require 1mm² of space per qubit, improving performance but demanding substantial space when scaled [14]. They require complex, expensive, and energy-heavy cooling solutions [44]. Many organizations lack in-house facilities or the technology available to integrate quantum solutions. Even if they have the facilities to run quantum computing, the costs (monetary and energy) of running algorithms are very high. To illustrate, Parker and Vermeer [66] calculated a rough cost estimate to run Shor’s algorithm in a working paper in 2023. With current qubit and energy demands, the costs to break one public key would be around 125 MW and \$64,000, mainly due to the high cooling costs. This energy demand imposes huge grid challenges at a time when the Netherlands faces net congestion struggles [67]. Cleanrooms are scarce and costly to build and maintain [68]. These high costs make it hard to switch from classical solutions due to the high switching costs [15].

The supply chain of quantum technologies also poses a barrier to adoption. Many components are needed, and a limited number of suppliers are capable of delivering the components needed, making it a challenge to get started. Europe lacks capabilities in the semiconductor manufacturing space, which impacts the fabrication of qubit control systems, quantum chips, and laser systems [69].

\$64,000

Cost to run Shor’s algorithm once

Currently, quantum technologies depend on many rare materials such as helium-3 (for cryogenics), Silicon-28 (for spin qubits), and Lithium Niobate (for photonic qubits) [70]. Cryogenic fridges also require special components that are currently very hard to find, with very limited suppliers [69]. The young age of the supply chain, combined with the focus on strategic independence, makes it harder to adopt quantum technologies.

Awan et al. [53] rank multi-stakeholder collaboration among the highest-ranked institutional barriers, but also with potential. “*This shows that technology firms should focus more on increasing R&D collaboration for implementing and executing QC*”. There is a need for more collaboration for the development of QT, e.g., by stimulating cooperation between industry and universities [53]. Alahmari [16] looked at the factors required for successful adoption of quantum technologies in blockchain systems and found that, among others, collaborations with quantum stakeholders and the sharing of knowledge and expertise are required for successful integration.

2.3 PUBLIC-PRIVATE COLLABORATION

Quantum development currently resides on the edge of public and private organizations, with most development occurring in corporations and universities. Between 2014 and 2024, corporations filed 54% of quantum technology patents and universities 37% [71]. In 2023, universities doubled the amount of patent filings compared to corporations, but the overall growth in filings indicates a clear interest in the development of quantum technologies by both public and private institutions. For the development of quantum technologies, these public and private institutions often collaborate, from active collaboration through (inter)national strategic alliances like QDNL in the Netherlands [72] or NQTP in the United Kingdom [73], to passive collaboration through, e.g., grant allocation. However, collaborations for the development of quantum are an underexplored topic, as the research gap confirms.

The topic of public-private collaboration has received significant academic interest in recent decades [74]. When looking at collaborations in the deep tech space, there is a lack of knowledge, but also an increase in attention [75,76]. These public-private collaborations can consist of varying parties and types of agreements. Collaboration for innovation can be passive and transactional through a grant, tax credits, or government contract. But their effectiveness, in comparison to public-private R&D relationships, is debated among scholars [77]. A Spanish study [78] even goes as far as to state that “*the tighter the relationship ... the greater the capacity for innovation*”, but it remains a debated topic. Rathje et al. [77] also show that collaboration between public and private actors for innovation more often leads to technologies with an enabling trajectory, generating (societal) value downstream, compared to technologies developed solely through private or public firms’ efforts. It is debated among scholars whether collaboration leads to more value on its own [30], but they have the potential to, among others, create unique value that is unattainable without collaboration [79], lead to more financial efficiency (*‘value for money’*) [80], lead to more innovation [81] and social value [82].

In general, active collaboration between public organizations, such as universities or governments, and private organizations, such as startups or established corporations, occurs on many different levels. These types of collaborations are also known as *Public-Private-Partnerships* (PPPs) or *Public-Private Innovation Partnerships* (PPIPs). As frequently used frameworks in infrastructure projects, but increasing in other sectors too, this innovation-focused cooperation between public and private actors has become more common [81]. PPPs and PPIPs lack a commonly agreed-upon definition and have been defined by many

researchers and practitioners [74,80,83–85]. Other common terms used to describe collaboration between public and private actors to stimulate innovation are TechPPINs (*Technological public-private innovation networks*) [81], or IPPPs (*Institutionalized Public-Private Partnerships*) [86]. There are a few aspects that characterize such a collaboration.

Firstly, risk sharing between parties [80,87], which is very applicable to quantum, given its uncertain nature. The investment through time, money, and labor required to generate substantial value from quantum might not lead to the expected results or during the expected timeline. Parties involved must be aware of this risk and share potential losses. Studies show that shared involvement and risk build trust and improve the chance of success [74]. Another aspect is the duration of collaboration, albeit varying by type. PPPs tend to have longer-term collaborations [80,88], while PPPs that focus on innovation in the public sector tend to have shorter collaborations [89]. Collaboration can lead to value in the short-term as knowledge is developed for the involved parties, but the longer-term goal of these collaborations is to create value through innovation. Given the uncertain nature of quantum technologies and expected value on long-term horizons, long-term collaborations will most likely lead to more value generation. The type of value varies for each partner. All involved stakeholders have their own objectives (e.g., monetary, social, safety, ...), but work together towards a joint target [79,90]. Achieving their own objectives is crucial for the collaboration's success. Various stakeholders are involved in these types of cross-sector collaborations, working as partners, leveraging their complementary skills and resources to innovate [91]. In practice, these innovation-focused collaborations, containing a mix of public and private actors, often have universities playing an important role. Collaborations between university, industry, and government, known as the *triple helix*, are a known and often utilized form of partnering [92].

Looking at the various key-elements of a public-private collaboration aiming to enhance innovation, this research created the following definition. Throughout this research, collaborations between public and private actors will be defined as '*Public-Private Collaboration*' (PPC), and can also be described in general as '*collaborations*' in the context of this report. They are defined as:

A cross-sector active collaboration between stakeholders from the public and private domains, with a mutual commitment aiming to improve innovation through a partnership while creating value for each participant.

The development of quantum technology features various types of collaboration. Using the Netherlands as an example, given its developed ecosystem and strong position in Europe [9], there are several use cases. Collaboration between universities and the industry is increasingly common. QuTech, a department at the Delft University of Technology, has collaborated with industrial companies such as Microsoft, Intel, and Fujitsu [93]. Quantum Delta NL is a national initiative, promoting multi-stakeholder collaborations among e.g., academia, industry, and government through several action lines [72]. Startups collaborate intensively with universities, as many quantum startups are spinoffs of universities, on projects like the Tuna-5 system [94]. Most startups are located within proximity to universities, indicating the focus on collaboration within the ecosystem. Additionally, startups have collaborated with public institutions such as the government or public companies. E.g., the Port of Rotterdam trial with startups demonstrated a scalable

quantum internet [95]. Startups also collaborate with each other, with the *Quantum Utility Block* as an example [96]. Also, industrial parties collaborate, although this is not very common in the Netherlands. In Germany, QUTAC is a consortium among several large industrial companies aiming to bring quantum computing to a level of practical application [97].

The government should act as launching customer

- PWC

When looking at the Netherlands in general, the importance of collaboration, e.g., between companies and universities or other schools, is confirmed by PwC's broader analysis [98]. One of their key recommendations is that the government should act more as '*Launching Customer*', and carry the risks of innovation where possible. Belenchia et al. [17] also stress the importance of collaboration for the development of quantum space technology. Consortia between academia and the industry can lead to exposure to commercial supply chains, standardization, industrial co-developers, and alternative funding streams. Stakeholder engagement furthermore ensures development longevity. Long-lasting funding, a quantum-skilled workforce, and regulation are among the critical ingredients to create this longevity and advance the development of quantum technology. Collaborations are uniquely positioned to generate value for all parties involved, as well as common values [79].

PPCs have the potential to create unique value and improve innovation when organized well. Successful collaboration requires alignment across various levels, such as policy, resources, and values and principles [21]. It is important that various stakeholders, such as public and private actors, have complementary roles [99], which allows them to utilize their complementary skills and resources. When looking at successful PPPs in construction, where the concept was introduced, several key success factors have been identified. Appropriate risk sharing, a strong consortium, political and public support, transparency, and a favorable legal framework are most mentioned as critical success factors [74]. Mei and Yang [82] found three conditions to generate public value through PPIPs. Firstly, risk management: sharing the risk and controlling possible risks. Secondly, sharing knowledge and utilizing the ideas and experience of the different stakeholders. Thirdly, transparency around the collaboration helps avoid negative consequences of PPIPs. Brogaard [91] identified variables that work as drivers or barriers for PPIs. Like most research mentioned above, building trust, a shared goal, and coordination were mentioned as important factors. Having a shared vision on innovation was recognized as particularly challenging, given the different types of partners. Public and private actors tend to have different, and often conflicting, motives and interests, which can hinder innovation. It is essential to focus on building cross-sector relationships to overcome these differences, create understanding, and build trust.

€615M

Allocated to quantum development by the National Growth Fund

Collaboration does not automatically lead to better results or more innovation. It requires more resources (time, money, and effort) and does not guarantee success [30]. Collaborations tend to be slower due to the increased number of involved actors. Successful collaborations require frequent re-coordination, which is more challenging with more parties involved. Furthermore, measuring the success of a collaboration is a challenge that needs to be taken into account [100]. When the National Growth Fund in the Netherlands allocated €615 million, the perceived result consisted of a certain number of startups, patents, and realized co-funding [101]. But there is a constant ongoing debate about what good metrics are for measuring innovation [102,103]. Many researchers stress the importance of creating trust, but as George et al. [100] show, this is not an easy feat. The willingness to be vulnerable and prevent opportunistic behavior by participants

“successful deep tech ecosystems are not passive; they are actively orchestrated”

- QuTech

is hard to realize, yet vital to successful collaboration. But well-crafted partnerships, with a clear scope and commitment, can mitigate this opportunistic behavior and create trust [104]. Most barriers can be overcome, and success factors can be achieved, as abstract as they might be, if pursued with intent. In order to realize success through collaborations, there must be players actively designing the PPC [100]. QuTech confirms this, stating that *“successful deep tech ecosystems are not passive; they are actively orchestrated.”* [20]. The architect of the collaboration must safeguard the interests and values of less dominant actors. With the development of quantum technologies and barriers such as information asymmetry, the risks of poorly designed collaborations are high. When a collaboration is set up, it requires constant adaptation, requiring agility and making it an iterative process.

Table 3: Barriers and key success factors to collaboration

Barriers to collaboration	Key success factors
Increased complexity	Alignment across various levels
Measuring success	Active orchestration and agility
Opportunistic behavior	Risk sharing
Conflicting motives	Transparency and knowledge sharing
Speed	Common goal
Increased (perceived) costs	Building relations and trust

Use case - Artificial Intelligence

Another disruptive technology that benefited from public-private collaboration is Artificial Intelligence. The development of AI initially started in universities, with the coining of the term 'artificial intelligence' in 1956 at Dartmouth College, but transitioned towards private firms such as Google and OpenAI [105], which increased the drive for commercialization. AI research experienced a growth in collaboration between academia and industry, reflected in the rise of public-private co-authored publications [106]. Williams et al. [107] found that research on AI that incorporated multiple types of actors (e.g., sectors, countries, types) led to higher impact. This is in line with Hagendorff and Meding [106], who found that research publications with high citations tend to be the result of academic-industry collaborations. In the United States, AI development initially stemmed from government-funded research and development programs [108]. But the renowned Dartmouth workshop was privately funded, the government stepped in only afterwards, right when the interest of major corporations (IBM and AT&T) cooled off. During the 70s AI development was struggling, leading to the 'AI Winter'. The Lighthill report [109] led to the end of almost all AI-related research funding in the UK due to a perceived lack of real-world applications. The 80s brought change in the US, where the Strategic Computing Initiative led to collaboration between industry, government, and universities [108]. Currently, the AI development is characterized by collaborative approaches between government and private organizations [110].

The European Union currently aims to enhance the position of its AI industry through several public-private collaboration schemes, realizing its lagging position in global AI development. Where the EU is a frontier in AI regulation, it is often criticized for the lack of innovation [4]. Through several programs, such as Horizon 2020, Digital Europe, the Apply AI Strategy, and the AI Continent Action Plan, the European Union aims to enhance its competitiveness and improve innovation. In 2024, the AI Act was released, aiming to create clarity and governance for AI development [111]. The AI Act highlighted the importance of collaboration among various stakeholders for the development of AI and its regulation. For example, through regulatory sandboxes and an advisory board for governance that consists of several stakeholders. Highlighting the importance of collaboration not just for the development of innovation, but also for the (proper) utilization of technologies. Recently, the AI Continent Action Plan was published [112]. One of the goals is to improve the transition from research to market through public-private partnerships.

The development of quantum technologies has many parallels to that of artificial intelligence. It currently presides in the phase where AI was in the 1960s. Many quantum researchers fear the upcoming quantum winter, which AI managed to survive in the 70s. Learning from the development of other technologies can help QT in maturing.

Table 4: Comparison AI development phases

Phase	Main actors	Focus	Challenges	QT
Early development (1950s - 1960s)	Academia, early private firms	Fundamental research, concept development	Fragmented efforts, theoretical complexity	Current phase
AI Winter (1970s)	Academia	Use case development	Loss of funding, expectations	Risks winter
Revival (1980s - 1990s)	Government, academia	Mission-driven innovation	Scaling infrastructure, establishing collaboration	-
Growth and commercialization (2000s - 2010s)	Government, large private firms, academia	Scaling, commercialization, ecosystem building	Managing growth, goal alignment	-
Integration (2020s - present)	Government, large private firms, SMEs, academia	Ecosystem development, regulation, integration	Balancing innovation with ethics	-

2.4 LITERATURE CONCLUSION

The literature review provides a foundation for the understanding of value creation through quantum technologies, barriers to adoption, and public-private collaboration. The potential value created through QT is substantial, ranging from strategic autonomy and national security to improving the well-being of citizens. Currently, development is mainly driven by economic motives. While these are important, the potential value of quantum technology stretches far beyond monetary. Value creation requires collaboration between various stakeholders, but setting up collaborations is challenging. Stakeholders often pursue different and conflicting goals, increasing the difficulty for collaborating. At the same time, realizing broad value makes differing priorities essential.

Organizations face many barriers to the adoption of quantum technologies. While technological immaturity is the most prominent, organizational, knowledge-based, and environmental barriers also hinder organizations in engaging with the technology. Organizational culture, financial challenges, language barriers, and dependency on infrastructure are among the most significant challenges. A common denominator throughout these barriers is the influence of uncertainty. Uncertainty about applications, value, timelines, costs, and which problems QT will solve influences the majority of the barriers.

Public-private collaborations utilize the different characteristics of organizations to increase value creation. Active ecosystem orchestration, coordination mechanisms, and the creation of a common goal are key enablers for these collaborations. While the value of collaborations is widely recognized, several initiatives have been established within the Netherlands to support the development of quantum technologies. The importance of shared goals is recognized, but research lacks insight into how such shared goals can be created when value creation is uncertain. The next chapter explores the experiences of stakeholders within the Dutch ecosystem. By verifying and expanding on the existing knowledge about adoption barriers, learning from collaboration experiences, and understanding the value that stakeholders seek to create, a qualitative study contributes to the academic understanding of quantum technology adoption.

A common denominator throughout these barriers is the influence of uncertainty.

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QUALITATIVE RESEARCH



3. RESEARCH METHOD

To further understand values that quantum technologies can create, the barriers to adoption, and how collaborations can be orchestrated, interviews were conducted. The interviews were conducted using a semi-structured process. This strategy was chosen for its flexibility, allowing the interviewer to adapt questions according to the flow of conversation [113]. Given the exploratory nature of the research, aimed at understanding the struggles of the interviewees, the semi-structured approach was considered most suitable. The framework was adapted based on the interviewee. An example can be found in the appendix.

The interviews, lasting between 30 minutes and 45 minutes, were conducted in person or online. The interviews that were done in person took place at the location where the interviewee worked. The interviews conducted online were done through MS Teams. The difference is considered insignificant. All interviews were recorded and transcribed. The interviews were done in Dutch or English, based on the native language of the participant. The transcriptions were translated into English for analysis.

The qualitative research aims to further the understanding of barriers to the adoption of quantum technologies, as well as build on the knowledge of collaborations set up to develop quantum technologies and to create an understanding of what value is to be created through quantum technology. As the research gap shows, there is a lack of understanding of how the varying stakeholders hope to realize value from collaborating. The study aims to shed light on what makes it difficult to set up collaborations and what prevents organizations from engaging in them.

3.1 SELECTION OF PARTICIPANTS

The participants were chosen based on their perspectives on values, barriers, and collaborations for quantum technology. Due to the nature of creating a deeper understanding, the participants selected were considered experts. Participants were required to actively engage in developing quantum technologies while also having an understanding of collaborations and barriers to adoption. Therefore, the majority of the participants played a non-technical role within their organization. Additionally, several different perspectives were sought out, aimed at creating a complete image. The experts were active in either the private or public sector. They held their occupation at various organizations, with a different role in quantum development. The startups that were contacted were those that had taken steps in commercializing their products. All participants were located in the Netherlands.

With approximately 1000 people working on quantum technologies in the Netherlands, the pool of people meeting the criteria is small. Given the small size, snowball sampling was used to acquire additional participants. Additionally, the sampling was done purposefully. Specifically, typical sampling was employed to understand the general consensus and limit the impact of outliers.

The organizations included in this study consist of startups, academics, an infrastructure provider, governmental organizations, and other public organizations. The organizations range in size from small startups to organizations employing thousands of employees.

The geographically homogeneous sample of stakeholders impacts the generalizability towards other ecosystems outside of the Netherlands. This choice was made deliberately, given the ease of reaching participants and the number of

Experts in the Dutch quantum ecosystem

interviewees required to reach full saturation for an international study. The number of participants interviewed for this study is deemed sufficient to draw qualitative conclusions.

A total of 15 experts participated in the study. Table 5 shows an overview of participants.

Table 5: List of participants

ID	Organization type	Expertise
P1	Academic	Quantum Technology
P2	Public – regional	Ecosystem
P3	Public - government	PPPs
P4	Academic	Business Development
P5	Public	Society
P6	Public	Society
P7	Academic	Communication
P8	Public	Business Development
P9	Startup	Business Development
P10	Public	Communication
P11	Industry	Infrastructure
P12	Government	Ecosystem
P13	Startup	Business Development
P14	Public	Quantum Technology
P15	Startup	Quantum Technology

3.2 INTERVIEW PROTOCOL

Participants were approached via email or in person. The participants received a brief introduction about the research, the purpose of the study, and, in some cases, questions were sent ahead upon request. The interviews took place either face-to-face at various locations or were conducted online. Upon approval of the participant, the interview was recorded and later transcribed. The participants were also asked for permission to use anonymized quotes in the reporting. During the interview, the interviewer took notes on their initial thoughts to support the transcriptions. All personal data was removed from the transcripts. The interviews took place in the time span of November 2025 to February 2026.

As the interviews were semi-structured, the majority of the interviews had the same interview structure. Flowing from value creation, to collaboration, to barriers to adoption. But as the interview progressed, certain topics were given more attention than others based on the expertise and experience of the participant. Over time, the structure was slightly adapted based on learnings from initial interviews.

3.3 ANALYSIS

The data was analyzed through a thematic content analysis approach [114]. This approach is considered suitable since it allows for in-depth exploration leading to nuanced insights. The analysis consisted of several steps. First, the audio recordings were transcribed and translated into English. The transcription was created automatically using transcription software, after which it was manually thoroughly checked and cleaned. The audio files were often consulted to verify the transcription and underlying meaning. The coding was done in the *Atlas.ti* software. The initial analysis consisted of 369 codes and 534 quotations. Following the coding process, the codes were converted into 117 groups. Those groups were categorized into 35 categories, which were placed in 9 sub-themes. These sub-themes were placed into 3 themes. This allowed for a hierarchical tree structure to show the relationship between several coding groups. The themes and groups were created with the research question and aim in mind. While the codes were mainly descriptive, the groups and categories were interpretive by nature. The coding process aimed to categorize insights based on the structured information, and a qualitative analysis was undertaken based on the transcripts along with the coding results. The aim of the results was not to create an exhaustive and exclusive coding tree, but rather to provide structure within the transcript. There was no initial goal in regard to the amount of codes, categories, or themes. Several codes were left out of the coding process as they were deemed irrelevant. In the process of creating the themes, the transcripts (both Dutch and English) were consulted to ensure the sentiment and meaning of the code were conveyed correctly into the theme. Several steps and checks were taken to ensure academic integrity during the coding process. The transcription and coding were done after all interviews were conducted. This was done purposefully to limit confirmation bias in the later interviews.

Finally, the results of the coding tree were visualized in figure 6, and a table below highlights the results.

369 codes,
117 groups,
35 categories,
9 sub-themes,
3 themes

Figure 6: Coding tree

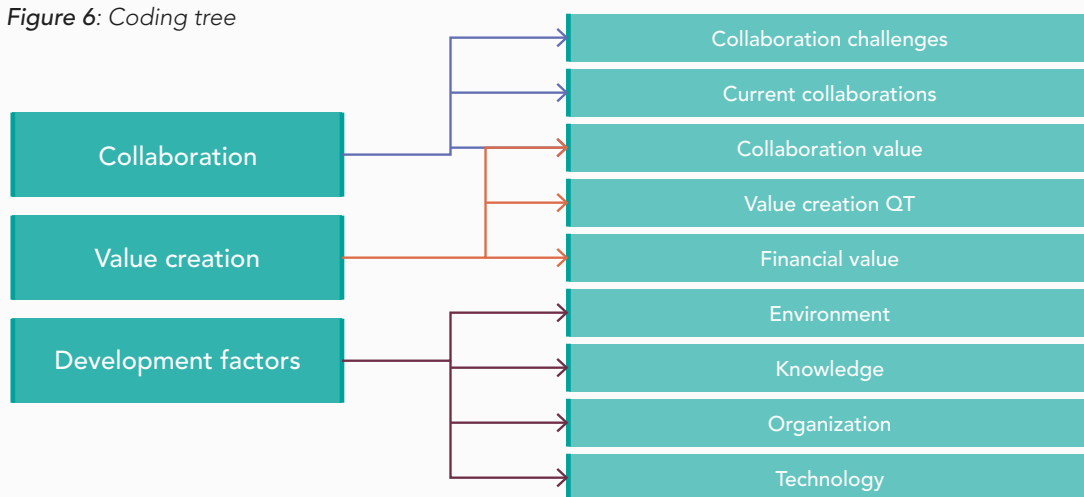


Table 6: Coding table

Sub-theme	Category
Collaboration challenges	Collaboration challenges
	Collaboration commitment
	Collaboration requirements
	Different stakeholder interests
	Stimulating collaboration
Current collaborations	Amount of collaboration
	Current collaborations for Quantum
Collaboration value	Reason to collaborate
Value creation QT	Application of QT
	Impact of quantum technologies
	Reason to invest
	Reason to work in quantum
Environment	Development focus
	Ecosystem
	Infrastructure challenges
	Political challenges
	Regulatory challenges
	Role stakeholders
	Societal impact
Financial value	Funding
Organization	Commercialization challenges
	Cultural challenges
	Funding challenges
	Organizational challenges
	Organizational interest
	Scaling challenges
	Uncertainty
	Organizational preparedness
Knowledge	Creating awareness
	Knowledge about quantum
	Language
	Quantum hype
	Quantum winter
	Talent and education
Technology	Technological challenges

4. RESULTS

This section presents the results of the qualitative study. Based on the transcriptions, codes, and notes of the interviewer, the analysis led to certain main findings, supported by quotes. The main aim is to find themes among different participants and to create an overview of barriers to adoption. This chapter is split into two parts: section 4.1 Themes goes into the themes and topics found as a result of the interviews. Section 4.2 Barriers to adoption highlights the barriers to adoption that were mentioned by the participants.

4.1 THEMES

The three themes identified were collaborations, value creation, and development factors. These themes are not mutually exclusive, and the content of the themes might find some overlap. This is because the three themes are very much intertwined, as made clear in the research gap and literature review. The most interesting findings are summarized and supported by direct quotes from the transcripts.

4.1.1 COLLABORATIONS

Collaborating was widely regarded as beneficial to quantum development. The complexity of quantum technology requires organizations to look beyond their internal capabilities and use the knowledge, resources, and expertise of other organizations. Various stakeholders are required to develop the technology. These collaborations can have a positive impact on costs, knowledge generation, use case creation, and exposure to different ways of thinking.

“ If the Netherlands and Europe work together a little better and can present a united front, then yes, we’ll blow them away.” – Participant 8

When looking at the current collaborations in place for quantum development, a mixed image arises. The Netherlands and Europe are relatively very good at setting up collaborations and have a lot of experience in bridging the gap between private and public organizations. There are several (international) collaborations in place to stimulate quantum development, and each participant mentioned a cross-sector collaboration they were a part of. But participants also stated that there is a distance between actors due to different interests, a lack of collaboration, and difficulty in finding each other.

“ I think we are seriously good at that in the Netherlands. Few countries are familiar with public-private partnerships, so I think we are doing really well in that respect.” – Participant 3

Collaborating is important but challenging

But collaborating is a difficult task to do properly and requires active orchestration. In setting up collaborations, it is important to find common goals and deal with the differing interests of stakeholders. Parties aim to achieve their own goals, and quantum technology needs to add value to achieving these goals. Otherwise,

actors are hesitant to collaborate or support development. Discussions regarding IP, transparency, uncertainty, time constraints, and costs are among the struggles in setting up the collaboration. Having an incentive, an explicit reason to collaborate, was mentioned as missing. This confirms that it needs to be clear for each actor in a collaboration which value they will create. Successful collaborations were indicated as having this higher goal, having intrinsic motivation, and being transparent. Collaborations also need proper structures, coordination, constant readjustment, and management, ensuring that expectations are met and timelines are clear.

“A lot of readjustment, a lot of meetings, a lot of expectation management, because it needs to be a win for the company, but it also needs to be a win for QuTech...” – Participant 4

“We then try to (find the) higher goal that everyone can agree on and benefit from, and then they are often willing to go along with it.” – Participant 2

“That they [collaborations] don’t exist yet and that they don’t fit into the current, perhaps somewhat conservative, structures. So ultimately, everything is quite fragmented, certainly within science, and you see that very clearly in the fact that it is difficult to engage in interdisciplinary collaboration ...” – Participant 10

Quantum adoption within organizations predominantly occurs because there is an individual who sees the potential and advocates for such a technology. They need to find a way to inspire others. But this is seen as a big challenge. Multiple people need to advocate for change and innovation for it to occur. But the initiator, person of contact, or quantum champion at an organization heavily influences the chance of success. Creating these initiators is a difficult task. A challenge lies in collaborating beyond the initial meeting or introduction.

“There is always someone who is enthusiastic, who also has this in their portfolio. I always call them the quantum champion, because they are very keen. They need to get people in their organization enthusiastic, because people need to make time and sometimes also budget for a project.” – Participant 6

“Maybe I just haven’t found the right person yet. I haven’t found the right ally. (at a certain organization) ... I think it also depends on who you get in management or who you get as an ally in this. That seems to be a big deal.” – Participant 4

Many organizations that are involved passively prefer to wait for the technology to mature before engaging in collaborations. But this *wait-and-see* mentality is not

Wait-and-see mentality

necessarily bad. For some organizations, it is too early to invest because of the development time and uncertainty, having a certain amount of risk aversion. At the same time, waiting too long will leave organizations exposed to risks. International organizations are better prepared, according to some participants, and are actively pursuing the early mover advantage.

“There were also a number of companies that said, ‘We’re really keeping an eye on this development, but it’s still too early for us to invest in it.’” – Participant 12

“The reason we don’t have more collaborations is primarily that we are still too far from usability and the market.” – Participant 7

“But I think many people are in expectations, especially the Dutch companies, are very much like, let’s wait and see what’s happening” – Participant 1

“So if you surrender to [the mentality of:] ‘It will take time and we’re not going to invest in it’, then you’re the last one standing.” – Participant 2

4.1.2 VALUE CREATION

The potential of quantum technologies is clear; through various application areas, such as logistics and medicine, quantum technologies could create a lot of value, although one participant did state that *“the role of quantum might be a little smaller than we originally thought”* (Participant 10). Especially, economic value and strategic autonomy were regarded by participants as important reasons to invest in quantum technology. Yet at the same time, there seemed to be a consensus among the participants that other problems and technologies also need attention and funding, which explains why resources are limited.

“That’s really autonomy. ... You want to maintain your autonomy, and with a quantum computer, you can.” – Participant 2

“... it’s the economic impact it can have. One to two trillion per year, possibly. And those are actually still conservative estimates.” – Participant 7

Quantum is a disruptive and enabling technology, meaning it can generate value for many different sectors. A participant explicitly mentioned that regional collaborations are useful because of the value spillover towards other industries.

“So if you can create a spillover effect there. You see this in many sectors, that it’s simply the exchange of knowledge that can lead to really interesting things.” – Participant 12

4.1.3 DEVELOPMENT FACTORS

There are several factors that impact the development and, therefore, adoption of quantum technologies. They are categorized into knowledge, uncertainty, and commercialization. Other factors were mentioned, but these categories are most prominently mentioned by the interviewees.

4.1.3.1 KNOWLEDGE ABOUT QUANTUM

Language was recognized as one of the main challenges for collaboration, but this was predominantly mentioned by participants with a focus on business development or the societal impact of quantum technologies. Each stakeholder speaks their own language, and creating that bridge is very difficult. It was widely recognized that quantum is a difficult and intimidating topic and that a lot of stakeholders lacked proper knowledge. But regarding the complexity and how to mitigate it, participants often resorted to picking up their phone or laptop and stating:

“ People know as little about that [quantum] as they do about how their phone works. Or how light or electricity works at all” – Participant 5

“Language. ... It’s not so easy to say to a quantum expert and a water expert, ‘Why don’t you two spend an afternoon talking?’” – Participant 5

Required level of knowledge is unclear

But interestingly, a participant also noted that the required level of knowledge for non-experts is unclear. What, for example, policy makers need to know is not evident. The way it should be communicated is in a normalized and fact-based manner, where possible, to mitigate speculation and hype. But when speculating or talking about future scenarios, which have a clear purpose, it can be done using metaphors and refraining from using science fiction language.

“... it’s also good to speculate a little and [draw up] those future scenarios and do that kind of thing, because then you can get a little ahead of [the development].” – Participant 10

Quantum hype is a topic that arose during almost every interview, even without being asked about it. Yet the opinions regarding quantum hype were varied, also regarding the possible impact of the hype and quantum winter that could result from it. The startups were a bit more optimistic, but did recognize that the way the media writes about quantum technologies might be exaggerated. The majority of the hype is surrounding the speed at which it will be developed and the areas of application where quantum technology will play a big role.

“Well, the hype is mainly about the speed with which things are being solved, the prediction. I think it will ultimately work out. But the question is how quickly” – Participant 14

Uncertainty around quantum technologies

4.1.3.2 UNCERTAINTY AND FUNDING

The biggest topic in quantum development is the uncertainty surrounding quantum technologies. Uncertainty regarding applications, a lack of showcases, regarding the value those applications will bring, and uncertain how this value can be measured. This is limiting organizations from engaging with the technology and supporting its development. There is a lack of a killer application that moves organizations towards the technology.

“Soon there will be a quantum computer, and what will it calculate? What will it do? It’s still a bit of a guessing game, of course.” – Participant 2

“That unknown factor is, I think, the biggest barrier, an open door, but it has to be said” – Participant 5

“But we can’t yet assess which of our customers are facing what kind of optimization problems and what they would be willing to pay to do that using a quantum method.” – Participant 11

There are a lot of challenges surrounding funding. Firstly, the imbalance between public and private funding in Europe. Ideally, public funding is followed by private investments, but there is a lack of the latter in Europe. There are plenty of institutions that provide subsidies and allow startups to start their journey, but once these companies want to scale, there is a lack of financial resources to do so. The participants also mentioned several downsides to those subsidies. They are slow, subject to many rules, require intense administrative tasks, and are often piecemeal, meaning they are for a specific task. That is why a participant advocated for base funding instead of project-wise.

Funding challenges in Europe

“I think that’s missing, a much more generous base funding rather than you have to meet these parameters and these parameters and these parameters, because then you’re restricting your research to this specific area rather than where it really should be.” – Participant 4

“And how do you ensure that funding is available for this? Not only from the government, but also from other sources. I think that’s the most complicated thing for quantum.” – Participant 3

4.1.3.3 COMMERCIALIZATION AND ROLE OF THE ECOSYSTEM THEREIN

The Dutch ecosystem was remarked as doing very well compared to other countries, and on a global scale Europe is performing better than some might think. But at the same time, there is a clear lack of central coordination, which is deemed very important. QDNL has been praised for being *“the gold class of an example”* (Participant 9), but there is a lack of narrative and a lack of clarity for when the Growth fund ends. The Dutch ecosystem furthermore lacks large organizations,

connections with other ecosystems and clear trajectories to mature. As the strength of quantum development in the Netherlands lies in its academic capabilities, the transition towards a more economic ecosystem requires attention and active improvement, especially since startups might move away.

“And economically speaking, it could be an opportunity. In the Netherlands, we are definitely in the top 3 in the world academically, but not yet economically, because we don’t invest as much as other countries.”
– Participant 14

“So quantum consists of a lot of SMEs and start-ups, scale-up companies. So you have to make sure that your instruments are in line with, in this case, an ecosystem that does not yet consist of large companies.” – Participant 3

Government has important role in commercialization

The role in facilitating this commercialization through funding and infrastructure is very important. The majority of the participants highlighted the role of the government in getting deep tech technology, like quantum technologies, off the ground. The participant from an governmental organization also stated that their goal was to stimulate the economy and valorize knowledge. This transition from knowledge at an academic level to startups which costs the most money. Given the lack of private funding available in the Netherlands and Europe, the government should fill that gap if they want the Dutch ecosystem to reach its potential. One of the ways to stimulate this commercialization is by acting as launching customer.

“... Rijkswaterstaat should buy a quantum computer and, as a kind of engineering firm for the entire Dutch government, including dredgers, to have a kind of integrator role” – Participant 8

“We had set up two labs, with [Prince] Constantijn, who is of course very active in tech. He said, almost irritably, that we should stop hoping for private money, ... but maybe it has to be public money after all. An investor does it to make a profit, but society can do that too, right?” – Participant 7

4.2 BARRIERS TO ADOPTION

Several barriers to adoption were mentioned throughout the research. Collaboration is required to adopt the technologies, and many barriers are associated with collaboration, such as a lack of clear value, IP challenges, or the need to readjust expectations throughout a collaboration. Those are not mentioned specifically. Table 5 shows the barriers that were mentioned by participants. Some participants also contradicted the existence of certain barriers, which are displayed in the table below in brackets ().

Table 7: Barriers mentioned

Type	Barriers	Participants
Technological	General technological scaling barriers	P2, P8, P14, P15
Organizational	Application uncertainty	P1, P2, P3, P5, P6, P7, P8, P11, P12, P14, P15
	Value uncertainty	P1, P3, P5, P11, P12, P14, P15
	Lack of funding	P2, P3, P7, P8, P9, P11, P15
	Organizational culture and structure	P1, P2, P4, P6, P11
	Organizational caution	P2, P4, P12, P14, (P5), (P7), (P15)
	Lack of quantum champions	P3, P6, P8
	Lack of commercial expertise	P1, P2, (P13)
Knowledge	Hype	P1, P4, P9, P10, P14, P15, (P3), (P6), (P13)
	Quality of knowledge	P1, P2, P4, P8, P9, P10, P14
	Language	P1, P5, P6, P8, P10
	Lack of talent	P1, P2, P9, P14, P15, (P3)
	Perceived complexity	P2, P3, P12
	Lack of showcases	P3, P6, P12
Environmental	Infrastructure	P3, P12, P13, P14, P15
	Lack of government support commercialization	P1, P7, P8, P11, (P13)
	Regulatory	P6, P9, P14
	Ecosystem coordination	P5, P12, P14
	Lack of large organizations	P3, P4, P14

Some participants did not give a clear indication whether or not something was seen as a barrier, those results are not included in the table. Furthermore, the participants were informed that the goal of the study was to understand the barriers to adoption outside of the technological challenges. Participants did mention the technological challenges, such as scalability, error-correction, and engineering challenges, but those are left out of the table on purpose.

5. RESEARCH DISCUSSION

To place the result in the context of existing findings and to reflect on those findings, the section below will shed light on what the results of the qualitative study mean. The interviews are discussed separately, after which they are placed in relation to the literature. It is followed by answering the 'So what?' questions, and lastly, limitations are mentioned.

5.1 RESULTS INTERVIEWS

As discussed in the literature, there are various barriers to adoption. The interviews confirmed that several factors limit organizations' ability to engage in quantum technologies. Several of those are not specifically applicable to quantum technologies. Lack of funding, the need for talent, the lack of reason to switch, and challenges regarding the infrastructure could be applied to many deep-tech developments. This does not mean that they are irrelevant. The lack of funding was very frequently mentioned by participants as a big challenge, especially in contrast to other places where more (private) funding is available for startups to grow. In line with overcoming the 'valley of death', it is evident that change is required in the EU to create more funding opportunities. If, due to for example cultural or geographical reasons, the lack of privately available funding is hard to resolve, then public organizations should aim to fill the gap if the development of quantum technologies is sought after. Several participants also pointed out that the financial objectives of private companies could also be pursued by public organizations.

Uncertainty common denominator interviews

As for the barriers that were specific to quantum technologies, the uncertainty was the common denominator throughout the interviews. Uncertainty regarding development timelines, regarding applications, regarding knowledge, regarding financial means, and even uncertainty regarding the value the technologies might bring. Because a lot of uncertainty will not be resolved until the technology matures, it requires active attention. Creating use cases and clear benchmarks are among the steps that should be taken to mitigate part of the uncertainty. Applications which were mentioned were predominantly those that are proven, like using Shor's algorithm to break RSA encryption. Until new 'killer applications' are found, the uncertainty has to be dealt with. Another specific challenge for quantum technologies was the communication barriers. Language was seen as a major obstacle in setting up collaborations and getting non-experts engaged. Interestingly enough, people tend to use metaphors in their communication to make it easier, claiming that with metaphors, it is easy to communicate. But a recent study done in the Netherlands showed that metaphors have very little effect on the perceived comprehension [115]. This is especially interesting since a lot of communication in general about quantum is done using metaphors. Where it is clear that there is no need to fully understand quantum technologies, it is not as clear what level of knowledge is required. That might be an even bigger challenge to tackle. This is also in line with the amount of knowledge that participants claimed organizations had. Many said that the majority of organizations knew about quantum technologies and had started to show initial interest, but that had stopped at knowing about it. Some organizations have done their research and found that it was too early for them to engage, which is the correct way to go about it. But if the understanding remains superficial, it becomes hard to truly see the potential amidst the uncertainty.

Value creation is an important aspect of developing the technology,

especially since it influences the potential for collaboration. The main values that were mentioned were strategic autonomy and the economic potential it has, often in line with the 'Wennink rapport'[38]. These values are very intertwined, as the main autonomy that is sought after is an economic one. When talking about other types of value, people often resort to mentioning applications such as medicine development instead of mentioning explicit value. The focus on strategic autonomy is mainly driven by the current focus on autonomy within Europe. As participant 8 mentioned: *"Strategic autonomy was very high on the agenda and has now really become the magic word"*. This might change once the priorities of the Netherlands and the EU alter.

QDNL was praised and criticized at the same time. Overall, participants were positive about the coordination mechanisms and the support provided by the government. The findings confirm the importance of having proper coordination mechanisms and active involvement in setting up an ecosystem. There is a need for active orchestrators of collaborations, especially with the many challenges that were recognized in setting up collaborations, with differing interests as the biggest challenge. Public and private organizations have different targets to strive towards, which leads to frustration. Finding a clear goal is vital, which is challenging given the uncertainty.

The role of the government is of utmost importance to realize a quantum future. Stimulating commercialization is one of the steps in valorization where public organizations play an important role. Through general funding, funding infrastructure, acting as a launching customer, providing regulatory frameworks, and stimulating collaboration, governmental organizations can drive the development. The transition towards valorization is important for the government as it starts to provide value for society, but this requires active participation.

5.2 REFLECTION ON THE LITERATURE

The findings align with the theory; there are many barriers to adoption of quantum technologies, collaborations are useful but hard to set up, and significant value can be created through quantum technologies, albeit it is uncertain which value. Compared to the literary findings, the topic of hype was much more disputed than the existing literature claims. Several individuals had different opinions regarding the existence of a quantum hype and the possible negative consequences because of it. Furthermore, when asked about a possible subsequent quantum winter, there were varying views as to the implications it might have.

The qualitative study highlighted the importance of the government in realizing development and stimulating adoption. This was not mentioned too frequently in the literature. Several researchers have shown the difference in the types of funding available within the EU compared to the US [4,54], something that several participants confirmed. Yet this is also an aspect where the government can take on responsibility to actively facilitate and encourage the transition from public to private funding.

Where the theory suggests the importance of triple helix collaborations [92]. This was seldom mentioned during the interviews. But the importance of setting up collaborations between various stakeholders, both public and private, became apparent. The term triple helix might be used more commonly among theorists than among practitioners of quantum development. These various actors should play an active role in the development in order to ensure adoption, and passive

collaborations hinder the adoption potential. Collaborations, and PPCs in this specific case, require active engagement [15,20,78,100]. This was confirmed by participants, who struggled with getting collaborations beyond initial meetings to an active partnership. The differing interests and uncertainty make this difficult.

There are several findings from this study that offer contributions to the existing literature, besides the critical reflection on the existing literature as written above. First, the importance of coordination and integration of several stakeholders. It is vital for the development of the technology, but for adoption, it also plays an important role. Lack of clear contact points, a missing structure, and uncertainties in the ecosystem hinder organizations from engaging with it. For example, a lack of large organizations in the ecosystem hinders other organizations from engaging.

The creation of 'quantum champions' is one of the coordination challenges. Collaborations stand and fall with people who are enthusiastic about the potential. This requires a lot of business development and networking to get people enthusiastic. This was not reflected enough in existing literature. This is in line with the communication challenges. Literature shows the perceived complexity, the quality of knowledge, and the challenges in finding a common language [15,57,115]. The interviews showed that there is no need to understand the inner workings of quantum, but at the same time highlighted the uncertainty of which level of knowledge is required.

5.3 LIMITATIONS

There are several limitations to the study. Firstly, there is the generalizability of the research outcomes. As all participants were active in the Dutch Ecosystem, the results might not be transferable to other ecosystems one-to-one. It provides an insight into the barriers to adoption, but would require further research to confirm the generalizability across other countries. Secondly, the unstructured nature of the interviews meant that certain topics were covered more dominantly than others per conversation. This led to the advantage that the acquired qualitative data was richer, but made cross-referencing interviews and quantitative analysis more difficult. A future quantitative survey amongst a wide range of participants could validate the findings.

The interviews were conducted in two languages, Dutch and English, based on the native language of the participant. As Dutch transcriptions were translated into English for analysis, some of the underlying meaning could be lost. Yet the influence of the translations had minimal impact on the results, as both Dutch and English transcripts were consulted during analysis. Most participants had a background in quantum technologies and a societal, business development, or ecosystem focus. This limited the heterogeneity of the pool. At the same time, it meant that they were able to provide a holistic view of the barriers to adoption. Expanding the pool to various other participants within the stakeholder pool would increase the validity of the research.

As the research into barriers to adoption is a relatively new topic, further research is needed to expand on the knowledge and create a complete overview.

5.4 SO WHAT?

As participant 10 stated: *“if only half of our plans for quantum or our expectations for quantum technology in the future come true, society will change drastically”*. It is undisputed that quantum technologies have a lot of potential, for the better and for the worse. Collaboration between stakeholders is required to ensure proper development, which means early engagement from organizations and other actors. To stimulate development and realize the value that a quantum future can bring, and to mitigate potential risks. Collaboration is key and should actively be encouraged.

One of the things that has become clear is that there is a lot of uncertainty around quantum technologies. While this is not groundbreaking on its own, there is a lot of struggle with how to deal with this uncertainty. Quantum technologies have a lot of potential to positively disrupt society. But currently, there are several barriers limiting organizations from engaging in the technology. It is important to understand these barriers to ensure a smooth integration of the technology into society. Quantum technologies can create a lot of value, but it is uncertain what type of value this might be. The lack of a clear application and the lack of clear problems to solve are stopping organizations from engaging with quantum technology. This lack of clear value and a common goal also prevents organizations from collaborating. A clear value is the cornerstone of successful development and adoption. But how do you deal with the uncertain value it can create, and how do you bring something that is far in the future towards today?

PART 2

Foresight method to deal with uncertainty and focus on value creation. Aimed to stimulate collaboration among stakeholders.

"The future is uncertain... but this uncertainty is at the very heart of human creativity."

Ilya Prigogine

Nobel Prize winner in Chemistry

6. METHOD INTRODUCTION

The research showed that uncertainty regarding applications and their values is among the main barriers to adoption. As the technology requires maturity, many applications will not be certain until the technology is ready. Nevertheless, initial applications do demonstrate significant potential. Monetary and economic values were predominantly mentioned as a reason to invest in or to develop the technology, although they are not equally important to all stakeholders. Research showed that having a common goal, aiming to achieve shared value, is required for successful collaborations. Additionally, diverging values are not inherently problematic, as long as the differing values and goals of stakeholders are acknowledged. Expecting a collaboration where the goals of all stakeholders overlap perfectly is optimistic. At the same time, differing goals of stakeholders are not a problem to be solved; they should be embraced, while stakeholders are brought together around a shared direction. There are several ways to identify common values, but mapping those values is a good start. The goal is a common point to work towards, with each participant following their own trajectory, but in a shared direction.

As the research showed, collaboration is required to stimulate the development and adoption of quantum technologies. Participants in the qualitative study indicated that more collaboration would be beneficial, while also acknowledging the challenges in establishing such collaborations. Addressing these challenges requires change at a societal level, as many are intrinsic to human nature. Nevertheless, inquiry-based research into how multiple stakeholders can be brought together supports the realization of better collaborations.

Part 2 explains the Future Value Mapping method. This method is one of the ways in which stakeholders can be brought together to realize a shared future, a future with quantum technology in this case. FVM serves as a tool to engage in conversations, aiming to stimulate collaborations by helping to tackle the uncertainty. The method is explained below in the following chapters, and two showcases are provided. The method aims to provide incentives for organizations to explore quantum technologies by highlighting their potential value.

FUTURE VALUE MAPPING

7. FUTURE VALUE MAPPING

Future Value Mapping is a strategic foresight method that combines future scenario creation with backcasting and speculative what-if scenarios. It is a structured approach designed to explore a future scenario and aims to aid decision-making today based on future outcomes. The purpose is not to predict the future, but to prepare stakeholders and stimulate development. The method is not a goal on its own, but rather a tool that can help provide insights and stimulate conversations. FVM starts with a point on the horizon, a normative scenario. Based on this scenario, several steps are taken to provide insight into what that means for today. It is not a predictive method, as the scenarios are not based on speculation, but rather on proof-of-concept. As with any future outlook, there is unpredictability regarding the realization of the scenario, but by basing the scenarios on likely scenarios, a level of ambiguity is removed. The aim is to provide actual information and incentives to talk about rather than enter the realm of science fiction.

The audience for which Future Value Mapping is created is non-physicists in quantum development, such as policy makers, philosophers, designers, and other people actively engaged in quantum technologies. The method could also be applied to other technologies where value uncertainty is one of the biggest barriers. Given the variety of potential stakeholders that are involved in the creation of a Future Value Map, proper visualization is important. Communication between several stakeholders might encounter several challenges due to intrinsic differences. Visuals can aid in the discussion and bridge the language gap.

The method is value-driven. This means that the main aim throughout the several steps is to emphasize the value that ought to be created. It requires constant reflection throughout the process. Highlighting the reason why steps are required to be taken, or what the implications of certain actions might be on value creation. With the term value, a broad definition is taken. For society, value creation is expressed as *'Brede welvaart'*, including various types of value such as economic value, environmental value, safety, security, and quality of life.

7.1 FVM METHOD

The Future Value Map consists of three main steps. It starts with creating a normative scenario in the future. As explained below, it is important to make sure the scenario is not too much like science fiction, as this pushes people away. Based on this scenario, you look back to today and ask yourself what needs to be done to realize that scenario. With several stakeholders in mind, you should create steps that can be taken over different horizons. The starting point of the roadmap that is created using backcasting is the future scenario. It leads to today, which consists of the current barriers and drivers to realize the scenario. Those barriers need to be solved for the scenario to materialize. Based on the scenario, you look ahead towards the future and explore possible implications if this scenario becomes a reality. The scenario is not the end goal, but it is the point on the horizon. Possible unforeseen consequences of the scenario should be highlighted today to deal with before they occur.

Below is a description of the various steps that are to be taken. In the following chapters, a more elaborate explanation is given using examples.

Table 8: FVM steps

Step 1: Orientation

- 1A Content familiarization
- 1B Stakeholder analysis
- 1C Scope setting

Step 2: Create scenarios

- 2A Idea generation
- 2B Scenario development
- 2C Initial value analysis

Step 3: Backcasting & Input gathering

- 3A Initial What-How-Who analysis
- 3B Participatory value analysis
- 3C Participatory What-How-Who analysis

Step 4: Refinement

- 4A Scenario refinement
- 4B Roadmap development
- 4C Analysis

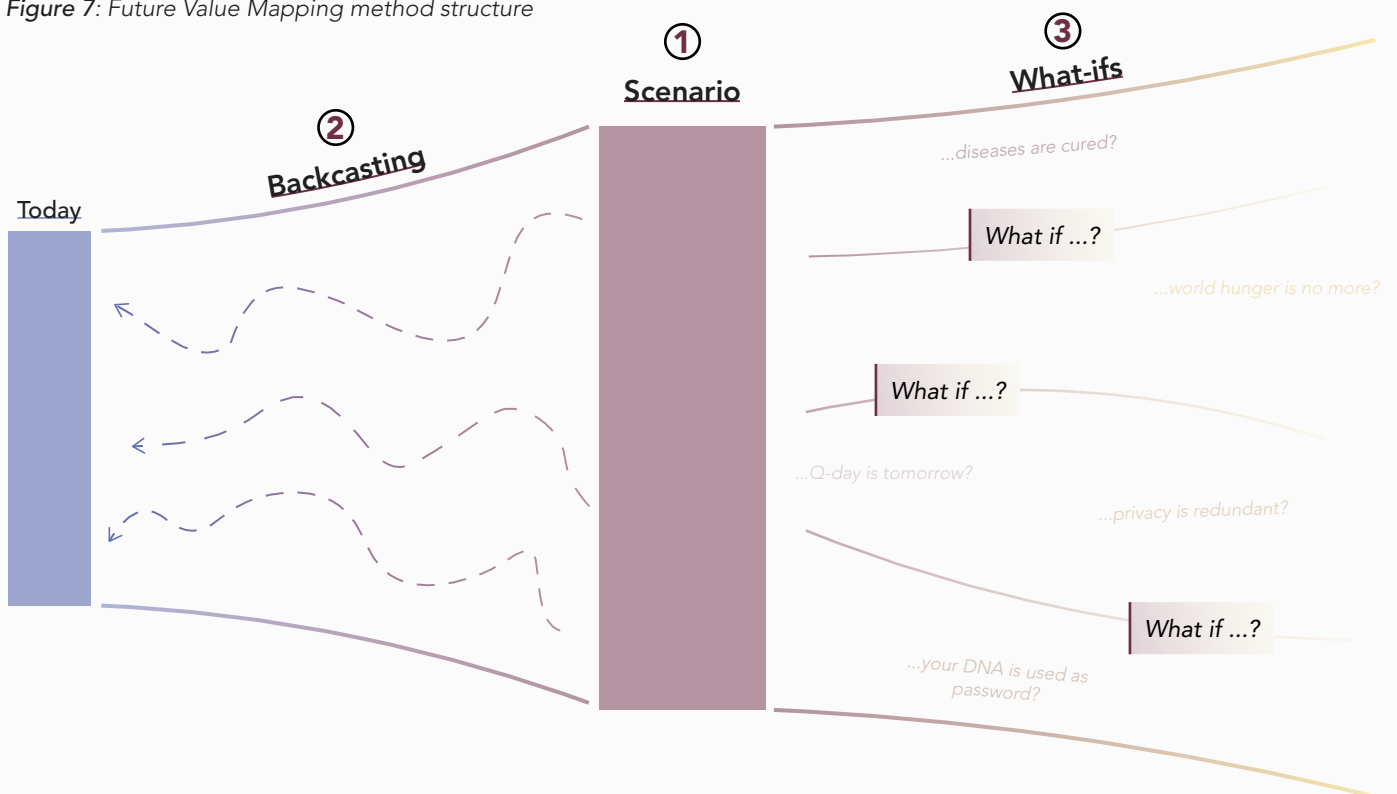
Step 5: What-if creation

- 5A Idea generation
- 5B What-ifs development
- 5C Analysis

Step 6: Reflection

- 6A So what?
- 6B What does this mean?
- 6C Goal alignment

Figure 7: Future Value Mapping method structure



Step 1: Orientation

Before being able to create scenarios, engage in a backcasting analysis, and think about what-ifs, it is important to have a level of familiarity with the content (*Step 1A – Content familiarization*). Through desk research and conversations, this knowledge can be acquired. This is not a step that is ever truly completed. During the process of developing the artifacts, the knowledge base expanded. But acting on little initial information makes it difficult to reach the level of richness and advanced understanding, resulting in a superficial result. This includes understanding the barriers and drivers of the technology and sector. The goal is to explore the problem from a systemic viewpoint, making analyzing various stakeholders very relevant (*Step 1B – Stakeholder analysis*). As one of the underlying goals is to bring stakeholders closer together and stimulate collaboration, it is vital to understand the stakeholders. Make a distinction between the stakeholders based on their degree of participation. Mainly the active stakeholders should be taken into account for the analysis. Lastly, creating the scope and setting where the process occurs (*Step 1C – Scope setting*). I.e., what is the geographical scope of the analysis? Who is the audience? What implications does that have for the language that is used? Make sure to formulate a clear goal. The method is just a tool and not a goal on its own.

In the case of the examples provided in this report, the results of the orientation phase are the outcome of Part 1. 7.4.2 Scenario creation contains a summary

Step 2: Create scenarios

The scenarios are the cornerstone of the method. They are the starting point of the roadmap and the basis for the what-ifs. Based on the knowledge that is acquired about the context and the scope that is set, start by generating ideas of scenarios (*Step 2A – Idea generation*). It is also possible that a specific scenario is taken as the point of departure for the FVM analysis. Using brainstorming or other methods, a list of scenarios can be created. These ideas can be clustered and filtered. Based on the application of the method, a list of criteria should be established to assist in choosing the concepts. When the scenario concepts are chosen,

they should be developed (*Step 2B – Scenario development*). Using a normative language and approach, the scenarios should consist of a description, a brief explanation of how it works, and a visualization. The visualization is an important part, as it influences the underlying message and understanding of people reviewing the scenario. When the scenario is completed, an initial value analysis should be executed (*Step 2C – Initial value analysis*). The aim is to create an initial insight into what this scenario can bring. The goal is not to realize the scenario for the sake of the scenario, but to create value for several stakeholders. One of the ways to look at value creation is to use the SDGs. Making them explicit encourages collaboration and stimulates development.

The list of criteria used in the examples provided in this report can be found in Chapter 8

Step 3: Backcasting & Input gathering

Based on the initial scenarios and value analysis, which are placed in the future, steps should be taken to connect the future scenario to today. Using three main questions, an initial backcasting analysis should be executed, with the scenario as the starting point, working towards the present (*Step 3A – Initial What-How-Who analysis*). The questions that structure the process are the following: What steps need to be taken to realize this scenario? How can these steps be realized? Who needs to act on the steps? This should result in an initial list of measures and incentives to realize the scenario.

With a scenario, an initial value analysis, and initial backcasting done, external input should be acquired. Through a participatory value analysis, interviewees, stakeholders, or workshop participants should shed light on what value they think the scenario will provide (*Step 3B – Participatory value analysis*). In addition, ask for risks or “negative value” they see. This is the foundation of the what-ifs. As value creation is subjective to the individual based on their background, to get a complete understanding of potential value creation is meaningful to retrieve insight from various stakeholders. Next, the participants should be asked to provide their perspectives on what needs to be done to realize the scenario (*Step 3C – Participatory What-*

How-Who analysis). Asking them the same three questions, information is gathered based on their perspectives to create a more complete overview of the process of realizing the scenario.

Step 4: Refinement

With the majority of the information retrieved the scenario can be refined (*Step 4A- Scenario refinement*). Several new insights might be generated regarding value creation and the importance of several stakeholders. Use this to create an overview of the values the scenario will generate. The backcasting processes lead to insight that forms the basis for creating a roadmap (*Step 4B – Roadmap development*). Place the several actions that need to take place across three horizons. The horizons are split based on collaboration milestones rather than time, given the uncertain factor of development and the rigidity of time. ‘Multi-stakeholder consortium is realized’ and ‘Commercial network is realized’ are collaboration-driven milestones that divide the horizons. It is also important to look at the aspects that stay more or less constant while developing the roadmap. Not everything can be directly influenced, and some developments require continuous attention. It is especially interesting to map the incentives that are required beyond continuous development. When placing steps and incentives on a roadmap, also include their outcome. With the scenario and roadmap created, it is required to analyze the results it generated (*Step 4C - Analysis*). Answer questions such as: What are the main steps that need to be taken? Where can value creation be influenced? Where are risks present?

As the roadmaps provide a static overview of development towards a scenario, it risks misalignment with reality as time progresses. To prevent a static overview from being out of touch, it is important to reflect on and adapt the findings periodically. Using pastcasting, a method that aims to learn from past steps as the roadmap develops, and recurring realignment meetings, the roadmap can be made more adaptive. More about pastcasting in *10.2 Backcasting process*.

Step 5: What-if creation

Based on the scenarios and input from the backcasting, look towards the future and aim to

answer the question: What if? Based on the scenarios, brainstorm several ideas for what-if-scenarios (*Step 5A – Idea generation*). There might be several risks that emerge, downsides to the technology, or other consequences when the scenario is realized. Exposing those consequences and starting a conversation is important because it has implications for how you develop the technology today. After developing several what-ifs, choose and work out the most applicable ones (*Step 5B – What-ifs development*). Start by creating a full sentence for the what-if. Based on the what-if question, create a normative situation sketch, providing the context of the situation. Based on the sketch, create stakeholder stories of fictive people living in a world where the what-if question is a reality. Expand with a visualization, a matrix featuring potential value and potential risks, and look at what steps need to be taken today. Depending on the positive or negative outlook, the steps can stimulate or prevent this what-if from actualizing. Analyze the content that is created and reflect on the possible implications (*Step 5C – Analysis*).

Step 6: Reflection

The final step is to reflect on the results of the process. Be conscious of the steps that were taken and the results they generated. There is a scenario, ways to get there, and possible what-ifs, but what do they actually say (*Step 6A – So what?*)? Look back at the roadmap and, with the stakeholders in mind, highlight the steps that need to be taken. It is great that there are visuals and a comprehensive story, but they should be used to initiate change. Answer the question: What does this mean? (*Step 6B – What does this mean?*) and put the results in the context of today. Put the theoretical findings in a practical light. What type of steps and changes are required? Look back at the goal that was initially created and verify that the results are in line with the goal. Or if the goal has changed, identify the reason it changed and align the FVM with the new goal. Lastly, reflect on the process. To learn from, but also to identify anything that might have influenced the process or steered it towards a certain direction. The method is subjective and qualitative, so certain bias will always be present. This is not a bad thing. But it should be clear what the implications might be.

7.2 WHY FVM

Quantum development is path-oriented and path-driven. This means that various stakeholders are interconnected to realize a future scenario. Together, several stakeholders collectively understand that actions are required that bring them closer to that future. At the same time, this future scenario is not the end goal; it is merely a part of the journey towards progress. But to bring the stakeholders together, the need to find a collective direction to pursue. This starts with a collective scenario, acknowledging the various types of value that are to be created. To realize the scenario, all stakeholders have a role to play, and they should be aware of the role and responsibility of each participant. This is where FVM can help provide structure in creating those insights.

“The main goal is to provide structure amidst uncertainty and chaos”

It aims to prevent the development of a technology for the sake of development. Technologies with a potential high impact need to be evaluated, and the process should be reflected upon. Technologies are created merely to provide value to the individual using them. For themselves, for others, or their environment. But the development of any technology needs to be done with intent. FVM assists in finding that intent and mapping the potential values that can be generated.

The main goal of methods such as these is to provide structure amidst uncertainty and chaos. Based on the circumstances, other methods might be more applicable. With the development of quantum technologies, there are barriers to adoption, uncertain value propositions, and barriers to collaboration. It starts with realizing that these struggles occur and that they impact the development. Individuals, tools, or frameworks can assist in overcoming those struggles. The FVM method could also be seen not only as a method, but as the embodiment of an individual bringing several stakeholders together for meaningful development.

7.3 COMMUNICATION

A big challenge in communication about quantum technologies is the tone. As the research showed, there are many language barriers: a lack of knowledge, a balance between simplification and sticking to the physics, and challenges in finding a common language are among them. Hype is furthermore a challenge when communicating about quantum technologies. When talking about the potential and neglecting the steps that are required to realize this potential, it quickly sounds like a technology that is destined to change humanity forever. At the same time, when just sticking to the cold hard facts, it might push people away. This requires a balance between creating anticipation and sticking to realism. Similarly, quantum technology and its applications can sound like science fiction, only adding to the potential hype or making it unbelievable. When communicating about quantum technologies, it should be grounded in normative reasoning. Normalizing the technology steers away from potential misconceptions and speculation.

The target audience influences the tone of communication. Creating an understanding of the level of knowledge they possess about quantum, and based on the goal change what level of understanding about quantum phenomena is required. As the research showed, there is no need to have a full comprehension of the inner workings of quantum technologies to think about and deal with them. When explaining the technology, it is important to explain enough so that people understand it and can envision how it works. Yet this is a challenging process, finding the right tone and level of comprehension for each audience.

“This requires a balance between creating anticipation and sticking to realism.”

7.4 SCENARIOS

7.4.1 INTRODUCTION TO SCENARIOS

The creating of the scenarios is the first step in Future Value Mapping. It consists of generating ideas, creating the scenario, and analyzing the value, which is creation through the scenario. These scenarios, also known as vision concepts, as defined by Simonse [116], are created to support an organization's strategic decision on future innovation directions [117]. When making the comparison to product development, scenarios are not intended to showcase a product that will be found on the shelf or to provide demonstration prototypes [116]. The main aim of the vision concepts or scenarios is to provide a clear image of how a future scenario could look. When combined with roadmapping, they communicate potential values and support strategic decision-making. As Simonse puts it: *"vision concepts have a strategic purpose and are specifically created to support a company's strategic decision-making on future innovation directions"* [116].

Scenario characteristics

Strong scenarios are characterized by four distinguished properties: clarity, value drivers, an artifact, and magnetism [116–120]. The clarity is sought after using normative language. By focusing on clear and concise communication, choosing a language that is understandable by the target audience, the scenarios that are created provide a clear overview. Active efforts have been made to avoid communicating in a science-fiction manner to mitigate potential hype. The desired result when reading the scenarios is for the audience to get an understanding of what it is and how it works, while striking a balance between diving deeply into a topic and keeping it superficial. The value drivers are the main aim of the scenario. Through a value analysis, the desired values are identified and highlighted. It seeks to provide insight into why a scenario should be pursued. As mentioned earlier in this report, visualizations play an important role in conveying a message. The visualizations act as artifacts in portraying different underlying values. They are capable of conveying messages that words are too literal for. Lastly magnetism. The scenarios should create desirability and attractiveness. The aim is to inspire stakeholders to pursue the scenario because of the value it can bring. At the same time, it should be attractive to all stakeholders playing a role in the development, as it cannot be realized in isolation. Stakeholders should have a feeling of passion and desire to strive towards the scenario.

"According to research, strong visions have four distinguished properties of clarity, value drivers, artifact and magnetism." - Simonse

Value creation

As Taylor (2017) described it, the definition of innovation is *"the creative process whereby new or improved ideas are successfully developed and applied to produce outcomes that are practical and of value"* [29]. The goal, therefore, is to apply it to produce practical and valuable outcomes. It should be utilized to create value. When looking at future scenarios, the main aim of the technology is to provide value for different stakeholders. As discussed previously, the type of value can differ based on the stakeholder. These differences in desired value could lead to a slower development, but also have the potential to create more inclusive and sustainable technology, in line with *'Brede welvaart'*. For inclusivity, it is vital to understand the different values that it can create. Furthermore, as indicated by the literature [79,90] and the interviews, having that common goal is seen as one of the main drivers of collaboration. Understanding the aspired values, how it impacts each stakeholder, and creating insight into 'why' the stakeholder should develop the technology helps with decision-making today. That is why value creation is at the center of the scenarios.

7.4.2 SCENARIO CREATION

Orientation

The literature review and qualitative study provide a solid foundation of understanding. The barriers identified (*technological, organizational, knowledge-based, and environmental*) all affect the adoption and development of quantum technologies. The potential is clear, for example, in national security or healthcare, but realizing this potential requires collaboration.

Several key stakeholders were identified and analyzed: governments and public institutions (including policy makers), academics and universities, investors and funders, quantum startups, industry partners and suppliers, and the general public. Stakeholders often pursue diverging goals; governments may seek national security and economic competitiveness, while academia prioritizes scientific progress. Or, private organizations may pursue financial returns, while governments and the general public aim for societal well-being. Different stakeholders have different levels of participation. The role of the government is particularly important.

The scope is set to the EU, with the Netherlands as the specific case. The model will be created for non-experts engaging in QT development, such as designers, philosophers, policy makers, and ecosystem developers. This means that the language should be professional, while avoiding quantum-specific jargon. The scenario will be placed in a context where national rollout is realized. The method aims to bring the different stakeholders together and provide a common tool to discuss, but the underlying goal is to stimulate collaboration to advance quantum technology development through a value-driven approach.

Scenarios

Several steps were undertaken to derive the scenarios, following steps 2A–2C of the FVM method. Initially, a list of more than 200 potential applications was compiled. These were based on previous work done by QDNL in mapping various applications [121] and enriched by desk research. This list of applications was sorted based on technology area (computing, communication, or sensing) and category (e.g., cybersecurity, energy, healthcare, agriculture, ...). Several potential

applications were identified as slight variations of the same application; these were removed or combined. The list was first reduced to 8 scenarios, after which 2 scenarios were selected using a Harris Profile-like structure with the criteria explained below. The results can be found in the appendix. Personalized medicine enabled by quantum computing and secure communication enabled by Quantum Key Distribution (QKD) were selected as the most applicable. Several criteria were considered in choosing these scenarios. Given the normative nature of the scenarios, there needed to be a level of proof that the scenarios were likely to emerge (1). As for QKD, a participant indicated: “... I’m sure there will be a QKD network in the Netherlands ... we’re building it right now.” (Participant 11). Next to that, the pilot project in the Port of Rotterdam showed the feasibility of QKD [95]. As for personalized medicine, literature shows that several proof-of-concept studies show the potential of quantum computing [122]. This application is somewhat further away, but still highly likely to occur. Additionally, quantum technologies should provide a clear advantage over other technologies (2). Major steps are set to be taken in realizing personalized medicine through the development of AI, but quantum technologies will be able to reshape medicine [123]. QKD leverages quantum phenomena to ensure secure encryption. Given the impact quantum computing might have on RSA encryption, the influence of quantum technologies on secure communications is evident [48,124]. Furthermore, criteria were selected based on their respective horizons: short-, medium-, and long-term (3). QKD will be realized in the relatively short term, whereas personalized medicine is more long-term. Different fields of application (4) were important too. The scenarios needed to have a decent level of specificity (5), not being too specific, but also not too broad. This was categorized by ensuring that potential value was realized for several stakeholders (5A), that the level of impact was high (5B), and that the application area was concrete and clear (5C).

After the scenarios were selected, further research was conducted, and the scenarios were developed. Each scenario includes a description, a brief explanation of how it works, and an artifact. For these scenarios, an initial value analysis was carried out for all active stakeholders.

7.5 BACKCASTING

7.5.1 INTRODUCTION TO BACKCASTING

Backcasting is the process of looking back from the future. It has been defined as *“generating a desirable future, and then looking backwards from that future to the present in order to strategize and to plan how it could be achieved.”* [125]. Several ways of backcasting have been created and studied, each altering some characteristics of the process based on the use case [126–130]. Differences lie among others in path-oriented or goal-oriented backcasting, the process that is followed, the level of participation, and the result that is generated, as nicely explained by Kishita, Höjer, and Quist [130]. The principle of backcasting as done while developing the Future Value Map, is based on the principles of Quist [129].

“the focus is on the steps required to realize it, rather than on realizing the scenario itself.”

All methodologies start with a scenario, mostly normative, and work backwards, answering questions about which steps *need* to be taken to realize the scenario. As explained earlier, this is also the root of the scenarios created for FVM. The development of quantum and the realization of the scenario is path-based. While the scenarios provide a clear endpoint, the focus is on the steps required to realize it, rather than on realizing the scenario itself.

When backcasting, there should be a clear distinction between what is within the scope and what is excluded. This applies to standard elements such as geographical scope, domain, and objective, but at a deeper level, choices are required. Not all aspects of development can be covered. Certain variables are assumed to be more constant, whereas others are less constant. In the case of applications of quantum technologies, several big steps in qubit development are required before quantum computing can realize any substantial value. This requires constant efforts from startups and academics to mature the technology. IBM has been able to double its Quantum Volume every year between 2018 and 2022 [131]. But, in recent years, their strategy

has shifted from volume to qubit scaling and error correction. The industry has recognized their roadmap as one of the standard technology roadmaps [132]. This development trajectory is assumed to be more constant. As the main aim of the backcasting process is to identify the incentives required to realize a scenario, these incentives are treated as actions that must occur. Another continuous, and therefore more constant, action that needs to be taken is ethical reflection and discussions. This is required throughout the whole process, making it not a separate initiative. For each use of the backcasting method, other variables can be deemed as more or less constant.

The backcasting steps are created by following a structure of three main questions. 1) What steps need to be taken to realize this scenario?, 2) How can these steps be realized? and 3) Who needs to act on the steps? Answering these questions provides a structured list of incentives to be taken. These incentives should be followed by providing an outcome of the incentive. Isolated incentives without outcomes provide less insight, especially since one incentive’s outcome might kickstart another.

The acquisition of information yields the richest results if done through participation. Using external input from several stakeholders through interviews or workshops, the initially created backcasting steps can be expanded. Several approaches can be taken to include people in the process of backcasting. When organizing a workshop, participants can answer the What-How-Who questions. The results can be used in addition to what was already found.

The results should be placed on a roadmap, visualizing the path that has to be taken to realize a scenario. It is good to highlight the distinction between the constant variables and the incentives. Using the Three Horizons model as inspiration [133], the roadmap should be divided into three horizons. Given the uncertainty of development and the binary character of deadlines in time, it is better to use a different guideline. Types of collaborations mark progress throughout development, starting with pilot projects and trials and ending with a mature commercial market.

'Multi-stakeholder consortium is realized' and 'Commercial network is realized' are collaboration-driven milestones that divide the horizons.

"The roadmap should be treated as a living document, allowing for change and adaptation as time goes on."

As the roadmap is merely a tool, it is about how it is used to convey a message or spark a discussion. The roadmap is not exhaustive; many other steps could be taken to realize this future scenario. The main aim of the roadmap is to offer a strategic tool for decision-making. The roadmap should furthermore be treated as a living document, allowing for change and adaptation as time goes on. If certain steps are realized, it is good to mark the incentives as completed. Taking an iterative approach and updating the roadmap as new insights are generated or time goes by adds to the usefulness of the roadmap as a strategic tool.

7.5.2 BACKCASTING PROCESS

To identify what needs to happen for personalized medicine through quantum technologies to mature and reach its potential, the TOE framework [134,135] is used, which looks at the adoption of innovation at the *technological, organizational, and environmental* levels. Perhaps the most significant steps need to be taken at the technological level. Maturing the technology and ensuring the appropriate hardware are essential. As the TOE framework is designed to examine the implementation of innovation at the level of a firm, the 'Organizational' component of the framework will, in this use case, reflect the organizations that interact with the technology and the actions required within these organizations. For personalized medicine, these will include healthcare providers, biotech and pharmaceutical companies, startups, academics, and other organizations that interact directly with personalized medicine. The environmental level examines the context in which organizations operate, including government regulation, ethical norms, and infrastructure. For secure communication, the organizational component also focuses on core stakeholders. However, given the government's role as a customer, they

are included as well. The stakeholders interacting directly with QKD are startups, the industry comprises infrastructure providers, vendors, and other organizations where QKD makes an entrance, academics, and the government as direct customers. The environmental level looks at the regulation, infrastructure, and the role of the government from a strategic perspective.

Participatory analysis

The initial What-How-Who analysis based on literature research led to a range of steps that were required to realize the scenarios [136–139] & [124,140]. This was complemented by interviews. During several interviews, participants were presented with a scenario and asked which steps were required to realize it. But the main insights were generated during the workshop. Using a template to guide the questions, several participants at QuTech were asked for their thoughts on value creation and what is required to realize the scenarios. A reflection on the workshop can be found in the appendix. The list of what-how-who was expanded and ordered using the TOE framework. This provided the foundation for the roadmaps developed.

Refinement

Based on input received from participants, the scenarios can be refined. As participants provided additional insights into value creation through the scenarios, the value analysis was adjusted accordingly. Chapter 8 contains the final results.

The roadmaps were developed based on input from desk research, interviews, and the workshop. The ideas were plotted across various horizons and structured according to their importance. For the incentives, several outcomes were developed to highlight their interconnectedness. Using an iterative process, several roadmaps were made to highlight various development stories.

The roadmaps are presented in the following chapters.

Adaptive process

Roadmaps risk becoming static documents. As time progresses, roadmaps risk becoming misaligned with reality and outdated. Technological development is not a linear and predictable process; it requires constant reflection and adjustment. Integrating 'pastcasting' and recurring events in addition to backcasting makes the roadmap more adaptive and credible [141,142]. With backcasting, the question is "what should happen?", with pastcasting, one reflects on the past and asks "what has happened, and what does that reveal?". Pastcasting begins at the present and looks back towards the past. In this case, this would occur when time has progressed, and incentives have been implemented, reflecting on the period between the present and the start of the roadmap. This provides insight into how development and incentives actually progressed. What was realized? What diverged from expectations? What new information is available? Answers to these questions help create new roadmaps based on more credible information. Alongside backcasting, it allows decision-makers to assess progress iteratively as it develops, identify additional barriers and drivers, and recognize potential patterns throughout development. As the roadmap spans several stakeholders, pastcasting and reflecting will highlight the interdependencies between stakeholders, allowing developers to improve the roadmap based on those interdependencies.

The actors involved in the development of the roadmaps and the backcasting process should revise the findings periodically. Through regularly scheduled events between stakeholders, for

example, annually, the roadmaps as presented can be adjusted to reflect the newly found information. Turning these moments into structured, predictable occasions will allow stakeholders to take them into account in their planning. Furthermore, the recurring nature of these events will allow the approach to be more iterative, learning from past experiences and improving the quality of results. At these meetings, questions can be asked, such as: Which steps have been achieved and which have not? Why? What occurred differently than expected? What does the difference between expected steps and realized steps tell us about the development? These pastcasting steps provide a foundation to update the roadmap through a new backcasting process: looking back from the scenario to the present.

The integration of pastcasting steps at recurring meetings helps tackle the structural weakness of roadmaps: the linear assumption of realizing a future scenario. Changes in environment, organizations, technology development, funding, regulation, and much more influence the trajectory of a future scenario. The iterative approach allows stakeholders to take these changes into account. It supports the path-oriented development that characterizes quantum technologies. It builds in flexibility while maintaining continuity and purpose.

Figure 8: Workshop template

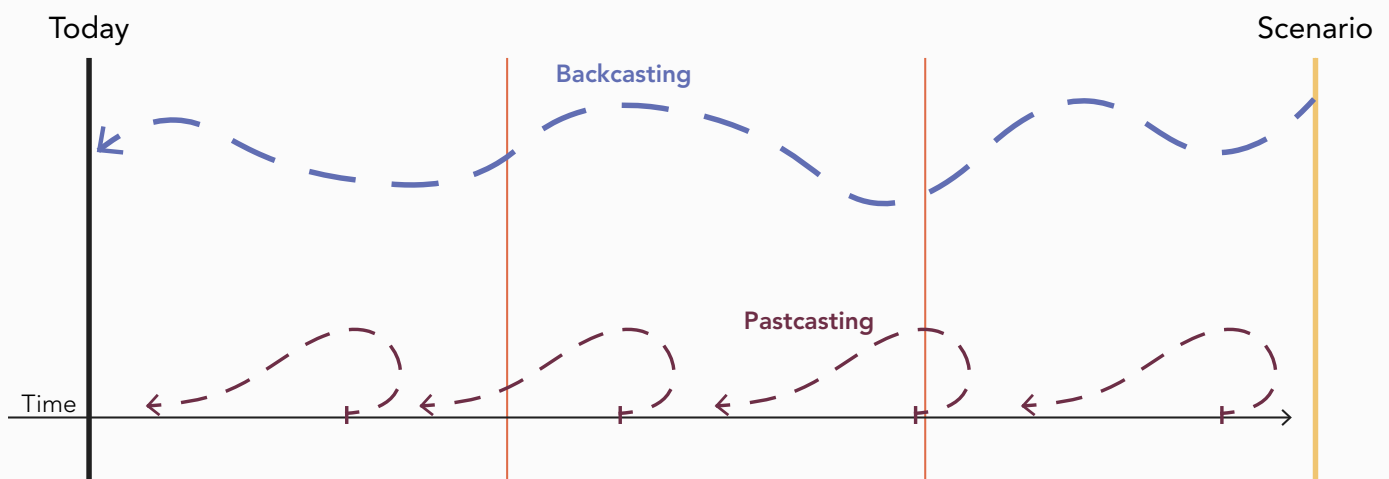




Figure 9: Workshop template

1

Personalized Medicine

<p>Today</p> <p>Horizon Long-term</p> <p>Focus Computing Pattern identification Drug discovery</p> <p>Barriers Technological Financial Knowledge Organizational</p>	<p>What needs to happen for this scenario to become a reality?</p>	<p>Scenario</p>  <p>Personalized medicine rolled out in hospitals throughout the Netherlands. Available for majority of Dutch citizens.</p>
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Secure Communication

<p>Today</p> <p>Horizon Short-term</p> <p>Focus Communication Cybersecurity Vital infrastructure</p> <p>Barriers Technological Financial Knowledge Organizational</p>	<p>What needs to happen for this scenario to become a reality?</p>	<p>Scenario</p>  <p>QKD communication for vital infrastructure is set up through (inter)national network using repeaters and satellites.</p>
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7.6 WHAT-IFS

7.6.1 INTRODUCTION TO WHAT-IFS

To look beyond the scenarios and highlight possible implications of their materialization, what-ifs are a way to guide the thought process. They bring creativity and imagination together to point to concrete possible consequences. Through open-ended questions, researchers and practitioners can construct several realistic scenarios. One example of the use of what-if questions in design is Dyson's vacuum cleaner [143,144]. By asking himself: *"what if I could make a vacuum cleaner without a bag"*, the development of the famous Dyson vacuum cleaners was initiated. However, this method is also applicable to other types of innovation. Asking what-if questions forces people to engage in a predictive mindset. This may lead to several new insights that influence decision-making today.

What-if scenarios may sound speculative and like science fiction. But they serve a clear purpose in creating resilience for the future. As Niistö, former president of Finland, put it: *"True preparedness requires us to be clear-eyed and avoid wishful thinking, and to be able to look at our own vulnerabilities and shortcomings objectively. We need to be willing to reflect on and think through worst-case scenarios, as a basis for our work on preparedness. This is not only about a sense of urgency, but also a sense of agency."* [145]. Thinking about possible consequences, both positive and negative, aids in steering decision-making today. When working towards the realization of a scenario or the development of a technology, one should be aware of the values and risks associated with it. As Kranzberg puts it in his first law: *"Technology is neither good nor bad; nor is it neutral."* [146]. Many technologies can be used to create value, but also to cause harm. Understanding the implications of a technology should inform today's development decisions. The goal of the what-ifs is to help decision-makers today deal with the deep uncertainty of future technologies. By highlighting future values and risks, this provides a perspective on the steps that should be taken during the development and implementation of a technology. For example, by having discussions regarding its ethical implications, or how it can be misused.

The what-ifs consist of a situation sketch, laying the groundwork for the story-based scenarios

that are created. It provides context about how the scenario unfolds, outlining initial implications and consequences. Written in a normative style, it aims to steer away from a science-fiction feeling. The situation sketches should be based on real applications and use cases. The most powerful what-ifs are those with a neutral situation sketch. Based on this neutral situation sketch, optimistic and pessimistic scenarios can be sketched through stories. Since any individual engaging with a what-if scenario brings their own perspective, stakeholder stories shed light on how it could impact multiple stakeholders. The aim is for the perspective of the individual engaging with the stories to be personal, eliciting a different reaction from each reader. To compartmentalize values and risks, they are placed in a value matrix. Many more values and risks could be associated with a what-if, but having an initial overview is powerful. To connect the what-if to strategic decision-making today, one should ask the question: *"What should we do today?"* This grounds the what-if and creates a sense of urgency.

7.6.2 WHAT-IFS PROCESS

The initial what-if ideas were created while exploring potential scenarios. After the scenarios were created, several more what-ifs were thought of, leading to 5 suitable candidates per scenario. This was brought down to the 3 and 2 most applicable, with the associated risks as identified when analyzing the scenarios and roadmap. The impact of accurately predicting your health, specifically targeting individuals based on their biomarkers and the editing of genetic material, was seen as the most applicable for personalized medicine. For secure communications, the biggest consequences lie in a lack of law enforcement intelligence and the human factor in using the technology. The workshop aided in choosing the what-ifs, as the majority of them were mentioned throughout the brainstorming process of value creation. Based on these 5 situations, the full what-if sentences were formed, the stories created, and a visualization made.

The what-ifs are presented in the following chapters.

8. PERSONALIZED MEDICINE

8.1 SCENARIO

Horizon: long-term

Description

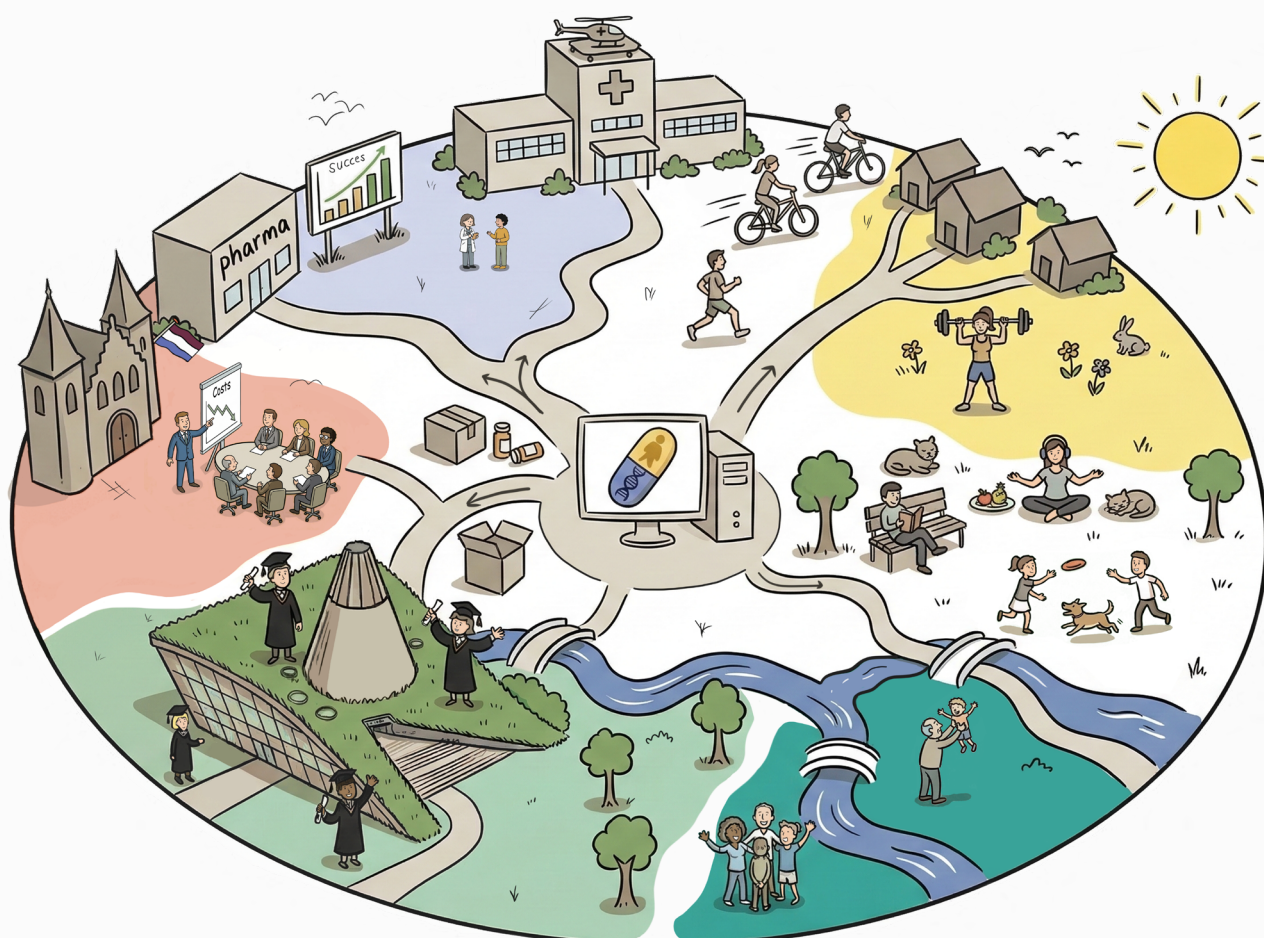
Personalized medicine uses quantum computing and quantum sensors to better understand the complexity of human biological systems [147]. This enables better treatment and more tailored healthcare by going beyond standard medical interventions. Enhancing machine learning with quantum phenomena leads to many applications in the health domain, such as understanding an individual better based on their data to improve diagnostics, individual medicine development, and predict molecular interactions for drug design [122]. The scale and complexity of this data set go beyond the capabilities of classical computers. An emerging concept is the creation of biological-digital twins, simulating entire biological systems of patients.

How it works

Quantum-enabled algorithms utilize quantum phenomena such as superposition and interference to search through high-dimensional data like EHRs (Electronic Health Records) and biological information of patients to link their genes, symptoms, lifestyle, and imaging data to uncover patterns. These patterns enable earlier identification of anomalies and help prevent illness. Quantum computing can furthermore simulate complex molecular interactions to understand the protein-drug interaction, which can help in creating patient-tailored drug choices and doses.

Quantum sensing also plays a big role in personalized healthcare. Quantum-enhanced sensors provide sensitivity and resolution that is unprecedented [148]. For example, detecting weak magnetic fields in the brain or heart, or detecting and labeling individual cells. As of 2026, multiple startups developing quantum sensors for healthcare are focusing on commercializing their technology, such as QT Sense in Groningen.

Figure 10: Personalized Medicine scenario



Value creation

Personalized medicine creates substantial value for many different parties. The technology has transformed the delivery of healthcare. The prediction capabilities have significantly improved, enabling the detection of anomalies that were previously undetectable. The ability and therefore focus have shifted from curing more towards prevention of sickness.

The roles of various stakeholders have also changed in recent years due to this technology. As healthcare increasingly relies on data, the role of hospitals and doctors has shifted from curing illnesses to that of institutions and professionals that improve patients' overall health.

The types of medication and how they are created have also changed due to quantum technologies. Medication creation is done more often through simulation rather than clinical trials, which tend to take a long time. The ability to simulate protein interactions leads to faster and cheaper drug development and has a higher chance of success.



Figure 11: Healthy lifestyle

Stakeholders

For the **government and public institutions**, whose main aims are to create long-term public good, public welfare, and mitigate risks during development, personalized medicine brings significant value. Most directly, it will improve the health of the population on a large scale, leading to a happier population and lower health costs. In the short-term, investments are required, but those will be recovered over time as fewer people require care due to the emphasis on prevention.

Personalized medicine also provides valuable information. Insight into environmental and lifestyle health dynamics, anticipated diseases, and potential pandemics allows for better prevention strategies and more informed budgeting.

For **academics and universities**, a whole new world of science is opened up. Discoveries in genomics, biomarker research, and diagnostics lead to a significantly better understanding of human biology. New opportunities arise to educate a workforce in quantum health care and to help shape the healthcare of the future. **Investors and funders** find new investment opportunities in a substantial and ever-growing market. Investments in startups developing technology for personalized medicine create opportunities for the growing emphasis on ESG alignment. These **startups** will find many new niche business opportunities, including the creation of new technologies for hospitals, wearable health sensors, or data analysis systems. Together with the **industry, partners, and suppliers**, personalized insurance models based on personal health data can be brought to market. The industry, which consists of hospitals, pharmaceuticals, and medical device manufacturers, finds value in new revenue streams. Lower costs and shorter development times, combined with higher clinical success rates in drug design, make healthcare development more cost-effective. This allows hospitals to offer care that is both cheaper and of higher quality, tailored to the individual patient. The **general public** stands to gain the most from personalized healthcare. The quality of care they receive improves, which in turn increases the quality of life. More effective medication raises the life expectancy of many patients, and better insight into potential future diseases shifts the focus from reactive treatment to prevention. The shift from reactionary care to preventive care will reduce costs while also increasing the feeling of control people experience.

“The general public stands to gain the most from personalized healthcare”

SDGs

There are various SDGs which personalized medicine contributes to, below are the two most applicable.



SDG 3: Good Health and Well-being

The 3rd SDG listens to the following title: *'Ensure healthy lives and promote well-being for all at all ages'* [149]. Personalized medicine improves individuals' health and well-being and can do so across all ages. The third SDG comprises several targets. When looking at the Netherlands specifically, as of 2026, the majority of targets in the 3rd SDG have been successfully achieved [150]. But the probability of dying from any of CVD, cancer, diabetes, or CRD between the ages of 30 and 70 was 9.9% in 2021, above the target of 9.3% [151]. But regardless of the aimed target, you could argue that any individual dying because of noncommunicable disease (NCDs) is one too many. Personalized medicine helps in the detection and prevention of diseases such as cardiovascular disease, cancer, and diabetes. It furthermore helps with early warning, risk reduction, and management of national and global health risks (target 3.d) by earlier identification of diseases. As noted previously, personalized medicine can lower the costs of drug and vaccine development, thereby aiding target 3.8.



SDG 10: Reduced Inequalities

The 10th SDG listens to the following title: *'Reduce inequality within and among countries'* [152]. Most modern-based medicine is based on clinical trials, which historically lack diversity [153,154]. This can negatively impact underrepresented groups. Quantum computers can process an individual's data, ensuring that medicine is inclusive and contributing to Target 10.3. For rare diseases, personalized medicine can help reduce inequalities. Diseases that are not economically feasible to cure due to their rarity become less expensive through quantum simulation. The focus on prevention, especially when done at low costs, decreases the financial strain that lower-income groups, which currently experience higher absolute and relative health-related costs [155].

What are the risks?

To ensure that Personalized Medicine realizes the value it has the potential to do, there are a few risks that need to be taken into account. Firstly, the improvement of the health of individuals will also lead to an aging population. This can lead to overpopulation and create financial strains. Governments are required to look at measures to limit the implications of a population that lives longer. For individuals, living longer is great, especially if done in good health. But a downside of knowing exactly how your health is progressing and having an accurate prediction of what health implications you might have in the years to come is a sense of doom. Is it nice to know what the future holds?

All the medical information of individuals is stored in the cloud. This must be done securely to ensure the privacy of the patients. The more complete the information that is collected, the more interesting it is for hostile actors to get their hands on, especially if the technology reaches the level of biological-digital twins. This could be used for identity theft, blackmail, or sold to advertising companies for better-targeted advertisements. Proper data security mechanisms should be put in place. This goes for the storage of the information, but also for the communication lines.

Emerging technologies often come with high costs, which could lead to inequality in the accessibility of the technology. Personalized medicine could have high initial costs, allowing only elite hospitals, rich individuals, or rich countries to acquire access. This might lead to more (global) inequality. Countries and organizations should collaborate to ensure equal access to the technology.

The boundaries of medical ethics might be pushed to new levels. As the technology develops, so will the possibilities. History has shown that technology is a catalyst for medical possibilities, and personalized medicine is no different. Society, together with experts, should ask themselves which boundaries we are willing to push and where we draw the line. Strict regulation is required to prevent misuse of the technology. The potential for value creation is high, but different stakeholders should join forces to ensure that the development and implementation are done meaningfully.

8.2 BACKCASTING

General roadmap

Personalized medicine has a long way to go to realize full integration in the Dutch healthcare system. Currently, personalized medicine is in the pre-collaboration phase, where initial trials are set up for validation. This requires several stakeholders to interact. Academics play an important role in creating awareness and educating people. Hospitals, pharmaceuticals, and other healthcare providers that interact with the technology need to start building capabilities for its implementation. The government is required to start by providing clarity and creating a National Quantum Health strategy. This public development roadmap shows intent and incentives for other actors to stimulate development.

Several enablers and barriers for the development of personalized medicine were recognized. A mature and reliable infrastructure needs to be created to share confidential information. High security of this data is essential for personalized medicine to succeed. Medical regulation often lags behind the development of the technology. Improper regulation can slow the development, while proper regulation can provide a boost to the development and adoption of personalized medicine. There are several funding mechanisms required to stimulate the development. Interoperability and standardization increase the implementation of the technology on a wider scale, just like training and workforce development. Proper understanding, from a technical and non-technical perspective, is required for the implementation to succeed. Lastly, there are several ethical dilemmas associated with personalized medicine that need to be resolved. This requires collaboration between various stakeholders.

Different incentives and outcomes are linked throughout the horizons. Some directly influence the achievement of the milestones, while others are mainly linked to actions further down the road. Some initiatives are standalone, but are required to be carried out.

As mentioned previously, the content of the roadmap is the result of the desk research, interviews, and workshops. It is intended to serve as a tool for strategic decision-making. Many other steps might be required to fully realize personalized medicine.

Personalized Medicine

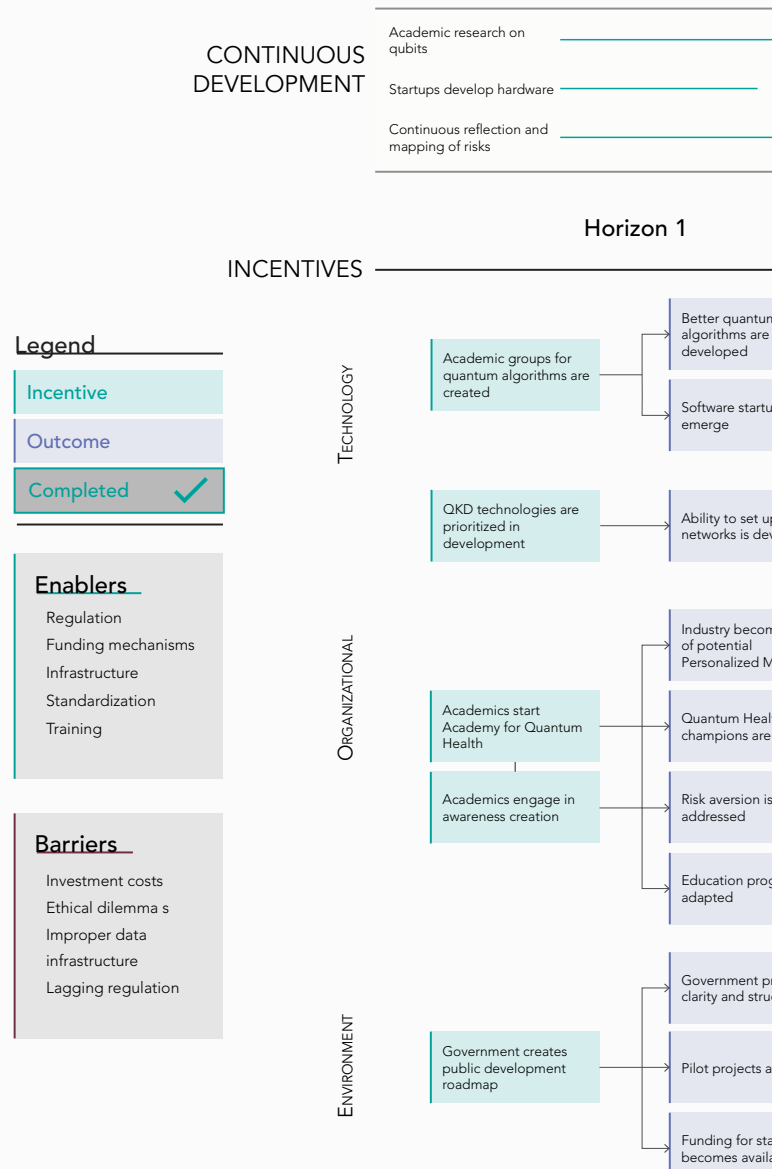
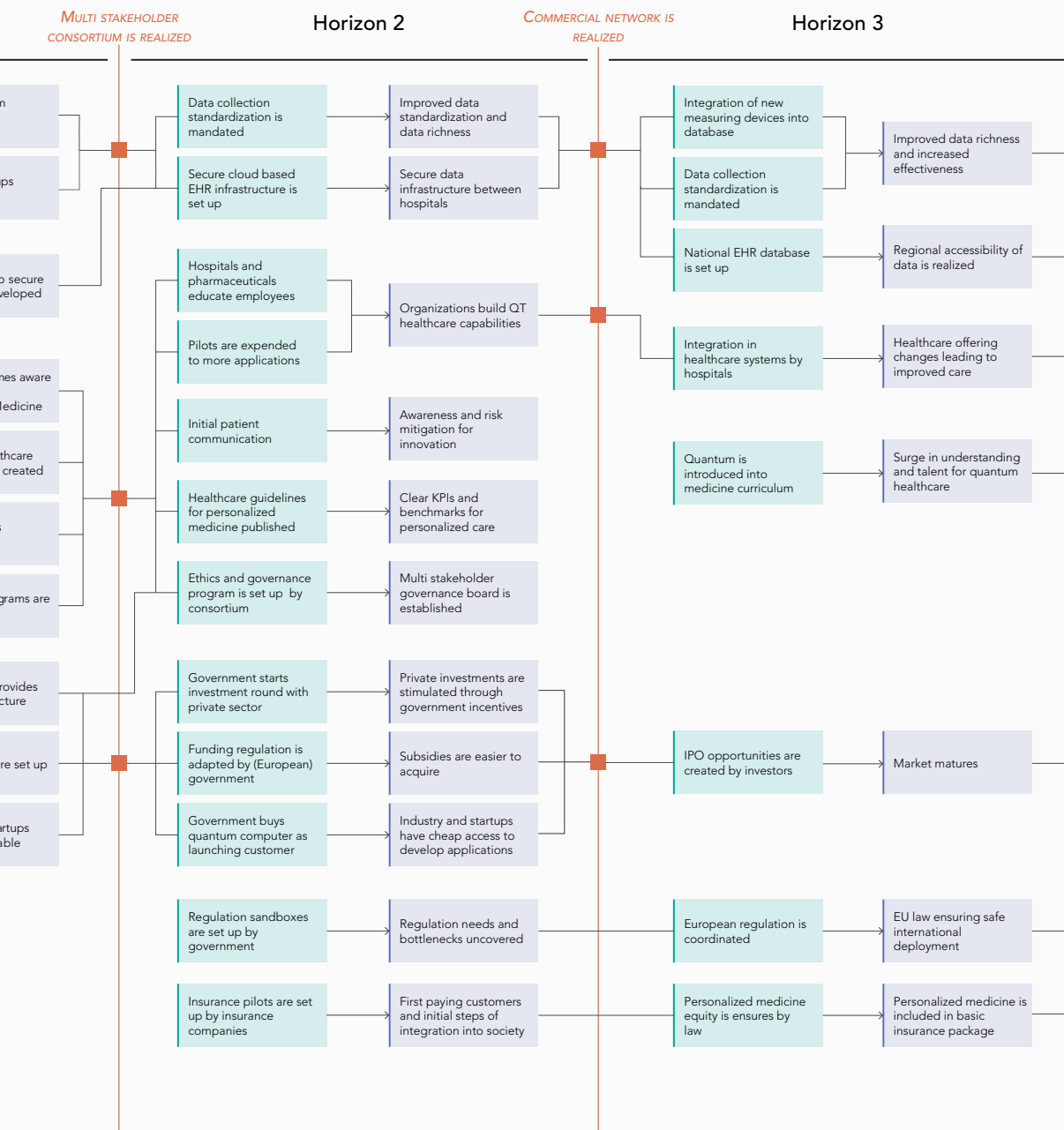
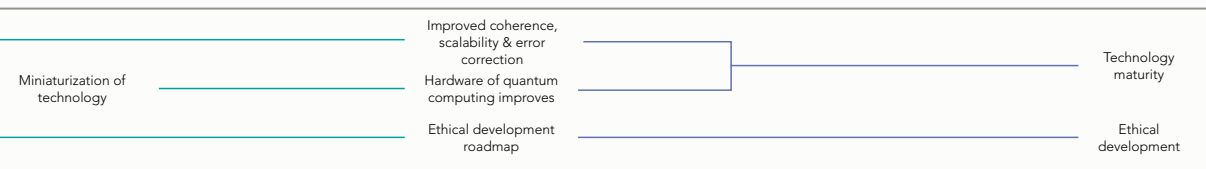


Figure 12: Roadmap Personalized Medicine 1



SCENARIO

Personalized medicine

Personalized medicine through quantum technologies is rolled out throughout various hospitals in the Netherlands

Improved health

Quality of life

Lower costs

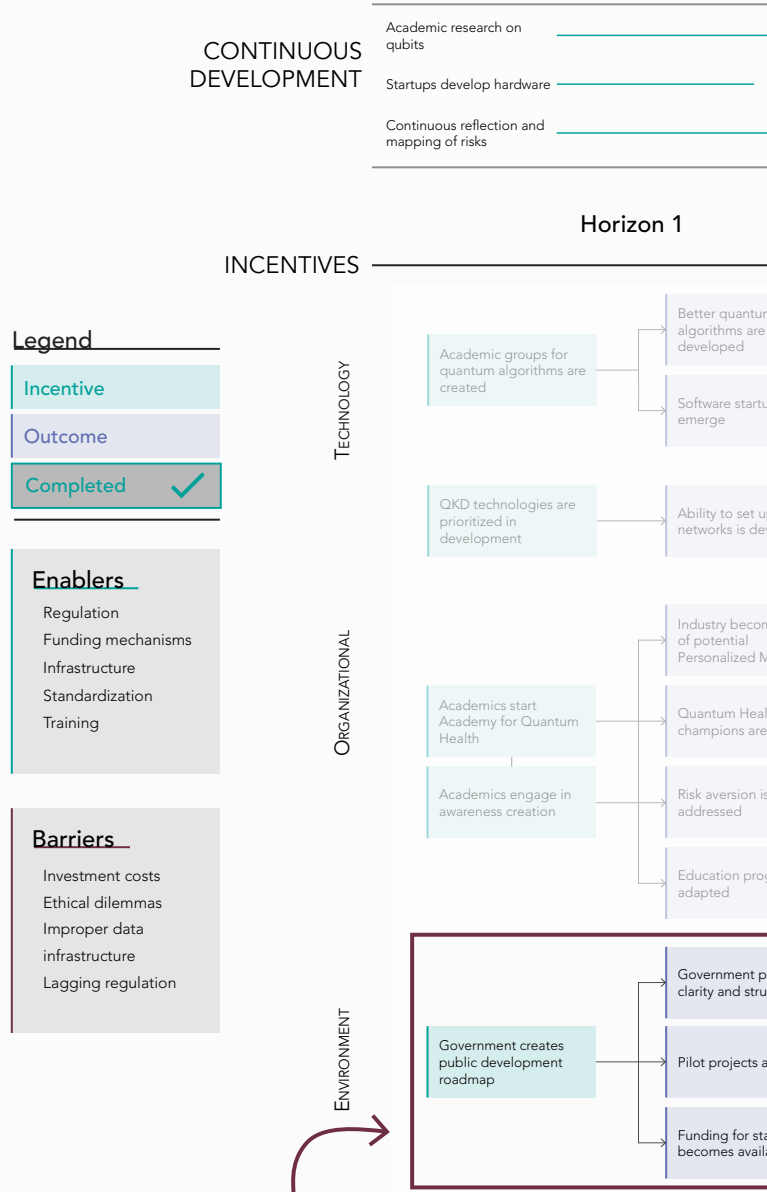
Knowledge

Clinical success

Roadmap 1

The government might play the most important role in the initial phase of development and commercialization of personalized medicine. It should enable development by providing clarity, direction, and support. This starts with a national agenda and roadmap highlighting the importance of personalized medicine. In turn, this will lead to more actors engaging in the development, pilot projects being set up, and more funding being available for startups. It is the essential first step in attracting private investors to help fund the development of personalized medicine. Public organizations should take the lead in organizing consortia with multiple stakeholders to show the potential and take steps towards the valorization of the technology. After initial pilots and consortia between various stakeholders are set up, governmental organizations should mitigate obstacles on the road towards scaling. One example is the purchase of a quantum computer by acting as the launching customer. This would allow startups, researchers, and other developers to develop applications, bringing valorization closer. Given the high investment costs and public impact of hospitals, the government is the right stakeholder to act as the launching customer. At the same time, amidst the ethical discussions, regulations for development and funding should be eased to promote and encourage development. As the technology and startups grow, the government has a role to play in maturing the market. Together with investors, the government should facilitate IPO or exit opportunities to create a truly integrated market.

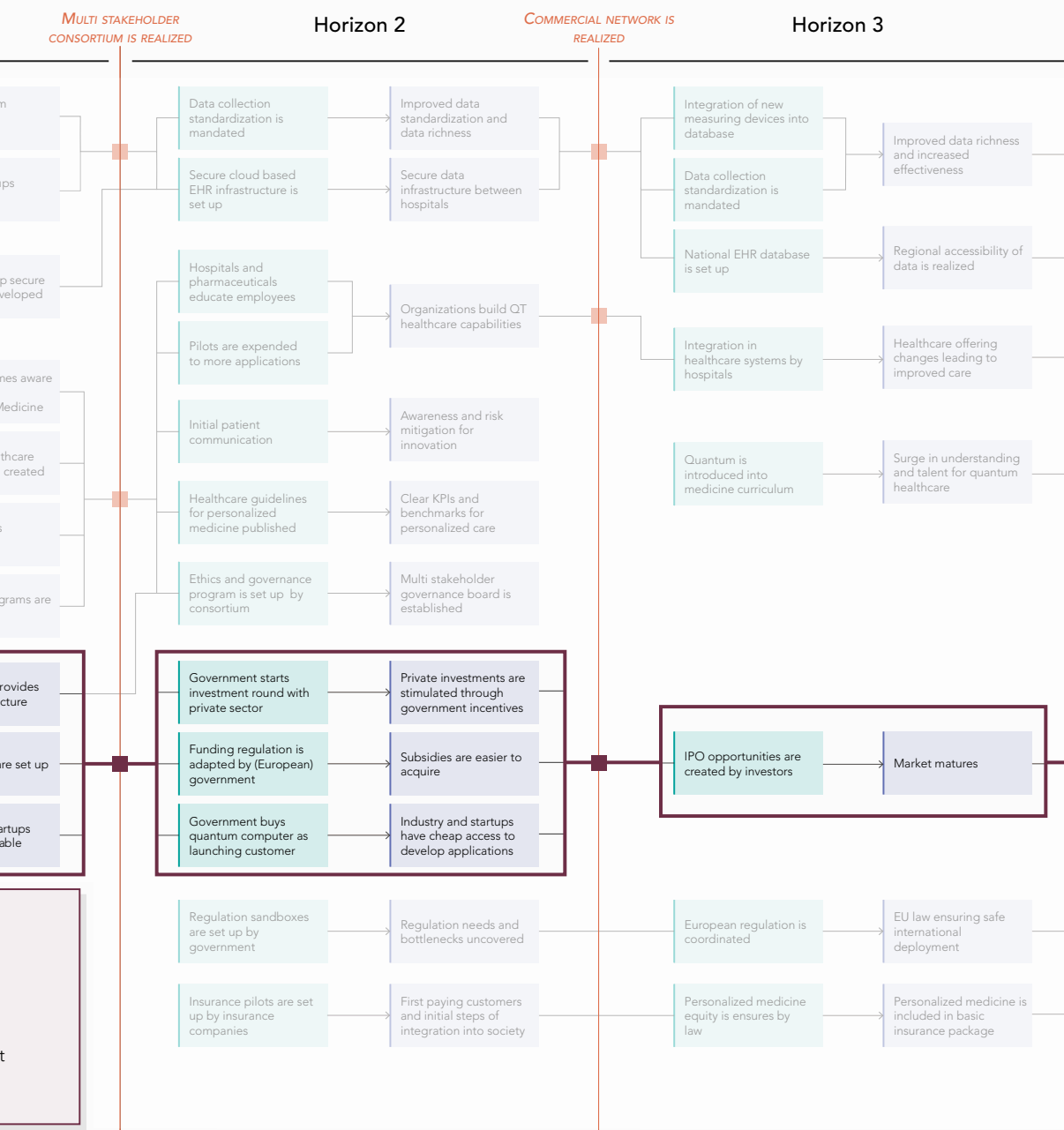
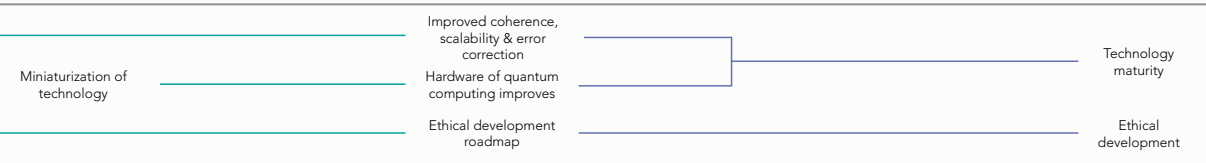
Personalized Medicine - 1



GOVERNMENTAL STEPS FOR COMMERCIALIZATION

Besides the equally important ethical and regulatory steps, the government plays a vital role in realizing commercially available personalized medicine. Because of the lack of privately available funding and the high costs associated with developing medical technology, the government should stimulate funding initiatives. By acting as launching customer after some pilot projects have been set up, the government can give the entire ecosystem a boost.

Figure 13: Roadmap Personalized Medicine 2



SCENARIO

Personalized medicine

Personalized medicine through quantum technologies is rolled out throughout various hospitals in the Netherlands

Improved health
Quality of life
Lower costs
Knowledge
Clinical success

Roadmap 2

Academics have a significant part to play in the creation of knowledge among stakeholders. Creating awareness starts with academics showing the potential of the technology to actors required to play a role in its development. It also involves educating talent working at various hospitals, pharmaceutical companies, and other organizations involved in the development. Showing the potential is vital for stakeholders to engage and for Quantum Healthcare champions to emerge. There is a need for individuals who are intrinsically motivated to implement, adopt, or develop the technology given its potential value. Given the risks associated with medical technologies, the awareness creation must be done very carefully. Careful collaborations between universities and hospitals should be established to learn from pilot projects. Together, they can build capabilities for hospitals to transition towards valorization and systemic integration into the healthcare system. As the technology shifts from the pilot phase to full integration, the need for talent will only increase. Over time, more quantum healthcare-related courses should be integrated into the medical curriculum to build a solid base of knowledge among healthcare professionals.

Personalized Medicine - 2

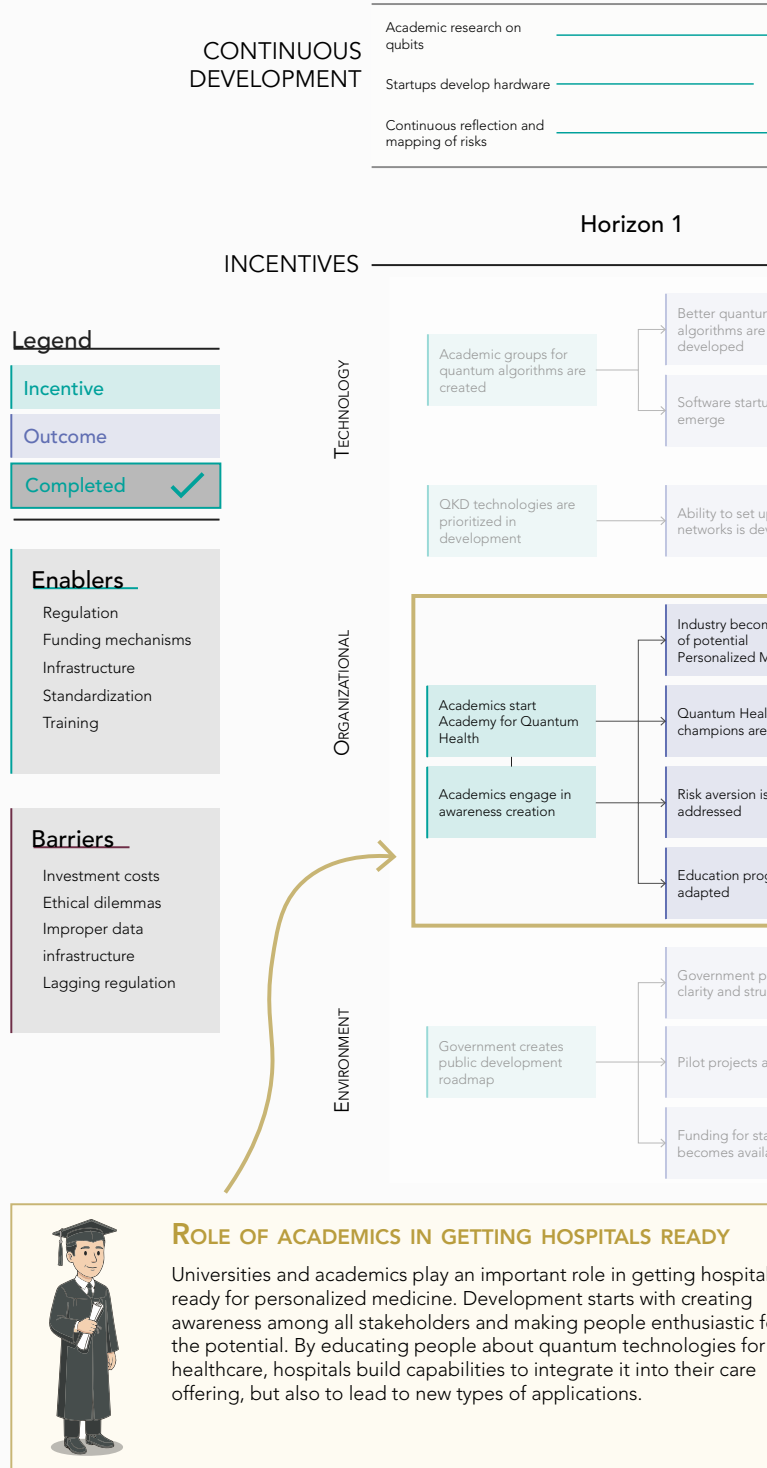
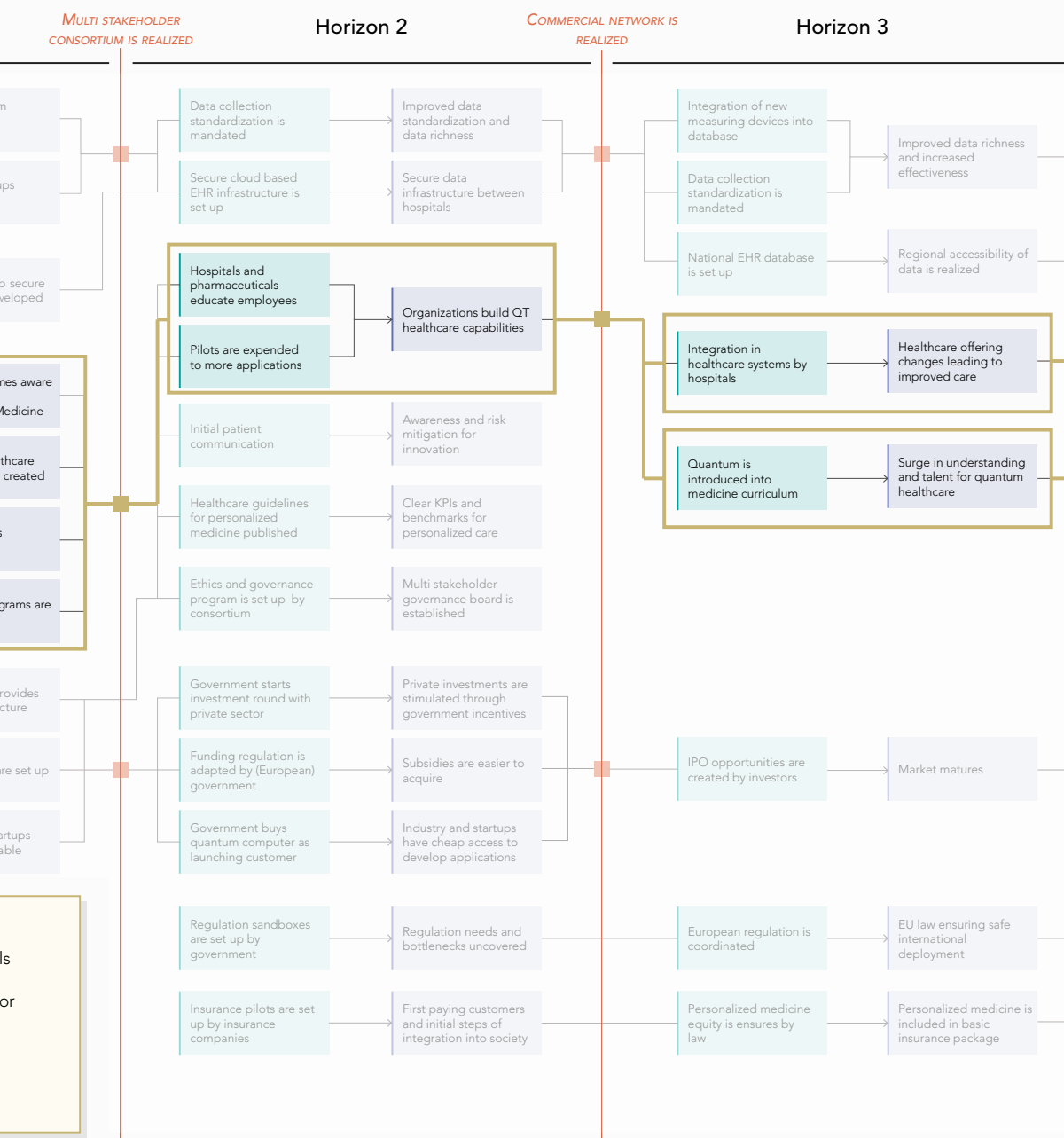
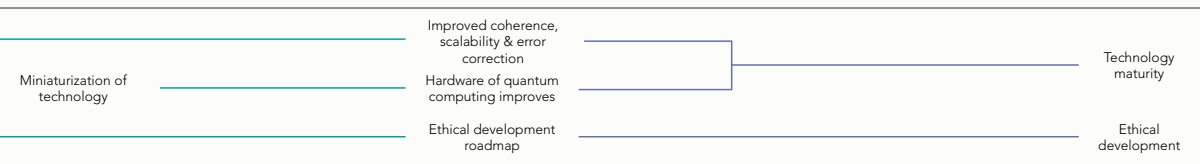


Figure 14: Roadmap Personalized Medicine 3



SCENARIO

Personalized medicine

Personalized medicine through quantum technologies is rolled out throughout various hospitals in the Netherlands

Improved health

Quality of life

Lower costs

Knowledge

Clinical success

8.3 WHAT-IFS - PERSONALIZED MEDICINE

8.3.1 HEALTH TRAJECTORY

What if your health trajectory can be predicted with 98% accuracy?

Situation sketch

Personalized medicine relies on large amounts of rich data to generate accurate predictions about potential diseases, with an accuracy of 98%. These predictions are generated in hospitals during a trajectory consultation and lead to Health Trajectory Predictions (HTPs). An HTP may include, for example, an 82% likelihood of developing type 2 diabetes within 15 years, and a 32% probability of developing heart problems before the age of 60. Key parameters highlighted in the reports include sensory data, genetics, lifestyle factors, and environmental factors. Based on HTPs, the medical files of patients are updated. Under certain conditions, parts of these reports may be shared with external organizations. For example, employers may receive information if stress is identified as a health risk. Insurance companies might be interested in the information to offer discounts in return for receiving parts of the HTPs. But strict EU data protection regulations safeguard the medical privacy of its citizens. Which organizations, if any at all, should get access to such information will be a big debate.

Stakeholder stories

Citizen – Mark – 33

Mark works in construction, just like his dad and granddad before him. Both of them developed heart problems in their fifties, something which Mark has always secretly worried about but never had a real reason to address. When the HTPs were introduced, he signed up for a consultation. The results showed an elevated risk of cardiovascular disease. For the first time, the risk was made concrete instead of hanging over him like a distant, dark cloud. The doctor recommended a prevention program. Through coaching on nutrition, plans to help him adjust his work environment, and a discount to go to the gym, the risk would decrease. He did discover a downside, though. His medical record would get updated to 'medium risk for CVDs'. He is in the middle of acquiring a mortgage for his house, and the broker would see the update in his personal file. He is in doubt whether he should join the program; his long-term health is very important to him, but should a prediction of the future shape his life today?

Politician – Elina – 56

Elina is a politician for a center-left party, with medical ethical dossiers and economic affairs in her portfolio. For years, she watched policymakers make decisions about public health based on incomplete statistics and biased information. The introduction of HTPs created a great opportunity. No more reliance on outdated, biased statistics, but access to real-life data. She believed that having insight into the health projections of people across the Netherlands would improve policy decision-making. For example, what is the impact of a factory located 1km from a town? But it also opens the door for personalized medical taxes, requiring people with higher expected medical costs to contribute more than those with lower expected costs. Elina is helping draw up a proposal to give parliament access to categorized HTP data to support policy-making. Several parties are lobbying for access by insurance companies and other private organizations, while others fear a slippery slope. Who should have access to this kind of information?

Physician – Helena – 49

Helena has been a physician for many years. For most of her career, she advocated for a focus on prevention, but struggled to convince people. She urged policymakers to invest in prevention, but without hard numbers, it was difficult for policymakers to justify the expenses. Helena saw that the majority of her patients did not need to be there if only their conditions were caught earlier. When HTPs were introduced, she was among the first at the hospital in Rotterdam to receive credentials to work with them. Finally, there was a way to quantify the need for prevention. She could encourage her patients to modify their lifestyle based on hard, quantifiable data. Over time, her views shifted somewhat. She noticed that other doctors were beginning to trust the HTPs more than their own professional judgement. Interactions with patients had changed, and care felt less personal. Helena began to wonder if they had gone too far. She still believes in technology, but were they letting mathematical models do too much of the thinking? Providing care is more than a statistical analysis. But how do you convince a society that has become so dependent on technology?

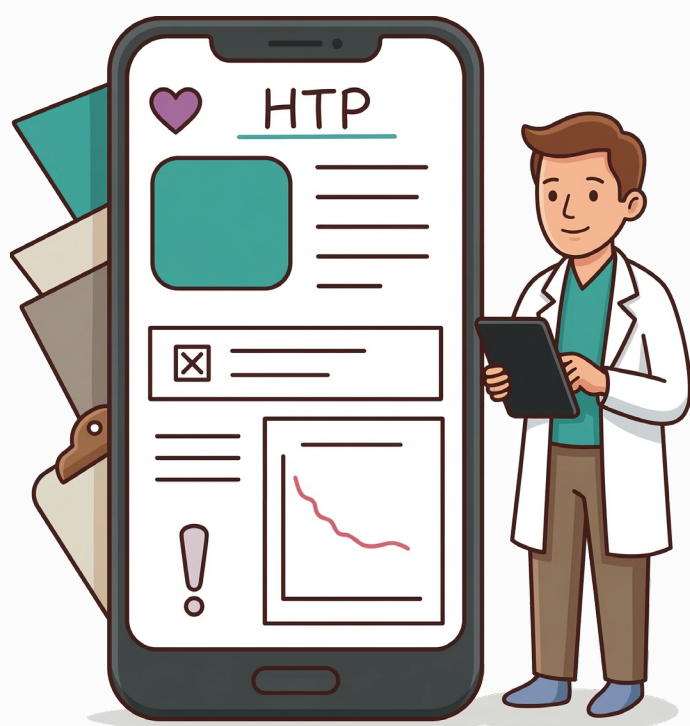


Figure 15: What-if HTP

Value matrix

Potential value	Potential risks
Accurate forecasts of disease burden, better resource allocation, insight for regulations	Privacy of citizens, over-reliance on predictions, discrimination because of data
Better insight into the causes of diseases, better understanding of humans, opportunities for interdisciplinary research	Ethical challenges, pressure to commercialize
New markets for new applications, insurance policies, new services.	Dependency on a few private organizations if realized through private organizations
Prevention focus, special programs, improved health, clearer information	Risk-scores, privacy, inequality, inequity, living based on predictions

& many more!

What should we do today?

There are many things we can do today if this is the point on the horizon. First and foremost, the initial discussions. For example, regarding who owns medical data and the possible data implications of HTPs. As the amount of data increases and it becomes more valuable, it is important to decide how it should be stored, who should be allowed access, and how it impacts policy-making, all while ensuring that privacy is still held in high regard. In a society that is ever more data-driven, it is a challenge that should be tackled soon. Regulations should be ready at the same time as the technology is developed. Furthermore, the mapping of risks and which parties should be involved in mitigating those risks.

8.3.2 AEROSOLS

What if it were possible to deploy specifically designed aerosols?

Situation sketch

Through the simulation of drug interactions, it is possible to accurately see how certain molecules would interact with each other. Engineered molecules, suspended in gases, can be spread over specific areas. These aerosols can be used to interact with specified targets, to counter, for example, pollutants, pollens, or biological markers. It opens the door to tackling environmental challenges, like air pollution, or spreading treatments during an epidemic over long distances. To illustrate, when a factory harms the health of the citizens living close by, these negative effects can be countered by spreading a dismantling aerosol. Or the health of whole countries can be improved, similarly to Australia, by adding Fluoride to their tap water to improve dental health. At the same time, there are also dangerous applications. Pathogens could be spread over whole cities, targeting a few individuals based on their bio-markers. This is an application of a technology that could be militarized and have huge implications. The potential upside, to improve the quality of life and health of many people without them having to take any action, is high. But the potential risks might be even higher. Proper use of such a technology is crucial.

Stakeholder stories

Citizen – Sarah – 38

Sarah lives with her family near a steel factory in the southern part of the Netherlands. They moved there recently because of the affordable housing and the space, but mainly because her grandparents used to live in the area. The town has been associated with health concerns because of the factory for years. Research has shown that residents have a higher chance of developing cardiovascular diseases and lung diseases. The factory and the city council are considering installing aerosol towers throughout the town. These towers would spread specifically engineered particles, which would neutralize specific pollutants generated by the factory. Because of the potential impact, people in the town are allowed to vote in a small referendum. It would lower the chance of getting heart disease, help with her son's asthma, and improve overall air quality, but the long-term effects are not fully understood. At the same time, she can't help but worry if this artificial solution will not just lead to more polluting factories throughout the country? Is this not just a bandage for a bigger problem?

Security analyst – Jonas – 29

Jonas works for an international organization monitoring compliance with treaties on chemical and biological weapons. Because of his background in Quantum and Health Technologies, he was hired about a year ago to track potential misuse of quantum technologies to develop pathogens and toxic chemicals. Having witnessed synthetically engineered aerosols make their introduction into agriculture, he is increasingly worried about the dual-use potential of this technology. Intelligence reports show that groups have tried to obtain and repurpose the technology, so far without any success. He is convinced that if a group succeeds in acquiring the technology, the consequences could be catastrophic. Pathogens could be developed to attack specific groups or even individuals. A silent but very deadly killer could be created. But Jonas struggles to convince policymakers of the potential risks, as the potential value is also tremendous. "Criminals will never get their hands on a quantum computer" is what he hears time and again. How does he convince people of the risks of a technology when they are blinded by its value?



Figure 16: What-if Aerosols

Public health official – Menno – 51

Menno works at the National Institute for Public Health and the Environment and is responsible for emergency response during disease outbreaks. Having experienced a few pandemics during his time at the institute, Menno and his team are constantly looking for better ways to deal with the delivery of drugs and vaccines once an outbreak begins. Through the advancements in quantum computing, the design of vaccines happens much quicker than it did when he started at the institute a few decades ago. Currently, the biggest bottleneck is getting the vaccines to high-risk neighborhoods and vulnerable groups. Having done a few pilot programs with the delivery of vaccines through aerosols, the technology shows promise to reduce hospitalization rates, especially among vulnerable groups who rarely see a doctor. But would they not be building an infrastructure that also could be used to harm people? And is it ethical to spread vaccines involuntarily across towns to improve the overall public health?

Value matrix

Potential value	Potential risks
Neutralization of pollutants, airborne delivery of protective agents	Weaponization of the technology, over complication
Curing diseases at large scales, curing diseases in remote areas	Ethical challenges, regulatory debates, unequal deployment
New markets for environmental science	High risks if executed poorly, difficulty in attributing mistakes, challenging governance
Better health, higher quality of life	Risk-scores, privacy, inequality, inequity, living based on predictions

& many more!

What should we do today?

Many technologies have a dual-use dimension, meaning they carry a significant potential and serious risks. These technologies require good governance and continuous discussion. Through development and implementation, people should strive to realize as much value as possible while mitigating the risks as much as possible. This requires constant evaluation and the creation of boundaries in which the technology should be developed. It also requires the creation of measurement and benchmarking tools. Key questions include: When is a technology too dangerous to be developed? How close are we to realizing the technology? How will countermeasures work? It requires conversations between people with a technological understanding and people with insights into potential societal implications. These debates, on how to develop a technology with huge potential in a responsible way, should happen today.

8.3.3 EDITING OF GENETIC MATERIAL

What if genetic material could be altered using specially developed drugs?

Situation sketch

Pharmaceutical science has advanced to a point where drugs are able to edit the genes of an individual with high accuracy. Quantum computing advancements have allowed to simulate the reaction of specific DNA sequences based on the interaction with certain drugs. It started with the ability to target specific cells and alter their DNA to tackle single-gene disorders and has evolved into the ability to alter your DNA on a wider scale. Applications soon started to emerge, reducing the likelihood of certain diseases, but also cosmetic alterations such as eye color, height, or the color of your hair. The ability to tackle genetic disorders can improve the health of many individuals, but the challenges arise around the ability to change genetics on demand. Many cosmetic alterations through genetic modification have potential when done with embryos. The practice of creating “designer babies” was very controversial for many years. But as the technology improved and the risks lowered, society slowly started to embrace the potential. Choices made today to alter the DNA of an individual impact the entire bloodline that follows, for better or worse. Still, many people question the practices of altering your DNA. Why should your grandkids be impacted by a choice you made? Does this not influence the perceived value of life? How desirable is it to have complete control over your genetics?

Stakeholder stories

Citizen – Thomas – 31

Thomas has been dealing with sickle cell disease his entire life, just like his mother before him. Since childhood, he has had to deal with sudden, severe pain episodes and frequent visits to the hospital. These surges of pain have influenced everything in his life. He has had to take on a job that allows him to be flexible, and he never wanted kids because he did not want to pass on the burden of a life with sickle cell disease. But after a recent consultation at the hospital, he found out there is an opportunity for him to go through genetic alteration therapy, slowly treating him from the disease. He decides to go ahead with the therapy with the prospect of a longer, healthier, and happier life. A few months after the therapy ended, he feels more confident about life than ever before. He finished his first 5k and decided to train for a half-marathon later that year, without any fear of a pain episode. As one of the first to receive genetic alteration therapy, he is a spokesperson and advocate of the technology which helped him greatly. But slowly, he starts seeing new directions emerge, possibilities to change genetics not for the benefit of curing disease, but to optimize genetics. He starts to wonder, are these still the type of applications he wants to promote?



Figure 17: What-if Genetic material

Prospective parent – Roger - 33

Roger is a consultant at a firm in Amsterdam. Just recently, he found out that his partner is pregnant with their first child, an extremely exciting moment. After years of trying, they are finally going to be parents, and they want nothing but the best for their child. Many of Roger’s coworkers have recently had children, and a big part of them have decided to do some form of genetic therapy for the embryos. Some made subtle tweaks, slightly boosting the metabolic efficiency of their child, others simply because “I don’t want my kid to become bald like me”. Roger is glad that the stigma towards genetic alteration is slowly fading, but he also sees prospective parents pushing it further and further. At this point, he feels almost pressured to optimize parts of his child’s genetic profile, just to keep up with the times. If he decides not to optimize some parts of the genes, would he be actively choosing to put his child at a disadvantage? Is this really the world they want to bring their child into?

Novelist – Rose – 40

Rose is an ethicist and philosopher, renowned for her books on medical ethics and moral dilemmas. She has always been an advocate for giving the wider society a role in these difficult discussions, aiming to stimulate conversations and not afraid to cross some lines and bring uncomfortable topics to the table. While working on a new book called ‘Designed Origins’, she immerses herself in the lives of families raising children with a designed genetic profile. Parents are often happy with the choices they made. Their children are growing up to be taller and more intelligent, and are more handsome than they ever were, with deep blue eyes. A 15-year-old girl shares a story of how she experiences genoism; discrimination based on her modified genes. The other day, a boy in her class called her a lab rat and said that ‘her grades don’t mean anything anyway since her parents just paid for her to be smart’. The girl also told Rose that she does not always feel at home with her parents, after all, she looks so different from them. Rose decides to close her book with a provocation: are we not creating more damage by trying to repair the small imperfections of life?

Value matrix

Potential value	Potential risks
Healthier population, halting generational suffering, lower long-term healthcare costs	Regulatory challenges, biosecurity threats, loss of diversity
Create genetic equity, understanding of genetics, new drug discoveries	Loss of identity, ethical and moral debate
Productivity gains, new markets for genetic therapy	Dangerous alteration markets, privatization of genetics
Improved health and well-being, a happier life, a feeling of control	Discrimination, financial inequity

& many more!

What should we do today?

Today, genetic alteration faces considerable social and regulatory resistance. But as technology matures and the risks of alteration decrease, the debate is likely to emerge at new levels. People might claim that technology is the solution to generational suffering, while others are against “pretending to play God”. Regulations must evolve with the technology and provide the framework in which experimentation is allowed. Disruptive technologies need proper risk mapping to ensure ethical development. This includes giving different stakeholders a voice and ensuring that all stakeholders have equal access to the technology. Similarly, there needs to be control that technologies like these are developed with transparency and not developed behind closed doors, just for the sake of development. Besides the discussions, proper governance is required, ensuring that the development occurs in an ethical manner.

9. SECURE COMMUNICATIONS

9.1 SCENARIO

Horizon: short-term

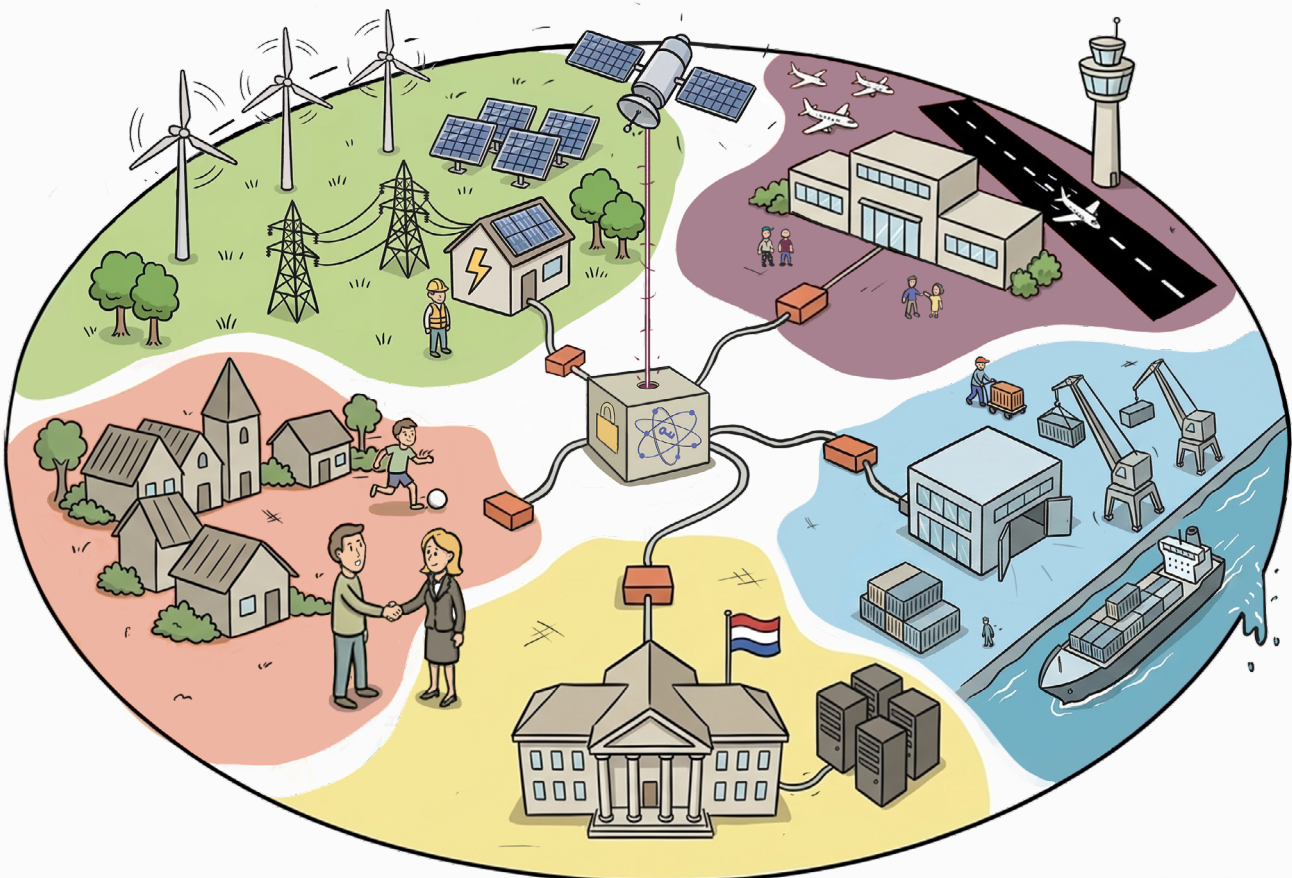
Description

Quantum Key Distribution (QKD) is a quantum encryption method. It creates encryption keys that are impossible to eavesdrop on and are resistant to future quantum computers that aim to decrypt the data [3]. Using quantum communication lines, an encryption key is created and used to encrypt the data sent over classical communication lines. Any attempt to intercept the quantum connection line is physically detectable, exposing eavesdropping. To maintain security over long distances, quantum communication lines require quantum repeaters or satellite links. This enables secure communication to be established between critical infrastructure, including energy grids, government data exchanges, airports, ports, and financial institutions. Such secure communication enhances sovereignty and strengthens resilience against hostile threats, helping to prevent failures caused by cyber-attacks.

How it works

As mentioned, QKD creates encryption keys using quantum mechanics. Encryption keys are used to encrypt data, making it unreadable without the proper key. There are several protocols, with BB84 and E91 being the most commonly used. These protocols are typically described using Alice (sender) and Bob (receiver). When Alice sends her data to Bob, it can be intercepted by a third party, called Eve. In BB84, Alice sends photons that are polarized in a certain direction, which Bob measures using random settings. Only the photons whose settings match are retained, forming a raw shared key. If Eve attempts to intercept the photons, she disturbs them. Alice and Bob then publicly compare a subset of their measurements; too many errors indicate Eve's presence, at which point the key is discarded. Using the properties of quantum mechanics, it is possible to create encryption keys that are unbreakable.

Figure 18: Secure communications scenario



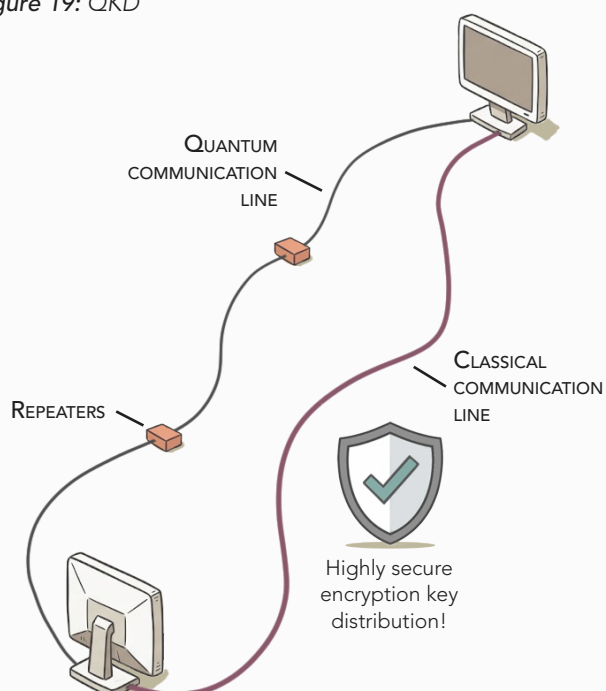
Value creation

Secure communications create significant value, even if this value is not always apparent. As ways to break encryption increase, the need to protect information becomes stronger. The entire world is data-driven. Energy grids are controlled remotely, governments communicate their information digitally, financial transactions are done online, and almost all other vital parts of the infrastructure are based on data. As quantum computers potentially allow hostile actors to harvest encrypted data today, to decrypt it later, organizations require ways to encrypt their data in a future-proof way. QKD offers that future-proof way of encrypting communications. Especially for information that is required to stay secure for decades to come, such as governmental information, this is of the utmost importance.

Having a secure communication system that is secure builds confidence and trust. Especially for vital parts of the infrastructure, this is important. Having an infrastructure that is resilient against attacks from hostile actors helps create a level of sovereignty and independence.

The main value lies in preventing significant losses from occurring. Data breaches, energy grids being shut down, rail network disruptions, or loss of communication networks are among the consequences if vital infrastructure is hacked into and hijacked. Secure communications through QKD help prevent the disruptions that occur if the system fails.

Figure 19: QKD



For stakeholders

Quantum Key Distribution can bring a lot of value to the **government and public institutions**. Their role in creating and supporting vital infrastructure, together with the aims to create public welfare and mitigate risks, makes secure communication a priority. QKD enables truly secure data exchange between critical systems, protecting sensitive communications from tampering. This strengthens the sovereignty of the infrastructure and increases the strategic autonomy, having less reliance on foreign technologies for cybersecurity. The security systems put into place are future-proof, protecting against possible external quantum computing threats. As a result, citizens and organizations develop greater trust in the government and country, knowing that critical infrastructure is safe and secure. This might move companies to the Netherlands due to a better business environment. A good and secure infrastructure **helps industry, partners, and suppliers** to do business. It also provides opportunities to help develop this infrastructure. Telecom infrastructure providers and equipment vendors provide the means necessary to set up a QKD network around the country, creating a competitive advantage through knowledge developed in the process of laying the network. Similarly, showing a credible and secure communication system inspires confidence among customers. For sectors like healthcare and finance, this confidence translates into a competitive advantage. **Startups** are benefiting from this emerging market as well. The development of new hardware, software, and integration technologies needed for QKD deployment creates numerous opportunities in the market. A market that brings many investment prospects for **investors and funders**. As quantum computing develops, so will the demand for secure communication infrastructure. Investing early in organizations that play a role in the development of QKD is expected to grow substantially. The **academics and universities** see new frontiers of research emerging. A deeper understanding of quantum communication technologies, developing new protocols, and opportunities around space-based communication. The **general public** benefits from having more reliable and secure infrastructure, which impacts their daily lives. More secure government communications, more secure data storage, and potentially increased privacy. The knowledge that critical systems are resilient will improve the sense of security and trust towards the government and the broader society.

SDGs

There are various SDGs which secure communications contributes to. Below are the two most applicable



SDG 9: Industry, Innovation and Infrastructure

The 9th SDG is called *'Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation'* [156]. The Netherlands has a very good data infrastructure, with mobile coverage being at a minimum of 98%, as mandated by the Dutch Government [157]. Furthermore, the Netherlands is among the frontrunners in the amount of households (%) that have access to the internet at 99% [158]. According to the National Cyber Security Index (NCSI), the Netherlands ranks 35th [159] and the CBS reports that 8% of organizations reported ICT security incidents [160]. There are major steps to be taken to improve the cybersecurity of vital infrastructure. Secure and reliable vital infrastructure and improved innovation contribute to the 9th SDG and its targets.



SDG 16: Reduced Inequalities

The 16th SDG is called *'Promote peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable and inclusive institutions at all levels'* [161]. Protecting sensitive government data and communications will increase trust in institutions. Having (governmental) institutions that operate effectively, with high standards of security, will be able to support society better. From a financial perspective, when transactions are executed more securely, this will result in a higher perception of security and trust. Similarly, for voting, which can be done digitally with the support of QKD technologies, aids in achieving target 16.7.

Furthermore, a robust and secure data infrastructure can support other SDGs. For example, having a secure energy grid can aid SDG 7: *'Ensure access to affordable, reliable, sustainable and modern energy for all'*. Medical data can be shared securely between medical institutions, aiding SDG 3: *'Ensure healthy lives and promote well-being for all at all ages'*.

What are the risks?

Having secure communications is great, but it does come with some risks. Firstly, the technical risks. Given the physical nature of the technology, it can be spoofed and overloaded. If the network is based on centralized nodes, for example, in Utrecht, this could compromise big parts of the network. Similarly, if the network is created by a few infrastructure providers and run by a few organizations, the dependence on these organizations could impact the security. If one of those organizations were compromised, it could have a great effect. While developing and implementing the technology and network, these risks need to be taken into account. Adding another layer to security also makes it more complicated. Physical fiber lines, satellite connections, and quantum networks are all extra gears in the machine to create secure communications. As more parts are added, the chance that somewhere the system fails also increases. Developers need to make sure that all different parts work together well and that fail-safes are included. Even if the technology works perfectly, there is still a human interacting with it. Humans are prone to error, and if unaccounted-for human errors, the secure communication system could lead to a false sense of security. Similarly, the communication lines might be secure, but there are still risks at the points where the information is saved. Implementors of the technology should focus on securing the entire part of the chain.

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9.2 BACKCASTING

General roadmap

QKD is further along in its development and valorization of the technology. Initial consortia and multistakeholder pilots have been set up, including the Port of Rotterdam consortium [95], alongside a clear focus from the EU on QKD through the Quantum Internet Alliance and EuroQCI [162,163]. The technology has been proven to work on a larger scale, and initial projects have been set up to scale it to an even larger level, with a satellite being launched in late 2026 or early 2027 [164]. Several stakeholders have collaborated in forming these multi-stakeholder consortia, with both public and private organizations involved in realizing the Port of Rotterdam project.

Secure communications through QKD technologies face several enablers and barriers in reaching a national network protecting all vital infrastructure. A proper data and communication infrastructure is required to realize the technology. Fiber companies and technology vendors play a significant role in creating this infrastructure and making it ready for QKD as supply chain actors. The government or other stakeholders should act as the launching customer to accelerate implementation. Technologies like QKD exhibit a high level of network effects. As organizations slowly transition, it becomes easier for others to engage with them too. A push from governmental organizations to prioritize data security acts as a catalyst in development and implementation. But a clear reason to switch is required, given the high costs, both monetary and operational, of applying QKD to communication security. Inadequate regulations and security frameworks hinder the advancement and implementation, making it difficult to realize the potential value. The technology can provide the most value when it is scaled to significant distances, but technological and environmental challenges prevent it from scaling further. Lastly, with any security technology, the human factor has to be considered. Humans will be interacting with the technology and will always pose a security risk that is not solvable by technology alone. The promise of 100% secure communications should be considered in the context of human risk.

Secure Communications

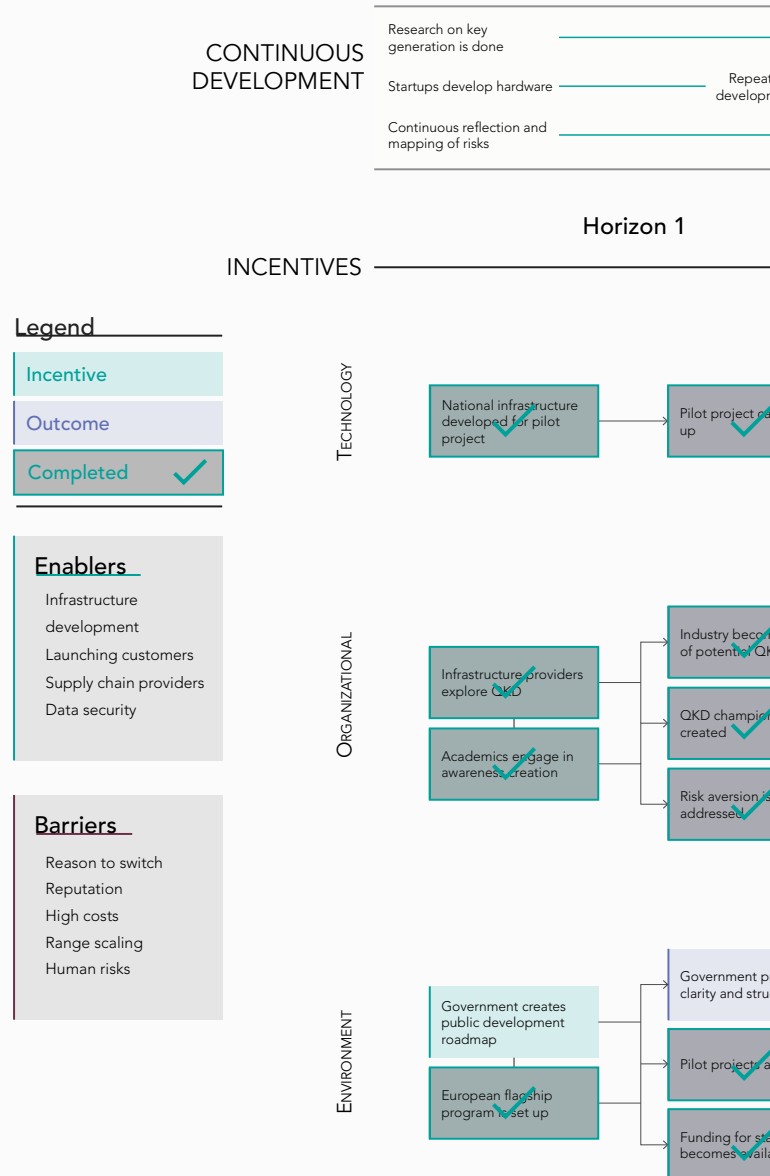
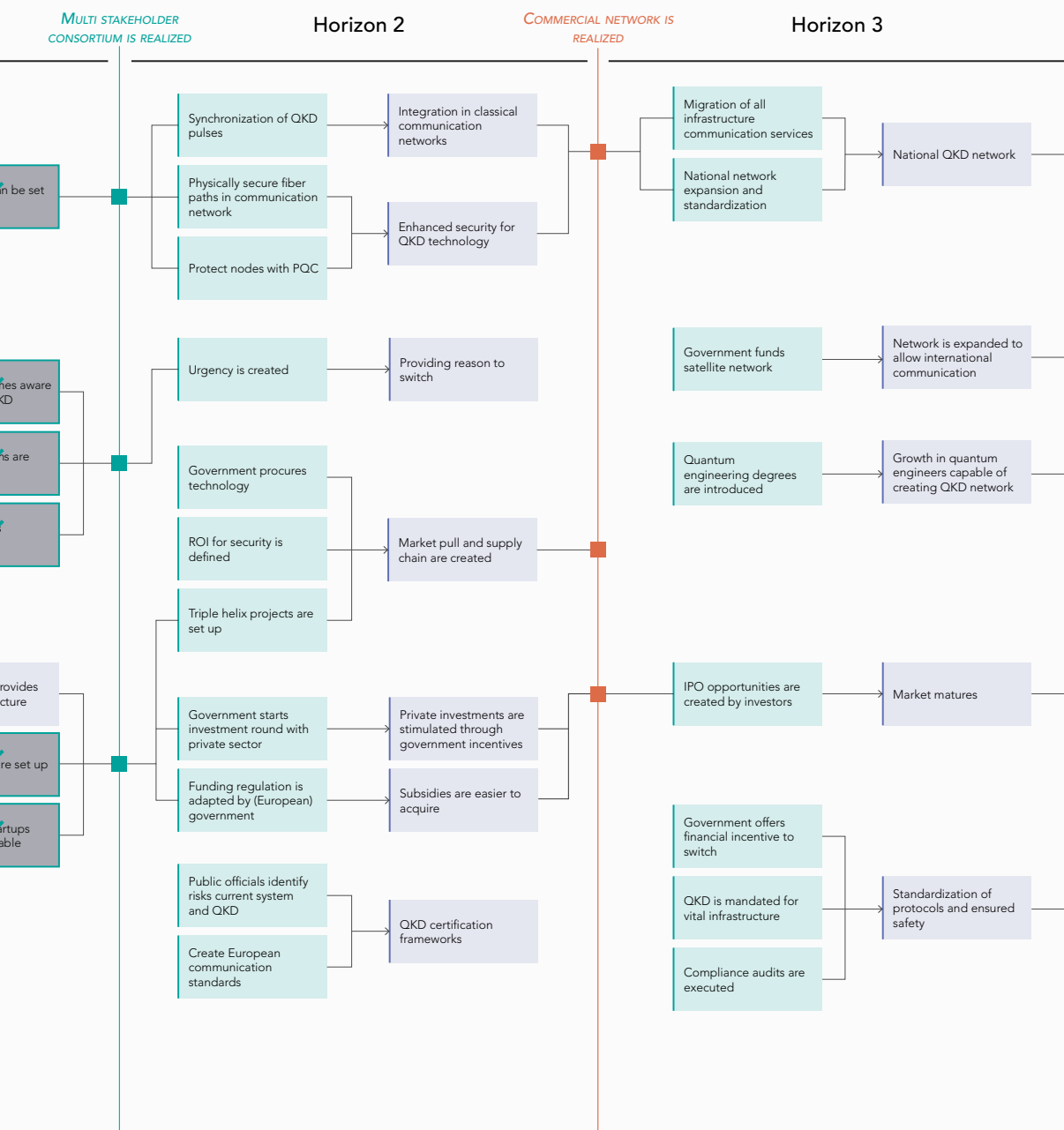
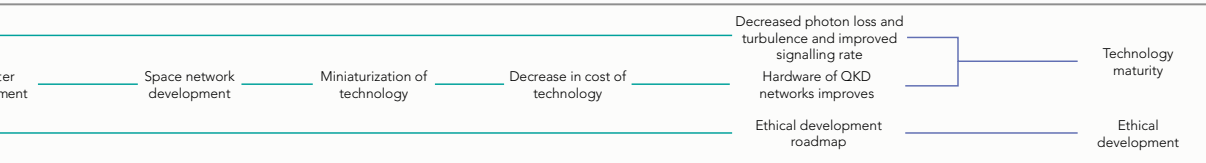


Figure 20: Roadmap Secure Communications 1



SCENARIO

Secure communications

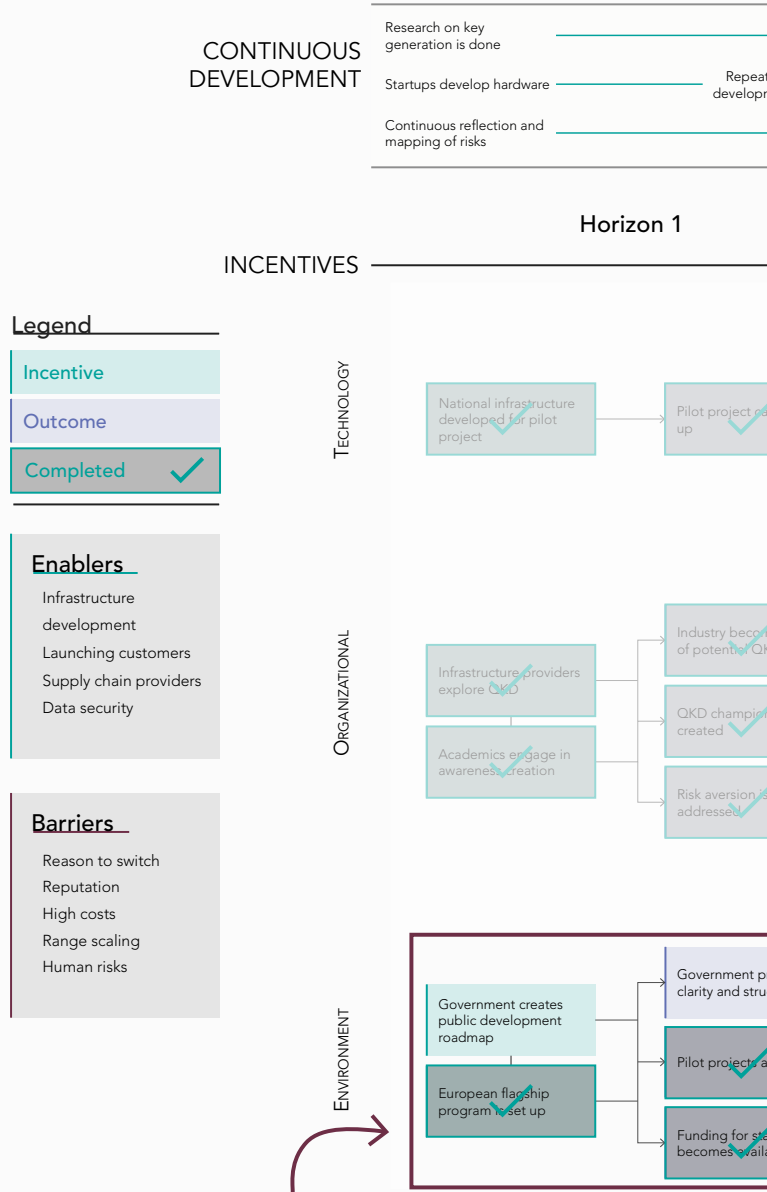
Secure communications network through QKD technologies in the Netherlands, protecting all vital infrastructure

Security
Safety
Trust
Sovereignty
Future-proof

Roadmap 1

For secure communications enabled by QKD, the government plays a different role compared to other technological advancements. Its responsibility to provide structure and clarity, and to start with pilot projects, is evident, but its role as a customer is equally large. While transitioning from pilot projects to a commercial network, governmental and public organizations need to take clear commercial steps. Procuring the technology through tenders, showing a clear reason to switch, and stimulating triple helix projects facilitate this transition towards valorization. By acting as one of the first commercial customers, the government will help establish the supply chain, bringing the market to new levels of maturity.

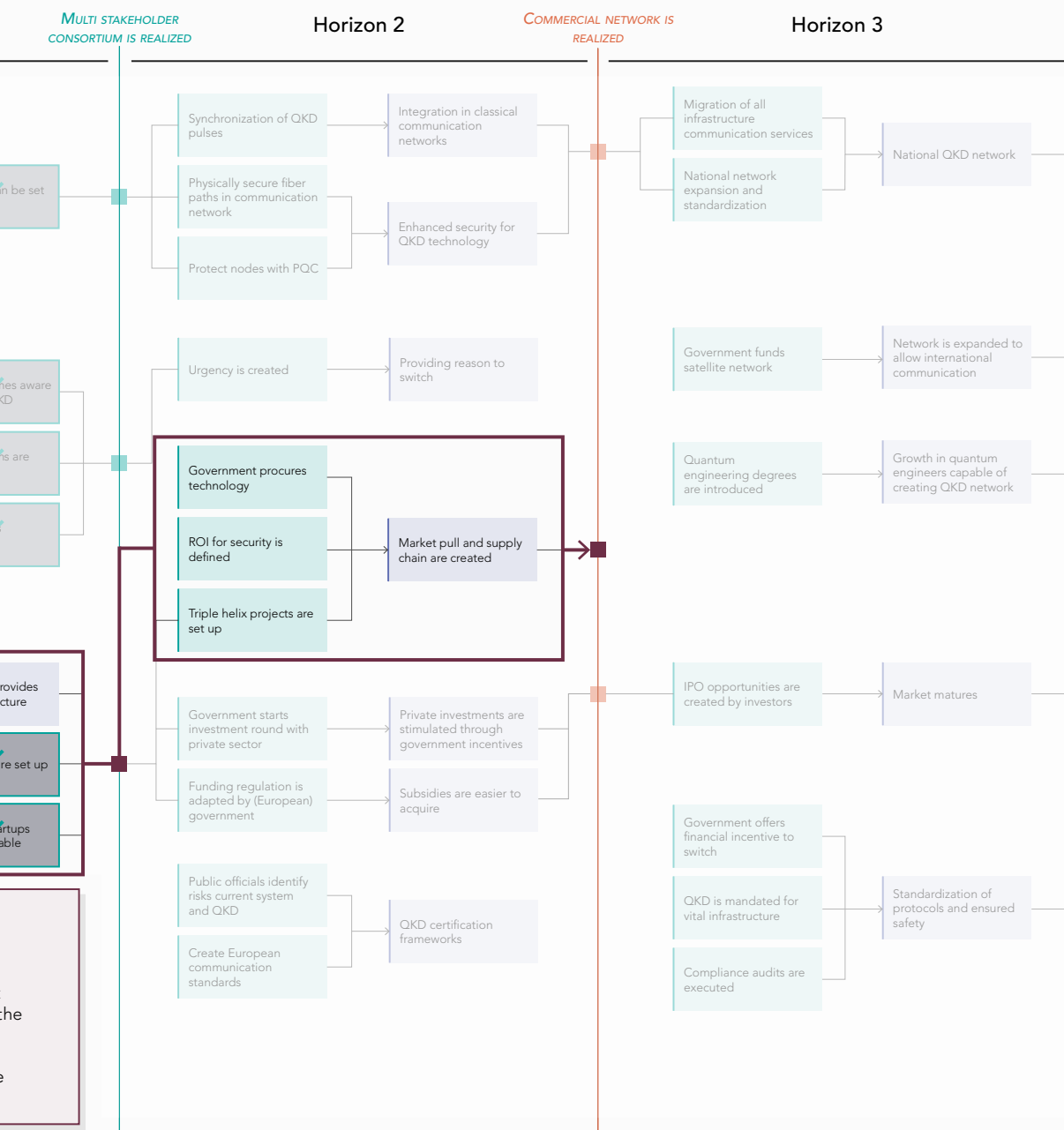
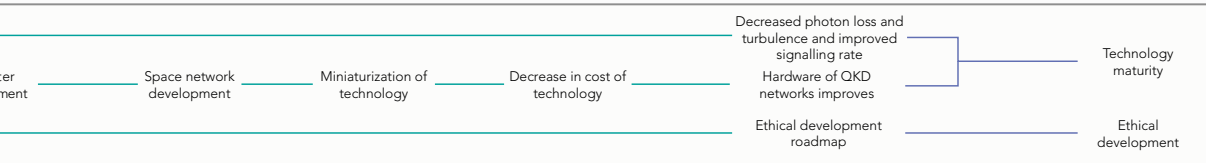
Secure Communications - 1



GOVERNMENT AS INITIATING CUSTOMER

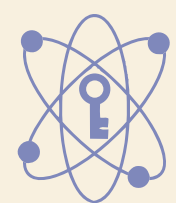
QKD can provide a lot of value for public services. This gives the government another role, namely that of customer. This requires initiative, by initially giving clarity and structure and explaining intent through a public roadmap. But as the initial pilot projects are done, the government slowly needs to start procuring the technology through tenders. This allows the supply chain to develop and companies to grow. Ideally this is done through triple helix projects, combining the knowledge of different stakeholders.

Figure 21: Roadmap Secure Communications 2



SCENARIO

Secure communications



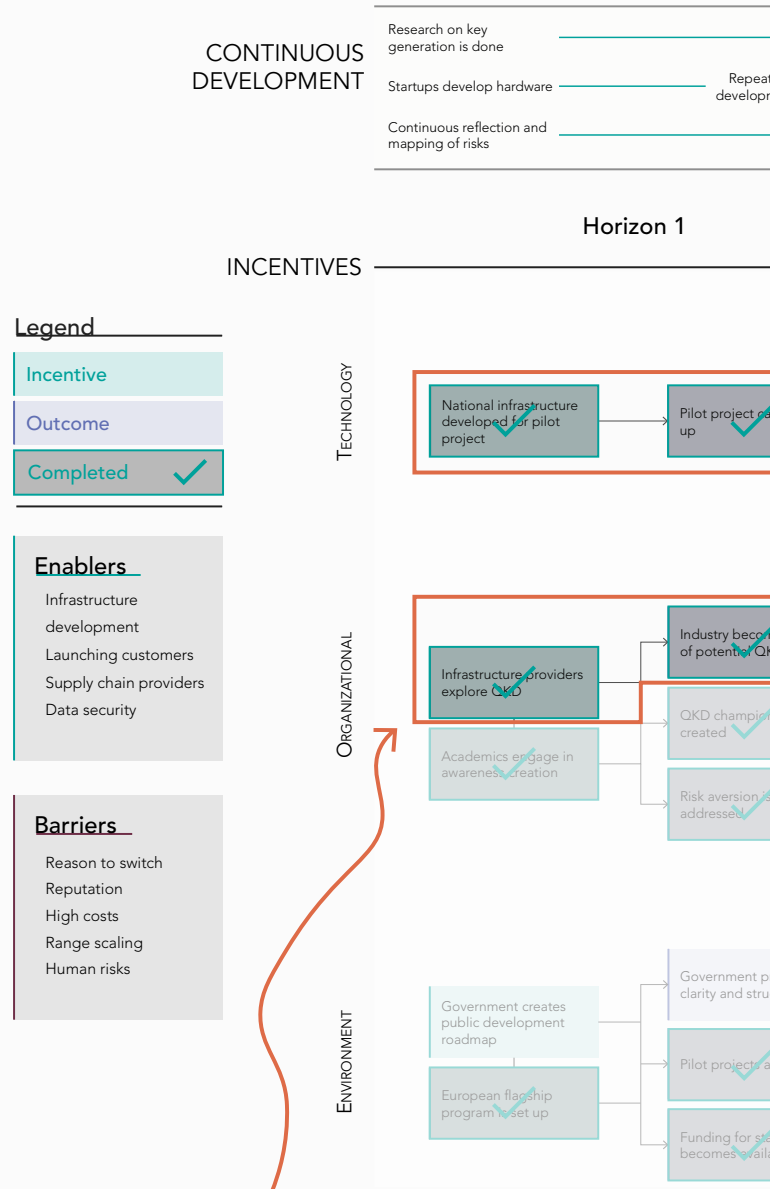
Secure communications network through QKD technologies in the Netherlands, protecting all vital infrastructure

Security
Safety
Trust
Sovereignty
Future-proof

Roadmap 2

The adoption of Quantum Key Distribution technology stands and falls with a proper infrastructure for the technology. Organizations such as Eurofiber must be actively engaged to stimulate the development of this infrastructure. In return, early engagement offers these organizations a commercial advantage as the technology scales, utilizing the first-mover-advantage. They need to cope with several technical challenges that emerge in the development of a communication infrastructure. Integration with existing infrastructure and enhanced security for the technology are to be pursued in the realization of a national QKD network. This requires constant collaboration between academic institutions, startups, and industry to develop the technology that is required. A proper infrastructure directly influences stakeholders' willingness to adopt the new technology. Only if a majority of the actors are willing to make the move to QKD can a national network ever truly be completed.

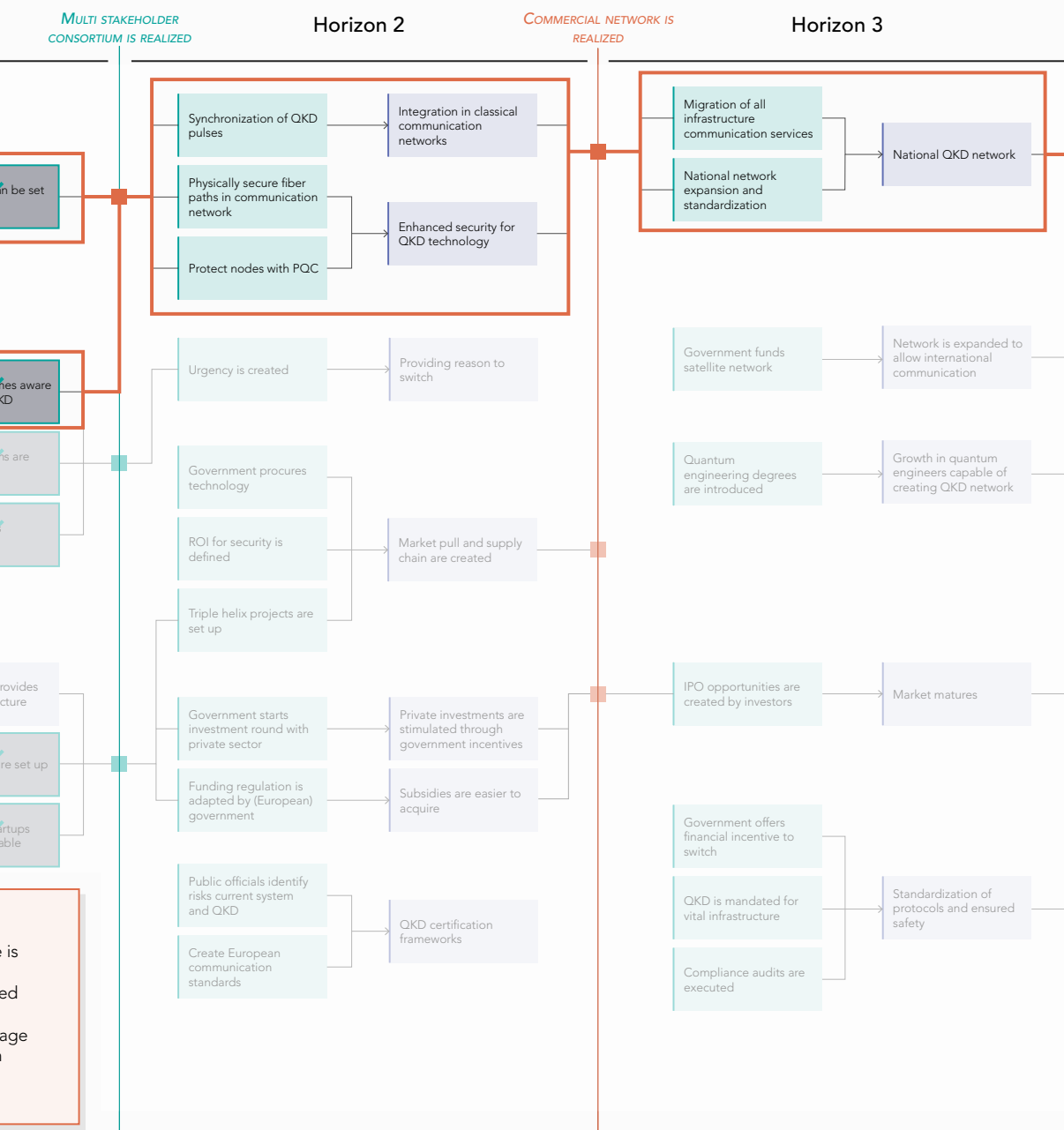
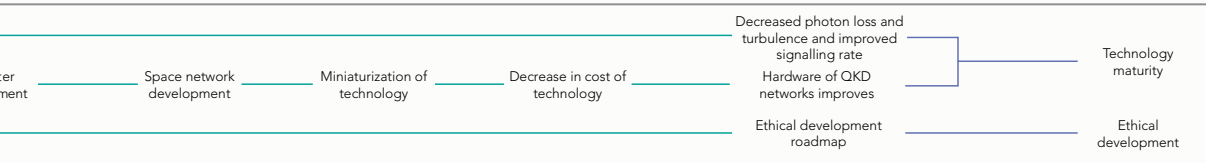
Secure Communications - 2



ROLE OF INFRASTRUCTURE PROVIDERS IS CRUCIAL

Secure communications through QKD only works if the infrastructure is ready. Fiber cables through the ground, satellites, key management, and integration with existing networks are some of the steps that need to be taken. Several infrastructure providers are required to realize a secure national communication network. In turn, companies that engage might benefit from a 'first-mover-advantage'. Collaboration between the government and infrastructure providers is required to build the supporting network where QKD can flourish.

Figure 22: Roadmap Secure Communications 3



SCENARIO

Secure communications

Secure communications network through QKD technologies in the Netherlands, protecting all vital infrastructure

Security
Safety
Trust
Sovereignty
Future-proof

9.3 WHAT-IFS - SECURE COMMUNICATION

9.3.1 GLOBAL ESPIONAGE

What if global espionage and law enforcement intelligence becomes redundant?

Situation sketch

Digital communication networks are under increasing stress. More frequent cyberattacks and data breaches prevent organizations from operating securely. Concerns about data security are growing. In an attempt to deal with cyber criminals, governments have deployed national surveillance networks. Together with private organizations, they aim to prevent crime, but in doing so, they track many ordinary citizens. The growing mistrust works both ways; tighter security drives groups to launch cyberattacks and people to be vocal, which in turn leads to stricter surveillance and activity tracking. As quantum-secure communication networks are introduced nationwide, the space for cybercrime shrinks. Organizations slowly see a more protected communication network translate into greater trust. As governments lose the capacity to intercept information as well as before, the nationwide surveillance is dismantled. Law enforcement agencies are limited in the use of spying software, turning towards a more humanistic approach to detect crime. Over time, trust continues to grow. The increase in privacy and security makes it hard for countries to spy on each other, improving the underlying trust as they realize that dialogue is the only way forward.

Stakeholder stories

Citizen – Jamal – 34

Jamal runs a logistics company coordinating the delivery of packages arriving at the port to several European countries. In recent years, many of his competitors have faced cyberattacks, with customer data being compromised. Many of his customers, large medical organizations with whom he has multiyear contracts, have expressed their concern about the communication containing customer data between his company and theirs. A few months later, he receives an information request from the Dutch intelligence agency. Given some suspicious activities in the logistics sector, they are asking all logistics companies to provide communication data on a regular basis. Surprised by the weird request, he initially refuses. But over the following months, he begins receiving further letters from the government, this time accusing him of harboring criminal activity. He is shocked; just because of the secure communication network he has set up, he is being accused of being a criminal. While he supports giving law enforcement the tools to catch criminals, should he betray the trust of his customers just because the government demands it? Is the ability of the government to spy on its citizens really something that improves safety?

Intelligence analyst – Sophie – 47

Sophie has worked at the Dutch Intelligence Agency for many years, specializing in detecting suspicious financial flows linked to terrorism. She used to analyze financial transactions tracked and decrypted through court-ordered wiretaps. This allowed her to identify sponsors of criminal activities, even when the money was stashed away in crypto. But she noticed that her room to use surveillance tools grew and that her managers often even actively encouraged her to place wiretaps. These tools slowly became harder to justify. When QKD networks began rolling out across the Netherlands, the blind spots grew. Initially, this felt very frustrating for Sophie, like trying to fight with an arm tied behind her back, but then she noticed something she did not expect. Cybercrime targeting crucial institutions began to drop, even though her attempts to stop it did not increase. Political winds shifted under public pressure, and tighter regulations were implemented to restrict mass surveillance. She still wonders if the crime that does occur is simply going undetected. But when looking at the broader picture, do surveillance tools decrease crime or mainly decrease trust?

QKD implementor – Hans – 55

Hans works for a data security firm and assists with the implementation of QKD communication networks for the government. For years, he observed how cyberattacks on critical government services increased, resulting in the government tightening surveillance, increasing law enforcement intelligence budgets, and pulling more information behind closed doors. When QKD was introduced, he feared the mistrust would only grow. But Hans noticed the exact opposite. The new technology prevented not just criminal organizations from intercepting communications, but also constrained the government. As the technical ability decreased, so did the political justification for surveillance. Governments were forced to abandon the closed-door mentality and strive for transparency. This led to people around him speaking differently about the role of government; less cynical, more willing to collaborate, and more trusting. The technology he had championed not only protected the infrastructure, but it also stimulated a culture change. He starts to wonder, maybe not all attempts to make everything more secure come at the cost of transparency and trust?

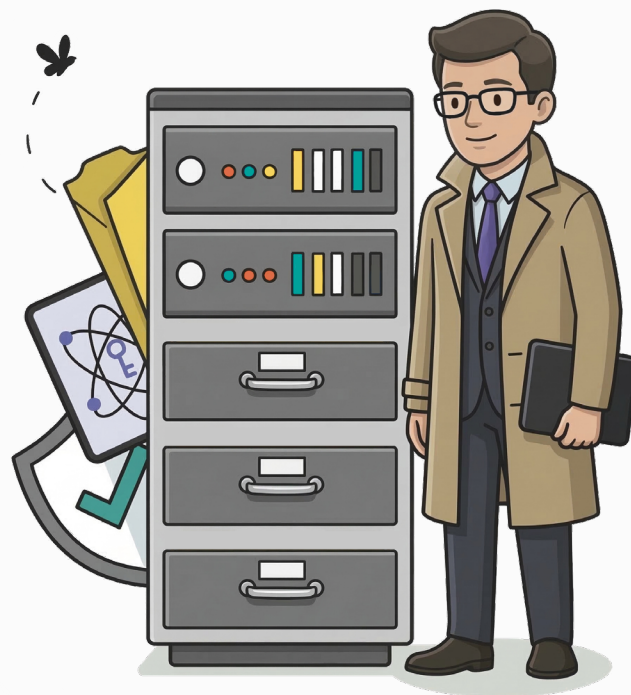


Figure 23: What-if espionage

Value matrix

Potential value	Potential risks
Secure communications, protection of vital infrastructure, sovereignty, trust	Lack of trust, lack of transparency, crime is harder to intercept
Less (global) espionage	Weaker intelligence agencies
More secure society, higher privacy standards	Dependence on governmental infrastructure, harder to hold actors accountable, mistrust in government, security inequality

& many more!

What should we do today?

It starts with having conversations and discussions about what it means when all communication is secure. What does this mean for transparency, what is the impact on privacy, and how will this impact trust? There should be a constant debate about the implications on security and privacy, with all potential stakeholders. Together with other nations, regulations should be established to ensure a smooth roll-out of the technology and prevent panicked pushes for back doors. As a frontrunner in quantum development, the EU should push for ethical and responsible development of the technologies. Intelligence agencies should reflect on what global QKD networks would mean for the way they operate and find new ways of acquiring information. Organizations should collectively recognize the implications it has on their operations and strive for collaboration and transparency rather than pulling up walls.

9.3.2 TECHNOSOLUTIONISM

What if we start to rely too much on the technology for security?

Situation sketch

Automated security systems have started to dominate AI-driven surveillance cameras, biometric checks at borders, autonomous drones surveilling the city, and all information collected through a global satellite-based QKD network, with automatic continuous key generation. Piece by piece, this security network has been expanded. With the rise of automation, human oversight has faded, removing the “weakest link” in a security system. Efficiency is at its peak. Large organizations, under government control, process massive amounts of data to find and predict security breaches. Attempts of hostile actors to interfere are negated as quickly as they are recognized. Organizations are slowly starting to realize how brittle this system actually is. If a piece of the pipeline fails, it could impact the whole system. The focus on technology has taken out human intuition and turned everything into binary predictions. At the same time, the discussion emerges: if it goes wrong, who is to blame?

Stakeholder stories

Port employee – Erik – 58

Erik has worked at the Port of Rotterdam for 35 years, ever since he got out of school. He was once the most tech-savvy person, so he slowly grew into a role where he was responsible for maintaining secure data communications within the port. A new QKD communication system rollout promised unhackable, future-proof communication links. Fiber optics, quantum entanglement, and key management, all too complicated for him in this day and age. But he kept being told: “You don’t need to understand how it works, it just works”. For Erik, it’s a black box. Every month, an employee of the QKD company comes to the port to update some systems and to verify that everything is still functioning properly. Erik trusts that it all works well, but how can he be responsible for something that he does not understand? Is the Dutch government’s attempt to secure and future-proof its critical infrastructure not just one that makes it more complicated? Are we not replacing one dependency with another, a dependence on a technology that is a black box to many?

Cybersecurity officer – Eva – 39

Eva is part of the cybersecurity team at an organization that is responsible for the security of the Dutch energy grid. Over time, she has seen her team shrink and being replaced by AI monitoring tools. Eva was a fan of this automatization, humans were the weakest link in the security systems after all. Just recently, customer data from a bank was acquired by hackers because they convinced an employee of the bank that they were part of the customer service. During a pretty regular day, Eva stumbles on a bug, and because of the error the energy grid is about to be shut down in part of a town, to protect the grid. A hospital might lose access to power. When trying to solve the problem, she is locked out by the system. Filled with adrenaline, she acts based on instincts and overwrites the admin access. Just in time, she manages to halt the shutdown of power. What if I had not been there, she wonders. Is technology ever truly capable of replacing human intuition?

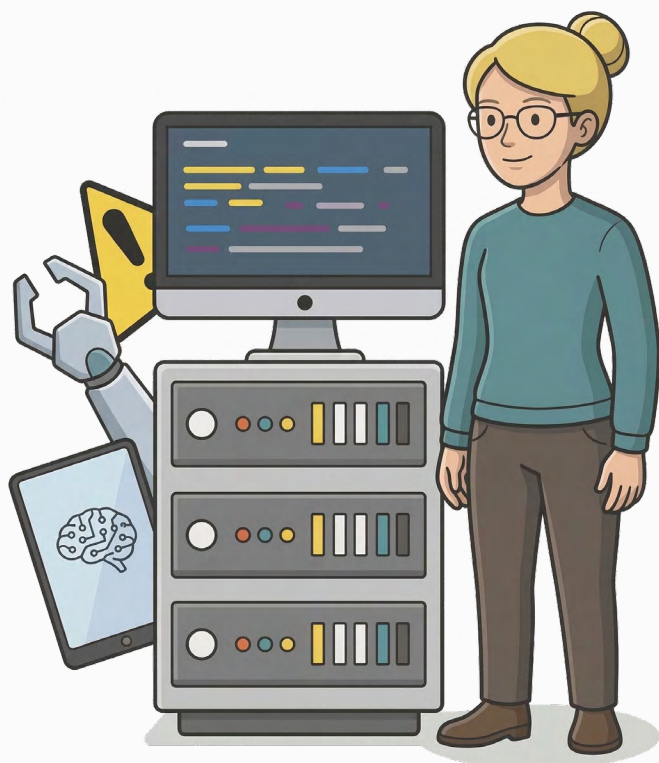


Figure 24: What-if technosolutionism

Lawyer – Fatima – 46

Fatima is an in-house lawyer for an airport near Amsterdam, specializing in tech contracts, IP, and liability. The airport recently installed a satellite-based QKD network to secure communications between the control tower and aircraft, following a rise in attempted signal hijackings. But then a solar flare disrupted the link with the satellite, triggering an automated fail-safe in the system. Runways cleared for 30 minutes, 26 flights grounded, losses running into the millions of euros. Now, Fatima receives questions from colleagues, the media, and shareholders about who is to blame for the malfunctioning. The developer of the technology blames an ‘unforeseen event’ and the slow reaction by the employees of the airport to switch to old systems. The airport, in turn, points the finger at the company that developed the technology for creating faulty technology and failing to educate its employees. A more general debate ensues, with Fatima right in the middle; can the developer of a technology be held accountable for the actions of the user? And when technology ultimately fails, who is ultimately responsible?

Value matrix

Potential value	Potential risks
Secure communications, protection of vital infrastructure, comfort	Loss of checks and balances, complication, over-centralization
Efficiency, integration of systems, riddance of human errors	Loss of human intuition
Data-driven decision making, innovation	Dependence on technology and on firms
Educating on new technologies	Specialized knowledge

& many more!

What should we do today?

Innovation and technology offer significant benefits to society, but they also risk reducing the role of human judgment. Much of today’s technology is driven by data and mathematical models, which lack the tacit knowledge and expertise that humans bring. When developing technology, it is therefore important to do so from a human-centered perspective. Especially when it comes to the security of vital services, there needs to be humans who can assist in the case of ‘black swans’. During development and implementation, frameworks should be put in place to ensure that this is done properly. Secondly, when implementing technologies on a national level, diverse vendors and companies should be contracted to ensure that the dependence is limited. This needs to be taken into account during the development phase too, through sponsoring pilot projects with a range of actors and ensuring that knowledge is broadly shared. During the implementation of a technology, there needs to be precautions taken for when the technology fails. No technology is perfect, but we have to make sure that we can deal with it nearly perfectly when it fails.

10. REFLECTION ON FVM

10.1 ANALYZING THE SCENARIOS

The scenarios show that both applications have the potential to generate value for many stakeholders. Both scenarios, personalized medicine and secure communication, provide a clear and normative overview of relevant values. They serve as a point on the horizon, rather than a concrete goal to work towards.

Personalized medicine, as explained in the scenario, is still far away from realization. The computing power required to run simulations on molecular interactions is substantial, and the technological maturity has yet to reach that stage. While initial EHRs are already being used in hospitals, the quality of the data is not sufficient enough to be able to run predictive analyses. Nevertheless, these uses of the technology will emerge and impact all actors. The general public will experience a major change in their healthcare. Perhaps not always consciously, but the quality of healthcare is set to improve significantly. The role of hospitals is going to change, which is an interesting side effect. The shift from reactive care to a more proactive approach alters the dynamic of care. For academics, it opens the door to new research directions, which in turn may generate more value. The enabling aspect of personalized medicine may be its most substantial value. It can have a global impact by improving the health of many. The scope of this scenario was set to the Netherlands, but perhaps the biggest impact can be made in underdeveloped countries.

Secure communication through QKD is achievable in the short term, but many steps are still required to fully realize the scenario. The challenging part about secure communications is that its value lies mainly in preventing loss. The quality of security is only measured by how often it fails, rather than being a measurement of the technology itself, making value assessment quite challenging. Furthermore, the most value is created when a network approach is adopted; the more organizations employ the technology, the more useful it becomes. This is simultaneously a risk, as organizations become reliant on one another in their adoption efforts.

Both scenarios differ in their approach.

Personalized medicine is broad in its scope, while secure communication is very specific. Viewing them side by side makes the contrast clear. This difference also influences the level of uncertainty. For QKD, the technology is more proven, the development timeline is shorter-term, and consequently the applications are more certain.

10.2 ANALYZING THE ROADMAPS

The participatory workshops and interviews provided many interesting insights. The role of the government in starting the development, but it should also engage in ensuring valorization is sought after. Acting as a launching customer is a good example of how this role can be filled. At the same time, the government has limited resources, as indicated in the interviews. This limits their capabilities to provide incentives and stimulate development and valorization.

“All stakeholders have a different role to play, but all are important”

Most value is created through the valorization phase, moving from initial pilot projects to a commercial network. Simultaneously, this is the horizon that requires the most attention, aiming to overcome the valley of death. All stakeholders have a different role to play, but all are important. For personalized medicine, the main steps to be taken in this horizon are to work on commercial viability and to for hospitals to build their capabilities. This phase is also characterized by the need for more ethical discussions. As the technology shifts towards implementation, these discussions should occur more frequently. Setting up ethics and governance programs should be done by multiple stakeholders to ensure that different perspectives are considered. Personalized medicine comes with many risks. As with any new medical technology, there are medical risks. Initial uncertainty of effectiveness as an example. But the risks for society are large too, with the possibility of personalized medicine leading to more inequality. All these risks should be considered and tackled by governance boards and by governments through regulation. For secure communications, Horizon 2 is

the phase where the technology adoption currently resides. But a big challenge lies in the implicit character of the value secure communications create. Having a secure communications network for vital infrastructure is important, but how much is it worth? Mainly when things go wrong, organizations are likely to improve their security networks. This makes a government that has to justify all the money it spends a difficult customer. Other main initiatives that are required are to develop the infrastructure and create standards. This makes the interoperability and expansion of a network possible. Secure communications through QKD do come with significant risks, not as much by the technology on its own, but mainly while utilizing it. Secure communication is an application that requires reliability; the main goal is to mitigate risks. With humans interacting with the technology, they will always pose a risk. At the same time, relying too much on a technology, removing human intuition, creates a whole new set of risks. Active dialog and holistic views are required to map these risks and try to limit their impact.

With many technologies that have similar characteristics, the initial steps leading up to the first milestone are similar. All technologies need to go through pilot projects and require prioritization by influencing stakeholders to reach maturity. While this might not be groundbreaking, this initial phase has a significant impact on the course of development of the technology. At the same time, the continuous steps that are required to be taken should not be overlooked. Even if all incentives are realized, if the technology does not mature at an appropriate rate or if the development does not occur according to ethical standards, the technology and the scenario will not be reached.

10.3 ANALYZING THE WHAT-IFS

When looking at the several what-ifs that are created, it is clear that numerous risks are associated with quantum technologies. Ranging from inequalities to causing physical harm, stakeholders should aim to mitigate as many risks as possible. Personalized medicine has the potential to create significant value for society, but only if privacy is ensured, potential weaponization of the technology is limited, and ethical conversations are conducted. If poorly

“it is clear that numerous risks are associated with quantum technologies”

executed, the impact on society can be substantial. Stakeholders engaging in development today should be wary of those potential implications and aim for meaningful development. Secure communications primarily find risk in the overreliance on the technology, forgetting about the human aspect in security. A decrease in global espionage is a serious risk, but one that is more manageable. As the technology is implemented, actors should engage in trust-building and ensure that transparency is maintained as a priority.

Many consequences lie further in the future, making it harder for stakeholders to feel the urgency to act today, as several risks are too speculative to be dealt with today. Engaging in conversations about these risks in the short term is essential. This allows stakeholders to prepare for situations that might arise and act before potential damage occurs. Governments and other public organizations should create regulations and frameworks well before the technology demands them. Here lies a challenge in providing structure in such a way that it does not limit technological development, as many claim is the case with AI in Europe [4].

Given the path-oriented development of quantum technologies and the role of Future Value Mapping in aiding decision-making, the what-ifs help by providing several consequential scenarios. They provide color to the path as it's being drawn. There are many ways in which quantum technologies can provide value to several stakeholders. However, this does require acknowledgement of potential future scenarios and action today to create meaningful technologies.

11. FVM IN PRACTICE

The Future Value Mapping method was showcased using two applications of quantum technologies. It can be used for various quantum technology applications and by various stakeholders, who should be aware of the value creation, interconnectedness among stakeholders, risks, implications, and required steps to realize their desired future. These are all uncovered through the Future Value Mapping method.

Organizations such as QuTech occupy a unique position in the ecosystem, bridging academic research and commercial application. As discussed by several interviewees, it is difficult to get past the first meeting when trying to set up partnerships. The uncertainty around value creation limits the potential for collaborations. Business developers at these organizations can use the FVM method to showcase the value that quantum technology can create, while also demonstrating the importance of each stakeholder in creating that value. By working through a specific scenario and the steps required to realize it, participants develop a more concrete and grounded understanding of the potential value, while staying away from speculation. At the same time, the potential risks and future implications are explained, creating a more complete picture.

The participatory nature of Future Value Mapping brings stakeholders together and generates unique insights. Each stakeholder brings their own perspective, priorities, and concerns to the same scenario. They reveal where interests align, where they diverge, and where the most important conversations still need to happen. Developing a trajectory of development and adoption in isolation will lead to lower-quality outcomes, so participation should be encouraged. For quantum technologies, where collaborations are scarce while their value is widely acknowledged, the FVM method, alongside the workshop tools, provides a structure for those conversations, making it easier to bring people together.

As discussed throughout this report, uncertainty significantly impacts quantum technology adoption and development. FVM helps make sense of that uncertainty by creating a path for development. This helps practitioners in providing direction and

meaning throughout development, while at the same time, potential implications and risks are uncovered. For policymakers and regulators, this proactive mapping is particularly valuable. It lays the groundwork to base regulation on and identifies where governance might be required. Given the uncertain implications of emerging technologies, FVM offers a means to explore those implications early.

The method can be used to align stakeholders on value creation and develop a shared roadmap. This, in turn, helps stimulate collaboration consortia. Policymakers, business leaders, and academics can collaborate on the creation of a shared path using FVM as the structuring tool. It showcases which steps various actors still need to take and where the gaps in development lie. For example, by highlighting commercialization gaps and enabling stakeholders to collectively determine how to address them. A guidebook for the method can be found in the appendix.

CONCLUSION

12. DISCUSSION

This report explored how collaboration between stakeholders can be stimulated to remedy barriers to the adoption of quantum technologies. The first part explored the barriers to the adoption of quantum technologies through a literature review and a qualitative study. The second part built on the core findings of the first part and showcased a methodology to address the uncertainty inherent in the development of quantum technologies. This chapter reflects on the inquiry-based nature of the report, the findings, and the implications for practitioners, policymakers, and academics.

“waiting for the technology to mature is not an option, especially not if the aim is value-driven development.”

12.1 FINDINGS IN CONTEXT

Uncertainty as a design challenge

The uncertainty that is associated with quantum technology lies at the core of many of the challenges it faces in development and adoption. The lack of clear applications and value creation was expressed throughout the literature and interviews. Part of this uncertainty will be resolved as technology matures, but not all of it. Applications need to be developed and explored, collaborations need to be set up, benchmarks should be created, and development trajectories formed. But having the uncertainty is a challenge for the creation of all of these instruments. That is why just waiting for the technology to mature is not an option, especially not if the aim is value-driven development.

The uncertainty requires active attention, something it does not receive enough. Through inquiry; understanding the situation as-is and investigating the possibilities, a methodology aids in making decisions amidst the uncertainty. The strategic-design-inspired method Future Value Mapping stimulates the creation of information and collaborations to deal with uncertainty. Actors involved in the development of quantum technologies need not only to be aware of the impact of uncertainty, but also to actively deal with it. The uncertainty is not something to just

accept; it requires a proactive approach. This is a meaningful shift in perspective that is not reflected well in existing literature. Design thinking is well-suited to deal with this uncertainty.

Value creation

The creation of value through quantum technology is the driving factor for collaboration, development, and adoption. Collaboration, PPCs in this specific case, and value creation have an intertwined relationship. A clear goal and value are driving factors for collaborations, and collaboration is required to realize meaningful value. Several experts confirmed this through the interviews: the importance of finding a collaborative target to work towards. But value creation is not very clear for quantum technologies, as this report confirms. Values such as strategic autonomy or economic value might appear apparent, but are also time-driven. Various frames of reference of stakeholders influence the sought-after value and reason to develop quantum technologies. Understanding these different frames of reference is a prerequisite for successful collaborations, which is well reflected in the literature. When a collaborative value or direction cannot be found, the development risks development for development's sake.

This report highlights the importance of focusing on value-driven development, which is not expressed enough in combination with collaboration and adoption throughout the existing literature. Most research explores the value of quantum technologies from an ethical or philosophical perspective, or adoption barriers from a commercial perspective. But as this research stresses, these factors are intertwined. There is no concern that quantum technology lacks potential, but rather that the potential is blind-siding the reason for development and with it the right intent.

Future Value Mapping

FVM was developed as a response to the gap and barriers identified in the literature and interviews. It resulted in the following core question: *What is required to realize a desired future and what are possible implications?* The desired future, created through a scenario, serves as a clear direction to work towards, grounded in normative language. The backcasting analysis looks to answer

what is required to realize this scenario, and the possible implications become clear through what-if questions. The scenario-based nature of FVM is one of its core strengths; it allows various stakeholders to engage who might not speak the same professional language. Especially amidst deep uncertainty, scenarios are a very powerful tool to aid in strategic decision-making. The development of quantum technologies should be path-oriented, not aiming to reach a single goal, but having a clear direction to head towards. There is too much uncertainty to create long-term and specific goals to work towards. Many foresight and futuring methods are goal-oriented or use a scenario as an endpoint, which is an unrealistic assumption, even if just used as a tool. Varying stakeholders, with different cultures, goals, and structures, all play a part in realizing a quantum future. Finding a shared path and bringing it towards the present gives organizations a reason to engage in the development.

FVM was developed in the particular context of quantum technologies, along with its challenges. But the method is standalone and could be used in other settings. The basis is built on dealing with deep uncertainty, disruptive and enabling technology, and the interconnectedness of various stakeholders. These conditions may also apply to other deep tech domains.

FVM draws on design thinking and existing methods such as strategic foresight, backcasting, and scenario planning, but utilizes them to tackle a unique set of problems that existing methods do not address. Strategic foresight is similar in many ways. Both methods aim to inform strategic decision-making and deal with an uncertain future. But strategic foresight typically starts with the status quo, testing different strategies to build resilience against a range of possible futures. Its primary aim is to ensure that organizations are prepared for what might come. FVM, on the other hand, starts at the opposite end; it begins with a normative desired future and asks *what should happen to realize this future?* It provides actors with a direction and reason to collaborate. The focus is on creating value rather than resilience. This is mainly due to an even deeper level of uncertainty. Strategic foresight deals with the uncertainty of the environment, while FVM also deals with the intrinsic uncertainty of the

technology.

Compared to backcasting and roadmapping alone, FVM adds numerous things. On its own, backcasting and the roadmap that follows from it tend to be goal-oriented, focusing on the steps required to realize the scenario. This does not place the scenario in the wider context of development. It risks the creation of a roadmap that is seen as static, without the use of pastcasting to turn the roadmap into a living document. Value creation plays a role in backcasting through the initial scenarios, but fails to embed various stakeholders' values. The roadmap could be seen as the goal, rather than the tool to realize the value. With deep uncertainties, continuous conversations about values, risks, and implications are required to ensure meaningful development.

Most scenario-based methods are explorative or speculative, while FVM is normative and focuses on value creation. The explorative nature of stand-alone scenarios serves a purpose to stimulate conversations and understand implications, but risks a futuristic language. This could alienate stakeholders. It furthermore lacks clear steps required to realize that future, which FVM does provide. Rather than developing different future scenarios to reflect on, FVM provides a clear future to work towards and explores its implications. This makes the method more applicable for strategic decision-making.

Measuring value

The challenges in measuring success are one of the challenges in setting up collaborations. This is a challenge that is not addressed explicitly throughout this report. Throughout the research, it has been researched extensively, but it requires further research given the complexity of the topic. Measuring value beyond GDP, or 'Brede welvaart' (*broad prosperity* in Dutch), to be more specific, is a major challenge. Several methods have been identified, such as the SDGs, with each having its own advantages and challenges [165]. The measurement of value through quantum technology is a separate challenge that needs to be tackled. This would stimulate collaborations, as the value would be made explicit. But the measuring of value beyond monetary is a challenge well beyond the scope of quantum technology.

12.2 CONTRIBUTION

On an academic level, this report contributes to the existing knowledge of quantum technology adoption barriers and provides a detailed foresight methodology. The literature review provides a complete overview of existing knowledge about barriers to adoption, a topic that is insufficiently explored. The semi-structured qualitative interview study provides additional insight into barriers present in the Dutch ecosystem. The dynamic between value, barriers to adoption, and collaborations was not sufficiently explored. This report shows the interconnectedness of uncertainty as a barrier to adoption with value creation and setting up collaborations. It furthermore expands on the concept of hype, whose impact is debated among interviewees. The impact of varying value goals between stakeholders on collaboration and the impact of value uncertainty on those collaborations is placed in the context of quantum technology uncertainty, providing a groundwork for future research. Other aspects, such as communication, organizational culture, and the quantum champion, were topics that were not significantly explored. This research provides initial insight into the impact of those aspects on the adoption of quantum technologies.

“FVM fills a methodological gap for early-stage, pre-collaboration enabling technologies.”

The development of the Future Value Mapping method contributes to the field of strategic foresight methods by creating a method specifically suited for deep uncertainty, a value focus, and stakeholder interconnectedness. Existing methods were developed for different contexts and are ill-suited to deal with the uncertainty of quantum technologies. FVM fills a methodological gap for early-stage, pre-collaboration enabling technologies. By combining normative scenario creation, backcasting, and what-ifs into a single integrated process, the method produces a comprehensive method well-suited for practice.

The implications of this report have concrete implications for practitioners. The knowledge

generated through the literature review and interview study provides useful insight for many stakeholders. It reinforces the role the government should play in the development and valorization of quantum technology. Which in turn, provides policymakers, ecosystem builders, and business developers with the theoretical backing to convince government organizations to take on this role. Due to the high development costs, acting as a launching customer will give the entire ecosystem a boost. The same is to be said about the development of infrastructure. Currently, insufficient infrastructure serves as a barrier to adoption, but by providing infrastructure, the government can create a landscape where several actors can engage in the development of quantum technology.

The lack of funding, often mentioned as a barrier to development and adoption compared to other countries such as the USA and China, requires initiative from public and private organizations. The difficulties in acquiring funding for scaling up and the regulatory burden associated with public funding limit the growth of startups. Quantum development requires high initial costs and comes with significant risks. Those risks should be shared among stakeholders, with a clear path-oriented development trajectory. Public roadmaps and prioritization by the government provide incentives for private funders while decreasing the perceived risks.

The role of QDNL is praised, but criticism was also raised by several interviewees, which should act as a wake-up call to improve the role QDNL currently plays in the Dutch ecosystem. The ecosystem requires active orchestration, and organizations such as QDNL and QuTech should take on that responsibility. The findings that collaborations frequently stall after initial contact, the critical gap is not awareness, but the challenges in setting up the active collaborations. This requires mediation, where FVM can play an important role.

QuTech aims to be a leader in the quantum ecosystem, not only in hardware development but also in mission-driven development. Due to their position, they are involved in many collaborations with the industry, but also experience the challenges in setting them up. FVM provides a framework to engage in conversations with potential partners, addressing value uncertainties.

QuTech could use FVM as a facilitation format when approaching new industry partners: running a structured value mapping session around a specific scenario relevant to that partner's domain. This gives the conversation a concrete object to work around, rather than leaving it in the abstract. Furthermore, as an organization with major influence on the trajectory of quantum technologies in the Netherlands, they hold a responsibility to develop it both mission-driven and value-driven. While some scientists might pursue science solely for the acquisition of new knowledge, their discoveries should add value to society. The importance of focusing on value creation and a tool to map those values is explained throughout this report.

The Future Value Mapping method provides experts and non-experts of quantum technologies with the tools to strive for value-driven development and therefore adoption. It has been showcased using two applications, personalized medicine and secure communication, but it can be applied to other quantum technology applications. The guidebook, alongside the method as explained throughout this report, serves as a tool for practitioners to use. It can help business developers in setting up collaborations, policy makers in creating a foundation to base their initial legislation on, and ecosystem developers in creating strategic roadmaps. It highlights the steps all stakeholders have to take to realize a desired future.

12.3 LIMITATIONS

Several research limitations were already discussed in *5.3 Limitations*. To summarize, the qualitative study was conducted only within the Dutch quantum ecosystem, which limits its transferability to other countries. The semi-structured nature of the study affects its repeatability, and a quantitative study involving a wide range of participants could validate the findings. The pool of participants leaned towards non-technical roles within quantum development to improve the quality of the findings; this scope could be widened for additional insights.

The FVM model was developed by a single researcher, based on input from several other researchers. This affects the model's neutrality, given that the researcher's values are intertwined with the model, albeit implicitly. Proper evaluation

and reflection from peers would improve the quality of the work. The model has been tested with two showcases, but further testing with more use cases could improve its validity. Only a single workshop was run to test the model, using the expertise of participants from QuTech. For improved quality, several workshops should be run, utilizing insights from a broader range of stakeholders. Running several iterations of the model would furthermore improve the reliability of the process and would undoubtedly lead to more insights into how the model can be improved.

The research and method were developed at a specific moment in the development trajectory of quantum technologies. The findings and model reflect the current state of development and are influenced by topics that are deemed relevant today. As mentioned previously, value is time-dependent, based on what we currently consider important. The same applies to the other results from the qualitative interview study. For example, startups might mainly share challenges they face at that moment in time, but a few weeks later, these could be redundant. It is important to be aware of the influence of time on the validity and repeatability of the results.

12.4 FUTURE RECOMMENDATIONS

Several future research directions and recommendations emerge. The results from the qualitative study could be validated and expanded through larger sample sizes. This could be done within the Netherlands, but also by including more countries. Expanding the study with a quantitative survey would increase its validity. Expanding the research across various countries would allow for comparison between nations, which would shed light on barriers specific to certain ecosystems. Funding challenges can be better understood by engaging in a comparative study.

The FVM method should be applied across various stakeholders and with several use cases to improve the method. Throughout the creation of the method, an iterative approach was taken. This improved the quality of the work, and by continuing this iterative approach, several additional sessions could improve the model. Throughout the implementation phase, a study can be undertaken to understand why organizations are

or are not likely to engage in the use of the model. The results, if collaborations are formed and shared value is sought after, should be tracked to better understand the impact of the model.

The model has been developed for a quantum technology context. Further testing among different technology domains would validate the claim that it can be used in other deep tech fields. Finding technologies with different TRLs, different stakeholders, and a different impact could shed light on the most valuable application of the FVM method.

The barriers to adoption arising from communication challenges and the communicative attempts made by the FVM method should be researched. As communication has a big impact on adoption, it should be understood properly. Further academic research into communication challenges around quantum technologies is required. The communication through the Future Value Mapping method should be tested alongside the academic research to enhance the communicative bridging abilities of the method.

Measuring value beyond economic value is a research field that should be expanded. Value exists beyond monetary, but given the challenges in measuring that value, it becomes increasingly difficult to strive for those other types of value. Societal progress is not just measurable through economic growth, but other concrete ways of measuring are scarce.

Technology is neither good nor bad, nor is it neutral. The development of quantum technologies will be shaped by the choices made now: which actors are involved, what direction is agreed upon, and how uncertainty is handled. This report argues that value-driven development is important and that collaboration is a prerequisite to creating a quantum future worth building.

13. CONCLUSION

Quantum technologies have the potential to change the world, but potential alone will not realize any value or bring organizations together. This report explored the barriers organizations face in adopting quantum technologies and proposed a method to map future values and stimulate collaboration.

Barriers to adoption

Barriers to adoption were explored through a literature review and a semi-structured qualitative interview study with 15 experts in the Dutch quantum ecosystem. The literature identified barriers across four categories: technological, organizational, knowledge-based, and environmental. The interviews confirmed these barriers and provided more nuance and context to some of them. Certain barriers were more dominantly present in the Dutch ecosystem than others.

The technological steps required to reach maturity are among the biggest challenges, albeit outside of the scope of this research. The uncertainty that comes with the development of quantum technologies was recognized as the most influential barrier: uncertainty regarding development time, costs, and funding, but also regarding the value it might create. The lack of clear, advantageous applications and a “*killer application*” serves as an organizational barrier and impedes engagement in and adoption of quantum technologies. Uncertain value creation hinders collaboration, as it leads to a lack of a clear goal or direction, which is required for successful collaborations.

Quantum technologies face many knowledge barriers to adoption. Language, in particular, is a major challenge for quantum technologies. Each stakeholder speaks their own language, and finding a common language between experts and non-experts is a constant challenge. A comprehensive understanding of quantum phenomena is not required for engaging in quantum technology development, however, differences in the level of understanding can lead to collaboration challenges. The required level of knowledge for non-experts is unclear, making it difficult to determine what and how to communicate. The

hype surrounding quantum technologies generates the required attention, but risks creating unrealistic expectations and a potential quantum winter if those expectations are not met.

The importance of proper infrastructure and the role of the government in commercialization were mentioned as the main environmental barriers. Proper infrastructure serves as the foundation for the development and valorization of quantum technologies. The government has a major role to play in stimulating infrastructure development, serving as the launching customer, stimulating collaboration, and valorization.

Future Value Mapping

Future Value Mapping (FVM) was developed in response to the barriers organizations experience when engaging with quantum technologies. Uncertainty, the need for clear value creation, limited collaborations, and widespread communication challenges all limit adoption and engagement in quantum technology development. FVM provides a structured approach to navigate this uncertainty, bringing stakeholders together and highlighting the value and risks of quantum technologies. FVM uses three interconnected phases. The first involves creating normative scenarios that show the value a future can bring for various stakeholders. The second phase is backcasting: identifying concrete interventions required to realize the future scenario based on *what-how-who* questions. The third phase involves developing what-if questions to identify the consequences, risks, and opportunities of the scenario. This report showcases the methodology using two cases: personalized medicine and secure communication. The distinct role of the government, the interconnectedness of stakeholders, and the potential implications of the technologies were identified.

Final remarks

This report adds to the academic literature by identifying and confirming barriers to the adoption of quantum technologies for organizations in the Dutch ecosystem. The resulting method showcases the importance of striving for value creation in technology development and provides a practical tool that brings stakeholders together amidst uncertainty.

14. ETHICS ESSAY

My perspective on creating meaningful quantum technologies

Talking about the future of quantum technologies cannot be done without considering ethical issues. Various aspects of the development and use of the technology affect many stakeholders. It is therefore important to be aware of those ethical questions and how they should influence the development trajectory of quantum technologies. The potential of the technology is great, but so are the risks. Below is my perspective on several ethical questions.

Quantum technology development is receiving a lot of attention. Through media coverage and from major governments of developed countries. In the Netherlands, quantum technologies have been recognized as a key technology, leading to significant funding. However, a major reason for the focus and investment is to win the so-called “quantum race”. Countries, through their organizations and universities, are competing to be the first to achieve quantum supremacy. This gold rush towards, i.e., the first country to have the capacity to break current-day encryption, has become a development battle that fosters protectionism. The Wennink report describes the potential impact quantum technologies can have on our economy and the global role the Netherlands could play by creating a mature ecosystem. While this is true, and the potential value of a leading quantum ecosystem could be high, the focus of its development influences the value that the ecosystem ultimately creates and how it is used. Striving to be the most dominant (commercial) actor in the global quantum technology arena is currently pursued from a geopolitical perspective, aiming to achieve what other countries do not have and leveraging that for national advantage. This kind of development is not one that should be prioritized.

Quantum technologies, if developed in isolation, can lead to a major increase in the divide between actors. Infrastructure, supply chains, financial capacity, and talent are currently concentrated within a few countries. While there is competition among those countries for talent and technology development, the main divide will emerge between nations that have the capabilities to develop quantum technology and those that do not. The barriers to entry are high, and they will only increase as the technology matures and nations build their capabilities. As

developers of the technology, these countries have a responsibility to create open networks and promote access for countries lacking the resources to develop it on their own. The value quantum technologies can create has enormous potential, but if this value is captured only by the countries already engaged in their development, then the overall potential is significantly lower. Equitable quantum technology development could serve as a showcase for other emerging technologies, such as nanotechnology, genetic engineering, and artificial intelligence, that can be developed responsibly. These fields share a potential to disrupt society positively and generate substantial value, while also carrying a risk of deepening global inequality. With quantum technology development, we hold a responsibility to show that the development of disruptive technologies can be done in an ethical and value-inclusive manner, which in turn will stimulate inclusive development across other technologies.

Supremacy and value creation

The concept of quantum supremacy or quantum advantage, the ability to solve problems that classical computers cannot, is often seen as the milestone to work towards. If this leads to new types of value creation, solving actual, useful problems that would otherwise be unsolvable, then it is a worthy milestone. But pursuing supremacy for the sake of supremacy is a different matter. Similarly, if winning the quantum race means winning a geopolitical race or breaking RSA encryption first, then we should ask ourselves if that really is the goal we want to achieve. Developing quantum technologies for development’s sake is far from value-driven or inclusive. The applications of the technology should create value for society, and we must be wary of losing that goal out of sight. As impressive as it might be from a technological

point of view to break RSA encryption or reach quantum advantage, neither achievement in isolation will actually improve the world. Actual value for society should be created; that should be the milestone toward which we should work.

The current focus on value creation is predominantly economic and strategic in nature. Winning the quantum race will lead to an advantageous global strategic position, and having large, commercially active quantum companies will improve the economic capacity of a country in the long run. Understandably, those are among the main and most apparent value drivers. But beyond GDP growth, quantum technologies hold significant broader potential that is often overlooked. Because GDP is relatively easy to measure and track, while other values such as 'Brede welvaart' (*broad prosperity* in Dutch) are not, there is a significant risk of the metric becoming the goal. While this is not a challenge unique to quantum technologies, it does influence the way the technology is developed. If the main focus is to create commercial economic value, stakeholders may make narrower choices during the development process. There needs to be room to stimulate the development of applications that might not have an immediate monetary impact. The government has an important role to play in ensuring value-driven development beyond GDP and should proactively embrace this role.

Actors involved in development

The various actors involved in the development of quantum technologies have a shared responsibility to ensure meaningful development. This requires the active engagement of all stakeholders: the developers who shape the technology, the governments that create the conditions for its growth, and the users and society who ultimately determine its value. The developers carry a responsibility beyond technical feasibility. In any design or development process, the choices made reflect a set of values, even if they are not made explicit. Technology developers need to be aware of their own responsibility throughout the development and should aim for responsible innovation. The government, in turn, creates the framework in which the development occurs. Through funding, regulation, and prioritization, it influences the applications that are pursued. This

requires holistic thinking and active involvement of various actors throughout the creation of the playing field. Governments must balance economic goals with broader societal goals, and protectionism with room for technological development. The users: citizens, organizations, and society, do not play a passive role in the development. They are the ones who dictate what value is created, which problems should be solved, which risks are acceptable, and for whom value should be created. Yet currently, this group is insufficiently involved; the conversations with society do not occur enough, and they should be given a far greater role. Meaningful development is a shared and collective endeavor, and that demands active collaboration between all three groups.

Concluding remarks

None of the abovementioned points will happen on their own. They require individuals, organizations, and governments to take an active role in pursuing the ethical and responsible development of quantum technology. It requires people to think beyond their own frame of reference and value system to understand different perspectives. Mediators can bridge the gap between different professional languages and bring stakeholders together, stimulating conversations and helping to remedy knowledge barriers. The Netherlands, as one of the leading countries in quantum technology development, should play a part in this. A leading position comes with influence, and influence comes with responsibility, specifically the responsibility to initiate the conversations about ethics, values, and meaningful development. Not all countries share the same regard for equality, democratization of technology, and value-driven development. The Netherlands and Europe therefore have a responsibility to pursue a path that actively includes these conversations and ensures that collaboration is prioritized. The risk of ethical deliberation slowing down development and becoming a competitive disadvantage is real, as seen with AI regulation within Europe. The challenge lies in integrating ethics and ambition, because disregarding the implications will only lead to a loss of value in the long term. The Netherlands has the opportunity to demonstrate that technological ambition and ethical responsibility are not opposites, but mutually reinforcing.

15. REFLECTION

My reflection on the process of creating this report and strategic design

When looking back at the report, I can say with confidence that I learned a lot over the past months and developed myself as a strategic designer, an engineer, and a person. Throughout this project, I wanted to dive into the world of quantum technologies and learn how strategic design can be used to create a bridge between deep tech, organizations, and people. I believe that I have been able to do so and am happy with the results.

15.1 REFLECTION ON THE PROCESS AND REPORT

Process

When looking back at the process that brought this report to realization, it was one with ups and downs, but overall, I look back on it confidently. The project started with my intrinsic curiosity about quantum technologies and the Draghi Report. When that report was published, I found many things in it that I agreed with. With a global stage that is changing, I felt that Europe should work on its independence and competitive position. ASML has a unique position, and I felt that the Netherlands should create more such organizations here, as it would benefit us greatly. Quantum technology is an emerging technology with great potential, so it felt like the right technology to focus on. Quickly, I realized that a lack of funding was a major barrier for many organizations to grow, resulting in them moving to the United States. These personal beliefs led to the start of my project. But as time went on, I realized that the lack of funding is mainly a political decision and therefore hard for me to influence. However, I also realized that many more challenges prevented such growth. I was initially very surprised to find out that so few organizations were actively engaged in the technology, given its huge potential impact. So, a very curiosity-driven approach led me to explore the barriers to the adoption of quantum technology.

If I were to summarize the process into one sentence, it would be: making sense of uncertainty. Fittingly, also the result of the project. When

the project started, there was no clear end goal, but through research and discovery, a trajectory formed. Kees called this an 'entrepreneurial mindset', which resonated with me because the process forced me to reflect and adapt frequently. This helped me overcome the difficult moments where the uncertainty and lack of direction were major challenges. I forced myself to zoom out, stand in front of a whiteboard, and reflect on my findings so far, to ask the question: 'So what?'. I would say this approach is what I am most proud of when looking back at the process. Designers are taught to deal with uncertainty, to make sense of problems when little is known. This project introduced a new level of uncertainty for me. Yet every time doubt or vagueness crept in, I went back to a whiteboard and restructured the project in my head.

Most design projects aim to solve a problem. This problem might not be well defined, but there is a clear problem to solve. This project explicitly does not try to solve a problem. Halfway through the project, I realized that there was no problem for me to solve. Challenges such as a lack of funding, difficulties in collaboration, and a lack of applications are all problems that are inherent to society and quantum technologies. This forced me to take on an inquiry-based approach. Initially, I struggled to figure out what this would mean for my process, but as time went on, it started to make sense. When looking back now, it might even feel naïve to attempt to solve a problem within this scope. It showed me that strategic design is a very useful tool even when no clear problems are defined.

Report

The report starts with a literature review and a qualitative study on the barriers to the adoption of quantum technologies. Conducting the interviews might have been the most fun part of the project. In general, people were happy to talk to me and share their thoughts, and did so with full enthusiasm. People who work in quantum technologies often do so from an

intrinsic motivation, making the conversations very positive and filled with passion. Interviewing people with various backgrounds and hearing their perspectives was a unique and joyful opportunity. After analyzing the results of the interviews through *Atlas.ti*, I was initially surprised by how much the literature and interviews resonated with each other. Certain topics were highlighted more frequently, but in general, most topics were expressed in both the literature and by the experts. Only when conducting a deeper analysis did I find new and unique insights, with the impact of uncertainty emerging as the most dominant.

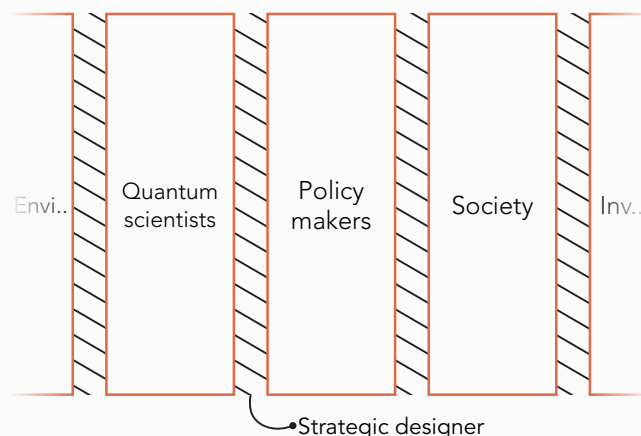
The development of the Future Value Mapping method started out difficult. The shift from problem-solving to inquiry-based research made the start difficult. I was forced to reflect on the goal of the project many times. At some point, I started to think about what type of method I would use to structure the process, which led to the FVM. I initially never intended to create a method; I wanted to provide structure amidst my uncertainty. But this led to a method that I believe is useful in many contexts.

15.2 REFLECTION ON STRATEGIC DESIGN

The deep scientific world was new to me as a designer. While I had a curiosity about the physics behind quantum, I had no official education in it. There were some instances where I felt underqualified while being surrounded by PhDs in quantum, but in general, I felt at ease in this new environment. Design education teaches you to ask questions, also in surroundings that you might not be familiar with. This allowed me to learn quickly. The human-centered approach of design serves as a tool to create a bridge between worlds. The inclusivity of various stakeholders and creative thinking allows strategic designers to operate between the silos. This might not be the most obvious use of design, which usually centers around the creation of products or services, but it provides real value. Collaboration between different stakeholders, each with their own goals and challenges, requires facilitation, and strategic designers are very well positioned to do so.

As mentioned, design excels at dealing with uncertainty. Any design process starts by aiming to understand the problem behind the problem and

Figure 25: Role of strategic designers



uncovering implicit factors influencing the process. Strategic design does so for strategic challenges, and the development of deep tech is a strategic challenge. There are many factors influencing the development of quantum technologies, such as the high number of stakeholders, the varying goals, the challenges, the political landscape, and more. Creating structure amidst this complex ecosystem and highlighting interdependencies is a task very suitable for strategic designers.

15.3 OTHER REMARKS

I hope that I was able to create a bridge between two worlds. While geographically very close, there is a big distance between Industrial Design Engineering and QuTech, unfortunately. As of writing, there are conversations underway to set up more collaborations, and I fully encourage them. I believe that both sectors would benefit significantly from each other's expertise.

I am satisfied with the result. The research part was important because I believe conducting research is an important part of science at a university. Being able to combine that with design thinking and develop something that I believe has value makes it a successful project for me. I am happy with how this project has developed me further as a professional. I believe that there is a need for people who can bridge the gap between hard technology and other experts, and I believe that I have developed skills to create that bridge.

I hope that with my report, I can inspire other professionals to take on a role as a mediator between the silos. Technology development needs people who are able to bring stakeholders together.

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Use of Artificial Intelligence tools

AI-assisted tools played a role in researching, synthesizing information and as creative facilitator. Perplexity and Gemini were used for research purposes to explore several scientific topics through for example, finding additional papers, comparing papers, and structuring large pieces of content. Especially Perplexity served as a useful research tool to find additional information and checking references. At all times were the results generated by the tools manually verified using the provided sources. The quality of the sources were checked every time.

No confidential information was used while interacting with the AI tools. In no part of the qualitative study were AI tools utilized.

AI tools were used as creative facilitator. By asking brainstorming questions and sparring with the tool new creative insights were generated. In the creation of illustrations, AI tools (especially Gemini) were used to fine tune illustrations and create cohesion. All illustrations were drawn by hand and optimized using tools. This worked well as long as very specific instructions were given.

The writing of parts of this thesis was checked using AI tools, specifically Claude through Perplexity. All text was written by hand by the author of this report, but since English is not the native language of the author, specific grammar rules were checked. These suggestions were taken into consideration and often disregarded.

The AI tools were only used as supporting tools.

17. APPENDIX

The following items can be found in the appendix:

A) Guidebook

B) Interview guide

C) Workshop materials

D) List of applications - top 7

E) Code table

F) Project brief

A) GUIDEBOOK

Introduction

The future is dominated by uncertainty. In the context of technology development, this uncertainty may prevent organizations from engaging altogether. Collaborations that aim to stimulate the development or adoption of new technologies require a collective goal and direction. Articulating the value technology can create, while accounting for the differences between stakeholders, is important. Quantum technologies hold the potential to realize transformative value, but are filled with uncertainty.

Uncertainty, the need for clear value creation, limited collaborations, and widespread communication challenges all limit the adoption of and engagement in quantum technology development. Future Value Mapping (FVM) provides a structured approach to navigate the uncertainty of quantum technologies, bringing stakeholders together and highlighting the value and risks of quantum technologies. FVM uses three interconnected phases. The first involves creating normative scenarios that show the value a technology can bring for various stakeholders. These do not serve as speculation or prediction, but as a concrete vision that forms the starting point for looking back. The second phase is backcasting: identifying concrete interventions required to realize the future scenario based on what-how-who questions. The third phase involves developing what-if questions to identify the consequences, risks, and opportunities of the scenario. All three phases inform decision-making today.

Together, the three phases and six steps form a coherent and iterative method that serves multiple purposes: stimulating dialogue between stakeholders with different values, goals, and expertise, highlighting interdependencies, and creating a shared direction. The purpose is not to predict the future, but to prepare stakeholders and stimulate development by transforming uncertainty into a starting point for action. FVM has been applied to two proof-of-concept cases, personalized medicine and secure quantum communications, demonstrating its adaptability across domains.



GUIDEBOOK

Future Value Mapping

Turning quantum technology
uncertainty into collaborative
value creation

Spring 2026

Case – Secure Communications

Scenario

Secure communications through Quantum Key Distribution (QKD) use quantum mechanics to generate encryption keys that are impossible to intercept or break. Using quantum communication lines, an encryption key is created and used to encrypt the data sent over classical communication lines. Any attempt to intercept the quantum connection line is physically detectable, exposing eavesdropping.

This enables secure communication to be established between critical infrastructure, including energy grids, government data exchanges, airports, ports, and financial institutions. Such secure communication enhances sovereignty and strengthens resilience against hostile threats, helping to prevent failures caused by cyber-attacks.



Stakeholder	Value
Government	National security, strategic autonomy, sovereignty, ..
Academics	Scientific advancement, quantum internet research, education, ..
Investors	Investment opportunities, growing security market, ..
Startups	Hardware development, business opportunities, ..
Industry	Infrastructure development, first-mover advantage, ..
General public	Privacy, sense of security, trust in digital systems, ..

Backcasting

QKD is far along in its development and valorization compared to many other quantum technology applications. But it requires further development in hardware, network infrastructure, and standardization. Quantum repeaters, error correction, and interoperability with classical networks are key technical milestones that need to be achieved. The development of compatible infrastructure, the creation of launching customers and supply chain providers are enablers, while high costs, a debated reputation, and range scaling issues are barriers to development. Governments, infrastructure developers, and critical infrastructure organizations should align on data security acts and implementation plans. Incentives from the

government should provide a clear reason to switch. Through pilot projects and expansion, a national network ought to be created. Below is a snapshot of the roadmap to indicate what it could look like.



What if (example)

What if we start to rely too much on the technology for security?

Stakeholder story – Port employee – Erik – 58
 Erik has worked at the Port of Rotterdam for 35 years. He was once the most tech-savvy person, so he slowly grew into a role where he was responsible for maintaining secure data communications within the port. A new QKD communication system rollout promised unhackable, future-proof communication links. Fiber optics, quantum entanglement, and key management, all too complicated for him in this day and age. But he kept being told: "You don't need to understand how it works, it just works". For Erik, it's a black box. Every month, an employee of the QKD company comes to the port to update some systems and to verify that everything is still functioning properly. Erik trusts that it all works well, but how can he be responsible for something that he does not understand? Is the Dutch government's attempt to future-proof its critical infrastructure not just one that makes it more complicated? Are we not replacing one dependency with another, a dependence on a technology that is a black box to many?

Reflection

QKD can play a big part in setting up secure communications. During a time when cybersecurity threats are increasing, these innovations can make a difference for national security. But the infrastructure needs to be developed, and launching customers are required. Collaboration between government, industry, telecom providers, and academia is needed to scale the technology. Stakeholders must be mindful of the risks and dependencies associated with the technology. Standardization, pilots, and cross-sector alignment are required today to secure a digital future.

FVM Method

The Future Value Mapping method consists of six structured steps designed to connect a desirable future to actionable steps today, while keeping value creation central throughout.

- 1. Orientation** — Familiarize yourself with the content, stakeholders, and the scope. This grounds the process in reality rather than speculation.
- 2. Scenario creation** — Generate and develop normative future scenarios, followed by an initial value analysis. Scenarios serve as a dot on the horizon leading to a shared direction rather than a rigid goal.

- 3. Backcasting** — Starting from the scenario, work backward using What-How-Who questions to identify what steps are needed, how they can be realized, and who is responsible, using input from external stakeholders
- 4. Refinement** — Refine the scenario using the gathered input and build a roadmap across three collaboration-based horizons, analyzing key risks and value opportunities.

- 5. What-if creation** — Explore speculative consequences of the scenario to surface unforeseen risks and opportunities, stimulating stakeholders to act preventively today.

- 6. Reflection** — Assess what the results actually mean in practice, verify alignment with the original goal, and reflect on any biases in the process.

More information can be found at: <https://qutech.nl/FVM>

Step 1: Orientation	
1A	Content familiarization
1B	Stakeholder analysis
1C	Scope setting
Step 2: Create scenarios	
2A	Idea generation
2B	Scenario development
2C	Initial value analysis
Step 3: Backcasting & Input gathering	
3A	Initial What-How-Who analysis
3B	Participatory value analysis
3C	Participatory What-How-Who analysis
Step 4: Refinement	
4A	Scenario refinement
4B	Roadmap development
4C	Analysis
Step 5: What-if creation	
5A	Idea generation
5B	What-ifs development
5C	Analysis
Step 6: Reflection	
6A	So what?
6B	What does this mean?
6C	Goal alignment

“The future is uncertain... but this uncertainty is at the very heart of human creativity.”

ILVA PRIGOGINE
Nobel Prize winner in Chemistry

Author
Lennart Hessels
QuTech
TU Delft

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This guidebook is intended to support meaningful technology development, stimulate collaboration, and aid in path-oriented development.

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B) INTERVIEW GUIDE

General

Goal: Learn about values, barriers and collaboration from Rebecca

Structure: Semi-structured interview

Introduction

- Aim of research
 - *I wish to understand your motivation to work in quantum, the value you seek to create*
 - *Aim to understand the barriers in adoption and commercialization of quantum technologies*
 - *Understanding collaborations between public and private actors for the development of quantum, previous PPP collaborations, the obstacles and opportunities for those PPPs.*
- Explain that the information will only be used for this research purpose.
- Takes +- 30 minutes.
- You will remain anonymous, unless you are okay with being mentioned by name
- Ask approval for recording

Questions

General questions [understand value's] (6 min)

- Could you start by explaining your role at X?
- Why do you work in Quantum? Why do you work at X?
- What is in your words the mission of X? What is the value they aim to create?

Private-Public questions (12 min)

- What types of organizations does your department collaborate with? (Which you are allowed to share)?
 - What is the motivation of those organizations to collaborate?
 - Have you experienced challenges in collaboration? Are there conflicting values from time to time
- Do you believe there is a need for Private and Public organizations to collaborate in order to develop quantum tech? Why/why not?
 - What are in your opinion the things that such a collaboration can bring that can't be realized without it? (benefits)
 - What do you see as challenges for a collaboration?
- The collaboration with X, could you elaborate a little on it? Why was it started, what were the main drivers, what went wrong?
 - Working with milestones and a timeline is something that private organizations often do, because it helps generate results, but that is difficult to translate to science and quantum, what is your view on that?

Barriers (12 min)

- What do you view as the biggest challenges in the adoption of QT? And what are the challenges in order to get it commercialized?
 - *If main focus is on the technological challenges* - Besides the technological challenges, what other barriers do you experience?
- Do you have examples of how and when you experienced these barriers?
- Are there ways you have tried to overcome these barriers?
- What do you see as potential solutions for these barriers?

In case time left

- Are there things that are still missing in the current quantum ecosystem?
- What do you see as the responsibility of X when it comes to the development of QT, given the leading role it has?


End questions (3 min)

- Are there things that you feel like I should take into consideration that I have not asked a question about?
- Are there people that you feel I should speak to?
- If in 2/3 months' time I have developed something like a framework or vision, would you be open to share your insights regarding my findings?


C) WORKSHOP MATERIALS

1

Personalized Medicine

<p>Today</p> <p>Horizon Long-term</p> <p>Focus Computing Pattern identification Drug discovery</p> <p>Barriers Technological Financial Knowledge Organizational</p>	<p>What needs to happen for this scenario to become a reality?</p>	<p>Scenario</p>  <p>Personalized medicine rolled out in hospitals throughout the Netherlands. Available for majority of Dutch citizens.</p>
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Secure Communication

<p>Today</p> <p>Horizon Short-term</p> <p>Focus Communication Cybersecurity Vital infrastructure</p> <p>Barriers Technological Financial Knowledge Organizational</p>	<p>What needs to happen for this scenario to become a reality?</p>	<p>Scenario</p>  <p>QKD communication for vital infrastructure is set up through (inter)national network using repeaters and satellites.</p>
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2

Technological	How can these changes be realized?	Who should act?
Financial	How can these changes be realized?	Who should act?
Knowledge	How can these changes be realized?	Who should act?
Organizational	How can these changes be realized?	Who should act?

Personalized Medicine through Quantum Computing – a scenario

Personalized Medicine

Personalized Medicine uses quantum computing to better understand the complexity of biological systems of individuals. By using quantum-enabled algorithms, it is possible to search through high-dimensional data like EHRs (Electronic Health Records) and other biological information of patients, such as genes, lifestyle, and symptoms, to uncover patterns. These patterns help accurately look for anomalies to better predict sickness, shifting the focus towards prevention rather than curing. Combined with the ability to simulate complex molecular interactions for drug design, these tools assist in determining accurately which medication, dose, and scheduling works best before any drugs are administered. If new data is entered, such as a change in lifestyle, an adjustment can be made to the care. Instead of healthcare based on statistics of the general population, it is personalized for each individual.

Stakeholders

Several key stakeholders are involved. Academia and startups researching and developing the technology, government forming regulations, industrial partners such as hospitals, pharmaceuticals, and laboratories, doctors and other professionals interacting with the technology, investors investing in the technology, and the general public.

Initial value analysis

- Improved healthcare for individuals, improving the quality of their lives
- Happier population and lower health costs (over time)
- Decreased time and costs required for drug development. Increased success rate

Initial necessary steps

- Qubit scalability, decoherence, and error-correction need improvement to mature the technology. Rich data about patients is required for analysis. Hardware requirements need to be met and miniaturized.
- Funding is required to make medical development possible, with its high financial costs. Pilots need to be funded by governmental parties, and private investors are required to scale the technology.
- To tackle knowledge challenges, professionals need to be educated, and new talent should be created in collaboration between universities and the industry.
- The organizations and environment need to adapt to the new technology. Having discussions about ethics, forming regulations, and integrating them into existing workflows.

Secure Communication through Quantum Key Distribution – a scenario

Secure Communication

Quantum Key Distribution (QKD) allows for the encryption of data, which is impossible to eavesdrop on and is resistant against future quantum computers that aim to decrypt data. Using quantum connection lines, an encryption key is created, which encrypts the data sent over classical communication lines. Any attempt to intercept the quantum connection line is physically detectable, revealing eavesdropping. Quantum communication lines require quantum repeaters or satellite connections to operate securely over long distances. Secure communication between critical infrastructure, such as energy grids, governmental data exchange, airports, ports, and financial institutions. Secure communication means more sovereignty and strengthens resilience against hostile threats, preventing failures due to cyber-attacks.

Stakeholders

Several key stakeholders are involved. Academia researching the technology together with startups and industrial partners such as equipment vendors and infrastructure providers who develop the technology, governmental and public organizations using the technology for the infrastructure, investors investing in the technology, and the general public.

Initial value analysis

- Secure future-proof communication, high cybersecurity
- Resilient and reliable infrastructure
- Increased autonomy and trust

Initial necessary steps

- QKD devices, repeaters, and satellites require technological improvement to increase utility. It needs to be integrated into classical communication systems.
- High setup costs require financial support from public organizations. Unclear ROI needs to be addressed, quantified, and long-term support is required.
- To tackle knowledge challenges, professionals need to be educated, and new talent should be created in collaboration between universities and the industry.
- Standardization of systems is among the organizational steps that are required. Creating legislation for a new type of communication, after creating awareness, is needed. Organizations need to adapt and develop their infrastructure to make it future-proof.

D) APPLICATION TABLE (Harris Profile (+/-))

# Scenario	Field	Description	Technology Term	Value creation for several stakeholders	Level of impact	Quantum advantage	Relevance	Specificity
1	Personalized medicine	Health	Tailor personalised treatments based on DNA.	Comp/Sens	Long	++	++	++
2	Secure communication	Cyber security	Probably secure cryptographic key exchange using quantum mechanical properties.	Comm.	Short/mid	++	++	++
3	Fertilizer development	Agriculture	Development of efficient nitrogen fixation methods to reduce fertilizer costs and environmental impact.	Comp.	Long	++	++	+/-
4	Climate and weather prediction	Nature & Climate	High-resolution simulation of atmospheric, oceanic, and ecological interactions for improved climate predictions.	Comp./Sens	Mid/Long	++	++	+/-
5	Material design	Material	Creation of novel materials with enhanced strength, conductivity, or other specialized characteristics. For example improved battery technology	Comp.	Short/mid/long	++	++	+/-
6	Optimized logistics	Logistics	Route optimization, inventory management, logistical planning, supply and demand prediction through quantum algorithms.	Comp.	Short/mid	++	+	++
7	Autonomous driving	Mobility	Improved LIDAR, GPS, traffic optimization, and AI decision making to improve potential of autonomous mobility	Comp./Sens	Mid/Long	+/-	+/-	++

E) CODE TABLE

Code Group	Code category	Sub-theme
Challenges during collaboration	Collaboration challenges	Collaboration challenges
Challenges in collaborating with other types of organizations	Collaboration challenges	Collaboration challenges
Challenges in setting up collaboration	Collaboration challenges	Collaboration challenges
Downsides of collaboration	Collaboration challenges	Collaboration challenges
IP challenges	Collaboration challenges	Collaboration challenges
Quantum Champion	Collaboration challenges	Collaboration challenges
Time challenges in collaborating	Collaboration challenges	Collaboration challenges
Transparency in collaboration	Collaboration challenges	Collaboration challenges
Difficulty moving past initial meeting	Collaboration commitment	Collaboration challenges
Passive commitment in collaboration	Collaboration commitment	Collaboration challenges
Collaboration requirements	Collaboration requirements	Collaboration challenges
Requirement of clear goal for collaboration	Collaboration requirements	Collaboration challenges
Differing interests	Different stakeholder interests	Collaboration challenges
Interests academia	Different stakeholder interests	Collaboration challenges
Interests government	Different stakeholder interests	Collaboration challenges
Interests private organizations	Different stakeholder interests	Collaboration challenges
Interests QDNL	Different stakeholder interests	Collaboration challenges
Lack of stimulance for collaboration	Stimulating collaboration	Collaboration challenges
No need for stimulating collaboration	Stimulating collaboration	Collaboration challenges
Stimulances for collaboration	Stimulating collaboration	Collaboration challenges
Collaboration goals	Reason to collaborate	Collaboration value
Collaboration in the region	Reason to collaborate	Collaboration value
Creating use cases as reason to collaborate	Reason to collaborate	Collaboration value
Impact collaboration on development	Reason to collaborate	Collaboration value
Infrastructure as reason to collaborate	Reason to collaborate	Collaboration value
Knowledge as reason to collaborate	Reason to collaborate	Collaboration value
Monetary as reason to collaborate	Reason to collaborate	Collaboration value
Position Europe as reason to collaborate	Reason to collaborate	Collaboration value
Pressure as reason to collaborate	Reason to collaborate	Collaboration value
Lack of collaboration	Amount of collaboration	Current collaborations
Sufficient collaboration	Amount of collaboration	Current collaborations
Collaboration in Europe	Current collaborations for Quantum	Current collaborations
Collaboration in the Netherlands	Current collaborations for Quantum	Current collaborations
Development goal	Development focus	Environment
Increased focus on applications	Development focus	Environment
Lack of focus on commercialization	Development focus	Environment
Lack of focus on solving problem	Development focus	Environment
Sufficient focus on commercialization	Development focus	Environment
Connecting challenges ecosystem	Ecosystem	Environment
Lack of coordination and standardization	Ecosystem	Environment
Lack of large organizations	Ecosystem	Environment
Startup retention	Ecosystem	Environment
Strengths ecosystem	Ecosystem	Environment
Weaknesses ecosystem	Ecosystem	Environment
Infrastructure	Infrastructure challenges	Environment
Politics	Political challenges	Environment
Regulation	Regulatory challenges	Environment
Role academia	Role stakeholders	Environment
Role government	Role stakeholders	Environment
Role industry	Role stakeholders	Environment
Role non-experts	Role stakeholders	Environment
Role QDNL	Role stakeholders	Environment
Role society	Role stakeholders	Environment
Role startups	Role stakeholders	Environment
Ethics	Societal impact	Environment
Risks	Societal impact	Environment
Funding	Funding	Financial value

Impact of funding	Funding	Financial value
Lack of awareness	Creating awareness	Knowledge
Success stories	Creating awareness	Knowledge
Existing knowledge about quantum	Knowledge about quantum	Knowledge
Impact lack of knowledge	Knowledge about quantum	Knowledge
Influence on knowledge	Knowledge about quantum	Knowledge
Intimidation Quantum	Knowledge about quantum	Knowledge
Knowledge about industry	Knowledge about quantum	Knowledge
Required level of knowledge quantum	Knowledge about quantum	Knowledge
Adaptive language	Language	Knowledge
Language barriers	Language	Knowledge
Language tips	Language	Knowledge
Quantum hype	Quantum hype	Knowledge
There is hype	Quantum hype	Knowledge
There is no quantum hype	Quantum hype	Knowledge
Quantum winter	Quantum winter	Knowledge
Increase in education	Talent and education	Knowledge
Lack of education	Talent and education	Knowledge
Lack of talent	Talent and education	Knowledge
Sufficient talent	Talent and education	Knowledge
Commercialization challenges	Commercialization challenges	Organization
Ecosystem culture	Cultural challenges	Organization
Organizational culture	Cultural challenges	Organization
Risk aversion	Cultural challenges	Organization
Difficulty raising funding	Funding challenges	Organization
Funding regulation	Funding challenges	Organization
Government funding	Funding challenges	Organization
Investment risks	Funding challenges	Organization
Lack of funding	Funding challenges	Organization
Complexity of organizations	Organizational challenges	Organization
No barriers to adoption	Organizational challenges	Organization
Organizational reputation	Organizational challenges	Organization
Customers	Organizational interest	Organization
Lack of organizational interest	Organizational interest	Organization
Stakeholder interest	Organizational interest	Organization
Wait-and-see	Organizational interest	Organization
Startup scaling	Scaling challenges	Organization
Application uncertainty	Uncertainty	Organization
Development uncertainty	Uncertainty	Organization
Lack of use cases	Uncertainty	Organization
Measuring value	Uncertainty	Organization
Uncertainty quantum metrics	Uncertainty	Organization
Value uncertainty	Uncertainty	Organization
Organizational preparedness	Organizational preparedness	Organization
Technological steps	Technological challenges	Technology
Long technical development time	Technological challenges	Technology
Technology availability	Technological challenges	Technology
Application as value	Application of QT	Value creation QT
Application of QT	Application of QT	Value creation QT
Certainty of value quantum technologies	Impact of quantum technologies	Value creation QT
Economic impact of quantum technologies	Impact of quantum technologies	Value creation QT
How value is created	Impact of quantum technologies	Value creation QT
Level of impact quantum technologies	Impact of quantum technologies	Value creation QT
Autonomy as value	Reason to invest	Value creation QT
Economic value	Reason to invest	Value creation QT
Prioritization	Reason to invest	Value creation QT
Reason to invest	Reason to invest	Value creation QT
Sustainability as value	Reason to invest	Value creation QT
Would not invest	Reason to invest	Value creation QT
Reason to work in quantum	Reason to work in quantum	Value creation QT

F) PROJECT BRIEF

Project Proposal form

IDE Master Graduation Project

In this proposal the agreements made between student and supervisory team about the student's IDE Master Graduation Project are set out. This document needs to be prepared for the Kick-off meeting and should be submitted in MyCase.

Name student Lennart Hessels **Student number** 4847040

Project title Creating effective PPPs for Quantum development

Please state the title of your graduation project (above). Keep the title compact and simple. Do not use abbreviations. The remainder of this document allows you to define and clarify your graduation project.

MSc programme Design for Interaction Integrated Product Design Strategic Product Design
 Other (in case of a double degree outside IDE): _____

Introduction

Describe the context of your project in the box below; What is the domain in which your project takes place? Who are the main stakeholders and what interests are at stake? Describe the opportunities (and limitations) in this domain to better serve the stakeholder interests. (max 250 words)

Innovation requires talent, knowledge and capital. With the location of QuTech in the TU Delft ecosystem there is a lot of knowledge that can be put to use. With that knowledge and by attracting talent from the area and internationally the Quantum ecosystem in Delft has the potential to become the new Brainport. But capital has always been a struggle for startups in the Netherlands and Europe. A lot of companies move away to places where bigger capital tickets are available.

It is imminent that quantum will play a role in the future. The Draghi report (2024) highlighted once more that Europe needs to invest in innovation to regain their competitive position and reduce the dependency on other nations. This also goes for a lesser degree of dependence when it comes to defense.

The Netherlands has the potential to become the biggest player when it comes to quantum. As quantum is part of the 10 key-technologies that the government aims to focus on, it is high on the agenda. But the Netherlands spends below average amounts on innovation, especially if you compare it to the US where corporations invest billions into quantum and China where over \$15 billion is to be invested. But if the Netherlands wants to create a new ASML for quantum, which is definitely possible, talent, knowledge and capital need to flow into the quantum ecosystem.

→ space available for images / figures on next page

Introduction (continued): space for images

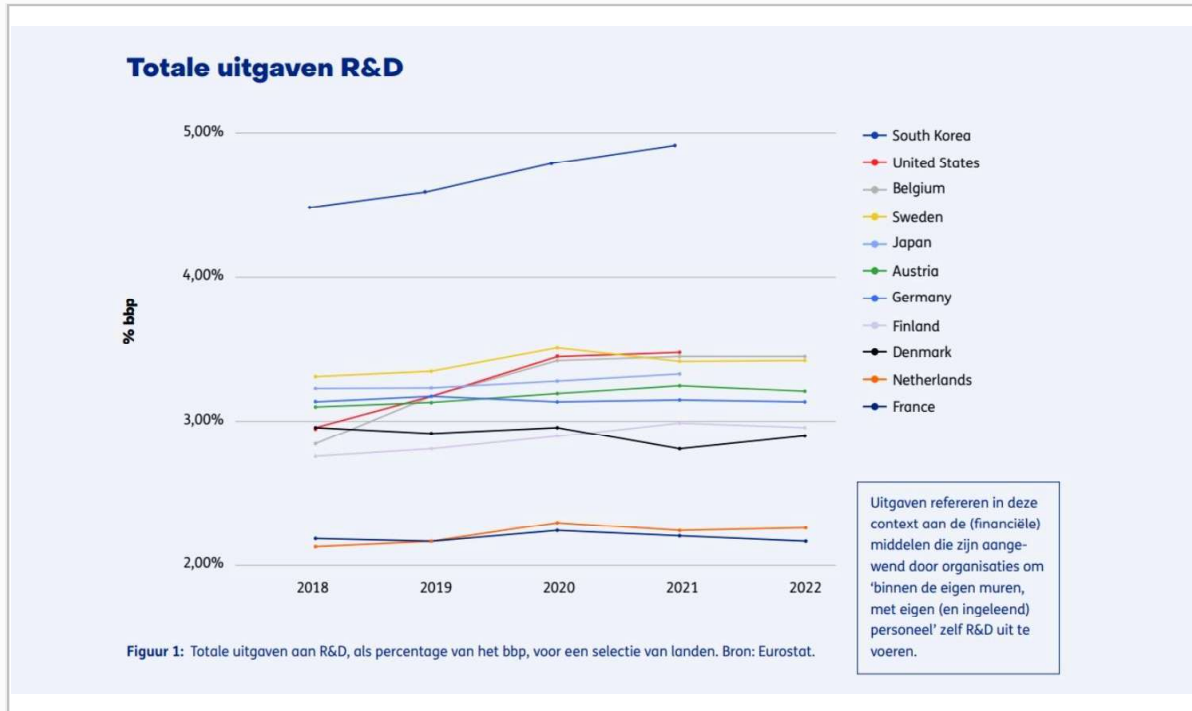


Figure 1: Total expenses for R&D, as percentage of GDP. source: Eurostat.

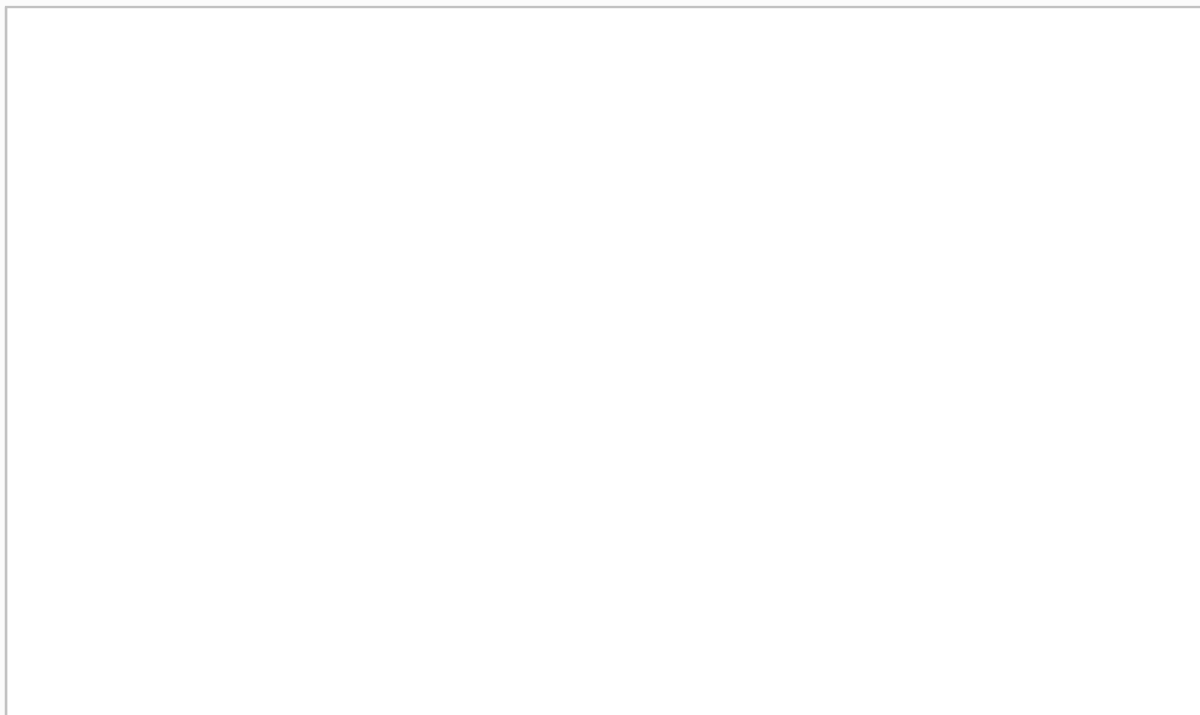


Figure 2: _____

Problem Definition

What problem do you want to solve in the context described in the introduction, and within the available time frame of 100 working days? (= Master Graduation Project of 30 EC). What opportunities do you see to create added value for the described stakeholders? Substantiate your choice. (max 200 words)

Quantum computing development occurs in a startup space with uncertain applications. Private investors in Europe are risk averse and there is a lack of availability of scale-up capital. As a result deeptech companies have a hard time flourishing here and many move away.

In Europe there is a big lack of privately available funding for quantum and other deeptech solutions. When looking at quantum, only 12% of total private funding occurs in the EU (Ecipe). One of the struggles that has been identified is a lack of effective Public-Private-Partnerships (PPPs). QuTech furthermore mention that 'the barriers to intensive public-private corporation prove high' (2025). The lack of PPPs has also been identified as a significant struggle for the development of 'dual-use' technologies (TNO, 2025).



Assignment

This is the most important part of the project brief because it will give a clear direction of what you are heading for. Formulate an assignment to yourself regarding what you expect to deliver as result at the end of your project (1 sentence. As you graduate as an industrial design engineer, your assignment will start with a verb (Investigate/Design/Validate/Create), and you may use the format:

(Investigate/Design/Validate/Create) a (what will be the deliverable → prototype/roadmap/process/intervention /approach/guideline/strategy/...) to (what should it do →(create/understand/evaluate/validate/improve/execute/analyse/...)) (the objective → experience/value/process/product/...) for (whom → target group/client/...) in (what context).

Create a strategy to improve the collaboration between public and private organizations to improve the development of quantum technologies and increase the potential of a resilient and strategic independent quantum ecosystem.



Explain your project approach to carrying out your graduation project and what research and design methods you plan to use to generate your design solution (max 150 words).

Create a strategy to improve the collaboration between public and private organizations to improve the development of quantum technologies and increase the potential of a resilient and strategic independent quantum ecosystem.

The aim is to understand and improve collaboration between public and private organizations through PPPs. By first understanding the situation and subproblems (e.g. desk research, interviews, Value Network analysis, stakeholder mapping) and defining the problem in order to turn it into a design question ('how can we...'). Utilizing the analysis to develop different collaboration scenarios in a Strategic foresight manner (possible future scenario's, with implications and steps), which is tested and verified with stakeholders. Through Road mapping and creating a report I want to visualize steps that are required to realize a possible desired future.



Project planning

To make visible how you plan to spend your time, you must make a planning for the full project. You are advised to use a Gantt chart format to show the different phases of your project, deliverables you have in mind, meetings and in-between deadlines. Keep in mind that all activities should fit within the given run time of 100 working days. Your planning should include the **Kick-off**, **Midterm Evaluation**, **Green Light** and **Finalisation** (ceremony). Please indicate periods of part-time activities and/or periods of not spending time on your graduation project, if any (for instance because of holidays or parallel course activities). Add (an image of) the planning in the box below. If it is not readable, you can add the planning as an attachment to My Case along with this Proposal.

Motivation and personal ambitions

Explain why you wish to start this project, what competencies you want to prove or develop (e.g. competencies acquired in your MSc programme, electives, extra-curricular activities or other).

Optionally, describe whether you have some (max 5) personal learning ambitions which you explicitly want to address in this project, on top of the learning objectives of the Graduation Project itself. You might think of e.g. acquiring in depth knowledge on a specific subject, broadening your competencies or experimenting with a specific tool or methodology (200 words max).

Quantum is an up and coming technology, with uncertain applications but with the potential to change the world. Being a part of that change is extremely exciting. Understanding the dynamics of collaborations between private and public institutions, with different goals and values is very interesting; the complexity of the triple helix model of innovation.

During my MSc I followed a course about investing from the perspective of a VC and I did an internship at a Private Equity firm. At both experiences it was about creating a deep understanding of something in a short period of time, in order to make proper decisions, which is very SPD like.

During 100 days I want to create a deeper understanding of the strategic side of quantum computing. I want to understand how decisions (such as financial) are made when it is hard to quantify proof and it contains so much uncertainty. At the end I want to understand how to be a bridge between deep tech researchers and people without a technical background.

My goal is to create a graduation project that contributes to real problems and challenges and I aim to graduate Cum Laude and I wish to maximize the 100 days.

