Scenarios and Interventions for the Dutch Energy Market: Preparing to be Quantum-Safe

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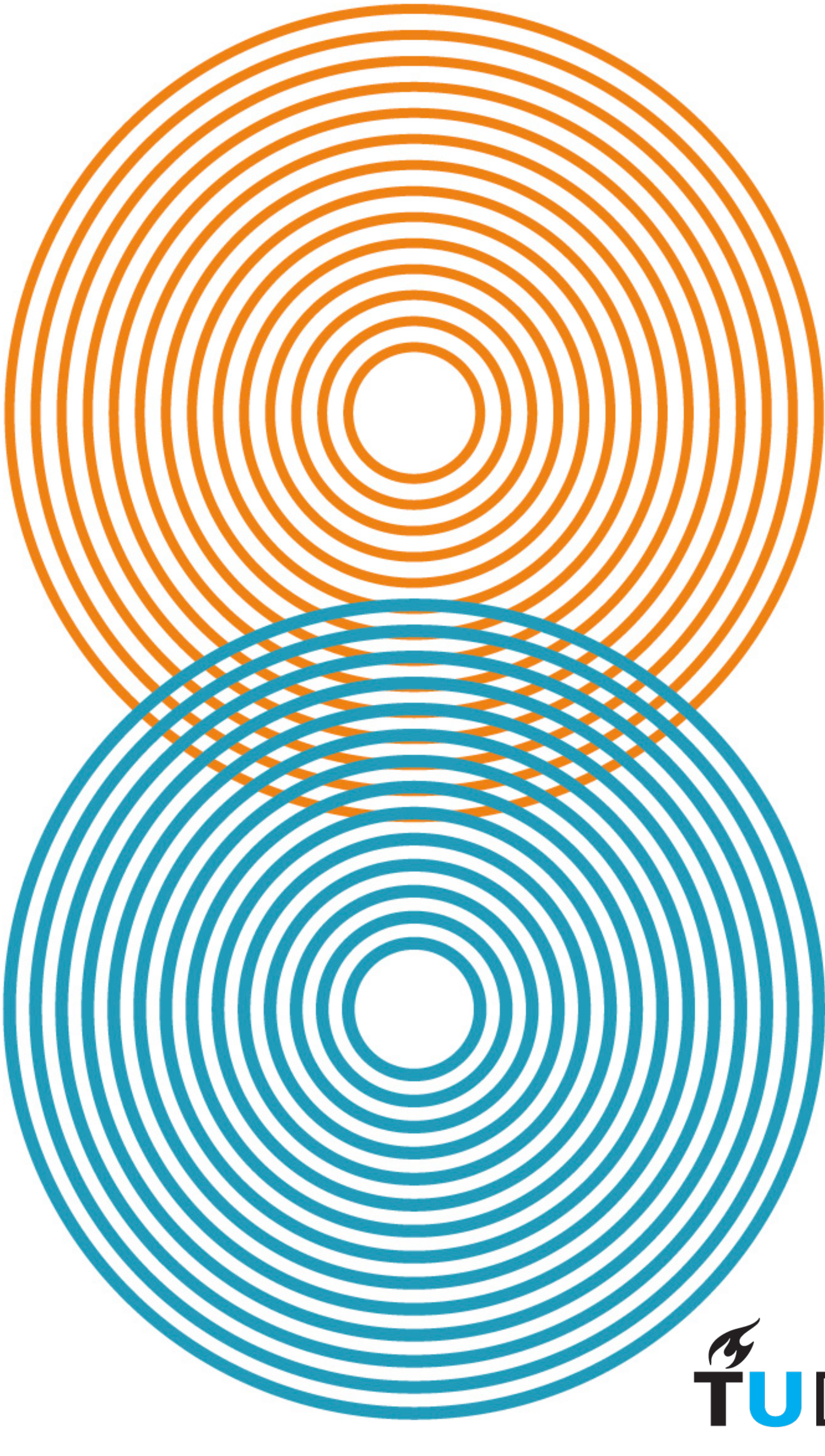

Scenarios and Interventions for the Dutch Energy Market: Preparing to be Quantum-Safe

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Keywords
Technological Transition, Quantum Transition, Quantum-Safe Technology, Post-Quantum Cryptography, Energy Market, Technological Innovation System

Abstract
In the Dutch energy market, the facilitation of digital communication and information exchange is essential. From monitoring real-time data of energy supply to ensuring secure energy distribution, varying applications operate together to communicate information in the energy sector. With the advancement of quantum computing technology, security threats to cryptographic algorithms may no longer be safe. While there is a need to shift towards quantum-safe solutions, there is little knowledge about quantum-safe technology and the trajectories of the Dutch energy market in the quantum era. This research aims to explore potential trajectories in the energy sector to allow better preparation for the quantum era. The results provide insights into the stakeholder and institutional layers that may require interventions to develop quantum-safe applications in the Dutch energy market. Viewing the system as a complex system and determining target areas using a Technological Innovation System (TIS) framework, data is abstracted from an extensive literature study and interviews with experts. The functions of the TIS are used as codes to analyse the interviews. The results of the desk research, literature review and expert interviews are triangulated. These results show potential for three scenarios of the Future Energy System (FES), varying in interconnectedness and decentralisation. Scenario 1 presents a simultaneous transition across the target system, scenario 2 shows a top-to-bottom approach with priority at the highest level of Internet of Energy (IoE) and scenario 3 focuses on the security of localised energy communities with a bottom-to-top approach.

Summary

Quantum computing (QC) has the potential to provide significant technological developments due to its considerable computational power compared to classical computers. For example, it can speed up the transition towards a climate-neutral energy system, such as the development of smart grids, optimisation of generation plants or the integration of electric vehicles. However, the development of quantum computing also poses security risks: it has the potential to break current cryptography used in society, such as the Public Key Infrastructure (PKI), which facilitates digital communication and information exchange. The transition towards a quantum-safe society that is resilient against quantum cyberattacks is, therefore, an important step to be taken, as current critical systems are vulnerable to such attacks. One of the most researched methods of ensuring the security of a system against quantum attacks is the migration to Post-Quantum Cryptography (PQC).

This thesis focussed on the threats, developments and potential policy implications for the quantum-safe transition in the Dutch energy sector by addressing the socio-technical drivers in the system for such a transition. Organisations are stimulated to perform a PQC migration of their assets, but sector-specific guidelines and analysis are not yet prevalent in the research field. This research introduces the analysis of the intersection between the development of the Dutch energy sector and the development of quantum-safe applications. By analysing functions in the target system, socio-technical factors and limitations can be identified, which contributes to the establishment of more applied guidelines for the quantum-safe transition.

This research contributes to the mitigation of the potential quantum threat and the security of the Dutch energy system, as it is a non-intermittent and critical system. It employs the use of innovation systems thinking to organise the drivers and functions in an otherwise technological system while also employing a novel approach to the Technological Innovation System (TIS) framework, as the focus is on the technological development of an uncertain technology. Combining the TIS with the Multi-Level Perspective (MLP) provides a systematic approach to explaining and targeting otherwise vague developments in a system where a combination of public and private actors is prevalent. Thus, it enriches the theoretical knowledge base, while also expanding current research efforts in PQC migration and the quantum-safe transition in the Netherlands.

The TIS and MLP are used as theoretical frameworks for analysis in this thesis. The TIS analysis is a tool that allows for the structural mapping of a system, the analysis of functions and their fulfilment in the target system, and the identification of barriers that inhibit the desired technological development. The structural analysis is done to delineate the Dutch energy sector, identifying the most important stakeholders and the developments that are currently underway in the target system. This initial phase is done through desk research and the use of knowledge acquired in the Master's Programme. The second phase includes a systematic literature review of the current research field of quantum-safe transition in the energy sector. The last phase employs the use of expert interviews to validate and expand the knowledge built in the previous phases by coding the interviews using the function of the TIS as indicators and noting emerging topics and sub-topics.

The structural analysis of the Dutch energy system showed an increasingly complex system that has a high degree of public-private interactions. Its hierarchical structure of governments, authority, TSO, DSOs and consumers shares a current system priority: congestion and expansion of the network. Current developments in the system see the decentralisation towards Renewable Energy Source (RES) integration, increasing efficiency and flexibility in the network, and the development of large offshore wind farms. Additionally, the integration of smart implementations on all levels of the supply chain, from individual households to operators, is an expected development. The functional analysis of the TIS revealed that the guidance of the search, as well as the expectations and vision across system actors, is a limitation to the PQC migration. Risk assessment and knowledge exchange on the quantum-safe transition are not adequate, and resources are predominantly mobilised at the level of private companies. The literature review showed that the current research field of quantum-safe transition in the energy sector is focused on the integration of future technologies, such as smart

grids, the use of quantum computing and Distributed Energy Systems (DER). Threats are mentioned to occur not only on the level of system-wide communication and national system disruptions but also on the human level, where mindset and behavioural change are required to ensure the grid's security.

These analyses describe varying trajectories of the future energy system. Three main trends either recommended or described by the experts and system analysis emerge, which are described in three scenarios: an extension of the current system; the decentralisation and interconnected system which consists of high data intensity and Internet of Energy (IoE); the decentralisation and disconnected system that sees localised energy communities and hubs. Each of these three scenarios requires a different approach to the quantum-safe transition. The first scenario requires a simultaneous implementation of PQC, where expectations across the entire system should be aligned, and the system does not see drastic changes in its socio-technical construction. The second scenario may require a top-to-bottom approach to the quantum-safe transition, as an interconnected network that is connected to the internet should first be secured on the highest level: the national platform. The third scenario may require a bottom-to-top approach to the quantum-safe transition, as localised energy communities are required to ensure their security, and data transfer on the highest level is limited.

Implications for the policy trajectories are made for each of these scenarios. Assuming the system remains relatively the same in the first scenario, the focus needs to be on a clear delineation of responsibility and ownership along the energy supply chain, assets inventory of all Information Technology (IT) and Operational Technology (OT), aligning the need for cybersecurity with the security of supply, and flexibility in IT and OT concerning their cybersecurity. In a decentralised and interconnected system, the focus should be on integrating the expected PQC migration in the purchasing policy for smart applications, priority in transition of the highest level first, and additional policymaking to ensure the compliance of private parties. In a decentralised and disconnected system, the focus should be on increasing the knowledge of the general public, decreasing the complexity of the grid through more efficient grid expansions, disconnection of unsafe or unsecured parts and responsibility delineation on more individualised levels.

General implications overlap over each of these three scenarios, as policy instruments for knowledge exchange, increasing resource mobilisation from private to public, and aligning visions concerning the cybersecurity of the energy system are relevant in all cases. Transparency in the standardisation of PQC schemes is possible and favourable due to society's participation in its validation, which in turn may reduce the threshold of demand for quantum-safe products from providers. Looking at the MLP, landscape pressure is needed to ensure the breakthrough of niche markets in the regime. Each scenario describes a different approach to the forces from niche and landscape, but all require the same notion that a complete system transition of the Dutch energy sector to be quantum-safe in the expected timeframe of the development of quantum computing is not feasible, and priorities should, therefore, be made. Breaking down the responsibilities in the system in a structured manner may provide a step-by-step approach towards transition while ensuring that the national security of supply remains intact. Each scenario furthermore describes varying efforts in the development of the energy sector, but the general conclusion of this research shows that the more effort is made in disconnecting and simplifying the system, the less need there is for a simultaneous system transition.

Recommendations for further research are divided into two topics, the first being the next steps for the quantum-safe transition in the Dutch energy sector and the second being further system analysis of quantum-safe development. Further research should be done on the clear mapping of IT and OT assets in the system and its transparency to society. Such knowledge may contribute towards a more accurate perception of risk by actors. The chain of supply and responsible parties of the Dutch energy sector have become more complex, which requires an overarching overview of the system to be made as soon as possible. Additionally, research into similar transitions for lessons and sector-specific research should be done on how organisations can start preparing for the transition, as each sector differs in behaviours, visions and flexibility.

Acknowledgements

This master's thesis is the final result of an academic career that bridges innovation system management (Utrecht University) and complex systems engineering (TU Delft). This combination has shown me the potential that socio-technical system design and analysis has for visualising technological trajectories and making connections between the technical layers of society and its implementation and impact on society. I am honoured to have been a part of this novel research field and am grateful for my graduation committee's efforts and guidance to perform this exploratory research on a novel topic.

To my first supervisor, Marijn Janssen, I am grateful for your insights, enthusiasm, efforts and refreshing point of view on the topic during my thesis process. Your curious and positive attitude during our meetings has been a motivating force more than once throughout the process. I am humbled by your participation and leading of the thesis committee and look forward to discussing this important topic in the future often. To my second supervisor, Ivo Bouwmans, thank you for your guidance, enthusiasm and positive energy throughout my studies at TU Delft. Being one of the first people to meet in Delft, as well as being the teacher for my favourite courses, you showed me the possibilities of bridging theories to better understand the energy sector and our part in our journey to sustainability. And to Ini Kong, the aspiring and outstanding PhD Candidate, thank you for all your effort, company, insights and your faith in me throughout the last year. As my supervisor for one of the courses and now part of the thesis committee, I am grateful for your guidance and time. Our meetings will not be forgotten.

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Cilia Annelieke Baanstra
August, 2024

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Glossary

AI	Artificial Intelligence
BC	Blockchain
CoSEM	Complex Systems Engineering and Management
DER	Distributed Energy Resources
DLT	Distributed Ledger Technology
DPM	Data Management Plan
DSO	Distribution System Operator
EC	European Commission
ENTSO-E	European Network Transmission System Operators for Electricity
EU	European Union
IoE	Internet of Energy
IoT	Internet of Things
IS	Innovation System
MLP	Multi-Level Perspective
NIST	National Institute of Standards and Technology
PKC	Public Key Cryptography
PKI	Public Key Infrastructure
PQC	Post-Quantum Cryptography
RE	Renewable Energy
RES	Renewable Energy Source
RQ	Research Question
SG	Smart Grid
SQ	Sub-question
TE	Transactive Energy
TIS	Technological Innovation System
TPM	Technology, Policy and Management
TRL	Technological Readiness Level
TSO	Transmission System Operator
TT	Technological Transition

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Master Programme Incorporation

Within the Energy Track of the MSc programme of Complex Systems Engineering & Management, there is a focus on the future socio-technological system of the energy market, as well as transitions and the complexity of a high degree of stakeholder participation. Identifying the different factors that make up a complex system, as well as analysing a technological transition's impact on that system, are relevant methods of research explored within the CoSEM programme.

Several courses have provided the author with valuable knowledge and skills that may be used during the course of this research. Design courses such as 'Introduction to Design in Complex Systems', 'Complex Systems Engineering' and 'Design Project' provide the necessary foundation for familiarisation with a complex system, incorporation of the relevant concepts and application of these concepts to understand and create interventions to be implemented on different levels. Courses like 'Law and Institutions' and 'Institutional Economics for Designing in Socio-technical Systems' provide insight into the institutions and governance that need to be taken into consideration during systems engineering. Finally, track-specific courses on the Energy track, primarily 'Electricity and Gas: Market Design and Policy Issues', provide guidance on the complexity of the (Dutch) energy market, with additional focus on the large degree of stakeholder interactions. The course 'Managing Multi-actor Decision-Making' adds to the process and stakeholder lens required for system design.

Finally, insights from the bachelor programme Science and Innovation Management[1] are used to incorporate innovation frameworks that provide additional support when concerning technological developments in complex innovation systems.

[1] Utrecht University, Dutch bachelor programme

1. Introduction

1.1 Background

The technological world is waiting for the day that quantum computers are introduced to the market, dubbed as 'Q-Day' (Herman, 2021). Quantum computing has the potential to change the current technological landscape significantly, as it uses quantum mechanics to enhances the capabilities of current technologies. Quantum technology and quantum computers have exponentially more data processing and computational power compared to classical technologies and computers (Riel, 2021; Upama et al., 2022). However, little is known about the changes needed in society to prepare for the integration of quantum computing.

Quantum computing has the potential to break encryption schemes currently used by governmental agencies such as public services and the protection of data and transactions from public entities in the Netherlands (Logius, n.d.). The encryption, using Public Key Infrastructure (PKI), is vulnerable to quantum attacks, which threatens the data integrity and cybersecurity of critical systems in the Netherlands (Baheer et al., 2020; Kong, Janssen & Bharosa, 2022). One of these systems is the Dutch energy sector, which is currently undergoing a transition of its own but may become at risk once the transition towards distributed energy systems is made (Ahn et al., 2022; Blumsack & Fernandez, 2012). As clear guidelines and steps for the migration towards quantum-safe measures are yet to be specified for specific sectors, research into system-wide transitions is needed to ensure the future safety of our energy supply.

This study presents qualitative research into potential interventions that may ensure the (cyber)security of the Dutch energy system when there are many uncertainties in the development of either the Dutch energy sector or that of quantum computing. The aim is to explore the socio-technical system in which such a transition should take place by establishing the stakeholders and factors that determine the transition's success. Due to the aforementioned uncertainties, scenarios are established to provide a foundation of potential trajectories that the Dutch energy system should take.

1.2 Societal Relevance

1.2.1 Quantum Threat

Government agencies know the threat that quantum computing poses to data and communication infrastructures. However, a quantum-safe technological transition is experiencing numerous challenges in achieving full market diffusion (Kong et al., 2022). Quantum-safe technology is necessary for the current encryption system to be protected against potential vulnerabilities (Strand, 2021). Post Quantum Cryptography (PQC) describes cryptography that uses larger keys or cyphertexts that are more secure against quantum threats than the current cryptography in use (Muller & van Heesch, 2020). Large critical systems whose main functions and activities are an inherent part of society's functioning are especially considered to need PQC. However, the effort and a clear trajectory for the development and implementation of quantum-safe technology, is yet to be recognised in its entirety (Kong et al., 2022).

Quantum computing has the ability to speed up the transition towards a climate-neutral energy system, such as the development of smart grids, optimisation of generation plants or the integration of electric vehicles (Ajagekar & You, 2022). However, this development of quantum computing in the energy sector does not parallel a development towards quantum-safe measures. For instance, communication between Dutch Transmission System Operator (TSO) TenneT and the electricity markets is secured by PKI certificates, which entails digital communication regarding several of the energy market activities (TenneT, n.d.-a). This communication within critical balancing activities in the energy market may be threatened by quantum computing. This may lead to regional or even national blackouts, congestion issues or threats to the security of energy supply. It is therefore pertinent to ensure that there is sufficient knowledge development on the potential threats and impact of quantum computing in the energy sector.

1.2.2 Contributions

This research aims to construct scenarios for the future energy system in the Netherlands based on qualitative data collection. If the potential construction of a future energy system is known, it may contribute to preparing and anticipating threats to cybersecurity. More specifically, stimulating a particular trajectory in the future energy system allows for more control on the part of policymakers to anticipate any developments needed in the field of quantum-safe ty. Considering that research into the quantum-safe ty of the Dutch energy systems has not been done before, this research contributes towards preventative measures against quantum attacks in the Dutch energy system, furthermore, ensuring the future security of supply. In addition, the results of this study further contribute to the resilience and flexibility of the future energy system by proposing potential implications.

The theoretical contributions of this study concern the use of system design thinking and the framework of innovation systems in a situation where future technological development is not yet known (further described in Section 3.1). Current literature does not include research into uncertainty technological developments concerning the quantum threat and the Dutch energy system. In most cases, the design of a system intervention requires knowledge of the desired technology that needs to be integrated into the target system. Due to the exploratory nature of this research, the technological development of quantum computing and quantum-safe applications is not yet known. Applying such frameworks on an uncertain technology successfully may allow for future research developments into preventative design thinking, where scenarios are combined with policymaking within the context of innovation systems thinking (Section 3.1.2).

1.2.3 Research Question

This research plots the potential impact of a quantum-safe transition on the Dutch energy market and highlights the areas of priority where possible gaps in the transition towards a quantum-safe system exist. The final deliverable aims to provide an overview of the current energy system and establishes scenarios in which a quantum-safe transition is realised. The main research question posed is as follows: '*What intervention is needed to ensure the development towards a quantum-safe transition in the Dutch energy market?'*

1.3 Thesis Outline

Chapter 2 provides insight into the context by describing key concepts, the state-of-the-art research and a preliminary literature review to highlight the knowledge gap that is targeted. Chapter 3 depicts the research approach, describing the theoretical framework and sub-questions that are created to provide an answer to the main research question. Data collection and methodology are then briefly described.

Chapters 4, 5 and 6 show the results of each of the studies done, building upon each other to create the scenarios in Chapter 7. Chapter 4 describes the current state and developments of the Dutch energy sector by performing desk research per structural element of the system. Chapter 5 shows the results of a literature review in the current research field of energy sectors in the quantum era. Chapter 6 describes each function in the system through expert interviews to determine which parts of the target system are not functioning adequately and what potential the trajectories of the energy system may be.

Chapter 7 and 8 include the scenarios describing the conclusions of the research and the implications for contributing towards the identified knowledge gap. Chapter 7 presents the possible trajectories in scenarios, showcasing possible actions that the energy sector may use for preparation for a quantum-safe transition. The implications of this research are presented in Chapter 8, and the conclusion and discussion are presented in Chapter 9.

2. Background

The background of this study includes the key concepts, the state-of-the-art knowledge and the knowledge gap identified through a preliminary literature review. The key concepts and current knowledge in the quantum-safe transition in the Dutch PKI are described with the work of Kong, Janssen and Bharosa (2022; 2023; 2024) used as a foundation. This chapter describes the process towards identifying the research gap that this research aims to contribute to.

2.1 Key Concepts

2.1.1 Quantum Technology

The field of applications of quantum mechanics in technology can be divided into three groups, according to the Quantum Technology Monitor of McKinsey & Company (2023): quantum computing, quantum communications and quantum sensing (sensor technology). TNO describes an additional use of current developments in quantum technology, being quantum simulations. These describe applications of two main characteristics that quantum mechanics can provide: superposition and entanglement (TNO, n.d.-a), which are both behaviours of small particles that can be, if controlled, used in technological applications.

These particle behaviours allow quantum technologies to process data at an exponential larger rate than classical technologies. Superposition allows for a particle to have multiple states at the same time at the quantum level. Entanglement allows for instant communication between two quantum particles, independent of their positions in space. Specifically, "the quantum state of each particle cannot be described independently of the quantum state of the other particle(s)", (Quantum Inspire by QuTech, n.d.). A quantum monitor by McKinsey & Company (2023), indicators by Forbes (Galer, 2023), and even national investment monitors such as Deep Tech Fund Invest-NL (2023) report that the current investment landscape in start-ups in quantum technology are expected to rise sharply in the coming decades.

In Europe, the European Quantum Industry Consortium (QuIC) is an association that dedicates itself to the development and growth of the industry, specialising in quantum technology. Specifically, they aim to increase the competitiveness in the sector by facilitating an ecosystem in which all kinds of parties can participate (European Quantum Industry Consortium, n.d.). Overall, quantum technology and its implementation are anticipated by a significant part of society's technological landscape.

2.1.2 Quantum Computing Development & Threat

Large governmental entities such as the National Institute of Standards and Technology of the United States and the European Flagship Programme 'Quantum Flagship' have set up cooperation programmes and goals and even have budgets for the development of quantum computing (QC) (NIST, 2022-a; Quantum Flagship, n.d.-a). quantum computing primarily exploits the characteristic of superposition, where instead of bits that are either one or zero, there are qubits which can be zero and one at the same time (Quantum Flagship, n.d.-b). This allows for the device to perform significantly more computations at the same time, which may allow for a working quantum computer to be able to solve problems that classical computers either cannot or take too long to compute (Quantum Flagship, n.d.-b). The current state-of-the-art quantum computers are not yet at the state of surpassing their simulators or classical computers (Hoving, 2018). However, they are expected to.

Despite the physical challenges, the sector shows a high degree of start-up participation and cooperation between private market parties, research institutions and governmental entities. The TU Delft and TNO are involved in a collaboration, QuTech, which is a government-funded "mission-drive research institute" to explore the possibilities of quantum technology and aim to build a functioning quantum computer (QuTech, n.d.). Furthermore, R&D investments of significant companies such as IBM and Google Research are focused on developing error correction and quantum fault tolerance[2] that is not yet realised (QuEra, 2023), as well as scaling the number of available qubits (Gambetta, 2022; Boixo & Smelyanski, 2023). Applications of quantum computing are anticipated in security, material manufacturing, banking and other manufacturing processes, where the main problems consist of large calculations that current computing power is not efficient in solving (Bova et a., 2021).

With the development of the first working quantum computer, potential threats emerge. An example of an algorithm for a quantum computer is Shor's algorithm, first proposed in 1994 by Peter Shor. This algorithm allows for finding prime factors of a large integer used in, for example, RSA (Rivest-Shamir-Adleman) based cryptography (Shor, 1997; Cobb, 2021). RSA is used in asymmetric cryptography, such as within the PKI of the Dutch government (see 2.1.3). Another example is Grover's algorithm, which provides the possibility to perform an unstructured search with a significantly lesser number of operations to solve problems (Grover, 1996).

Current estimates for the first actual quantum computing are varying, but as current efforts are focused on the error-correcting ability of quantum computing, estimates on timelines range from a few years to more than a decade (Dargan, 2023). McKinsey Digital (Gschwendtner et al., 2024) reported a growing trend of combining quantum computing hardware, which allows for previous start-ups to prepare to enter the commercial market. Overall, the quantum computing sector is in a so-called 'race' for the development of fault-tolerant quantum computing power (NIST, 2024). The quantum industry and technological universities in the Netherlands have proven themselves to be one of the forerunners in the global industry (Beenakker et al., 2019).

2.1.3 Public Key Infrastructure (PKI)

Public Key Infrastructure (PKI) provides security for communication services between two parties through a chain of certificates that are authenticated to ensure the validity of the communication (Bharosa et al., 2015). One of the examples of a PKI is the 'PKIoverheid', a governmental PKI in the Netherlands which employs the use of asymmetric cryptography (Bharosa et al., 2025; Logius, n.d.). The facilitation of PKI depends on the today's most widely used cryptography algorithm such as Rivest-Sharmir-Adleman (RSA) algorithm (Logius Policy Authority, 2013; Rivest, Shamir & Adleman, 1978).

Asymmetric cryptography is often used in large communication systems, where each party has a public and a private key. The public key is available to anyone, while the private key is only held by the party and is secret to others. The RSA algorithm exploits the difficulty of prime factorising large numbers when the initial two prime numbers are not known, which makes deriving the private from the public key extremely difficult through conventional methods. (Johnson, 2020). There are multiple actors involved in facilitating a PKI, such as digital certificates, public and private key distribution, and authentication, which create a chain of digital security that involves the parties (Logius, n.d.).

As detailed before, prime factorisation is a mathematically significant computational problem, which makes asymmetric cryptography difficult to break down using current computational power. However, the high computational power of a quantum computer can potentially use Shor's algorithm to break asymmetric cryptography like RSA (Bharosa et al., 2015). For other cryptographic schemes, a quantum computer can use Grover's algorithm to break the symmetric cryptography (Grover, 1996).

The Dutch energy sector uses cryptographic algorithms throughout its communications and operations. The PKI between TenneT and the market parties concern the communication layer of the Dutch energy system, where DSOs and other market parties remain in constant contact to ensure the stability of the Dutch energy network (TenneT, n.d.-a). Within market parties and operators, communications are also secured using cryptographic algorithms. In addition, within the operations layer, cryptography becomes more important

[2] Fault tolerance in quantum computing means that the error correction threshold is met, the spreading of errors is limited to local areas and no influence from the environment on the information (QuEra, 2023).

(Topsector Energie, 2022). The operations concern the physical aspect of the sector's functioning, including the supply, distribution and balancing of energy on the grids. Implementing quantum-safe cryptographic algorithms for authentication, verification, and protection within the operations of the Dutch energy sector is therefore vital to its security.

2.2 State of the Art

2.2.1 Post-Quantum Cryptography

In general, the term 'quantum-safe' is used to refer to technologies and cryptography being secure against the potential power of quantum computers. Post-Quantum Cryptography (PQC) refers to cryptography that is developed to withstand potential quantum threats. The field of PQC is currently in the phase of standardisation, with the announcement of the standardised algorithm expected to be chosen in 2024 by the NIST (NCSC, 2023).

There are current efforts in the Netherlands to develop PQC that would be able to replace current schemes in place. This is possible due to PQC being based on classical cryptography – there is no need for a quantum computer to make cryptography quantum-safe . The most notable public project is the 'Hybrid Approach for quantum-safe Public Key Infrastructure Development for Organisations (HAPKIDO)', an initiative that has both private and public parties working on collecting and developing knowledge to ensure quantum-safe transitions can be made by Dutch organisations (HAPKIDO, n.d.). The need for differentiating between actor types in Dutch society is addressed by HAPKIDO, as well as the need for interdisciplinary cooperation across varying impact levels, such as the European Commission (EC) at the macro level and banks at the micro level of implementation (Christiansen, Kong & Bharosa, 2023).

Additional research for PQC and its migration is also performed by individual parties, with TNO being one of the more prevalent actors. Together with the cryptology group at CWI and the Netherlands National Communications Security Agency (AIVD), TNO published 'The PQC Migration Handbook', a handbook with guidelines for organisations for preparing for the PQC migration (2023). However, these guidelines are not specific for a vital, uninterruptable and dynamic sector such as the Dutch energy sector. This reduces the clarity needed for such actors to start a quantum-safe transition.

2.2.2 Challenges in Quantum-Safe Transition

Research has been done to identify the challenges of quantum-safe transitions in the Netherlands. Most notable is the work by Kong et al. (2022). Within the findings, sub-categories of challenges include technological, organisational and environmental challenges, as well as interdependencies that may form a barrier (Kong et al., 2022). Within the Dutch energy sector, potential challenges of relevance are the incompatibility of legacy systems, the lack of one-size-fits-all processes for transition, the lack of crypto-agility, the need for collaboration and problems in the bureaucratic processes (Kong et al., 2022). The main challenge may be identified as having a notable degree of wickedness, showing different possible trajectories for policy to ensure the transition is made. This translates into the lack of one clear solution to bridge the gaps in a quantum-safe transition, as described in Kong et al. (2023).

In addition, the findings of Kong et al. suggest the need for a synchronous transition across the socio-technical system: challenges found in the ecosystem and technological context should be addressed at the same time. Interestingly, all challenges show interdependency, showing the complexity of a transition (Kong et al., 2023). Policy recommendations made based on the identified challenges and their interdependencies are categorised by Kong et al. (2024) in the following four topics: assessment of impact and readiness, collaboration in the organisational system, financial incentives and funding, and policy guidance. Risk assessment and collaboration are intensive activities that need to be set up, which necessitates a strong intervention to ensure the transition takes place. These interdependencies and multiple possible trajectories for potential interventions make it difficult to determine what steps the Dutch energy sector needs to take to become quantum-safe . This issue may be mitigated by exploring the potential scenarios and developments of the energy sector through discussions and information from within the sector.

2.3 Knowledge Gap

Section 2.1 highlights the necessity of transitioning towards a quantum-safe system, while Section 2.2 shows the difficulties of transitioning, as well as potential challenges that the Dutch energy sector may face. The identified interdependencies in current research and the dynamics of the energy sector call for a research approach that explores potential trajectories and scenarios so that the system can adequately prepare for a quantum-safe transition.

This preliminary literature review has been conducted to identify knowledge gaps in current research on energy sectors in the quantum era. The databases Scopus and Web of Science have been selected as reliable and relevant sources of information. The main themes and relevant keywords are provided in Table 1. Due to the limited amount of research regarding this topic, as well as the novelty of this research field, the number of search terms were limited and encompass energy systems in general, as delineation to the Dutch energy system may limit the number of relevant studies significantly.

Table 1; Overview of Search Term for Search String Preliminary Literature Review

Quantum Technology	**Energy Sector**
Quantum-Safe	Energy Sector
Quantum-Safe Techn*	Energy System
Post-Quantum Cryptography	Energy Industry
Quantum Cryptography	

The search string was created by combining the words from each column using the 'OR' operator and combining the columns using the 'AND' operator. Several exclusion criteria were used before exporting the sources for manual assessment (Table 2). These include the exclusion of document types such as books and proceedings, as well as any article published before 2010, as most development in the quantum computing field, and its corresponding but smaller field of quantum-safe computing, has happened in the last decade (Kong et al., 2022). Using the 'Preferred Reporting Items for Systematic Review and Meta-Analyses (PRISMA)' guidelines, a final ten articles are included for further analysis (see Figure B1).

Table 2 provides an overview of a concise synthesis of the articles included for further analysis. A complete overview of the included articles is provided in Table B2. Below, insights are provided based on the included literature, followed by the identification of a potential knowledge gap and the subsequently resulting research focus of this study.

Table 2; Results of literature analysis for the impact of quantum computing on the energy sector

Knowledge Gaps	**Energy System Development**	**Reference**
Areas for Potential Quantum Computing Implementations	Smart Grid	Ahn et al., 2021 Paudel et al., 2023 Desai et al., 2018 Alshowkan et al., 2022
	Distributed Energy Systems	Ajagekar & You, 2022 Ahn et al., 2022 Ahn et al., 2021 Alshowkan et al., 2022
Areas that may be Vulnerable	Increasing Consumer Participation	Alshowkan et al., 2022 O'Neill et al., 2016 Tran, Hu & Pota, 2023
	Smart Grid	Desai et al., 2018
	Energy System Operations	Ajagekar & You, 2022

		Kim et al., 2022
	Decentralisation & Distributed Energy Systems	Ahn et al., 2022 Shen et al., 2022 Tran, Hu & Pota, 2023

2.3.1 Areas for Potential Quantum Computing Implementation

According to the literature, the decentralisation and increased distribution of energy sources are seen as potential drivers for the implementation of quantum computing (Desai et al., 2018). As decentralised systems require a higher degree of system and network operation, the introduction of quantum computing for efficiency could provide the ability for regulation. (Ahn et al., 2021; Alshowkan et al., 2022; Shen et al., 2022).

Interestingly, the literature points out an extensive communication and information network in energy systems (Alshowkan et al., 2022; Shen et al., 2022). Such a large communication system shows the importance of encryption for security. Potential vulnerabilities may exist in a future energy system with a high dependency on data transfers (Shen et al., 2022; O'Neill et al., 2016; Kim et al., 2022).

Moreover, the literature states that the future energy system may include the application of smart grids (Ahn et al., 2022; Paudel et al., 2023; Desai et al., 2018; Alshowkan et al., 2022). These grids would include more prosumers, a more distributed energy system and a large operational system for demand and supply. With smart meters collecting data, there is a possibility of more data transfers taking place in the smart grid. The areas for potential quantum-safe implementation in the energy section indicate future considerations for security.

2.3.2 Areas that may be Vulnerable

The results shows that quantum-safe technologies are predominantly geared towards system-wide application (Kim et al., 2022; Ahn et al., 2022; Desai et al., 2018; Shen et al., 2022). These include technologies that have to be implemented at a privately-owned or public-owned point of the energy system. However, it may be necessary for system-wide applications to be done simultaneously, as current communication cryptography is not yet quantum-safe . This aligns with the state of the art previously discussed in Section 2.2.

The articles do not include steps on how to make an energy sector quantum-safe , but rather discuss the dangers of quantum computing in the energy sector and how to mitigate them. Other than one article (O'Neill et al., 2016), none of the articles discuss what actors or policies are needed to ensure the proper integration or use of quantum computers of in energy systems. Even though the included articles propose several solutions for the mitigation of quantum threats, there is a lack of institutional recommendations or structural developments needed for preparation for the quantum era.

Going forward, there is a lack of research and understanding of which actors and specific aspects of the system should be targeted in the energy sector. While there is research in the technological applications and European guidelines, knowledge on what is going to change and the security issues that may come up within the quantum era is lacking. Because of the broad implications of the quantum-safe technological transition, it is imperative to create an initial insight in areas of the energy system that may be influenced by a quantum-safe transition. There is a need for insight into the potential threats and vulnerable parts of the energy system and the steps that should be taken to ensure its security in the quantum era. Due to the volatility and dynamic nature of the Dutch energy system, several scenarios may need to be examined to better prepare the energy sector to become quantum-safe .

3. Research Approach

This study concerns a recent technological development in an environment of many interrelated dynamic transitions and technologies. Outlining the key concepts and technologies is necessary to ensure a technological foundation on which the research of this study can be built. Ensuring a consistent and robust framework is in place contributes to transparent and reproducible results on the topics of institutions, policies and stakeholder management, as is the focus of this study.

This chapter first describes the theoretical framework of this study, combining complex and innovations systems thinking with scenario descriptions in a socio-technical system. Then, the research questions are introduced, and brief descriptions of their contribution to the complete study are provided. The data collection process and methodology for analysis are then described, after which their limitations are mentioned.

3.1 Theoretical Framework

3.1.1 Complex Systems Design Thinking

This research takes a *qualitative, exploratory approach*. Within system design thinking, it is pertinent to first delineate and identify all moving parts within the system in order to provide opportunities for intervention (Dym, Little & Orwin, 2014). Traditionally, content analysis is performed in a quantitative manner. However, the qualitative approach aligns more firmly with behavioural factors and is performed as described by Bryman (2016). To analyse the complex system at hand, factoring in stakeholder management and the institutional structure is pertinent.

From the viewpoint of complex systems thinking, potential interventions can be designed using three interlocking and influencing parts: the technological aspect, the process aspect, and the institutional aspect (Enserink et al., 2022). The Dutch energy system is viewed as a complex system in this issue due to the large number of participating stakeholders; the high degree of institutional involvement; and the technological transitions currently developing. The process lens encompasses all that is the decision-making processes, stakeholder involvement and interactions. Within the institutional lens, the governance structures on various levels are considered. The technological lens encompasses the technical elements of the systems. As the technologies involved in this proposal are complicated and require a thorough understanding of the possible technologies, the impact of the technologies is mostly considered.

Complex systems thinking has characteristics similar to those of the Technological Innovation System (TIS) framework but adds an additional layer of interdependencies across the three lenses. Figure 1 shows the three lenses within a complex system, as well as their advantages and disadvantages. The lens of technology is less developed for systems in which technological trajectories are not yet known. As the trajectory of the

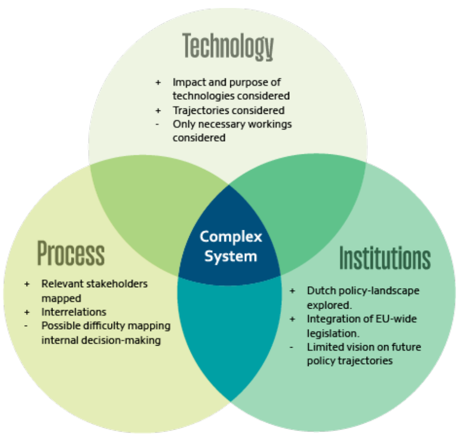


Figure 1; A Complex System Design (Koppenjan & Groenewegen, 2005).

quantum era and its impact on the Dutch energy system is unknown, the establishment of scenarios and trajectories of the entire system is, therefore, relevant to ensure that the full potential of this framework is used.

3.1.2 Technological Innovation System

Innovation systems (IS) thinking provides the opportunity to explore possible methods for technological diffusion (Ortt & Kamp, 2022). Edquist (2004) provides a detailed description of what constitutes a system of innovation: "[Also] the determinants of innovation processes, [which include] all important economic, social, political, organisational, institutional and other factors that influence the development, diffusion, and use of innovations." (Edquist, 2004). Considering the uncertainty in quantum computing developed and its potential threats, considering all these factors in the target system are essential in understanding how a quantum-safe transition should be started.

Advantages of the approach of innovastion systems include the focus on the interdisciplinary perspective, inclusion of learning processes as a driving factor, interdependence and the non-linear characteristic of the system, highlight of the role of institutions and the development of existing knowledge structures (Edquist, 2004; Suurs, 2009). Once a system is analysed and understood from the IS approach, interdependencies and interactions in the system may be identified whose functioning would ensure the diffusion of a technology such as PQC.

The Technological Innovation System (TIS) (Hekkert et al., 2007) is employed together with complex systems designing, both requiring qualitative methods to identify aspects of the system that hinder technological development. The TIS framework is part of the IS paradigm, but it has a starting point and delineation on the level of the potential technology (Suurs, 2009). Furthermore, as opposed to other types of innovation systems, it highlights the importance of knowledge diffusion and entrepreneurial activities (Suurs, 2009). The main characteristics of applying the TIS framework are distinguishing several functions and determining their level of maturity and potential weakness.

Hekkert et al. (2011) provides a structured guideline for performing a structural analysis, being the actors, institutions, interactions and infrastructure. Within actors, market parties, educational entities, government and supporting bodies, industries and knowledge institutions are included. Within institutions, the difference is made between hard institutions that present themselves as laws and regulations, as well as soft institutions established as customs, habits, norms, etc. Interactions exist at multiple levels, over large networks and on individual levels. In the Dutch energy system, interactions are significantly correlated with the infrastructure (e.g. physical network, technologies, communication networks) and institutions (e.g. policies, public opinion). Infrastructures include physical, financial and knowledge infrastructures (Wieczorek & Hekkert, 2012; Hekkert et al., 2011).

The technological change in a system is mapped and analysed by delineating the system into seven functions to highlight areas of interest. These functions entail the entrepreneurial activities within the target system, knowledge development, knowledge diffusion through networks, the guidance of the search, market formation surrounding that technology, resource mobilisation, and the creation of legitimacy regarding the technology (Hekkert et al., 2007). The seven functions are used as guidelines to determine which part of the system is not adequately working yet in order to ensure the successful development and subsequent diffusion of the desired technology.

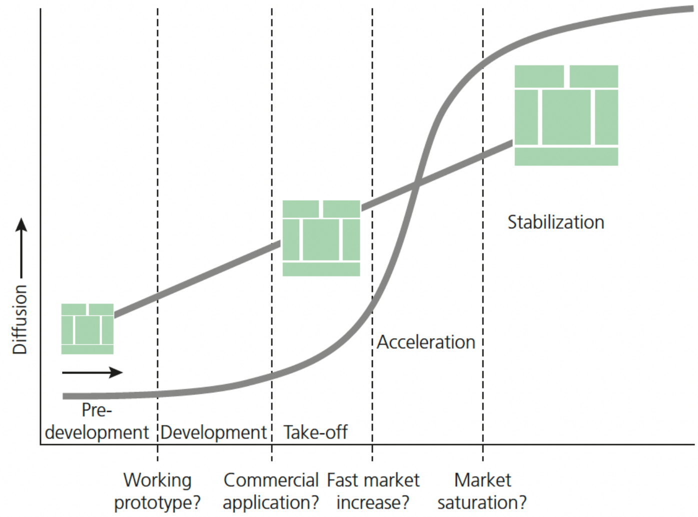


Figure 2; Phase of Development in a System (Hekkert et al., 2011)

Depending on the trajectories a socio-technical system takes, any of these functions may be targeted for policy. Due to this, combining the analysis of the system and a scenario approach requires an overarching framework that visualises these trajectories. The interdependencies identified in the knowledge gap (Chapter 2) may stem from functions not being adequately fulfilled, allowing for a structured and targeted analysis of system barriers. Furthermore, the analysis of the functions provides additional insight into the phase of the system development (see Figure 2). Knowing the phase in which a technological development is provides further insight on which functions need to be prioritised.

Although the TIS framework has predominantly been applied to known technological trajectories, the use of the framework in the context of a quantum-safe transition may provide several important insights. Thorough analysis of a system may identify the forces needed to stimulate the desired technological trajectory. As the technology in the quantum-safe context is still unknown, combining the TIS with the development of scenarios to formulate potential future structures of the system may be the insight needed to prepare for a quantum-safe transition. Furthermore, analysis of the functions can be aligned with the intervention design as proposed by Koppenjan and Groenewegen (Section 3.1.1). Figure 3 shows the functions and the corresponding lens.

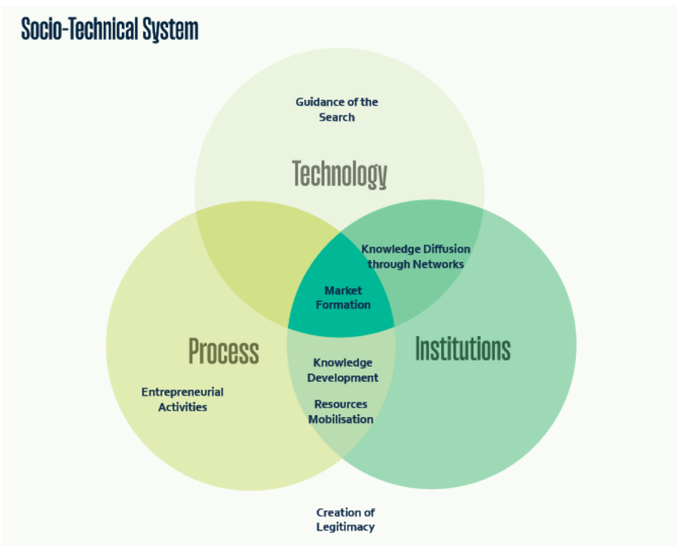


Figure 3; Socio-technical System Design and Technological Innovation

3.1.3 Multi-Level Perspective

The Multi-Level Perspective (MLP) is a framework describing Technological Transitions (TT) and the dynamics in a hierarchical order of levels within society (Geels, 2022). This framework is used to visualise the trajectories and thereby determine the influencing factors in the scenarios. When considering TTs, considering the socio-technical landscape and the dynamics between different layers of a socio-technical system is needed. The MLP describes three levels of development: landscape, socio-technical regime, and technological niche markets (Geels, 2022). The landscape can pressure the regime, which acts as a destabilising factor that allows niches to break through. The destabilisation of the regime may also occur primarily from the niche layer, as disruptive innovations and developments change the functioning of the regime. Figure 4 shows the interactions between the hierarchical layers of a socio-technical system, as presented by Geels (2002).

The MLP and TIS frameworks are intercorrelated: both stemming from the overarching view of the innovation systems approach. Both frameworks analyse similar patterns in socio-technical systems. Four elements can be considered to combine the functional analysis of the TIS framework with the hierarchical approach of the MLP as presented by Markard and Truffer (2008): disruptive niches; the TIS, with emerging properties; a socio-technical regime that provides push-back; and the landscape. These elements are considered when establishing the scenarios of the future energy system in the quantum era. The framework, as presented in Figure 4, is provided in the results with highlights on these factors.

Due to the complexity of the issue at hand, with no clear one solution for a quantum-safe transition, identifying the driving factors of the desired technological developments may prove valuable for future policy recommendations and possible avenues for a quantum-safe energy sector.

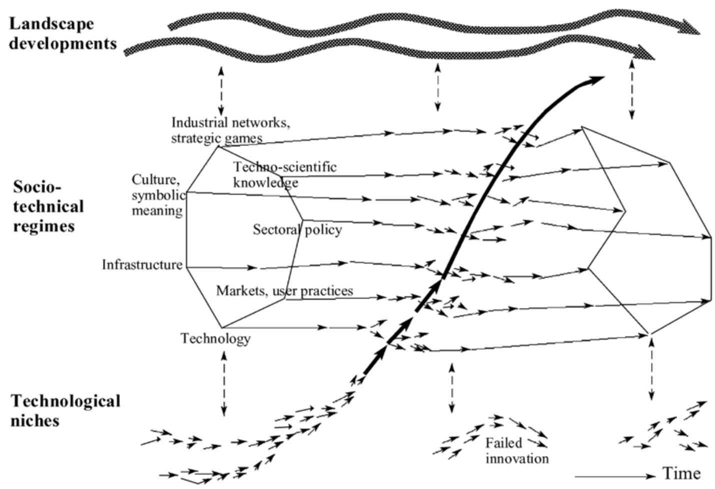


Figure 4; Interactions between the hierarchical levels, MLP (Geels, 2002).

3.2 Research Questions

The main research question, '*What intervention is needed to ensure the development towards a quantum-safe transition in the Dutch energy market?*' is delineated and answered in a structured manner that follows the proposed framework of complex systems design thinking and the innovation systems approach. Each sub-question (SQ) aims to shed light on each type of information needed to answer the main research question. SQs 1, 2 and 3 correspond with the results of Chapters 4, 5 and 6. SQ 4 and 5 correspond to the implications and conclusions of Chapters 7, 8 and 9. The main research question is answered in the conclusion.

SQ 1: Research in the Structural Dimensions Target System

SQ 1 (Chapter 4) results in the first of three layers of data collection: '*What is the current state of the Dutch energy system and its transition towards Renewable Energy Sources (RES) implementation?*', an overview of the Dutch energy system is constructed through desk research and literature study. Desk research is done by analysing documents by market parties such as the TenneT, information from courses, and governmental documents. The result from this question is pertinent for anticipating the structure of the Dutch energy system in which a quantum-safe transition should be completed. Insight into potential future trajectories of the Dutch energy system provides insight into the areas of interest and relevant stakeholders that are needed to facilitate a quantum-safe transition.

To perform a systemic approach towards mapping the system of interest, the structural dimensions as proposed by Wieczorek & Hekkert (2012) as part of the innovation system are depicted first. These consist of the actors, institutions, interactions and infrastructure of the system. Within the TIS framework, the technological factors that need to be considered are depicted within the identified infrastructures (Hekkert et al., 2011). It is pertinent to note the structure of the European energy system and the degree of interaction between the different member states. Even though the target system is set at the national boundaries, various energy, policy and monetary exchanges occur on an international level.

SQ 2: Research in quantum-safe Technology in Energy Sector

SQ2 (Chapter 5) is the second of three layers of data collection: '*What are the possible implementations of quantum-safe technology and security measures in the energy sector?* ', is answered through a literature review on the current research field of an energy sector in the quantum era and quantum-safe implementations, as further addition to Section 2.2. This literature review highlights potential gaps in research for transitioning the energy sector, as well as areas in the supply chain of an energy system that may be vulnerable for quantum attacks.

SQ 3: Research in Functions Target System

The third sub-question (Chapter 6) is the last of the three data collection layers: '*What part of the system hinders the quantum-safe transition of the Dutch energy sector?*', employs the use of the previous literature and desk research and triangulating it with expert interviews to describe the different functions of the TIS framework by Hekkert et al. (2007). Describing the performance of the seven functions provides insight in certain barriers in the diffusion of the technology.

The technological change in a system is mapped and analysed by delineating the system into seven functions to be able to highlight areas of interest. These functions entail the entrepreneurial activities within the target system, knowledge development, knowledge diffusion through networks, the guidance of the search, market formation surrounding that technology, resource mobilisation, and the creation of legitimacy regarding the technology (Hekkert et al., 2007).

SQ 4: Scenarios

The fifth sub-question (Chapter 7), '*What are possible trajectories for intervention and policy structures?*', is answered by assessing to what degree and in what area quantum technology can have an impact and where quantum-safe technological development should be promoted. The data required to answer this question can be extracted from experts and policymakers while cross-referencing this with the structure of the Dutch energy sector. The research done for SQ1, SQ2 and SQ3 provide a foundation of information that facilitates the establishment of scenarios.

Scenarios are created by an adapted six-step process, as proposed by Schwartz (1991). These include defining the main issue, identifying the relevant forces in the target system, selecting a logic to adhere to, created scenarios surrounding uncertainties in the system, and evaluating the implications (Chapter 8). The main forces that are needed to stimulate a quantum-safe transition are defined in Chapter 6.

SQ 5: Implications

The last sub-question (Chapter 8), '*What are the implications of these findings with respect to recommendations to the relevant stakeholders?*', is answered by evaluating the implications of the scenarios as described in Chapter 7. Each of the scenario's policy implications are described, while visualised within the MLP to further delineate the areas of focus.

3.3 Data Collection & Methodology

3.3.1 Desk Research & Literature Study

The data required for the sub-questions research through literature studies is acquired through academic research engines such as Scopus, Web of Science and relevant journals. These journals include Energy Policy (ScienceDirect, n.d.), Renewable and Sustainable Energy Reviews (n.d.), and Technological Forecasting and Social Change (n.d.). For data on quantum and quantum-safe technologies, journals such as EPJ Quantum Technology (EPJ Quantum Technology, 2024) are consulted.

Insight into the current institutional structure surrounding this issue can be abstracted from the guidelines and conferences of the European Commission (European Commission, n.d.-a) and the member states' declaration of cooperation on quantum technologies (European Commission, n.d.-b). As the research focus is the Dutch energy sector, Dutch governmental agencies and documents are also consulted on the topic of quantum and quantum-safe technologies, such as the Quantum Delta NL project by the Ministry of Economics and Climate (Rijksoverheid, n.d.). Further knowledge on technological developments is retrieved from literature provided through the relevant courses (Master Programme Incorporation), announcements from governmental entities and market parties, and the previously mentioned journals and energy policies.

3.3.2 Literature Review

SQ 2 is answered through a systemic literature review to gain insight into the existing knowledge development of the intersection between the energy sector and a quantum-safe transition. To gain an understanding of this research field, broad search terms are used to acquire as much literature as possible. Keywords such as 'quantum computing', 'energy sector', 'energy market' and 'quantum' are used to identify articles. No keywords that specifically concern quantum-safe ty are used, as that limits the number of articles that pertain to post-quantum or quantum-safe applications within the energy sector. This is furthermore due to the novelty of this research field.

A total of 18 articles were selected from the 1738 articles resulting from Scopus, Web of Science, Mendeley and IEEE. 3 Articles were the result of snowballing through the included articles. A comprehensive overview of all articles, the PRISMA flow and the topics discussed are depicted in Appendix C.

3.3.3 Interviews

Due to the exploratory nature of this study, interviews are conducted with experts in both the Dutch energy sector and those working on a quantum-safe transition. Experts in the energy sector include representatives of Distribution System Operators (DSOs), TenneT (TSO), the private energy industry, and research institutions. Experts that are involved cybersecurity issues, quantum-safe ty or PQC are also involved, including those research institutes and a governmental agency (see Table 3). The experts include those with knowledge on market dynamics, regulation and policy and governmental tasks. This variation in interview participants allows for a broad and varied exploration of the Dutch energy sector in the quantum era.

Table 3; Overview of Interview Participants, their Roles and Organisation

Code	Role	Organisation	Date
IP1	Industry Expert	DSO	12th of April
IP2	Data Scientist	Academic Institution	12th of April
IP3	Senior Scientist	Research Institution	17th of April
IP4	Researcher	Research Institution	17th of April
IP5	Consultant	Research Institution	18th of April

IP6	Energy System Developer	Energy Industry	19th of April
IP7	Researcher	Academic Institution	25th of April
IP8	Researcher	Academic Institution	26th of April
IP9	Researcher	TSO & Academic Institution	26th of April
IP10	Lawyer	Regulatory Authority	8th of May
IP11	Security Expert	Government Agency	13th of May
IP12	Digital Expert	DSO	27th of May
IP13	Industry Expert	Software Provider	27th of May
IP14	PKI Expert	Government Agency	29th of May

These interviews are in a semi-open format, during which questions are asked that regard the outcome of the initial system analysis and the participant's field of expertise. Analysis is done by using the system functions described in Section 3.1.2 as guidelines for the coding process (see Appendix E). Each quotation of relevance is highlighted and provided with a code referring to one of the system functions or a fitting code. An overview of all identified codes and their origin is provided in Appendix F.

3.3.4 Data Management & Privacy

For the expert interviews, a thorough protocol is put in place to ensure the security of the participant's data and provided information. In accordance with the Human Research Ethics guidelines provided by TU Delft, all necessary forms are filled in for approval in cooperation with the responsible Data Steward (TU Delft, n.d.). All risks, approvals and risk mitigations are communicated with the participant through Informed Consent Forms.

To ensure the security and protection of data acquired from and by the interview participants, three documents are prepared per the TU Delft General Data Protection Regulation and Human Research Ethics Committee guidelines. These include the creation of a Data Management Plan (DPM), describing all types of data collections and its subsequent storage and management plan. The DPM of this author was approved on the 21st of March, 2024.

The Informed Consent Form (ICF) template used to ensure explicit consent of the interview participants is presented in Appendix D. The ICF includes the types of data collected, the manner of data handling and the further communication with the participants as initiated by the researcher. All participants received e-mails at the following points: the fully transcribed interviews, coding and highlighting of interesting quotations, and the incorporation of the data within the results of the draft of this study. The participants were asked for approval of their role and organisation as described in Table 3.

3.3.5 Tools

Due to the large amount of qualitative data, a structured organisational and coding approach is necessary to come to a comprehensive and accurate synthesis. The literature review is conducted using Zotero (Corporation for Digital Scholarship, 2016). The interviews are coded using ATLAS.ti (ATLAS,ti, n.d.) by highlighting relevant quotations using the proposed functions of the TIS framework as guidelines. These codes are exported in reports to share with the interview participants.

3.4 Limitations

Limitations in the use of qualitative frameworks for the analysis of a system and creation of proposals, is the lack of quantitative data on its effect. Ensuring complete transparency in the process of this research is a necessity, as the reproducibility needs to be ensured. Interpretation of content and interviews depends on the author, which may bring subjectivity as a possible constraint (Dudovskiy, n.d.). A method of ensuring the reliability and reproducibility of this research approach is to base the chosen indicators on strong frameworks mentioned before. In addition, this research approach demands clear delineation and a great attention to conclusions provided, as it is not a conclusionary research (Dudovskiy, n.d.). Specifically, due to the limited resources to thoroughly research the workings of the technologies involved, only their impact is considered. The focus is, therefore, primarily on the policy landscape and the stakeholder interactions within the system. Finally, the integration of the TIS approach is limited to considering the separate functions within the system and does not include the scoring and coupled analysis that is proposed to be performed after such analysis. This is both due to limited resources, as well as due to the results of the literature review (Section 2.2) show a limited amount of insight and development in this subject matter.

4 Structural Analysis – Dutch Energy Sector

Chapter 4 explores the current state of the Dutch energy sector by answering SQ1: '*What is the current state of the Dutch energy system and its transition towards Renewable Energy Sources (RES) implementation?*' The system is first described using the following structural elements: Infrastructure, Actors, Institutions and Interactions. Then developments in the system and future expectations are described, as these impact the potential trajectories that the Dutch energy system takes in the quantum era. Note that the impact of the quantum era is not explored in this chapter.

As a starting point, a generalised overview of the electricity system is used for reference, constructed by de Vries et al. (2019) (Figure E2). Figure 5 shows a template of the Dutch energy sector as a result of this desk research, which is used in Chapter 7 to show the differences in structure per established scenario.

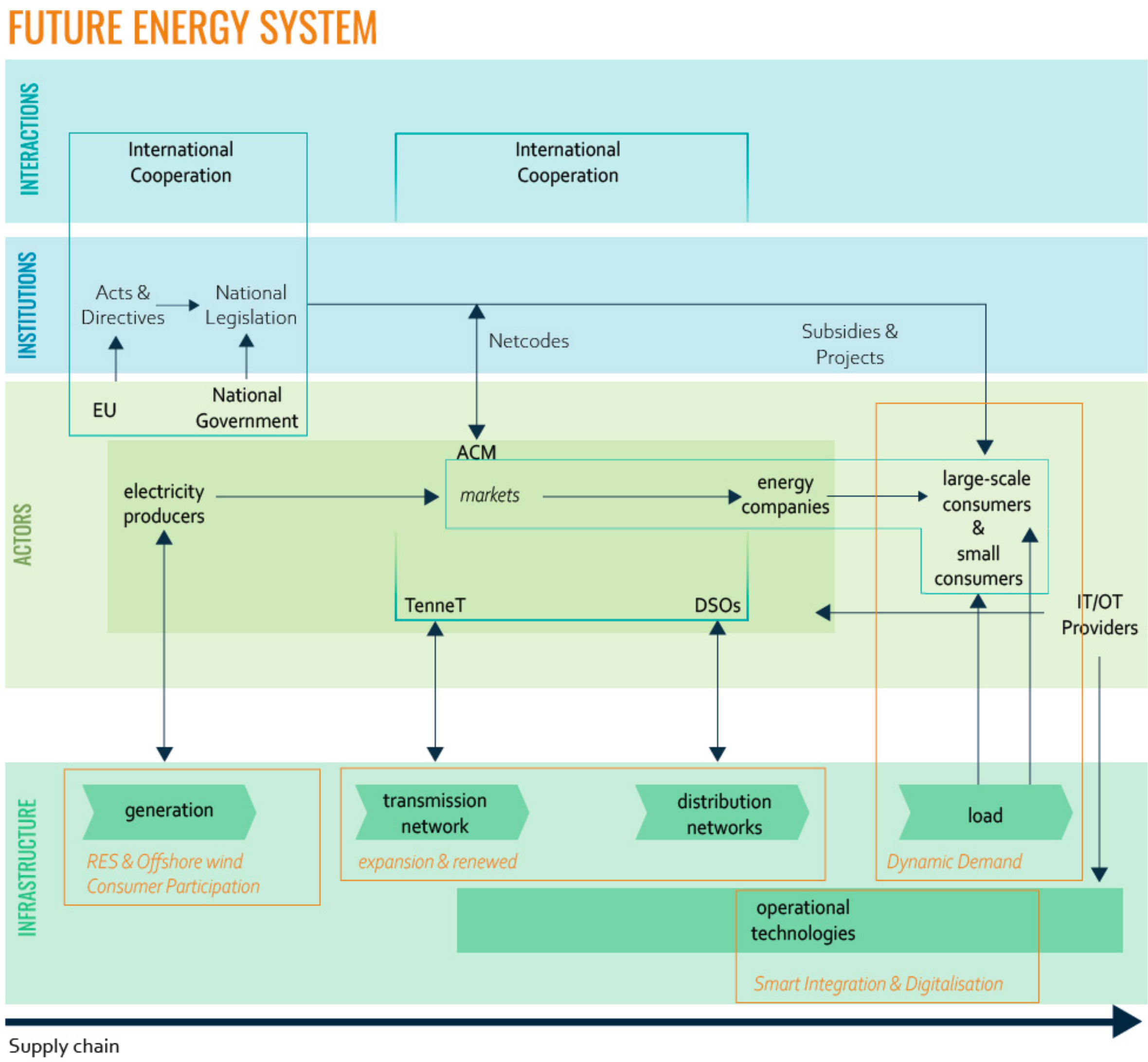


Figure 5; Overview of the Dutch Energy Sector and its Structural Dimensions

4.1 Infrastructure

The concept of infrastructure is included to cover all the physical elements of the Dutch energy sector that are relevant for this study, including the technologies involved, knowledge and the structure of the financial system.

The main dimensions under infrastructure are the physical elements, knowledge infrastructure and financial infrastructure. The relevant elements are described according to this delineation.

4.1.1 Physical Infrastructure

Physical infrastructure encompasses all physical attributes, artefacts, networks, etc. in the target system that the other structural dimensions are in contact with (Wieczorek & Hekkert, 2012). This includes the physical electricity grid, encompassing both high-voltage and low-voltage networks, both from onshore and offshore distribution networks, and connections inland and internationally (TenneT, 2023-a). The physical infrastructure encompasses those elements described in Figure E2; the generation, transmission network, distribution networks and load (de Vries et al. 2019). Note that only the electricity grid is included in this research, with the gas grid not taken into consideration.

4.1.1.1 Transmission & Distribution

The first interconnected electricity network in the Netherlands appeared after the Second World War, from a locally managed power system towards a nationally and even internationally connected electricity network (van Vleuten, 2003). This shift was accompanied by a shift in expectations and end-goal; the electricity supply was not meant to have economic benefits as a primary function but the security of supply (van Vleuten, 2003). Figure 6a shows the first interconnected grid consisted of two main rings with the sole purpose of ensuring supply security in case of blackouts. The grid was not used as structural transport of electricity (Schot et al., 2000). Image 6b shows the most recent depiction of the main onshore high-voltage network in the Netherlands, showing the converter stations and cross-border interconnections.

Figure 6a; First national grid in 1954 (Schot et al., 2000).

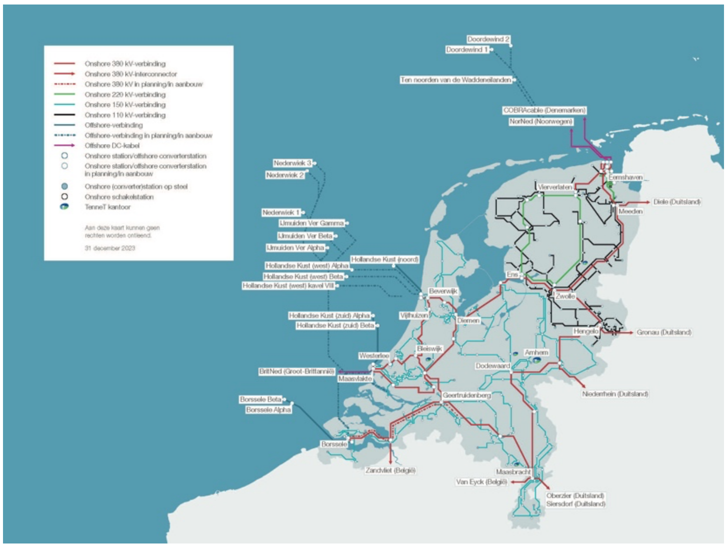


Figure 6b; Current national grid in 2023 (TenneT, 2023-a).

Currently, the generation, production and retail of electricity are privatised, with the transportation and local distribution networks being operated by Distributed System Operators (DSOs) (de Bijl & Fourie, 2019; de Vries et al., 2019). Each energy-producing facility is connected to a connection point that is owned and operated by TenneT, a high-voltage station that connects to the high-voltage grid of the same calibre. The network also consists of transforming stations from high- to low-voltage grids to the distribution networks connected with households and other consumers (see Figure 6b).

The network that leads from gas companies to gas-fired powerplants are not included in this study, as only electrified networks are deemed relevant. Other than the transmission networks described, there are a multitude of local networks included in the system delineation. A primary example of such a network is the infrastructure surrounding offshore wind production. The grid in the North Sea consists of national project, international projects and potential interconnected grids (Konstantelos et al., 2017). As seen in Figure 6b, several wind farms connected on the same main connection are not uncommon.

4.1.2 Technology

4.1.2.1 Operations & Load

Both the high- and low-voltage grids are operated and managed by the responsible parties. There is an extensive information network to monitor these grids. The current system in use consists of the Energy Management System and the Supervisory Control and Data Acquisition, also called the EMS / SCADA system (Tennet, n.d-c.). A SCADA system is a combination of hardware devices and software that allows the owner to gain real-time insight into the system, acquiring information on, e.g. certain devices and processes in the system, analytics of usage in the network, monitoring capabilities and data storage (Enescu & Bizon, 2017). The EMS / SCADA systems used by TenneT, other system operators (e.g. DSOs) and electricity companies combine the ability to secure, collect and analyse data (TenneT, n.d.-c; Soekhram, 2011). Grid monitoring also contributes towards compliance to the network code for System Operation as proposed by the Agency for the Cooperation of Energy Regulators (ACER, n.d.).

Infrastructure at the consumption side of the system is considered as well. This includes (smart) meters and other monitoring devices on the consumer side, energy storage options (e.g. electric vehicles (EVs)) and the needed technology for prosumers (Schleicher-Tappeser, 2012; de Vries et al., 2019; Bouffard & Kirschen, 2008). These technologies allow consumers to gain insight into the energy market, the dynamics due to the price-setting structure, and their participation in the system. This element of the infrastructure may experience significant development in the future.

4.1.2.2 Generation

The physical element of generation encompasses the supply side of the sector. Where decades ago, the primary energy supply came from coal, oil and gas plants, the energy mix worldwide has changed towards a more diversified and RE integrated system (Ellabban et al., 2014). In the Netherlands, this shift in generation is seen even in shorter timeframes, such as the last three years (see Figure 7).

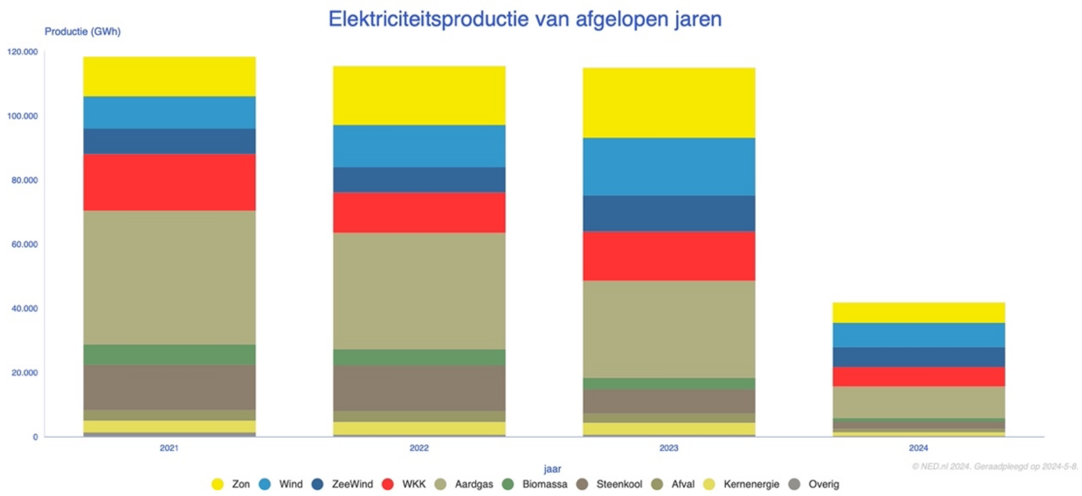


Figure 7; 'Electricity production of the last few years.' (Nationale Energie Dashboard, 2024).

The main electricity producers' portfolios consist of gas-fired generation plants, currently covering more than 18 GW of installed capacity in the Netherlands (Schram et al., 2019; ENTSO-E, 2024-a). A conventional gas-fired powerplant uses gas to fuel the combustion to create steam from water, which in turn produces electricity. Gas-fired powerplants ('Aardgas') emit less greenhouse gasses than coal-fired plants ('Steenkool'), of which there are few left in the Dutch energy mix (Schram et al., 2019) and are therefore considered as a bridge towards a climate-neutral energy system to balance volatile energy sources (Hanel et al., 2022). In addition, co-generation plants ('WKK') that utilise both the electricity and heat output of the plant are also a significant addition to the total energy mix. In addition, waste centres burn non-recyclable waste and utilise the heat to create electricity as well ('Afval'). (Nationale Energie Dashboard, 2024).

RES include on-shore and off-shore wind energy by use of wind turbines ('Wind' and 'Zeewind'); solar PV both in large quantities and employed by individual households ('Zon'); and biomass generation plants ('Biomassa'). In addition, although not classified as RES, nuclear power plants provide additional consistent energy to the total energy mix. (Nationale Energie Dashboard, 2024). This diversified and increasing distribution of energy sources is deemed likely to continue developing in the future and is therefore taken into consideration for the establishment of scenarios.

4.2 Actors

4.2.1 Industry & Market Design

TenneT manages the high-voltage energy system in the Netherlands and part of Germany as a Transmission System Operator (TSO) but has established a distinction between the two countries for operational purposes related to each countries' policies (TenneT, 2024). TenneT operates and manages over 25.000 kilometres of onshore and offshore connections, services over 40 million end-users of supply and aims to become an influential energy operator in Europe (TenneT, 2023-b).

The market design of the Dutch energy sector has changed throughout the years with each iteration of the regulations and European influences. TenneT is fully owned by the Dutch state as of 1998, when the Electricity Act put an end to the cooperation of energy-producing companies[3] throughout the country and their diversified ownership. TenneT is acting as an overseer of all producers, consumers and traders active on the network, keeping in constant communication with all influential.

Technical Publications from TenneT by the Market Design department show the delineation between the Dutch and German operations due to the structure of the Dutch energy market. The energy market consists of multiple 'sub-markets' that each have their own timing. The energy market most familiar to consumers is the Day-Ahead (DA) market, even though this only comprises a part of the total Dutch energy market. Generation and consumption bids are placed at the DA market and are cleared by the market operator (Morales et a., 2014). For more long-term contracts, preceding the day-ahead market is the Forward and Futures market, as well as bilateral contracts that span a large period of time (TenneT, 2022-a).

[3] The 'N.V. Samenwerkende Electriciteits-Productiebedrijven' was a cooperation of electricity production companies in the Netherlands from 1949 to 1998 (CBS, 2015).

After liberalisation, there is one network manager per region, the Distribution System Operators (DSOs), which is separated entirely from production, consumption, and other market activities on the energy grid (de Vries et al., 2019). DSOs have a comparable functioning as the TSO but operate on the regional level and have direct connections with low-energy demand consumers. The DSOs with the largest area of operation are Stedin, Enexis Netbeheer and Alliander (Netbeheer Nederland, 2022).

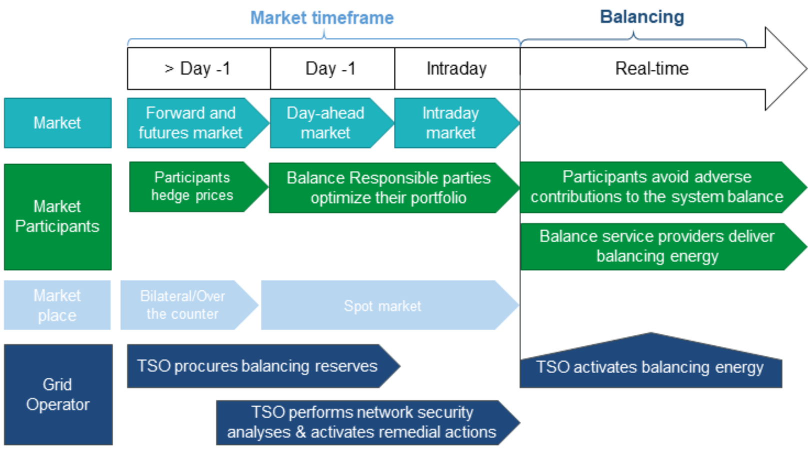


Figure 8; Timeframes of electricity and balancing (TenneT, n.d.-d).

4.2.1 Market Actors

Energy providers and energy producers are different types of market actors but may be the same actor in the same cases. The major energy producers / providers are Essent, Eneco, Vattenfall and ENGIE. Overall, there are approximately 60 energy providers active in the Dutch electricity market (Autoriteit Consument & Markt, 2024-a). As seen in Figure 8, these are the retail companies that buy from the wholesale market and sell to consumers. The best-known market, the Day-Ahead (DA) market, is where energy producers and buyers (providers) trade electricity for the next day (Batlle, 2013).

Energy producers, including the previously mentioned four market actors, provide electricity and are connected to Balance Responsible Parties (BRPs) that deliver forecasts to TenneT as accurately as possible, which allows for TenneT to ensure correct balance on the national grid (Batlle, 2013; TenneT n.d.-e). These may be energy providers, producers or other types of market parties that contribute to the balancing market. Additionally, there are Monitoring Responsible Parties (MRPs) that ensure correct monitoring of consumption on the demand side of the market (TenneT, n.d.-f).

Other market actors that are outside the national boundaries of the target system include technological companies that provide the operational and information technologies (OT and IT) of the national network. These market actors operate on an international level, and their behaviour and trajectories are therefore harder to stimulate. However, these need to be taken into consideration in the development of the Dutch energy sector, as technological incumbents are in a position that allows them to control or influence the socio-technical system, as proposed by Geels (2011).

4.2.2 Research, Knowledge & Educational Institutes

Due to the broad target system delineation at the national level, knowledge production and research is shared among a variety of actors, including those described before. Universities and organisations such as TNO perform research on new technological developments, research in the energy transition, policy recommendations, and the education of future experts on the topic.

Most universities provide courses and study programmes concerning the (future) energy system in the Netherlands and simultaneously participate in research. The Netherlands Energy Research Alliance (n.d.) has members from technological universities, general universities, and research institutes, including TNO and NWO. Other than collaboration on energy transitional agendas by research institutes, the private parties within the energy sector also established R&D procedures and goals for facilitating and contributing towards the changing energy sector, including energy providers and producers.

Global R&D and research efforts impact the Dutch electricity transition as well. It has been shown that developments in RES further enhance the investments made in the energy sector and may result in additional benefits for the public (Wen et al., 2022). Overall, many and varying levels of society are involved in the development and functioning of the Dutch energy sector, in both research facilities, education and R&D expenditures. These expenditures are not limited to public actors but further include the private sector involved, as the energy system is one of the few large-scale systems that has a certainty of existence in the future.

4.2.3 Government Bodies & Support

The government bodies influencing the Dutch electricity system are divided into the following hierarchies: the global entities, the European Union, the Dutch national government, local municipalities, and other policy creators and enforcers. For this analysis, the global entities are described within the institutions (4.3).

The European Union (EU) is involved as a higher-level governmental body in the establishment and enforcement of policies and regulations and the creation of cooperation between other parties (de Vries et al., 2019; Batlle & Ocaña, 2013). One of the European bodies includes the Agency for the Cooperation of Energy Regulators (ACER), which contributes to the facilitation of the European electricity network, aids and helps national authorities and monitors the markets (European Parliament & Council of the European Union, 2011).

The Dutch national government enforces European directives and regulations. The Ministries for Economic Affairs and Climate Policy and the Ministry of Infrastructure and Water Management are involved with the current infrastructure, energy transition and other technological developments within the national energy supply. Local municipalities further enforce regulations or are involved in regional energy applications (Vereniging van Nederlandse Gemeenten, n.d.).

The 'Autoriteit Consument & Markt' (ACM, Authority Consumer & Market) provides supervision on all parties involved in the Dutch energy sector, including the TSO, DSOs, and energy producers. Furthermore, they translate and enforce regulations from the EU and provide permits for market parties to deliver energy (Autoriteit Consument & Markt, 2016).

4.3 Institutions

These include hard and soft institutions, with hard institutions being rules, laws and regulations, and soft the habits, commons, practices, norms, expectations, etc. (Hekkert et al., 2011). There is a line between these two types of rules on which public expectation can be put: the stronger public support or opposition is, the more likely it is that it translates from a soft institution towards a hard one. Within the energy transition, this is especially true: expectations towards TenneT and the government on ensuring that the living environment is untainted while also aiming to satisfy those who wish strongly for the energy transition (Fouquet, 2016).

4.3.1 Hard Institutions

Hard institutions are enforced by both the national government and the EU regulations that supersede the national regulations. The Electricity Act of 1998 is the basis on which the current electricity market is based. Two of the main factors leading to the changes in the current electricity system are the liberalisation of the grid and the Electricity Act, which established the activities and non-private entities taking control of the national grid (de Vries et al., 2019). The liberalisation led to the separation of the chain within the electricity supply, unbundling the energy generation from transportation (de Vries et al., 2019). In 2006, the Independent Grid Administration Act was introduced by the Dutch government to split the commercial activities in the energy market with the infrastructural operations (de Bijl & Fourie, 2019). Each of the directives set by the EU is translated into national regulations and governance to enhance the unification of the European energy market and its transition towards a more integrated RES (European Commission, 2023).

Main elements of the financial infrastructure include tariffs for network use; financial flows on the various markets; and subsidies and grants for energy sources. Individual consumers pay the energy tax, tariffs and energy prices to their chosen energy supplier (Government of the Netherlands, n.d.). Energy suppliers pay to the DSOs, and the DSOs pay some to TenneT. Each of the DSO and TSO uses the revenue to operate, build and maintain their respective grids, networks and other physical elements of the network, as enforced by the ACM (TenneT, n.d.-g; Autoriteit Consument & Markt, 2024-b).

To change the behaviour of consumers in the Dutch electricity market, the Dutch government introduced several subsidies and grant projects to enforce the adoption of solar panels, for example. These include crediting electricity to ensure surplus energy can be 'bought' from the consumers; rebates for energy tax; and grant schemes to stimulate adoption of RES by organisations (Ministry of Economic Affairs of the Netherlands, 2016).

4.3.2 Soft Institutions

Within soft institutions, one of the main driving factors in the energy market is the consumers. The pressure from the public and cultural expectations resides in the landscape of a socio-technical system, putting pressure on the regime and its actors for change (Geels & Schot, 2007).

A clear example of public forces that enforce a certain development is the rapid adoption of solar energy on the level of individual households (Linders et al., 2021). It can be argued that the willingness of consumers and cultural factors for the management of monetary assets create a strong push for consumers to adopt RES.

4.4 Interactions

4.4.1 Government

The relevant interactions identified in the Dutch energy sector are geographically scattered, bridging internationally and intercontinental. The most direct interactions consist of the network cooperation between all European member states that are interconnected on one 50-Hertz grid (TenneT, n.d.). In the case of a black-out, damage to the network or any other event that results in a (temporary) interruption of electricity flow impacts the entirety of the grid, requiring the TSOs to manage this change. TenneT furthermore has strong connections with the TSOs of other European Member States through the European Network Transmission System Operators for Electricity (ENTSO-E) (ENTSO-E, 2024-b).

National governments on a global level are involved in several agencies, collaborations and accords to unify efforts in energy system developments (International Renewable Energy Agency, n.d.; International Energy Charter, 2016; United Nations Climate Change, n.d.). Governments and governmental agencies are involved in the energy system to a high degree as the sustainable transition is pushed through. Furthermore, public-private cooperations are prevalent throughout the system, as governmental agencies and research institutes work together with private (technological) companies for different purposes. These partnerships include tenders and investment cooperation in infrastructure (RVA, n.d.) and inter-organisational projects that pool together knowledge and resources (TNO, n.d.-b).

4.4.2 Operators

The relevant interactions identified in the Dutch energy sector are geographically scattered, bridging internationally and intercontinental. The most direct interactions consist of the network cooperation between all European member states that are interconnected on one 50-Hertz grid (TenneT, n.d.-h). In the case of a black-out, damage to the network or any other event that results in a (temporary) interruption of electricity flow impacts the entirety of the grid, requiring the TSOs to manage this change. TenneT furthermore has strong connections with the TSOs of other European Member States through the ENTSO-E (ENTSO-E, 2024-b).

Due to the rapid increase in energy demand and the number of prosumers[4], there are currently some issues with congestion on local grids (TenneT, 2022-b) for which TenneT has announced an increased effort in the search and development of innovative solutions (TenneT, 2023-a). TenneT has furthermore announced to participate in the national action plan regarding the overused grids in the Netherlands (TenneT, 2023-a; Rijksoverheid, 2022).

The Memorandum of Understanding between ENTSO-E and the EU DSO Entity is to ensure more cooperation on equal-to-equal level and established more commitment to future regulation changes and goals (ENTSO-E & EU DSO Entity, 2022). Additional cross border interactions are also established on large scale projects, such as the North Sea Wind Power Hub Programme (NSWPH), a consortium with the TSOs of Denmark, the Netherlands and Germany, as well as with the gas operators of these countries (NSWPH, n.d.).

Interactions on national levels primarily exist between TenneT as the TSO, the DSOs and market parties identified in 4.2.1. Furthermore, interactions between the different energy providers, operators, and end-users happen frequently. One example is the balancing market, where TenneT communicates with Balancing Responsible Parties (BRP) and Balancing Service Providers (BSP). These communicate to the degree of once per several minutes to ensure correct balancing of the national network and be able to limit the damage of a potential complete black-out (van Breukelen, 2021; de Vries et al., 2018).

4.4.3 Consumers & End-Users

As the energy system is a critical infrastructure, all levels of society in the Netherlands have at least some degree of interaction with the electricity system. Due to developments in the decentralisation of the Dutch energy system, consumers are more involved in the value chain. The relationship between the Dutch electricity sector and its consumers may drastically change in the coming years when expectations of the decentralised system come true (Bouffard & Kirschen, 2008; Biresselioglu et al., 2024)

Currently, most interaction between the market and consumers exists in the wholesale and retail market in the sector (see Figure 4). Consumers and large end-users are active on the market that provide contracts for energy, after which these consumers enter the contract with that energy provider. These providers are private market parties, that in turn have a contract with network operators for the energy's supply. This supply chain has been relatively unchanged throughout the decades but has seen a shift in the recent years, where home automation is more prevalent, and consumer behaviour is changing (PwC, 2016).

[4] A prosumer is an energy user that both consumers and produces energy (Kenniscoalitie Energietransitie, 2024).

4.5 The Future Energy System

4.5.1 National Network

In recent years, TenneT has experienced a changing energy sector, managing a significant increase in demand, diversification in suppliers and working towards a grid that fits the energy transition as proposed by the (inter)national community and policies (TenneT, 2023-a). In 2022, TenneT has invested 4.5 billion Euros in grid expansions, RES integration and further development in the energy transition (TenneT, 2023-b), a record at that time, with an expected increase in investment capacity each year. Needless to say, TenneT is in a unique position of pressure for change on varying sides while handling a significant year-to-year increase in demand and company growth. For the energy transition, new and renewed infrastructure is needed that is able to incorporate the demands of the future energy system (TNO, 2021). Furthermore, the parties involved take into consideration the international position of the Netherlands as a precursor in the energy transition (2021).

Another large avenue of the Dutch energy system pertains to the offshore wind sector. For TenneT, the consortium and others in the government, this development is well underway. More importantly, it seems that there is much focus on this project as part of the future energy system. The NSWPHP is also of interest due to the hub-and-spoke approach, which includes two-way connections to other countries as well (North Sea Wind Power Hub Programme, 2021).

4.5.2 Technological Development

One of the anticipated developments is the implementation of smart meters and smart grids to battle the congestion issues that are currently in place. As an answer to the demands made in the Climate Accord and the congestion issues on the current grid, TNO contributed to a roadmap (2021) that describes the plans made for the electrification of the grid, while also ensuring an accelerated approach to sustainable integration.

Most important is the decentralisation of the energy network that can be managed with a smart grid. The number of energy providers increases, as well as the number of prosumers; more dynamic contracts and two-way connections to the low-voltage grid; RES are volatile and intermittent, which increases the need for a steady baseload (Blumsack & Fernandez, 2012).

Additionally, solar PV technology and offshore wind projects are likely to experience large developments (Ellabban et al., 2014). Specifically, due to the economies of scale experienced by solar PV, its adoption by consumers increases. To mitigate the volatile nature of these RES, the addition of batteries may be further explored (Moriarty & Honnery, 2016; Luo et al., 2015), especially in combination with projects to produce and employ the use of hydrogen for EVs (van Bree et al., 2010). With the introduction of the NSWPHP, TenneT and its consortium aim to introduce the production of hydrogen production in its projects, as to facilitate the flexibility of an energy system based on intermittent RES (North Sea Wind Power Hub, 2021).

4.6 Conclusion

The question '*What is the current state of the Dutch energy system and its transition towards RES implementation?*' is described. The current state of the Dutch electricity system shows a varying number of stakeholders, of public, non-private and private nature. Technological developments in generation and operations change the sector's landscape, while the sustainable energy transition stimulates consumer behaviour. Interactions slowly move from a supply chain towards a more circular and interconnected system.

There are varying paths of development towards the future energy system one of the more significant expectations lies in the decentralisation of the energy system. There are more dynamic contracts and participation by the public. To ensure the desired security of supply, large offshore wind projects have started, signifying a shift towards more volume of intermittent RES supply. This increase, in turn, requires development of hydrogen as a replacement for gas and energy storage options to mitigate the intermittency and volatility of the potential future energy market. These developments

Figure 5 shows a general overview of the energy sector as described in Section 4.1 to Section 4.4, with each of the structural dimensions and its main elements. In green, the future developments in the target system as described in Section 4.5 are highlighted, which forms a starting point for the expert interviews in Chapter 6 and the establishment of scenarios in Chapter 7.

5 Literature Review - Quantum-Safe in Energy Sector

A literature review is performed to analyse the research field on the energy sector in the quantum era, including potential quantum-safe implementations. Based on the limited number of articles found in the preliminary literature review from Chapter 2, several search methods were applied to collect relevant articles for analysis (see Appendix C).

Due to the novelty of the research field, there are different topics and themes appearing from the included articles when applying a systematic literature search on the described search engines. These include cybersecurity within certain aspects of the energy sector, communication and information infrastructures and technologies in the energy sector, quantum technologies and quantum computing, PQC, and quantum-safe technologies. Each of these topics is further detailed. Below, the synthesis of the topics is shown. An overview of the included articles and their topics can be found in Table C1. Below in Table 4, the main topics found in the included articles are presented.

Table 4; Topic Synthesis of Included Articles

Sub-topic	Topic	Reference
Internet of Things	Smart Grid (SG)	Aljaafari & Alotaibi, 2023
Blockchain		Hasan et al., 2022
Quantum Computing		Ajagekar & You, 2022 Paudel et al., 2022 Ullah et al., 2022
Quantum AI		Ajagekar & You, 2022
Quantum Computing	Decentralised Energy Resources (DER) and Transactive Energy Markets (TEM)	Ajagekar & You, 2022
(Quantum) AI		Ajagekar & You, 2022 Mazhar et al., 2023
(Cyber)security		Sundararajan et al., 2018 Zografopoulos et al., 2023 Sousa-Dias et al., 2023
Post-Quantum Cryptography (PQC)		Sundararajan et al., 2018
Technological Applications	Future Energy System (FES)	Ahmad & Zhang, 2021 Ajagekar & You, 2022 Hasan et al., 2022 Paudel et al., 2022 Zhao et al., 2023 Aljaafari & Alotaibi, 2023
Threats		Joshi et al., 2022 Körner et a., 2022 Mazhar et al., 2023 Sundararajan et al., 2018 Zografopoulos et al., 2023
Threat Mitigation		Hasan et al., 2022 Kumar et al., 2022 Zografopoulos et al., 2023
PQC	Quantum Applications	Hasan et al., 2024 Nakka et al., 2024
Quantum Technology		Aljaafari & Alotaibi, 2023 Purohit et al., 2024 van Deventer et al., 2022
Quantum Computing		Joshi et al., 2022 Paudel et al., 2022

5.1 Cybersecurity of Energy Technologies

5.1.1 (Smart) Grids

The communication and information transportation in 'classical' grids and smart grids are discussed. The future energy grid that is decentralised and distributed may rely on Distributed Ledger Technology (DLT) that employs cryptography for protection (Zhao et al., 2023). For the cybersecurity of such grids, peer-to-peer network architecture may be employed to increase its security (Zhao et al., 2023). Quantum computing provides applications that ensure the security of smart grids by employing QKD in microgrids that provide resilience and potential agility to mitigate Denial of Service (DoS) attacks (Ullah et al., 2022; Mazhar et al., 2023). In addition, AI can be used to further develop smart grids, as well as provide security.

Furthermore, the security of smart grids should not only be assured on the technological level but also on the human level (Mazhar et al., 2023; Hasan et al., 2022). The need for new security measures that could collectively secure all (micro)grids present in an energy sector is highlighted (Zhao et al., 2023; Ullah et al., 2022; Mazhar et al., 2023). However, there are a number of potential solutions whose implementation to the Dutch energy sector would require a thorough analysis of all proposals presented.

5.1.2 Distributed & Decentralised Energy Systems

Current developments of the FES show a trajectory towards decentralisation, and it is important to provide standards on data sharing and communication in such a system in the future. Privacy-oriented data exchange for individual households are deemed important (Körner et at., 2021). Increased coupling and interconnections in the system provide additional flexibility, which is favourable in congestion cases (Körner et al., 2021; Sundararajan et al., 2018; Sousa-Dias et al., 2023).

Distributed Energy Resources (DER) describe an energy network in which energy resources are more distributed, sometimes more volatile and require a complex interconnectedness to the (local) grid (Zografopoulos et al., 2023; Sundararajan et al., 2018). Cybersecurity of such energy systems needs to be adequate on the cyber-physical levels, concerning the communication and IT structure of the Decentralised Energy Resources (DER), as well as the physical properties of the resource, including software and hardware (Zografopoulos et al., 2023). Such resources may be vulnerable to cyberattacks on the cyber-physical level.

Vulnerabilities in DER are identified on all levels within the chain of system data, due to e.g. lack of encryption, remote access possibilities, and unauthorised expansions of the grid (Zografopoulos et al., 2023; Sundararajan et al., 2018). Typically, RES such as solar Photo Voltaic (PV) is often remotely controlled through the use of Internet-Of-Things (IoT), which is subsequently relatively easy to access by external parties. Further descriptions of shortcomings include the lack of end-to-end encryption on such devices, secure authentication or the vulnerability of Electric Vehicle (EV) connections to the grid due to simplistic security; no (adequate) cryptography in the communication network (Zografopoulos et al., 2023; Sundararajan et al., 2018). quantum-safe cryptography application to legacy systems is deemed infeasible (Zografopoulos et al., 2023).

Another term for the distribution of energy resources includes the Transactive Energy (TE) grids, which describes a network with a high degree of prosumers. Sousa-Dias et al. (2023) describe the vulnerabilities of including DLT such as blockchain, including the lack of regulation concerning the incorporation of DLT in energy systems. In addition, devices and systems that use IoT are less developed concerning power, while the communication in TE grids is vulnerable to potential future quantum attacks (Sousa-Dias et al., 2023; Zhao et al., 2023).

5.2 Threats & Threat Mitigation

5.2.1 Threats

The literature identifies several threats to the future energy system predominantly. Most attacks on energy infrastructures across the world have been to enter the system, collect data or cause blackouts or disruptions (Joshi et al., 2022). Some of these attacks include 'attacking smaller, less secure companies' in the system, and entering the system through the user-side or localised grids (Joshi et al., 2022). Such compromises in data exchange and management are mentioned to be one of the risks associated with the increased digitalisation of energy infrastructure (Körner et al., 2022). Centralised energy systems that include a general platform may become a risk of their own, as the most impact can be made by targeting that one part (Körner et al., 2022). Mazhar et al. (2023) even state that the operators of the network are 'just as vulnerable to attacks as the network itself', highlighting the importance of awareness for the operators as well.

As the system moves towards more decentralised and digitised systems, other threats need to be considered as well. In smart grids, multiple types of cybersecurity threats are discussed. These include attacks using physical data links, network links and even social links in which human interaction is used to gain access to certain systems (Mazhar et al., 2022; Sundararajan et al., 2018). These threats on the social level are also included in the potential attacks on decentralised systems (Zografopoulos et al., 2023), where attackers gain access through consumers or other human links to the system. Joshi et al. (2022) highlight the importance of securing even the smallest smart meter in the system, as these reduce the security of the distribution side of an energy system.

The threat of quantum computing is also discussed. Hasan et al. (2024) describe the threat as having three major concerns currently: the estimated time before the first practical quantum computing is very close, data is not protected yet and needs to be for a long period of time, and a quantum computer may be a one-time purchase or cost for the attacker. To ensure the adequate protection of critical infrastructures such as the energy sector, it is pertinent to ensure the governance of OT is current and updated.

5.2.2 Threat Mitigation

Maintenance of cryptographic inventory is important, as well as a full asset inventory, especially the mix between IT and legacy systems (Hasan et al., 2024; Kumar et al., 2022). Graph theory may provide insight into the interdependencies of assets in order to be able to protect otherwise not high-priority assets (Hasan et al., 2024).

There are several mentions of behavioural and mindset changes mentioned on the human level of the system. Behavioural change and aligning of goals in the organisation to adequately incorporate the threat environment (Kumar et al., 2022). quantum-safe cryptography has required a shift in the values of influencing stakeholders, as seen with the memorandum made by the U.S. government (Purohit et al., 2024). Knowledge on the application of quantum computing is needed as well, as it constitutes more the specific application for certain processes, instead of the often-assumed versatile function of classical computers.

QKC are believed to be one of the potential solutions for a quantum-safe grid. Europe is shown to be a well-prepared actor globally concerning the preparation of quantum-safe technologies (Joshi et al., 2022). Sundararajan et al. (2018) describe mitigation of threats on varying levels, such as accountability for assets and data storage cryptography on the physical level of the system and strong keys for the transport layer. Furthermore, they describe the need for data limitation to prevent sensitive data from getting into the system where they are not necessary.

For DER, a study found that one of the NIST finalists may provide the necessary PQC to secure distributed systems (Nakka et al., 2024). It proposes a network architecture that includes several PQC tools to be implemented in varying DER servers and gateways (Nakka et al., 2024). Lastly, another approach towards the quantum-safe transition may stem from the current standardisation efforts in quantum computing and quantum technology in Europe in general (van Deventer et al., 2022). In the case of a European standardised method for quantum cloud computing, for example, the accompanying threat may be constructed more specifically. The preparation for the quantum-safe transition may be enforced if threat assessment is more concise and precise.

5.3 Technological Trajectories in FES

The most mentioned application for quantum technology is in the (smart) grids. There is an emphasis on the need for 'smarter' grids to ensure optimisation, increase efficiency and productivity, and ensure the integration of new(er) technologies (Ahmad & Zhang, 2021). The IoT is highlighted as an application with high potential for improving the grid. Furthermore, quantum computing is mentioned as a potential solution to small-scale problems in the grid, as it allows for incorporation with e.g. AI, cryptography, modelling and prediction (Ahmad & Zhang, 2021; Ajagekar & You, 2022).

Other potential quantum implementations include the use of quantum computing with AI for modelling and simulation in the grid (Ajagekar & You, 2022). In addition, quantum computing is described as being able to contribute to (cyber)security in the future energy system (Ajagekar & You, 2022; Aljaafari & Alotaibi, 2023). Quantum computing provides a revolutionary simulating power that allows for the optimisation of energy assets and, the operation of electrical grids, contributes to more efficient scheduling and may even provide additional insights into human behaviour (Paudel et al., 2022).

These technological developments need to be taken into consideration when creating potential scenarios. The research field of energy sectors in the quantum era shows that most topics include a (potential) FES, where increased digitalisation and decentralisation stimulate the implementation of smart devices, quantum computing implementations and connections to the internet. These developments show increased risk in the system, for the threat of cyberattacks exists on all systemlevels: from the large-scale operations to the small-scale smart meters in the consumers' households.

6 Interviews - Technological Innovation System

Chapter 6 aims to provide an answer to SQ3 '*What part of the system hinders the quantum-safe transition of the Dutch energy sector?'*, By systematically analysing the results of expert interviews according to the TIS framework (Hekkert et al., 2011), parts of the system are determined to be functioning or not. First, a description of a future energy system is presented, after which the systemic functions and their evaluation are described and determined. A summarising overview of the codes and their corresponding references is shown in Table 5 below. The complete overview can be viewed in Table F2 in Appendix F.

Table 5; General Overview of Codes on Energy System and TIS

Indicator	Code & Occurrences
Future Energy System	**FES** n=35 in 8 references
Technological Innovation System	
Entrepreneurial Activities	**F1** n=127 in 13 references
Knowledge Development	**F2** n=103 in 14 references
Knowledge Dissemination	**F3** n= 89 in 13 references
Guidance of the Search	**F4** n=168 in 13 references
Market Formation	**F5** n= 90 in 14 references
Resource Mobilisation	**F6** n=86 in 14 references
Creation of Legitimacy	**F7** n=94 in 14 references

6.1 Future System Developments

Section 6.1 provides an overview of the energy network and the (expected) technological developments, as discussed by the experts.

6.1.1 Energy Network

The description of the physical infrastructure as provided in Chapter 4 is validated by the experts. The potential developments are expected to require increased data intensity, as more information may be collected, analysed and communicated throughout the different layers of the energy system. For example, in order to work towards a sustainable energy system, increased data collection contributes to reducing the peaks and subsequent congestion. Flexibility in the network by using data more efficiently distribute energy may contribute towards a reduction in overall energy usage and congestion as well. This decentralisation provides the opportunity to disconnect parts of the system, which in turn reduces the complexity of the infrastructure required to maintain a national-wide system. This is an option that is not broadly accepted or discussed.

Congestion occurs due to high (inflexible) demand and intermittent RES, limiting the use of the grid at certain times. The need for flexibility and efficiency in the network reduces this congestion and allows more room for RES integration. The expected technological developments in the network include decentralisation, additional smart technologies for balancing, increased digitalisation and Internet of Energy (IoE), and consumer participation due to dynamic contracts and energy storage options.

6.1.2 Technological Developments

The implementation of technological applications such as AI, blockchain and local balancing measures are mentioned as potential tools to be integrated but add additional data transfers and requirements for software implementation. All these developments that increase the complexity of the system are stated to increase the vulnerability of the network as well. The result show that the market's drive to innovate is an inherent characteristic of the energy sector.

One of the main trends mentioned by the experts concerns the introduction of smart applications. Smart grids may provide additional flexibility through constant communication and calculation for dispatch. These are mentioned as innovations in localised areas such as harbours that consist of multiple private consumers and as smart devices in households. These trends develop due to an increasing need for congestion management. This shift shows that when the need for grid expansion is high, end-users and consumers participate more often in the energy system.

A timeframe for the development of quantum computing is expected by the experts to be likely between 5 and 15 years. This further includes the use of quantum applications within the energy network. The applications of quantum technology and quantum computing in the energy system as described by the experts validate the results of Chapter 5.

6.2 Systemic Functions

Section 6.2 describes each of the TIS functions and its construction in the target system. Each function follows the structure of description and limitations seen within that function in that system.

6.2.1 Systemic Function Descriptions

The *entrepreneurial activities* refer to the innovative and experimentative activities performed by the actors in the system. These also pertain to small-scale actors that are present within the system that perform activities that are not currently within the regime of the system. Within both the energy sector and the IT sector, entrepreneurial activities are prevalent. The main trends within the entrepreneurial layer of the system pertain to the increased participation of private companies and small-scale companies within the system.

Knowledge development within the target system pertains to all activities concerning research, R&D, academic and research institutions and the quality of the knowledge developed. Insight in the type of knowledge and its quality may present opportunities to delineate the missing knowledge even further.

Knowledge dissemination consists of the spread of knowledge and its strength between private parties, public entities, providers and users, etc. The number and types of established collaborations and knowledge sources provide insight in the degree of knowledge exchange. The more knowledge is exchanged through the target system, the more a desired technology may be developed.

Guidance of the search is the most referred to function within the expert interviews. Guidance of the search refers to the general direction of the target system, the actors' vision and views, expectations, policy goals and the alignment of the expectations and visions. The information provided by the experts regarding this system function indicates that this function is still in development.

Market formation refers to the function that describes the current and future size of the market, as well as the creation of (niche) markets. This function overlaps to a degree with *entrepreneurial activities* and *resource mobilisation but* includes descriptions of the niche market. The niche and regime of the target system are hereby discussed.

Resource mobilisation is functionally similar to the dissemination of knowledge, but pertains human, monetary and physical resources. During the expert interviews, attention was furthermore provided to the behaviour within the system that dictates the flow of resources.

The *creation of legitimacy* can be seen as the amount of resistance to change within the target system. The length of projects and overall resistance by system actors provides an indication of how legitimate the desired technological development is seen by those who would adopt it.

6.2.2 Entrepreneurial Activities

Entrepreneurs are active in both the energy sector and quantum-safe development, with experimentation done within energy collectives as well as on the implementation of quantum technology in the energy field. Cooperation on the experimentation regarding quantum technology is predominantly seen between the research institutes and DSOs. Small-scale experimentation is seen within research institutions that create and test cryptographic schemes in the field of PQC. Large-scale experimentation and production happen through the NIST standardisation and incumbent IT companies implementing PQC. Cryptography has become more diversified with the growth of the IT sector, which may open up the market for quantum-safe implementations and more entrepreneurial activities. This type of PQC experimentation is not prevalent in the Dutch energy sector, as most efforts and investments in IT go towards increasing the efficiency of the grid, improving the EMS systems and incorporating smart applications.

Within the field of IT, software developers experience a low threshold to the market due to little or no need for startup capital. However, within the energy sector, there is a gap between IT and OT in the energy system. The increasing complexity within the system further reduces transparency in the system assets, especially as grid expansions, digitalisation and decentralisation take place. Furthermore, uncertainty regarding the development of quantum technology and quantum computing leads to limited experimentation on quantum-safe implementations. Lastly, there is little knowledge on all assets and OT integrated into the system, due to lack of adequate asset inventory. Due to these knowledge gaps and uncertainties, the need for adequate cybersecurity increases significantly. These issues further increase the complexity a quantum-safe transition might bring, which increases the threshold for entrepreneurs to experiment.

There is a shift in responsibility for cybersecurity seen when it concerns the technological developments described in Section 6.1.2, where software developers and IT providers should ensure the cybersecurity of their products. The responsibility of security for OT remains on the operator's side. This separation of responsibility may lead to parties not taking the responsibility they should, allowing entrepreneurs to enter the market without adequate knowledge. The governmental and authority entities are stimulating behavioural change in the actors' activities through awareness-raising programmes and enforcement of the existing policies. These initiatives are still at the stage of awareness raising and basic cybersecurity.

Overall, entrepreneurial activities are prevalent in the development of IT and quantum technology within the energy system and quantum field. However, due to limitations seen in the energy sector, experimentation on cybersecurity is limited. The cooperation between energy and technological companies concerning IT integration in the energy system may provide opportunities for the integration of PQC in the field of cybersecurity and the development of quantum-safe applications.

6.2.3 Knowledge Development

Knowledge creation in the field of quantum computing and its applications is shared by both public and private entities. Regarding the application within the Dutch energy sector, knowledge on the application of quantum technology for optimisation and energy transport is created in cooperative environments. The potential of quantum computing in the energy sector is seen and exploited in such research efforts. Project Hapkido, as mentioned by multiple experts, is one of the few large-scale cooperations between public institutions and private companies. The potential impact of quantum computing on cryptography and methods of migration are currently being researched. Public research institutes include the creation and testing of cryptographic schemes and guidelines for actors on future migration. At the moment of writing, TNO is creating a follow-up on the 'PQC

Migration Handbook' that includes more concrete steps for organisations to change. In addition, research in the quantum-safe transition is continuously changing, which asks for a dynamic approach to creating guidelines and the expectations towards the potential of quantum computing

The developments in quantum computing increase the potential of technological advancements, as it provides modelling opportunities, among other applications. Experts state that its potential is one of the reasons research projects into quantum computing is more prevalent. quantum computing is expected to change most technological fields, and knowing its potential corresponds with more insight into its potential threat as well. The interviews show that resilience in the energy sector should be created and stimulated through the creation of knowledge, as having in-depth knowledge of the network allows for more adaptability in case of cyberattacks or quantum computing threats.

On the highest level, research on PQC is done through the standardisation process of the NIST. As mentioned by one of the experts: "Due to this large standardisation process, there's a strong interaction with researchers that analyse and judge the schemes that were put in for the competition." (IP4). Visibility and transparency in research lead to more robust results. The same occurrence was seen in the creation of the first handbook by TNO. The knowledge provided within this handbook is mentioned to be not new knowledge, but its publication allowed for feedback from organisations internationally. This insight contributed to identifying the type of guidance needed to help guide a quantum-safe transition.

Limitations and shortcomings of research within the target system include asset inventory, the risks and threats of quantum computing on the Dutch energy sector, the trajectories of technology and system development, and energy usage and data collection. Asset inventory is mentioned to be one of the first steps in the PQC migration. Within the energy sector, each party with their assets may require performing such inventory in their system, which is essential in bridging the IT / OT gap. Furthermore, knowledge of the potential security risks is limited to public institutions, but specification is needed for the energy sector. Additionally, results from current research on the potential structure of future cryptographic schemes are needed to ensure adequate preparation for the migration. This dependence on such knowledge creation results in potential lagging in subsequent research for specific systems. As will be discussed within Section 6.2.6 (*Resource Mobilisation)*, the private sector's interest and investments are (at the moment of writing), mostly limited to the quantum technology development, the creation of quantum computing and potential implementation to increase profits.

6.2.4 Knowledge Exchange

There are three forms of knowledge exchanges identified from the expert interviews: dissemination between parties and organisations, dissemination from public entities, and dissemination from regulation. The latter is treated as a distinct source from the public entities. Knowledge exchange between public entities is predominantly present in the aforementioned collaboration, including Project Hapkido, the Quantum Application Lab and the standardisation process of the NIST regarding quantum development. Within the energy system, the DSOs and TSO are in constant communication regarding the balancing of the system. Furthermore, there is communication between the ACM and the operators, and between research institute TNO and the operators. Such exchanges, specifically those between policymakers and operators, lead to knowledge spillovers in the private sector regarding policy and government activities in the energy system. However, operators do not have complete insight into the activities of consumers regarding the installation of RES technologies or EV adoption, for instance.

Publications made on an international scale led to a high degree of knowledge dissemination throughout society. On the national scale, the entities such as the TSO and national government disseminate knowledge through their channels to the public, such as through the 'PQC Migration Handbook', which includes 'PQC Persona's' with which actors can identify themselves. Indirect dissemination happens through regulations.

European regulations, such as those for energy network operators, provide insight into the functions of operators through the expected compliance. Energy providers or private energy collectives that gain access to the energy grid are also deemed responsible for compliance with those regulations, such as the net code cybersecurity. This leads to those parties further acquiring information on the needed cybersecurity to be able to participate. Policy is mentioned to be key by one of the experts, acting as a source of information.

Even though it seems necessary to strive for as much knowledge dissemination, experts argue that knowledge on a quantum-safe transition may not be necessary for the public. Although a level of understanding is deemed important for raising awareness, knowledge on how a quantum-safe transition or PQC migration works is not pertinent as current knowledge on cybersecurity and computing is not general knowledge. However, the opposite is argued as well, as awareness of the workings of cryptography and the quantum computer allows for the public to stimulate a PQC migration from their providers. A similar sentiment exists within the field of energy system development, where an increase in knowledge exchange on data may contribute towards a more efficient network, while a decrease in data collection and dissemination may lead to a less complex network with fewer security vulnerabilities. A balance is needed to be found in the general knowledge dissemination to and from consumers.

6.2.5 Guidance of the Search

6.2.5.1 Limitations in Guidance of the Search

The perceived limitations in the guidance of the search predominantly concern the difficulties that OT provides. There is a lack of adequate cybersecurity of OT systems and a lack of knowledge on what type of cryptography is used or is needed. OT is not always connected to IOT platforms: "…OT sensors require little manpower, can do much on their own, do not require continuous monitoring, are loved… It is also cheap. " (IP5). This highly correlates with the lack of knowledge of assets in the system, as well as the perception and assessment of risks. Inadequate asset inventory prevents the level of preparedness by actors. Furthermore, the invisibility of potential risks leaves actors unable to determine which direction to go to, or even address the potential quantum computing threat. "Before you work out a perspective of action, or even carry it out, one of the first steps you must take is to make a good risk inventory. And for that, you need to look far into the future and speculate." (IP8). The risk that is realised is most often an unexpected risk.

> "[I saw] companies writing detailed descriptions of 10 risks and their measures to mitigate that risk. But often, these measures were not useful at all because those 10 risks won't exist." (IP3)

Results of the interviews show that the creation of vision within organisations is important, for which internal stakeholder management is necessary. As society pushes the energy transition through regulation and public expectations, alignment between operators and energy parties is needed to ensure a push towards cyber agility. The lack of awareness of cybersecurity is one of the important limitations in vision creation, as it prohibits the identification of shared goals. There is a gap in this awareness between providers of services and users, as users expect the cybersecurity of their purchased services to be adequate, therefore making being knowledgeable in the quantum-safe transition unnecessary. Even though consumers increasingly employ the use of smart devices and other digitalisation methods to combat congestion issues, the expectation remains that the provider of those services is responsible for their cybersecurity.

In both the current and future energy systems, the protection of data transfer and communication should be known by all involved parties, as the risks are significant. "If you talk about the energy sector, you talk about control systems that communicate with each other, and those channels have to be protected. Almost everything becomes vulnerable at the moment the quantum computer arrives." (IP8). There should be awareness of the fact that an interconnected network such as the energy network is "as strong as the weakest link" (IP7).

The general limitation within the guidance of the search in the energy sector regarding the quantum-safe transition pertains to the primary activities of the actors: the provision and security of supply. If there is a lack of awareness and knowledge concerning cybersecurity and potential quantum computing threats on the energy system, most efforts and activities are geared towards the security of supply.

6.2.5.2 Policy and Governance

Several topics are discussed that concern future policy and vision on the energy sector. At the moment of writing, a new net code on cybersecurity for the energy system is established to ensure resilience. In addition, it may be beneficial to include cybersecurity and the quantum-safe transition in organisations' daily policies to ensure compliance. This may already be underway with the current establishment of the NIS2 Directive, which includes PQC as a requirement in the coming years.

Future energy supply is known to be coming from offshore wind farms and other intermittent RES. The current policy that is made on the European level ensures the maturing of such technologies. However, additional attention needs to be paid to future agility in current measures taken by energy sector organisations. For instance, including the expectation of PQC when purchasing services from providers stimulates those providers to implement such measures in their products. Ensuring that the desired quantum-safe transition is translated into added value for companies may be effective.

6.2.5.3 Drivers and Requirements

There are several drivers of cybersecurity mentioned. A common driver discussed is the influence of the geopolitical environment on awareness of threats, more specifically the current war in Ukraine. The threat of black-out scenarios that are caused by attacks on IT rather than OT may prove to be a motivator for regulation to include adequate cybersecurity. In addition, the U.S. recently passed a bill to migrate completely to PQC in 2032, which drives the topic into the global discussion. This relates to one of the main requirements mentioned to ensure a collective vision on the quantum-safe transition in energy: the need for sovereignty. Due to the geopolitical climate and the desire to be a forerunner in technological advancement, the need for sovereignty and independence is mentioned to be highly relevant. The desire to be independent could stimulate actors in the Dutch energy sector to ensure the security of the system, as well as motivate national actors to invest more in the quantum-safe transition. Additional requirements relate to the sense of urgency, and the need for resilience and agility, as mentioned before, which all require adequate risk perception of quantum computing threats.

6.2.6 Market Formation

The general notion regarding quantum technology and quantum-safe technologies is that these are currently on the niche level of the system. There is no dominant design yet, and incumbents that are developing such technologies are not yet the majority. Tools to be able to scan inventory and cryptography used is also still in the niche market, although it is mentioned to be somewhat commercialised. However, the regime shows incremental innovation and changes in incumbents. These incremental changes are mentioned to either prevent sudden changes and loss of consumers or limit the potential sunk costs and exploit the current status quo as much as possible. IT companies are already integrating PQC in their systems, but the focus is more on the implementation than on the creation within such incumbents.

One of the limitations in this function is the lack of preparedness of the incumbents. This may be the result of technological lock-in, which is especially relevant for the energy sector and the degree of OT integration in the system. Furthermore, there are no clear incentives to prepare the quantum-safe transition, as the general goal of the energy sector is to ensure the security of supply. In light of this, experts mention the guiding role that the government. Within the ministries, the quantum-safe transition is a topic of discussion that has led to a government-wide programme. The main goal is to spread awareness, which may reduce the threshold for companies to participate in the market. Currently, there is authority needed over the energy sector, as structured goal setting is difficult: "…as soon as there are things that have an impact on our clients, the security of supply and the security of the grid, there needs to be control over the operators." (IP5).

6.2.7 Resource Mobilisation

The investment landscape surrounding the energy sector, and a quantum-safe transition show several trends. The development of quantum technology and quantum computing sees much (global) private investment while investment in quantum-safe implementations and PQC is mostly limited within companies. The results of the interviews show behavioural factors need to be considered. A quantum-safe transition is mentioned to be a transition not seen before, so there is no clear or direct reference on how such transitions need to be done. Furthermore, people are likely to put short-term problems over long-term problems due to the perceived visibility. Due to the fear of sunk costs, long-term investments are less favoured than investments that have an immediate effect on the added value of the company. This also relates to company and market behaviour. Even if long-term investment in risk mitigation concerning cybersecurity is, in absolute terms, less costly than the cleanup after a cyberattack, it is not always the preferred course of action. Furthermore, investing in technological advancement for competitive advantages is preferred over investing in PQC, which does not necessarily add value.

> "But you still need the power of private assets to make big changes [in a quantum(-safe) transition]." (IP13)

The cost of being the first company to 'take the jump' is one of the limitations of investment in the target system. In addition, the timing of investments is a crucial factor that may limit the willingness of parties to redirect resources: "You don't want to start investing too much too soon because you may lose valuable resources, materials and people to something that might not even happen." (IP1). Time as a resource is also mentioned within the cryptographic community, where new schemes and cryptography take time to be approved by the community. This is validated by the time it takes for the NIST to perform the standardisation.

Before the quantum-safe transition can take place in the energy sector, the expectations may be redirected as investments in OT and IT need to be increased. Asset inventory requires human resources as it is a practice that has not been done before. As every party within the system may need to perform such asset inventory, the party that performs it first may become the point of reference for other parties. IT services such as cloud servers and software are outsourced by energy developers to IT companies, which puts the expected responsibility on these IT companies.

Due to the timing issue, it may be valuable to bundle recourse with similar parties in the energy sector. Efficient mobilisation of resources can be done by limiting the increase of technological adoption and decreasing the complexity of the network. Additionally, within the energy sector, it may be favourably to see the development of quantum technology as part of resource building, as quantum technology provides methods that may make the company's activities more efficient. Similarly, the integration of quantum-safe technologies should be viewed as part of the security of supply.

6.2.8 Creation of Legitimacy

There are three main themes discussed by the experts: the drivers of legitimacy and their exploitation; the public legitimacy creation; and the resistance seen on the private side of the target system. Drivers of legitimacy are mentioned to be knowledge of potential risks, the advancement of technology, an increase in transparency, and incentives. Safety concerns lower the resistance to protection, as seen as a result of the geopolitical environment or the awareness of risks as stimulated by the government. In addition, transparency on data transfers and functions of devices within the energy system allows for more informed decision-making by management, which in turn reduces the resistance towards change. Overall, knowledge decreases the actor's resistance towards the quantum-safe transition, as stepping into the unknown may result in sunk costs. Lastly, if the burden is shared proportionally across the relevant actors, resistance is seen to decrease as well: "That is part of the mentality, if you truly see a big fire coming, it is easier to do something about it together quickly." (IP1).

On the public legitimacy side, there are several processes seen. One of them is the general speed of the bureaucratic processes within the system. Policymaking and alignment of governmental entities takes time, as is seen within the energy transition itself. However, a policy is one of the key tools mentioned to mitigate resistance: "People in the government state that NIS2 should be used as [way] to get parties moving. That is the best I have [on governmental influence]." (IP7). The invisibility of the risks to the general public is mentioned as contributing to the general resistance towards a quantum-safe transition. It may be beneficial for public entities to ensure transparency on such risks to the public. Comparable to the pressure the energy regime experienced from the public, such pressure on security may contribute towards reduced resistance.

As mentioned before, one of the main factors for resistance in the private sector is said to be the perceived sunk costs of transitioning. If the costs of a quantum-safe transition are seen as unnecessary for future functions, only short-term investments are made towards their perceived priority. Investment into the integration of PQC is not yet seen as legitimate, which results in discrepancies across the sector regarding the state of cybersecurity. Specifically, there is resistance in OT providers to replace and start the transitioning process. Lastly, the perceived pace of a quantum-safe transition is said to be too fast for incumbents to incorporate. The resistance to quick transitions is not new, as incumbent activities are relatively slow to change compared to the niche market due to technological lock-ins.

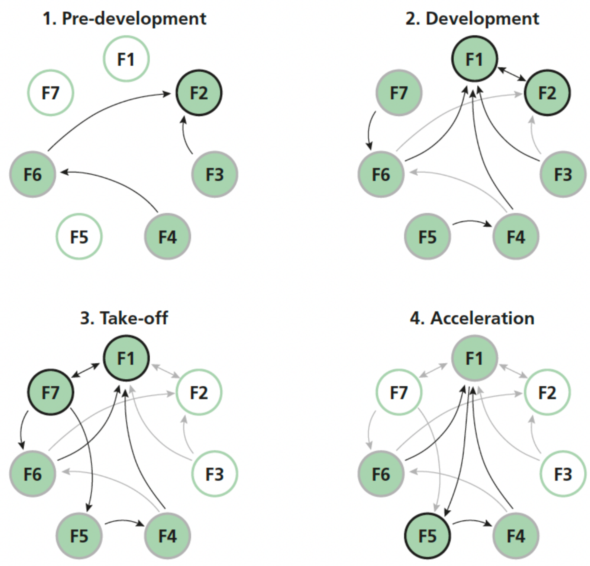
6.3 Function & System Evaluation

Section 6.3 provides an evaluation of each of the functions in the system and where the main barriers in the system's development may be.

6.3.1 System Development Phase

The functions are reviewed on their functionality and the degree to which they may be forming a barrier in the quantum-safe transition in the Dutch energy sector, the target system. Based on the knowledge acquired in Chapter 4 and the function descriptions, the target system's development on the quantum-safe transition in the Dutch energy sector is assumed to be between the 'pre-development' stage and the 'development' stage. The development phase is a situation where the prototypes and applications are already working and adopted in the system, but they are not yet available on the general market (see Figure 2). According to Hekkert et al. (2011), this phase of the development is expected to see functions F2 *Knowledge Development* as one of the main functions that are influenced by F3 *Knowledge Development*, F4 *Guidance of the Search*, and F6 *Resource Mobilisation*, as seen in Figure X below.

Figure 10; 'Functional Patterns per [development] Phase', Hekkert et al. (2011)



6.3.2 Entrepreneurial Activities

Within both sectors of the target system, entrepreneurial activities are present but differ per technological field and what the main types of actors present are. Within quantum technology applications, these activities are prevalent, with public-private cooperations occurring and incumbents investing in the development of quantum technology and quantum computing. Within the energy sector itself, the market is fully formed, with entrepreneurial activities and experimentation happening on the advancement of RES, smart applications and increasing the efficiency of the system.

However, within quantum-safe technologies, this activity is still limited towards public entities, with research institutes and the government participating in international standardisation, but no major investment is happening. Therefore, this function can be deemed to be not adequately fulfilling within the target system. This may be due to the lack of the fulfilment of other functions, specifically *knowledge development, knowledge exchange, guidance of the search*, and *resource mobilisation.*

6.3.3 Knowledge Development

"...especially with this issue, we must invest in public-private cooperation." (IP11)

Knowledge creation is seen in both private sectors, through public-private cooperations and public entities, albeit in different technological fields. Knowledge creation on the applications of quantum technology and quantum computing is seen on most levels within the socio-technical landscape: investments by private companies; public-private cooperations between DSOs, private companies and a national research institute; and through national and international platforms such as the Dutch Quantum Delta, and the European Quantum Flagship.

Knowledge creation on quantum-safe applications and PQC is mostly concentrated on public research entities. PQC standardisation is done through the American NIST, governmental efforts are made on awareness and Project Hapkido. PQC development is furthermore most prevalent within academic and research institutes. There is, however, a gap in knowledge creation concerning cybersecurity on the level of individual organisations within the Dutch energy sector. Due to congestion on (local) grids and the energy transition from fossil fuels to more RES integration, priorities are on the development of efficient energy provision and distribution, network expansion and RES development and integration. This lack of knowledge creation on asset inventory, cryptographic knowledge and even knowledge on cybersecurity may be a barrier in the pre-developmental phase of the system, as it prevents organisations from investing in knowledge development on the quantum-safe transition.

6.3.4 Knowledge Dissemination

Channels for knowledge exchange are identified throughout the Dutch energy sector. Communication between the TSO and DSOs is established, as well as between DSOs, energy providers and end-users. Concerning system functioning, there is monitoring from the authority entity and the operators, as well as between research and academic institutes and energy parties. Knowledge exchanged on those networks predominantly relates to the day-to-day supply of energy, the energy transition and regulations.

Knowledge exchange on the quantum-safe transition or PQC migration is mostly seen to occur from public entities to the rest of Dutch society in the form of governmental programmes and research institutes, such as the TNO handbook, regarding awareness and security. Specific quantum-safe technologies have not yet been developed, and PQC is still being standardised. Therefore, knowledge has not yet been exchanged with all energy parties, but knowledge of assets and cryptography used within the system may already be exchanged. PQC development and research by IT incumbents are implemented in their systems and have not yet been disseminated through the Dutch energy sector system.

Overall, the functionality of this function is not yet stimulating the development of a quantum-safe energy sector and needs to be considered in the intervention. Knowledge dissemination is, however, dependent on knowledge creation. If knowledge creation is limited in a system, it may result in the necessary dissemination channels not developing adequately. One of the main barriers that this function provides in the system may be the international knowledge dissemination, which is experiencing a conflict of interest. There is a desire for sovereignty in knowledge development, but the PQC migration and overall quantum-safe transition require cooperation.

6.3.5 Guidance of the Search

This function may be the least fulfilled in the target system. As the Dutch energy system is in a transition towards more RES integration, a decrease in fossil fuels and rapid network expansion, there is no clear vision of what the structure of the future energy system might be. Visions on the future energy system differ, as do the opinions on the degree of consumer participation in the energy system.

There are several limitations identified in the guidance of the search, including the lack of proper risk assessment and perceived potential sunk costs. Concerning the quantum-safe transition, due to the lack of risk assessment (or even perception), there are variating levels of cybersecurity implementations seen across the energy sector, with new smart technologies often having some degree of cybersecurity, but OT and legacy systems sometimes do not have proper cybersecurity. This variation across the network translates into variations in expectations across actors in the system. A lack of united expectations and aligned vision on the quantum-safe transition in the energy sector may lead to a situation in which responsibility delineation is not adequately done. This concerns the inventory of assets, for example. The quantum-safe transition, therefore, is deemed to be of differentiating importance across the system – as cybersecurity is not the main activity of most energy parties -even though quantum threats may present themselves on all levels of the energy supply chain.

This function's fulfilment may provide the most impact on the development and transition towards a quantum-safe energy system. The identified drivers mentioned may be used to translate the urgency needed for actors to understand. This function is currently not adequate and is deemed to provide a barrier to an efficient quantum-safe transition.

6.3.6 Market Formation

The market formation of PQC and quantum-safe applications is still in its forming phase. However, it is relevant to note the levels of markets that are included in and related to the Dutch energy system. quantum technology and quantum-safe technologies are still in the niche market, but the actors developing those technologies differ. IT incumbents are integrating PQC, and the standardisation of PQC is currently underway, but the incumbent regime in the Dutch energy system is showing as unprepared for the quantum-safe transition. The risk of sunk costs limits their preparedness for the transition. However, the market formation of the Dutch energy sector, in general, does include large projects planned despite potential risks.

The market size of the Dutch energy system, including every stakeholder on the supply chain, is significant compared to the market size of quantum-safe applications or even quantum technology. This size and its complexity may present as a barrier to a full-system transition. If trajectories and development are clear across the system, the alignment of expectations may make the complexity of the system less of a barrier. Therefore, this function is deemed to be not yet fulfilled but highly dependent on the previously mentioned functions and not a limitation on its own. If the technological lock-in in the current IT/OT landscape can be mitigated, there are no clear indicators that the market can be formed adequately for the quantum-safe transition in the Dutch energy sector.

6.3.7 Resource Mobilisation

Resource mobilisation is showing similar trends as entrepreneurial activities, as most monetary assets invested in the quantum-safe transition are limited to public entities and intra-organisational applications in IT incumbents. Private investment in the quantum-safe transition in the energy sector is not prevalent, and there is little communication about investment from the operators. The results show that the responsible parties in the energy system are predominantly focused on the expansion of the grid and energy transition.

One of the limitations in the mobilisation of resources is the risk of being the first adopter, which carries the risk of investing in a technological trajectory that does not become the dominant design in the system. Additionally, the timing is crucial when investing in the quantum-safe transition. For actors in the energy sector, performing adequate asset inventory, risk assessment, and investment timing while expanding the grid and mitigating congestion issues may all take precedence over the cybersecurity of legacy systems, for example.

Overall, resource mobilisation concerning the quantum-safe transition is not yet as prevalent as desired, but the current mobilisation in the energy sector does show an established network that may easily be employed for the quantum-safe transition. This function is, therefore, deemed not to be a significant barrier.

6.3.8 Creation of Legitimacy

The creation of legitimacy is an interesting function in the target system, as it shows conflicting trends. Even though there is less resistance to change because of the energy transition, resistance to changes in cybersecurity seems to be prevalent. This resistance is mentioned to be because of a lack of knowledge of the risks and the potential sunk costs.

However, the geopolitical environment seems to decrease the resistance, as security and independence become topics more often discussed in society and the energy sector. The transparency that is created when asset inventory is done may also prove to be a driver of legitimacy. Sharing the burden across the energy actors is therefore pertinent in reducing the resistance to change, especially if it comes to the quantum-safe transition. This function is deemed to be fulfilling, as it depends on other functions fulfilled, and current energy transitions show that legitimacy can be created on a large scale when the problem and transition steps are clear and known.

6.4 Conclusion

The question '*What parts of the system hinder the quantum-safe transition of the Dutch energy sector?*' is answered. The analysis of the target system development shows that the functions corresponding to the pre-development phase, as identified by Hekkert et al. (2011) are non-fulfilling at the moment. The most important functions in the target system are the creation (F2) and dissemination of knowledge (F3), and the guidance of the search (F6). This is validated by the perceived phase of development (Section 6.3.1), as the same functions are seen to need a push. The stakeholders and their vision on the quantum-safe transition are one of the main barriers in the quantum-safe transition in the Dutch energy sector, as experts explained that the lack of urgency, knowledge and clear vision of what the future cybersecurity should look like results in a system development that does not align with the need for the quantum-safe transition.

One of these discrepancies is the gap between IT and OT concerning cybersecurity. OT and legacy in the current energy sector pose a barrier to the migration towards PQC, as there is little knowledge of all OT assets, and there are indications of some OTs not having adequate cybersecurity in the first place. A quantum-safe transition that requires migration to PQC would, therefore, have a significant impact on the integration of (future) OT in the energy system. In addition, stimulating the mobilisation of resources needed for a system-wide transition is necessary. Ensuring alignment of expectations and proper decision-making can be done, knowledge dissemination and transparency are needed for actors to perform risk assessments and start the quantum-safe transition. In addition, the guidance of the search concerns the legitimacy of the transition as well. The degree to which the quantum threat is known and (cyber)security is needed still needs development across the energy system, not excluding the end-users and their participation. The potential trajectories of the future energy system may include a high degree of interconnectedness and a dynamic energy supply, which affects consumers as well.

Although there is a high degree of cooperation in the current energy sector, the lack of shared societal goals and the behaviour of companies limit the unification of expectations in the target system. For instance, the threat of the sunk costs associated with transitioning too fast limits the development that companies and other market parties dare to make. This results in resource mobilisation being limited concerning a quantum-safe transition, research on quantum-safe implementations or a cryptographic migration.

7 Scenarios

The experts' descriptions of the (future) energy system, the gaps in development and the behaviour of the systemic functions are used to establish the scenarios and implications in Chapter 7 and Chapter 8. This chapter aims to answer SQ 4 '*What are possible trajectories for intervention and policy structures?'.* The areas of interest per scenario are discussed, as well as the developments needed to stimulate the quantum-safe transition and potential problems that may arise. Each scenario is established as proposed by Schwartz (1991), by determining the difference per scenario on the uncertainty of the energy market's development.

Common Factors in All Scenarios

Several common factors are identified across all scenarios. Projects shared include the offshore wind expansion by the NSWPHP, the addition of two nuclear energy reactors in the Netherlands, the adoption of PV solar panels by households and the expansion of the network as established by the system operators (Chapter 4). In addition, based on the literature review (Chapter 5) and the expert interviews (Chapter 6), the addition of smart applications is expected. There are policies and regulations announced on European and national levels, including the NIS2 Directive by the European Parliament (Negreiro, 2023), the update on the 'Netcode' cybersecurity as implemented by the ACM, and potential policies on the integration of solar and wind in the balancing market. Lastly, each scenario assumes the same structural dimensions as described in Chapter 4. This also includes the current mix of IT and OT in the energy system, as well as legacy devices still in use.

For the establishment of scenarios, a time period of around ten years is uphold. Each scenario is established through the description of the (future) Dutch energy sector (Section 6.1), which includes various levels of decentralisation and interconnectedness. Then, the roles of the actors in the target system, the potential form of threats to the cybersecurity of that scenario, and what the proposed quantum-safe transition would look like are described. These are based on the limitations identified in Section 6.3, as each scenario mitigates a limitation differently.

7.1 Scenario 1: Slow Development as an Extension of the Current System

The first scenario assumes that the current state of the energy system remains relatively unchanged in the upcoming years, coinciding with the timeline in which the quantum-safe transition should be underway, and the first quantum threats may be realised. It is feasible to assume that the development continues at the rate it has happened until now, meaning that the quantum-safe transition and PQC migration would be done in a system similar to at the moment of writing.

7.1.1 Actors' Roles

Assuming that the future energy system would be an extension of the current system, one of the priorities for operators would be to expand the grid and mitigate congestion issues that occur. Future projects for large supplies of energy that are planned, including the addition of 70 GW of offshore wind energy in the North Sea, are connected to the national grid and remain under the operation of the TSO TenneT. There is increasing cooperation between DSOs across the European Member States. The ACM, as the authoritative entity, ensures the translation of international and national regulation to the energy sector and its participants.

Consumers, prosumers, private companies and other end-users of energy are expected to behave similarly to now. Currently, there is limited knowledge of detailed functions of the energy system, end-users enter contracts with energy providers under ACM regulation, and there is little transparency on the usage data of end-users across the sector. The integration of smart meters, smart grids and EVs increases the complexity of the system, but the adoption of quantum computing and quantum technology applications within the system may mitigate congestion issues.

7.1.2 Cybersecurity

Vulnerabilities in the cybersecurity of scenario 1 are concentrated on the gap between IT and OT infrastructure. As there is a lack of asset inventory and cryptographic knowledge, performing adequate risk assessment is difficult. There is uncertainty on the timeline and feasibility of quantum computing and the need for network expansion supersedes the prioritisation of cybersecurity. Research on the security of new technologies is more prevalent than research on the potential quantum threat on the energy system or the cybersecurity of current technologies. Replacing the cryptography of OT in the energy system may therefore pose one of the main challenges in scenario 1.

Due to the limited knowledge of the public on cybersecurity, there is little societal push for cybersecurity which leads to responsibility put on software and server providers. Changes in security and behaviour are seen once a hack has occurred, or when compliance is expected due to regulation. The main driver for awareness of cybersecurity in scenario 1 would therefore be to ensure that the cybersecurity is an inherent part of the daily policy. The advantage of scenario 1 is that the Dutch energy system could put its focus on one transition at a time, incrementally moving towards a quantum-safe system. Therefore, drivers of the RES transition such as societal expectations and the push from institutions and governments, may be similar as potential drivers for a quantum-safe transition. However, in a system that is only incrementally changing, technological lock-in is more prevalent and agility is therefore difficult to attain. As seen in Chapter 6, agility and flexibility are deemed to be important requirements for a PQC migration and subsequent quantum-safe transition.

7.1.3 Quantum-Safe Transition Trajectory

Scenario 1, similarly to the current system, sees the responsibility for a secure system put on the parties who possess the knowledge on cybersecurity, potential quantum threat and PQC. Parties that do not possess this knowledge seem to not align with the vision of ensuring a quantum-safe transition, which may lead to a lack of direction in the entire system. It is expected these knowledgeable parties ensure the knowledge exchange to help prepare the energy system for the quantum-safe transition (Section 6.2.4). Therefore, structured knowledge exchange should be the first function to be addressed, stimulating awareness across the entire system. The trajectory of the quantum-safe transition in scenario 1 is therefore expected to happen in a simultaneous manner, as identified as a challenge in Chapter 2.

This simultaneous transition does come with the difficulty of sharing the proportional burden: the first 'mover' in the system may experience more sunk costs than those transitioning later. This may lead to dependency on an outside agency to ensure that the PQC standardisation can be adopted within the system. Furthermore, energy market parties are deemed unlikely to make significant investments or costs if it is not directly related to the chain of supply. This is in line with the perceived inflexibility of the current cybersecurity in the energy system, where a change in trajectories and innovation are difficult to realise.

7.2 Scenario 2: Decentralisation and the Internet of Energy

The second scenario describes a highly complex system with a high degree of interconnectedness. It is based on the technological developments described by some of the experts on the trajectory of the FES (Section 6.1) and the findings of Chapter 5 on the technological developments within the system (Section 5.3). Scenario 2 describes an energy system in which the decentralisation of energy sources is significant, with an increase in consumer participation. Furthermore, due to the integration of smart grids (Section 5.2, Section 6.1), smart meters in households and infrastructural devices connected to the Internet (the 'Internet of Energy' (IoE)), digitalisation is more prevalent. The further automation and use of internet and cloud services facilitate efficiency and is deemed a feasible development of the FES. Such digitalisation may lead to a potential decrease in congestion issues.

7.2.1 Actors' Roles

The roles of the actors are similar to those of the current energy system, but there is additional complexity to be taken into consideration. Primarily the increased interconnectedness of the network that increases the complexity of operations for system operators. Managing a network with a high data density may be difficult due to the increased need for data security and data management systems. Furthermore, smart applications and devices connected to the internet would require energy management as well.

The ownership of data and management of data is an unknown terrain when it comes to an interconnected energy system. Especially in the case of IoE where online servers are managed by parties that are not necessarily within the Dutch energy system. Consumers, furthermore, have a different role as well, as they are both data producers and energy consumers. Their adoption of smart technology influences the functioning of the total system, due to increased data traffic, amendments that are needed in privacy questions and the delineation of the consumers' influence on the provision of energy.

Increased regulation and automation of the energy supply may increase the burden on operators in terms of system oversight but may also lead to an increase in burden on the ACM and policymakers that oversee the compliance cybersecurity regulations. In addition, technological providers of OT in the energy system may be expected to include such technologies in their products, which shifts the responsibility of cybersecurity onto existing OT management and new OT products. Lastly, the argument can be made that the public and society is required to acquire knowledge in the system as well. However, this may not be necessary if software and smart application providers ensure the security of individual devices that they produce.

7.2.2 Cybersecurity

Cybersecurity is a topic of interest within decentralised smart energy systems (Chapter 5). Though there are many perceived advantages to such technological developments, increased interconnectedness and data transfer also lead to increased potential for cyberattacks. In addition, the higher-up the cyberattack may occur in a nationally connected system, the more impact it may have. The addition of (smart) devices in the system increases the complexity of cybersecurity as well, as more devices connected require replacements and migrations need to take place. In such a system, it is therefore pertinent to establish a clear value chain and standardisation protocols for all devices.

Drivers of the awareness on cybersecurity in an interconnected system may be put on the technology development side. As demand for smart applications increases, the demand can be made for adequate cybersecurity as well. This is where the burden on the policymakers presents itself, as compliance to regulation and the establishment of clear purchasing policy become pertinent drivers. However, even in a system transition towards increased interconnectedness may allow for a quantum-safe transition parallel to that, as increased adoption of smart devices and replacement of OT unconnected allow for the opportunity to ensure adequate cybersecurity and agility.

7.2.3 Quantum-Safe Transition Trajectory

As new technologies are adopted in significant numbers, the agility of their cybersecurity can be ensured at the moment of system integration. The order of quantum-safe transition would therefore differ from the approach proposed in Scenario 1. A quantum-safe transition in Scenario 2 would take a more hierarchical approach from top-to-bottom. As everything would interconnect in one large grid using IoE, it is pertinent that the area of largest vulnerability is secured first, which would be on the highest (national) level.

Focus should be on the security of the national layer of the system, which may fall under the responsibility of the TSO and DSOs. As this is a shared 'platform' within the system, alignment of expectations of the operators should be stimulated, which increases the fulfilment of the function of guidance of the search within the system

(Section 6.2.5). There should be extensive communication between the decision-makers of operators and the governmental entities to ensure a quick implementation and replacement of cryptography, as knowledge exchange can happen from the knowledge creators in the public sector.

The focus on ensuring the security of supply is significant in Scenario 2 as well, as maintaining that goal would align the actors even more. This would ensure that the guidance of the search is more fulfilled, leading to potentially more resource mobilisation. This top-to-bottom approach furthermore may lead to hierarchical knowledge and resource mobilisation, through which responsible parties can guide end-users and consumers in ensuring that cybersecurity can be agile and adopted.

7.3 Scenario 3: Decentralisation and Disconnection

Scenario 3 sees a similar decentralisation of energy sources as in Scenario 2, but instead of being interconnected, the energy system develops into a dis- or unconnected system. This scenario describes an 'extreme' in the disconnection of the energy system, where data exchange across the system is limited as much as possible. As current developments are seen to be more similar to the first two scenarios, Scenario 3 describes a more drastic change in the energy system.

This potential structure of a FES is validated by experts (Chapter 6), as well as through European initiatives that stimulate the formation of energy hubs and energy communities (Chapter 4). It consists of energy grids being managed and operated primarily locally, where communities or company collectives gain responsibility over their local grid. Such initiatives are currently already present in the Dutch energy system. In addition, RES are decentralised but connected directly to the point where consumption occurs. The large national networks can therefore remain 'simple', only transporting in bulk and not including smart applications or complex IT integrations. Congestion issues may therefore be limited to more localised areas of the system and blackouts may be limited generally and locally.

7.3.1 Actors' Roles

As mentioned by the expert of the TSO, the only information that DSOs and the TSO need is the behaviour of the energy market, which is deductible from its volatility and price points. Data transfer could therefore be limited to this level, which reduces the complexity of the operator's activity, as well as the amount of data it has to manage. Additionally, the TSO and DSOs may focus their main activities on ensuring international interconnectedness on the main grid, large-scale projects and energy provision.

The responsibility of the local grid, however, would shift from the DSOs to more localised communities, organisations or even private collectives. Furthermore, this system would change the roles of the consumers and end-users drastically, from more passive energy consumers to active participants in the (local) energy system. This requires a change in behaviour and knowledge that may see an increase in resistance to change.

On the system-wide level, such a trajectory in the FES would require a drastic change in the vision and expectations of the energy system. Current technological developments move towards smart applications, automation, and increased data intensity, which makes this scenario require the development of more simplified devices. The providers of energy technologies would therefore experience a shift in market formation.

7.3.2 Cybersecurity

The cybersecurity of such a system differs from Scenario 2 in two main ways. First, the disconnectedness on high levels reduces threats to the entirety of the national system. Cybersecurity is, therefore, focused much more on the local level. Second, a potential local increase in complexity and shift in responsible parties may provide new vulnerabilities in the cybersecurity of the system. Knowledge exchange is easier in smaller networks, which may stimulate the spread of awareness on cybersecurity quicker and easier. Agility in cybersecurity is also more feasible in localised networks, as dependence on the grid is less and the number of connected parties is less as well.

7.3.3 Quantum-Safe Trajectory

The trajectory of a quantum-safe transition differs from Scenario 2, as in Scenario 3 this entails the disconnection of the network. As national communication and interconnectedness would be limited to only the necessary data, the main priority on national levels may be the intra-organizational transition and the PQC migration of the PKI certificates. The entirety of the system would entail a bit more of the bottom-to-top security of the system, employing the use of smart grids and energy communities and hubs that are responsible for their connection. As mentioned before, the operators do not require information on every action of the market, as the outcome shows how the market is doing. Therefore, integration of IoT is less necessary at the highest level.

This also corresponds with the policy that a collective of private parties can join behind a single connection, therefore making that party responsible under the 'Netcode' as well, including that for cybersecurity and the integration of NIS2. When more private parties and consumers are expected to comply with such regulations, the PQC migration may see an increase in development due to the overall system-wide expectations. Such a disconnected system also would be an 'easier' platform to enforce the quantum-safe transition, while keeping unsafe or unsecured parts of the network more separate from the rest. This would allow for the quantum-safe transition to be more spread out over time, securing the parts of the system piece-by-piece while ensuring that the security of supply remains for the majority.

7.4 Conclusion

The scenarios each differ in feasibility and complexity. Figure 11 below shows the perceived feasibility and complexity of each scenario, with Scenario 1 deemed neutral, Scenario 2 a high degree of complexity but also feasibility, and Scenario 3 a low degree of complexity, but less feasible as a trajectory. The feasibility of the scenarios depends on the drive of society to develop technology and digitalise.

The author proposes to take Scenario 3 into consideration as the most applicable in preparing the Dutch energy sector for the quantum era. Reducing the complexity of the energy sector while simultaneously stimulating the energy transition to localisation and decentralisation may be the best trajectory to ensure the resilience of the Dutch energy sector in terms of sustainability and cybersecurity in the future. Scenario 3 proposes a more realistic approach to ensure a quantum-safe transition, as the transition would not need to be completed in the expected 10 years before quantum computing is realised. Disconnecting the system as much as possible limits the threat to the national supply of energy in the short-term, and leaves room for the creation of a structured approach to secure the system in the long-term.

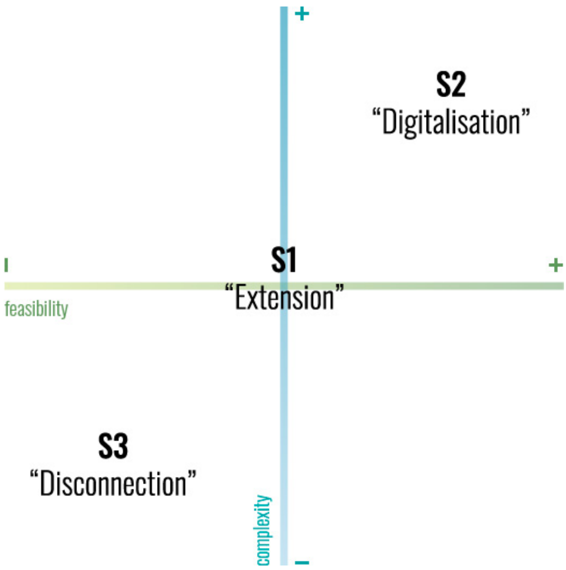


Figure 11; Feasibility and Complexity of each Scenario

8 Policy Implications

Chapter 8 describes the policy implications based on the described scenarios by answering the SQ '*What are the implications of these findings with respect to recommendations to the relevant stakeholders?*' These implications are established generally for the system and per scenario. To describe the forces within the system that may stimulate the quantum-safe transition, the MLP is applied to create an overview to further visualise the expected forces needed for the desired trajectory (see Figure 12). It is hereby important to consider the complexity of the system and its feasibility (Chapter 7).

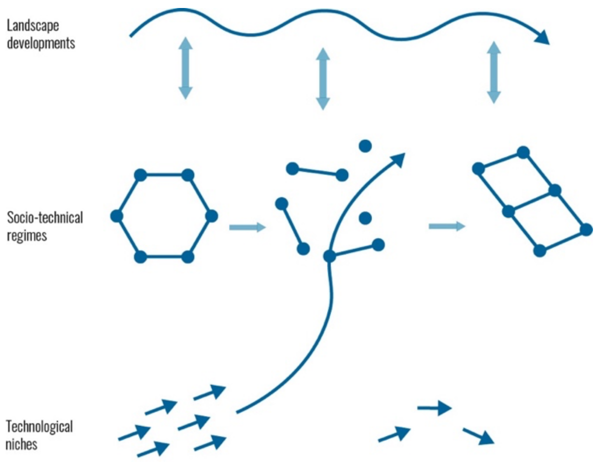


Figure 12; MLP Template, based on Geels (2007).

8.1 General Implications

Some implications are relevant regardless of the system trajectories. The author takes into consideration the feasibility of both the energy transition and a quantum-safe transition, considering the difficulties of a system-wide transition. One of the most impactful implications for stakeholders is the need for an extensive overview of assets and potential risks, as mentioned by the experts, TNO and policies in the making. In addition, long-term plans should be made for PQC migration, ensuring the security of OT and integration of adequate cybersecurity in future technologies.

The guidance of the search is deemed limited in function (Chapter 6). One of the first questions that needs to be answered is therefore how the expectations and visions should be aligned, and which party would be deemed responsible. As indicated by several experts, guidance of the energy sector should not be dependent on the government alone, but on a public-private and government-operator cooperation that includes those knowledgeable. In addition, organisations should ensure that inventory is done on all (cryptographic) assets, regardless of whether the standardisation of PQC is completed. However, there should be a clear delineation of responsibility and dedicated stakeholder management, as most IT and OT infrastructure may have been outsourced to outside parties. The advantage of a PQC migration is that knowledge of the potential schemes could be shared system-wide. This is due to the limited complexity of these potential schemes. Transparency on the standardisation and other PQC efforts may provide the push needed to ensure the quantum-safe transition as well.

8.2 Scenario 1: Simultaneous Transition

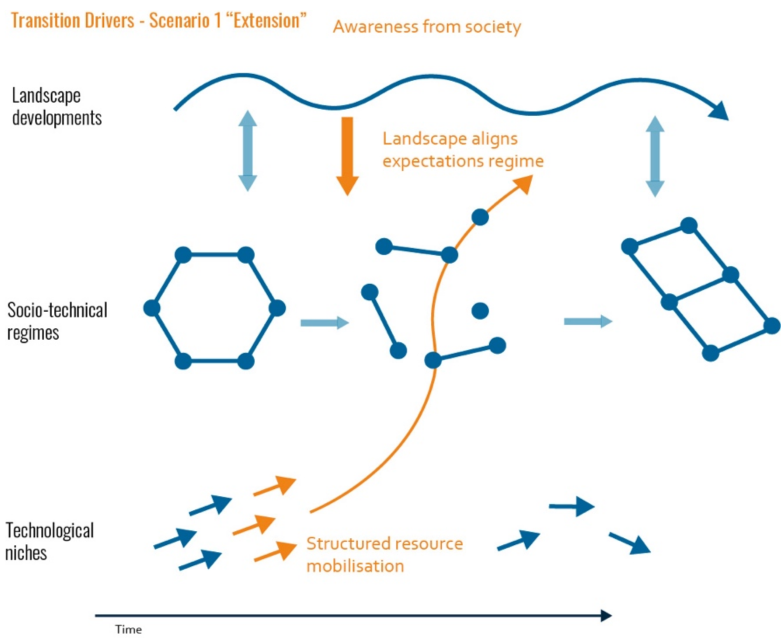


Figure 13; Driving Forces needed for Scenario 1 "Extension"

Research on PQC is publicly available in this scenario, while PQC integration within companies is not. The resource mobilisation is limited to public entities and the development of quantum technology and quantum computing. At the niche level, quantum technology and quantum computing are developing quickly, as their applications are already starting to be devised in the current socio-technical system. quantum-safe technology and PQC are still in the developing stages of the niche, as its drivers are mainly public entities.

Based on the need for a simultaneous transition in the Dutch energy sector, it is pertinent that the transition drivers come from both the landscape and niche level at the same time (see Figure 13), as to ensure its introduction into the regime. To push the niche towards the regime, more structured resource mobilisation is needed in addition to the current PQC standardisation: the creation of a niche market and the subsequent development of entrepreneurial activities in the system are necessary to provide direction and clear dominant designs in this field. From the landscape, societal and institutional pressure in the form of awareness is needed to align the expectations of the regime. An analysis of the main driving forces at the beginning of the energy transition may reveal what enforcement is needed to ensure an additional transition in the target system, as with the RES transition. The focus should be on the landscape and societal expectations regarding the target system.

8.3 Scenario 2: Top-to-Bottom

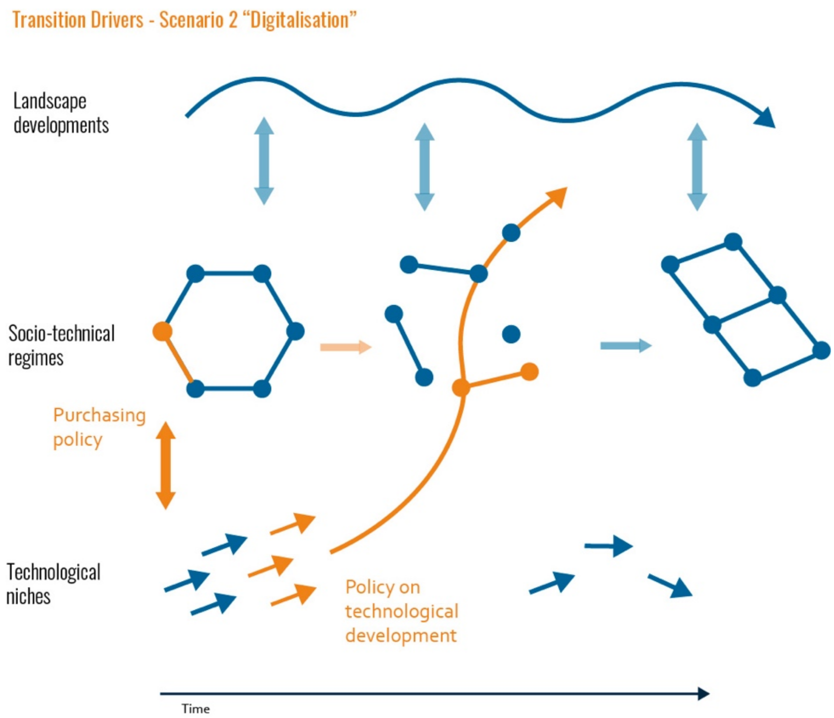


Figure 14; Driving Forces needed for Scenario 2 "Digitalisation"

One of the main implications of the development of the target system is the technological trajectories, as described in Scenario 2, where increased decentralisation and interconnectedness result in the integration of smart applications and additional communication systems. The more purchasing policy is brought in, the more providers are forced to ensure the safety and agility of their system. This ensures that the responsibility for the migration of the specific technology remains on the side of the producer. Then, knowledge across the users is not necessarily needed. Knowledge exchange that is not as pertinent in society, limits the pressure from the landscape on the regime.

As the regime is developing and incorporating technologies from the niche market on a potentially high level in this scenario, the area that would need the most enforcement would be the policy targeting technological providers at the niche and regime levels. The top-to-bottom approach to the quantum-safe transition implies change on the regime level that 'trickles' down to the niche markets developing (Figure 14). Policy enforces are therefore situated on the higher regime level in the target system: the operators and authority agencies that create and enforce regulations that the Dutch energy sector has to comply with.

8.4 Scenario 3: Bottom-to-Top

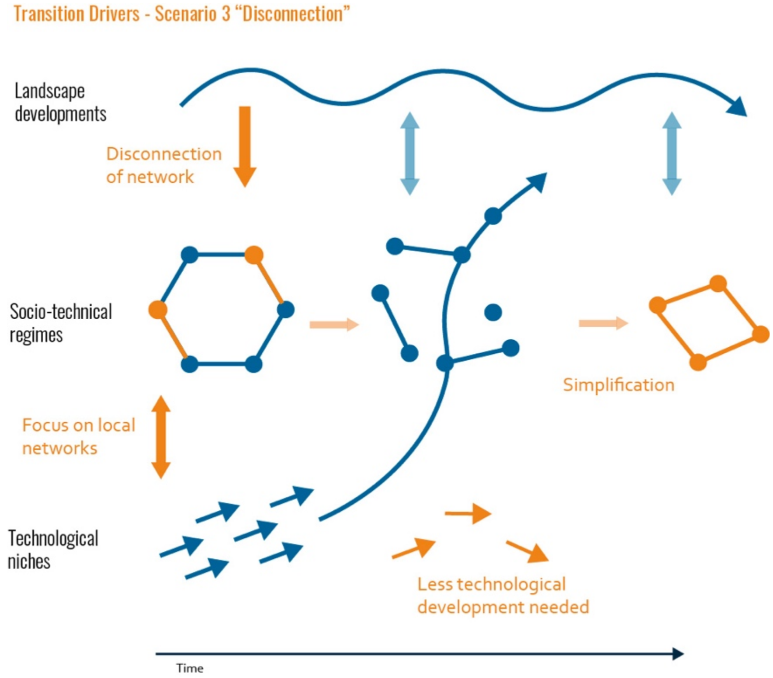


Figure 15; Driving Forces needed for Scenario 3 "Disconnection"

Scenario 3 sees an increase in participation on lower levels of the target system. A decentralised and disconnected approach to the future energy system requires a change in behaviour and expectations on the consumer-side. As this requires a simplification of the technological system, less is required from the niche level (Figure 15). Furthermore, based on the condition that system participants would be required to possess a certain degree of technological knowledge, incremental changes may be enough on the regime level. The societal push and level of resistance to change are lower, ensuring more cooperation and more ease the bundling of resources if the need for security of supply remains prioritised. The more the net is disconnected, the less knowledge and awareness dissemination is needed.

These implications require a focus on the socio-technical landscape due to the implied behavioural and mindset change needed. Specifically, the delineation of responsibility and the redistribution of responsible parties becomes important in the beginning stages of the quantum-safe transition. Energy communities and collectives on the local level need to be more prevalent, which further requires changes to the market behaviour.

8.5 Implications for the Research Field

The results of Chapters 5 and 6 show a significant knowledge gap on the intersection of the quantum-safe transition and the Dutch energy sector. This intersection is analysed, incorporating outside influences of the target system, as well as actors and institutions that are not established as part of the structural dimensions as presented in Chapter 4.

This novel approach to the application of the TIS shows the potential of analysing technological innovation systems if the technology is not yet certain or a dominant design has not yet presented itself. Taking into consideration the limitations of such an approach (Section 9.2.1), this approach may allow future research into innovation systems if the trajectories are not yet clear, or to analyse potential future systems to prepare for the development of the desired technology. Additionally, in combination with the MLP, potential trajectories may be mapped, and structural policy implications can be established.

9 Conclusion & Discussion

9.1 Conclusion

9.1.1 Main Conclusion

The research question '*What intervention is needed to ensure the development towards a quantum-safe transition in the Dutch energy sector?'* is answered. In its current state, the Dutch energy sector is not ready to start a quantum-safe transition or a complete PQC migration. Assuming that the introduction of quantum computing in the market may happen within the next 15 years, the effort needed in the Dutch energy sector to prepare and anticipate a quantum-safe transition is extensive and may not be feasible due to the expanding gap between IT and OT. A change in system structure to already mitigate potential threats is therefore needed, potentially even before a PQC migration can be made. This allows for a more structured approach to a quantum-safe transition, providing a clear prioritisation of system parts. The author proposes that focus should be on Scenario 3, despite the low feasibility. Taking into consideration a realistic timeline of a complete quantum-safe transition, Scenario 3 would allow for a more long-term approach while ensuring security in the short-term.

9.1.2 Sub-Questions

SQ 1: What is the current state of the Dutch energy system and its transition towards RES implementation?

The structural analysis revealed a changing energy system that is increasingly decentralised, intermittent and volatile. The system operators, DSOs and TSO, are focused on mobilising their resources to the mitigation of congestion issues and the expansion of the network to meet the demand. Consumers are increasingly participating in the system through the adoption of solar PV and offshore wind projects are planned. Furthermore, there are various developments in the energy system that are of interest, including the increasing adoption of smart applications, increasing interconnectedness with the international network and a shift to more supply-based functions. The sector is complex, consisting of multiple markets that influence each other, such as the balancing market and intraday market. Technologies are developing rapidly as the push for a sustainable and sovereign system motivates the private sector to innovate.

SQ 2: What are the possible applications of quantum-safe technology in the (Dutch) energy sector?

The results of the included articles show that the specification of 'quantum-safe' in the energy sector is not prevalent and quantum-safe or quantum technology applications in the energy system are not researched broadly. Included articles range from reviews of threats to smart grids, to the application of quantum technology in a future energy system. This further highlights the need to take the trajectories of the future energy system into consideration.

Topic synthesis shows that threats in smart grids and decentralised energy systems not only potentially occur on the communication platform and data links but that the human factor should be considered as well. Governance of OT is low, and the need for asset and cryptographic inventory is discussed. This research shows that there are proposals for solutions in DER and smart grids, and knowledge is created on how to manage and implement quantum computing applications in combination with other tools (such as AI) in decentralised systems. However, knowledge of current system considerations for the quantum-safe transition shows gaps in this knowledge creation.

SQ 3: On what part of the system and which stakeholders will be the most affected from a quantum-safe transition?

The results show that the functions of knowledge development, knowledge dissemination guidance of the search the most limiting in the development towards a quantum-safe system. This is validated by perceiving the phase of the system development as being in the pre-development phase. Guidance of the search, which includes the alignment of expectations and visions within the energy system, may limit the other functions. This results in a variation in knowledge acquisition and a sense of urgency across the system. Furthermore, the results show that resource mobilisation needs to be taken into consideration, as sunk costs and timing of investments may limit the flexibility and investment of the private sector. Additionally, it is shown that a structured approach to knowledge exchange regarding the awareness of cybersecurity is needed in the Dutch energy system, as its primary focus is seen to be the security of supply.

SQ 4: What are the possible trajectories for intervention and policy structures?
The developed scenarios show three potential trajectories that the Dutch energy sector could take, each differing in feasibility and complexity. Scenario 1 requires a system-wide simultaneous quantum-safe transition, where challenges such as asset inventory, unclear responsibility delineation, and unalignment vision across the system occur. Scenarios 2 and 3 are trajectories that require additional effort. Scenario 2, in which increased interconnectedness and digitalisation happen, requires more focus on the protection of the national system. Intervention should focus on integrating the expected PQC migration in the purchasing policy for smart applications, priority put on securing the highest level first, and additional policymaking to ensure the compliance of private parties. Scenario 3, which describes the disconnection of the energy system, combines the advantage of reducing the size of the networks and reduced interconnectedness allow for additional time for a quantum-safe transition. A focus should be on increasing the knowledge of the general public, decreasing the complexity of the grid by more efficient grid expansions, disconnection of unsecured parts and responsibility delineation on more individualised levels.

SQ 5: What are the implications of these findings with respect to recommendations to the relevant stakeholders?
This SQ is the stepping-stone and the foundation of the main research question '*What intervention is needed to ensure the development towards a quantum-safe transition in the Dutch energy sector'.* Implications for stakeholders vary across each of the scenarios. General implications across all scenarios include the pertinent decision-making of responsibility in the system. A clear overview of the supply chain and its responsible parties delineates the perceived difficulty of a system-wide quantum-safe transition.

Furthermore, the decision needs to be made to what degree the public possesses knowledge on the quantum-safe transition in the energy system, as participation in the sector may allow for transitions due to increased fulfilment of guidance of the search. If the general public (consumers) possess in-depth knowledge on the system and the need for the quantum-safe transition, the push on the incumbents to transition and provide PQC in their products becomes stronger, as it is viewed as added value to the company. This may be most relevant in Scenario 3, where energy communities are prevalent. On the other hand, knowledge on cybersecurity and quantum-safe may not be needed, if the integration of automation methods and technological applications such as quantum computing and AI in smart grids is more prevalent (Scenario 2).

9.2 Limitations

9.2.1 Research Limitations

One of the early limitations encountered by the author is the difficulty of gaining insight on the inner workings of TenneT and other organisations and access to those with expertise. The experts interviewed do not consist of heads of security of the respective organisations, which may have provided additional insight in the current management of cybersecurity. The experts selected are but a selection of potentially relevant experts that could have been included. AIVD was also contacted for a possible interview. Instead, the author was referred to previous publications by the AIVD.

This research assumes that the development of quantum computing is within the next 10 to 15 years. As the energy transition has been most prevalent in the last decade, it is assumed that changes to the national grid may be made in the same time frame. However, priorities in the current system include expanding the network to mitigate congestion.

Full information saturation is hard to measure with such exploratory research, as it leads to a potentially descriptive end result instead of a clear answer to a question. Further research into the socio-technical system of quantum computing and quantum-safe technologies is therefore needed, as all small companies and influencing actors outside the Netherlands are not considered.

9.2.2 Theoretical Limitations

An additional limitation is the difficulty of placing the technology at hand within the boundaries of the chosen frameworks. This is partly due to the fact that no dominant design has yet been developed in the system, as well as due to the overarching necessity of the technology at hand. This translates furthermore towards limitations found within the paradigm of this research, where socio-technical systems design thinking is often used in the framework of a specific technological need or development. There are significant uncertainties in the system that need to be considered.

Furthermore, it is relatively difficult to be able to delineate the development of such technology. Specifically, the international and interdisciplinary nature of the development of quantum computing needs to be taken into consideration. Quantum applications are described as a tool that enhances the function of existing systems and technologies, which may make it act differently compared to specific technologies.

The author's background in innovation management provides a unique insight into technological systems. This can be both an advantage and a disadvantage. An advantage is that systems thinking provides the opportunity to look at drivers of technological adoption and diffusion from the perspective of influencing factors. This perspective on socio-technical system development A disadvantage in the technological insight. A cryptographer might have additional or other perspectives regarding the development of the technology (PQC) itself.

9.3 Future Research

Some experts have recommended potential future research that may be pertinent in ensuring the future energy system is quantum-safe. The chain of supply of energy in the Netherlands is known, but it might be interesting to have a more thorough insight into all energy sources, all networks and the responsible parties to establish a correct responsibility chain as well. This would put the responsibility of transition and migration to PQC on the parties that are actually responsible. Such transparency that is not limited within organisations might help researchers of system transitions to make more informed recommendations to the stakeholders.

It is furthermore questioned what the borders are of the schemes that are created, what kind of variations there will be and what the minimal structure should be of a scheme. At least, each actor that needs to migrate would have some direction, reducing the perceived potential sunk costs as well. This puts additional pressure on the developers of PQC.

The author recommends the following future research, beginning with the systemwide research. Research the flexibility of the energy system, as to what degree technological lock-in exists, and to what degree we need to break free from that. This corresponds with frameworks within the innovation sciences, as the determination of technological lock-in depends on a variety of factors.

Additionally, an extensive overview of the entire energy chain, including the types of cryptography. This may need substantial human resources to perform for each actor, but in the case of the critical energy infrastructure may be needed. The insights from Strategic Niche Management may provide additional recommendations how to stimulate the niche of quantum-safe applications in the Dutch energy sector, where currently limitations in resource mobilisation and direction occur.

Further research into the actual perception of risks of market parties, specifically the variation in that. Risk assessment on a system-wide level would provide more information on the more drastic risks of black-out that may go beyond the jurisdiction of individual operators and market parties. Research into similar system transitions may further be beneficial in identifying overlaps in drivers. This reduces the effort and time of a transition if certain patterns are recognised. Furthermore, the knowledge gap identified in the state-of-the-art research in Chapter 2 can be delineated into several research areas that are currently still lacking in the quantum-safe transition. Sector-specific research should be done on how organisations can start preparing for the transition, as each sector differs in behaviours, visions and flexibility.

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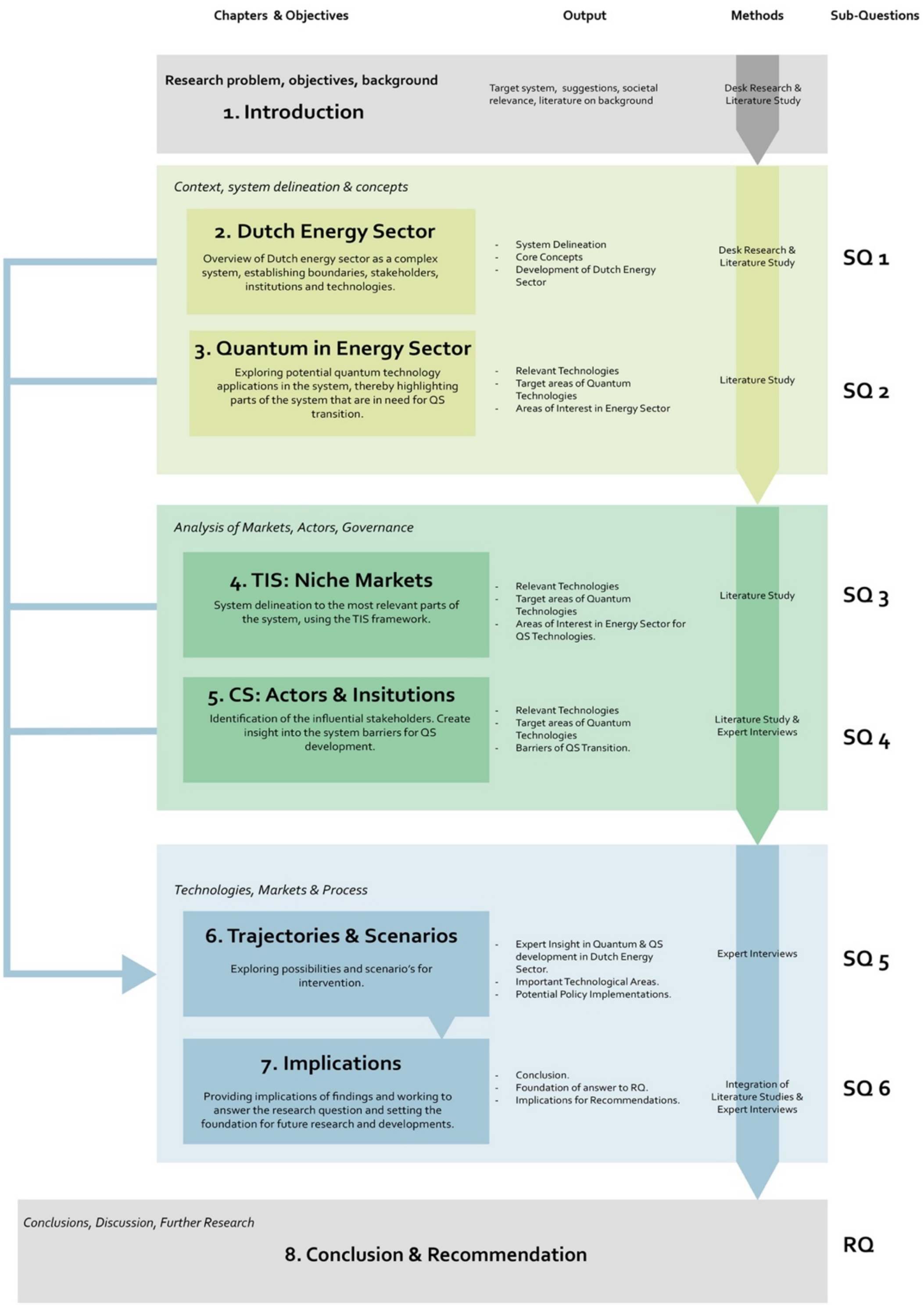
Appendix

Appendix A – Research Flow Diagram

Figure A1; Research Flow Diagram of this Study



Appendix B – Preliminary Literature Review

Table B1; Search string used for key terms in search engines

	Full search string used	**No of references**
Scopus (December 5th, 2023, last document export)	TITLE-ABS-KEY (('quantum-safe' OR ('quantum-safe' AND technology) OR 'post-quantum AND cryptography' OR 'quantum AND cryptography') AND ('energy AND sector' OR 'energy AND industry' OR 'energy AND system'))	72
Web of Science (December 5th, 2023, last document export)	(ALL=(('quantum-safe' OR ('quantum-safe' AND technology) OR 'post-quantum AND cryptography' OR 'quantum AND cryptography'))) AND ALL=(('energy AND sector' OR 'energy AND industry' OR 'energy AND system'))	250
Total		322
Exclusion based on language	Not English	320
Exclusion based on document type	Book Chapter / Book / Proceedings	305
Exclusion based on date range	1998 / 2001 / 2002 / 2003 / 2004 / 2005 / 2006 / 2007 / 2008 / 2009	266
Records identified for manual assessment		266

Figure B1; PRISMA Flow Diagram for Article Selection Chapter 2

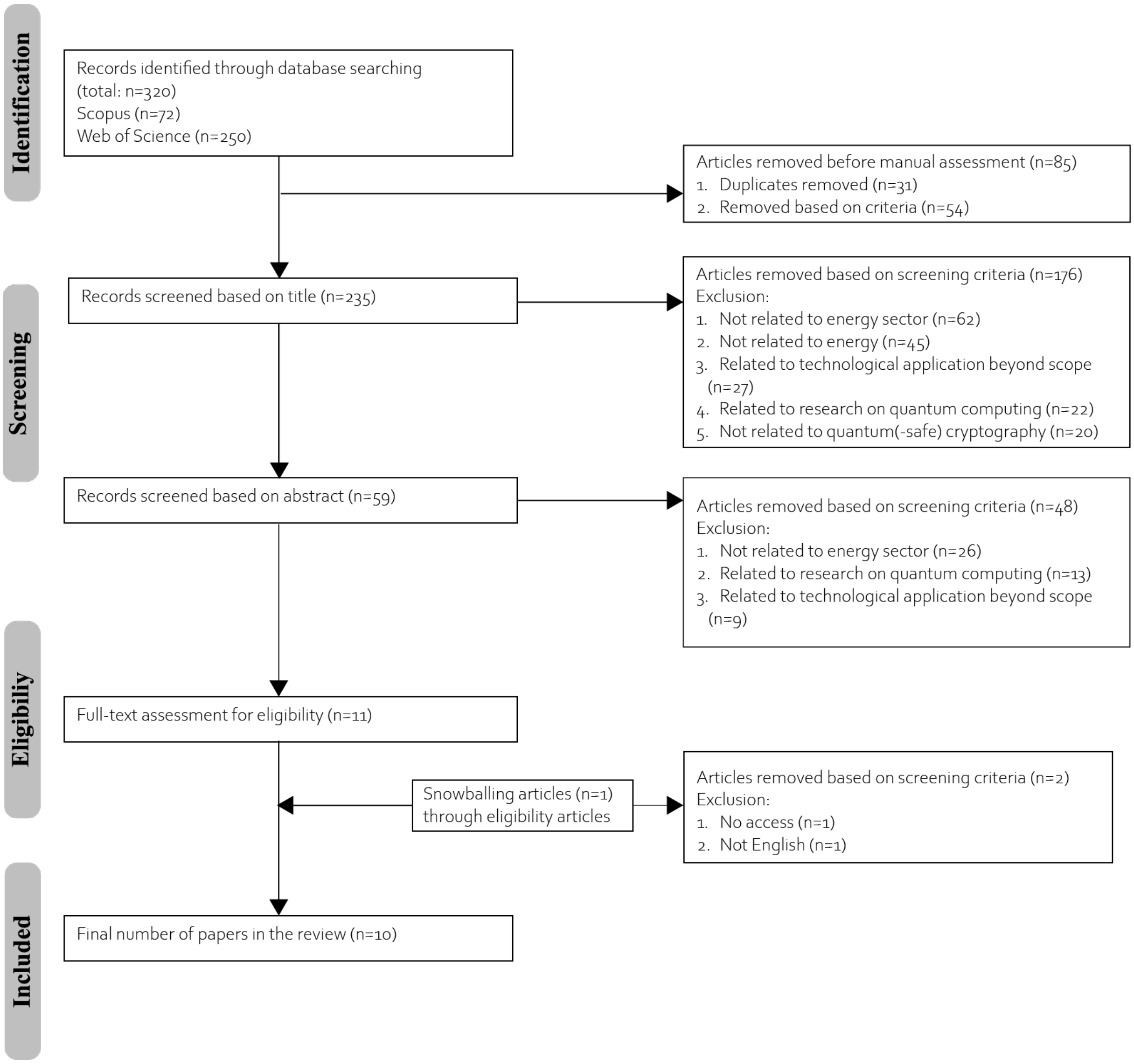


Table B2; General Overview of Included Articles

Authors	**Topic**	**Impact Quantum Computing on Energy Sector**
Ajagekar & You, 2022	Various applications of quantum computing in the energy transition.	Quantum computing contributes towards optimisation issues, machine learning and quantum chemistry.
Desai et al., 2018	Proposal for mitigating vulnerable system operations for smart grids post-quantum cryptography.	Smart grids can be efficiently automated but need to be protected against attacks using quantum computing, suitable for real-time computation.
Ahn et al., 2021	Exploring new vulnerabilities in cybersecurity of distributed energy systems.	Current distributed energy system encryption methods are still vulnerable. There are multiple points in which quantum-safe technology could be applied for protection.
Ahn et al., 2022	Exploring vulnerabilities in cybersecurity of distributed energy systems and proposal of security measures.	Quantum attacks are feasible within a couple of years. A possible protection system is expensive and is established over a large area.
Alshowkan et al., 2022	Cybersecurity of new communications and information technology for distributed smart grids.	Proposal for quantum key distribution for protection of smart grid networks and distributed energy resources.
Kim et al., 2022	Presentation of processor for use in post-quantum cryptography in Internet of Things devices.	Processor that is lightweight and can be implemented in a small area in a network. Possible applications in energy sector.
Shen et al., 2022	Protection of encryption used in Internet of Things, large data transfers.	Proposal of an encryption scheme where the controller of the Internet of Things generates quantum random numbers and is applicable to classical communication networks.
Paudel et al., 2023	Overview of recent developments of quantum applications in network and communication systems in energy sector.	Quantum computing may impact the deployment of electric vehicles, smart grids, microgrids, more decentralisation of energy sources, and renewable energy source inclusion.
Tran, Hu & Pota, 2023	Increasing vulnerability due to deregulation of energy systems.	Proposal of state-estimation schemes for privacy vulnerability in deregulated power systems.
O'Neill et al., 2016	Proposal of post-quantum cryptography solution for large ICT-networks, including energy systems.	Funded by the EU, these solutions replace existing encryption for security.

Appendix C – Systematic Literature Review

Table C1 – Overview of search terms for search string Literature Review

Quantum	**Energy Sector**
Quantum Computing	Energy Sector
	Energy Market

Table C2 – Initial Source Selection Literature Review

		No. of references
Scopus (last retrieval on 12th of April)	('quantum AND computing') AND ('energy AND sector' OR 'energy AND market')	1234
Web of Science (last retrieval on 16th of April)	('quantum AND computing') AND ('energy AND sector' OR 'energy AND market')	641
Total		1875
Excluded due to Retraction	Retracted	1869
Exclusion based on document type	Conference Collection / Short Text / Editorial Material / Letter	1863
Records identified for manual assessment		1743

Figure C1 – PRISMA Flow Diagram for Article Selection Chapter 5

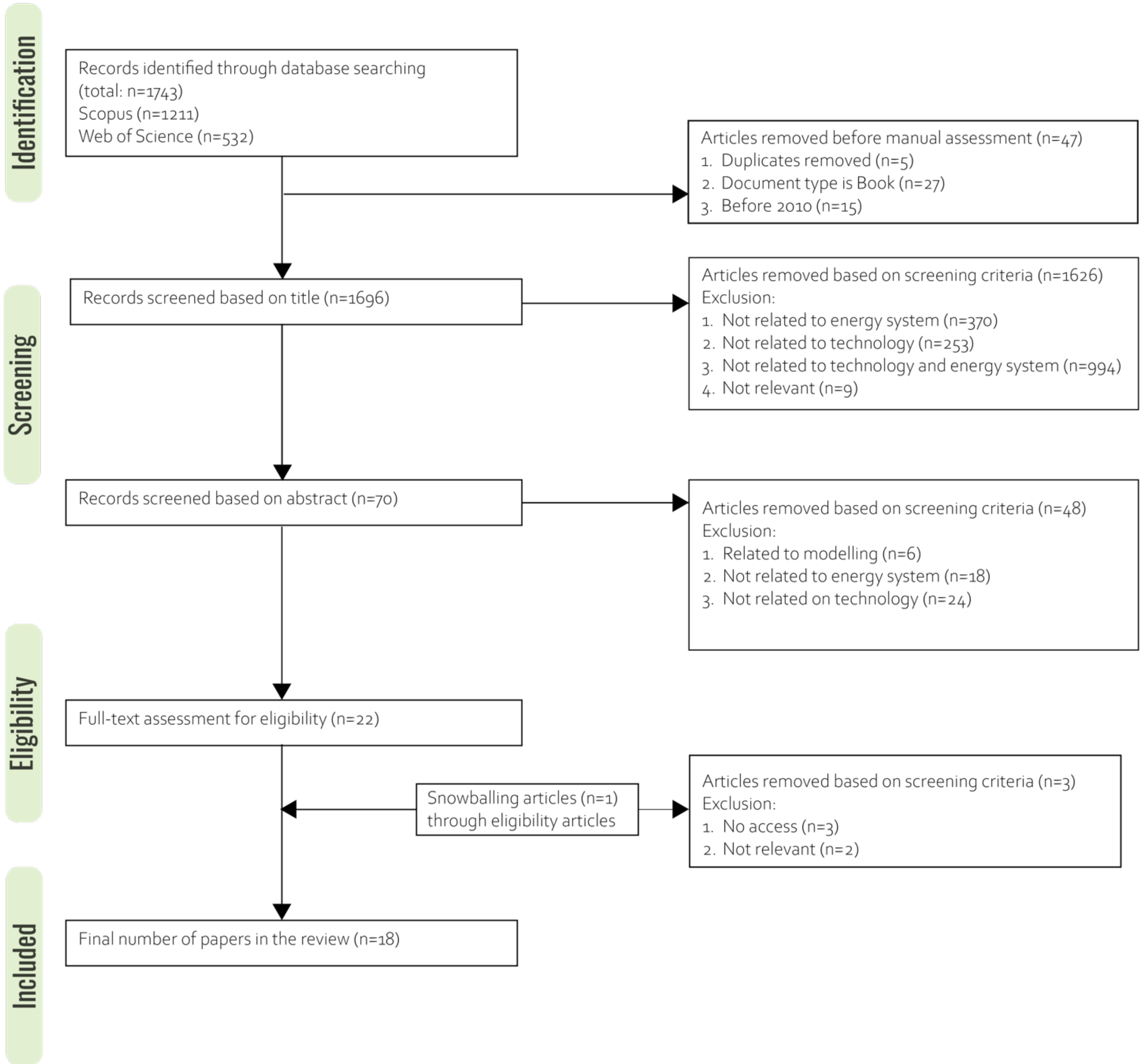


Table C3 – Overview of Article Topics and Description

Author(s)	**Topic**	**Description**
Ahmad & Zhang, 2021	FES	Application of IoT for smart energy networks
Ajagekar & You, 2022	FES & Quantum Computing	Implementation of quantum computing and Quantum AI for renewable and sustainable energy systems.
Aljaafari & Alotaibi, 2023	QuTech	QuTech and IoT for circular economy purposes
Hasan et al., 2022	Blockchain in FES	Analysing threats and challenges of SG and how blockchain may mitigate

Hasan et al., 2024	PQC Migration	Framework for guidelines for PQC for enterprises
Joshi et al., 2022	Quantum Computing & Security	Analysis of grid threats and how quantum computing may mitigate
Körner et a., 2022	Security & FES	Intensified data exchange in complex system, their threats and how to employ digital technologies
Kumar et al., 2022	(Cyber)Security	Recommendations on mitigating cyber physical threats
Mazhar et al., 2023	Security of SG	Risks that affect SG and security solutions
Nakka et al., 2024	PQC in FES	Proposal for PQC integration in DER and its feasibility
Paudel et al., 2022	Quantum Computing for FES	Review of quantum computing and simulation exploitations for future energy systems, referring to current trends
Purohit et al., 2024	Quantum Safe	Evaluation of readiness for quantum technology in an ecosystem
Sousa-Dias et al., 2023	Security of TEM	Review of the cybersecurity of Transactive Energy Markets
Sundararajan et al., 2018	Security of DER	Review of threats in DER systems and potential solutions
Ullah et al., 2022	Quantum Computing & SG	Review of state-of-the-art quantum computing in SG applications
van Deventer et al., 2022	Quantum Technology	Insights on European standardisation of quantum technologies
Zhao et al., 2023	ICT in FES	Review of emerging trends in ICT in FES
Zografopoulos et al., 2023	Security of DER	Overview of threats and oversights in DER systems and mitigation

Appendix D – Informed Consent Form Template

Figure D1; Informed Consent Form Template

Participant Information & Opening Statement

You are being invited to participate in a research study titled 'Potential impact of the quantum transition on the Dutch energy market: How to become Quantum-Safe', a Master Thesis project for the master programme Complex Systems Engineering and Management at the Delft University of Technology (TU Delft). This study is being done by Corresponding Researcher and master student Cilia Baanstra in cooperation with the Thesis Committee: Responsible Researcher and Supervisor prof.dr.ir. Marijn Janssen, Second Supervisor dr.ir. Ivo Bouwmans and Consulting PhD Candidate Ini Kong.

The purpose of this research study is to provide insight in the stakeholder and institutional layer that require intervention for the development of quantum-safe applications in the Dutch energy market, by mapping the Dutch energy market, possible quantum computing and quantum-safe applications in that market. This is exploratory research. This interview will take you approximately 30 to 60 minutes to complete. We will be asking you to provide insight in the market, elaborate on your expertise on topics surrounding quantum computing; quantum-safe technologies; technological developments in the (Dutch) energy market; the structure of the Dutch energy market; scenarios in technological development; potential policy implementations; and relevant stakeholder management questions. Of course, the course of questions differs depending on the expertise of the interviewee / participant.

The information provided by the participant during the interview are audio recorded for full transcription by the Corresponding Researcher. This transcription is coded using an inductive coding approach to answer the aforementioned questions.

Interviews may be conducted in face-to-face encounters or digitally through Microsoft Teams (as facilitated by TU Delft). In case of face-to-face encounters, the Corresponding Researcher will travel to the participant's location.

Sanity check: what is data is collected, where is it stored, who has access. What is made public. What is deleted and when.

As with any online and/or research activity the risk of a breach is always possible. To the best of our ability your answers in this study will remain confidential. We will minimise any risks by ensuring that:

- all personal data will be stored with TUD storage up until two years of completion of study (July 2026);
- recordings (.mp3 files) are kept on the TUD OneDrive only accessed by the Corresponding Researcher and Responsible Researcher;
- recordings are deleted after the first instance of transcription review by the participant (see following paragraph);
- transcriptions of the interview (.docs files) are anonymised kept on TUD OneDrive only accessible by the Corresponding Researcher, Responsible Researcher and relevant participant;
- this Informed Consent Form is stored on TUD OneDrive only accessible by the Corresponding Researcher and Responsible Researcher, and removed from the digital transfer medium through e-mail;
- access to the transcripts by the participant are facilitated through TUD OneDrive as to minimise digital transfers of the information;
- transcriptions are not publicised with the thesis.

Your participation in this study is entirely voluntary and you can withdraw at any time. You are free to omit any questions. There are three instances put in place where you may omit, alter or retract information: after completion of the transcription, after initial incorporation in the research is completed, and before final submission. These instances are initiated by the Corresponding Researcher by providing access on OneDrive where the transcripts are stored.

All personal data collected during the study (recording, transcripts and consent form) will be preserved for up to 2 years after the completion of the study. The data may be reused for research or education activities on the topic of Quantum Safety, (future) Energy Systems and technological applications in the Energy Systems. You will be anonymous in any publicly available output. Should we want to use the data for any other purposes, we will reach out to you, and ask for your explicit permission.

For contact for remarks, complaints, requests, etc., the following information can be used. Any correspondence is read on a day-to-day basis by the Corresponding Researcher.

Corresponding Researcher:	Cilia Baanstra	c.a.baanstra@student.tudelft.nl
Responsible Researcher:	Prof.dr.ir. Marijn Janssen	M.F.W.H.A.Janssen@tudelft.nl

Signatures

I have read and understood the information above and I consent to participate in the study and to the data processing described above:

________________________	________________________	________
Name of participant	*Signature*	*Date*

I, as researcher, have accurately read out the information sheet to the potential participant and, to the best of my ability, ensured that the participant understands to what they are freely consenting.

Cilia Annelieke Baanstra	________________	________
Researcher name	*Signature*	*Date*

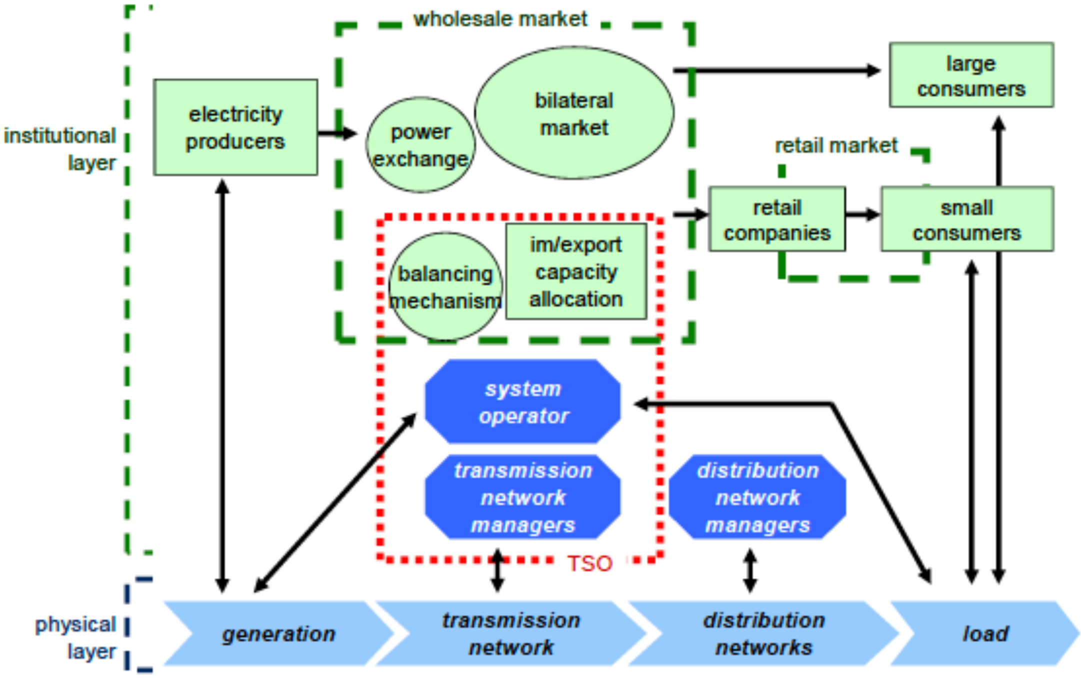
Study contact details for further information: C.A. Baanstra, , c.a.baanstra@student.tudelft.nl

Appendix E – Theoretical Additions

Figure E1; Diagnostic Questions on TIS Functions (Hekkert et al., 2011).

Functions and indicators	Diagnostic questions
F1 - Entrepreneurial Experimentation and production - Actors present in industry (from structural analysis)	- Are these the most relevant actors? - are there sufficient industrial actors in the innovation system? - do the industrial actors innovate sufficiently? - do the industrial actors focus sufficiently on large sale production? - Does the experimentation and production by entrepreneurs form a barrier for the Innovation System to move to the next phase?
F2 - Knowledge Development - Amount of patents and publications (from structural analysis)	- Is the amount of knowledge development sufficient for the development of the innovation system? - Is the quality of knowledge development sufficient for the development of the innovation system? - Does the type of knowledge developed fit with the knowledge needs within the innovation system - Does the quality and/or quantity of knowledge development form a barrier for the TIS to move to the next
F3 - Knowledge exchange - Type and amount of networks	- Is there enough knowledge exchange between science and industry? - Is there enough knowledge exchange between users and industry? - Is there sufficient knowledge exchange across geographical borders? - Are there problematic parts of the innovation system in terms of knowledge exchange? - Is knowledge exchange forming a barrier for the IS to move to the next phase?
F4 - Guidance of the Search - Regulations, Visions, Expectations of Government and key actors	- Is there a clear vision on how the industry and market should develop? - In terms of growth - In terms of technological design - What are the expectations regarding the technological field? - Are there clear policy goals regarding this technological field? - Are these goals regarded as reliable? - Are the visions and expectations of actors involved sufficiently aligned to reduce uncertainties? - Does this (lack of) shared vision block the development of the TIS?
F5 - Market Formation - Projects installed (e.g. wind parks planned, site allocation and constructed)	- Is the current and expected future market size sufficient? - Does market size form a barrier for the development of the innovation system?
F6 - Resource Mobilization - Physical resources (infrastructure, material etc) - Human resources (skilled labor) - Financial resources (investments, venture capital, subsidies etc)	- Are there sufficient human resources? If not, does that form a barrier? - Are there sufficient financial resources? If not, does that form a barrier? - Are there expected physical resource constraints that may hamper technology diffusion? - Is the physical infrastructure developed well enough to support the diffusion of technology?
F7 - Counteract resistance to change/legitimacy creation - Length of projects from application to installation to production	- What is the average length of a project? Is there a lot of resistance towards the new technology, the set up of projects/permit procedure? - If yes, does it form a barrier?

Figure E2; Conceptual Framework Diagram of Electricity System (de Vries et al., 2019).



Appendix F – Interview Codes

Table F1; Overview of Codes regarding Future Energy System

Indicator	Topic	Interview Participant
Future Energy System		IP1, IP4, IP6, IP7, IP8, IP9, IP10, IP11, IP12, IP12, IP13, IP14
Future Energy System (n=41) in 12 references	**FES-1** Decentralisation & Disconnect (n=7)	IP9, IP7, IP6, IP14
	FES-2 Network (n=10)	IP9, IP6, IP1, IP10, IP11, IP12
	FES-3 Policy (n=6)	IP9, IP1, IP12, IP13
	FES-4 Future Security (n=7)	IP7, IP6, IP8, IP12, IP14
	FES-5 Data Intensity (n=11)	IP9, IP7, IP4, IP1, IP8, IP6, IP13

Table F2; Overview of Codes Regarding Technological Innovation System

Indicator	Topic	Sub-Topic	Participants
F1 Entrepreneurial Activities (n=112) in 14 references	F1-A Cooperation (n=21)	F1-A1 Private Collective on Energy Net (n=3) F1-A2 Private Cooperation (n=7) F1-A3 Public-Private Cooperation (n=6) F1-A4 Organisations Require Outside Help (n=3) F1-A5 Non-Private Cooperation (n=2)	IP1- IP14
	F1-B Private Parties & Consumers Participation (n=5)	F1-B1 Private Parties (n=4) F1-B2 Consumer Participation (n=1)	
	F1-C Non-Private Initiatives (n=12)	F1-C1 Behaviour Control (n=4) F1-C2 Government Initiatives (n=6) F1-C3 Research Initiatives (n=2)	
	F1-D Experimentation & Production (n=36)	F1-D1 Small-Scale Experimentation & Production (n=19) F1-D2 Technological Development Energy Applications (n=6) F1-D3 Large-Scale Experimentation & Production (n=11)	
	F1-E Limitations in Full Development (n=30)	F1-E1 Limitations Due to Lack of Knowledge (n=8) F1-E2 Limitations in Assets (n=3) F1-E3 Decrease Needed in Complexity (n=17) F1-E4 Cost Considerations (n=2)	
	F1-F Responsibility (n=7)	F1-F1 Responsibility on Operators (n=2) F1-F2 Responsibility on Developers (n=5)	
F2 Knowledge Development (n=85) in 14 references	F2-A Knowledge Creation in PQC (n=19)	F2-A1 Public Research (n=14) F2-A2 Public-Private Research (n=5)	IP1 – IP14
	F2-B Knowledge Creation on QT [5] Applications (n=16)	F2-B1 Public Research (n=5) F2-B2 Public-Private Research (n=6) F2-B3 Private Research (n=5)	
	F2-C Knowledge Creation on Future Energy System (n=6)	F2-C1 Energy Parties Research (n=4) F2-C2 Academic Institutions (n=2)	
	F2-D Lack of Knowledge (n=30)	F2-D1 Lack of Knowledge on Assets (n=7) F2-D2 Lack of Knowledge on Implementation (n=2) F2-D3 Lack of Knowledge on Risks (n=6)	

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		F2-D4 Lack of Knowledge on Trajectories (n=5) F2-D5 Additional Knowledge Creation (n=10)	
	F2-E Learning by Doing (n=14)	F2-E1 Quantum Computing Creates Knowledge (n=5) F2-E2 Learning by Doing (n=9)	
F3 Knowledge Dissemination (n=70) in 13 references	F3-A Dissemination between Parties (n=15)	F3-A1 Public Knowledge Exchange (n=6) F3-A2 Public-Private Knowledge Exchange (n=5) F3-A3 Exchange between Private Parties (n=4)	IP2 – IP14
	F3-B Dissemination from Public Entities (n=13)	F3-B1 Knowledge Institution (n=8) F3-B2 Government (n=5)	
	F3-C Dissemination through Regulation (n=6)	F3-C1 European Regulations (n=3) F3-C2 National Regulations (n=3)	
	F3-D Lack of Knowledge Exchange (n=23)	F3-D1 Between Parties on Risks (n=5) F3-D2 Between Developers and Users (n=3) F3-D3 Within Organisation (n=2) F3-D4 Between Private Parties (n=6) F3-D5 Transparency Needed (n=5) F3-D6 Between Public and Private (n=3)	
	F3-E quantum computing Knowledge can be Limited for General Public (n=14)	F3-E1 quantum computing Knowledge (n=9) F3-E2 Between Consumers and Operators (n=4) F3-E3 Risks of Knowledge Development (n=1)	
F4 Guidance of the Search (n=196) in 14 references	F4-A Transition Limitations (n=49)	F4-A1 Limitations due to OT (n=10) F4-A2 Difficulties quantum-safe Transition (n=6) F4-A3 Lack of Knowledge on Management (n=3) F4-A4 Lack of Adequate Risk Assessment (n=10) F4-A5 Lack of Cybersecurity (n=4) F4-A6 Lack of Risk Perception (n=7) F4-A7 Lack of Asset Inventory (n=4) F4-A8 Lack of Awareness (n=2)	IP1 – IP14
	F4-B Transition Requirement (n=24)	F4-B1 Need for Sense of Urgency (n=11) F4-B2 Knowledge Needed for PQC Awareness (n=7) F4-B3 Need for Agility (n=4) F4-B4 Need for Resilience (n=1)	
	F4-C Policy & Governance (n=48)	F4-C1 Future Policy on Energy Distribution (n=6) F4-C2 Future Policy on Grid Security (n=6) F4-C3 Future Policy on Cybersecurity (n=13) F4-C4 Future Policy on PQC (n=8) F4-C5 Policy on Purchasing (n=5) F4-C6 Consumer Expectations (n=5) F4-C7 Delineation in Responsibility (n=5)	
	F4-D Awareness (n=11)	F4-D1 Spread of Awareness (n=8) F4-D2 IT Applications (n=3)	
	F4-E Societal Need (n=8)	F4-E1 Need for Sovereignty (n=5) F4-E2 Need for Quantum-Safe Transition (n=3)	
	F4-F Drivers of Cybersecurity (n=10)	F4-F1 Geopolitics Drives Cybersecurity (n=8) F4-F2 Transition Feasibility (n=1) F4-F3 Pressure on Security of Supply (n=1)	
	F4-G Technology Drivers (n=20)	F4-G1 Opportunity-Driven (n=7) F4-G2 Societal Expectations (n=7) F4-G3 Other (n=6)	
	F4-H Uncertainty (n=8)	F4-H1 On Technological Development (n=7) F4-H2 On Technological Implementation (n=1)	
	F4-I Future Energy System (n=21)	F4-I1 Flexible Energy Balance (n=11) F4-I2 Development of System (n=10)	

F5 Market Formation (n=83) in 13 references	F5-A Energy Sector (n=15)	F5-A1 Simplification of Energy System (n=5) F5-A2 Market Expansion towards Localised Energy (n=4) F5-A3 Efficient Energy Development (n=5) F5-A4 Conflict between Private and Operators (n=1)	IP1, IP3 – IP14
	F5-B Independency (n=6)	-	
	F5-C IT/OT Gap (n=4)	-	
	F5-D International Drivers (n=7)	F5-D1 International Competition (n=2) F5-D2 International Standardisation (n=4)	
	F5-E Niche Developments (n=5)	F5-E1 quantum-safe Technology (n=3) F5-E2 Material Development (n=1) F5-E3 Asset Inventory (n=1)	
	F5-F Regime (n=29)	F5-F1 Incremental Innovation (n=4) F5-F2 Vulnerabilities in Incumbent Systems (n=9) F5-F3 Preparedness Needed by Incumbents (n=11) F5-F4 Incumbent Competition (n=1) F5-F5 International Cooperation (n=3) F5-F6 Difficulty in Cooperation (n=1)	
	F5-G Stimulation from Public Entity (n=15)	F5-G1 Public Private Cooperation (n=6) F5-G2 Authority Needed (n=3) F5-G3 Research Institute Stimulating Demand (n=2) F5-G4 Government Guiding Regime (n=4)	
F6 Resource Mobilisation (n=70) in 14 references	F6-A Behaviour (n=21)	F6-A1 Human Mindset (n=4) F6-A2 Company & Market Behaviour (n=13) F6-A3 Risk of Sunk Costs (n=4)	IP1 – IP14
	F6-B Investments (n=17)	F6-B1 Investment in quantum technology Development (n=8) F6-B2 Investment in PQC (n=6) F6-B3 Investment Needed (n=3)	
	F6-C Limitation (n=12)	F6-C1 Limited Resources in quantum technology (n=7) F6-C2 Active Assets Needed (n=1) F6-C3 Time as a Resource (n=4)	
	F6-D Resource Allocation (n=20)	F6-D1 quantum technology Becoming a Resource (n=3) F6-D2 Resource Imbalance (n=4) F6-D3 Bundling of Resources (n=6) F6-D4 Efficient Mobilisation (n=7)	
F7 Creation of Legitimacy (n=101) in 14 references	F7-A Legitimacy Drivers (n=35)	F7-A1 Decrease in Resistance due to Perceived Risk (n=16) F7-A2 Decrease in Resistance due to Technological Advancement (n=4) F7-A3 Decrease in Resistance due to Incentive (n=3) F7-A4 Decrease in Resistance due to Transparency (n=11) F7- A5 Decrease in Resistance due to Shared Burden (n=1)	IP1 – IP14
	F7-B Private Limitations (n=31)	F7-B1 Resistance due to No Perceived Value (n=11) F7-B2 Resistance due to Potential Sunk Costs (n=12) F7-B3 Resistance to Quick Transition (n=5) F7-B4 Legitimate Investment (n=3)	
	F7-C Public Legitimacy (n=35)	F7-C1 Bureaucratic Processes (n=14) F7-C2 Resistance due to Lack of Knowledge (n=18) F7-C3 Researchers Push Market (n=3)	