# Comparative case study into the barriers that prevent QKD and Tokamak nuclear fusion power plants from large scale diffusion

MSc Management of Technology

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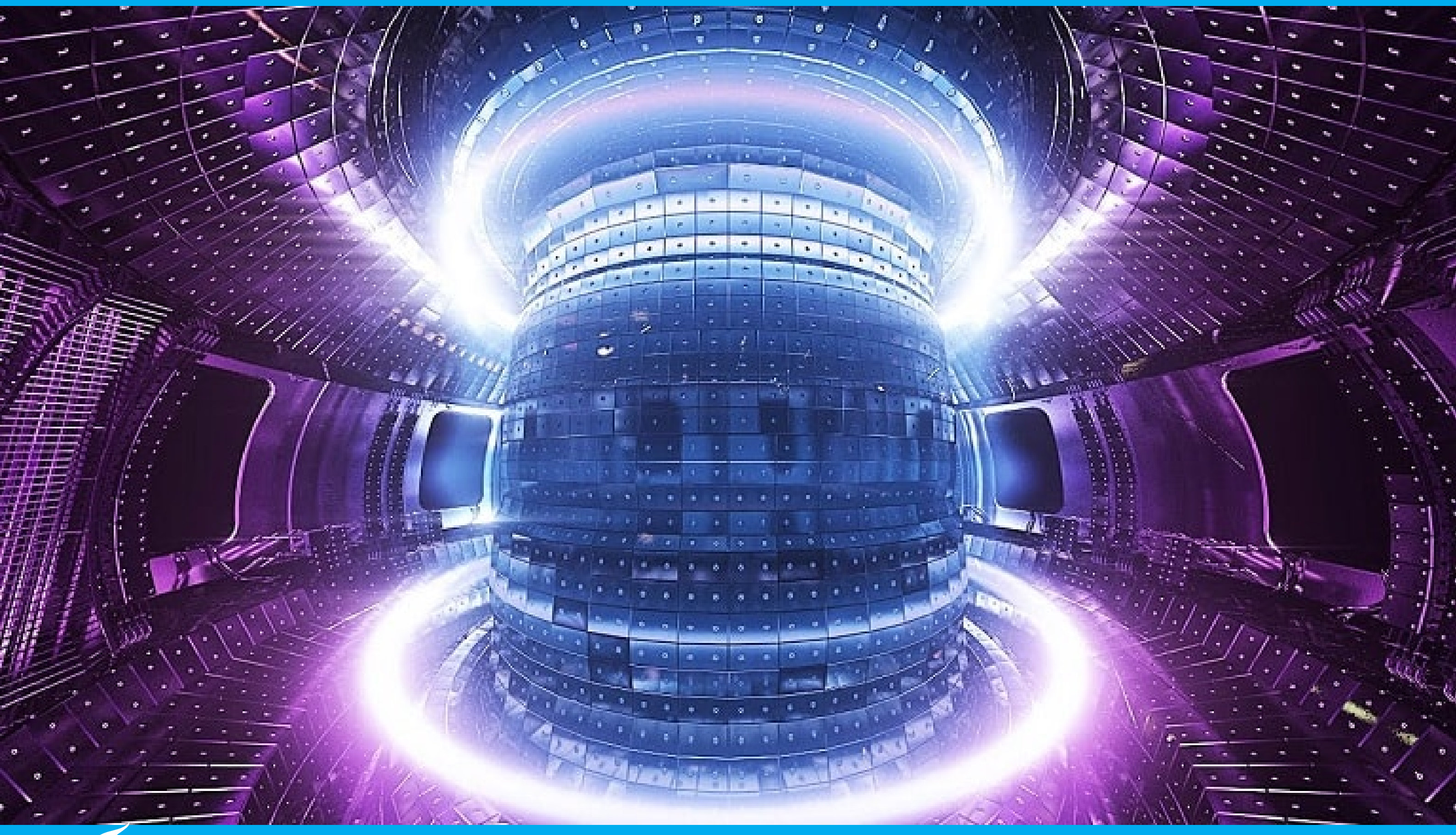

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DELFT UNIVERSITY OF TECHNOLOGY

# Comparative case study into the barriers that prevent QKD and Tokamak nuclear fusion power plants from large scale diffusion

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requirements for the degree of MASTER OF SCIENCE in Management of Technology

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# EXECUTIVE SUMMARY

This research has the aim to investigate the large pre-diffusion period for two technologies: quantum cryptography and nuclear fusion power plants. Both technologies originate from basic physics research, have a high societal value and are a business to business product. First, a status overview of the technologies is given together with its principles and (dis)advantages. Hereafter, the high-tech products are positioned in a life cycle pattern and pre-defined factors that could create a barrier to large scale diffusion are investigated.

In the following chapters, other literature is investigated and different reasons for a long pre-diffusion period are explored. The literature that is used to determine the position in the life cycle pattern and investigation of factors, is critically reviewed and discussed. Different factors outside the existing framework are found that apply to the cases of quantum cryptography and nuclear fusion power plants. Additionally, a bias due to the telecom industry data that has been used to build the framework has been observed in different aspects of the diffusion theory. This research is conducted by the means of a comparative case study, including a literature review and the opinion of an expert.

The final delivery of this research is a proposition for an extended diffusion theory and a thorough discussion on validity and decision making within the framework. In this proposition the diffusion theory is extended with additional factors: type of funding, potential misuse of a technology, competition, managing expectations and a case specific factor. The current and additional factors are categorized into different types of factors. Additionally, a distinction between niche applications, innovations and split-offs in the life cycle pattern is made and discussed. Finally, notes on the validity of the assessment of factors are given.

# Acknowledgements

First, I would like to thank my supervisors Dr. J.R. Ortt and Dr. P.E. Vermaas for their time, guidance and good advice. Roland as my first supervisor and chair gave me very good insights and supported me a lot. I am thankful for our good collaboration, as well during my exchange semester in Nancy as during my thesis. Furthermore, I would like to thank my friends and family for their support and interest shown in this research. My expected working spaces changed a lot due to the COVID-19, which resulted in long days at the kitchen table with my housemate Eva. I would like to thank her and my other housemate Carmen a lot for their support and SET! & Krypto games during our lunch break.

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# 1 INTRODUCTION

With the rise of the emerging quantum computer and the increasing global warming, innovations in these fields are highly demanded. However, the commercialisation of two respective solutions to these problems: quantum cryptography and nuclear fusion, seems not to develop rapidly. Commercial quantum cryptography systems have been available on the market since 2007, and are still only present in niche markets. (IDQuantitique, 2019a) (Gisin & Thew, 2010) The most frequently used reactor in nuclear fusion projects, the Tokamak, has been demonstrated to be working in 1968 but no nuclear fusion power plants are available on the commercial market until today. (ITER, 2020) The question that arises is why the commercialisation of these technologies takes this long.

Since both quantum cryptography (QKD) and nuclear fusion technologies cover a large field, the scope of this thesis will first be clarified.
Classical and quantum cryptography both secure data (transfer), but the principle behind it is very different. Namely, classical cryptography is based on binary digits: bits, which implies a system of 0 (low voltage) and 1 (high voltage). In the case of quantum cryptography, the bits are called qubits, which is a unit of information. Several qubits in a row can, as a whole, form a two-level quantum mechanical system. Qubits have next to the possibility of being 0 or 1, the possibility to be in superpostion of both. More details on the principles of quantum cryptography will be discussed in Chapter 2. Other fields of quantum information processing, which will not be included in this thesis, are: Quantum computing, Quantum computation, Quantum error correction and Quantum entanglement. The focus of this thesis is thus on the quantum cryptography, being the process of transferring a quantum state between different locations. The most well-known and used application of quantum cryptography is Quantum Key Distribution (QKD), these terms will therefore be used with the same meaning from now on. (Ma, 2008) As will be explained later on, QKD systems are already commercially available.

In nuclear energy, two power sources can be seen: nuclear fission and nuclear fusion. Nuclear fission in the technology that is being used in current power plants, while nuclear fusion power plants are still under construction. (Breeze, 2014) There exist different technologies to generate power out of nuclear fusion, as will be explained in more detail in Section 2. The largest and most developed technology and projects make use of the Tokamak design reactor. (ITER, 2020) This type of reactor is currently used for several nuclear fusion power projects and will therefore be the focus of this thesis.

Quantum cryptography and Tokamak nuclear fusion plants have mainly been chosen as subjects of this study due to their long pre-diffusion period (period between invention and large scale diffusion), origin in physics and high societal value. This will be further discussed in Chapter 2.

In this research the question of why QKD and nuclear fusion power plants take so long to reach mass market will be studied. This has been done using the diffusion theory of R. Ortt et al. (2013), which consists of two parts: a product life cycle pattern and barriers to large scale diffusion framework. Both of these parts will be investigated and discussed thoroughly and applied to the cases of QKD and nuclear fusion power plants.

## 1.1 Practical relevance

The societal value of both technologies, quantum cryptography and nuclear fusion, is high. With the upcoming quantum computer, a saver communication method has to be developed. (IDQuantitique, 2019a) Quantum computers are supposed to make calculations much faster than classical computers, by executing much more instructions per second. (Talele, Shukla, & Bhat, 2012) Besides the many advantages that this fast computer would possess over a classical computer, harm could be done as well. Namely, current cryptography methods will not protect data from quantum computer attacks. Because the speed at which quantum computers could guess and check classical encryption algorithms is much higher and the chance of cracking the encryption is therefore too. (Talele et al., 2012) This could therefore cause big privacy and safety issues. Quantum cryptography is one of the cryptography methods that could protect data against such quantum computer attacks.

For the case of nuclear fusion, the societal problem it concerns is the green energy shortage problem. The world is running out of fossil fuels and the energy consumption only increases, which has led to the Paris agreement that states that global warming has to be limited. (European Union, 2015) Since nuclear fusion can be considered a green energy source because of its zero CO2 emission, it is a candidate for the future power grid. (Claessens, 2020)

This thesis will give an insight in the current status of QKD systems and Tokamak reactor power plants and define barriers that currently cause their large pre-diffusion phase; the time between invention and large scale diffusion. This research could be a stepping stone to further research into how to reach mass market faster for these systems, and therefore contributing to a solution for the growing societal problems of global warming and privacy protection.

## 1.2 Academic relevance

The main method that will be used in this research is the diffusion theory of R. Ortt et al. (2013). For the cases of QKD and the Tokamak reactor, it will be investigated in which phase of the life cycle pattern they are currently, using the life cycle pattern developed by J. R. Ortt and Schoormans (2004). If it can be concluded that the technologies have not reached the mass market yet, it will be relevant to investigate why this is the case. The pattern of diffusion and development of high-tech products (life cycle pattern) can be described by three milestones according to J. R. Ortt (2010). The three milestones are: Invention, Introduction and Large scale production and diffusion. The innovation phase is stated to be between invention and introduction and the adaptation phase is the the period between introduction and large scale diffusion. Additionally, literature by R. Ortt et al. (2013) can be found which describes 12 different factors that are defined to possibly cause a barrier to large scale diffusion for high-tech products. Different combinations of barriers lead to different niche strategies that could be adopted to circumvent or remove these barriers. Barriers defined in R. Ortt et al. (2013)'s article might apply to these cases and cause their long period between introduction and large scale diffusion or between invention and introduction, the adaptation and innovation phase respectively. This will be investigated in Section 4. The goal of this thesis research is to hopefully add factors to or sharpen factors of the framework, and therefore contribute to literature on the commercialisation of high-tech products. Not only will factors be added and sharpened, but suggestions will be made as well on how to adjust the theory as a whole.

## 1.3 Research objective

The objective of this research is to extend and sharpen existing literature on the long period between invention and market introduction or between market introduction and large scale diffusion of high-tech products. And how to shorten the duration of the phase and/or remove the barriers causing this. Data on the cases of quantum cryptography and Tokamak based nuclear fusion systems will be used in order to test the existing framework of R. Ortt et al. (2013), and hopefully complement the framework with new factors and relevant information. At the same time, an overview of the current status of these technologies will be constructed. And their position in the life cycle pattern will be determined. This objective has been derived from knowledge gaps that were found during a literature review. This literature review has been the foundation of the theoretical background chapter (2) and has been useful throughout this whole thesis. To reach this objective, research questions have been proposed which can be found in Section 1.4.

## 1.4 RESEARCH QUESTIONS

The main goal of this thesis is to investigate different barriers to large scale diffusion that currently hold for the cases of QKD systems and the Tokamak reactor nuclear fusion power plant. In order to explore this field, the following main research question has been defined:

***Why are quantum cryptography (QKD) systems and nuclear fusion power plants not available on large scale?***

In order to answer the main research question, smaller research questions have been proposed to help in answering the main research question:

*1. What is the current phase in the life cycle pattern that quantum cryptography is in?*

*2. What is the current phase in the life cycle pattern that the Tokamak design nuclear fusion power plant is in?*

To conclude that these high-tech products indeed have a large time between invention/introduction and (large-scale) diffusion, their position in the life cycle pattern described by J. R. Ortt (2010) has to be determined. These sub-questions will be a guideline in order to answer this question.

*3. Which already defined barriers by R. Ortt et al. (2013) can be appointed for quantum cryptography?*

*4. Which already defined barriers by R. Ortt et al. (2013) can be appointed for the Tokamak design nuclear fusion power plant?*

These sub-questions have been defined to describe the current status of these high-tech products by making use of the existing framework of R. Ortt et al. (2013). In this way, the currently existing factors can be critically examined.

Next to investigating the factors from the framework, it will be interesting to have a look at the framework as a whole and see if there are any ill defined parts that can be improved or completed. In order to answer this, the following sub-question has been proposed:

*5. Can adjustments to the framework be found?*

The answers to these sub questions will hopefully give a foundation for the research into the main question.

## 1.5 CONTEXT AND ASSUMPTIONS

For this thesis, the barrier framework of R. Ortt et al. (2013) and life cycle pattern of J. R. Ortt (2010) are often used and form the foundation of this research. First, the literature on the life cycle pattern and thus diffusion pattern of a high-tech product will be discussed. The paper of J. R. Ortt and Schoormans (2004) investigates the pattern of development and diffusion of breakthrough communication technologies. In this paper the classical S-curve diffusion pattern seems not to apply to the communication technologies treated in the paper. Four points in time are identified for the cases:

1. Invention of a breakthrough a technology
2. Development and technical refinement of a technology
3. Market introduction of a technology
4. Large scale diffusion and adaption of a technology

For item 3, it is mentioned that an introduction is meant as the commercial availability of a technology and not a pilot. For the telecom cases, often the application as we know it, was not the application where the product was initially introduced for on the market. The initial small scale applications can be seen as a different diffusion curves. In the article, three different phases are introduced: the innovation phase, the market adaptation phase and the market stabilization phase. (J. R. Ortt & Schoormans, 2004) This has resulted in the pattern as described in Figure 1.1. J. R. Ortt and Schoormans (2004) state that the S-curve takes place in the market stabilization phase, and that the preceding innovation and adaptation phases have to be added.

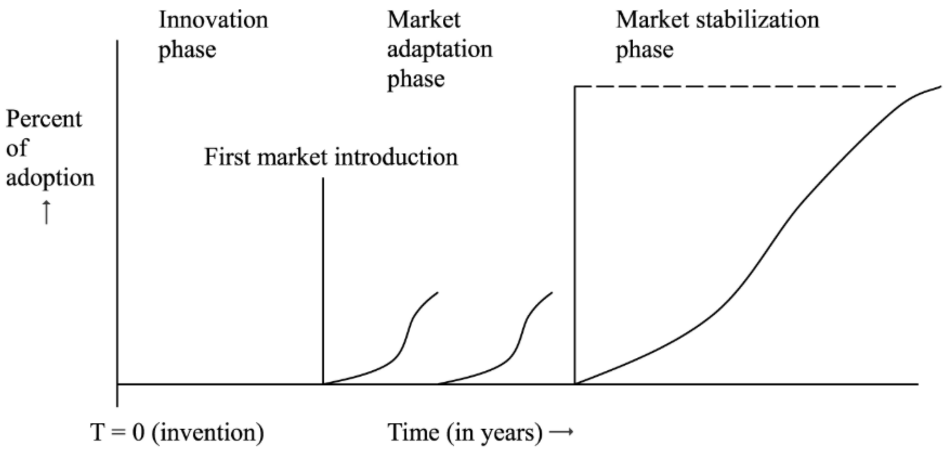


Figure 1.1: Three phases extracted from J. R. Ortt and Schoormans (2004).

The observed pattern seems to apply to cases for which: "technological change represents a technological breakthrough; technology can be incorporated in multiple product forms, which can be considered major innovations from the perspective of potential consumers; technology can be applied in multiple market applications; and diffusion has to cope with considerable externalities, such as a network, in the case of telecommunication appliances". (J. R. Ortt & Schoormans, 2004)

Later on, a new study was executed to investigate the duration of the pre-diffusion phase (innovation phase and market adaptation phase together) for high-tech product from different categories. (J. R. Ortt, 2010) These results showed that the pre-diffusion phase is not only long for communication technologies, but for technologies from many different disciplines. Three different scenarios have been observed. The first scenario shows a long innovation phase, the second a long adaptation phase and in the third scenario the high-tech product reaches mass market quickly after market introduction. (J. R. Ortt, 2010) In this situation it is however assumed that the high-tech product reaches the mass market, in real life sometimes products fail to reach mass market, or will not even be introduced to the market.

In the same article possible factors that could create the long period between invention and large scale diffusion have been researched. Three groups of factors have been identified: related to the main organizations, the technological system and the wider market environment. (J. R. Ortt, 2010)

In the article of R. Ortt et al. (2013) a barrier framework has been proposed that combines the information from the earlier mentioned articles. The barrier framework consists of 12 factors of which 6 core factors and 6 influencing factors could create a barrier to large scale diffusion. Different pain point factors require a different niche strategy in order to circumvent or remove a barrier and reach mass market. This framework will be further discussed in Chapter 4.

The first version of the framework was constructed in the context of the telecommunication industry. Several characteristics of the telecom market can be found, for example; the introduction of telecom technologies is postponed several times or when the technology did get introduced, it is withdrawn when sales are disappointing. (J. R. Ortt & Schoormans, 2004) In a subsequent article of J. R. Ortt (2010), different high-tech product categories are explored. High-tech product categories are characterized by a novel combination of functionality and technological principle. (J. R. Ortt, 2010)

In the article of J. R. Ortt (2010), the life cycle pattern is described using three milestones: invention, introduction and large scale diffusion. In the paper of J. R. Ortt and Schoormans (2004), a fourth milestone was described, namely "development and technical refinement of the technology". The three milestones that are currently used for the creation of the life cycle pattern are defined to be very specific points in time. In real life this might however not always hold, as argued by J. R. Ortt (2010). Some inventions happen at different locations at different times without any knowledge of one another. The determination of when a product is introduced and reaches large scale diffusion is not always straightforward either.

It is also assumed that during the life cycle pattern, the unit of analysis stays the same. It is however possible that different technologies merge into one and the product thus changes. Does this imply that the tracked technology disappears or does the unit just change?

In the articles that are published on this subject as briefly described above, all have different assumptions that have been made for that particular framework. In the first article of J. R. Ortt and Schoormans (2004), the telecom technologies where the pattern is based on, are considered breakthrough technologies. Breakthrough technologies are characterised by opening up a new market and using a technology which is totally different than before, either price/quality wise or the addition of new features. Moreover, telecom technologies are both directly sold to businesses and households. Also, it is assumed that multiple inventions of the same technology can take place around the same time and a pilot is not considered an introduction to the market. (J. R. Ortt & Schoormans, 2004)

Based on the literature as described above, certain assumptions will be made and used throughout this study:

- The life cycle pattern and barrier framework are designed for and based on *commercial high-tech products*, and initially from the telecom industry
- The barrier framework focuses on factors that play a role in the *adaptation phase*
- The government is seen as an external factor, not as the market introducer
- Niche applications can be seen as a different diffusion curve in terms of users

These assumptions are the initial requirements for the use of the framework by the authors. It can be explored if it only holds in situations that fulfill these requirements, or if it can be applied more widely.

For this research the life cycle pattern and barrier framework are used as described in the article of R. Ortt et al. (2013). A graphical summary is displayed in Figure 1.2.

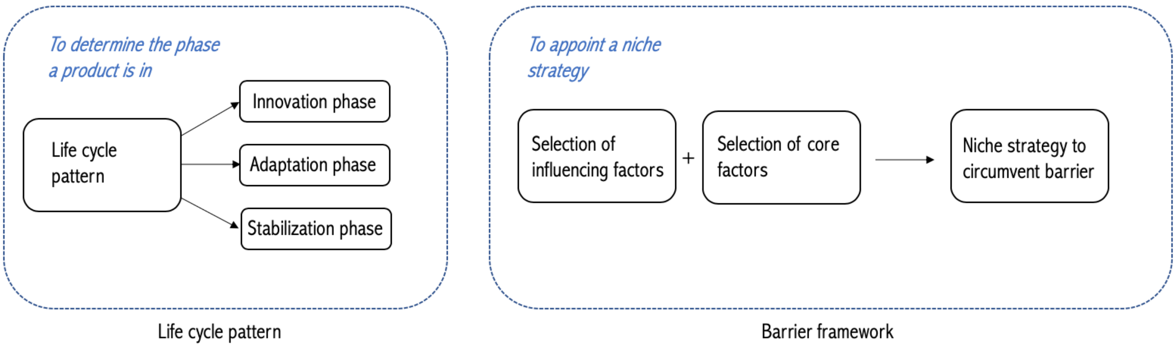


Figure 1.2: Literature that will be used and its connection.

## 1.6 Thesis outline & methodology description

This thesis consists of different sections in which different (sub) research questions will be explored. First, the principles behind and (dis)advantages of QKD and Tokamak power plants will be discussed. This is done in order to get a better understanding of the functioning and current status of these two technologies and can be found in Chapter 2.
After that, the literature written by R. Ortt et al. (2013) on barriers to large scale diffusion of high-tech products will be thoroughly discussed. The life cycle pattern of the two cases will be determined on the basis of R. Ortt et al. (2013)'s framework. (J. R. Ortt, 2010) In the following chapter, Chapter 4, the existing 12 factors from R. Ortt et al. (2013)'s framework will be investigated for the two cases, in order to appoint current factors that influence the development of the technologies. In the following chapter (5) other possible factors outside the framework will be explored. This will be done through a literature review. Thereafter, a critical eye is given on the framework as a whole and suggestions are made to improve the validity of the framework. The research methodology of each part of this research will be explained at the beginning of each section. At the end of each chapter, the two cases will be compared to look for similarities and/or contradictions. Adjusted versions of the life cycle pattern and barrier framework will be proposed in Chapter 8. The final chapter of this thesis will contain a conclusion and recommendation section, in which results will be discussed in dept and recommendations for future research will be given. Four phases in this report can be observed as displayed in Figure 1.3.

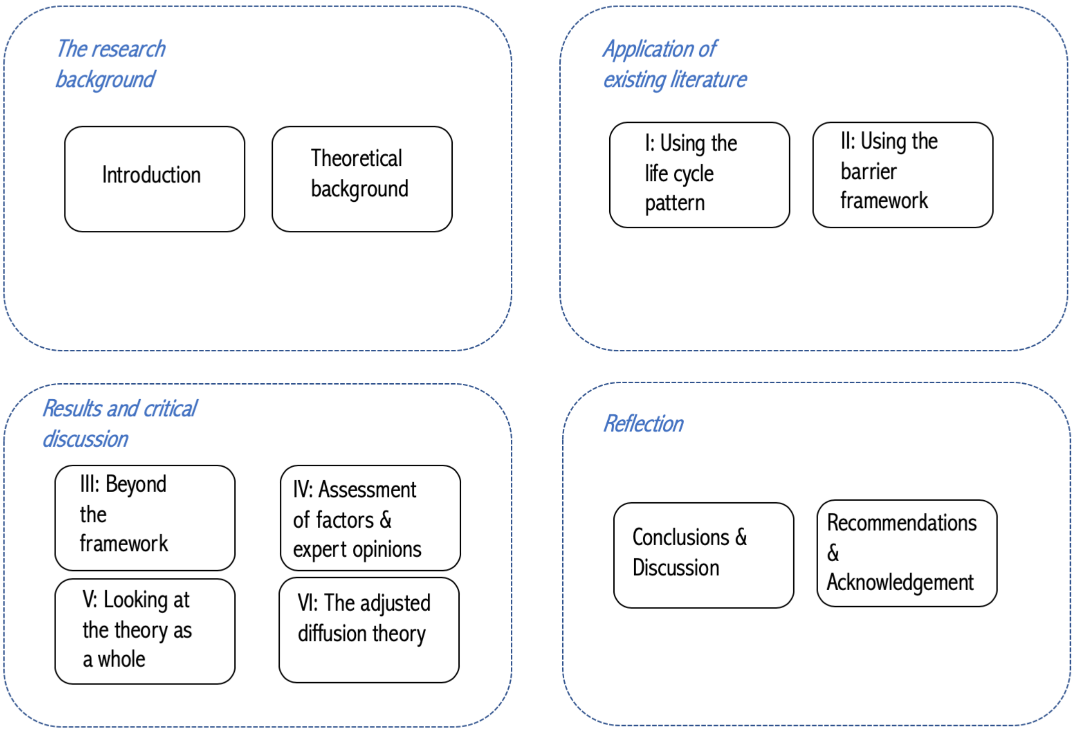


Figure 1.3: Thesis outline.

For the overall research a case study approach has been chosen. Case studies are an often used method that answers "how" or "why" questions. It is a study into a real world case that has not been manipulated by external factors. (Yin, 2014) A case study often starts with an in-dept literature review, which has been done prior to this research and resulted in Section 2. (Yin, 2014) Generalisation from case studies is often considered difficult. Therefore two comparative studies have been chosen instead of one. Next to that, case studies are often carried out with the aim to analytically generalise instead of statistical generalisation. In other words; to generalise and elaborate theories instead of working with probabilities. (Yin, 2014)

# 2 THEORETICAL BACKGROUND

The foundations of this chapter have been acquired during the literature review that has been conducted preceding to this thesis research. (Stam, 2020) This chapter has been written solely on the basis of a literature review. Sources have been found on digital data banks, such as Google Scholar and Scopus.

## 2.1 PRINCIPLES OF QKD

ID Quantitique is a market leading company in the field of quantum communication. This company states that with the probable quick arrival of the quantum computer, the need for a saver cryptography method grows. (IDQuantitique, 2019a) According to IDQuantitique (2019a), Quantum Key Distribution in combination with cryptography, also called quantum cryptography, is the form of communication encryption that is considered to be the safest. It will be able to protect data from future attacks and hacking from quantum computers. (IDQuantitique, 2019a) The main feature of quantum cryptography is the impossibility of eavesdropping.

Quantum Key Distribution is not the only cryptography method that could resist attacks from quantum computers. Quantum safe cryptography algorithms are under development, also called post-quantum cryptography. These algorithms are supposed to protect data from both quantum and classical computer attacks. (ETSI, n.d.-b) (Quantum Delta Nederland, 2019) Post-quantum cryptography algorithms are based on mathematics, like most of current classical encryption methods, and not on quantum physics principles like QKD does. (Quantumxchange, 2020) Currently often used classical cryptography algorithms, such as SSL and TSL, could not stand an attack from a quantum computer using Schor's algorithm. (Quantumxchange, 2020)

Cryptography works as follows: the sender encrypts its message with a secret key and sends it to the receiver. The receiver possesses the same secret key and uses this to decrypt the message. In classical encryption, this key is often a mathematical algorithm. (IDQuantique, 2005) The key used for quantum cryptography consists of photons with different polarization that are send between a sender and receiver, often called Alice and Bob. These photons are called qubits and can be in four states of polarization. This key cannot be measured without this being noticed, since when a photon state is measured, the polarization state changes and thus an eavesdropper is identified when the key at the receiver differs from the key send by the sender. Alice (A) and Bob (B) are connected through both a classical channel and a quantum channel. Messages are send over the classical channel, while the quantum channel is used to send quantum signals and exchange the key. (Scarani et al., 2009) (IDQuantique, 2005)

Currently, the distance over which a quantum channel can be used is still limited. Since the number of photons arriving at the receiver decreases when distance increases. Optical repeaters have the same effect as a possible eavesdropper: it measures the polarization state and therefore changes it. Candidates to solve this problem are: trusted nodes, quantum repeaters and satellites. (IDQuantique, 2005)

## 2.2 Advantages & Disadvantages QKD

The main disadvantage of QKD compared to current classical cryptography methods is the limitation of the distance over which Alice and Bob can communicate via a quantum channel. (Gisin & Thew, 2010) The distance limitation is a field in which a lot of research is done currently, and the technologies already become more and more mature. Besides that, no disadvantages concerning health or safety related to use of QKD systems can be found in literature.

Some researchers question if the straight forwardness of the safety of QKD is indeed true. (Yuen, 2016) Yuen (2016) states that QKD is so highly technical, that it is hard for non-experts to check the security proofs. He also states that not all possible attacks (by a quantum computer) have been explored. Pereira, Curty, and Tamaki (2019) also states that the security of QKD is not that straightforward, the theoretical proof does not imply that the practical implementation holds since experimental device imperfections are ignored in security proofs.

The biggest of advantage of quantum cryptography is the assumed protection against quantum computer attacks. (IDQuantitique, 2019a)

## 2.3 Ethics

Discussions in grey literature are seen about the question if quantum cryptography will function as a protection tool or if it will make criminals more powerful. Most people think that the technique is too difficult and expensive to copy, but there is no evidence for this assumption. Also, the knowledge of mastering this technique could create a power issue between governments and countries. (Bloomberg, 2017)

The ECP (Dutch platform for information society) also mentions the problems regarding inequality of possession of the technology and the impossibility of eavesdropping criminals. (ECP, 2019)

Vermaas (2017) states that it is important to incorporate responsible innovation and values early in the research. And adjust research and governmental public accordingly. He believes that philosophers can help lay people understand the principles of quantum technologies so that they can participate in debates. (Vermaas, 2017)

## 2.4 Companies offering commercial QKD systems

The following companies offer commercial QKD systems (at least up until 2020). Next to these companies, there are many companies that are currently conducting research in the field of QKD or even developing prototypes, such as the company Toshiba. (Toshiba Corporation, 2019)

- *ID Quantique* (IDQuantitique, 2019a)
- *MagiQ* (MagiQ, 0)
- *Quintessencelab* (Quintessence Labs, n.d.)

## 2.5 Principles of Tokamak design based fusion systems

Global warming has to be limited according to the first legally binding global climate change accord; known as the "Paris agreement". (European Union, 2015) Countries that participate have to explore new zero emission energy sources and are obliged to new emission restrictions. Together with the increasing energy consumption worldwide, which is not expected to be decreasing soon, the need for a zero emission energy source grows. In addition, fossil fuels are running low, in particular oil. Nuclear fusion is currently considered one of the only zero emission sources that would produce sufficient energy. (Smith, 2005)

Many people do not think that fusion power is the solution to our global energy problem. They find other green energy sources a more suitable candidate. Renewables such as solar and wind power are particularly seen as a better candidate. Disadvantages of these sources are the non-widely spread availability and not yet existing ways of long distance transporting or storing electricity. (Smith, 2005)

### *The principles of nuclear fusion power*

#### *Two directions in fusion research*

There are two types of reactions that can generate nuclear power: nuclear fission and nuclear fusion. Nuclear fission the most developed and used principle for generating nuclear power. However, nuclear fusion plants are not in use commercially yet. The reaction to generate nuclear fusion energy goes as follows:

$$ {}_1^2H + {}_1^3H \rightarrow {}_2^4He + {}_0^1n + energy $$

A very high temperature and pressure is needed in order to fuse the deuterium (${}_1^2$H) and tritium (${}_1^3$H) molecules. The results of this reaction are helium, a neutron and energy (warmth). The nuclear fusion reaction is also the process that generates energy in the Sun and stars, this reaction is however slightly different, since hydrogen atoms synthesize into deuterium and then deuterium and hydrogen fuse into helium and energy. The pressure for this solar fusion has to be much higher, but the temperature is lower than the reaction which is used for future nuclear fusion power plants. (Breeze, 2014)

A temperature of approximately 100 million degrees Celsius has to be reached in order to let the deuterium-tritium reaction happen. All atoms break down into subatomic particles such as nuclei and electrons at this temperature, the result of this subatomic mix is called a plasma. A magnetic field can be used to control the subatomic particles, since these are all electrically charged. No materials exist that can resist 100 degrees Celsius, which leads to a magnetic field as the only solution to create and hold a plasma. Two different technologies exist to contain plasma: toroidal magnetic fields and inertial confinement. (Breeze, 2014)

*Toroidal magnetic field/magnetic confinement*
Different reactors are used in projects, depending on the choice of technique to contain plasma. The Tokamak design reactor is the most well-known and used reactor for the magnetic confinement based technique. A toroidal shaped magnetic field exists inside this reactor. (Breeze, 2014)

*Inertial confinement*
The inertial confinement technique resembles more to the mechanism that happens in the Sun. Pulses of energy are created through capsules of deuterium-tritium mix that collide with high-energy lasers. In this way, bursts of energy are created instead of a continuous plasma. (Breeze, 2014)

An excessive amount of energy is released during a fusion reaction in the form of warmth. This warmth can be used to heat water which becomes steam that in its turn can be converted into electricity for future commercial power plants.

One of the big advantages of nuclear fusion power is the great amount of resources. A reaction of lithium produces tritium, and systems that produce large amounts of Tritium are being developed. The other required resource deuterium, can be extracted from water. (Breeze, 2014)

## 2.6 Advantages & Disadvantages Tokamak design based fusion systems

Research in the field of nuclear fusion has been confidential for a long time in the past, since nuclear fusion is also the basis for a hydrogen bomb. This fear of misuse of knowledge for wrong purposes still remains. (Breeze, 2014) Radioactive waste will still be produced during nuclear fusion, the amount is however much lower than during nuclear fission. Security measurements will therefore have to be taken. Tritium could possibly escape which would be corrosive for the equipment and would pollute the environment. Precautions have to be taken for possible hazards such as explosions. (Perrault, 2019) A thorny issue with nuclear fusion, are the costs associated with the research and projects. Still no commercial plants are in use, while a lot of budget has already been spend on past and current projects. Research has however shown that the fusion energy price per kWh would be fairly competitive. (Ward, Cook, Lechon, & Saez, 2005)

## 2.7 Ethics

Two groups of people can be distinguished in the case of nuclear power, those who oppose and those who support nuclear power. (DiPaolo, 2015) ITER is supposed to be a project that is safer and concerns less ethical issues than currently used nuclear fission power plants. Issues that do raise during ITER (and other fusion projects), will now be discussed. One big ethical issue is the issue of choosing safety and therefore delays or the in time completion of the project. High costs are involved in the project, so every extra safety measure or check that results in delays results in even higher costs. Codes of ethics are then harder to follow, while they are binding and important. (DiPaolo, 2015) This issue is however not case specific and can be found during projects in other fields as well.

There is a large stigma around nuclear power, due to nuclear fission power. The difference between nuclear fission and nuclear fusion power is very big in terms of safety and (radioactive) waste. It is however proven that due to nuclear fission power, nuclear fusion power has a big stigma around it. While the issues that this stigma is build upon do not apply to nuclear fusion in many cases. (Horlick-Jones, Prades, & Espluga, 2012)

## 2.8 Tokamak based projects

The following nuclear projects are currently being executed using a Tokamak design reactor. Projects that are stated here have a direct interest in commercialising their reactor, e.g. as part of a power plant.

- *ITER* (ITER, 2020) Public, first scientific intentions then commercial (DEMO).
- *Tokamak Energy* (Tokamak Energy, n.d.) Private, a commercial reactor.
- *MIT's Plasma Science and Fusion Center* (PSFC, n.d.) First scientific, then commercial intentions.
- *Commonwealth Fusion Systems* (Commonwealth Fusion Systems, 2020) Spin off from plasma center, direct commercial intentions.

## 2.9 Comparison

From this section, it can be concluded that both high-tech products have not reached the mass market yet and both have a high societal value. The principles of the two technologies both originate from physics, but the two high-tech products do not rely on the same principles. Which make it two independent technologies. Their (dis)advantages are therefore different as well and hard to compare. For both of the cases it holds that the high-tech product itself, i.e. QKD system and Tokamak based nuclear power plant, will not be sold to an individual. The products most probably will be sold to companies and/or governmental institutions that will deliver their clients a product or a service. In the case of QKD this means that the public at large will have their personal and often private data safely stored and transferred. In the case of nuclear fusion power plants it will be in the form of electricity. Both technologies are not the only candidate for solving their respective societal problem. They both have their (dis)advantages and ethical issues that have to be considered. The reasons why they are not in the large scale diffusion phase yet, have been investigated in Chapters 3, 4 and 5.

# 3 PART I: USING THE LIFE CYCLE PATTERN

## 3.1 DEFINITION OF DIFFERENT PHASES IN PATTERN

J. R. Ortt et al. (2015) have identified a life cycle pattern for high-tech products based on three milestones: invention, introduction and large scale diffusion. The phase between invention and introduction is called the innovation phase, between introduction and large scale diffusion the adaptation phase and after large scale diffusion the market stabilization phase, as displayed in Figure 3.1. In this life cycle pattern, the time is plotted against the cumulative percentage of adoption of a high-tech product by customers. A life cycle pattern for the cases of QKD and nuclear fusion has been constructed in this section using these milestones.

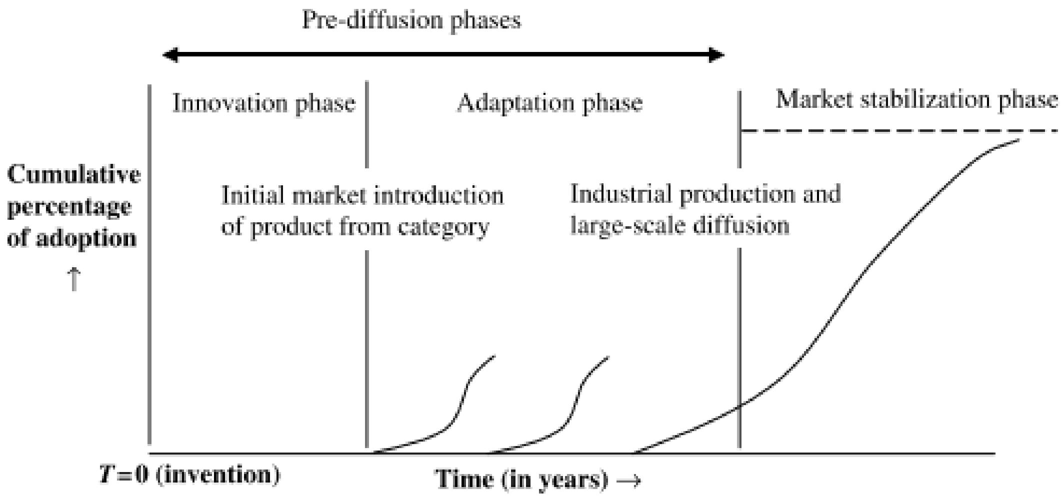


Figure 3.1: Life cycle pattern, extracted from J. R. Ortt (2010).

In literature different descriptions can be found for the invention, market introduction and large scale diffusion of a high-tech product. For this research, J. R. Ortt (2010)'s descriptions have been used. J. R. Ortt (2010)'s definition of invention of a high-tech product is as following: "The invention of a new high-tech product category is defined to be the first time that the technical principle of this category is demonstrated and mastered. " (J. R. Ortt, 2010) The introduction of a high-tech product to the market is defined as following: "The introduction date is defined to be the date at which the product is available for sales or can be transferred to users. In some cases, products are not sold, for example, if a government institute develops a new weapon that is used by the military forces." (J. R. Ortt, 2010) Large scale diffusion is characterised as following: "The milestone is defined using three elements:

- A standard product that can be reproduced multiple times (or standard product modules that can be combined in many different ways but are based on the same standard platform);

- A (large-scale) production unit with dedicated production lines (industrial production of a standard);
- and diffusion of the product

". (J. R. Ortt, 2010)

Often, niche applications of a high-tech product can be observed. A so called "early niche" emerges between introduction and large scale diffusion of a high-tech product, thus during the adaptation phase. If a niche emerges after large scale diffusion it is called a "mature niche". (R. Ortt et al., 2013) According to Dalgic and Leeuw (1994) a niche is defined as follows: "A small market consisting of an individual customer or a small group of customers with similar characteristics or needs". As stated by R. Ortt et al. (2013), in 80% of the cases of new high-tech products, early niche applications emerge. On average two early niche applications emerge and the duration of the adaptation phase is on average 7 years. (R. Ortt et al., 2013) It has been investigated in this section if such "early niche" applications exist for the two cases of QKD and Tokamak nuclear fusion.

Two types of innovations can be defined: incremental and radical. Incremental innovations are innovations that improve the already existing product, while radical innovations are the exploration of new solutions. (Norman & Verganti, 2014) The innovations can be continuous or discontinuous modifications, which respectively correspond to incremental and radical innovation. (Norman & Verganti, 2014)

Innovations, both incremental and radical, can lead to the emerge of new niche markets. The new improved product can attract new or different customers and therefore create a new market or segment. (Norman & Verganti, 2014)

## 3.2 Position in pattern of QKD

J. R. Ortt (2010)'s life cycle pattern theory applies to high-tech products, it has therefore first to be concluded that the QKD technology is considered a high-tech product. J. R. Ortt (2010) defines a high-tech product as: "a new combination of a technological principle and a specific functionality at the time of invention". Quantum physics, that guides the QKD technology, was already discovered, but the application to cryptography was not yet. It can therefore be concluded that QKD is a high-tech product. In Table 3.1 an overview of the history of the QKD technology can be found. Using J. R. Ortt (2010)'s definitions of invention, introduction and large scale diffusion, it can be concluded that QKD has not reached the large scale diffusion milestone yet.

*Invention*
As can be seen in Table 3.1, the discovery of the QKD principle was in 1984 by Bennett and Brassard. Discovery does not imply invention, since at that point the technology was not yet mastered and reproducible. (J. R. Ortt, 2010) Five years later, in 1989, the BB84 quantum

cryptography scheme for QKD was demonstrated by its discoverers and therefore invented.

*Introduction*
ID Quantique was the first company to offer commercial QKD systems on the market. (IDQuantitique, 2019a) QKD systems are for sale since 2007, it can therefore be concluded that the year of introduction is 2007 for the commercial QKD systems. (IDQuantique, n.d.) The first time that one of these QKD systems was commercially used was in the same year, when ID Quantique's system was used during the Swiss elections to ensure integrity of the data and the results of the election. (IDQuantitique, 2019a)

*"Early niche" applications*
As mentioned earlier, often niche applications of a high-tech product emerge during the adaptation phase. (R. Ortt et al., 2013) In the case of commercial QKD systems, no straightforward niche applications can be appointed.

Within the QKD technology an emerging slightly different technology is under construction, namely the key distribution via satellites instead of photons. This can be considered an incremental innovation that creates a different technology and therefore possibly different markets and suppliers. (Pan, 2018) Whether this form of quantum cryptography can be considered a niche technology, split-off or innovation has to be investigated.

A life cycle pattern has been graphically displayed in Figure 3.2. The innovation phase, the phase between invention and introduction, took 18 years. The adaption phase is the phase in which the technology is still in and takes already 13 years.

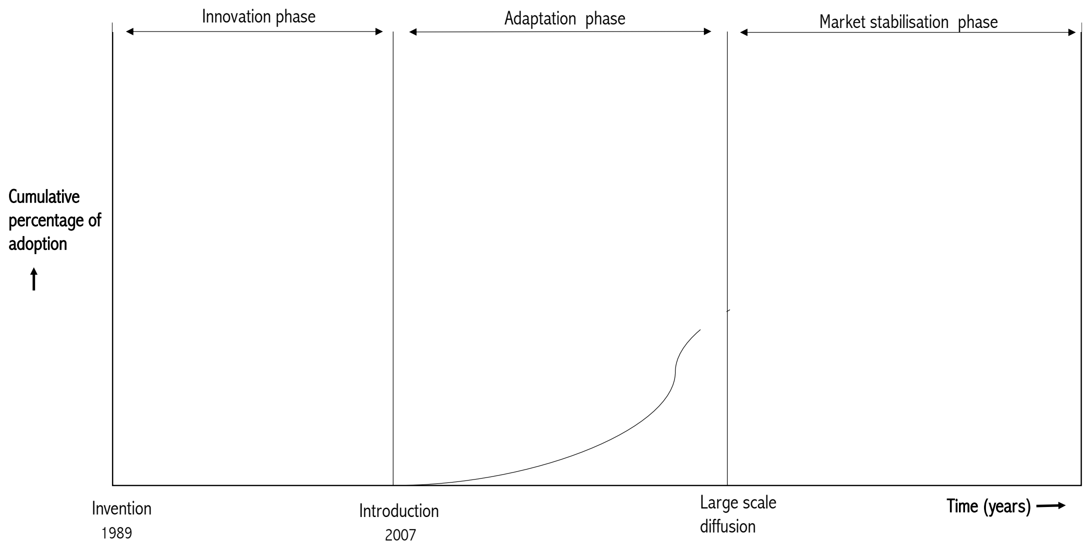


Figure 3.2: Life cycle pattern for QKD. (J. R. Ortt, 2010)

| Year | Activity | Source |
|---|---|---|
| 1984 | Proposed solution to key distribution problem by Bennett and Brassard based on quantum physics | (Scarani et al., 2009) |
| 1989 | Demonstration of the BB84 protocol | (Lo & Zhao, 2008) |
| 1991 | E91 protocol published by Ekert which is based on quantum entanglement | (Scarani et al., 2009) |
| 2003 (October) | DARPA network in use in laboratory | (Elliott et al., 2005) |
| 2004 (June) | Communication over the DARPA network's telecommunications fiber between Harvard University, Boston University and BBN (world's first quantum cryptography network) | (Elliott et al., 2005) |
| 2007 | IDQuantique starts offering QKD systems on the commercial market | (IDQuantique, n.d.) |
| 2008 | The first live presentation of a working quantum key distribution (QKD) network | (SECOQC, 2019) |
| 2010 | IDQ becomes present in both government and commercial markets all over the world with their solutions | (IDQuantitique, 2019a) |
| 2016 | IDQ develops the world's smallest Quantum Random Number Generator | (IDQuantitique, 2019a) |
| 2016 | Quantum Experiment Science Satellite (QUESS) shows world's first satellite-based entanglement distribution over 1200 kilometers | (Pan, 2018) |
| 2017 | First long distance (over 1900 km) land line in China, from Beijing to Shanghai | (Yiu, 2018) |
| 2017 | Quantum video call from Beijing to Vienna via a satellite Micius | (Yiu, 2018) |
| 2019 | Launch of 3 year project OPENQKD, EU funded project with 38 organizations | (IDQuantitique, 2019b) |

Table 3.1: Timeline of the history of quantum communication technology QKD, Table partially extracted from Stam (2020).

### 3.3 Position in pattern of Tokamak design based fusion systems

With the earlier mentioned definition of a high-tech product, it can be concluded that nuclear fusion technology to generate power is a high-tech product. Namely, nuclear physics (the guideline for this technology) in combination with generating power was a new application of this knowledge. J. R. Ortt (2010)'s definitions of invention, introduction and large scale production will be used again to determine Tokamak based nuclear fusion technology's position in the life cycle pattern.

*Invention*
The discovery of generating power out of nuclear fusion was in the 20s. In the 50s, the design of the Tokamak reactor was developed. (Lppfusion, 2020) The world's first Tokamak reactor called T1 that reached the required temperature and created a plasma was finished in 1968. 1968 can therefore be seen as the invention year of the Tokamak nuclear fusion reactor. (ITER, 2020)

*Introduction*
Multiple properties regarding the introduction of the Tokamak reactor to the market have to be taken into account. Tokamak is a design of a reactor of which many projects make use, as for example ITER. (ITER, 2020) Currently no commercial Tokamaks are on the market yet. But the design is used in many projects aiming for nuclear power worldwide. It can therefore be concluded that the Tokamak based power plants are still in the innovation phase.

*"Early niche" applications*
In the 1950s nuclear fusion was also used to create hydrogen weapons. A lot of research into nuclear fusion had therefore been kept a secret until half of the 1950s. When it was clear that nuclear fusion energy production had no military purposes, research results became more public. (Lppfusion, 2020) Nuclear fusion as a technique is the principle of both of these applications, but hydrogen bombs cannot be seen as a niche application of the Tokamak based nuclear fusion plants. Hydrogen bombs have a totally different purpose, do not consist of a Tokamak reactor and are not commercially available.

A niche market has been developed during the research into Tokamaks, fusers are now commercially available in order to produce neutrons. These neutron producers are used in the industry as well as in medicine. (Sparc, n.d.) The IEC (Inertial Electrostatic Confinement) device produced by Daimler Chrysler Aerospace was the first commercial application that makes use of the confinement of fusing plasma. (Miley & Sved, 2000) This niche market is however a different product than the Tokamak that is made use of nowadays, a simpler version could be said. It is considered a split-off of the Tokamak reactor.

Next to magnetic confinement which is used in Tokamak reactors, inertial confinement is also used for other types of nuclear fusion reactors. More information on this principle of inertial confinement can be found in Section 2. This approach to creating and confining plasma has been developed in the 1970s. (Breeze, 2014) Nowadays, projects using magnetic confinement as well as inertial confinement are being executed. Inertial confinement based setups could be considered a different product since the technology differs.

*Different types of Tokamak designs*
Throughout the years, different designs of the Tokamak reactor can be observed. (ITER, 2020)

- ± 1950-1980 These Tokamak designs were small in size and their main purpose was to show that plasmas could be produced and confined. Experiments have been done to show that a larger sized Tokamak could also increase plasma confinement.
- ± 1980s Medium sized Tokamaks were introduced and features (divertor and wall conditioning) were added.
- After that, new reactors with new added techniques and features were build to study plasmas.
- These latest designs were fundamental for ITER, world's largest Tokamak.

In total about 200 Tokamaks have been build worldwide since its invention. Using the definition of incremental innovation as described in Subsection 3.1, these changes in design of the Tokamak can therefore be seen as incremental innovations. The product remains the same but improves in terms of features and quality. (ITER, 2020)

These milestones and niche strategies can be summarized in a life cycle pattern, which can be found in Figure 3.3. Since no electricity produced by a nuclear fusion plant and no nuclear fusion plants are yet for sale, it is hard to determine if and when the introduction has taken place. The Tokamak design is namely widely known and taken into use. For this pattern it has been chosen that the moment in time of invention of the nuclear fusion power plant is stated in 1968. This was the moment that the technology (Tokamak reactor) was mastered and taken into use in the construction of nuclear power plants. But not on a commercial base. Its discovery (the design) took already place in the 1950s. Several niche applications can be observed over the years; within the Tokamak design itself and as neutron producers. The moment of introduction of the nuclear fusion power plant can however not be seen in Figure 3.3, since that has not taken place (yet).

Another note that can be made is that the niche applications emerged already in the innovation phase of nuclear fusion power plants, already before early niche applications, since these normally emerge in the adaptation phase.

As can be concluded, a niche application has emerged during this innovation phase as commercial fuser. Next to that, different generations of the Tokamak design can be found. Finally, the reactors as we currently know have two possible technologies that create the plasma inside a reactor. One which was invented later (inertial confinement). All these niche applications and generations can currently not be displayed in the life cycle pattern of J. R. Ortt (2010), as it is defined currently.

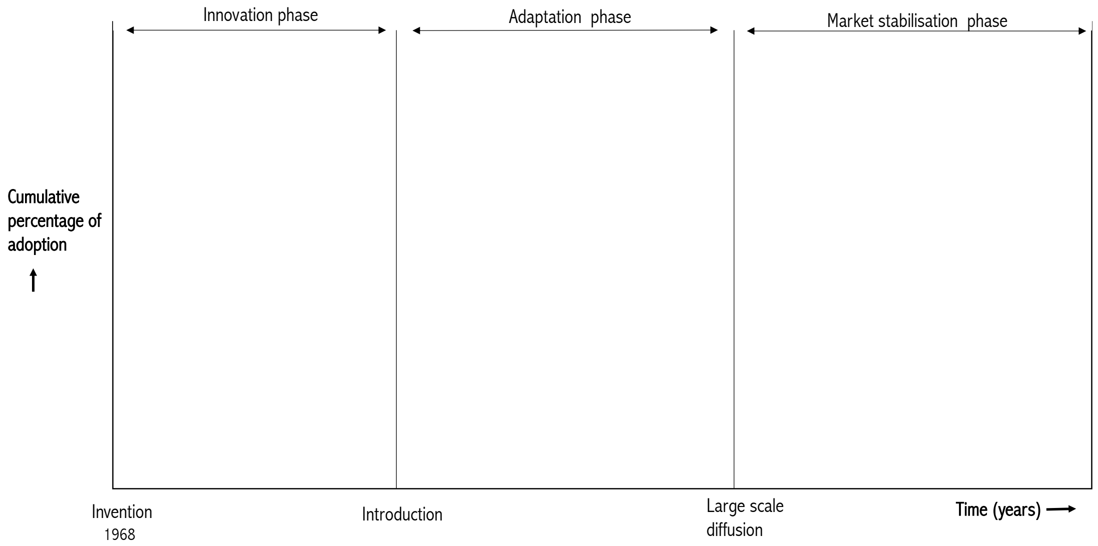


Figure 3.3: Life cycle pattern for Tokamak nuclear fusion reactors. (J. R. Ortt, 2010)

| Year | Activity | Source |
|---|---|---|
| ± 1930 | Discovery of possibility of nuclear power by amongst others Hans Bethe | (Lppfusion, 2020) |
| ± 1960 | Invention of the Tokamak reactor in the Soviet Union | (Lppfusion, 2020) |
| 1968 | First demonstration of Tokamak with required temperature and plasma creation | (ITER, 2020) |
| 1979 | Start of construction of Joint European Torus (JET) | (EUROfusion, 2020) |
| 1982 | Begin operation reactor TFTR at Princeton Plasma Physics Laboratory | (ITER, 2020) |
| 1983 | First plasma created by JET | (EUROfusion, 2020) |
| 1985 | Idea launch for ITER at Geneva Superpower summit | (ITER, 2020) |
| 1986 | Agreement between European Union (Euratom), Japan, the Soviet Union and the USA was reached | (ITER, 2020) |
| 1988-2001 | Design phase ITER | (ITER, 2020) |
| 1994 | Start of IFMIF project - an accelerator-based neutron source | (IFMIF, 2020) |
| 1997 | World record (current) amount of energy produced by fusion in JET (16.1MW) | (EUROfusion, 2020) |
| 1997 | Termination of TFTR | (ITER, 2020) |
| 2003 | China & Republic of Korea join ITER | (ITER, 2020) |

| Year | Activity | Source |
|---|---|---|
| 2005 | India joins ITER and location has been determined: south of France | (ITER, 2020) |
| 2006 | Official ITER agreement | (ITER, 2020) |
| 2007 | ITER Organization was officially established | (ITER, 2020) |
| 2007 | IMFIF is purchased by the Japanese government and EURATOM | (IFMIF, 2020) |
| 2010 | Start of construction of ITER | (ITER, 2020) |
| 2014 | EUROfusion was established | (EUROfusion, 2020) |

Table 3.2: Timeline of the history of nuclear fusion, partially extracted from Stam (2020).

## 3.4 COMPARISON

From this section it can be concluded that QKD systems are in the adaptation phase for already 13 years. No clear niche applications can be found in the market of QKD systems. Contradictory, for the Tokamak based nuclear fusion market many split-offs and generations of the reactor can be observed. The Tokamak reactor itself has undergone several incremental innovations regarding designs with all different purposes, but also other applications such as neutron producing fusers and inertial confinement fusion reactors can be found. These can however not be considered niche applications as formulated in the diffusion theory. Since in these cases, the unit of analysis and/or technology changes. For Tokamak based nuclear fusion, it is harder to determine when and if the introduction has already taken place. No nuclear fusion power plants are on the market, and neither is their product: nuclear fusion power. While for QKD systems this is the case; QKD systems are commercially available and data is already secured by this technique. The Tokamak reactor design is however widely used and known, which can be seen as an introduction as well. It is therefore concluded that Tokamak reactors are already introduced to the market, but Tokamak based fusion power plants are not. The commercial QKD systems are therefore concluded to be in the adaptation phase, since introduction into the market has taken place, while large scale diffusion has not been reached yet. Nuclear fusion power plants are defined to be in the innovation phase, the period between invention and introduction.

On average, the period between invention and large scale diffusion (pre-diffusion phase) takes about 17 years, the innovation phase takes half of that time and the adaptation phase the other half. (J. R. Ortt, 2010) The innovation phase of commercial QKD systems took 18 years, and until today the adaptation phase takes already 13 years. This results in a pre-diffusion phase of at least 31 years, and thus above average. Nuclear fusion based power plants are considered to be still in the innovation phase, with its invention in 1968, leading to an innovation phase of at least 52 years. As mentioned by J. R. Ortt (2010) himself, the research was based on 50 cases that went through all phases in the pattern and cases that did not were left out. For these two cases, the possibility exists that they will not reach the next or final phase. If this happens, the average duration cannot be compared to these two technologies pre-diffusion phase length. Assuming that both products will reach large scale diffusion, it can be concluded that their pre-diffusion phases are currently already above average.

It can be noted that for both cases some deficiencies during the use of the life cycle pattern have been encountered. The description of niche applications is unclear and no distinction is made between niche applications and split-off technologies or innovated products. Another note has to be given about the sudden stop of the curves of the niche applications, which implies that the product is then stopped using and existing. While even after sales have stopped, a product could still be used and the total amount of customers that ever purchased the product remains equal. Finally, the stabilization phase seems to start at a lower amount of cumulative percentage of adoption than for preceding niche applications.

# 4 Part II: Using the barrier framework

## 4.1 Methodology & Search description for part II

In this chapter the existing barrier framework of R. Ortt et al. (2013) has been used in order to define current barriers that prevent the two technologies from large scale diffusion. This framework exists of 12 factors, which is a collective term for actors, factors and functions. These different factors can cause barriers for large scale diffusion if they lack for a high-tech product's system. The different factors can also demand for different niche strategies in order to circumvent the blockages. These niche strategies have been examined later on in this research. (R. Ortt et al., 2013) All 12 factors that are proposed in this framework have been investigated for both of the cases. The 12 factors with their description can be seen in Table 4.1. The literature review method has been chosen in order to answer the third and fourth sub questions: "Which already defined barriers by R. Ortt et al. (2013) can be appointed for quantum cryptography?" and "Which already defined barriers by R. Ortt et al. (2013) can be appointed for Tokamak design nuclear fusion systems?".

Factors 1 until and including factor 6 are considered core factors, and 7 until and including 12 are considered influencing factors. The influencing factors can explain why the core factors can become a barrier. (J. R. Ortt et al., 2015) While identifying the factors that could have possibly let to the long adaptation phase, a distinction has been made between the strongest influencing and core factor and the other factors involved. All factors that have a possible blocking power are in **bold**. The strongest influencing and core factor are also <u>underlined</u>. (J. R. Ortt et al., 2015) The ranking of the factors into strongest to weakest influencing has been done through a literature review and the decision maker's interpretation of this.

| **Factors** | **Description** |
|---|---|
| 1. New high-tech product | The product can be defined and distinguished using three elements: the functionality provided by the product, the technological principle(s) used and the main components in the system (first tier of subsystems). The unavailability of (one or more components of) the product means that large-scale diffusion is not (yet) possible. The product needs to have a good price/quality compared to competitive products in the perception of customers before large-scale diffusion is possible. |
| 2. Production system | Availability of a good production system is required for large-scale diffusion. In some cases a product can be created in small numbers as a kind of craftsmanship but industrial production technologies are not yet available. In that case large-scale diffusion is not possible. |

| Factors | Description |
|---|---|
| 3. Complementary products and services | Complementary products and services refer to products and services required for the production, distribution, adoption and use. The product together with complementary products and services forms a socio-technological system. The unavailability of elements in that system means that large-scale diffusion is not (yet) possible. |
| 4. Suppliers (network of organizations) | The producers and suppliers refer to the actors involved in the supply of the product. Sometimes multiple types of actors are required to supply the entire system. In that case a kind of coordination (network) is required. Sometimes actors with considerable resources are required, for example to provide an infrastructure. If one or more vital roles, resources or types of coordination are not present in the socio-technological system, large-scale diffusion is blocked. |
| 5. Customers | The availability of customers means that a market application for the product is identified, that customer segments for these applications exist and that the customers are knowledgeable about the product and its use and are willing and able to pay for adoption. If applications are unknown or if customer groups do not exist, are not able to obtain the product or are unaware of the benefits of the product, large-scale diffusion is blocked. |
| 6. Institutional aspects (laws, rules and standards) | The regulatory and institutional environment refers to the laws and regulations that indicate how actors (on the supply and demand side of the market) deal with the socio-technological system. These laws and regulations can either stimulate the application of radically new high-tech products (such as subsidy that stimulates the use of sustainable energy) or completely block it (such as laws prohibiting something). |
| 7. Knowledge of technology | The knowledge of the technology refers to the knowledge required to develop, produce, replicate and control the technological principles in a product. In many cases a lack of knowledge blocks large-scale diffusion. |
| 8. Natural resources and labour | Natural resources and labour are required to produce and use a new high-tech product. These resources and labour can be required for the production system, for complementary products and services or for the product itself. In many cases a lack of resources and labour block large-scale diffusion. |
| 9. Knowledge of application | Knowledge of the application can refer to knowing potential applications. If a technological principle is demonstrated but there is no clue about its practical application, large-scale diffusion is impossible. A lack of knowledge of the application can also refer to customers that do not know how to use a new product in a particular application. In that case large-scale diffusion is not possible. |

| Factors | Description |
|---|---|
| 10. Socio-cultural aspects | Socio-cultural aspects refer to the norms and values in a particular culture. These aspects might be less formalized than the laws and rules in the institutional aspects but their effect might completely block large-scale diffusion. |
| 11. Macro-economic aspects | Macro-Economic aspects refer to the economic situation. A recession can stifle the diffusion of a new high-tech product. |
| 12. Accidents or events | Accidents or events such as wars, accidents in production, accidents in the use of products can have a devastating effect on the diffusion of a new high-tech product. |

Table 4.1: Factors that can create barriers defined in R. Ortt et al. (2013)'s article.

## 4.2 Application of existing literature on barriers to large scale diffusion

The factors as described in Table 4.1 will be investigated in this section for the two cases: commercial QKD systems and nuclear fusion power plants.

### 4.2.1 Barriers QKD

*1. New high-tech product*

The functionality of the product is clear, namely protecting data with a save cryptography method. The technological principle, Quantum Key Distribution, is in place. The commercialisation of the principle has however encountered some difficulties, as discussed before. Compared to current cryptography methods, it is more expensive but does offer more features, therefore the quality increases. (IDQuantitique, 2019a) Quality in terms of communication speed (key rate) and distance covered is however shorter for QKD than classical communication. The theoretical proven security sometimes differs from the practical security, due to implementation imperfections. (Diamanti, Lo, Qi, & Yuan, 2016) A QKD system exists of different components, the QKD system itself that sends and receives the signals. But also the network over which the signals are send is important. The main components of the sending system (Alice) are: optical source, quantum state preparation (QSP), modulation scheme (Mod-Sch) and a Digital Processor & Communication (DP&Comm). The receiver, Bob, consists of: an optical receiver that receives the quantum state of Alice and translates it into an electrical output signal that is connected to a demodulation scheme (Demod-Sch). (Lopez-Leyva, Talamantes-Alvarez, Ponce-Camacho, Alvarez-Guzman, & Garcia-Cardenas, 2018)

*2. Production system*
No sales numbers or information on quantities produced by companies such as ID Quantique are available and open to access. This makes it hard to determine if production systems could produce large quantities. Systems are getting smaller and cheaper and sales are increasing. (Quantum Flagship, n.d.) This could imply that large quantities of systems could be produced.

*3. Complementary products and services*
One of QKD's big challenges is its integration in the existing network infrastructures. (Quantum Flagship, n.d.) Al Natsheh, Gbadegeshin, Rimpiläinen, Imamovic-Tokalic, and Zambrano (2015) have conducted a research in 2015 by interviewing QKD experts to find out what blocks the commercialisation of QKD. A finding was that the after-sales services are currently insufficient. Maintenance services are not in place and insufficient metrology systems are offered. (Al Natsheh et al., 2015) An other finding of this study is conforming Quantum Flagship (n.d.)'s statement about the integration in existing network infrastructures. There is a lack of available or adequate infrastructures to support QKD. (Al Natsheh et al., 2015)

*4. Suppliers (network of organizations)*
Network operators have to be willing to work together with QKD companies and use QKD systems on their networks. Collaborations between network providers and QKD systems offering companies already exist, ID Quantique partners with Fortinet as well as with SK Telecom Network for example. (IDQuantitique, 2019a) It is therefore important that quantum theorists and telecom engineers work together to develop QKD protocols that make use of telecom photons, are compatible with standard optical fiber networks and include quantum features in order to stay secure. (Gisin & Thew, 2010) Al Natsheh et al. (2015)'s study has however shown that building a supply chain has been difficult in the case of QKD. Some components of the QKD system do not yet exist on the market and the newness of the product makes it more difficult too. (Al Natsheh et al., 2015)

*5. Customers*
The key markets of leading company ID Quantique are the following: Telecom & Data Center Service Providers, Financial Services Companies, Governments & Defence, Healthcare Organisations, Critical Infrastructure and IP-rich Enterprises. (IDQuantitique, 2019a) A few years ago, the target market was still the military and governments, but the market has expended to telecom providers and other commercial companies. (Inside Quantum Technology, n.d.)

*6. Institutional aspects (laws, rules and standards)*
In 2020 a collaborative project between 38 partners from 13 European countries has started. This project called "OpenQKD" is financed by the European Union's Horizon 2020 research and innovation programme. (OPENQKD, 2020) It can therefore be concluded that the Euro-

pean Union stimulates the development of QKD in the form of funding research. A subsidy per unit has not been mentioned on the internet. The European Telecommunications Standards Institute (ETSI) is currently bringing together multiple actors to discuss the standardisation of quantum cryptography. (ETSI, n.d.-b)

*7. Knowledge of technology*
The distance of safe QKD network channels is still a big problem. The currently existing technologies are not yet mature enough to reach long distances. Possible solutions to this problem could be quantum repeaters or satellite based QKD. (Gisin & Thew, 2010) Additionally, the key rate does not meet the speed of current used communication methods. (Diamanti et al., 2016)

*8. Natural resources and labour*
No lack of resources can be directly appointed in literature. However, different types of labour and knowledge have to be combined to commercialise and standardise QKD systems. (ETSI, n.d.-a)

*9. Knowledge of application*
The application of QKD in combination with cryptography gives quantum cryptography which will protect us from future quantum attacks and hacking. With the high probability of the emerge of the quantum computer, a new safe method of cryptography will be necessary. (IDQuantitique, 2019a)

*10. Socio-cultural aspects*
In grey literature, speculations can be found on what would happen if the technology would come in the hands of criminals. Their communication could then not be eavesdropped. (Bloomberg, 2017)

Other grey literature can be found in which it is implied that with the advent of quantum cryptography many jobs will become irrelevant. (RF Wireless World, n.d.) Besides this, there are no other disadvantages for the public at large published.

*11. Macro Economic aspects*
Until December 2019 no big economic trends can be appointed that would prevent QKD from large scale diffusion. The COVID-19 virus has had, and will have enormous impact on the economy throughout the world which could result in a recession. Research has however been done and the impact of COVID-19 on the diffusion of QKD is stated to be limited. (BusinessWire, n.d.)

*12. Accidents or events*
No noted accidents or events have happened that were related to the production, development or use of QKD.

#### 4.2.2 Barriers Tokamak design based fusion systems

Since it has been concluded in Section 3.1 that Tokamak nuclear fusion power plants are still in the innovation phase, the same barriers are investigated as for the case of QKD but taking the innovation phase into mind.

*1. New high-tech product*

The opinion on nuclear fusion power is very divided, many people think that other green energy sources such as solar or wind power, have a better price/quality ratio. Nuclear fusion power would however generate way more and consistent power. (Smith, 2005) The price per unit of nuclear fusion power is expected to second cheapest power. (Entler, Horacek, Dlouhy, & Dostal, 2018) However, the functionality might be more clear to experts than to lay people. Several projects, such as SERF and ITER, have been established to inform the lay public on its possible economic viability and social acceptability. (López, Horlick-Jones, Oltra, & Solá, 2008) A Tokamak nuclear fusion power plant can be in general divided in several parts: (CRAIG FREUDENRICH, n.d.)

1. *The fusion reactor*
   A stream of deuterium and tritium will be heated to create a plasma at a high temperature. A high pressure is created and therefore fusion takes place. Approximately 70 megawatts of power will be necessary to start the fusion, about 500 megawatts will be produced. The fusion reaction will take between 300 and 500 seconds.
2. *Lithium blankets (outside the plasma reaction chamber)*
   These blankets will capture the neutrons which are produced during the fusion reaction. These are used to make more tritium (fuel).
3. *Water cooling loop & heat exchanger*
   In order to produce steam.
4. *Electrical turbines*
   They will use the steam to produce electricity.

The current technical issues lay within the fusion reactor (1), the plasma does not hold the 300-500 seconds yet and the energy produced is not 500 megawatts yet either. (ITER, 2020) When the electricity is generated, it has to be delivered to customers via the electricity network. This is not supposed to be a big problem.

*2. Production system*

Since no commercial plants exist yet, production systems do not exist yet either. Projects are however being executed that focus on the production of commercial nuclear fusion plants, such as the project DEMO. (EUROfusion, 2020) The costs related to the construction of a nuclear fusion power plant are expected to be high, which results in high intrinsic costs. (Entler et al., 2018) These costs may create a barrier for entering the nuclear fusion market.

*3. Complementary products and services*
In commercial plants, nuclear fusion power will heat water that becomes steam and which will produce electricity. (Breeze, 2014) The complementary product to nuclear fusion power would then be its connection to the electricity network.

*4. Suppliers (network of organizations)*
As mentioned at *3. Complementary products and services*, the electricity generated from nuclear fusion has to be transported and sold over the already existing electricity networks.

ITER, world's largest fusion project, has undergone a lot of organisational and coordination lack problems which have (amongst others) led to large delays in its development. (ITER, 2020)

*5. Customers*
The application for the product will be the production of electricity that will be consumed by the public at large.

*6. Institutional aspects (laws, rules and standards)*
Different laws and regulations concerning nuclear waste and materials have been established in 1954 in the United States. (United States Nuclear Regulatory Commission, n.d.) The same holds for the European Union, where the European Commission has set rules and restrictions on the amount of nuclear waste and safety. (European Commission, n.d.) There are projects, such as ITER, that are funded by governments and the EU, but nuclear fission energy per unit does not receive a subsidy. Whether the subsidy would hold for nuclear fusion power per unit is undefined. (World Nuclear, n.d.)

*7. Knowledge of technology*
This is probably the main barrier that prevents fusion energy from being available on the (mass) market. The knowledge about the technology is still insufficient to produce commercial nuclear fusion power plants. As explained at *1. New high-tech product*, the conditions are not yet met to recreate the process that happens in our Sun and stars in terms of temperature and pressure. It has to be noted that the barrier framework is intended for the adaptation phase, and it is therefore assumed for this factor that the high-tech product has already been introduced to the market. In the cases of nuclear energy, this is not true.

*8. Natural resources and labour*
The resources needed for nuclear fusion power are widely available, this is one of the main advantages of this energy source. (Breeze, 2014) Deuterium can be extracted from water and tritium can be produced during the fusion reaction from the neutrons hitting lithium, as explained at *1. New high-tech product.* (ITER, 2020)

*9. Knowledge of application*
The application is clear, electricity consumption is only increasing, so new energy sources have to be explored. Nuclear fusion is considered a good candidate. (Ward et al., 2005)

*10. Socio-cultural aspects*
The stigma of nuclear fission power, as earlier discussed in Section 2, gives a stigma to fusion power as well. (Horlick-Jones et al., 2012) Both technologies produce nuclear energy, but the (dis)advantages are very different.

*11. Macro Economic aspects*
Until December 2019, no big economic trends can be appointed that would prevent Tokamak design based nuclear fusion from large scale diffusion. The ITER project has been affected by the COVID-19 virus, and different measures have been taken which could cause delays. (ITER, n.d.) The same could hold for other fusion projects.

*12. Accidents or events*
The stigma of nuclear fission power, as earlier mentioned, exists because of accidents that happened related to nuclear fission power. No such accidents or events have happened until today regarding nuclear fusion power. (Horlick-Jones et al., 2012) Hydrogen bombs, that work partially on nuclear fusion and are often seen as related, have not been used in any wars or conflicts either.

### 4.2.3 Barriers that can be appointed for the two cases

*Methodology of categorisation of factors*
As described earlier, the decision maker/judge has categorised the factors based on information found during a thorough literature review.

*So which barriers can be appointed for QKD?*
Using the framework of R. Ortt et al. (2013), *Complementary products* can be considered one of the main core factor that prevent QKD systems from large scale diffusion. The influencing factor that affects this core factor is the *Knowledge technology* factor, due to technical issues it is hard to connect QKD to the current communication channels. Additionally, the *Production system* and *Suppliers* influencing factors are not totally in place either. The current networks have to be used for the implementation of QKD and the technology has to be adapted accordingly. Furthermore, the technology itself has to be improved by means of distance over which can be communicated to enter new markets. Which therefore influences the core factor *Product*. All factors that currently create a barrier to large scale diffusion are displayed in **bold**. Core factor *Product* and influencing factor *Knowledge technology* are considered the most important, and are therefore underlined.

| **Influencing factors** | **Core factors** |
|---|---|
| 7. **Knowledge technology** | 1. **Product** |
| 8. Knowledge application | 2. **Production system** |
| 9. Labour resources | 3. **Complementary products** |
| 10. Socio-cultural | 4. **Suppliers** |
| 11. Macro economic | 5. **Customers** |
| 12. Accidents and events | 6. Institutions |

Table 4.2: Factors from the framework that hold for QKD. The description of the factors can be found in Table 4.1. The influencing factors are placed left since they influence the core factors which are placed on the right.

*So which barriers can be appointed for nuclear fusion power plants?*
A summary of the factors and their importance regarding creating a barrier to large scale diffusion can be found in Table 4.3. It can be concluded that for Tokamak based nuclear power plants the knowledge about the technology creates the biggest barrier, based on what is often mentioned in literature. The required temperature and pressure have not been produced in order to create a plasma. Next to this, other factors also play a role. Within the framework of R. Ortt et al. (2013) factors 1, 2, 4, 5, 10 and 12 can also be appointed as possible barrier creators. The *Knowledge technology* factor that influences the core factor *Product*, are considered the highest influencing factors for a possible barrier, and are therefore underlined. All factors that currently create a barrier to large scale diffusion are displayed in **bold**. The *Accidents and events* & *Social-Cultural* factors influence the *Customers* core factor, due to the stigma of nuclear fission power onto nuclear fusion power.

| **Influencing factors** | **Core factors** |
|---|---|
| 7. **Knowledge technology** | 1. **Product** |
| 8. Knowledge application | 2. **Production system** |
| 9. Labour resources | 3. Complementary products |
| 10. **Socio-cultural** | 4. **Suppliers** |
| 11. Macro economic | 5. Customers |
| 12. **Accidents and events** | 6. Institutions |

Table 4.3: Factors from the framework that hold for Tokamak design based nuclear fusion power plants. The description of the factors can be found in Table 4.1. The influencing factors are placed left since they influence the core factors which are placed on the right.

## 4.3 Niche strategies according to J. R. Ortt et al. (2015)

Next to niche applications, niche strategies can often be observed during the market formation of high-tech products. It has been identified that often different subsequent niche strategies can be observed during the market emergence of high-tech products. (J. R. Ortt et al., 2015) The 12 core and influencing factors as described in Table 4.1 can create barriers that can be circumvented or removed using niche strategies. (R. Ortt et al., 2013) (J. R. Ortt et al., 2015)
R. Ortt et al. (2013) has developed a model in which different missing factors from the product's system lead to certain niche strategies. The different niche strategies and their explanation can be found in Table 4.4. Using these definitions, some niche strategies in the cases QKD and nuclear fusion power plants can be observed.

In the model of J. R. Ortt et al. (2015), after the factors for a certain case are identified, the niche strategies that could match with the appointed factors are investigated. The potential strategies are proposed based on a big data set that had been investigated before. Strategies from similar cases are selected. For cases where only one connected core and influencing factor cause the barrier to large scale diffusion, the choice of niche strategy is rather straightforward. The diffusion of these two technologies is however influenced by several core and influencing factors which makes to choice of suiting niche strategies more difficult. Also, no tool has been published which connects the factors and the niche strategies, so the decision maker has to judge. Therefore, for the cases of quantum cryptography and nuclear fusion power plants, literature has been studied to identify niche strategies implemented by companies offering the respective products. Insufficient factors at the moment of implementation of the niche strategy are identified.

For the case of QKD a *Demo and develop niche strategy* can be identified. Even though the distance over which QKD can be used was and is still limited, several experiments have been performed to show the feasibility of the technology. (IDQuantitique, 2019a) In this case, the core factor *Product* and influencing factor *Knowledge technology* were insufficient, and therefore this niche strategy had been chosen. A *Subsidized niche strategy* can also be observed, namely the establishment of the OPENQKD project which has been funded by the European Union. (OPENQKD, 2020) The goal of the project is to rise awareness of the possibilities with QKD and shows its importance. This strategy was implemented to stimulate the development and diffusion of QKD and therefore stimulates multiple factors, from *Knowledge technology* to *Production system* and *Customers*.

In the case of nuclear fusion power plants other niche strategies can be observed. The *Redesign niche strategy* can be identified in the form of the niche application "Fusers", this is another version of the Tokamak reactor in order to produce neutrons. (Sparc, n.d.) (Miley & Sved, 2000) The need for fusers existed and since the *Knowledge of technology* of the nuclear fusion power plants was still insufficient, the "fuser" was brought to the market instead.

Projects such as ITER are established in order to inform the public more about nuclear fusion and its advantages. It can therefore be concluded that the *Educate niche strategy* has been used. (ITER, 2020) Before such projects, the *Socio-cultural, Accidents and events* and *Customers* factors were not satisfied.

It can be noted that the chosen niche strategies did not work (yet) to remove the barriers, since the factors causing the barriers are still present as has been identified in Section 4.2.3.

| **Factors** | **Description** |
|---|---|
| 1. Demo and develop niche strategy | A strategy to demonstrate the product in public in a controlled way so that the limited quality or performance is not a problem. An important part of the strategy is experimenting with the product to develop it further. |
| 2. Redesign niche strategy | A strategy to redesigned a product and position it in a different application to better fit the market situation. The redesign can refer to a simpler version, which can be produced at a lower price. A redesign can also be created for an application in which it better conforms to the market situation. |
| 3 Stand-alone niche strategy | A strategy to use the product in stand-alone mode, or as a dedicated system combining necessary complementary products and services. For example, a local network if the infrastructure is not available on a wider scale. |
| 4. Hybridization or adopter niche strategy | A strategy to use the product in combination with an existing product, allowing the use of existing complementary products and services. For example, providing an adaptor to make the product compatible with existing products. |
| 5. High-end niche | A strategy to make a small number of products to order, for a high-end strategy segment, also referred to as 'skimming'. For example, offering hand-made products at a high price in advance of a cheaper, mass-produced version. |
| 6. Educate niche strategy | A strategy to transfer the necessary knowledge about the technology to suppliers or customers. |
| 7. Lead user niche | A strategy aimed at innovators or lead users, whereby the product can be co-strategy developed. Firms can learn about suitable designs, as these highly involved and expert users experiment with the product and develop it further. |
| 8. Explore multiple markets niche strategy | A strategy to try out multiple market applications and by trial and error find successful applications. When the first applications' are visible, this may stimulate use in new applications. |

| Factors | Description |
|---|---|
| 9. Subsidized niche strategy | A strategy to subsidize the product development with public funds. This is possible if society considers a particular segment of customers' use of the product relevant or important. |
| 10. Geographic niche strategy | A strategy in which the choice of market is based on local or regional characteristics, for example, when a product launch is moved to another geographic area where resources, suppliers, or customers are available. |

Table 4.4: Niche strategies proposed by J. R. Ortt et al. (2015)

## 4.4 Comparison

From Tables 4.2 and 4.3 it can be extracted that for both cases different factors apply. For QKD the factors that could potentially cause a barrier are mainly related to suppliers and integration with existing communication networks. These two factors are however influenced by the knowledge of the technology. The factors that hold for nuclear fusion are mainly related to the knowledge about the technology that is insufficient to introduce a product to the market. The nuclear fusion technology does have to be connected to the existing electricity network, which is something that has to be taken into account during constructions. The knowledge about the technology for QKD is not optimal either, since QKD over long distances is still underdeveloped. Especially for the case of QKD, not that many and diverse sources could be found for several factors. This could result in a less valid explanation of that factor.
For both of the technologies, the core factor *Product* and influencing factor *Knowledge technology* are considered to be the most important. In the case of nuclear fusion, these factors have caused the impossibility to introduce a product to the market. For QKD the limited knowledge of technology decreases the speed of diffusion.

Next to the different factors that miss for the two cases, the identified niche strategies differ as well. In the case of QKD, the *Demo and develop niche strategy* has been identified. Even with a limited technology demonstrations have been done to show that the principle works. The *Subsidized niche strategy* can be identified as the OPENQKD project. For the case of nuclear fusion the *Redesign niche strategy* and *Educate niche strategy* have been identified. Different niche strategies correspond to different barriers. Often subsequent niche strategies are adopted before large scale diffusion takes place. So for both of the cases, other niche strategies could still be implemented to circumvent other barriers. (J. R. Ortt et al., 2015) It has to be noted again, that also this theory of J. R. Ortt et al. (2015) is intended to apply to the adaptation phase, in which nuclear fusion power is not.

During the investigation into the different factors that may or may not apply to the cases of QKD and nuclear fusion power plants, other factors that are not described in the barrier framework were encountered. As for example already mentioned in Chapter 2, information on research into nuclear fusion was kept as a secret for a long time because the government was afraid that it would be misused in the form of a hydrogen bomb. (Breeze, 2014) For the case of QKD, potential misuse of the technology can also be seen in the form of inequality of possession of the technology and the impossibility of eavesdropping criminals. (ECP, 2019) This potential misuse of a technology can not be categorized into one of the factors of the current framework. This is also the case for the following factors that have been encountered during the literature research:

- The funding of QKD projects has mostly been privately funded in the past. In 2020 a publicly European project has been established. (OPENQKD, 2020) For the case of quantum cryptography more publicly funded projects are carried out. The type of funding of a project has an influence on the diffusion of a technology. (Sobol & Newell, 2003)

- A societal debate with the aim to explain quantum technologies can help all stakeholders to understand the technology better and increase popularity. (Vermaas, 2017)
- Only several companies offering or working on the QKD technology can be observed, as can be found in Section 2.4. Competition is therefore considered low. Substitutes in the form of other post-quantum cryptography methods and other green energy sources is however present.
- Due to a lack of organizational skills, the ITER project has taken much longer than initially planned. (ITER, 2020)
- During the ITER project, it took a long time to get a license and start with the construction of the reactor. (ITER, 2020)
- Initially, the expectations by the public of nuclear fusion power were very high. These expectations are however decreasing quickly. (Smith, 2005)

All of these encountered factors will be investigated in Chapter 5 to identify their possible influence on the diffusion of the high-tech product.

# 5 Part III: Beyond the framework

During the literature review into the two high-tech products, eye-catching events or characteristics have popped up which could not be explained by the diffusion theory of R. Ortt et al. (2013). Some difficulties have been encountered while using the framework for identifying the place in the life cycle pattern for the cases. First, there is not place for split-offs in the pattern, the description of niche applications is unclear and niche curves seem to stop abruptly. Some of the reasons why the two technologies currently have not reached large scale diffusion could not be explained by the factors proposed by R. Ortt et al. (2013). Therefore, next to the factors from the framework of R. Ortt et al. (2013) which have been studied in Chapter 4, other factors that could create a long innovation or adaptation phase have been explored. These encountered factors are listed in Section 4.4, and further investigated in this chapter. This has been done using the data of the cases QKD and Tokamak nuclear fusion power plants. It has also been noted that the framework is called a barrier framework, while not all factors cause a barrier when not in place. Some factors are stimulating or can even be both. The encountered issues and remarks have been described in Section 5.1 and Section 5.2 for the life cycle pattern and barrier framework respectively.

## 5.1 Critical view on existing framework: the life cycle pattern

### 5.1.1 Gartner's hype cycle

In the case of nuclear fusion power plants, it has been observed that the expectations of the public-at-large were very high after invention. The question rises whether these expectations have had any influence on the development of the technology. Gartner's hype cycle is another way of representing the adoption and maturity of technologies and their applications. When time is displayed versus expectations of customers, different phases can be identified. The hype cycle often starts with an *innovation trigger*; the first discovery of a new concept, often no commercial viability can be seen. The expectation of customers goes up. After that phase, often a *peak of inflated expectations* can be seen. Only a few companies take action and many companies fail. The next phase is often the *trough of disillusionment*, experiments and applications fail and only a few companies succeed to satisfy early adopters' needs. The *slope of enlightenment* follows, in which companies succeed to make more generations of a product, and more companies take a chance in the market. Finally, the *plateau of productivity* has been reached. The technology starts to become mature and widely used. (Gartner, n.d.)

As stated by Gartner (n.d.), the hype cycle can be used to distinguish between these hypes and genuine drivers of commercialisation of a product. It has to be investigated for the two cases if the factors appointed in Section 4 are separate from the hype cycle.

For the case of nuclear fusion power plants, it can be stated that it could be in the *peak of inflated expectations* phase. In the past decades some success stories of the generation of energy out of fusion have been published, but no real product has been developed yet. Different projects fail and/or lead to enormous delays. If this were true, the expectations of the product "nuclear fusion power plants" would be low which could result in less research and investments. (Rosenberg, 1982)

Since QKD is already commercially available and the market is expending, it could be stated that the product is in the *slope of enlightenment* phase. (IDQuantitique, 2019a) Companies are entering the market and building prototypes. (Toshiba Corporation, 2019) The position of the two technologies in Gartner's hype cycle can be found in Figure 5.1.

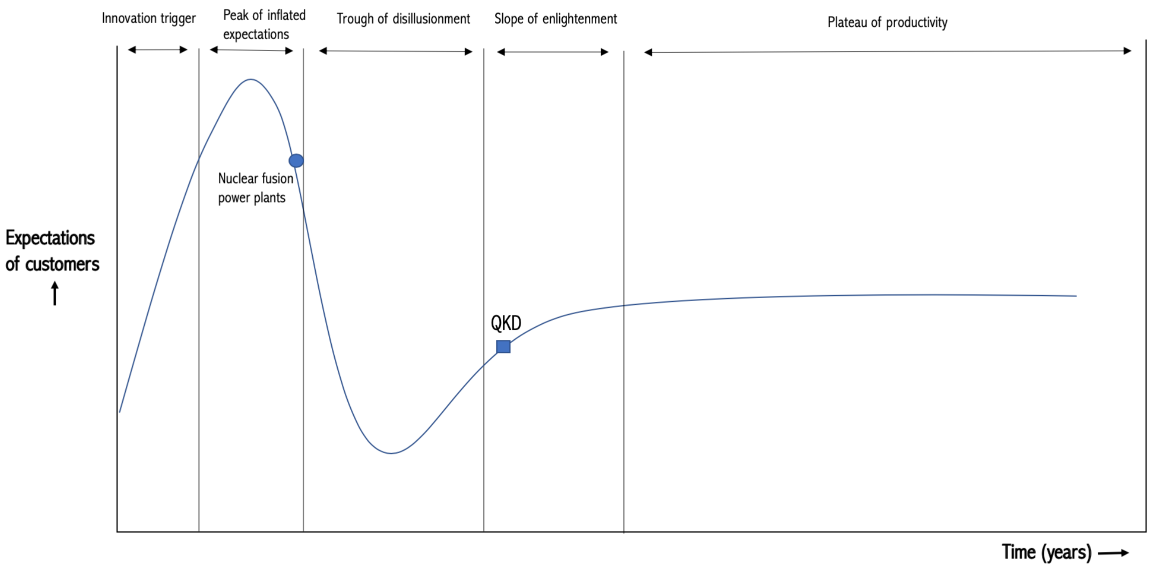


Figure 5.1: Gartner's hype cycle including the position of the cases QKD and nuclear fusion.

This Gartner's hype cycle has not been taken into account in the framework of R. Ortt et al. (2013), which is however a method explaining a possible barrier to large scale diffusion of a technology. To integrate the Gartner hype cycle model into the barrier framework, some suggestions can be made:

1. An influencing factor *Managing expectations* could be added to the framework. If expectations are well managed, more customers will be interested in the product. And budget for research could possibly be more easily allocated.
2. Gartner's hype cycle could be integrated in the life cycle pattern by adding an axis expectations over time next to diffusion over time.

It can be concluded that in Gartner's hype cycle the high-tech product goes through all phases, just as it is assumed by the diffusion theory of R. Ortt et al. (2013). It has to be noted that Gartner's hype cycle is subjected to a lot of criticism. Its validity is questioned as well as its scientificity. (Steinert & Leifer, 2010) For this reason, the hype cycle will not be integrated in the life cycle pattern.

Expectations of customers is however an interesting aspect that could be considered as a factor for the barrier framework and will be discussed later on.

### 5.1.2 Innovations, niche applications & split-offs

For some cases it might be hard to determine whether an adjusted form of a high-tech product, is an innovated (adjusted) product or whether that is a niche application and therefore a "different" product. As mentioned before, innovations can lead to the emerge of new niche markets. (Norman & Verganti, 2014) But this does not have to imply that it is also a niche application.

Dalgic (2006) defines niche as a small market which includes one or more individuals with very similar needs and/or characteristics. Niche marketing is often considered similar to a part of segmentation. Segmentation is however looking at a market and dividing it into groups, while niche marketing is looking at one group and after that expend to other groups. One of the marketing activities of most companies is selecting niche customers. After that, for each product group different niches are created to serve different customers groups (niche customers). (Dalgic, 2006) A company can therefore choose to offer, next to their mainstream product, a customized niche product and therefore serving an additional niche market. But a company can also choose a customer segment, create a product for this group, and strive or not strive for mass market later on.

Often high-tech products are used in niche markets before it becomes a mass product. (R. Ortt, 2012) Now in the pattern it seems like the niche applications stop, while often the market just expands and customers are added instead of replaced. This holds however, when the old product and new product are considered to still be one and the same product.

R. Ortt et al. (2013) have defined the so called *early* niche applications and *mature* niche applications, which emerge in the adaptation and stabilization phase respectively. For the case of nuclear fusion, a niche application or split-off in the form of neutron producing fusers can be identified in the innovation phase already. It is hard to determine if this split-off can be considered a niche application.

For the case of quantum cryptography satellite based quantum cryptography is a variant to the traditional photon based QKD. It seems like this slightly different technology has the same application and thus customers. It could be considered a niche technology or innovation on the classical QKD.

Both university as corporate spin-offs happen often and is therefore something to consider to add to the diffusion pattern. (Clarysse, Wright, & Van de Velde, 2011) According to Clarysse et al. (2011) a corporate spin-off is a company that develops and offers a product that is based on the technology or skills of the "parent firm". The technological principle on which the main and split-off product are based, will then possibly "diffuse" in another form. It does not necessarily have to imply that if a technology splits off, a new spin-off company is established. This could also happen within a company itself. From now on, we will just study the split-off technologies of the main product that is investigated.

Split-offs could be considered as totally new product within the same discipline as the main product. It can therefore be discussed if split-offs should be shown in the diffusion pattern of the main product, or if they should have their own diffusion pattern.

All together, it remains difficult to make a clear distinction between split-offs, niche application and innovated product. From now on split-offs are considered to be products that are partly based on the same technology but have a total new function and different customer group. Niche applications can be a variation in product to serve an additional group of customers. Innovations are considered a change in product that or serves the same group of customers with often a higher satisfaction or therefore attracts more customers and thus opening up an additional niche market.

### 5.1.3 Start of stabilization phase

In the articles of R. Ortt et al. (2013) and J. R. Ortt et al. (2015), the stabilization phase starts at a low number of cumulative adaptions compared to the total number of adoptions that will be reached eventually. It can be observed, in Figure 3.1, that the number of adoptions is higher for the niche applications at the point at which the stabilization phase starts than for the eventually main product. When a product has gone through all phases, it can be concluded afterwards when the stabilization phase started. When still in the adaptation phase, it is hard to determine whether the product in its current state will reach the mass market or whether it will become another niche application. Since the framework is for products in the adaptation phase, it is always hard to predict when the stabilization phase will start. But it seems straightforward that this is at a point where the cumulative percentage of adoption is at least higher than for the preceding niche applications.

The diffusion theory of R. Ortt et al. (2013) does however not only consist of the life cycle pattern, but also of the barrier framework. It can therefore be concluded that when all core factors are in place, the large scale diffusion can start. The connection between the life cycle pattern and the barrier framework makes the life cycle pattern more predictable. It can therefore be argued that in an ideal situation, the stabilization phase starts at the point when all core factors are in place. The start of the stabilization phase will then be case specific.

## 5.2 Critical view on existing framework: the barriers

### 5.2.1 Distinction stimulating and suppressing factors

Most of the factors of the framework of R. Ortt et al. (2013) are now formulated in a way that if the factor is not satisfied, large scale diffusion can be blocked. This holds for factors 1, 2, 3, 4, 5, 7, 8 and 9 as described in Table 4.1. Factor 6, *Institutional aspects* can either be stimulating (subsidy per unit of product) or suppressing (law that forbids the product) if present. This factor can therefore have both a positive and negative influence. Factors 10, 11 and 12 are formulated such that if these factors are present, they will have a negative impact on the diffusion of a high-tech product.

It would seem like a straightforward thing to say that the factors could be all formulated in a way such that they are in the form of "If not satisfied, large scale diffusion is blocked". It is however not always true that if a factor has a negative influence when it is not in place, that it has a positive influence when it is satisfied.

The correlation between two variables can be positive or negative. (Sekaran, 2016) The correlation between a factor (variable 1) and large scale diffusion (variable 2) can thus be positive or negative. Positive correlation means that both variables change in the same direction, e.g. variable 1 increases so does variable 2 or variable 1 decreases so does variable 2. Negative correlation means that variable 1 increases and therefore variable 2 decreases, or the other way around. (Sekaran, 2016) We take the factor *Knowledge of application* as an example to explain the correlation. Research has shown that when knowledge of application of a high-tech product is lacking, large scale diffusion is hindered. So when a positive correlation can be identified, the less knowledge of application of a product would imply the less diffusion of this product. This does not however have to imply that when knowledge about the application is in place, that more diffusion can be observed if this has not been researched.

Another reason why you cannot always assume that factors have both a positive and negative influence when they are and are not satisfied, can be explained by the KANO model. The KANO model is about quality attributes of a product and customer value, but the mechanism will be explained and applied to the factor model. The KANO model distinguishes between 5 types of quality attributes: Must be, One-dimensional, Attractive, Indifference and Reverse. Attractive attributes have the highest influence on satisfaction, when met high satisfaction can be observed but when not met no dissatisfaction can be observed. One-dimensional attributes are attributes for which satisfaction increases linearly. Must-be attributes have to be present, if not the customer will be very dissatisfied, but if met, satisfaction will not increase. Indifferent attributes do not cause either satisfaction or dissatisfaction and reverse attributes cause dissatisfaction if not met. (Violante & Vezzetti, 2017)
A similar distinction between the factors for the model can be made, which also explains why not all factors work both ways (both positive and negative influence). As an example,

the understanding of a new high-tech product has to be clear, but this does not imply that the more an application is known, the faster the diffusion is. This could be considered a *Must-be factor.* The customers factor could be considered a *One-dimensional factor,* the more customers are identified, the faster the diffusion goes. *Reverse factors* are for example Accidents and events & Macro-economic aspects, the more there are the slower the diffusion will probably go. Whether the factors can really be divided into these five groups, would have to be investigated. In Table 5.1 an overview of the different attributes and an example factor are displayed.

It has to be noted again that the traditional KANO model is constructed for the distinction between features of one product and their influence on customer satisfaction. Violante and Vezzetti (2017) In the case of the framework, the KANO model is used for the distinction between factors of a socio-technical system and their influence on the diffusion of a high-tech product.

In the current barrier framework it is stated that the core factors have a direct influence on diffusion, while the influencing factors have an indirect influence. R. Ortt et al. (2013) state that all six core factors have to be in place to enable large scale diffusion of a high-tech product. It can therefore be concluded that the core factors are currently considered *Must-be factors,* if not present no diffusion will take place but when in place, no extra diffusion will take place. It can however be stated that for diffusion in general, the core factors could be considered indeed must-be. They all have to be in place in order to enable diffusion of a high-tech product. After diffusion has taken place and if large scale diffusion is aimed for, the core factors could change into *One-dimensional factors.* For example, the more customers there are, the larger the change for large scale diffusion becomes. This would imply that the function of the factor could change over time and might be depended on the position in the life cycle pattern.

| Type of attribute | Description of type of attribute | Example factor |
|---|---|---|
| Must-be | Must-be features are features that must be present, if not it results in dissatisfaction. If present, no extra satisfaction can be observed. | Network of suppliers *If no network of suppliers is available, no diffusion nor production can take place.* |
| One-dimensional | These quality attributes are linearly related to satisfaction. The more/better the feature, the higher the satisfaction. | Customers *The more customers, the larger the diffusion of a product.* |
| Attractive | When present, high satisfaction can be observed. While is not present, no dissatisfaction can be noticed. | Institutional aspects *If stimulating laws (for example in the form of a subsidy) satisfaction can be observed. But when no subsidy is given, people might not considered it as a possibility anyway.* |
| Indifference | Features that do not bring dissatisfaction or dissatisfaction. | - *These factors are not integrated in the barrier framework, since these factors are considered irrelevant for the framework.* |
| Reverse | If present, dissatisfaction is the result. If not present, satisfaction is the result. | Accidents & Events *If accidents related to the product have happened, dissatisfaction can be observed. It is considered that no accidents is normal.* |

Table 5.1: Different types of attributes with examples for products as well for factors. (Violante & Vezzetti, 2017). Looking at the adaptation phase.

### 5.2.2 Subsidies

The World Trade Organization (WTO) defines three types of programs that can be considered a subsidy: (World Nuclear, n.d.)

- Budgetary outlays (financial transfers) of the government or by the government mandated transfers made by private companies.
- Programs that provide services or goods below market price or for free.
- Regulatory policies or preferential rules that lead to transfers from one group to another, resulting in a benefit to the recipient.

Moreover, other ways of subsidizing can be identified for the energy sector: (World Nuclear, n.d.)

- Governmental research (R&D).
- Direct subsidy per unit (for example per kWh).
- Indirect subsidies, external costs that are paid by the government.

Using these definitions, it can be stated that the factor *Institutional aspects* could be more specifically defined. Especially the subsidies for R&D can increase the speed of the development of a product. If the product is introduced to the market, the sales could increase if there is a subsidy per unit, since then the product would be cheaper to consumers. The price/quality of the product might therefore increase. So looking at the innovation phase, governmental subsidies concerning R&D and the financial programs for budget or goods are an important factor to decrease the length of this phase. During the adaptation phase the subsidies per unit can make a big difference, as well as extra research to improve a product.

### 5.2.3 Categorisation of factors into not influencing, medium influencing and strongly influencing

In Section 4, the severeness of influence have been decided upon using logical reasoning of the decision maker. This is however subjective and therefore could be considered to have low scientific value. Suggestions will have to be made on how to use the framework and categorise the factors. A suggested method will be given in Section 6.

## 5.3 Validity of sources

In Chapter 4, the factors from the framework of R. Ortt et al. (2013) have been explored. For each of the factors, different sources have been used to check the completeness of the factors. The validity, quantity and origin of the sources did however differ a lot for each factor investigation. This also influences the validity of the factors, which will be further discussed here.

Validity in the case of the framework can be divided into two directions: validity of the factors for a specific case or the validity of a factor in the framework in general. In this section, the validity of factors for a specific case is investigated.

### 5.3.1 Indicators for validity of factors

The validity of the sources differed a lot for each factor. The current "judge's opinion" method therefore seems insufficient. Indicators for the quantity and validity of sources have to be thought of in order to determine the validity of the factors. Different aspects for a valid source, and therefore valid factors, can be considered. There are two directions for sources in general: peer reviewed literature and so called "grey literature". Peer reviewed literature is literature that has been peer reviewed by experts in that field before being published, while grey literature is often found in news articles, blogs or non-rated journals. (Beech, 2017) There are however pros and cons for both types of sources. For the peer reviewed articles, quality is assured but it can be subjected to "group think" which results in less new and out of the box information. Grey literature is often more up to date and out of the box, which could come in handy if you are investigating a current and rapidly changing subject. (Beech, 2017)

To check the validity of the factors as described in Section 4, the sources for each factor will be examined as can be seen in Table 5.2 for the case of QKD and in Table 5.3 for the case of nuclear fusion. It has been examined if peer reviewed literature or grey literature has been used and if more sources can be found in which the same is stated. For this literature study, a lot of information has been taken from governmental websites or projects funded by the government. The sources cited for this research are often not the only sources that provide similar information, this has been taken into account in the table. For some of the factors, literature has been used to speculate but no literature corresponding to the exact factor could be found. This option has also been mentioned in the table, it is namely hard to decide if a possible factor does not exist if no literature about it can be found.

| Factor | Peer reviewed literature | Governmen publica-tions | Grey literature | Relevant literature | Valid/Not certainly valid |
|---|---|---|---|---|---|
| 1. New high-tech product | Yes | No | Yes | Yes | V |
| 2. Production system | No | No | Yes | No | NCV |
| 3. Complementary products and services | Yes | Yes | Yes | Yes | V |
| 4. Suppliers (network of organizations) | Yes | No | Yes | Yes | V |
| 5. Customers | No | No | Yes | Yes | NCV |
| 6. Institutional aspects (laws, rules, standards) | No | Yes | Yes | Yes | V |
| 7. Knowledge of technology | Yes | Yes | Yes | Yes | V |
| 8. Natural resources and labour | No | Yes | No | No | NCV |
| 9. Knowledge of application | Yes | Yes | Yes | Yes | V |
| 10. Socio-cultural aspects | No | Yes | Yes | No | NCV |
| 11. Macro economic aspects | No | No | Yes | No | NCV |
| 12. Accidents and events | No | No | No | No | NCV |

Table 5.2: Examination of validity of factors as described in Section 4 for QKD.

| Factor | Peer reviewed literature | Government publica-tions | Grey literature | Relevant literature | Valid/Not certainly valid |
|---|---|---|---|---|---|
| 1. New high-tech product | Yes | Yes | Yes | Yes | V |
| 2. Production system | Yes | No | Yes | No | NCV |
| 3. Complementary products and services | No | Yes | No | No | NCV |
| 4. Suppliers (network of organizations) | Yes | No | Yes | No | NCV |
| 5. Customers | No | No | Yes | Yes | NCV |
| 6. Institutional aspects (laws, rules, standards) | No | Yes | Yes | Yes | V |
| 7. Knowledge of technology | Yes | Yes | Yes | Yes | V |
| 8. Natural resources and labour | Yes | Yes | Yes | Yes | V |
| 9. Knowledge of application | Yes | Yes | Yes | Yes | V |
| 10. Socio-cultural aspects | Yes | Yes | Yes | Yes | V |
| 11. Macro economic aspects | No | No | Yes | No | NCV |
| 12. Accidents and events | Yes | Yes | Yes | Yes | V |

Table 5.3: Examination of validity of factors as described in Section 4 for nuclear fusion.

A similar table could be a complement to the existing barrier framework in order to always check the validity of a source. Different criteria combinations can lead to a valid source. A multi criteria decision making (MCDM) tool could be used to decide if a factor is valid or not. The origin of the factor is important for this but so is the availability of literature corresponding to the factor. In general the following conclusions can be made:

- If information comes from a peer reviewed article/journal and contains relevant information for the factor, the factor can be considered **valid**.
- If information comes from a peer reviewed article/journal and contains relevant information for the factor, while next to that similar information can be found in grey literature or in governmental publications, the factor can be considered **valid**.

- If information comes from a governmental source and contains relevant information the factor can be considered **valid**.
- If no relevant information for investigating a factor can be found, the factor is considered **not certainly valid**.
- If information can only be found in grey literature but does is relevant for a factor, the factor is considered **not certainly valid**.

With these guidelines, the last column of the Tables 5.2 and 5.3 has been filled in. V stands for valid and NCV stands for not certainly valid. It can be observed that for the case of QKD several factors are not certainly valid, namely factor 2, 5, 8, 10, 11 and 12. This is important to take into account in Table 4.2, since most of these not certainly valid factors are considered unimportant as barrier to large scale diffusion. For the case of nuclear fusion it can be observed that factors 2, 3, 4, 5 and 11 are considered not certainly valid. Yet again these are the factors that were considered not highly contributing to the barrier to large scale diffusion.

These guidelines can be used to decide on the validity of factors. Especially for the cases in which no relevant information can be found, it is hard to decide if a factor really is not present or whether just no publications can found or no research has been conducted. This can be a good complement to the framework to give more information on the validity of the sources and thus factors.

In Tables 5.2 and 5.3 the validity of factors for each case are examined. This data could also be investigated for the validity of the factors in general. If certain factors are never certainly valid or relevant, their validity in the framework could be questioned. For example, factors 2, 5 and 11 are not certainly valid for both cases. It could therefore be investigated if this is a coincidence or if this applies to more cases.

## 5.4 ADDITION TO THE FRAMEWORK

Next to the factors described in the model of R. Ortt et al. (2013), other factors could exist that can cause a barrier to large scale diffusion. In this section different possible factors are appointed in literature and often extracted from the literature research into QKD and Tokamak nuclear fusion power plants.

### 5.4.1 TYPE OF FUNDING

For both of the cases it can be concluded that the funding of research differs, it can either be publicly funded or privately funded. The funding of existing QKD and fusion projects will be discussed in this section. It has to be mentioned that research projects often take place in the *innovation phase* and not in the adaptation phase. It has also be taken into account that the framework has initially been designed for *commercial high-tech products*, which was not straightforward for the case of nuclear fusion. The first nuclear fusion projects were publicly funded and not aimed at commercialisation straight away. (EUROfusion, 2020) For quantum cryptography the commercialisation goal was there since the beginning, because it was invented by IBM researchers Bennett & Brassard. (Bennett Ch & Brassard, 1984)

*Funding QC*
For the case of quantum cryptography, several companies can be found that offer QKD systems commercially. The market leading company ID Quantique, protects data from over 60 governments and companies with their QKD solutions. (IDQuantitique, 2019a) ID Quantique was originally a spin-off from the University of Geneva focusing on research. When they separated from the University, they started working on commercial applications. (IDQuantitique, 2019a) On the 20th of October 2019, EU funds announced to be funding a project named "OPENQKD", which is a collaborative project between 38 companies and academia worldwide. The main goal of the project is to provide secure ICT for all European citizen. (IDQ Press Release, 2020) (OPENQKD, 2020)

*R&D funding fusion energy*
Both public and private nuclear fusion power plants projects are currently being carried out or have been carried out in the past. There seems to be a difference in strategies and goals for each type of funding. Public projects main goal is to reach feasibility of the technique, before focusing on commercialisation . While private funded projects aim for commercialisation and profits straight away. (EUROfusion, 2020) The optimal way of funding R&D for fusion projects has been researched. In general, R&D funding in the energy sector has become less attractive. The liberalisation of the R&D in the energy sector has let to spill-over effects that makes it less attractive to invest. Bednyagin and Gnansounou (2011) therefore state that it is interesting to further explore public funding for nuclear fusion R&D.

The commercialisation of university research outcomes has its advantages and disadvantages. For both of the cases, QKD and Tokamak nuclear fusion, spin-offs from universities have been established to commercialize inventions. Most of the problems concerning this transfer from research to commercialisation are due to the very different cultures in the two organizations. (Sobol & Newell, 2003) Literature has been published about the research on how to ease this knowledge transfer. Licenses and royalties also play a role in the knowledge transfer. (Siegel, Waldman, Atwater, & Link, 2004)

The suggested factor *Type of funding of research projects* is described in Table 5.4 and could be considered a factor which could be *suppressing*. Suppressing when a project has been carried out by a university and knowledge therefore is more difficult to transfer to a company to transfer it in a commercial high-tech product. (Sobol & Newell, 2003) The product could therefore be harder to commercialize or customers are harder to attract. If it is also stimulating when the research project has been executed within a commercial company has to be researched. This factor would be considered an influencing factor, it could for example influence the *New high-tech product* since the knowledge is hard to transfer.

| **Factor** | **Description** |
| --- | --- |
| Type of funding of research projects | A research or project can be publicly or privately funded. Both of the types of funding have its (dis)advantages. The initial funding for the first part of the project can also have a big influence. If for example a project is a spin-off from a university (therefore often public funding), it can be hard to transfer the knowledge to a commercial company. |

Table 5.4: Description of factor *Type of funding of research projects*

### 5.4.2 Inform lay people

For both of the cases literature can be found on the lack of knowledge about the topic amongst lay people. As has been discussed already in this paper, the stigma of nuclear fusion power due to nuclear fission power has been investigated. (Horlick-Jones et al., 2012) A research has been conducted by Horlick-Jones et al. (2012) in which lay people have been asked for their opinion on nuclear fusion power. Not many of the participants knew about the existence of nuclear fusion and soon the discussion was about nuclear fission accidents. It can be seen that after discussion and providing more information on the topic, people changed their attitude towards nuclear fusion. (Horlick-Jones et al., 2012)

### 5.4.3 Starting a socio cultural debate in order to get more people involved

The possible (dis)advantages of a high-tech product are not always straightforward and known by the public at large, and could lead us to another factor. Namely, if a high-tech product is introduced to the market but a social cultural debate has not taken place yet, disadvantages can possibly not be found yet. As discussed in Section 2.3, it is important to incorporate responsible innovations and values right at the beginning of a research. Debates have to take place in which lay people can be informed. A factor that could create a barrier to large scale diffusion could therefore be *Presence of socio-cultural debates*. This factor would be considered an influencing factor, since it could affect a core factor such as *Customers* or *Socio-cultural aspects* and then indirectly influence the large scale diffusion of a high-tech product.

On the National Dutch Quantum Agenda a debate concerning quantum technologies is planned, but has not happened yet. (Quantum Delta Nederland, 2019) In the case of nuclear fusion it can be seen that attention has been paid to inclusion of lay people in the later years of nuclear fusion research as well. For example, the program Socio Economic Research of Fusion (SERF) has been established to inform the fusion community on economic and social viability. SERF has investigated lay perception on nuclear fusion. Research has shown that lay people can easily participate in technical debates and include social matters in the debate. (López et al., 2008)

Discussions on whether lay people should be included in debates on technology can be found in literature. Sometimes discussions cannot reach consensus because different opponents all had a different understanding of a technology. That is why sometimes lay people are left out of the discussion. While others state that for example citizens have non-technical considerations that should be taken into account. (Kleinman, 2000)

In Table 5.5, a description of the suggested factor *Presence of social-cultural debates* can be found. This factor can be considered both a *stimulating* factor as well as a *suppressing*. When socio-cultural debates are held, the public at large can be involved and opinions can change both in a positive as well as a negative direction. This factor would be considered an influencing factor, it could for example increase the number of *Customers* by increasing or decreasing the willingness of potential customers.

The *Presence of socio-cultural debates* factor could also be integrated in the *Socio-cultural aspects*, since they are closely related.

| **Factor** | **Description** |
|---|---|
| Presence of socio-cultural debates | During socio-cultural debates lay people can be informed or express their opinion if they have already been informed on before hand. In this way values of the public at large can be taken into account. |

Table 5.5: Description of factor *Presence of socio-cultural debates*

### 5.4.4 Potential misuse of technology

Currently the factor *Accidents or events* from the framework of R. Ortt et al. (2013), concerns accidents or events that have happened during the production or use of a product. For the case of QKD it can however been observed that there is a potential misuse of the technology, which has not happened yet. Namely if the QKD technology comes in the hands of criminals. (ECP, 2019) Next to ending up in the hands of criminals, the technology could possibly cause power inequality between countries. (Bloomberg, 2017) The same phenomenon can be identified for the case of nuclear fusion. Research into nuclear fusion has been kept a secret for a long time because the government was afraid of the possible misuse in the form of nuclear weapons (hydrogen bomb). This has however never happened. (Breeze, 2014) This withholding of information could have let to a slower diffusion of information and development of the high-tech product. The existence of these possible misuses of technologies/high-tech products could cause a barrier to large scale diffusion. This factor could be included in the factor *Socio-cultural aspects*, but the difference is that these potential misuse is not always straight forward and known by the public at large. This new factor could be defined as *Potential misuse of technology*. This factor would be considered an influencing factor, since it could for example influence the core factor *Institutional aspect* if the potential misuse of technology would lead to laws forbidding the technology.

In Table 5.6, the description of the factor can be found. This factor is considered a suppressing factor since the potential misuse of a technology can lead to less diffusion or even prohibition. The factor can also be considered an influencing factor that could lead to for example new laws and rules concerning the product (*Institutional aspects*) or less *Customers*.

| **Factor** | **Description** |
|---|---|
| Potential misuse of technology | A technology or high-tech product must be safe in terms of other applications. If a technology could possibly have an other application that leads to misuse or criminality, it can possibly not reach the mass market. |

Table 5.6: Description of factor *Potential misuse of technology*

### 5.4.5 Competition leads to innovation and product improvement

Literature can be found on the role of competition in the diffusion of a technology. Technological innovations are often unfamiliar to customers. These innovations are often expensive and switching costs are involved. (Robertson & Gatignon, 1986) Robertson and Gatignon (1986) state that more suppliers of a technology leads to a faster diffusion and higher market penetration of a technology. In the framework of R. Ortt et al. (2013), the factor of suppliers has been described as a network of organisation and as a quantity in relation to competitiveness. If there is high competitiveness among suppliers, the prices are more likely to be lowered and resources are more allocated resulting in quicker and more diffusion. (Robertson & Gatignon, 1986)

Robertson and Gatignon (1986) however also state that the maximum diffusion will take place at an intermediate level of competitive intensity. Lots of competition in early phases can eliminate certain products or companies. Competition happens on different levels and different moments in time, so can be both stimulating and suppressing.

For both of the cases it can be concluded that the competition is not that high: for QKD only three companies offer commercial QKD systems and in the case of nuclear fusion systems only several projects are being executed at the moment.

In Table 5.7, a description of the factor *Competition* can be found. The factor is considered to be a *stimulating* factor: the more competition there is on the market, the faster the diffusion. (Robertson & Gatignon, 1986) The factor could be considered an influencing factor, it could affect all of the core factors. For example, the more competition there is, the more suppliers will appear.

| **Factor** | **Description** |
|---|---|
| Competition | When competition is present in a market and therefore multiple suppliers, a technology tends to diffuse faster. Since the prices are tend to be lower and resources more allocated. So the higher the competition, the faster the diffusion of a high-tech product. There is however an intermediate level of competition at which the maximum diffusion takes place. |

Table 5.7: Description of factor *Competition*

#### 5.4.6 Substitutes

As explained before, in case of both of the technologies there are other candidates as well that could solve the respective problems to which the technologies are a solution. In the case of QKD, post-quantum algorithms are another solution to protect data from possible quantum computer attacks. (Quantum Delta Nederland, 2019) For nuclear fusion, other green energy sources such as solar and wind energy are present as well. (Smith, 2005)
If the technology and products of these others solutions (the substitutes) would become much more advanced and popular, QKD and/or nuclear fusion could become much less attractive and sales could go down. If another technology becomes more popular, it will affect the sales and thus diffusion of the product in several ways. New customers will choose the substitute product, but also current customers might switch to the substitute product.

(Norton & Bass, 1987) Norton and Bass (1987) states that substitutes can also have a positive influence on the diffusion of the initial product. When the substitute emerges, the initial product's sales increase with it, as long as the time between the introduction of the two products is not too long. (Norton & Bass, 1987)

*Substitutes* can therefore have *both* a stimulating as well as a suppressing influence. The factor would be considered influencing. It could for example influence the core factor *Customers*, by targeting new customer groups or disappearance of new customer groups.

Substitutes can however be considered a form of competition as well. Competition is between companies that offer the same product, while substitution is competition between technologies. It can therefore be discusses if these two factors can be integrated into one.

| **Factor** | **Description** |
|---|---|
| Substitutes | Substitutes for a high-tech product can both have a negative or positive influence on the diffusion of the product. Positive when the diffusion of the high-tech product increases along with the increasing diffusion of the substitute. On the other hand negative, when the substitute takes over the customers of the high-tech product. (Norton & Bass, 1987) |

Table 5.8: Description of factor *Substitutes*

#### 5.4.7 Lack of strategy in high-tech companies

The technology adoption life cycle consists of five subsequent groups of consumers: innovators, early adopters, early majority, late majority and laggards. This cycle is used to see the customers reaction to a new high-tech product. For each of these consumer groups, a different strategy and marketing approach is needed. There is this so called "Chasm" that refers to the period with low sales often between the early adopters and early majority phase. In order to avoid this chasm and go straight for the mass market, a suitable strategy has to be in place. (Meade & Rabelo, 2004) A correct and suitable strategy could be a core factor added to the barrier framework. A strategy can be influenced by the *Knowledge of the application* or *Labour resources* factor. This new core factor could be defined as *Strategy of high-tech company*.

In the case of the nuclear fusion project ITER, a lack of strategic view has led to many delays. ITER has encountered many organisational problems and disagreements between the participating countries. (ITER, 2020)

The description of the suggested factor can be found in Table 5.9. This factor is considered a *stimulating* factor: when a suitable strategy is in place, the chasm can be circumvented.

(Meade & Rabelo, 2004) The factor could be considered influencing, the right strategy could target the right customer group and therefore have positive influence on for example the core factor *Customers*.

The goal of the framework is however to appoint a niche strategy for companies. It can therefore be discussed if *Strategy of a high-tech company* is a factor, or if it is already recognized by a company that a strategy lacks the moment they are going to look for a niche strategy. If the framework is used by a researcher that wants to examine a certain industry, the factor could play a role.

| **Factor** | **Description** |
|---|---|
| Strategy of a high-tech company | In order to reach mass market, a clear and suitable strategy has to be in place in a high-tech company. Different consumer groups demand for a different strategy. A suitable strategy can lead to the avoidance of the chasm. |

Table 5.9: Description of factor *Strategy of a high-tech company*

#### 5.4.8 Licensing and patenting

Licensing is used by companies to let other companies work with their technology while at the same time receiving royalties. This phenomena speeds up the diffusion of a technology. (Avagyan, Esteban-Bravo, & Vidal-Sanz, 2014)

Licensing can also slow down the process, if licensing is considered as the permit to start selling or constructing a high-tech product. This was the case for the ITER project, it took about 14 years to get the license for the construction of ITER. (ITER, 2020) Several patents for Tokamak designs exist.

For QKD systems, patents can found as well. (Data, Examiner, & Colin, 2010)

The *Licensing and patenting* factor can both be *stimulating* and *suppressing*. It would be considered an influencing factor that could for example influence the core factor *Institutional aspects*, as a rule.

It could therefore be possible to extend the *Institutional aspect* by explicitly mentioning licensing and patenting in its description.

| Factor | Description |
|---|---|
| Licensing and patenting | Licensing a high-tech product to another company can increase competition and therefore diffusion of the product. If a product is kept at one company, diffusion could be restricted. Getting a license in order to be allowed to produce a high-tech product can however block diffusion, but this mostly stretches the innovation phase instead of the adaptation phase. |

Table 5.10: Description of factor *Licensing and patenting*

#### 5.4.9 Managing expectations

Price and quality expectations of a product may cause a potential buyer to buy now or wait. If technology is supposed to improve quickly and the price is expected to lower, the customers will not buy yet and the diffusion will take place later. (Ireland & Stoneman, 1986)

Expectations of the future of a technology cause a change in behavior of stakeholders. When a large innovation is announced, credit availability and investments increase. Contradictory, high expectations for possible substitutes can lead to a slower diffusion. High expected technological change of the product can slow down diffusion, if potential customer therefore "wait" for the new version. (Rosenberg, 1982)

When nuclear fusion power plants were invented, the expectations were high. It was supposed to be the promise for the future energy supply. Now with the increasing costs of projects that still have not resulted in a commercial product, expectations are only decreasing. (Smith, 2005)

Managing expectations could be integrated in the product factor, since it is a question of price/quality.

| Factor | Description |
|---|---|
| Managing expectations | Expectations of a product by (potential) customers can influence the moment at which they will purchase the product. When expectations for a product or innovation are high, more credit and investment money is available. |

Table 5.11: Description of factor *Managing expectations*

#### 5.4.10 Case specific factor

Each technology and therefore each case is unique. It is therefore hard to determine when and if the barrier framework will ever be complete. For each case different factors that play a role can be appointed, this subset of factors will probably be unique for each case. A suggestion is therefore to add an "open" factor, that can be formulated for each specific case.

The stigma that nuclear fusion energy has, due to nuclear fission energy, could be an example for such a case specific factor. The accidents that have happened during the generation of nuclear fission power, have been very impactful and distinctive. Stigmas around technologies exist often, but in this case a stigma of one technology impacts another. (Flynn, Slovic, & Konreuther, 2001)

The *Case specific factor* could be *both* stimulating or suppressing. The *Case specific factor* could be considered influencing and core, depending on its chosen description.

| **Factor** | **Description** |
|---|---|
| Case specific factor | Every case is unique, therefore unique factors can be observed. This "open" factor gives the opportunity to look further than the framework. |

Table 5.12: Description of factor *Case specific factor*

## 5.5 Connection innovation and adaptation phase

If the barrier framework were to be used to identify barriers in the innovation phase, the framework would be slightly different. First of all, the factors as explained in Table 4.1 can be totally missing instead of "not sufficient to reach large scale diffusion". Or in case of the suppressing factors, blocking instead of contracting. While looking at the adaptation phase, all the factors are at least minimally satisfied. There are for example customers and the knowledge and application of the technology is sufficient to be at least introduced to the market. In the innovation phase it can however be the case that a factor is totally missing e.g. a lack of the factor. As can be found in the case of nuclear fusion, the technology is not well enough understood to be even introduced to the market. It could therefore be suggested that the framework could be used in the innovation phase as well, for pointing out the factors that create a barrier to introduction of a high-tech product to the market. The main difference is then the "presence" of a factor instead of the "sufficiency" of a factor.

In the innovation phase there is a possibility that an invented technology cannot be translated into a high-tech product. That it is not feasible, in this case all the other factors can be in place, but introduction will never take place. This is what some people are afraid of with the case of nuclear fusion power plants too, that the technology will be never be mastered to turn it into a commercial power plant.

It can be seen that some factors that played a big role during the innovation phase, as for example the *Type of funding* factor, still have an influence on the diffusion of a product. If it has been chosen to carry out research within a university or governmental environment, it is hard to transfer knowledge and therefore establishing new companies offering the product. (Sobol & Newell, 2003)

## 5.6 Generalisation of factors

The factors extracted from the literature about the development of QKD systems and nuclear fusion plants could be a one time event or something that can be observed for multiple high-tech products. One of the hallmarks of scientific research is the generalisability of research. Generalisability refers to the possibility of applying your results to other (potential) cases. The more cases it can be applied to, the more valuable a finding or study becomes. (Sekaran, 2016) For this research this would imply that if a factor can be applied to both case studies, it is more generalisable compared to only one. Validity for qualitative research consists of two parts: internal and external validity. Internal validity refers to the correct representation of the data and the external validity refers to the generalisability to other cases. (Sekaran, 2016) High external validity can be reached by a large number of events or include devious (contradictory) cases. In this research only two cases have been investigated, therefore another way of reaching a high external validity has to be explored. Another way to reach a high external validity is to carefully describe the cases used in the research and let the person who wants to transfer knowledge to another case judge. (Sekaran, 2016)

## 5.7 Comparison

This section started off with a critical eye on the life cycle pattern of the existing framework. It was concluded that Gartner's hype cycle, which explains the adoption and maturity of technologies and their application, is not integrated in the existing framework of R. Ortt et al. (2013). For QKD systems it has been concluded that it is currently in the *slope of enlightenment* phase, which is described as the phase in which several generations of a product are produced and slowly more companies enter the market. Nuclear fusion has not reached this phase yet, this technology is still in the *peak of inflated expectations* phase, some success stories have been published that raised expectations, but currently no product is available on the market and several projects fail and lead to delays. These two respective phases align with the conclusion that nuclear fusion power plants are still in the innovation phase, while QKD systems are already in the adaptation phase.

In the case of nuclear fusion, a split-off from the Tokamak reactor can be identified: a commercial fuser. This finding has drawn attention since the option to show this split-off in the pattern is not there yet. For the case of QKD, no split-offs have been found.

As appointed in this chapter, some of the factors might be more valid than others for a particular case depending on the sources that could be found. For the case of quantum cryptography, 6 out of 12 factors were explained by not certainly valid sources. This means that the sources do not come from a peer reviewed journal or governmental publication and/or the required information in order to investigate the factor could not be found. In the case of nuclear fusion, 5 out of 12 factors are labelled not certainly valid. For the case of nuclear fusion, these not certainly valid factors are mostly related to the technology and its production system, suppliers, customers & complementary products and services. This could be the case since commercial nuclear fusion power is not available on the market (yet). However, QKD systems are commercially available and even more factors are not certainly valid, which draws attention. It could also be stated that when certain factors turn out to be "not certainly valid" for many cases, that the validity of the factor itself could be questioned.

It has been observed that the factors have different effects on the diffusion of a high-tech product. Factors can be stimulating, suppressing or both. It is even examined whether the distinction can even be more specific, namely by categorising the factors according to the KANO model.

It is important to mention that the case of quantum cryptography matches better with the framework and its assumptions. Namely, from the assumptions made in Subsection 1.5, QKD meets most of the assumptions. From the beginning on it was intended to be a commercial technology and product, the product is currently in the adaptation phase and the government is considered an external factor. Nuclear fusion power plants on the other hand, are in the innovation phase and the market introducer could still be the "government", for example by the project ITER. (ITER, 2020) The suggested factors that are based on data from the nuclear fusion energy case can therefore be considered to be factors that belong more to the innovation phase than the adaptation phase. Such as the *Strategy of a high-tech company* factor, which can mostly be observed in the case of nuclear fusion. Factors that have been found with the help of data of the cases of quantum cryptography and nuclear fusion can be considered to be relevant for both of the phases of the life cycle pattern.

Some of the criticism and suggested factors are based on data of both of the cases, but some can only be found in the literature of one of the two cases. As for example the factors concerning a *Socio-cultural debate to inform lay people* and *Potential misuse of a technology* can be extracted from both of the cases. While on the other hand, the *Licensing and patenting* factor can mostly be observed in the case of nuclear fusion where it took many years before the license was issued, therefore blocking production and diffusion. The nuclear fusion project ITER is a good example of the factor *Strategy of a high-tech company*, since it has encountered many organisational issues and disagreements regarding the strategy of the execution of the project. This factor does seem in place for the case of QKD.

Since many of the new factors are based on data of both of the cases, the generalisability increases.

# 6 PART IV: ASSESSMENT OF FACTORS & EXPERT OPINIONS

From this research it can be concluded that different factors are involved during the diffusion of different high-tech products. In this chapter, several suggestions are proposed on how to assess factors from the framework. The current method that is used to assess the factors of the framework, as has been used in Section 4.2.3, is on the basis of the decision maker's judgement. In this section propositions for a more objective approach, in the form of calculations and possibly machine learning are given. Experts have been approached to share their opinion on the different propositions and the factor-choice decision itself. Experts have been chosen for their expertise in the field of decision making (often in a technical environment). This chapter gives an overview in the form of a discussion of the different possibilities on how to identify and rank the factors of the framework of R. Ortt et al. (2013), varying from subjective expert opinions to objective calculation approaches.

## 6.1 WEIGHTING THEN RANKING

The first proposition is to first weigh the factors, i.e. decide which factors of the framework play a role in the investigated case. After that, the factors will be ranked from highly influencing to minimally influencing.

***Step 1:***
There will be a difference between factors that play(ed) a role in the diffusion of the product that now have been solved or that were never involved anyways. Another problem, which has been mentioned before, is that if no literature can be found concerning a certain factor this does not directly have to imply that that factor then does not play a role. For example, as a judge it is easier to observe if macro-economic trends have been identified or if accidents have happened than if suppliers are willing to cooperate and check the production system's capacity.

In this approach the factors will be "weighted" according to the decision maker's logical reasoning. If no literature about a factor can be found at all, neither in valid nor grey literature, the factor is considered unimportant for the specific case. The end result of this step would be a selection (group) of factors that play a role during the diffusion of the high-tech product.

***Step 2:***
The decision of which factors are considered the most important and which less important, can be considered a multi criteria decision making problem. A set of alternatives and a set of decision criteria have to be defined, as a first step of the MCDM problem. (Triantaphyllou, 2000) In this case, the alternatives would be the different factors and the set of criteria has to

be thought of and is considered more difficult. We will start of with accurately defining the problem. (Triantaphyllou, 2000)

Problem:
Many factors that can lead to a barrier to large scale diffusion can be thought of in general. However, probably not all factors have an equal influence on the obstruction to large scale diffusion for each specific case. Factors therefore need to be categorised, according to their influence.

Since this research is dealing with a qualitative research and problem rather than quantitative, it is harder to come up with numerical criteria. Often in the case of qualitative data, relative importance is used to compare the alternatives. (Triantaphyllou, 2000) For qualitative data, often a pairwise comparison method is chosen. (Triantaphyllou, 2000) The alternatives are in this case defined as following:

Alternatives:
The alternatives in this case would be the twelve factors defined by R. Ortt et al. (2013) with possibly an addition of factors from this research.

An important aspect to mention is the distinction between core and influencing factors. For the criteria some suggestions, which are displayed here, that have to be considered when deciding on the decision making criteria are written down.

- Valid [1] literature can be found in which the factor has been described as a limiting aspect of a high-tech product.
- Distinction between core factors and influencing factors. The twelve factors in the framework are subdivided into two groups: core and influencing factors. The core factors are factors 1 up to and including factor 6 from Table 4.1 and the influencing factors are factors 7 up to and including factor 12. The core factors directly influence large scale diffusion, while the influencing factors have an indirect influence. The core factors could therefore be considered more influencing, since there are different influencing factors that could affect a core factor.
- Number of hits that appear when a certain factor combined with the technology is searched for in a digital data bank. This could be related to how certain the factor is related to the problem.
- In general certain factors might be more influencing than other factors anyways. If a high-tech product gets forbidden by law, the product has to be taken of the market and thus no further diffusion will happen at all. While socio-cultural aspects could concern certain groups with certain beliefs, that still many other groups will still be interested in the product. We are however looking into the adaptation phase, so from diffusion to large scale diffusion. If a product gets forbidden by law, no diffusion will take place at all.

[1] Validity has been described in Subsection 5.3.1

It has also been observed that the knowledge of technology is insufficient for both technologies which causes big problems. The knowledge of technology factor is hard to circumvent with a niche strategy.

- The easiness of the satisfaction or removal of a factor. If a factor causes a barrier and that factor is very hard to change it might be a more influencing factor than a factor that can be changed easily.
- Can counter opinions be found? Meaning articles in which a publication that has been used to confirm a factor, is contradicted.
- Asking experts for their opinion, this is however very time consuming.

Citation analysis is a method to rank an article based on the journal it is published in and the author's performance. The Impact Factor is used to measure the relative importance between articles based on the journal it is published in. The Hirsch Index compares a certain article's number of citations with the number of citations of another article of the same author. (RUG, 2019) This citation analysis has given inspiration for the following criteria for this MCDM problem. In the case of this framework, often upcoming technologies are investigated on which not always a lot of "valid" articles can be found. Grey literature is therefore also important to take into account.

<u>Criteria:</u>

1. Valid literature can be found confirming the existence of the factor.
   *1 = no literature at all, 2 = grey literature article, 3 = a valid article can be found, 4 = more than one valid article can be found, 5 = more than ten valid articles can be found*
2. If valid literature can be found, how many times has this article been cited.
   *1 = no cites, 2 = one to 5 cites, 3 = five to twenty cites, 4 = twenty to fifty cites, 5 = more than fifty cites*
3. Can counter opinions of the literature that has been used to evaluate criterion 1 & 2, be found.
   *5 = no counter opinion articles, 4 = grey literature counter opinion(s) can be found, 3 = one valid counter opinion article can be found, 2 = more than one valid counter opinion article can be found, 1 = more than ten valid counter opinion articles can be found*

Now that the problem, alternatives and criteria are decided upon, a multi criteria decision method (MCDM) has to be chosen. Since the decision problems mostly contains qualitative data, pair wise comparison methods have been explored. It can be concluded that qualitative decision making problems are often hard to solve with a multi criteria decision making method. Most of the pair wise comparison methods still make use of weights for each criteria.

A matrix could be made showing all the alternatives on one axis and the criteria on the other. Grades could be given for each of the criteria, rating to what extent a criterion is met. The scale goes from 1 to 5, as indicated for each criterion. An example of such a decision matrix can be seen in Table 6.1. The weight of the factor can be zero, in case no data about this factor is available at all.

| F/C | Criterion 1 | Criterion 2 | Criterion 3 | Weight | Total |
|---|---|---|---|---|---|
| Factor 1 | 4 | 1 | 2 | 0.8 | 5.6 |
| Factor 2 | 3 | 3 | 2 | 0.6 | 4.8 |
| Factor 3 | 2 | .. | | | |
| Factor 4 | | | | | |
| Factor 5 | | | | | |
| Factor 6 | | | | | |
| Factor 7 | | | | | |
| Factor 8 | | | | | |
| Factor 9 | | | | | |
| Factor 10 | | | | | |
| Factor 11 | | | | | |
| Factor 12 | | | | | |

Table 6.1: Matrix with the alternatives on the vertical axis and the criteria on the horizontal axis. The data is filled in as an example.

However, since the framework is made for emerging high-tech products, (valid) literature is not always available in large entities. For this MCDM method the criteria are based on the quantity and origin of sources, which might not be available for new emerging technologies. Another comment has to be made about Step 1, the selection of factors that are involved in a specific case. A factor might seem not relevant if it is in place for a long time already, however if a situation would change and that factor is therefore not in place anymore, the factor could become important. It is therefore difficult to determine if a factor will never cause of problem during the market formation or if it will at some point in time. If the market environment changes, a new niche strategy would be necessary. These subsequent niche strategies have also been observed by J. R. Ortt et al. (2015).

## 6.2 Evidential Reasoning approach

The subjectivity and uncertainties that are encountered while using it could influence the reliability of the method. Xu and Yang (2001) has encountered similar problems. They came up with a slightly different MCDM method than described in Section 6.1: the Evidential Reasoning Approach. This approach will be explained in this section.
Xu and Yang (2001) consider the following characteristics to be part of a MCDM problem:

- The problem can be assessed on multiple criteria.

- Criteria are often conflicting, practical aspects often decrease appearance for example.
- A MCDM has a hybrid nature. Criteria often have different units of analysis or even non-quantitative. Some criteria can be measured with a numerical outcome and others have to be described in words. Some criteria might be influenced by other criteria.
- There are two issues that result in uncertainty. First of all, subjective judgements to asses the criteria that are answered in a non-numerical way, are not 100% certain. In addition, uncertainty can arise when a lack of information exists.
- A large amount of criteria can exist for a problem.
- Multiple solutions can come out of a problem, depending on the decision maker and assessment.

From the above mentioned characteristics, the uncertainty issues seem to be an issue in the decision making problem of the choice of factors too. In the current situation the judge's opinion is reflected in the assessment of the factors.

Xu and Yang (2001)'s solution to these problems is the Evidential Reasoning Approach (ER). In this approach the decision matrix is extended by using a belief structure. In this way a factor is assessed on a criteria, and it is also noted how believable this assessment is. In this way it is possible to display the accuracy of the assessment. Probabilities and subjective judgements can be integrated in this way. (Xu & Yang, 2001) In this method, if no data is available to assess a criterion, the belief degree is 0.

*ER applied to the case of barrier framework*
If this method would be applied to the case of the barrier framework, it could look like as following. Similar criteria as in the method of Section 6.1 can be used to assess the factors (alternatives). However in this case, the criteria will be appointed a YES or a NO, and a belief degree will be appointed to this assessment. The belief degree would then depend on the availability of data and the amount of data that can be found. If for example just one source can be found to support a statement, the belief degree is lower than if multiple sources can be found.

<u>Criteria:</u>

1. Valid literature can be found, describing the existence of the factor for the specific case. *0% = no literature at all, 0-20% = grey literature article, 20-30% = a valid article can be found, 30-60% = more than one valid article can be found, 60-100% = more than ten valid articles can be found*
2. If valid literature can be found, how many times has this article been cited. *0-20% = no cites, 20-40% = one to 5 cites, 40-60% = five to twenty cites, 60-80% = twenty to fifty cites, 80-100% = more than fifty cites*
3. Can counter opinions of the literature that have been used to evaluate criterion 1 & 2, be found. *80-100% = no counter opinion articles, 80-60% = grey literature counter*

*opinion(s) can be found, 60-40% = one valid counter opinion article can be found, 4-20% = more than one valid counter opinion article can be found, 20-0% = more than ten valid counter opinion articles can be found*

The elaborated decision matrix would is shown in Table 6.2. A YES would correspond with 1 point and a NO with 0 points.

| F/C | Criterion 1 | Belief degree | Criterion 2 | Belief degree | Criterion 3 | Belief degree | Total |
|---|---|---|---|---|---|---|---|
| Factor 1 | Yes | 80% | Yes | 20% | No | 80% | 1 |
| Factor 2 | Yes | 60% | No | 80 % | No | 80% | 0.6 |
| Factor 3 | Yes | 40% | .. | | | | |
| Factor 4 | | | | | | | |
| Factor 5 | | | | | | | |
| Factor 6 | | | | | | | |
| Factor 7 | | | | | | | |
| Factor 8 | | | | | | | |
| Factor 9 | | | | | | | |
| Factor 10 | | | | | | | |
| Factor 11 | | | | | | | |
| Factor 12 | | | | | | | |

Table 6.2: Matrix with the alternatives on the vertical axis and the criteria on the horizontal axis. Some random examples have been filled in.

### 6.2.1 General notes to take into account

Ajzen and Fishbein (1977) state that a person's attitude towards an object has an influence over this person's response to the object. It is therefore important to first weigh the factors, before making a ranking based on the level of influence. If not, subjectivity of the decision maker could influence the ranking of the factors.

Research from J. R. Ortt et al. (2015), has shown that often a core factor is explained by an influencing factor and are therefore connected. One core factor could also be explained by multiple core factors, or the other way around: one influencing factor affecting multiple core factors. This relationship between the factors is hard to ignore.

Some information on certain factors is not openly accessible. Especially since companies are often commercial, and sales numbers are for example not public. That makes the factors less easy to investigate. This is however not a problem if the decision maker is part of the company and thus has access to this information.

## 6.3 HUMAN REASONING MIGHT STILL BE PREFERRED?

As expert[2] Dr. Hadi Asghari has said: 'I do not prefer computations over human reasoning", more researchers question whether logical reasoning is less true. The computational models as described in Section 6.1 and 6.2 might be preferred by some researchers, but not by all.

The process of decision making is often based on predictions. Namely, predicting what the best choice will be. Silver (2012) states that with the internet the availability of information is growing, but that does not have to imply that the usefulness of the information is too. His book recommends a strategy to close the gap between what humans think they know and what they know, based on the Bayesian way of thinking. The first Bayesian note is about probability. Thinking in a probabilistic way can enable the consideration of the imperfections in your way of thinking. Which can result in a better way of decision making. (Silver, 2012) Secondly, the Bayesian way of thinking requires us to use common sense before we look at the statistics. Another Bayesian principle is the creation of forecasts, and the adjustment of these using new information accordingly. Silver (2012) points out that a bias could be created when a decision maker is too personally or professionally involved or automatically focusing on the newest data. He concludes that making predictions should be done objectively as well as subjectively.

Page (2018) states that not only one method should be used, but multiple. In this way multiple angles and disciplines look at a problem. Models are precise and make use of calculations instead of words. It is also a simplification of the real world and enables logical thinking. Complex systems should however not rely solely on such a mathematical model states Page (2018). That's why in his opinion, multiple models should be used for one system. (Page, 2018)

## 6.4 COMPARISON BETWEEN METHODS

Different methods have been proposed in this chapter, both objective as more subjective ones. As both the experts and Silver (2012) state: the best solution might be a combination of objectivity and subjectivity.

As Page (2018) stated, the best solution might be a combination of the above described methods.

The models proposed in Section 6.1 and Section 6.2 are quite objective MCDM methods. On the other hand, there are the opinions of the expert and different researchers that claim that objectivity should at least be combined with subjectivity.

The cases that will be investigated with the diffusion theory are often relatively new high-tech products where not that many publications can be found about. The MCDM methods

[2] Conducted from a discussion with Hadi Asghari

proposed in this section would therefore not be very suiting as only method for this framework.

From this discussion it can thus be concluded that a method that includes both objective as subjective methods is recommended.

# 7 PART V: LOOKING AT THE THEORY AS A WHOLE

In Chapter 5 the different components of the theory, the pattern and barrier framework, have been critically examined. Some characteristics have been found that could be related to the whole theory and might be caused by an initial telecommunication industry bias. In this chapter a critical eye is given on the development of the theory from beginning to end and its approach of theory extension is examined.

## 7.1 TELECOMMUNICATION INFLUENCE THROUGHOUT THE THEORY

According to Popper, induction and verification are not part of the scientific process, since it is a psychological and not logical way of reasoning. A new case that contradicts, instead of agrees, with your findings can always come up and therefore your generalisation is not highly valid. Another argument against verification according to Popper is the low testability that occurs during the verification process. It is impossible to test all situations/cases in the world. (Rothman & Lanes, 1988) In the case of the pattern and barrier framework theory, from now on called "diffusion theory", verification has been used.

The difference between "context of discovery" and "context of justification" is a broadly discussed topic. There are several ways of looking at the situation whether the step from the telecommunication industry to other high-tech industries can be considered a process of justification or as the discovery phase of the model development. Different philosophical views have different opinions on the distinction of the two phases. (Hoyningen-Huene, 2006) If the method used to construct the diffusion theory is considered scientific is therefore not possible to conclude. What can be concluded is the fact that the step from telecommunication to other industries has created a bias as will be explained thoroughly.

The first publication (J. R. Ortt and Schoormans (2004)), was based on findings found during experience in the telecommunication industry and literature. The initial diffusion theory had been derived following a deductive way of reasoning. After that, the theory was applied in other fields to other data, and turned out to apply to those cases too. Resulting in a direct example of *verification*, namely results that conform with the initial theory. The foundations of this diffusion theory have been made based on data of the telecommunication field. This field can have field specific characteristics that influence the theory, or so called; creates a bias. One of the findings in the first article published by J. R. Ortt and Schoormans (2004), is that telecom technologies are often introduced and then withdrawn from the market when sales turn out to be disappointing. In the pattern this is displayed as a curve that stops at a certain point in time (when the product is taken off the market). On the y-axis, the cumulative percentage of adoption is displayed. The amount of new adoptions could indeed go to zero, when the technology/high-tech product is not for sale anymore. The total amount of cumulative users, will however not change. If users will continue on using the product, depends on if it is a physical object or a service. If a service is withdrawn from the market, it can not be used anymore. While if a product is withdrawn from the market, it can still be used by the buyers. It could be stated that the market therefore still exists. This is an example of how the diffusion theory could be biased because of the foundations of the theory that have been made based on the telecom world, since in the telecommunication industry products are often services. Besides that, it is an example of the fact that the diffusion theory is falsifiable, namely that the life cycle pattern does entirely hold, namely that a curve of cumulative users does not stop. Akkermans and Vos (2013) also states that service operations must be treated differently than manufacturing management wise.

In the telecom industry, it is quite straight forward that with each technology or product, mass market is aimed for. Mass market is described as "A product that is designed for the mass market is intended to be bought by as many people as possible, not just by people with a lot of money or a special interest" in the Cambridge dictionary. Mass market is aimed for in the telecom industry since network effects are very important in this industry. Network effects is the phenomenon that a product increases in value when more customers use it. The more people make use of a device or application, the more people can be reached via this channel and the more valuable it thus becomes. (Fuentelsaz, Maicas, & Polo, 2012) It is however possible that some products are introduced to the market without this purpose, just to serve a niche market or application.

The telecom industry is characterized by a high level of innovation. (Bourreau & Doğan, 2001) This could explain the high amount of niches that has been observed by telecom technologies. If the high-tech product is often innovated, new versions can be introduced to the market rapidly.

Both physical products (equipment) as services can be observed in the telecom industry. A communication service is delivered but must be enabled by equipment. This could explain the first four core factors of the framework. Those factors are all related to a product as a system with subsystems and therefore different suppliers and complementary products. In the telecom industry the infrastructure is often complicated and extensive.

In this case it can thus be concluded that this method of justification has led to a bias from the telecommunication industry. If it really is a case of justification depends on the philosophical view that is given on the topic.

Another note that has to be made is that the theory is thus based on data of cases that have reached the market. All of these cases were already in the stabilisation phase when the theory has been applied. The question now rises that if the theory is as relevant to predict "future diffusion" of cases. The theory and framework therefore go from an analysis method to a prediction method.

## 7.2 Proper use of a model

As George Box stated in 1976: "All models are wrong, some are useful.", describes the phenomenon of a model. A model is a simplification of the real world that is based on assumptions. It is therefore important to take the assumptions as stated in Section 1.5 in mind while applying the diffusion theory. The clearer the assumptions of a model are, the more accurate a model can be used. New assumptions can be thought of, so that the current model fits real life better or the model can be adjusted to fit better. Adjusting the model does however often mean expending the model and thus more difficult to use.

## 7.3 The government's role

In the diffusion theory the government is mostly considered an external factor. The government can have an influence on diffusion via subsidies, laws and regulation as mentioned in the description of the factor *Institutional aspects*. The framework has been build based on data of commercial companies, where the government mostly had a regulating function.

However, in the cases of QKD and nuclear fusion power plants, it can be observed that the government has taken other roles as well. In the case of nuclear fusion power plants, the government can also be considered a researcher and possibly market introducer. The same holds for QKD, where the government has recently established the OPENQKD project to improve the technique and therefore speed up diffusion for QKD systems.

It can be noted that however the government did play a role in the telecommunication industry, and not only as an external factor, this cannot be observed as an influence in the pattern. This is contradictory to the other telecommunication influences that can be observed as mentioned in Section 7.1.

# 8 PART VI: THE ADJUSTED DIFFUSION THEORY

In this section the remarks of Chapters 5, 7 and 6 have been taken into account to propose an adjusted diffusion theory. The life cycle pattern has been adjusted accordingly to the problems encountered with the distinction between split-offs, niche applications and innovations. The niche application curve has been discussed. Possible missing factors have been added to the barrier framework, as well as a discussion on the factor assessment. Therefore different types of adjustments can be identified. The distinction between split-offs, niche applications and innovations is a complement to the theory as well as the categorization of influence of the factors. The encountered factors that could not be described by the current framework are added in the form of additional factors to the barrier framework. Finally, to the problem of the validity of the factors for a specific case, possible solutions are discussed and a direction for a solution is given.

## 8.1 ADJUSTED LIFE CYCLE PATTERN

Looking at the current life cycle pattern of J. R. Ortt (2010), a niche application or market refers to a new application of a product and therefore other customer groups. For the case of nuclear fusion, it can however be seen that a split-off of the Tokamak reactor is now present on the commercial market. Namely, as a neutron producing fuser. (Miley & Sved, 2000) Additionally, different generations of the Tokamak reactor can be observed over the years. In the current graphical display of the pattern (3.1), these kind of split-offs or generations are not displayed. Solutions to these element have been added to further specify the life cycle pattern.

Additions to the life cycle diffusion pattern:

- Distinction between niche applications and split-offs and innovations
- Niche application curves do not stop, since on the y-axis the cumulative amount of users has been displayed. The cumulative amount of users, i.e. customers ever that ever used or purchased a product, does not change over time.

An example life cycle pattern including these additions has been displayed in Figure 8.1.

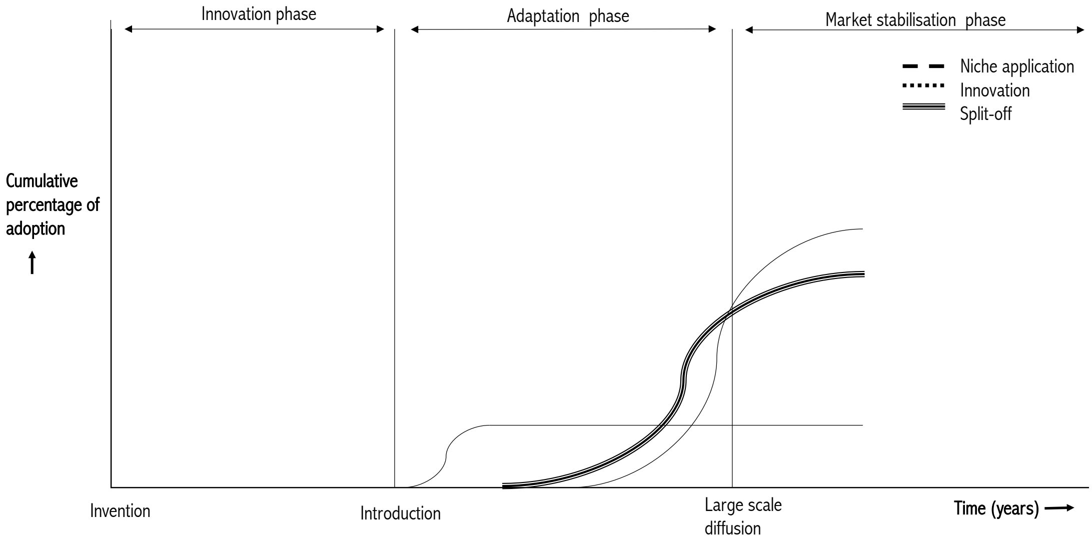


Figure 8.1: Adjusted life cycle pattern with as an example a niche application not for sale anymore and therefore adoption decreased, a successful split-off and the main high-tech product.

## *Examples*

Applying this adjusted life cycle pattern to the cases of QKD and nuclear fusion power plants results in the following figures. If these life cycle patterns are compared with the ones in Chapter 3, differences can be identified. In the case of QKD, Figure 8.2, an extra curve is added for the split-off in the form of satellite based QKD. In Figure 8.3, it can be seen that a split-off has had success in the innovation phase already for nuclear fusion power plants, in this case being commercial fusers that produce neutrons.

The difference between the original and adjusted life cycle patterns might not seem big for these two cases. This could be due to the fact that both technologies have not reached mass market yet and still niche markets/applications and split-offs are able to emerge in coming phases.

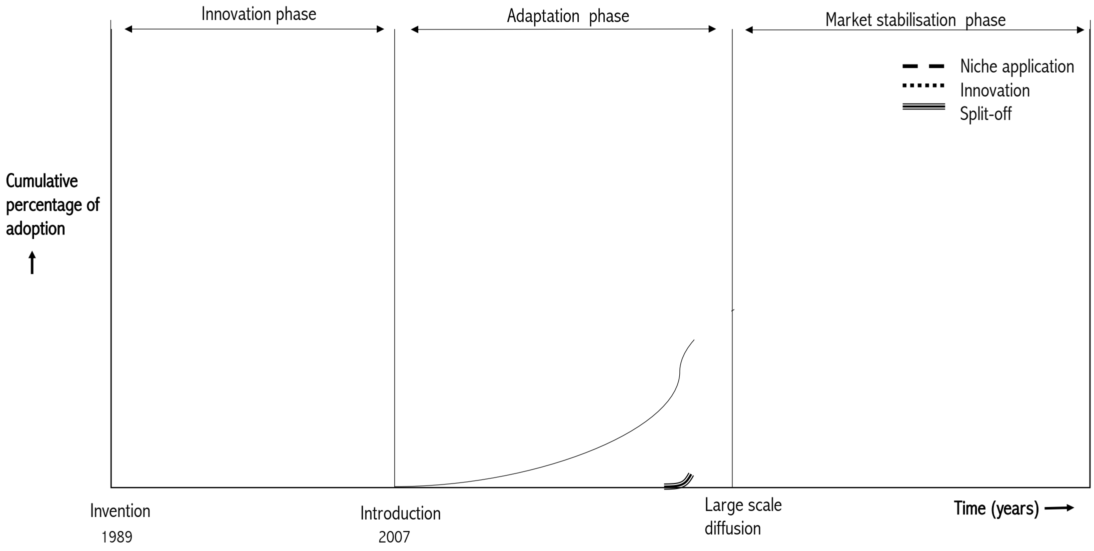


Figure 8.2: Adjusted life cycle pattern inserted with the data of the case of QKD.

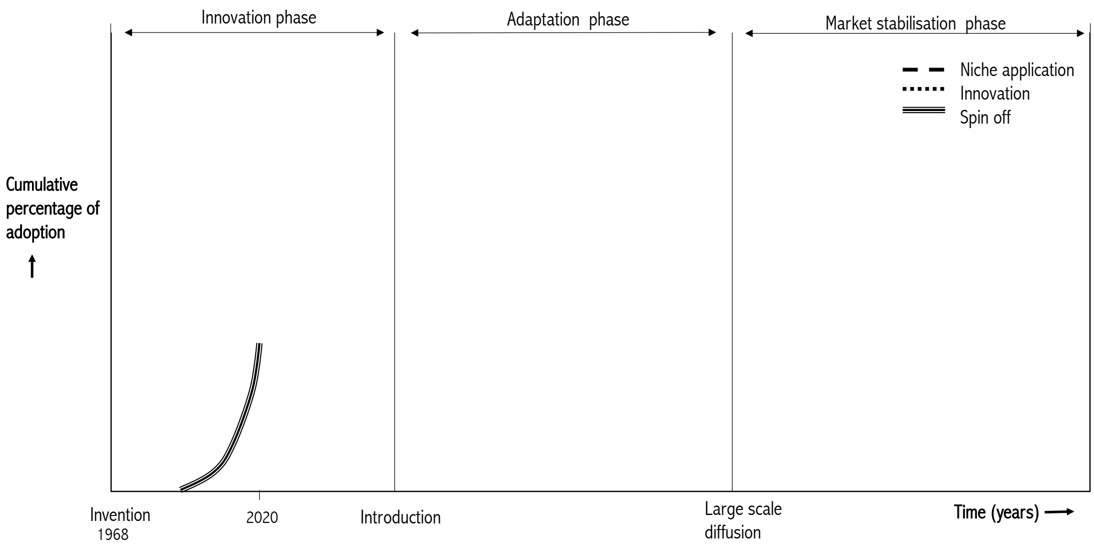


Figure 8.3: Adjusted life cycle pattern inserted with the data of the case of nuclear fusion power plants.

As can be seen in the adjusted life cycle patterns, 8.2 & 8.3, split-offs during the innovation and the adaptation phase can be observed. In physics, often fundamental research is carried out which often results in applied research in a certain field. (Dineley, 2019) Both technologies, QKD and nuclear fusion power plants, are based on findings during fundamental physics research. It therefore makes sense that split-offs can be observed often in these cases and that related technologies exist.

## 8.2 Adjusted barrier framework

Some additions that have been suggested in Section 5, can be integrated in the base framework of R. Ortt et al. (2013). First of all, several supplementary factors have been found that can be added to the framework. Additionally, the validity of the factors has been discussed. The validity depends on the relevance of used information as well as the source. A system has been thought of to show which factors are considered valid and which not certainly valid.

The 10 suggested additional factors as presented in Section 5.4 differ in importance and newness. Some of the factors are therefore integrated in already existing factors, since they are in the same direction of the existing factors. The *Licensing and patenting* factor has has been explicitly added to the *Institutional aspects* core factor. And the *Presence of socio-cultural debates* factors, which can be explicitly mentioned at the *Socio-cultural aspects*. The *Socio-cultural aspects* factor would therefore become both stimulating and suppressing, since a socio-cultural debate can cause both. The *Competition* and *Substitutes* factors have merged into one factor, since it is both a form of competition. The difference is the competition between similar products or different products. The *Strategy of a high-tech company* factor has not been added to the framework. The factor is only relevant if the framework is used by someone to investigate an industry for research, but the framework is designed for companies to develop a strategy. Therefore already recognizing that their company's current strategy is not suitable. Additions to the barrier framework table are displayed in *italic*.

Two extra columns have been added to the framework, which in one the factors are categorised into *stimulating* (+), *suppressing* (-) and *both* (+/-). Stimulating can be described as "when in place, has a positive influence on the diffusion", while suppressing means that when this factor is in place, diffusion is blocked. It is important to identify the influence of a factor, since it is not straightforward that a stimulating factor is also suppressing when not satisfied, as has been explained in Section 5.2.1.

The other additional column displays the categorization of the factors into: must-be (M), one-dimensional (O), attractive (A), indifferent (I) and reverse (R) as has been explained in Section 5.2.1. It has already been mentioned that especially the core factors can change in type over time. Therefore multiple possible types can be mentioned for each factor.

| Factors | Description | Influence | Type |
|---|---|---|---|
| 1. New high-tech product | The product can be defined and distinguished using three elements: the functionality provided by the product, the technological principle(s) used and the main components in the system (first tier of subsystems). The unavailability of (one or more components of) the product means that large-scale diffusion is not (yet) possible. The product needs to have a good price/quality compared to competitive products in the perception of customers before large-scale diffusion is possible. | + | M, O |
| 2. Production system | Availability of a good production system is required for large-scale diffusion. In some cases a product can be created in small numbers as a kind of craftsmanship but industrial production technologies are not yet available. In that case large-scale diffusion is not possible. | + | M |
| 3. Complementary products and services | Complementary products and services refer to products and services required for the production, distribution, adoption and use. The product together with complementary products and services forms a socio-technological system. The unavailability of elements in that system means that large-scale diffusion is not (yet) possible. | + | M, O |
| 4. Suppliers (network of organizations) | The producers and suppliers refer to the actors involved in the supply of the product. Sometimes multiple types of actors are required to supply the entire system. In that case a kind of coordination (network) is required. Sometimes actors with considerable resources are required, for example to provide an infrastructure. If one or more vital roles, resources or types of coordination are not present in the socio-technological system, large-scale diffusion is blocked. | + | M |

| Factors | Description | Influence | Type |
|---|---|---|---|
| 5. Customers | The availability of customers means that a market application for the product is identified, that customer segments for these applications exist and that the customers are knowledgeable about the product and its use and are willing and able to pay for adoption. If applications are unknown or if customer groups do not exist, are not able to obtain the product or are unaware of the benefits of the product, large-scale diffusion is blocked. | + | M, O |
| 6. Institutional aspects (laws, rules and standards) | The regulatory and institutional environment refers to the laws and regulations that indicate how actors (on the supply and demand side of the market) deal with the socio-technological system. These laws and regulations can either stimulate the application of radically new high-tech products (such as subsidy that stimulates the use of sustainable energy) or completely block it (such as laws prohibiting something). *Licensing and patenting can both stimulate and suppress diffusion.* | +/- | M, R, I, A |
| 7. Knowledge of technology | The knowledge of the technology refers to the knowledge required to develop, produce, replicate and control the technological principles in a product. In many cases a lack of knowledge blocks large-scale diffusion. | + | M |
| 8. Natural resources and labour | Natural resources and labour are required to produce and use a new high-tech product. These resources and labour can be required for the production system, for complementary products and services or for the product itself. In many cases a lack of resources and labour block large-scale diffusion. | + | M |
| 9. Knowledge of application | Knowledge of the application can refer to knowing potential applications. If a technological principle is demonstrated but there is no clue about its practical application, large-scale diffusion is impossible. A lack of knowledge of the application can also refer to customers that do not know how to use a new product in a particular application. In that case large-scale diffusion is not possible. | + | M, O |

| Factors | Description | Influence | Type |
|---|---|---|---|
| 10. Socio-cultural aspects | Socio-cultural aspects refer to the norms and values in a particular culture. These aspects might be less formalized than the laws and rules in the institutional aspects but their effect might completely block large-scale diffusion. *Socio-cultural debates have to be taken into account, during this debates where lay people get informed about a technology, lay people's opinion can change both in a positive as a negative direction towards the technology.* | +/- | M, A, R |
| 11. Macro-economic aspects | Macro-Economic aspects refer to the economic situation. A recession can stifle the diffusion of a new high-tech product. | +/- | A, R |
| 12. Accidents or events | Accidents or events such as wars, accidents in production, accidents in the use of products can have a devastating effect on the diffusion of a new high-tech product. | - | R |
| 13. *Type of funding of research projects* | *A research or project can be publicly or privately funded. Both of the types of funding have its (dis)advantages. The initial funding for the first part of the project can also have a big influence. If for example a project is a spin off from a university (therefore often public funding), it can be hard to transfer the knowledge to a commercial company.* | +/- | R, A |
| 14. *Potential misuse of technology* | *A technology or high-tech product must be safe in terms of other applications. If a technology could possibly have an other application that leads to misuse or criminality, it can possibly not reach the mass market.* | - | R |

| Factors | Description | Influence | Type |
|---|---|---|---|
| 15. *Competition* | *When competition is present in a market and therefore multiple suppliers, a technology tends to diffuse faster. Since the prices are tend to be lower and resources more allocated. So the higher the competition, the faster the diffusion of a high-tech product. There is however an intermediate level of competition at which the maximum diffusion takes place. Substitution is also a form of competition, but between different products. Substitutes for a high-tech product can both have a negative or positive influence on the diffusion of the product. Positive when the diffusion of the high-tech product increases along with the increasing diffusion of the substitute. On the other hand negative, when the substitute takes over the customers of the high-tech product. (Norton & Bass, 1987)* | +/- | O, R |
| 16. *Managing expectations* | Expectations of a product by (potential) customers can influence the moment at which they will purchase the product. When expectations for a product or innovation are high, more credit and investment money is available. (Rosenberg, 1982) | +/- | A, R |
| 17. *Case specific factor* | *Every case is unique, therefore unique factors can be observed. This "open" factor gives the opportunity to look further than the framework.* | +/- | M, O, I, A, R |

Table 8.1: Proposed adjusted framework, factors in *italic* are added factors from Section 5.4

The division of factors into core and influencing would give the following table: 8.2. In which the different influencing factors can still be linked to core factors that they influence.

| Influencing factors |
| --- |
| 7. Knowledge technology |
| 8. Knowledge application |
| 9. Labour resources |
| 10. Socio-cultural |
| 11. Macro economic |
| 12. Accidents and events |
| 13. Type of funding of research projects |
| 14. Potential misuse of technology |
| 15. Competition |
| 16. Managing expectations |
| 17. Case specific factor |

| Core factors |
| --- |
| 1. Product |
| 2. Production system |
| 3. Complementary products |
| 4. Suppliers |
| 5. Customers |
| 6. Institutions |

Table 8.2: Adjusted barrier framework

Next to the additional factors, the assessment of the factors has also been discussed in Section 6. After exploring different MCDM methods and taking into account expert's opinions it can be concluded that many options are available and that there is no exact right or wrong. All methods have their pros and cons.

### *Examples*

The adjusted barrier framework has been applied to the cases of QKD and nuclear fusion power plants and can be found in Tables 8.3 and 8.4. Compared to the applied original framework in Section 4, new influencing factors are appointed for both of the cases. For the quantum cryptography, the potential misuse and substitutes (competition), in the form of criminality and post-quantum cryptography are considered influencing. For the case of nuclear fusion power plants the type of funding, potential misuse and substitutes (competition) have had and still have a high influence on its diffusion.

| Influencing factors |
|---|
| 7. **Knowledge technology** |
| 8. Knowledge application |
| 9. Labour resources |
| 10. Socio-cultural |
| 11. Macro economic |
| 12. Accidents and events |
| 13. Type of funding of research projects |
| 14. **Potential misuse of technology** |
| 15. **Competition** |
| 16. Managing expectations |
| 17. Case specific factor |

| Core factors |
|---|
| 1. **Product** |
| 2. **Production system** |
| 3. **Complementary products** |
| 4. **Suppliers** |
| 5. **Customers** |
| 6. Institutions |

Table 8.3: Adjusted barrier framework for the case of QKD.

| Influencing factors |
|---|
| 7. **Knowledge technology** |
| 8. Knowledge application |
| 9. Labour resources |
| 10. **Socio-cultural** |
| 11. Macro economic |
| 12. **Accidents and events** |
| 13. **Type of funding of research projects** |
| 14. **Potential misuse of technology** |
| 15. **Competition** |
| 16. Managing expectations |
| 17. Case specific factor |

| Core factors |
|---|
| 1. **Product** |
| 2. **Production system** |
| 3. Complementary products |
| 4. **Suppliers** |
| 5. Customers |
| 6. Institutions |

Table 8.4: Adjusted barrier framework for the case of nuclear fusion power plants.

## 8.3 PROPOSED NICHE STRATEGIES FOR THE CASES

J. R. Ortt et al. (2015) proposes 10 niche strategies to circumvent or remove barriers to large scale diffusion, and thus to reach mass market. The 10 different strategies are described in Table 4.4. In Section 4.3, several niche strategies in that have been used in the past were explored. Based on this research, niche strategies can be proposed to reach large scale diffusion.

In the case of quantum cryptography, the knowledge of technology factor turned out to be insufficient. Several core factors were therefore affected. First of all, the *Demo and develop* *niche strategy* can be continued to be implemented. This strategy results in many experiments to further develop the technology. This strategy has already been implemented in the past as well. The same holds for the *Subsidized niche strategy*, which can be observed in the form of the OPENQKD project which is established in 2020. A not yet implemented niche strategy could be the *Stand-alone niche strategy*, where local networks are promoted. In this way, when the technology does is able to be used over large distances, the smaller networks can be connected and the technology reaches mass market.

In the case of nuclear fusion power plants, it is harder to determine niche strategies since the technology is still in the innovation phase. The currently used niche strategies, the *Subsidized niche strategy* and *Educate niche strategy*, are suggested to be continued.

## 8.4 VALIDITY, PROS, CONS AND CONTEXT OF THE ADJUSTED DIFFUSION THEORY

The adjusted diffusion theory is extended compared to the original theory. The extension makes it slightly less easy to use, since more factors, innovations, split-offs and the factor choice have to be taken into account. However, the model in the adjusted version applies to more cases, since more cases can be identified with the adjusted version.

The current validity of the adjusted diffusion theory is very low. Several suggestions can be made on how to improve this validity. For example, a workshop could be organised with experts that test and use the framework. If experts agree with the framework, the validity could increase.

For the construction of the adjusted diffusion theory, the data of only two cases has been used. A bias could have been created again due to the sole use of physics research based data. For the construction of the current diffusion theory, more data and from different industries had been used. Additionally, the two cases have not reached mass market up until today, while all the cases used to construct the original diffusion theory went trough all the phases of the life cycle.

# 9 CONCLUSIONS & DISCUSSION

The investigation into the cases of quantum cryptography and nuclear fusion power plants has generated ideas on how to complement the framework of R. Ortt et al. (2013). The framework exists of two parts that have been examined separately: the life cycle pattern & the barrier framework. For both parts of the framework suggestions have been made and adjusted versions have been proposed.

To answer the sub-questions "*What is the current phase in the life cycle pattern that quantum cryptography is in?*" and "*What is the current phase in the life cycle pattern that the Tokamak design nuclear fusion power plant is in?*", the life cycle pattern as described by R. Ortt et al. (2013) has been applied to the two cases. For the case of quantum cryptography, the product has been introduced onto the market and is currently in the adaptation phase. One curve for the time versus cumulative percentage of adoptions of the technology QKD has been observed, and no niche applications. For the case of nuclear fusion power plants, no curve could be seen at all since no market introduction has taken place yet and the technology is still in the innovation phase. If the high-tech products will reach the stabilization phase in the form they are now is uncertain, the products could become a niche application or could possibly never reach large scale diffusion at all. Several problems were encountered during this research into the life cycle patterns of the technologies. First of all, the distinction between split-offs, innovations and niche applications was vague. Besides that, there was no possibility of showing split-offs and innovations (in the form of generations of a high-tech product) in the life cycle pattern. Finally, the cumulative amount of users seemed to go to zero abruptly in the case of niche applications, which is not possible. To solve these problems, an adjusted life cycle pattern has been proposed in Chapter 8. In this adjusted life cycle pattern it is possible to show niche applications as well as split-offs and generations of a product, therefore being an extension to the diffusion theory. In the current life cycle pattern, niche application curves are now not able to decrease in number, but only able to increase or stay at the same number.

Factors defined in the model of R. Ortt et al. (2013) have been investigated for the cases of quantum cryptography and nuclear fusion power plants. These factors could create a barrier to large scale diffusion for high-tech products. This has been done in order to answer the sub-questions "*Which already defined barriers by R. Ortt et al. (2013) can be appointed for quantum cryptography?*" and "*Which already defined barriers by R. Ortt et al. (2013) can be appointed for Tokamak design nuclear fusion power plants?*". For both cases different factors could be appointed, but the factor *Knowledge of technology* was insufficient for both. In the case of nuclear fusion power plants even so insufficient that the product cannot even be brought to the market (yet). During the case study investigation into why these products are not available on the mass market (yet), other factors than described in the model were encountered. In the adjusted diffusion theory, these encountered "new" factors have been added to the barrier framework as a solution to the lack of these factors in the current framework. Additional influencing factors in the adjusted theory are: *Type of funding, Potential misuse of a technology, Competition, Managing expectations* and *Case specific* factor. Besides the new factors, existing factors in the framework have been expanded. For the *Potential misuse of a technology* factor it has been decided to create an additional factor since for the two investigated cases in this research it turned out to be an important factor. It will have to be investigated if this implies to other industries as well, or if the factor should be integrated in the *Accidents and events* factor. It has to be mentioned, that all of these added factors are based on the two physics cases. A bias could therefore have been created again, now due to the physics research characteristics instead of telecommunication industry characteristics, what currently holds for the original diffusion theory of R. Ortt et al. (2013).

During this literature review to answer the first sub-questions, problems with the application of the framework to the cases were encountered. These problems have been turned into adjustments to the existing framework and therefore answered the fifth sub-question "*Can adjustments to the framework be found?*". Next to the solution of distinction between split-offs, niche applications and innovations and the additional factors, other problems have been observed. These different observed problems and their respective solutions are discussed here. The solutions proposed in this report are in the form of: a specification of the theory, an additional factor to the barrier framework or a discussion in which a proposal for a solution is given.

As was discussed, currently in the barrier framework, no distinction has been made between stimulating and suppressing factors for reaching large scale diffusion. It is not straightforward that a stimulating factor is suppressing when not present. Or that a suppressing factor is stimulating if not present. It is therefore hard to rephrase the barrier framework in such a way that all factors are suppressing or stimulating. It is thus important to note if the factor has a positive or negative influence, as has been added to the adjusted barrier framework in Section 8.2. The KANO model theory has been investigated to see if a similar distinction between attributes could be made for the factors. Thereby dividing factors not only into suppressing or stimulating, but into must-be, one-dimensional, reverse, attractive and indifference factors. Some factors might just have to be present but do not increase the speed of diffusion (must-be) or diffusion increases linearly with the presence of a factor (one-dimensional). None of the factors of the framework in general are considered an indifference factor, because the indifferent factors are left out of the framework. However, case specifically seen, some factors could be indifferent for that particular case. In the adjusted barrier framework, the table with factors is therefore specified with a categorization into suppressing or stimulating and a categorization into the five KANO categories: one-dimensional, must-be, reverse, attractive and indifferent.

In Chapter 6, a discussion is described in which different methods for the assessment of the factors are discussed. Currently in the diffusion theory, it is the decision maker who decides which factors have and influence on the diffusion of the specific high-tech product and which ones are considered the most influencing. The objective methods that are proposed in Chapter 6, are based on the number of articles that could be found on a topic and the validity of the articles. This is however a time consuming and difficult process, especially for high-tech products on which not that many publications can be found. An expert in the field of multi-criteria decision making as well as several literature sources state that a combination of objective (calculative) and subjective (opinion) methods is often the best solution. This combination of methods is therefore proposed as a solution direction for this encountered problem.

The influence of the telecommunication industry has been observed throughout the whole diffusion theory. First of all, the assumption that mass market is always the goal when a product is introduced to the market. In the case of the telecommunication industry this is straightforward since communication services are not valuable if not many users exist. Besides that, a high level of innovation, which is the case in the telecom industry, leads to many niche applications. This bias probably had an influence on the life cycle pattern and barrier framework, which has to be taken into mind.

Some notes on the research conducted in this report have to be given. A point of interest is the initial assumptions of the framework and the fit in of the case of nuclear fusion power plants. After Chapter 3, it has become clear that nuclear fusion power plants are still considered to be in the innovation phase and not the adaptation phase for which the barrier framework is initially proposed. It can be observed that the framework could still be used, but the description of the factors has to be approached differently. In the case of barriers in the adaptation phase, it can be stated that the factors cause a problem to large scale diffusion but the product has been introduced to the market. Barriers in the innovation phase can even block introduction, causing the blockage of the launch of a high-tech product. If the framework were to be used in the innovation phase, the factors must be divided into: factors that block introduction and factors that block large scale diffusion.

As mentioned a few times before, the case of QKD seems to fit much better with the pattern and framework than nuclear fusion does, not only because it is in the adaptation phase and nuclear fusion power plants are not. This could be due to the bias of telecommunication approach. QKD is part of the telecom industry, since it is a complementary product to the telecommunication in the form of privacy protection. The telecom industry is characterised with high speed of innovation, therefore more niche applications can be observed, while for QKD this does not seem the case. So, QKD fits nicely with the model on many fronts except for this point.

In the current framework, the *Socio-cultural aspects* factor describes the ethical aspects of a technology. This factor is however not specifically described in terms of socio-cultural debates. This aspect is added to the description of the *Socio-cultural aspects* factors. Such a debate where all stakeholders are participating, is considered very important and useful. (Vermaas, 2017) The ethical aspects of a technology could however even be more elaborated on than now proposed in the adjusted diffusion theory.

To answer the main research question "***Why are quantum cryptography (QKD) systems and nuclear fusion power plants not available on large scale?***", all above aspects can be taken into account. The reason why the technologies are not available on large scale can be explained by several factors. For the case of QKD, the influencing factors *Knowledge technology*, *Potential misuse of technology* and *Competition* play a role and affect the core factors *Product*, *Production system*, *Complementary products*, *Suppliers* and *Customers*. In the case of nuclear fusion power plants the core factors *Product*, *Production system* and *Suppliers* seem to be the problem for now and which are affected by *Knowledge technology*, *Socio-cultural*, *Accidents and events*, *Type of funding of research projects*, *Potential misuse of technology* and *Competition*. For nuclear fusion power plants it has to be noted that it is still in the innovation phase and that the factors could change when the adaptation phase is reached.

Managerial implications result from the adjusted diffusion theory. The observation that the influence of factors on barriers to large scale diffusion can change over time, implies that different approaches for each influence type are necessary. Additionally, for the cases of quantum cryptography and nuclear fusion power plants, suggestions for niche strategies are given. For the case of QKD a new niche strategy is proposed: the *Stand-alone niche strategy*. Therefore implying to establish local networks, that could be connected later on when the technology is able to communicate over larger distances. In the case of nuclear fusion power plants, it is difficult since it is not in the adaptation phase. Therefore it is suggested to carry on with the currently used niche strategies: *Subsidized niche strategy* and the *Educate niche strategy*. Furthermore, the government's role turned out to be high in these investigated cases. The collaboration between the government and companies should therefore be enabled, this is further discussed in Chapter 10.

In Chapter 8, different types of solutions to the encountered problems are presented. The distinction between split-offs, niche applications and innovations can be displayed in the adjusted life cycle pattern. Additional factors to the barrier framework are proposed to include the factors found during the literature review that could not be explained by the current barrier framework. The discussion from Chapter 6 has led to a recommendation to combine both objective and subjective methods to assess the factors of the framework. Finally, the observation of the fact that factors can also be stimulating instead of suppressing has led to the addition of the categorization of factors. It can therefore be concluded that the research into the main research question of why quantum cryptography and nuclear fusion power plants are not available on large scale has led to an extension of the literature on the diffusion of high-tech products as well. It has to be noted that all proposed adjustments originate from a study into physics based technology which could create a bias as mentioned before. The adjusted theory does fit better with the cases investigated in this research, but the fit with other industries has to be investigated. Suggestions for future research on this topic are discussed in Chapter 10.

# 10 RECOMMENDATIONS

Several recommendations for future research can be made in response to this research.

- The adjusted diffusion theory framework as presented in Chapter 8 could be tested by experts to increase the validity. A suggestion would be to organise a workshop during which experts of different high-tech industries apply the framework to their expertise industry. Suggestions to improve weak parts of the framework can be made by the experts. By applying the adjusted framework to non-physics based technology cases, the bias of this industry could be decreased.
- The adjusted diffusion theory has been developed through the cases of physics originating technologies. If the adjusted diffusion theory were to be applied to other industries, some adjustments have to be made. The factors as displayed currently should be investigated to check its relevance for a specific industry. Besides that, the *case specific factor* has to be filled in to specify and adjust the framework to the specific industry or even case.
- The approach of the assessment of the factors of the barrier framework could be explored further. Combinations of models and methods could be tested. Chapter 6 has given an overview and discussion on different methods. It has been concluded that a combination of a subjective and objective method is a good solution according to several researchers.
- The KANO model combination with the assessment of the factors could be tested and designed. In Section 5.2.1, it is suggested that the KANO model could also apply to the factors instead of attributes. This could be tested with several cases.
- A more detailed study into the differences between niche applications, split-offs and generations of a product is proposed. Currently, there is not a lot of literature available on what a niche application is exactly and how it differs from generations of products and split-offs. A study could be done into the distinction between these different terms. For this study it is proposed to define the three different expressions in terms of change in technology, change in application and change in customer group.
- Ethical aspects of high-tech products could be further investigated and added to the diffusion theory. The influence of socio-cultural debates where all stakeholders are involved on the diffusion of a high-tech product could be further researched. It can be considered, if ethical aspects turn out to be very important for the diffusion of high-tech products, to focus more on this in the framework. A core factor about ethical aspects could then be added for example.
- Indicators for start of stabilization phase. In the current framework, the start of the stabilization phase is described as following: "The milestone is defined using three elements:
  - A standard product that can be reproduced multiple times (or standard product modules that can be combined in many different ways but are based on the same

standard platform);
  - A (large-scale) production unit with dedicated production lines (industrial production of a standard);
  - and diffusion of the product

  ". (J. R. Ortt, 2010)
  These milestones could be investigated and specified in order to specify the large scale diffusion milestone.

Next to recommendations for future research, managerial recommendations for companies and the government can be given. Besides the appointed niche strategies to speed up the diffusion of the respective technologies and therefore circumvent barriers, the following recommendations are given:

- Managerial implications to the observation of changing types of factors have to be explored and thought of. A dynamic strategy is therefore important, that can be adjusted and changed over time.
- For the case of quantum cryptography we would recommend the government to develop QKD systems in-house and use these to protect their data. In-house development (within governments) assures independence. The possible power imbalance between countries/governments should be avoided and all governments should be able to use QKD protection. Collaborations between different governments is therefore recommended. Companies working with sensitive data have a high motivation to invest in research of QKD systems since for them the need is high to protect their data in the future. These companies could be approached for funding by QKD developing companies, possibly in exchange for future sales, therefore creating a business incentive.
- Nuclear fusion power is not available on the market mostly due to its technical issues and the high costs involved with the research and development. The technology is not well enough developed to generate net nuclear fusion power. Where many private and leading companies can be observed in the case of QKD systems, the opposite can be observed for nuclear fusion power. The largest and most developed reactor is a collaborative project between different country governments. A few smaller projects carried out by private companies can be observed. In the case of nuclear fusion power it would therefore be interesting to stimulate private companies to research or invest in nuclear fusion technologies. Since the costs of a nuclear fusion project are extremely high, several existing start-up could cooperate to accelerate the process. The technology is difficult and expensive to research, but the incentive will be high. Nuclear fusion would be a breakthrough technology in the energy transition problem. Currently, Google has collaborated with TAE in a nuclear fusion power plant project. Google's high energy consumption could be related to this investment as well. Collaborations like these should be encouraged. This recommendation could also be considered a

solution to the additional factor that has turned out to be influencing for the case of nuclear fusion power plants: the *Type of funding of research projects* factor. Stating that the type of funding of a research projects has an influence on the diffusion speed of a technology.

- One of the additional factors in the adjusted diffusion theory "*Potential misuse of a technology*" is appointed as an important influencing factor for the cases of QKD and nuclear fusion power plants. Solutions on how to avoid that the technologies end into the wrong hands have to be thought of if this turns out to be a real threat after investigation. If the threat turns out to be low after investigation, social-cultural debates could be organized in which the possible threat is explained and discussed with all stakeholders.
- An overarching association for both cases individually could be established in order to collect *lessons learned* and *best practices* from different research projects. These data have to be stored and coded in a clear way, such that every new project can use these to avoid unnecessary mistakes.

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# 11 APPENDIX

## 11.1 REQUEST FOR EXPERT OPINION

### *Goal*

The goal of this discussion is to get a better understanding of the criteria that should be considered while weighting and selecting factors in the model. Hopefully, with the insights from this interview, the multi criteria decision making model that could be a practical addition to the diffusion theory of R. Ortt et al. (2013) will be adjusted and extended.

### *Selection of interviewees*

Potential interviewees will be approached based on their expertise and experience in the field of (multi criteria) decision making. The interviewees all have some technical/engineering background or currently work in a technical environment. Suggestions: Hadi Asghari, Hans de Bruijn and Jafar Razaei.

### *Interview setting/Duration*

The interviews will probably be conducted via Skype instead of face to face due to the Corona virus that forbids physical meetings. The interview will exist of three parts:
I) A small introduction to the research were the interview is part of. Explanation of the subject and the goal of the interview.
II) Discussion about what the criteria are that the interviewee considers
III) Explanation of the criteria that are presented in this research. A discussion about the relevance and correctness of these criteria.
All together the interview will take about an hour and an email with some information will be send beforehand to the interviewee.

### *Reporting*

If the interviewee agrees, the interview will be recorded and written up after the interview. This draft report will be send to the interviewee to ask for correctness and permission to use in this display.

### *Questions*

The interview will mostly be an open explorative interview where room is for creativity. In order to keep some structure and not create a bias, the interview will be divided in three parts.

- Part I: Do you have any questions upfront about the material that was sent to you before the interview?
- Part II: What would in your opinion be criteria that could be used in order to select these qualitative factors?
- Part II: What would in your opinion be criteria that could be used in order to rank these qualitative factors?

- Part III: What do you think about assessing the factors on their "validity"?
- Part III: What do you think about assessing the factors on their "number of citations" ?
- Part III: What do you think about assessing the factors by looking for "valid and often cited counter opinion articles"?
- Part III: Which factors match better with the weighing decision?
- Part III: Which factors match better with the ranking decision?
- Part III: Could it be possible that some factors are in general more important than others?
- Part III: Would you think that the knowledge of technology factor is a factor that cannot be circumvented using a niche strategy?

An explanation will be given for the terms valid and citations as described in Section 6.

*Personal information*

- Name:
- Family name:
- Year of birth:
- What is the highest degree or level of school you have completed?
  - Associate degree
  - Bachelor's degree
  - Master's degree
  - Professional degree
  - Doctorate degree
- Field of expertise:

## *Email*

Dear,

For my thesis for the master Management of Technology, I am investigating a diffusion theory for high tech products. Part of this theory is a barrier framework that consists of different factors that could potentially create a barrier. I am looking at a model that can decide on the importance/influence of each factor's contribution to a barrier to large scale diffusion. Criteria have to be thought of, on which the factors are assessed. To brainstorm more about potential criteria, I would like to conduct open interviews of about an hour via Skype. Concerning your expertise in the field of decision making, I was wondering if you would be interested in taking part of this interview? Attached a file can be found in which more information on the content of the interview has been given.

Thank you very much in advance.

Kind regards, Birthe

## *Pre knowledge interview*

For my master thesis I am investigating a diffusion model, created by R. Ortt et al. (2013). This diffusion theory explains why it often takes long before a high tech product reaches large scale diffusion after introduction of this product to the market. One part of this model is a so called "barrier framework". This framework exists of 12 factors that could cause a barrier to large scale diffusion for high tech products. In this research, I have been investigating how one could select and rank this factors from lowest to highest influence on the long adaptation phase. The adaptation phase is the phase between the introduction and large scale diffusion of a high tech product. It has been seen that often for a case, not all factors play a role and often have a different level of influence on the length of the adaptation phase. To make the theory more easy-to-use as an analyzing tool, a scientific logic way of weighting and selecting the factors that play a role for a certain case would be convenient. A multi criteria decision making matrix with the factors as alternatives seems like a solution. But now criteria on which the factors are assessed have to come up with.

The Alternatives are the twelve factors as proposed by R. Ortt et al. (2013). These factors are described in Table 11.1.

| **Factors** | **Description** |
|---|---|
| 1. New high tech product | The product can be defined and distinguished using three elements: the functionality provided by the product, the technological principle(s) used and the main components in the system (first tier of subsystems). The unavailability of (one or more components of) the product means that large-scale diffusion is not (yet) possible. The product needs to have a good price/quality compared to competitive products in the perception of customers before large-scale diffusion is possible. |
| 2. Production system | Availability of a good production system is required for large-scale diffusion. In some cases a product can be created in small numbers as a kind of craftsmanship but industrial production technologies are not yet available. In that case large-scale diffusion is not possible. |
| 3. Complementary products and services | Complementary products and services refer to products and services required for the production, distribution, adoption and use. The product together with complementary products and services forms a socio-technological system. The unavailability of elements in that system means that large-scale diffusion is not (yet) possible. |

| Factors | Description |
|---|---|
| 4. Suppliers (network of organizations) | The producers and suppliers refer to the actors involved in the supply of the product. Sometimes multiple types of actors are required to supply the entire system. In that case a kind of coordination (network) is required. Sometimes actors with considerable resources are required, for example to provide an infrastructure. If one or more vital roles, resources or types of coordination are not present in the socio-technological system, large-scale diffusion is blocked. |
| 5. Customers | The availability of customers means that a market application for the product is identified, that customer segments for these applications exist and that the customers are knowledgeable about the product and its use and are willing and able to pay for adoption. If applications are unknown or if customer groups do not exist, are not able to obtain the product or are unaware of the benefits of the product, large-scale diffusion is blocked. |
| 6. Institutional aspects (laws, rules and standards) | The regulatory and institutional environment refers to the laws and regulations that indicate how actors (on the supply and demand side of the market) deal with the socio-technological system. These laws and regulations can either stimulate the application of radically new high-tech products (such as subsidy that stimulates the use of sustainable energy) or completely block it (such as laws prohibiting something). |
| 7. Knowledge of technology | The knowledge of the technology refers to the knowledge required to develop, produce, replicate and control the technological principles in a product. In many cases a lack of knowledge blocks large-scale diffusion. |
| 8. Natural resources and labour | Natural resources and labour are required to produce and use a new high-tech product. These resources and labour can be required for the production system, for complementary products and services or for the product itself. In many cases a lack of resources and labour block large-scale diffusion. |
| 9. Knowledge of application | Knowledge of the application can refer to knowing potential applications. If a technological principle is demonstrated but there is no clue about its practical application, large-scale diffusion is impossible. A lack of knowledge of the application can also refer to customers that do not know how to use a new product in a particular application. In that case large-scale diffusion is not possible. |
| 10. Socio-cultural aspects | Socio-cultural aspects refer to the norms and values in a particular culture. These aspects might be less formalized than the laws and rules in the institutional aspects but their effect might completely block large-scale diffusion. |

| Factors | Description |
|---|---|
| 11. Macro-economic aspects | Macro-Economic aspects refer to the economic situation. A recession can stifle the diffusion of a new high-tech product. |
| 12. Accidents or events | Accidents or events such as wars, accidents in production, accidents in the use of products can have a devastating effect on the diffusion of a new high-tech product. |

Table 11.1: Factors that can create barriers defined in R. Ortt et al. (2013)'s article

To weigh and rank these factors, criteria have to be generated on which these factors can be evaluated. The end product will be a decision making matrix with alternatives on the vertical axis and the criteria on the horizontal axis, as can be seen in Table 11.2. Two matrices will be generated, first one to determine the weigh of the factor (could be 0 as well), which will look like Table 11.2 but without the Weight column. And a second one in which the importance and the weigh will be combined to give a total score, as can be seen in Table 11.2

| F/C | Criterion 1 | Criterion 2 | Criterion 3 | Criterion 4 | Weight | Total |
|---|---|---|---|---|---|---|
| Factor 1 | | | | | | |
| Factor 2 | | | | | | |
| Factor 3 | | | | | | |
| Factor 4 | | | | | | |
| Factor 5 | | | | | | |
| Factor 6 | | | | | | |
| Factor 7 | | | | | | |
| Factor 8 | | | | | | |
| Factor 9 | | | | | | |
| Factor 10 | | | | | | |
| Factor 11 | | | | | | |
| Factor 12 | | | | | | |

Table 11.2: Matrix with the alternatives on the vertical axis and the criteria on the horizontal axis