CURRENT STATE OF
QUANTUM INFORMATION TECHNOLOGIES IN TURKEY

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ABSTRACT

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Quantum Information Technologies is a relatively new field of research with respect to already established industries. Especially subjects like quantum computing, quantum sensing, quantum communication, and quantum cryptography are expected to be disruptive technologies to many sectors of today. In this study, the field of quantum information technologies is investigated with respect to Perez and Soete's approach of techno-economic paradigms. In this respect, study at hand investigates the current conditions in Turkey regarding these technologies and aims to develop policy suggestions accordingly. To achieve this goal, information gathered via National Thesis Center, Web of Science database, market study and assessment reports, public access policy papers, and semi-structured interviews with experts in the field of quantum technologies are utilized. The results of the descriptive analysis reveal that Turkey does not meet the minimum requirements to appropriate the phase one window of opportunity created through the technological revolution to upswing its entire economy. However, it does possess enough scientific knowledge and locational advantages to justify a coordinated and national effort on quantum metrology and cryptography.

Keywords: Techno-economic paradigm, quantum technologies, science policy

ÖZ

TÜRKİYE'DE KUANTUM BİLİŞİM TEKNOLOJİLERİNİN
MEVCUT DURUMU

Seskir, Zeki C.

Yüksek Lisans, Bilim ve Teknoloji Politikası Çalışmaları Bölümü

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Kuantum Bilişim Teknolojileri yerleşmiş endüstrilere kıyasla görece daha yeni bir araştırma alanıdır. Özellikle kuantum bilgisayım, kuantum algılama, kuantum iletişim ve kuantum kriptografi gibi alanların günümüz sektörleri için yıkıcı yenilik teknolojileri olması beklenmektedir. Bu çalışmada, kuantum bilişim teknolojileri Perez ve Soete'nin tekno-ekonomik paradigmalar yaklaşımı üzerinden ele alınmaktadır. Bu bağlamda, eldeki çalışma Türkiye'de bu teknolojilerin mevcut durumunu inceleyip bunlara uygun politika önerileri geliştirmeyi amaçlamaktadır. Bu hedefe ulaşmak adına, Ulusal Tez Merkezi, Web of Science veritabanı, piyasa araştırma ve değerlendirme raporları, kamuya açık politika yayınları ve kuantum teknolojileri alanında uzmanlarla gerçekleştirilen yarı-yapılandırılmış mülakatlar kullanılmıştır. Betimsel analizin sonuçları Türkiye'nin mevcut teknolojik devrimin oluşturduğu birinci faz fırsat aralığını tüm ekonomiyi iyileştirme adına gerekli minimum koşulları sağlamadığını göstermektedir. Ancak, kuantum metroloji ve kriptografi alanlarında koordineli ulusal bir çabayı haklı gösterebilecek bilimsel bilgi zeminine ve bölgesel avantaja sahiptir.

Anahtar kelimeler: Tekno-ekonomik paradigma, kuantum teknolojileri, bilim politikası

To the KOBİT community

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LIST OF ABBREVIATIONS

ARDEB	Academic Research Funding Program Directorate
BİLGEM	Informatics and Information Security Research Center
BTK	Information and Communication Technologies Authority
COST	Cooperation in Science and Technology
CPU	Central Processing Unit
DPT	State Planning Organization
ERA	European Research Area
FET	Future and Emerging Technologies
HDD	Hard Disk Drive
ICT	Information and Communication Technologies
ISO	International Organization for Standardization
KOBİT	Quantum Optics and Information Meeting
KOSGEB	Small and Medium Industry Development Organization
MAM	Marmara Research Center
NISQ	Noisy Intermediate-Scale Quantum
NIST	National Institute of Standards and Technology
NSA	National Security Agency
NQIA	National Quantum Initiative Act
PAR	Photosynthetically Active Radiation
QED-C	Quantum Economic Development Consortium
QIA	Quantum Internet Alliance
QIT	Quantum Information Technologies
QKD	Quantum Key Distribution
QPU	Quantum Processing Unit
QRNG	Quantum Random Number Generator
QT	Quantum Technologies
QUESS	Quantum Experiments at Space Scale
R&D	Research and Development
RAM	Random Access Memory
ROM	Read-only Memory

S&T	Science and Technology
SSD	Solid State Disks
TEP	Techno-economic Paradigm
TEYDEB	Technology and Innovation Grant Programs Directorate
TR	Technological Revolution
TRL	Technology Readiness Level
TÜBİTAK	The Scientific and Technological Research Council of Turkey
UKNQT	UK National Quantum Technologies
UME	National Metrology Institute
YÖK	Higher Education Council

CHAPTER 1

INTRODUCTION

Second quantum revolution is a term coined by Dowling and Milburn at 2003 in their article *Quantum technology: the second quantum revolution*, which coincidentally coins the term quantum technology as well. Back then, the word quantum was exciting to most people, but nobody was interested in investing hundreds of millions of dollars in startups specialized in anything quantum. It was a novelty, but not a risk worthy opportunity. The tide has turned in the last 15 years, today there are billions of dollar worth of investment in the areas labeled as quantum technologies.

The main idea of this thesis was formed between late 2016 and early 2017, as developments in the field started accelerating globally but in Turkey, there seems to have been a limited response from only a handful of people. As a developing nation with ambitions of being a regional powerhouse in science and technology (S&T) fields, and with an already envisioned plan for quantum technologies (TÜBİTAK, 2004), the level of local interest in these fields appeared to be missing the level of enthusiasm abroad. Reasons for this lack of apparent interest caused the first intriguing appeal of the subject as a possible thesis study.

Within the context of techno-economic paradigm approach, technological revolutions can be used as a window of opportunity for developing countries to catch-up (Perez & Soete, 1988). The first quantum revolution brought forth inventions such as the laser and transistor, which are the building blocks of Information Age. Therefore, for a developing nation, identifying whether the second quantum revolution in science is going to translate into a techno-economic paradigm shift is an important issue. And if this is the case, does Turkey possess the means to utilize this window of opportunity to gain an advantage against already developed competitors seemed like a legitimate question of concern.

After combining these two, the backbone of this thesis appeared as a study on describing the current conditions regarding quantum technologies in Turkey, and if there is an actual window of opportunity that Turkey can or should try to exploit as a catching-up mechanism. For a research question, the one above does not possess a clear-cut yes or no answer. Instead, it serves as a guide in order to develop a set of policies that can be adopted regarding this particular field of technologies.

To devise these policies, there are several questions to be answered initially. First one is, whether quantum technologies actually be accounted as a technological revolution by themselves. A somewhat extensive discussion on this topic is provided in Chapter 2, though the answer given is not a distinct yes or no. Quantum physics is definitely going to play a major role in this centuries technological developments, as it has already played a major role in the 20th century. Whether this role will overshadow the other major technological developments in the fields of biotechnology, artificial intelligence, smart technologies etc. and allow it to be the defining piece of the next paradigm is an open question which cannot be answered right now in a definitive manner.

The second one is where the world stands regarding the extent of these technologies. There are many developments around the globe, national and international plans, established firms getting into the field and new startups popping up every month. However, compared to other major technological developments, the market penetration still seems rather limited and actual returns on investments are future-oriented. There is clearly a hype, but whether this hype is going to be followed by an era of market growth or a quantum winter (Economist, 2018) is unclear.

The third one, which constituted the major effort in this study, is where Turkey stands regarding quantum technologies. There is clearly a certain amount of activity, though it appeared to be focused in the academic realm. During the course of last two years, within the limits of this study, 15 interviews and a group meeting were performed, hundreds of public access documents investigated, and available datasets such as National Thesis Center were scattered to find information on quantum technologies related activities. The main limitation of this thesis is also the one that made it most interesting for the author, the events are unfolding at a fast pace as this study is being written. Therefore, it is duly noted by the author that policy suggestions developed in this thesis are only aimed for Turkey and for a very specific point in history.

An important point of techno-economic paradigm approach is that there are two windows of opportunity for developing countries to take advantage of at every paradigm. First one is at the beginning, while the technological revolution is occurring. The second one is near its end, as the technology is mature and developed to its almost final form. These two have different prerequisites and patterns of growth, therefore to make a choice between them requires extensive knowledge on the current conditions that Turkey is in regarding the new and unfolding paradigm.

There is an extensive appendix section covering specific quantum technologies (Appendix A), firms on quantum technologies (Appendix B), reports on quantum information technologies (Appendix C), the interview guide followed by certain outcomes of code analysis (Appendix D), the list of academic theses accessed through National Thesis Center and further information on Turkish academia (Appendix E), and a list of potential shareholders for a national quantum coordination effort (Appendix F). This is aimed to benefit both academic and non-academic readers, to be utilized in further studies.

In the following chapter, quantum technologies are introduced. Questions such as why the current information and communication technologies (ICT) paradigm is closing to its end, what is different in a 'quantum internet' with respect to the already existing classical one and how are they related, what is considered as a 'quantum technology' and some developments in national and international levels are covered in that chapter.

Chapter 3 contains the literature review and a discussion on whether quantum information technologies is a technological revolution. Concepts of systemic problems which are utilized in the following chapters, the rationale for public intervention, and catching-up in technology are presented in this chapter. Furthermore, a brief side note on mission-oriented policy approach is also included there to express that there are other theoretical constructs which can be adopted to study this subject.

Chapter 4 is the methodology chapter and also includes the introduction of methods employed in this study. Both quantitative and qualitative methods are utilized for data collection and generation on national and global scales. For quantitative sections document analysis and numerical analysis are used, and for qualitative sections interviews, group meeting and observations are performed. Data collected through quantitative means are for exploratory and descriptive outcomes while data generated by qualitative methods are mainly reserved for interpretative purposes.

Chapter 5 focuses on data and findings through descriptive analysis. Global quantitative data on spending, publications, patents and number of firms in quantum information related fields are given initially. This is followed by the qualitative data on EU Quantum Flagship and the importance of China in global discussions. Quantitative data on Turkey through strategic plans, Vision 2023, spending data of State Planning Organization (DPT), reports from TÜBİTAK, National Thesis Center findings, and network mapping constructed through Web of Science data are presented. The qualitative section on Turkey mostly consist of data generated via observational means, 15 interviews and a group meeting.

Descriptive analysis section of Chapter 5 focuses on developing national and global themes through data. The Turkish themes generated are *Resource Management*, *Strategic Thinking*, and *Trust*. These themes are considered as umbrella terms for systemic problems. Extensive notes on code clusters and systemic problems are presented in Appendix D on their own, however, they are not included in the descriptive analysis section. The global themes developed are *Lock-in*, *Exploration vs. exploitation issues*, and *Excessive focus on innovation and commercialization*. These themes are noted as possible pitfalls that policies imitating the ones in Europe and the US might entail in future and caution prehand is advised.

Chapter 6 focuses on policy suggestions for Turkey in the face of this second quantum revolution, this chapter also concludes the thesis and lays possible questions for further studies. Policy focuses in this chapter are *Resource Management*, *Strategic Thinking*, and *Trust* that are directly translated from Chapter 5. Sets of policy focuses are provided for each topic, a brief summary of these are provided in Table 1.1 below. This chapter also includes suggestions for further studies, and three sets of practical milestones for short-term, mid-term and long-term policy implementations.

This thesis study is aimed to fill an important gap in the current conditions in Turkey on a newly emerging field of technologies. There are other studies investigating the development and catching up in the technology of certain sectors and industries in Turkey, this work can be utilized as a complementary study to those, or as stand-alone descriptive research. It covers global and national data in order to give a complete understanding of the current conditions, not only in Turkey but globally.

Table 1. 1: Three sets of policy focuses

Resource Management - Training a 'quantum aware' workforce - Expanding education - Focused R&D *Strategic Thinking* - Hybridization - Standardization - Integration to value chains and market formation - Prioritization *Trust* - Centralization of authority and impact assessment - Supporting national and international collaboration - Increased awareness on public, academia and industry scales

The societal relevance of quantum technologies is a hot topic of discussion too. Funding of research on quantum computation is heavily related to Shor's algorithm, which can be used for cracking RSA, the most widely used cybersecurity infrastructure of today's virtual world of everyday interactions. Meanwhile, methods developed in the field of quantum cryptography such as quantum key distribution are shown to provide 100% secure communication. China openly declares its interest in quantum cryptography and it has a clear lead on the US on benchmark achievements (first quantum communication satellite, first commercial quantum network and so on) and patents.

Quantum technologies promise many developments from simulating molecules to develop much more efficient chemical processes for agriculture, medicine, and every aspect of chemical processing. It promises heightened resolution on sensing devices which can see beyond large masses or much more smaller objects that can be used for oil exploration, search and rescue operations or detecting stealth jet fighters. Quantum computing promises unimaginable speed-ups for optimization processes that can be used for numerous ways. How much of these promises can be delivered depends on the paths that are going to be taken during the development of these technologies, and for a developing country, it is essential to be aware of the gravity of this ongoing technological revolution.

CHAPTER 2

QUANTUM INFORMATION TECHNOLOGIES

As a newly emerging interdisciplinary area of research, quantum information technologies does not possess the strict disciplinary lines of already established fields under physics. To an even further degree of confusion, the terms quantum technologies and quantum information technologies are usually used interchangeably, including this thesis study as well. This is due to the fact that there is no unanimous agreement on what falls under the second quantum revolution and what should be left outside. All in all one thing is clear, there needs to be an upgrade to the current technologies that are either based on classical physics or the first quantum revolution.

In this chapter, the first section is reserved for the question of why ICT needs a 'quantum' upgrade. This is followed by the specific example of quantum internet and its relation to the classical internet. Further exploration of what quantum technologies are, expectations from these technologies, and the current era of quantum computation as a locator follow this. Finally, national and international initiatives around the globe are provided.

2.1 Why ICT Needs a 'Quantum' Upgrade?

Information and communications technologies (ICT) has been the leading paradigm since the 1970s (Perez, 2010). Although it is a relatively new paradigm, it has deep roots grown in 1940s such as the Bombe machine developed by Alan Turing to crack Enigma codes in 1940 (Turing, 2014), the von Neumann architecture published in the First Draft of a Report on the EDVAC around 1945 (von Neumann, 1945) and ENIAC built in 1946 (McCartney, 1999). In his book titled *The Control Revolution*, James Beniger (1986) tracks the lay causes of ICT paradigm shift to even earlier dates such as the tabulating machines used for assessing American census data in the 1890s. Later in the 1930s, IBM took over the tabulating machine business and the term 'supercomputing' was originally used by a newspaper to identify IBM's new machine used for this (Fierheller, 2006).

The ICT paradigm actually has two distinct but intertwined technological aspects, which are information processing and communication. The ideal information processing device in the ICT paradigm is a Turing machine which is an abstract machine that can manipulate symbols on a strip of tape according to a table of rules (Turing, 1937). Although this seems too abstract, any activity which can be performed on an actual computer can be done on a Turing machine as well, hence a universal Turing machine is the ultimate machine which can perform any logical action allowed. The von Neumann architecture is a specific way to implement this abstract Turing machine and it has been the dominating type of architecture for the last 70 years. This implementation rests on separating the memory unit and central processing unit (CPU), furthermore dividing the CPU into Logic Unit (which can perform logical gates) and Control Unit (which can control the outcome of these gates). Other than adding certain computing bus modifications that carry information between components of a computer, the main von Neumann architecture has been and still is the way information processing devices are built.

This model has been standardized as using microprocessors for CPUs, random access memory (RAM) and read-only memory (ROM) as memory units. There are of course additional devices like bus systems, input and output devices (speakers, monitors, USB drives etc.) but the main hardware requirement for a computational machine is CPU and memory. Investigating the trajectory of these two units can answer the need for a quantum upgrade in the information processing side.

The second aspect of ICT paradigm is the communication side. In 1984, the Open Systems Interconnection (OSI) Reference Model was published by the International Organization for Standardization (ISO) which uses the seven-layer model developed by Charles Bachman (Zimmerman, 1980). First three layers of this model are for the media used and final four layers are for hosting, or in more simplified terms the first three are physical infrastructure oriented and the final four are software design oriented but all the layers use both hardware and software components.

This is important because all the ISO devices developed after this date, meaning all of the computers, smartphones, and smart-devices which can communicate, transfer data between themselves or with other devices use this layout. The first layer of this layout is the physical layer which uses bits, ones and zeros. These bits then later transfer through a data link in frames and access networks as packets, from this point on they are transported, segmented and become the ‘information’ in the ICT that everybody knows of. This model also demonstrates very clearly why a quantum upgrade is required eventually.

There is an idea which is referred to as Moore’s Law in computation. It is attributed to Gordon Moore, a co-founder of Intel. Moore’s Law states that the number of transistors per square inch on integrated circuits will double every year (Schaller, 1997). However, there is a fundamental limit to this ‘law’, the size and separation distance between the transistors. The diameter of an atom is around 0.1-0.5 nm and Intel currently have 14 nm wide transistors. Furthermore, the separation between transistors is a problematic issue. To fit more transistors on a chip they are required to be put closer, but when transistors are closer they leak to each other. IBM has announced that it has developed a 5 nm wide transistor with some novel techniques, though it can be clearly seen that this line of progress will meet its end rather soon.

Another main problem in computation is that the von Neumann architecture is reaching its limits. To increase the computational power of devices parallel processing has been seen as a quick solution. This basically means putting another CPU core and divide the processes in between, which has been a main element of upgrades starting from IBM’s POWER4. However, this approach also has a fundamental physical limit and that is the speed of electrons. As these different processing components require further synchronization to tackle harder computational problems, the latency becomes an issue. To overcome this situation, proposals such as optical computing which use photons instead of electrons as basic carriers of information has been put forward, but this requires a complete overhaul of the entire architecture and changing the basic elements of computation from silicon-based transistors to optical elements.

A final major problem in the computation front is the memory. Hard disk drives (HDD) are introduced by IBM in 1956 and became the dominant form of secondary memory units in the personal computers era. However, HDDs have a fundamental limit, which is the motion of the pinhead to write and read. The mechanical motion required due to this pinhead causes latency and write/read problems. As more and more advanced HDDs are developed, the pin has to write and read from a smaller distance. This distance has shrunk from around 0.2 mm to 0.07 mm in years, which bring out problems because any error in this process may cause loss of data permanently. To overcome this and several other problems, the concept of solid state drives (SSD) has been developed and starting from the mid-1990s it's been deployed to military and aerospace uses (Drossel, 2007).

Solid state drives do not have any moving parts but they have lesser data write cycles than HDDs. HDDs basically carve the surface of a disk with high precision and read these marks later. SSDs, on the other hand, hold data in the form of electron formation and gate status, so as the manipulation of fewer electrons and smaller gates become available, SSDs can further develop. This technology is one of the cornerstones of flash disks, SD cards and all other memory devices without moving parts.

For the communication part, a similar but altogether different fundamental limit is coming up. As fiber optic cables are being used for much of the communication today, the need for encoding with more precision and accuracy is needed. This requires the ability to generate, manipulate and detect fewer and fewer photons with ever-increasing fidelity. Hence using non-conventional sensors and single photon sources will become necessities after a certain point.

The actual interest and hype on the communication side of ICT for a quantum upgrade comes from the threat of quantum computers to classical cryptography and communication. Most of our online activities involve public-key cryptography which heavily relies on the complexity of protocols applied. For example, RSA (Rivest–Shamir–Adleman) was published in 1977 (Rivest et al. 1978), in those days it was considered as "A new kind of cipher that would take millions of years to break" (Gardner, 1977). In 1994, it was decrypted in 8 months. Hence the encoding processes have been getting more and more complex every day with increased key sizes which creates additional costs both in latency and the size of data transmission. However, there is a more important problem than the ever-increasing costs, that is the possibility of a universal quantum computer. Through an algorithm devised for quantum computers in 1994 by Peter Shor, breaking RSA becomes exponentially easier for quantum computers, so a decryption requiring millions of years of computation time in classical computers can reduce to mere weeks or days. This is sometimes referred to as quantum crypto-apocalypse.

Certain proposals to overcome this apocalyptic scenario has been proposed. Two of these are the mainstream approaches. First one is to create quantum key distribution schemes utilizing phenomena like quantum superposition and entanglement, there are many companies researching, developing and selling such systems and devices. The second approach is to develop post-quantum cryptography schemes which are resilient to Shor's algorithm or to any future quantum computation algorithms if possible. Both of these approaches require a complete overhaul of already existing security infrastructure for online shopping, finance, e-mail services etc. basically everything that requires a password from the user.

In conclusion, both sides of the ICT paradigm are becoming to hard limits due to the physical restrictions imposed through classical physics on the further development of such technologies. Manipulating fewer number of electrons and photons, working with ever-shrinking sizes and in higher efficiency environments (meaning colder environments due to laws of thermodynamics) are forcing the developers of information processing and communication technologies to explore physics beyond the classical realm, which is the domain of quantum mechanics.

Even without any reference to the new capabilities that can be obtained through the use of quantum mechanical phenomena such as superposition or entanglement, one can still expect huge progress on the quantum engineering part of ICT. Even more, as discussed above a quantum upgrade does not only allow higher efficiency or a possible extension to Moore's law but will also bring forth previously non-existing capabilities to the fields of computation, information processing, and communication. To see an example of this overall transformation process, quantum internet can be taken as a particular case (for other specific technologies such as quantum radar and lithography, please refer to Appendix A).

2.1.1 Quantum Internet

The concept of a quantum internet was popularized by Jeff Kimble at Caltech over a decade ago. Today, that vision of integrated quantum networks which can "accomplish tasks that are otherwise impossible within the realm of classical physics" (Kimble, 2008) is becoming a reality. Hence, it is important to identify what is a quantum internet, how is it different from the classical internet and who are working on it to what end.

A quantum internet is basically a widened quantum network which has the capacity to send quantum bits (qubits) faithfully, perform distributed quantum computing and enable two-way quantum communication. Through using these properties such a network provides secure communication (Liao et al., 2018), secure identification (Boulat et al., 2015), position verification (Dür et al., 2017) and secure dedicated computing through the cloud (Barz et al., 2012).

The differences from the classical internet are due to two peculiarities of quantum mechanics. First one is that quantum information cannot be copied (Wooters & Zurek, 1982). Due to the no-cloning theorem, it is theoretically impossible to create an exact copy of a quantum state. This doesn't necessarily mean that an approximate copy cannot be generated, however, it guarantees that if such an effort has been undertaken a trace of such an action will be left on the state which can later be identified revealing that the state has been tampered with.

The second peculiarity is quantum entanglement (Einstein, Podolsky & Rosen, 1935; Schrödinger, 1935). This property of quantum mechanics allows the generation of schemes such as quantum key distribution - QKD (Bennett and Brassard, 1984) and quantum teleportation (Bennett et al., 1993), which in return pave the way to quantum cryptography (Townsend, 1994). There are numerous protocols and algorithms related to quantum cryptographic processes today and the initial hype which sparked the interest in quantum networks was due to the secure communication promise of quantum cryptography. Below, on table 2.1, quantum networks dedicated to QKD protocols can be found.

Table 2. 1: Major quantum networks dedicated to QKD protocols

Location	**Year**
DARPA QKD Network, Boston	2001
SECOCQ QKD Network (in Vienna)	2003
Tokyo QKD Network	2003
Hierarchical Network in Wuhu, China	2009
Geneva Area Network (SwissQuantum)	2010
Los Alamos National Laboratory	2011
Kazan Quantum Network (Russia)	2016
Beijing-Shanghai Trunk Line	2017

Even though there are many quantum networks over the globe right now, some of which are commercialized (Martina, 2017), a fully operational quantum internet still presents many technical and theoretical difficulties. Since a quantum internet is radically different from a classical internet, there are technical problems which do not exist for the current infrastructure. One of the main challenges is to distribute entangled particles over great distances (Briegel et al., 1998). There are many different proposals to overcome this problem but the differentiation between these ideas is not possible mainly because no standardized infrastructure is in place. This means that there is no way to decide which of the theoretical proposals will fit better to the global quantum internet infrastructure, it is a textbook technological path dependence problem (Liebovitz & Margolis, 1995).

There is a group called Quantum Internet Alliance (QIA) which identifies their goal as "to develop a Blueprint for a pan-European entanglement-based Quantum Internet", that is being funded by EU Flagship for Quantum Technologies. All of the partners of this alliance are from Western European countries and the initial main objective is to realize a model quantum internet in the Netherlands between Amsterdam, Delft, Leiden and The Hague by 2020. This 4-node model was adopted to resemble a quantum version of the ARPANET, which was developed by US Military in the 1960s and had 4 nodes initially (Castelvecchi, 2018).
Similar efforts can be found in the US, China, Canada, and Japan as well. Microsoft, IBM, Google, and many other major IT companies have their dedicated 'quantum' departments. China and Canada have major academic investments and the Japanese NTT has patents on subjects like 'quantum repeater network systems' which is a possible infrastructure that a quantum internet can be built upon. QKD networks are already here and a step further is quantum intranets. There seems to be some time before a global quantum internet that resembles the current classical internet arrives due to infrastructure and standardization issues. However, the QIA is appearing to be playing an important role in this sense. Intel invested $50 Million to QuTech (Intel, 2015) and the Chinese QUESS (Quantum Experiments at Space Scale), which launched the world's first quantum satellite in 2016 (Liao et. al, 2017), is coordinating with Austrian Academy of Science IQOQI. Both QuTech and IQOQI are the main partners of QIA.

As a conclusion, it should be noted that a model of the quantum internet is planned to be implemented by 2020 in the Netherlands within a wide pan-European network with external connections to US, China, and Canada. It is a regional effort which in return can divert the technological development path of a possible future key general purpose technology similar to the classical internet (Clarke, Qiang & Xu, 2015). As with any radically new technology, all applications of a quantum internet cannot be foreseen yet. All applications of the classical internet cannot be foreseen either. However, since a quantum internet will be intertwined with the global classical internet of today, it won't be a surprising phenomenon to see that two of them being combined.

All these distinctions of a 'quantum' internet seem to invoke an image of a separate entity, when in fact, both networks are required to be employed simultaneously to perform even today's applications of quantum cryptography and distributed computing. Therefore it would be ill-advised to discard quantum internet as a novelty item which will require time to be of much importance when in fact it should be regarded as an extension to the already present infrastructure of the classical internet, that will enable new feats which are impossible now. A new era of the current internet rather than a new internet by itself could be expected.

2.2 What are Quantum Technologies

The clear term of quantum technologies was not adopted immediately. There are many articles and newsletters referring to the field as 'quantum information processing and communication technologies', 'quantum information and communication technologies', 'quantum information technologies (QIT)' and finally 'quantum technologies (QT)'. The last two, QIT and QT, are used widely. Therefore during the course of this study, QIT and QT are used interchangeably.

The discussions above revolve around considering quantum technologies as a natural extension (or even a subgroup) of information and communication technologies, still, it needs a more precise description to be handled in the policy realm. According to the National Quantum Initiative Act (NQIA) of 2018 (H.R. 6227), the term "quantum information science" means the storage, transmission, manipulation, or measurement of information that is encoded in systems that can only be described by the laws of quantum physics. Early documents on EU Flagship for Quantum Technologies group these in three categories; computers/simulators, communication systems, sensors/measuring devices (EC, 2016). On the final report (HLSC, 2017), quantum communication, quantum computation, quantum simulation, quantum sensing and metrology were decided as the definitive grouping into categories. Therefore, when quantum technologies are referred to in public area, they are a combination of technologies that fall under NQIA's definition but can be grouped according to QT Flagship Final Report (2017, p.9).

As it can be seen in the case of quantum internet, it is not easy to separate or distinguish these categories completely. Quantum internet, which is mainly a technology related to quantum communication can also be used for distributed quantum computation, or synchronized timing to aid higher precision measurements (i.e. quantum metrology). These technologies are interconnected, hence together they form a technology system which allows them to be named as 'quantum technologies'. The discussion on technology systems in the next chapter illustrates the importance of this bundling together more clearly, and how progress in one field can benefit the entire bunch due to reinforcing externalities generated.

2.2.1 Expectations from Quantum Technologies

The expected timeline for most of the technologies above vary from 5 to 20 years and beyond. Quantum communication, as an example, is projected to have a 1 billion euro worth of market size in the year 2020 and a growth rate of 20 percent for each following year, the potential overall global market for just quantum cryptography could reach 23 billion dollars within twenty years (Jennewein & Choi, 2014).

Quantum sensing is another field with anticipated near-term applications in healthcare, biotechnology, infrastructure monitoring, security and defense. Sensing and imaging devices utilizing quantum technologies will not just have higher precision or performance but they will also enable new capabilities and feats which were previously not possible through classical means.

Quantum computation and simulation are expected to be dispersed into key sectors like finance, pharmaceuticals, transportation, and energy efficient materials & processes (CIR, 2018). This is due to the fact that quantum computers having a wider range of possibilities than classical computers. For certain tasks quantum computers will be exponentially faster than classical computers, for others, they will have the same efficiency, but the ones that quantum computers allow speed-up are societally relevant (Wolf, 2017). For example, quantum computers can help to solve complicated nitrogen fixation problems (Reiher, 2017), giving the researchers ability to surpass the Haber-Bosch process which has been the main method for artificial nitrogen fixation procedure used for the production of ammonia in the industry for over 100 years. Simulating the quantum effects in photosynthesis

(Thyrhaug et al., 2018) is another major expectation, which has the potential of revolutionizing energy efficiency related processes in industries.

Another important and relevant type of problem that quantum computation can speed-up is the traveling salesman problem (Moylett et al., 2017), and constrained optimization problems in general (Hen & Spedalieri, 2016). This type contains a wide range of practical problems that would be economically and societally desirable to solve, such as traffic route optimization, logistics of trade, water distribution and so on. This is also closely related to how quantum computing is going to affect the big data analytics (Shaikh & Ali, 2016).

A combination of these technologies together can further add to their potential impact on other sectors. ESA is exploring 'Quantum Computing for Earth Observation' and NASA has its own quantum computing project (Biswas & Rieffel, 2017). Quantum sensors can provide the most precise measurement results, using the superior computing power of quantum systems to process the vast amount of data collected from satellites via these sensors can yield efficiency increases in agricultural planning, help monitor schools of fish, and many other processes that have nothing to do with quantum technologies at first glance. Therefore, the expectations are getting higher with every new idea where these technologies can be employed to obtain an advantage against their classical counterparts.

This does not mean everybody expects or desires quantum computing to become the next major paradigm, there have been people trying to develop classical counterparts of quantum algorithms for years, even for the most iconic algorithms like Deutsch's algorithm (Calude, 2007). However, these efforts are also in align with the studies in quantum computation and aimed at developing it, figuring out where quantum computation actually exceeds classical computation rather than blocking the progress of the field. Even from the early 2000s, the concept of quantum-inspired algorithms was used in the context of classical computation paradigm to develop classical algorithms that were 'inspired' by the quantum computational thinking (Han & Kim, 2002). It is a common practice now for every quantum algorithm, there is someone trying to figure out a better classical algorithm using this touch of inspiration from the quantum case[1].

[1] for a list of quantum algorithms, check the Quantum Zoo page on NIST's website; 'Algebraic and Number Theoretic Algorithms' - https://math.nist.gov/quantum/zoo/

2.2.2 Current Era of Quantum Computation

The current era of quantum computation is called as NISQ era, the noisy intermediate-scale quantum (Preskill, 2018). To understand this era, initially the difference between a logical and a physical qubit should be defined. In a broad sense, a logical qubit is a mathematical abstraction of a perfect operating unit devoid of any error. A physical qubit is the realization of this abstraction on a physical system, which can range in size from just a single electrons spin to millions of photons behaving in a certain way. A logical qubit can be realized in a multitude of physical ways, each having their strengths and weaknesses.

In the last couple of years the number of physical qubits that can be produced is increasing rapidly, but a physical qubit does not necessarily correspond to a logical qubit perfectly. To perform quantum operations, it is the logical qubits that are required. Hence, the current goal of many researchers is to increase logical to physical qubit ratios through either error correction mechanisms or novel design methods for physical qubits.

The discussion above directly translates to which aspects of quantum technologies will enter the market first. Quantum cryptography and sensing are going to be widely available before computation; for Shor's algorithm, thousands of logical qubits are required, for quantum sensing protocols ten are enough, for quantum key distribution only one suffice.

Therefore it is argued by Preskill that NISQ era developments are not likely to change the world, but rather provide advantages against classical counterparts. The main idea here, which is also emphasized in the Quantum Manifesto document, is that the transformation process toward quantum technologies is going to unfold in many decades, not within just 5 to 10 years. However, the direction in which these developments are going to be, especially on the economically relevant side, is going to depend on decisions taken today. Silicon-based microprocessors were not the only candidate for a basis of classical computation devices, adoption of this particular technology laid the foundation of Information Age's infrastructure. Similar choices are being made for the quantum technologies of the future, now.

2.3 Developments Around the Globe (up to late-2018)

In this section, some of the big developments and plans around the globe are covered up to late-2018. As the idea of this thesis formed, there were only quantum annealers of D-Wave and the toy model devices of IBM. At the moment, there are attempts by at least four major tech-players (IBM, Intel, Google, Alibaba) to achieve universal quantum computing. There was no National Quantum Initiative Act (NQIA) or EU Flagship for QT. Even if the hype slows down, many more developments are surely bound to happen before this study reaches to its respective audience. Therefore, the timeline for the developments in this section is limited up to late-2018.

2.3.1 National Initiatives and Developments

Table 2. 2: Overview of the national initiatives and programs

Name of the programme	Country and year of origin	Overall Budget
Centre for Quantum Technologies (CQT)	Singapore - 2007	158 M$ (million dollars)
UK National Quantum Initiative	United Kingdom - 2013	270 M£ (million pounds)
QuTech Delft	Netherlands - 2014	145 M€ (million euros)
Austrian Quantum Technology (AQT) Initiative	Austria - 2017	35-40 M€ (million euros)
National Quantum Technology Program of Hungary	Hungary - 2017	11 M€ (million euros)
Wallenberg Centre for Quantum Technology	Sweden - 2017	100 M€ (million euros)
New South Wales Quantum Computing Fund	Australia - 2017	26 M$ (million dollars)
Quantum Canada	Canada - 2017	---
Quantentechnologien – von den Grundlagen zum Markt	Germany - 2018	650 M€ (million euros)
Helen Diller Center for Quantum Science, Matter, and Engineering	Israel - 2018	50 M$ (million dollars)
National Quantum Initiative Act	United States - 2018	1.2 B$ (billion dollars)
Quantum Information Sciences Center in Hefei	China - 2020	10 B$ (billion dollars)

A general overview of the programs introduced here can be found in table 2.2 above. Extended information on these is provided following this summary. Some of the initiatives given are not national programs in a strict sense. For example, the “Helen Diller Center for

Quantum Science, Matter, and Engineering" is a donation to Technion in Israel rather than a public investment scheme, and Quantum Canada is a public program with an indeterminate budget with the aim of coordinating the already ongoing endeavors in the country. It should be noted that countries like Israel, Russia, and Japan do have their own approaches, however, any public access documents explicitly noting these activities could not be reached. This can be attributed to both the language barrier and cultural differences on public access policy papers.

The UK National Quantum Technologies (UKNQT) Programme was put forward in 2013 with a 270 million pounds budget to "accelerate the translation of quantum technologies into the marketplace, to boost British business and make a real difference to our everyday lives". Under this initiative, four quantum technology hubs were formed to allow collaboration between universities, and reinforce industry-university relations. Centres for Doctoral Training in quantum technologies were founded to train the next generation of researchers equipped with the necessary skills to deal with potential problems, and utilize opportunities that may come. Innovation and industry are central to the structure of UKNQT. Events like Quantum Innovation Lab are being held annually to figure out how quantum technologies can be integrated with already existing sectors to develop solutions for practical problems they have. Finally, social awareness campaigns and promotional events are funded through this program to increase the diffusion of knowledge on these technologies to the public.

QuTech Delft is another relatively early initiative that was launched in 2014, with an overall estimated budget of 145 million euros. It was founded as the result of a collaborative process between TU Delft and TNO (Netherlands Organisation for Applied Scientific Research) and later expanded with additional support from funding sources like Microsoft and Intel (QuTech, 2017). One of the main objectives of the center is to demonstrate a model quantum internet with four nodes by 2020. Large networking groups like Quantum Internet Alliance (QIA) help form bonds between European researchers and institutions. Open online courses through QuTech Academy allows public greater access to developments in quantum technologies.

Austrian Quantum Technology (AQT) Initiative (Weitgruber, 2017) is another national programme that allocates around 35-40 million euros for funding in research and development (R&D) related to quantum technologies in a five year period between 2016-2021. The main goals of this program are related to developing relevant skills and infrastructure in quantum technologies, and to support the transfer of R&D outcomes into value. Maybe the essential difference between AQT and the other programs mentioned above is that the Austrian initiatives aim to design are more focused on reinforcing Austria's position in the European frame, therefore it seems to be tailored in accordance with the Flagship programme.

Another national program is the National Quantum Technology Program of Hungary (Domokos, 2017) developed by National Research, Development and Innovation Office (NKFIH), which also incorporates the HunQuTech consortium. The Office allocates 11 million euros for research projects under QTech program, between the years 2017-2022. The consortium allows coordination and collaboration between universities, research groups, and industry members such as Bonn Hungary Electronics, Ericsson Hungary, Nokia-Bell Labs, and Femtonics. The program is focused on strengthening the national research capability by investing in human resources, mobility, and infrastructure.

Wallenberg Centre for Quantum Technology is a decadelong SEK 1 billion (around 100 million euros) investment programme in Sweden, which is largely funded by the Knut and Alice Wallenberg Foundation (WACQT, 2017). Its core ambition is developing a quantum computer, however there is also research on quantum sensing, communication and simulation.

Germany's Framework Program of the Federal Government (Rahmenprogramm der Bundesregierung) on quantum technologies within the High-Tech Strategy Innovations for Germany (Hightech-Strategie 2025) is published in September 2018 by the Federal Ministry of Education and Research (Bundesministerium für Bildung und Forschung-BMBF, 2018). In the document, it is noted that funding for quantum technologies has been handled within the framework of the basic financing of research organizations and individual project support measures. Current available quantifiable funds in Germany amounts to approximately 100 million euros per year. Along with this program, additional measures will be funded by the federal government from 2018 to 2022 in the amount of approximately 650 million euros. It is planned, to continue the program until 2028. However, the priorities and responsibilities of financial decisions after 2022 are left to be decided by Federal Government and Parliament in accordance with the further scientific and economic development in the field of quantum technologies and their use. A holistic strategy covering different contributions from four ministries is employed in this program, with a strong policy mix of national and international networking, forming academia-industry partnerships, and signaling.

Singapore's Centre for Quantum Technologies (CQT) was founded in 2007 with a funding of 158 million dollars for ten years. CQT Singapore was the first of Singapore's Research Centres of Excellence to be established (NRF Singapore, 2018). The centre acts as an international hub for leading researchers in the field, where experts from 35 different countries form networks. Currently, there are two startup companies focused on applications of quantum computing which were sprung from the center (check Appendix B for the detailed list of Quantum Companies).

In Australia, the New South Wales government launched a 26 million dollar quantum computing fund (Redrup, 2017). It focuses on forming hubs and clusters of research groups to accelerate the development of the field in Australia. Sydney Quantum Academy is a near-term projected outcome of this initiative, which is expected to be formed near Sydney Nanoscience Hub to leverage the already existing physical and institutional infrastructure.

Canada is one of the forerunners of quantum technologies. D-Wave Systems is the first start-up which was solely focused on quantum computing, it was founded in 1999. In the last decade, it is estimated that over 1 billion dollars went to quantum technologies in Canada (NRC Canada, 2017). Quantum Canada, initiated by National Research Council Canada in 2016, is a national programme to use the relevant S&T knowledge base accumulated in the system and create a market around it. A report published in April 2018 by the NRC titled "Economic Impact of Quantum Technologies" estimates that by the year 2040 the annual revenues from the economic activity of quantum technologies to reach 142.4 billion dollars, and create around 229.000 jobs. To achieve this, Quantum Canada targets strategic industries on how to proceed with the commercialization of quantum technologies. These sectors identified by the program are; communications, mining/extraction, finance, defense & security, health, energy, big data

Another aspect of Canadian involvement in quantum technologies is the story of the Institute for Quantum Computing (IQC) at the University of Waterloo, which is an experimental complement to the Perimeter Institute for Theoretical Physics. Both of these are world-leading institutes in their respective fields. This is to a great extent due to one man, Mike Lazaridis, the founder of Blackberry. It is estimated that Lazaridis and his wife have committed more than 122 million dollars in support of developing quantum technologies (Mastrangelo, 2017). He is also a founding member of Quantum Valley Investments, an organization dedicated to the development and commercialization of quantum technologies.

A similar story is unfolding in Israel, where a 50 million dollar gift by Helen Diller Family Foundation been presented to support the “Helen Diller Center for Quantum Science, Matter, and Engineering” (Technion, 2018). This is considered as the single largest gift from an American donor to Israel Institute of Technology - Technion. This is an important development due to the fact that Israel is not involved in quantum technologies on a national level, very unlike the Canadian case where the prime minister explained quantum computation to the public (Butterworth, 2016).

China is constructing a 10 billion dollar worth of Quantum Information Sciences Center (Decker & Yaseijko, 2018) at Hefei to be opened in 2020. They have sent the first quantum communication satellite, called Micius, as a part of QUESS mission, which has successfully demonstrated long-range quantum key distribution, entanglement and other features of quantum information theory. A commercial quantum network is already being used in China for more than a year now (Martina, 2017). ‘General Purpose Quantum Computers’ are also included in the book/report titled ‘Information Science & Technology in China: A Roadmap to 2050’ (Li, 2011) as an area of specific interest.

In the United States, the first quantum computing grant from the government came from DARPA in 1994 (Lloyd, 2016). Countless developments have occurred in the US. IBM and Google are the leading firms in the production of quantum processor units (QPU), much similar as a device to CPU and GPU of today’s classical computers. However, the main development in the US is National Quantum Initiative Act (NQIA) of 2018. It is a direct response to rapid advancements in quantum technologies happening at China[2]. Under this act, a National Quantum Coordination Office within the White House Office of Science and Technology Policy is going to be established, new research centers and projects are going to be launched, and industry integration supported. The estimated budget for NQIA is 1.2 billion dollars for 5 years. Additionally, the Department of Energy announced 218 million dollar funding for 85 research awards in quantum information science in September 2018 (DoE, 2018).

[2] the discussions on Wednesday, June 27, 2018 - 10:00 am session of House Committee on Science, Space, and Technology can be accessed publicly - https://www.youtube.com/watch?v=MlmtqPyFNoc

Turkey does not have a national initiative. Other than two DPT projects completed, around $6 M in total costs, there is no large scale completed infrastructure projects accessible through public channels. There are ongoing Ministry of Development projects and several smaller-scale projects focused on sensing and metrology at National Metrology Institute (UME), however, they are scattered and not coordinated under a national roadmap or coordination office. It is clear that there is an active will towards setting a national course and defining a roadmap in Turkey as well, though the specific direction of this roadmap seems rather unclear and scales are much smaller in comparison with the leading countries like US, UK, Canada or China.

These are several developments happening all around the world in quantum technologies on a national level. Some are focused on generating S&T skills and knowledge base related to the field, some others are aiming to commercialize their already existing basis. Policies do have certain similarities, institutes play an important role, industry-academia partnership is also another main constant. The important lessons to be learned from these initiatives can only be understood by grasping the context they were developed in, and the Turkish context with respect to the particular area of technology.

2.3.2 International Initiatives

European Cooperation in Science and Technology (COST) is a framework that has been active since 1971, supporting cooperation among researchers and scholars across Europe. There are currently over 300 active COST Actions with an average annual budget of 134.000 euros per action (COST, 2017). Out of these, six actions are directly on quantum information technologies, many others are in related fields. Possible basis technologies for quantum technologies such as ion traps, ultra-cold atoms, superconducting qubits, nanoscale quantum optics have their own dedicated actions, and another action is dedicated to quantum technologies in space.

QUESS (Quantum Experiments at Space Scale) is a joint initiative of Chinese Academy of Sciences (CAS), the University of Vienna and the Austrian Academy of Sciences (AAS) that was initiated in 2011 (Kramer, 2018). Micius, which is the world's first quantum satellite, was launched in 2016 (Liao et. al, 2017). First intercontinental quantum communications were performed in early 2018 between Austria and China (USTC, 2018). Neither the cost of Micius nor the operating budget of China's quantum network is public.

EU Quantum Flagship is the third major initiative under Future and Emerging Technologies (FET) programme, following The Human Brain Project and The Graphene Flagship. FET Flagships are joint and coordinated research initiatives with a budget of 1 billion euro each. The initial push for a Quantum Flagship was already present, and 'The Quantum Manifesto' which was signed by over 3400 researchers around Europe gave the necessary momentum for the flagship to be realized. It is closely related to programs like QuantERA, which is a consortium of 32 organizations from 26 countries, and Digital Single Market Strategy for Europe. The first round of calls went around in 2018, and accepted projects will officially be funded starting from 2019. The EU Quantum Flagship is a 10-year project with a roadmap designed for quantum technologies up to 2050.

There are many other small-scale agreements are being signed and put into action. On June 2018 a Memorandum of Understanding was signed between several German and Canadian firms and institutions (TRIUMF, 2018). On September 2018, a collaboration agreement between Singapore and UK on quantum-secured networks was introduced (NRF, 2018a). Similar agreements between many countries, US and Canada as a possible example, are expected in the following period.

2.4 Conclusion

In this chapter, the aim and extent of this study is introduced, and a relatively extensive introduction to the concept of quantum technologies is presented. In the next chapter, concepts of technological revolution and techno-economic paradigm are put forward, together with the idea of technology systems. These are utilized to give an argument on how quantum information technologies can be considered either as a technological revolution itself or a herald of one.

CHAPTER 3

QUANTUM INFORMATION TECHNOLOGIES IN THE CONTEXT OF TECHNO-ECONOMIC PARADIGM (TEP) APPROACH

In this chapter of the thesis study, initially, the essential concepts, technological revolutions and techno-economic paradigm (Perez, 2010), and the rationale for public intervention within systems of innovation approach (Chaminade & Edquist, 2010) is introduced. Later, technological revolutions as a window of opportunity in catching up mechanisms for developing countries (Perez & Soete, 1988) is argued. Finally, these are expanded and operationalized in order to make a case for (i) newly emerging field of quantum technologies show strong signs of a technological revolution, and (ii) public intervention to address either current or soon to appear systemic problems will be beneficial on the long run for any country that will adopt such efforts.

3.1 Techno-economic Paradigm (TEP) Approach

Technological revolution (TR) is a concept located in the neo-Schumpeterian analysis of innovation that examines the structure and role of rate and direction of innovation in accordance with the evolution of technical change. In a reduced context, it can be defined as "a set of interrelated radical breakthroughs, forming a major constellation of interdependent technologies" (Perez, 2010). TR plays an important role in rejuvenating the whole economy as it opens up a new techno-economic paradigm (TEP).

A TEP can be understood, in a crude sense as, a shared best practice 'common sense'. A technical paradigm, introduced by Dosi (1982), is a tacit agreement of the agents involved on many issues such as what accounts as a valid search direction or considered as an improvement against the current version of a product, service or technology. Hence, a techno-economic paradigm is "a best practice model for the most effective ways of using the new technologies and beyond the new industries" (Perez, 2010).

The space of the technologically possible is much greater than of the economically profitable and socially acceptable. Therefore innovation does not occur in a solely technical space, on the contrary, technical change needs to be studied in innovation space where technology, economy and the socio-institutional context converges. Schumpeterian distinguishing of innovation from invention is a key concept for this (Schumpeter, 1911). Invention belongs to the realm of science and technology, wherein innovation, entrepreneurs and managers are focused on turning these technical possibilities into profitable economic realities.

This is not a one-way relation, funding choices and investment decisions of these people in return can steer the research efforts toward a particular direction. These decisions are not made regardless of the socio-economic context. Institutional layout, perceived market potential, and other factors play into this process. Path-dependence also plays a key role here. Market potential often depends on what is already being accepted or rejected, and incorporation of technical changes requires coming together of various sources such as already established codified and tacit knowledge base (Nelson & Winter, 1982; Cowan, David & Foray, 2000). Therefore, the trajectory (Dosi, 1982) of technical change is a dynamic concept, it is not deterministic but it relates to much more than just the technical space.

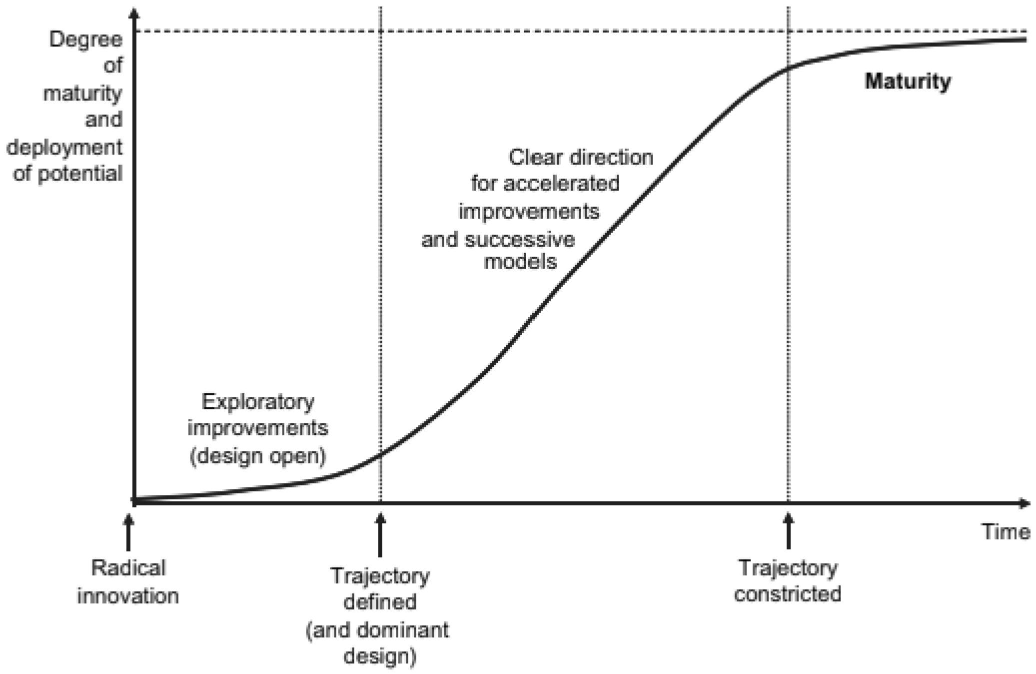

Figure 3. 1: The trajectory of an individual technology (Perez, 2010)

Trajectory of an individual technology (Figure 3.1) starts its course with a radical innovation. Once the market accepts it, the innovation process continues with a series of incremental innovations. The exploratory phase of this trajectory is where a multitude of designs compete. After a period of time and feedback learning processes of producers, designers, distributors, and consumers, a dominant design (Arthur, 1988) settles in and the trajectory is set on its course. After maturity is reached, the law of diminishing returns (Wolf, 1912) prevails in investment decisions toward innovation.

Economic growth and expansion depend on incremental innovation while major innovations play a central role in determining new investment (Enos, 1962). The importance of incremental innovations on processes overtakes those of product changes after the take-off period (Utterback & Abernathy, 1975) and market expansion is accompanied with process innovations that take most of the investment for scaling upward.

Innovations do not occur randomly. Technologies interconnect, appearing in the vicinity of other innovations (Schumpeter, 1939). Their evolution does not take place in isolation either. Suppliers, distributors, consumers, and others partake as agents of change to the innovation process; it is a system. Techno-economic and social interactions of consumers and producers act as complex networks, clusters as referred to by Schumpeter. A radical enough innovation can stimulate whole industries. Introduction of TV did not only led to the growth of broadcast equipment manufacturing, but it also transformed and uplifted advertisement, entertainment industry and so forth. In a similar sense, a TR can stimulate the entire economy, and it does not occur in a random manner.

These clusters referred to by Schumpeter are formed and evolve in a dynamic and interrelated manner. These processes are encompassed in the notion of technology system by Freeman (1974). Diffusion can be taken into account within this system along the trajectory of a technology. Incremental innovations building upon the innovative space opened by the initial phase of radical innovations can even be new industries or mere products and services. As this system evolves, its effect on the outside of the business space is the defining feature for a TEP.

As a new technology system settles, it alters the socio-political environment. New rules, regulations and institutional shifts become necessary. Not only the technological infrastructure is affected but also institutions such as education, healthcare, and social services need to be transformed as well. These institutions have a strong feedback mechanism too, hence as a technology system interacts with them, they shape and guide the direction of its evolution.

Individual technologies do not get introduced in isolation, they are shaped by the already existing innovations in the system. This plays an important role during the exploratory phase of the technologies evolution. Innovations that are radically different but able to exist on current infrastructure and capabilities may have a significant advantage over the short-run even if a better alternative on the long-run is in play. If the opportunity space of that particular system is exhausted through such a product in an early phase, the advantageous version on the long-run may never be actualized. Later innovations on a path tend to be of incremental in nature as discussed earlier.

The complex and elaborate network of interactions on which a technology system evolves is considered as a national system of innovation (Freeman, 1987; Lundvall, 1988). It is also possible to investigate such systems of innovation on regional and sectoral levels (Howells, 1999; Arocena & Sutz, 2000; Malerba, 2002). This is a web of interrelated technologies, knowledge and experience bases, infrastructures, service networks, and learning processes. A well functioning system of innovation provides externalities for all participants and allow competitive advantages for the entire economy.

A collection of technology systems can be considered as a TR if, (i) the technologies and markets are strongly interconnected and interdependent, (ii) they possess the capacity to profoundly transform the socio-economic structure. For a TR to set a new TEP, it needs to guide a vast reorganization, rejuvenation and rise in productivity across already existing industries and rest of the economy at large. It should open an extensive innovation opportunity space, provide previously non-existent generic technologies, infrastructures and organizational principles, which can yield a significant increase in effectivity of all industries and activities (Perez, 2010).

Diffusion and assimilation process of a TR and its accompanying TEP to an economy and society results in elevated levels of productivity and great surges of development (Perez, 2002). It should be noted here that this elevation of productivity does not occur immediately but occurs at a later time, which has been an issue during the IT revolution in the 1980s and captured in essence by Solow Productivity Paradox (Solow, 1987).

Perez (2010) defines five levels on which the interconnection of technologies of a revolution taking place. These are related to their source, requirements of skill, stimulation of upstream development, mutually driving each other through strong interlinkages and coherent consumption patterns that reinforce each other by learning in one system facilitating learning in another, one set of products becoming an externality for the other.

Structure of a revolution demands inter-related new products and production technologies to be significant in number, increasing the importance of new industries. Historically, a TEP tends to have a core all-pervasive low-cost input and one or more new type of infrastructure (Perez, 2010). The core industries of previous revolutions are ranged into three main categories by Perez (1983) and a fourth one is introduced later (2010), they can be found on table 3.1.

Table 3. 1: Four main categories of core industries of previous revolutions by Perez

Motive Branches	Production of cheap inputs with pervasive applicability (such as semiconductors today and cheap steel, coal, water power before)
Carrier Branches	Most visible users of the inputs, paradigmatic products of the revolution (computers and smartphones today, automobiles, steel steamships before)
Infrastructures	Technologies that are part of the revolution which shapes and extends the market boundaries (internet today, transcontinental railways and steamship routes before)
Induced Branches	A set of industries that are not revolutionary in technological terms but indispensable to the TR, they are usually already existent but now take on a different role (globalized trade and internet shopping today, construction industry which made suburbanization possible, that helped the expansion of automobiles and electrical appliances before)

The emergence of a new TEP is identified by a dynamic set of new technologies that bring about transformation across the board, having a multiplied impact on the economy and eventually modify the way socio-institutional organizations are structured. Within such a paradigm, the most successful and mutually compatible practices in terms of inputs, methods, technologies, organizational structures, business models and strategies become implicit criteria and principles to be considered for decision-making processes (Perez, 2010). Newly emerging routines are slowly internalized by agents of all kinds in an economy, and establish a shared logic, a sort of new 'common sense'.

A TEP is constructed simultaneously in three main areas of the following type on table 3.2.

Table 3. 2: Three main areas on which a TEP is constructed upon

Dynamics of the relative cost structure	Appearance of a new (i) key input that is; 1- cheap and getting cheaper 2- inexhaustible or highly abundant 3- all-pervasive in its applications 4- capable of reinforcing the power and decreasing the cost of capital and labor, (ii) infrastructure which; 1- decreases the prices 2- allows greater economies of scale through increasing market reach
Perceived spaces for innovation	Perception of the profitable opportunity space for (i) producers of the new technologies, (ii) users. These opportunity spaces must be internally driven and mutually-reinforcing while creating new spaces for innovation in the rest of the economy
Organizational criteria and principles	Transformation of work and consumption patterns, together with the way production and businesses are organized

To sum up, a TEP is the outcome of a complex collective learning process occurring in a dynamic mental model regarding the best of economic, technological and organizational practices. It is located within the socio-economic system and combines shared directions of change, practices, and perceptions.

Diffusion of TEP provides a common understanding among different agents in a socio-economic structure, however, it is not necessarily a straightforward process, there is always resistance to a certain degree. Organizational inertia in a market economy is overcome by competition, therefore less competitive sections of the structure transform slower. Historically, governmental agencies lag behind and only imitate the TEP principles developed in firms after a while. It is the younger generation that had never learned the principles of the earlier TEP, are the ones whom most naturally adopt these new principles.

As the new TEP becomes the ‘common sense’ understanding both in an economic and socio-institutional framework, it creates a biased context in which an inclusion-exclusion mechanism operates to reinforce the compatible innovations and discourage the incompatible ones. Working and management skills of the former TEP may become obsolete, inefficient or incompatible with the requirements of the current TEP. Therefore this adaptation process demands unlearning, learning and relearning; it disturbs the previously existing socio-economic relations.

In a greater context, technical change is not a random but a path-dependent process. It is not linear, but progressive in a certain sense. It usually spurs from an exhaustion of possibilities along a particular trajectory in terms of productivity and market expansion. Investment decisions and societal concerns affect the new trajectory, the new trajectory in return affects them. Through social learning and adaptive redesign of the institutional framework, wealth-creating potential of a new TEP is actualized. As this new potential is exhausted, another TR begins to form. Those 'new' principles which led to the exponential wealth creation during great surge of development becomes an inertial force against the next surge.

The societal impact of a TR and setting in of a new TEP is transformative on a massive scale. Suburbanization would hardly happen without mass production and automobiles as a means of transport. Globalization could not flourish in a world without fast transatlantic communication, satellites and the internet. All these are developments coming from a place of basic science and engineering, but it is their innovative transformation that helped shape the modern world today.

As stated above, the space of the technologically possible is much greater than of the economically profitable and socially acceptable. Therefore, superior technologies do not necessarily make their way into the socio-economic space and become the new TEP. To bring forth such a huge transformation in a society, the government needs to come into play.

In the context of quantum information technologies, a technological revolution has already begun. The new TEP is not going to be solely based on 'quantum', but quantum information technologies will be an integral part of the newly emerging technology system at the core of next TEP. The fundamental building blocks of future technological fields such as biotechnology, nanotechnology, artificial intelligence, internet of things and so on are going to be physical systems on an atomic scale. Dealing with information systems on this scale necessarily requires the application of quantum information theory, the argument for a 'quantum' upgrade of existing ICT is already given in the previous chapter.

The current transformation can be considered as a TR due to the fact that, as this upgrading seems like a natural progression of the ICT paradigm it opens up a possibility space that is not just an extension of classical ICT. The emergence of a new input, non-classical effects which include entanglement and superposition, the requirement for new infrastructures, and a complete re-thinking of theoretical and practical aspects of the current way of doing things are entailed in this process. At this point, both uncertainty and potential for societal benefit are high, private sector is swooping in for commercialization of matured technologies while most of the possibility space lies still outside of what is economically profitable and socially acceptable. To accommodate this, and maximize the social benefit, public intervention is required.

3.2 The Rationale for Public Intervention

The question of whether the government should or should not intervene to support R&D and innovation can be traced back to the mid-20th century (Arrow, 1962; Nelson, 1959). Designing policies in this respect require balancing a division of labor between private actors and public organizations. The rationales for such intervention to the operations of a free market differ under the neoclassical and the evolutionary theory (Bach & Matt, 2005; Lipsey & Carlaw, 1998; Smith 2000).

The neoclassical approach take the steps between research activity and products or processes that are suitable to be used in the economy as a black box (Rosenberg, 1982; 1994). Under this light, the process of innovation is usually considered as consisting of a fixed path, and research outcomes eventually yield new products almost automatically. Therefore innovation is about generating the knowledge, which is the same as information. It is codified, generic, easily accessible and adaptable.

For the evolutionary case, these assumptions are overturned. In this approach, knowledge emanating from research has some specific properties: uncertainty, inappropriability, and indivisibility (Lipsey & Carlaw, 1998). These three properties, which are also put forward by Nelson (1959) and Arrow (1962), lead to underinvestment in R&D activities by private firms in societal terms. This is considered as a market failure and provides the policymakers with a rationale for the intervention.

Uncertainty in this context means that it is impossible to fully predict the outcomes of a research process and risks attached. Inappropriability implies that firms are not able to appropriate the benefits derived from their own inventions fully and there will always be externalities associated with the research process. Indivisibility refers to the fact that there is a minimum investment limit in knowledge before any new knowledge can be generated (Chaminade & Edquist, 2010).

In this new context, innovation does not occur in isolation. Continuous interactions between organizations at regional, sectoral, national and international levels (Edquist, 1997; 2005; Lundvall, 1992) form the collective underpinnings of innovation. The overall system creates and distributes the knowledge, not the individual firms or actors. Knowledge, whether it is general or specific, is always accepted to be costly to create and diffuse. Therefore it diverges from the neoclassical approach sharply.

The discussion above represents a shift in mindset. Mainstream approach is a linear model, where research automatically evolves into new products and the focus is on allocation of resources for invention that is conducted by individual firms. This has its merits, it is relatively easy to implement and assess. On a macroscopic scale, under the assumptions of equilibrium and homogeneous distribution of information, the mainstream model can be more attractive. However, a newly emerging field like quantum information technologies is neither a system at equilibrium nor its scientific and technical knowledge base is equally accessible or adaptable by all actors. It requires a context-specific approach with a holistic conception of the innovation process that addresses systemic problems by focusing on interactions, networks and framework conditions.

Some of the systemic problems in the literature can be found on the table 3.3 (Carlsson & Jacobsson, 1997; Norgren & Haukness, 1999; Smith, 2000; Woolthuis, Lankhuizen et al. 2005). On the rest of this study, these issues are referred to by their shorthand names.

In this point, it should be noted that the systemic problems above allow a rationale for public intervention only if; (i) the private actors cannot solve these automatically (ii) the public actors have or be able to acquire the ability to solve or mitigate these problems (Edquist, 2001; Chaminade & Edquist, 2006). Later this point is going to be revisited in the context of quantum information technologies and Turkey.

Solving systemic problems can also be a projective endeavor towards the future. A 'problem' might be an issue which has not yet emerged but expected to do so. In this respect, problem-solving of this kind can also be labeled as 'opportunity creating' or anticipatory policy (Chaminade & Edquist, 2010). For example, training the workforce to meet a demand which does not exist yet but projected to be an issue in the following years can also be accepted as a legitimate rationale for public intervention.

Table 3. 3: Shorthand name of the systemic problems found in literature

Shorthand name of the issue	**Explanation**
Infrastructure provision and investment problem	Infrastructures such as transportation (physical), research labs (scientific) and telecoms (network) can be either missing or costly to access/use. Investment requirements for compensation of these lacking infrastructure may be too high for the private actors involved.
Transition problems	Firms and other actors might not be able to deal with the high uncertainty that entails the emergence of new paradigms or significant changes to the market structure that requires new technological solutions.
Lock-in problems	Overdependence on already existing socio-technological systems might hamper or deem too costly the transition toward the new paradigm or prevent the firms even to foresee the emergence of new opportunities.
Hard and soft institutional problems	Institutional factors of formal (regulations, laws) and informal (social and political culture) types play a very significant role in the production, adoption, and dissemination of knowledge. Any problem arising from these factors directly affect innovation processes.
Network problems	Too weak or too strong linkages may prove incompatible with the required changes demanded by an emerging new paradigm. Network types also play a significant role in either adopting or missing out to new developments.
Capability and learning problems	Insufficient competences of institutions in terms of human capital, organizational and technological structure, which in return might affect their capacity to learn, adapt or produce new technologies. This can be the case even if the system possesses the right infrastructure and institutional framework.
Unbalanced exploration-exploitation mechanisms	A system might have the capacity to generate enough diversity but lack the mechanisms to make selections, or have developed selection mechanisms without any means to generate diversity.
Complementarity problems	Different competencies of the system might not be complementary to each other or connected in the appropriate form to yield desired positive outcomes to allow full exploitation of the available capabilities.

To intervene at an early stage of the innovation process may have an exponential impact during the following years. High risk and uncertainty provide incentives for private actors to be cautious, therefore large-scale and radical technological shifts usually require public intervention (Carlsson & Jacobsson, 1997). This kind of early public innovation policies often had a military character in the US (Mowery, 1996), but led to the creation of expansive new markets later (Mazzucato, 2013). Hence, adopting a holistic approach with a projection towards the future may bear plentiful fruits.

This early move needs thorough planning and may still affect the overall system in a negative manner. Identification of new sectors of high uncertainty and possible systemic problems is not a straightforward process and even if they were, policymakers need to make choices between strengthening already existing systems or creating new ones (Norgren & Hauknes, 1999). During the design phase, policymakers must decide on not only the expectations from a policy (why intervene) and the policy tools (how to intervene) but in addition which problems to address by this policy intervention. These decisions can only be made based on a comparison between existing systems of innovation since there is no optimal system to be identified (Edquist & Chaminade, 2006).

Systemic problems require systemic coping mechanisms, or systemic instruments in innovation policy (Smits & Kuhlmann, 2004). Such instruments can be exemplified as supplying information to different actors in order to define innovation strategies and facilitating the production of learning/experimenting instruments/environments to these actors in order to handle uncertainty. Public technology procurement, R&D incentives, business services or capacity building efforts are possible policy tools to achieve these goals.

In this line of thinking, the choice between sticking with the already existing systems of public intervention versus creating new mechanisms is a vital one. An early move can affect the development of a sector hugely and making the right moves return elevated results. There is sort of an opportunity cost attached to every choice of policy at this point.

As a side note to this section, mission-oriented policy approach has risen as an alternative to the concept of systemic problems in recent years (Mazzucato, 2016). This new understanding focuses on public intervention not as a tool for fixing market failures or being a facilitator but as a co-creator and co-shaper of market. One of the main points of mission-oriented policy is that instead of just funding certain endeavors, it also denotes the importance of understanding the organizational structure of institutions. According to Mazzucato, it was not just the funding that led to the success of the US in creating tech industry but also institutional design like the DARPA model affected as well. Missions such as “getting to the Moon” are not just challenges for a certain industry, they present challenges on a cross-sectoral scale. Getting to Moon required innovations not only in aeronautics but also in textiles, food, medicine and so on. Therefore it allows bottom-up exploration and experimentation processes, which includes lots of failures too. This newer approach is not adopted in this thesis study due to practical reasons such as using more extensive literature and focusing on problems rather than missions. A similar study through the lenses of mission-oriented policy approach can also be of interest.

To sum up, for a system at disequilibrium consisting asymmetric distribution of information the mainstream policy approaches yield insufficient outcomes. Newly emerging fields and instances of paradigm shifts fit this description perfectly. Therefore there are both theoretical and practical aspects of public intervention in such cases. Identifying, mitigating and eventually solving systemic problems through the application of holistic policies is necessary to see high returns on investment made in these newly emerging technologies. It is important to develop and apply systemic solutions to systemic problems. Policymakers have to decide on many aspects such as whether to use already existing systems of intervention or create new ones and how to intervene. A thorough analysis of the current situation and future expectations is required to support the decision-making process of policymakers in this respect, the main motivation of this thesis is to fulfill that need to a certain extent.

In the following section, possibility of appropriating technological revolutions as a window of opportunity as a catch up mechanism for developing countries (Perez & Soete, 1988) is introduced. Every public intervention is costly and effects the system drastically in one way another. It is crucial for the policymakers to steer the trajectory of development into desired paths with clear intent. Therefore, before arguing for whether quantum technologies can be considered as a sign of an ongoing technological revolution, the possible upward transformative process of these period for developing countries needs to be covered.

3.3 Catching-up in Technology: Technological revolutions as a window of opportunity

It is a historical fact that international diffusion of foreign technology was an important factor for the industrialization process of both continental Europe and the United States in the 19th century, and for countries like Japan and Korea in the 20th century (Perez & Soete, 1988). The conditions of closing the structural gap between developed and developing countries, how technologies evolve and diffuse in this context, and the process of effective technological catching up plays crucial roles in understanding the potential of rapid industrialization on the developing countries' side.

Technological catching up is a complex process that is bound by 'developmental' constraints. These constraints can be economic or political in nature, related to immigration (Scoville, 1951), the role of government (Yakushiji, 1986) and so on. In the following part of this section, these are further explored. It is the proposal of Perez and Soete (1988) that technological revolutions can be a window of opportunity for developing countries to be used as a catching up mechanism. The 'can be' part is especially important because their main argument is that although it opens up a window of opportunity, these constraints mentioned above either make it easier or exceptionally harder for developing countries to get an advantage of these opportune moments in history.

Development is path-dependent. Previous capital, knowledge, available skills, and infrastructure all play out as determinants to a certain degree on the path to be followed. By adopting mature technologies, less developed countries may gain a comparative advantage. Use of these imported technologies seems beneficial since the cost of developing would be skipped over, they can fast forward the previous steps. The problem here is that these mature technologies are, by definition, mature. Return on investing these obey Wolf's diminishing return (1912) rule and they represent a risk of being stuck in a low wage, low growth path.

This is a clear problem because if development is path dependent and advancement depends on previous successes, how can a country ever catch up? To overcome this dilemma, Perez and Soete (1988) propose the idea of running in a new direction. The periods of technological revolutions are the ones most suited for radical innovations, as the technology system evolves into a new paradigm, it is the agility of developing countries that can truly embrace the new because they have less to lose by cutting their ties to the old and established TEP.

A key point here is that this is not an automatic or even widely applicable idea. These windows of opportunity are only temporary during the technological transition periods, and can only be taken advantage of by parties in a suitable position. Also, it is not the idea that these new and transformative innovations would originate in developing countries. A vast majority of new technologies are expected to be developed within technologically advanced countries. It is the conditions allowing diffusion of these novelties into the opportunity space of developing countries that matter. The term technologically advanced indicates heavy investment in established technologies as actual production, skilled labor, management, regulations etc. The developing countries (imitators) that are in a position to transform these much quicker than the original innovator can use this transition period as a window of opportunity.

Table 3. 4: Main groups of elements associated with the actual cost of entry into a new technology in TEP approach

Fixed investment	Purchasing and/or developing any and all necessary products, essential purchases
Scientific and technical knowledge	Hiring consultants or qualified personnel, educating workforce, absorbing the new knowledge (It is assumed that most trial and error costs are handled by the original innovator, which makes it advantageous for the imitator as an entry point)
Skills and experience	Skills and experience related to the new technologies on the levels of management, production, distribution and marketing. This cost varies on the already existing skills base and may involve unlearning, learning, relearning elements associated with it
Overcoming locational disadvantages	Distance from suppliers and end market (geographic and cultural), unavailability of scientific and technological capacity of the surrounding ecosystem, lack of consumer awareness

The locational disadvantages could be large enough to be an effective barrier by themselves. Characteristics of a domestic market, the legal, social and institutional framework, and other factors play into this. There is a certain cost attached to educating the consumers, but this is lowered by each additional producer in a country. The same argument can be made for many of the locational disadvantages above, each new producer can help to form networks, establish linkages and in overall create an ecosystem. There is a thin line between new players reducing the cost of these disadvantages and reducing the return per investment due to competition. These costs are reduced as the technology matures, but the returns are also diminished as this happens.

There are some minimum thresholds regarding the levels of scientific and technical knowledge, practical experience and locational conditions. A market cannot be created where regulations forbid it to, flying cars will not be realized if the local scientific community has no idea on levitation or aerodynamics. These minimum thresholds vary during different phases of a techno-economic paradigm. Below, four different types of costs with respect to the phases of maturity of a technology are shown.

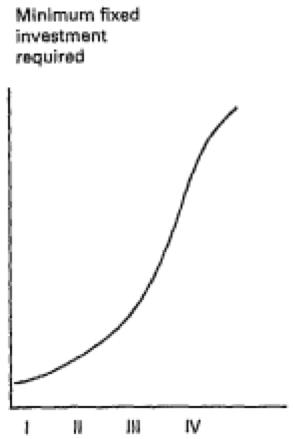

Figure 3. 2: The minimum amount of fixed investment required

The minimum amount of fixed investment required increases almost exponentially during phases two and three because each incremental innovation adds to the cost of obtaining the up-to-date version of that technology.

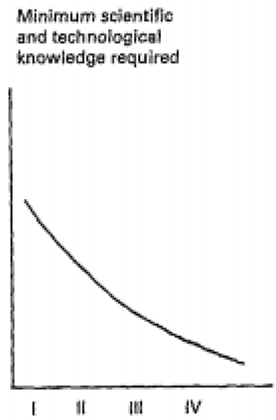

Figure 3. 3: Minimum S&T knowledge required

An inverse relation can be observed between the minimum scientific-technological knowledge required and level of maturity. This is due to the fact that with each incremental innovation, more of the knowledge requirements become embodied in the product and the equipment as phases go by.

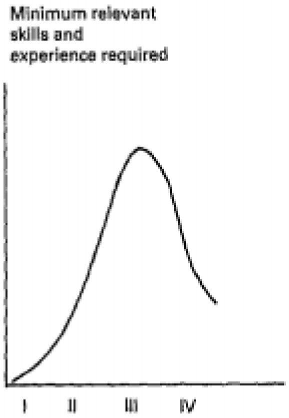

Figure 3. 4: Minimum relevant skills and experience required

Intensive learning and relearning processes dominate the initial phases. During the early phases, since everybody starts from a relatively primitive point, the minimum relevant skills threshold is low to non-existent. This does not indicate that being successful at this point requires no skills, it means that the experience level required for 'entry' is low. The situation changes rapidly following phases two and three since the focus shifts from making the technology to work or extensive focus on incremental innovations toward managing firm growth and capturing market share. At phase four, required skills are well codified and can be purchased. However, again, this does not guarantee an efficient production without effort on the buyers' side (Bell, 1984).

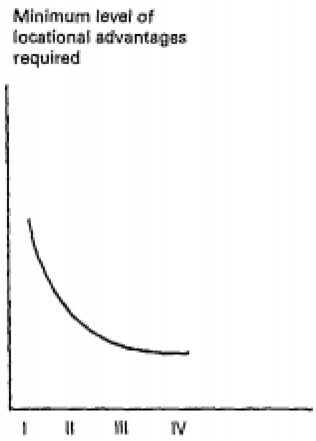

Figure 3. 5: Minimum level of locational advantages required

Locational disadvantages become less costly to overcome quickly as the initial phase is done, but they never disappear completely. Even at the maturity phase, there need to be at least some locational advantages so that the country can adopt that technology transformation. These locational advantages can be created through time and effort, such as consumer education. However, it is crucial for countries to have these if there is an intention to exploit a window of opportunity at phase one allowed by a technological revolution.

The minimum level of requirements stated above can only be compensated via each other to a minimal extent. An illiterate peasant who won the lottery cannot start a successful biotechnology firm the next day, it takes time and effort to leverage advantages at one aspect into accounting for the disadvantages at another.

The argument above is made to illustrate that, timing is important. First and the fourth phases have the lowest or easier to attain thresholds as entry points, but their requirements are dramatically different. An entry point at phase one would demand high levels of sophistication at the relevant scientific and technical knowledge, in addition to very favorable locational advantages. On the contrary, entry on phase four depends on making intensive investments and technology purchases.

It should be noted that a phase one entry does not guarantee survival, let alone success, in this race. Running in a new direction may yield high returns, but only if others will follow you into that direction. Entrance at maturity level is a safer bet, with the problems of low wage, low growth and diminishing returns discussed above. Also, even though it is safer, entrance to a mature and old technology during a technological revolution would be a really bad investment.

Each new technology benefits from the knowledge and experience developed for its predecessors and this generates externalities. The knowledge, skills, experience, and externalities required for various technologies within a system are interrelated and they support each other (Perez & Soete, 1988). Identifying those families of technologies which will become essential during the technological revolution and help the catching up process is a key point in this narrative.

Truly radical and innovative approaches toward the development of new technology systems do not necessarily originate in leading corporations. Small firms and startups, sprouting from an institutional structure with well-qualified university personnel may provide a strong basis for a relatively autonomous window of opportunity into a newly emerging technology system at phase one. If a growing flow of investment and a capacity to interrelate evolving technology systems can also be provided, this can be the formula for generating synergies for self-sustained growth processes, and a rejuvenation of the whole economy through a major TEP shift.

To be in an opportune position to take advantage of this technological revolution, a developing country should have probably made major investments during the maturity phase of the previous paradigm. Therefore, the proposition that phase one of a new techno-economic paradigm as a window of opportunity for catching up is somewhat misleading. A country aiming to swing its entire economy upwards should start this course from the maturity phase of previous TEP. Successful endeavors accomplished in that maturity phase, without trenching too deep to create heavy investments into an aging paradigm, should be the start of a journey for any developing country aiming to forge ahead in the race for technological superiority in a market economy.

Treating each new radical technological development as a paradigm shift would beat the purpose of all the discussions provided above. Therefore providing strong arguments for why or to which extent quantum technologies fill the requirements of heralding a new TEP is important. The next section focuses on these arguments.

3.4 Quantum Technologies and the Sixth Technological Revolution

The techno-economic paradigm approach diverges from Kontradieff’s (1935) long term economic cycles theory as the focus shifts toward technologies rather than prices and interest rates. This does not mean there are no similarities. Perez (2010) lists the five revolutions as provided in table 3.5.

Table 3. 5: Five technological revolutions according to Perez (2010)

Industrial Revolution	1771
Age of Steam and Railways	1829
Age of Steel and Electricity	1875
Age of Oil and Mass Production	1908
Age of Information Technologies	1971

Averaged over, these coincide with Kontradieff's 50-year cycles, four shifts in 200 years. It is not surprising to see this correlation since the TEP argument predicts a great surge of development following the technological revolution, which necessarily affects the prices and interest rates. In a sense, Kondratieff seems to be vindicated.

The search for possible candidates of a sixth technological revolution is not new. Whether it be nanotechnology (Knell, 2011) or a general mindset as 'smart green growth' (Perez & Leach, 2018), major shifts in socio-economic structures are expected in the following decades. Quantum technologies received little to no attention during the early 2000s on the part of economists in this sense, and they were right to dismiss it. As discussed in the previous chapter, even the optimistic predictions put universal quantum computers in the early 2050s, and since the quantum-apocalypse was still way off, there was no urgent need to shift the cybersecurity infrastructure to a post-quantum level. All this narrative changed in the last decade, and rightly so.

Nobody expects the Spanish Inquisition. When thought of quantum technologies in the early 2000s, nobody expected China to build a 10 billion dollar worth of Quantum Information Sciences Center (Decker & Yaseijko, 2018) at Hefei to be opened at 2020, which coincides with the Chinese agenda to implement the basic structure of their social credit system nationwide (Meissner, 2017). Or China to be the first country to launch a quantum communication satellite (Gibney, 2016), or to perform the first satellite-to-ground quantum key distribution (Liao et. al, 2017). Leveraging the newly emerging character of these technologies to gain an advantage against Western surveillance and adapt their internal policies in accordance with the technological development.

As quantum technologies and their expected impact become more societally relevant, the issue of translating 'quantum theory' to the general public and introducing the ideas of responsible research to academics began to emerge. A special issue titled "The Societal Impact of the Emerging Quantum Technologies" was published by the journal of 'Ethics and Information Technology' in December 2017. There were five contributions, three of which focused on the possible impacts of quantum technologies on science, industry, and society (Veermas, 2017). One was on responsible research and innovation, and the other popularisation of quantum theory in historical context.

One of the articles in that special issue ends with the sentence; "Billions more will be spent, and over the decades the staggering will hopefully emerge" (DiVincenzo, 2017). The author is David DiVincenzo, a senior researcher at IBM who is best known for his work in identifying the criteria for physical implementation of a quantum computer (2000), which are referred to as DiVincenzo criteria. The special issue article starts with EU Flagship for Quantum Technologies, mentions on Feynman's famous "There's Plenty of Room at the Bottom: An Invitation to Enter a New Field of Physics" (1959), explains the end of Moore's law and so on. These are familiar arguments for anyone involved in quantum technologies, but it is their familiarity that makes them rather important.

Any paradigm shift requires altering the grand narrative; it needs heroes, problems to be solved, and great promises of riches. James Watt, Thomas Edison, Henry Ford, and Alan Turing are some of the names almost everyone involved with technological development knows, they were heroes of their respective paradigm shifts. Richard Feynman was the youngest group leader in the theoretical division of the Manhattan Project (Feynman & Leighton, 1997), a Nobel Prize winner in physics due to his contributions on quantum electrodynamics (1965), and considered as the originator of nanotechnology and quantum computing in his famous 1959 lecture given at the annual American Physical Society held at Caltech. In this sense, he is already referred to as a hero for the upcoming revolution and the narrative above supports this.

The focus on Moore's law and the need for a 'quantum upgrade' to existing information and communication technologies paradigm is already covered in the previous chapter. It is brought up here again because in a grand narrative of a paradigm shift, highlighting the problems of the current paradigm provides a strong incentive for change. In a Kuhnian sense (1962), these are the anomalies which push for revolution. Accumulation of enough anomalies will result in a paradigm shift eventually. It is how these anomalies are dealt with sets the principles, the new common sense (Perez, 2010) for the next paradigm. Assuming a straight-path forward, considering the technological development as a linear progression is exactly what the TEP approach negates, and this 'running in a new direction' (Perez & Soete, 1988) allows the window of opportunity for developing countries to catch up.

Grand problems are also being presented as technological development progresses in the field. In 2017 researchers at IBM announced they have successfully obtained exact solutions for molecules up to the size of beryllium hydride with a six qubit system (Kandala, 2017).

In itself, it is not a commercially meaningful act, however, it signals the potential of quantum devices performing chemical simulations. One of the general arguments proposed for a quantum computer is its ability to solve nitrogen fixation problem (Reiher, 2017). Currently, more than 1% of total energy consumed globally goes into producing nitrogen based fertilizers (Wood & Cowie, 2004). Any significant efficiency increase in this process would result in reduced fertilizer prices, that in return affects the entire food industry and flow upstream from there. Optimization problems, secure communication, increased precision for gravitational measurement (which allows seeing through any obstacles) and many other applications are put forward for quantum technologies, not to mention the usual suspects of financial forecasting and hacking secure systems fast. The number of 'grand' problems that can be solved through a revolution seems to be only getting higher as new firms are formed and studies followed.

Finally, the focus on EU Flagship, ending with the phrase "billions more will be spent" are actually signals. In this grand narrative of 'second quantum revolution', it is argued as the race is on. The patent and spending data seems to support this idea, as it is presented in the following chapters, but this was not always the case. Only a decade ago, before 2008, quantum technologies were seen as more of a novelty rather than something that venture capitalist could be interested in (at least in the foreseeable future). Now, there are many funds set up only to invest in 'quantum' start-ups. Legislation such as 'National Quantum Initiative Act (NQIA) of 2018' or formation of EU Flagship for Quantum Technologies provides strong signals to the market. Investment of telecom companies in quantum sensors or developing a 'quantum' internet also show signs that the private sector can be (and are) becoming a part of the R&D effort on developing these technologies.

The NQIA is a legislation built upon the National Nanotechnology Initiative (NNI) of 2000. Most of the centers around the globe are being set up near nanotechnology hubs, due to quantum technologies and nanotechnology having many similarities with respect to experimental requirements. Therefore, it can be argued that what is witnessed today is the formation of a new technology system (Freeman, 1974). So the next paradigm won't be nanotechnology, quantum technologies, biotechnology or artificial intelligence; it will be a cluster of technologies which are supporting each other, generating externalities that reinforce the development of the rest, and quantum technologies seem to be one of these that sits at the heart of this revolution.

3.5 Conclusion

Literature review of this study revealed several key points that were translated into methodology and data analysis stages. Considering quantum information technologies in the context of being a technological revolution provided that, major transformations brought through developments in this field contain a potential for developing countries to start catching-up. It is also given in the theory itself that, this is neither easy nor a general window of opportunity which can be utilized by every country. There are entry barriers in different areas such as fixed amount of investment, S&T knowledge, relevant skills and experience, and level of locational advantages. Furthermore, lacking in any of these areas in return makes it that much harder to meet the requirements of the rest. And even if all the barriers can be overcome through heavy effort, success is not still guaranteed since technological trajectories are not linear and investment made into 'wrong' fields may only result in setting the local progress back.

Even in the face of these odds, the rationale for public intervention persists due to probable market failure mechanisms. A truthful assessment of systemic problems and taking appropriate action, which may not have been taken by private actors otherwise and those that the public agents possess the ability to implement, remains as the sensible path towards prosperity.

This thesis focuses on Turkey as a developing country, and aims to reveal the conditions in which quantum technologies are being diffused and produced locally. It should be noted here as well that, although quantum technologies are bound to play an important role in the upcoming techno-economic paradigm, the lock-in point for them to be the dominant ones is not a settled issue.

Earlier assessments forecasting the invention of an universal quantum computer at 2050s, and those who argue that scaling up will be impossible to desired levels may still turn out to be correct. The literature review, and especially collected data, reveals that the current hype may just have begun as a spending war between China and the rest. However, even if that is the case, recent developments make it crucial for developing countries to decide on a path. If a country desires to utilize this possible window of opportunity, time is of the essence. If not, still a solid and well thought-out policy plan can prepare it for taking advantage of this new paradigm at the maturity phase.

In conclusion, it seems clear that major socio-techno-economic changes are on their way and many believe (and invest in) that quantum technologies are going to play an important role in these transformations. Mapping out the current conditions in Turkey regarding these fields, to identify systemic problems, S&T knowledge base, relevant skills & experience, and locational advantages & disadvantages is an essential effort in order to device sensible policy suggestions tailored for the Turkish case.

CHAPTER 4

METHODOLOGY

The literature indicates that during techno-economic paradigm shifts, developing countries may use the window of opportunity occurring in phase one of the new paradigm to start on a path to swing their entire economy upwards (Perez & Soete, 1988). Considering that the second quantum revolution heralds new and radically disruptive technologies, in addition to other revolutionary developments such as artificial intelligence, virtual reality, bio-engineering, nanotechnology and so on; the world seems to be either experiencing or on the verge of a new techno-economic paradigm shift. Therefore, it is natural to wonder where Turkey stands in all this. In this study, that question is asked in a specific context. What are the current conditions in Turkey regarding quantum information technologies, and can or should Turkey try to exploit the window of opportunity described by Perez and Soete in their theory?

As introduced in the first chapter, the policy chapter of this thesis contains policy suggestions to be taken during a paradigm shift. In order to devise sensible policy suggestions, a strong understanding of the current conditions is required. For the purposes of this study, the main area of interest is decided as the extent of diffusion concerning quantum information technologies and the factors which are either slowing or accelerating this process in Turkey. Descriptive analysis is used to identify these conditions. Descriptive research is primarily concerned with the question of what is and it can either be qualitative or quantitative (Knupfer & McLellan, 2001). In this chapter, a detailed account of methodology and methods used is given.

To apply a descriptive analysis to the subject at hand there were two main sources of information. First one is the people involved in quantum information technologies academically, politically and commercially in Turkey. The second is the set of official documents and databases such as strategy plans of governmental institutions, policy papers, end of year reports, higher education documents and else. Qualitative methods were used with the people involved for this purpose, due to the fact that they can produce more detailed and contextual data, can reveal the complexity and are flexible (Miles & Huberman, 1994) enough to be applied to different sources of information such as academics and private sector actors without much alteration. To generate data from people involved, a series of semi-structured interviews (Glesne, 2011) was conducted and document analysis techniques (Glenn, 2009) were used for the rest.

While Turkey is the focus of this thesis, an analysis on the development of quantum technologies market around the globe is also included. This serves the purpose of estimating the gap between Turkey and international markets. To this end, second hand patent data analyses, established firms adopting quantum technologies, startups focused on quantum technologies, and venture capital groups investing in these companies around the world are covered.

The initial focus and aim of this study are to be of exploratory in nature. To identify the field itself and the conditions of it, on which the activities related to quantum information technologies are operated. In order to cover a greater range of conditions, a mixed method research design has been employed (Creswell, 2014). Although pure qualitative or quantitative approaches are applicable to the situation at hand as well, since no previous studies have been performed, it did not seem sufficient to limit this study to such constraints.

Out of the five approaches defined in Creswell's book on qualitative inquiry and research design, case study approach seemed most suited to the task at hand. Even though there are those who do not consider case study as a methodology itself (Stake, 2005), there are also many who accept it to be a stand-alone methodology (Merriam, 1998; Yin, 2003; Creswell, 2013) which is distinguishable from other approaches in social sciences.

Grounded theory approach has also been considered for this study; however, due to the fact that for policy suggestion reasons the techno-economic paradigm approach (Perez & Soete, 1988; Dosi, 1982) has been adopted, potential merits of grounded theory did not seem attractive enough to abandon the previous approach. It may be insightful to conduct a similar research through using grounded theory instead of a pre-set development economics-oriented approach.

Utilizing both quantitative and qualitative types of data is a self-reinforcing process. Interviewed people may argue that a concept is rather important to national security, though their reporting is reflective of an interest to a certain degree, if no mention of that concept is translated to strategic plans of related public institutions, then it would be misleading to rely only on the reporting of interviewees. On the other hand, reports may neglect or omit certain conditions that can only be uncovered via direct access to people involved. Therefore, to obtain the necessary context, a mixed method approach is adopted.

4.1 Quantitative Data Sections

In the quantitative section of this study, mostly secondary data has been used. There were four main sources; strategic plans of national institutions, graduate-level theses obtained via National Thesis Center, roadmaps published by national and international entities related to quantum information technologies and finally patent and market prediction analyses of the field.

Strategic plans of Turkish national institutions were obtained through www.sp.gov.tr/tr/stratejik-plan website, which is a site dedicated to publishing and allowing navigation of strategic plans. These reports were searched for the keywords ‘kuantum’ (quantum), ‘kuvantum’ (quantum with a different spelling), ‘bilgi güvenliği’ (information security) and ‘bilişim’ (information, informatics or ‘information & communication’ depending on the context) when encountered the related section was investigated to identify in which context these terms were used.

Through these means, strategic plans of 73 central organizations (merkezi idareler), 91 public universities and Vision 2023 document of TÜBİTAK were covered. There were three central organizations and four public universities which had published strategic reports either in scanned pdf format which did not allow for keyword search or had broken links on their websites or basically is not yet uploaded.

Additionally, four available top policy documents (üst politika belgeleri) and 20 out of 44 accessible sectoral/thematic strategy documents (sektörel ve tematik strateji belgeleri) were also covered, 22 were uploaded in a form that did not lend itself to the keyword search. Out of these 165 institutions only three contained the word quantum (kuantum/kuvantum) in them, which can be found in table 4.1.

Table 4. 1: Document names, frequency and context of occurrences for ‘kuantum/kuvantum’

Document	**Frequency of occurrence**	**Context**
National Boron Research Institute 2013-2017 Strategic Plan	Once	Referring to other fields included in Vision 2023 document
Vision 2023	Seven times	Defining “nanoscale quantum information processing” as a strategic field
İzmir Institute of Technology 2014-2018 Strategic Plan	Six times	Information about “Applied Quantum Research Center” in IZTECH

Conducting keyword search at National Thesis Center was the second source of quantitative data. This method is considered under quantitative section because the results are used in a format of the table, indicating years and topics of the theses to identify overall interest to topics in quantum information theory at the graduate level studies. Even though the outcomes are of quantitative in sort, searching National Thesis Center database for academics who have carried out graduate-level research on these subjects provided a baseline for snowball sampling to recruit participants on the qualitative section. Additionally, it serves as an indicator of human capital in academia regarding these areas.

As a third source of quantitative data, the roadmaps and other similar public documents were used, such as vision statements, spending plans, end of the year reports, white papers etc. In this part, especially the roadmaps of UK and EU were useful. Their early projections of market growth, number of firms present and expected, timelines for key technological progress provided a mean of comparison with both the Vision 2023 document of TÜBİTAK and actual developments, such as development of quantum processors by American firms (IBM, Google, Intel) or the launch of a QKD satellite by Chinese QUESS mission.

Pre-2010 spending plans of Turkish State Planning Organization (DPT) was investigated to identify the actual money spent on QIT in Turkey from this source. Additionally, a policy draft document titled “Quantum Sciences and Technology Working Plan” prepared by TÜBİTAK was also utilized as a data source. A list of the documents utilized can be found in table 4.2.

Table 4. 2: Name, region and year of publishing for documents utilized

Name of the document	Region/Country	Year of publishing
Quantum Information Processing and Communication: Strategic report on current status, visions and goals for research in Europe	European Union	2010
National strategy for quantum technologies	United Kingdom	2015
A roadmap for quantum technologies in the UK	United Kingdom	2015
European roadmap for Quantum Information Processing and Communication	European Union	2016
Future Directions of Quantum Information Processing	United States	2016
Seizing Canada's Quantum Opportunity	Canada	2017
Quantentechnologien – von den Grundlagen zum Markt	Germany	2018
National Strategic Overview for Quantum Information Science	United States	2018
Quantum Computing: Progress and Prospects	United States	2018
Quantum internet: A vision for the road ahead	Netherlands	2018

A fourth source is the number of papers published that are covered by Web of Science database containing some specific keywords. This source is added in a later period of the study as a double check on the collaboration mapping type of Turkey and countries with publication and population size. Although data on 14 countries with similar publication size to Turkey, 100-200 papers in total, are identified, some of them are disregarded due to differences in population, such as Slovakia with a population of 5.4 million.

The final source of quantitative data was public access analysis documents prepared by independent entities like patent analysis firms or media organizations. In this section, several articles from The Economist, and previews of some patent landscape and market analysis reports proved rather useful due to the fact that they already contained large amounts of quantitative data gathered from related sources in compact forms. The full reports of patent and market analyses could not be accessed simply because they were rather expensive, around 5000 USD each. It seems that these kind of reports are increasing in number and scope every day, therefore a list of existing such reports, as of the day this study concluded, is added to the appendix section (Appendix C - Reports on QT).

4.2 Qualitative Data Sections

In the qualitative part of this study, data is generated through semi-structured interviews and a focus group meeting. This data forms the backbone of study at hand. Structure of the interviews is constructed in accordance with the main topics of interest, and the concepts related to techno-economic paradigm approach. Concepts like commercialization, comparison between national-international academia, collaboration and awareness of technologies are taken as central ones for the interview guide.

Snowball sampling method was used for recruiting participants in academia, starting from academics with publications and who have advised masters or Ph.D. theses on related subjects. For private companies, convenience sampling was employed and for the governmental organization, the interviewee was recruited purposively.

Initial contacts were established through email. 35 people were contacted out of which 29 replied back. Each email asked for a suggestion of other people involved in the field whom might be interested in giving interviews too. Some of the academics contacted recommended others even though they did not want to participate themselves, and in three cases although interviews were set they had to be canceled due to logistical problems. For the participants from industry, all three participants were suggested by other parties who’ve also played the role of ‘point of contact’.

The interviews took place in Ankara, İstanbul, and İzmir during the first three months of 2018. Three of the interviews occurred at coffeehouses and other thirteen (including the group meeting) were conducted at the offices of participants. All interviews were face to face.

In total 15 semi-structured interviews and a group meeting with four participants were performed. On the academic side, interviewees were from Koç, Sabancı, Bilkent, METU, TOBB, İzmir University of Economics, IZTECH, BOUN, ITU and Hacettepe universities. Their positions varied from Ph.D. candidate to full rank professor. On the industry side, there were three participants from different firms. These firms were all in the ICT sector but involved in different forms of R&D. Their main activities were software development, cloud computing, and satellite communication, respectively. The ranks of the interviewees were R&D officer, chief of R&D, and CEO. Below, a table of interviewee identifier numbers with respect to their institution and department can be found. This method has been employed to ensure anonymity within a reasonable extend. The interviewees are addressed as i1 to i15 in text.

Table 4. 3: Numbers, institution type and department of interviewees

Interviewee #	Institution	Department
Interviewee 1 (i1)	Public University	Computer Engineering
Interviewee 2 (i2)	Public University	EE Engineering
Interviewee 3 (i3)	Public University	Physics
Interviewee 4 (i4)	Public University	EE Engineering
Interviewee 5 (i5)	Public University	Institute of Nuclear Sciences
Interviewee 6 (i6)	Public University	Physics
Interviewee 7 (i7)	Private University	Physics
Interviewee 8 (i8)	Private University	Physics
Interviewee 9 (i9)	Private University	Physics
Interviewee 10 (i10)	Private University	Physics
Interviewee 11 (i11)	Private University	Material Science and Nanotechnology
Interviewee 12 (i12)	Public Institute	R&D Officer
Interviewee 13 (i13)	Private Firm	R&D Officer
Interviewee 14 (i14)	Private Firm	Chief of R&D
Interviewee 15 (i15)	Private Firm	CEO
Group Interviewees	Public University	Physics

The interview guide (Appendix D - The Interview Guide) was pilot tested on two people, with slight alterations like the ordering of questions. Data obtained from these people are not included in this study. The guide was more oriented toward academic interviewees, hence the interviews with people from industry were more unstructured.

Out of 15 interviews, nine were audio-recorded, six were not recorded with respect to the interviewees' request. The group meeting was planned ahead as four separate interviews, but due to logistics of time and distance, the interviewees proposed a group meeting instead, which was also audio-recorded. Extensive notes were taken for interviews that are not recorded and reminder notes were taken for the recorded ones. The raw data generated from interviews were initially transcribed into digital form, the handwritten notes were also translated into digital form. After this process, these transcriptions were coded using the QDA Miner Lite software. Initial codes were assigned in line with the questions asked through interview guide and with respect to techno-economic paradigm approach; however, during the coding process, there were several changes. Some of the prescribed codes were rarely used hence they were removed, while others proved to be multi-dimensional, and needed to be split into more specific codes. Some original codes became categories. Following this, the outcomes were visualized using charts and tables.

Table 4. 4: Name, place, time and organizing entity of events attended

Name of the event	**Place and Time**	**Organizing Entity**
The Lisbon Training Workshop on Quantum Technologies in Space	Instituto Superior Técnico in Lisbon / 11-14 September, 2017	COST Action "Quantum Technologies in Space" - CA15220 / qtspace.eu
KOBIT 2 (Quantum Optics and Information Meeting 2)	Mimar Sinan Fine Arts University in İstanbul / 1-2 February, 2018	KOBİT 2 local organization committee fen.bilkent.edu.tr/~kobit/
Quantum Flagship Kickoff in Vienna	Vienna / 29-30 October, 2018	Flagship Coordination Office
3rd Quantum Technology - Implementations for Space Workshop	ESA/ESTEC, The Netherlands / 20-21 November, 2018	ESA Conference Bureau
Workshop on Quantum Technologies	Bolu Abant İzzet Baysal University / 17-18 January, 2019	Bolu Abant İzzet Baysal University / Koç University
KOBIT 3 (Quantum Optics and Information Meeting 3)	Ankara University / 31 January-1 February, 2019	KOBİT 3 local organization committee fen.bilkent.edu.tr/~kobit/

As an additional source of qualitative data, observation notes were taken during several events related to quantum technologies. A list of the events can be found in table 4.4.

Attending these events proved beneficial in two respects. First, it helped to develop a sense of comparison between national and international events regarding quantum information technologies. Second, some key anecdotal observations were made during these events, some of them are included in this study. Furthermore, attending these allowed some insight to position Turkey and understand where it stands in midst of this ongoing technological revolution regarding quantum information technologies. An overview of the methods employed can be found in table 4.5.

The combined use of these methods allowed a diverse set of data to be collected and generated. Due to the complementary nature of methods employed, information on different levels become available for analysis purposes. This simultaneously resulted in identifying the current conditions and systemic problems in Turkey while setting a landscape of developments around the globe. In the next chapter, data is presented without much discussion other than paving the connections between results obtained from different sources and methods.

Table 4. 5: Overview of the methods employed

Type	**Method**	**What for?**
Quantitative	- Document Analysis - Numerical Analysis	- Exploratory - Descriptive
Qualitative	- Interviews - Group Meeting - Observation	- Interpretative

CHAPTER 5

DATA AND FINDINGS

In this part of the study, data from quantitative and qualitative sections are presented. This is followed by the descriptive analysis sections introducing the themes developed from the data generated and obtained from different sources. Outcomes of these analyses are translated into the next chapter to form policy suggestions and discussions.

Initially, quantitative data around the world is given. This includes information on spending, publications, patents and number of firms for top players in the quantum information technologies fields. Another distinction is made for areas under quantum technologies, and special interest is given to quantum computing as it is the focal point of this current elevated level of activity. Following this, qualitative data on the global front is provided. Anecdotal data obtained from events attended, public access videos, and policy discussions are included here.

Data on Turkey is provided at the second part of the data section. Quantitative data contains a mapping of master's and doctoral theses submitted to National Thesis Center with respect to universities and areas under QIT, and a comparison between network maps of Turkey, Saudi Arabia and South Africa, which all have similar number of publications in QIT. Additionally, information such as spending data of DPT on QIT related projects and information from public access policy papers prepared in Turkey are also included.

Again, the qualitative data section contains anecdotal data obtained from events attended and information regarding the interviews and group meeting performed in Turkey, followed by the results of content analysis. Themes generated via coding are given at that point. These themes lay the foundation of policy suggestions presented in the following chapter.

5.1 Global Data

Global data presented here mostly consists of quantitative data gathered from second hand sources. However, the data set utilized in global companies in quantum technologies is generated for this study through publicly accessible web sources. Qualitative part of this section is mainly anecdotal.

5.1.1 Quantitative Data

The quantitative data provided here is mostly second-hand and outdated due to the rapidly changing nature of the field. Therefore it is represented not for the sake of allowing a thorough analysis but to give an idea about the magnitude of international activity even before all the current hype began. Data on companies dealing with quantum information technologies is much more up-to-date. The data collecting period ended at December 2018 after reaching 200 firms and a strong saturation point, where no new firms could be found on available public access documents. A number of firms mentioned in these documents were not included in the dataset, because it was not possible to confirm the firm's actual involvement in quantum technologies related activities.

5.1.1.1 Spending, Publications, and Patents

Table 5. 1: Ranking of countries in amount spend, publications, and patent applications

Country	**Amount Spend**	**Publications**	**Patent Applied**	**Total ranking**
US	1	2	1	1
China	2	1	2	2
Germany	3	3	6	3
UK	4	4	4	4
Japan	8	5	3	5
Canada	5	6	5	6
Australia	6	11	7	7
France	9	8	10	8
Italy	11	9	12	9
South Korea	17	10	8	10

In the introduction chapter, examples of national and international initiatives were given. The oldest of those was UK National Quantum Technologies Programme, which was initiated at 2013. Table 5.1, which is reconstructed from the figure denoting ranking of the UK in comparison to rest of world for quantum science and technology (Cross et al. 2016), provides a general overview of how quantum information technologies landscape looked back then. Source data of spending and publication rankings were from 2015 and patent applications were from January 2016, therefore it would be safe to assume this picture more accurately represents how things were in 2015 rather than 2016.

Reporting of a McKinsey consulting survey by Jason Palmer at a widely cited Economist article, in 2015 around 7,000 people globally, with a total estimated budget of 1.5 billion euros, were working on research directly on quantum technologies. Estimated annual spending on non-classified quantum technologies research in million euros, as of 2015 for top 20 countries is given below (Palmer, 2017). Out of this 1.5 billion euros, it is estimated that 550 million were spent in EU countries, which puts the combined EU-spending on top of the list even excluding UK after to reflect Brexit.

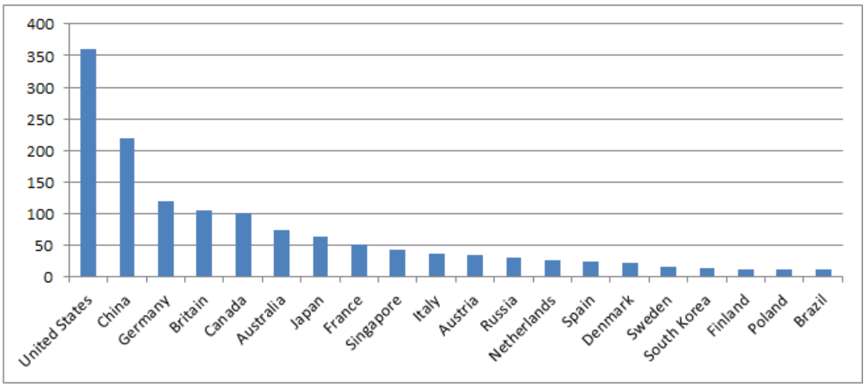

Figure 5. 1: Estimated annual spending on non-classified quantum-technology research in 2015 for top 20 countries

A set of data generated by bibliometric analysis conducted by a team at Naval Surface Warfare Center Dahlgren Division (NAP, 2018) gives the number of research papers published per year in respective fields of quantum technologies and the top five producers of research papers. Since only top five is included, Canada is not covered in this set.

Bibliometric data over 20 years show a steady increase in the number of new articles, which should correspond to a polynomial increase at the number of total articles. Similarly, it can be seen that the number of new articles in all fields of quantum technologies are rising steadily with some small fluctuations. These data also gives chance of clustering between top countries with regards to their number of new articles per year.

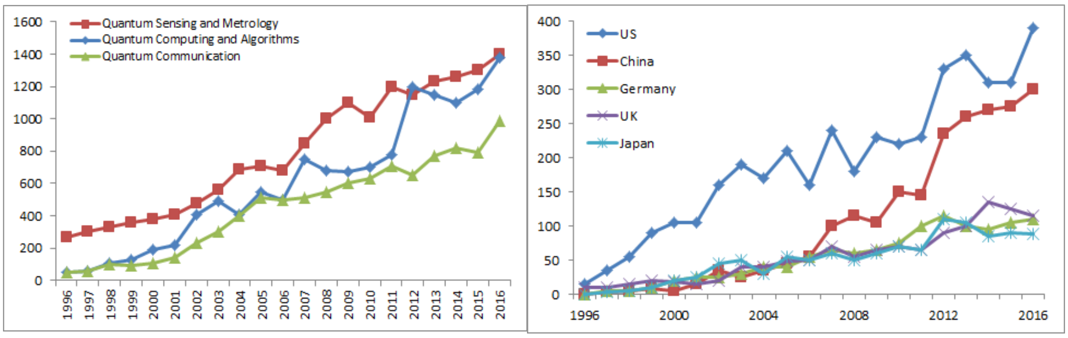

Figure 5. 2: Number of research papers published per year in respective fields globally and number of research papers published each year by nation of origin for top five leading countries in quantum computing and algorithms. Source: Reconstructed from the figures provided in "Quantum Computing: Progress and Prospects" report of National Academies of Sciences, Engineering, and Medicine (NAP, 2018)

In addition to the number of research papers, data on Palmer's article also covers academic collaborations on quantum computing between countries. Table 5.2 here contains data between 2004 and 2013, just before the first grand scale national initiative started.

Table 5. 2: Authorship of papers on quantum computing by nationality of authors, top 6 nations between 2004-2013 (Palmer, 2017)

	Total	**Canada**	**Japan**	**Britain**	**German y**	**China**	**USA**
Canada	1205	1057	45	85	88	42	239
Japan	1535		1443	108	81	71	197
Britain	1719			1543	137	45	177
Germany	1884				1683	94	216
China	4232					4125	250
USA	4886						4511

Another aspect included in the Economist article is patent applications. The data from UK Intellectual Property Office and European Commission is utilized to this purpose. Following figure contains four graphs and give the total number of patent applications to 2015 with respect to fields and countries or origin.

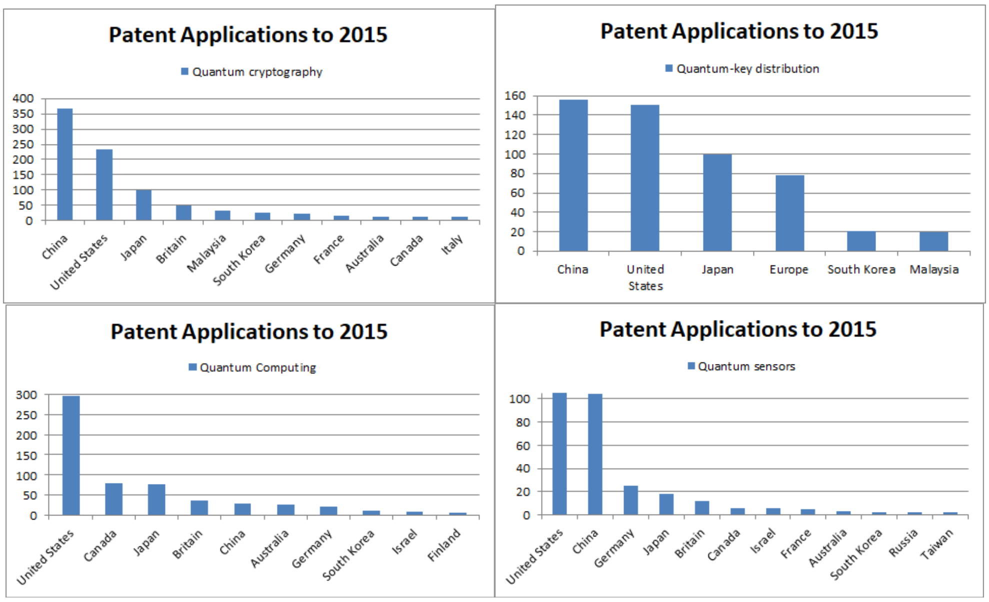

Figure 5. 3: Patent applications to 2015 in quantum cryptography, quantum-key distribution, quantum sensors and quantum computing with respect to countries. Source: Reconstructed from the figures provided in Palmer, 2017

There are other reports and analyses carried out on patent data. A widely used one was an extensive patent landscape report on quantum information technologies carried out by Patinformatics, LLC and published in 2018, which covered data between 2000 and 2017. Due to copyright issues, their figures won't be reproduced here, however, five key findings and results from their report are listed below.

- *Patenting in the field of Quantum Information Technology (QIT) has accelerated over the last three years. Computer related patent family publications are projected to increase by 430% between 2014 and 2017. Application related patent family publications are projected to increase by 350% between 2014 and 2017.*

- *Chinese organizations are dominating the patenting of quantum applications, and within QIT they have nearly two times as many patent families projected for 2017 as the United States, the next closest country – They are particularly interested in cryptology.*

- *Approximately 72% of the academic patent families published in QIT since 2012 have been from Chinese universities. US universities are a distant second with 12%.*

- *Quantum computer manufacturers tend to be based in North America while non-manufacturers, dominated by Asian organizations are focusing on quantum cryptology and communication within the QIT field.*

- *North American organizations may control the computer, but Asian organizations may end up controlling how those machines are used.*

Another finding that is supplementary gives that since 2013, the number of publications listed China as the priority country have grown by 750%, and United States as the priority country have grown by 300%. The data indicates a clear acceleration of patent activity in both countries, which seems consistent with increased publications from them given in figure 5.3.

5.1.1.2 Quantum Companies around the Globe

In this part of the global data section, tables and figures containing information on firms dealing with quantum technologies related activities are provided. The extended version of this information can be found in Appendix B as a list under the title of 'Quantum Companies'. This list is put together through utilizing public access documents. 200 firms are covered in this part, however it should not be accepted as a globally representative set. Startups from non-Western countries, especially China, are not easily located through public access sources in English. Firms from Japan, South Korea, Russia, Israel and India, which may possess enterprises in quantum technologies, fall into this category as well due to the language barriers and startup culture. Additionally, during the sweep for these firms there were some 'stealth' startups. Even though the ones encountered are added to the list, there maybe more which don't even have a website.

It should be noted here that some of the public access documents contained misleading information regarding the nature of activities performed by some firms. There were more than 20 companies disregarded in this manner that were encountered in public access documents, such as lists of companies dealing with quantum technologies prepared by business oriented centers or platforms. The two most common activities among these firms were quantum dots and photonics integrated circuits. Even though quantum dots contain the name quantum, they should not be regarded as activities within the realm of quantum information technologies, just as silicon based transistors or lasers (both of which are accomplishments due to first quantum revolution). The second one, photonics integrated circuits, is also a field of technology that contains quantum elements but not strictly reserved for quantum information technologies. The semi-classical optical theory is enough to perform some of the optical computation on large scale systems (large in comparison to single photon emitter-detector based quantum optical devices). Therefore, these companies are not regarded as firms dealing in quantum information technologies either.

Another issue to be addressed here is about companies dealing with quantum sensing, PAR (Photosynthetically Active Radiation) sensors are included due to their acceptance as being "quantum sensors". A considerable number of companies in the dataset that are not startups but dealing with quantum sensing are companies with PAR sensor based products. This is highlighted as an issue here because this technology precedes the wide acceptance of quantum information theory, and quantum sensing has a much more extensive coverage on imaging, sensing and metrology than just a specific type of sensing. However, since it seems PAR sensors are accepted as quantum sensors, they are not excluded from the dataset.

Locating the exact date of involvement for the already existing firms also proved to be challenging, especially for the companies associated with the military-industrial complex. Two main paths followed here were using "Internet Archive: Wayback Machine" for related web pages of companies and checking Google Patents for initial dates of earliest patents obtained by these companies.

Out of these 200 firms, 120 of them are startups and 80 of them are already existing firms that expanded into quantum technologies market. Below, a distribution of the firms over their self proclaimed primary area of interest in quantum technologies is given.

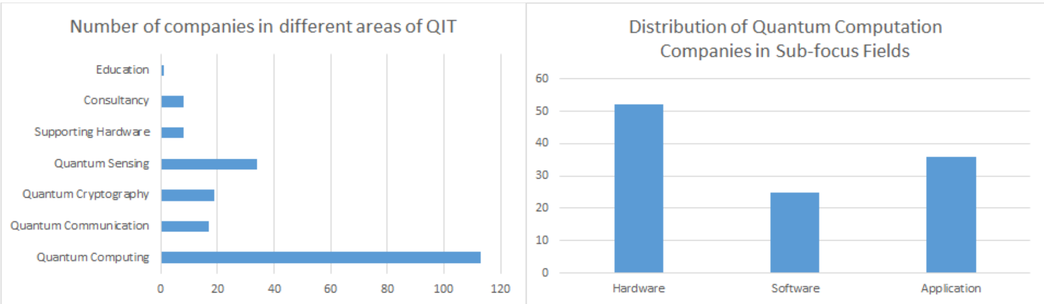

Figure 5. 4: Distribution of firms (in dataset) over different areas of QIT and distribution of quantum computation companies in sub-focus fields

This distribution should only be taken seriously to denote the increasing interest in quantum computation and how private sector is defining or promoting what they are doing. Some of the companies claiming their work to be quantum computation are actually conducting quantum simulation. A similar situation also persists in distinguishing firms operating in quantum cryptography and communication. Since the most popular applications of quantum communication are in the field of cryptography, a specialized field seems to have emerged to promote these applications.

Within quantum computation, another division can be formulated to three categories. Firms focused on hardware, software and applications. The table below gives a distribution of 107 firms covered with respect to their primary fields with a decreasing priority of hardware, software and applications. If a firm deals with hardware and software or applications, it is counted as hardware. If it deals with software and applications, it is counted as software. Firms that are strictly doing consultancy work are not included here.

Certain firms focusing on hardware such as IBM, Google, Intel, Rigetti and others also develop their own software stacks. In other cases and for smaller startups, such as Alpine QT, sole focus remains on hardware. Therefore, relatively lower number of firms primarily focused on software should not be considered on face value.

Furthermore, developing software for quantum computation is also an endeavour belonging in academic realm and open-source coding. A recently published article (Fingerhuth, Babej & Wittek, 2018) evaluating over 20 open source softwares for quantum computing showed that Python, C, C++ and Julia are languages that are actively used for developing software in quantum computing. Finally, there are languages such as Microsoft's Q-sharp that are new and developed in a domain-specific fashion for quantum computing.

Firms investigated here are distributed globally. The table below provides a comparison between countries with respect to the number of companies they possess. China seems to be an outlier here, a more vibrant ecosystem is expected to exist there with the number of patents they contain, but it may have went unnoticed during data collection due to language and cultural barriers.

Another possible explanation is concentration of activity around companies like state-owned giants such as China Aerospace Science and Industry Corporation (CASIC), China Aerospace Science and Technology Corporation (CASC) and China Electronics Technology Group (CETC), together with tech giants Alibaba, Baidu, Huawei and Tencent. Rest of the classes seem appropriately distributed with respect to publication and spending data provided above.

Table 5. 3: Cluster of countries with respect to number of companies dealing with QIT

Number of firms in data set (out of 200)	Countries
1-4	Austria, Czech Republic, Denmark, Estonia, Finland, India, Israel, Italy, Norway, Poland, Russia, Scotland, Singapore, South Korea, Spain, Sweden, Switzerland, UAE
5-9	Australia, France, Netherlands
10-19	Germany, Japan, China
20-39	Canada, UK
40+	United States

Finally, the graph in figure 5.4 denotes number of companies founded or departments formed within companies focused on quantum technologies with respect to years. Straight line shows the total number of firms while dotted line gives the number of firms established within that year. The data for 2018 is incomplete since this data is mostly collected via public access documents and there is a certain lag between a company being formed and gaining visibility on public access.

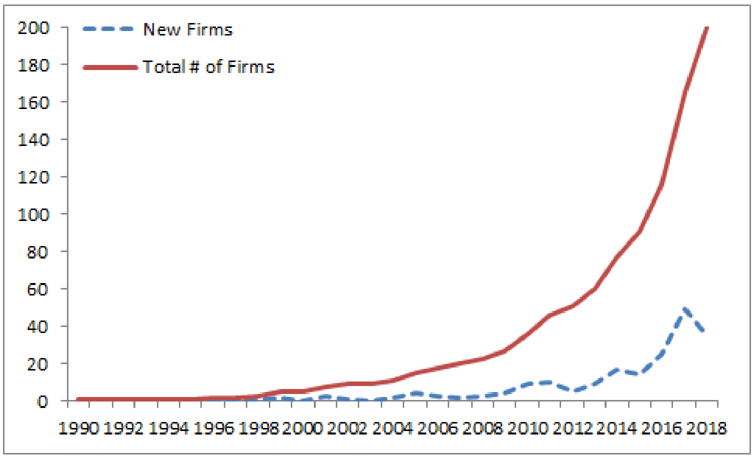

Figure 5.4 Number of new firms founded or departments formed within companies focused on quantum technologies with respect to years and in total

5.1.2 Qualitative Data (Global)

In this part of the study, qualitative data on global perspective is presented. This section is added because there were several anecdotal and pivotal instances that couldn't be mentioned under quantitative data section.

Initially, the number of proposed and funded projects for FET Quantum Flagship program is introduced. It can clearly be seen that Europe has a significant tendency towards fundamental science and researchers require funding schemes such as the Flagship. It can also be seen that the Flagship is not a program designated towards providing support to fundamental science.

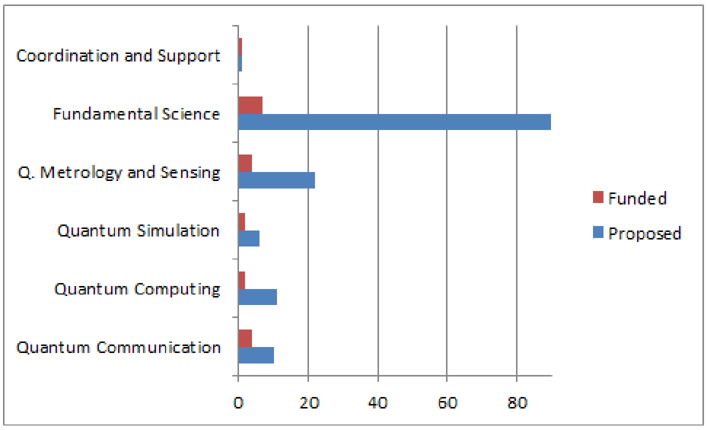

Figure 5. 5: Number of proposed and funded projects for FETFLAG-03-2018 ramp-up phase

This is actually made more evident as the rationale for FET Flagship is presented in the Kickoff Event in Vienna between 29-30 October of 2018. It is given as;

- Maturing field - no longer “proof-of-principle”
- 550 M€ investment in 20 years - return on investment?
- First QT commercial products & companies emerge - growing steadily
- Accrued industrial interest, Big IT companies, Non-traditional users
- Other regions invest massively
- No dominant player yet - build an European industry

Therefore it would be ill-advised to consider this international initiative worth 1 billion euros as a scientific or even R&D based effort. Innovation is a key aspect and building an European industry to compete with other regions has been a vocal point being made as a reason for this initiative to become a reality (HLSC, 2017).

The main ‘other’ region being pointed at here is initially China, and to a lesser extent US. Some anecdotal data can be presented to see the importance of China in these discussions, especially when it comes to space related subjects.

During the “The Lisbon Training Workshop on Quantum Technologies in Space”, a researcher from Portuguese FCT Space Program thanked the Chinese saying “without them, there would be no funding”. In a reserved meeting in Vienna Kickoff on a possible FET program for ‘Quantum Spaceship’, the discussion was mainly on whether involving China in Galileo (the European global navigation satellite system) is necessary or not. Finally, it was openly discussed in Vienna whether it was meaningful for firms to develop this technology in Europe since “Chinese would end up manufacturing it in two months, for cheaper and in better quality”.

Importance of Chinese investment in quantum technologies is a recurring theme not only in EU but also in US as well. News articles, Senate discussions, private panels are almost obligated to mention the fact that China is spending more than US. This is showing in patent data and some techno-economic achievements as well. The marks of first quantum satellite and first commercial quantum network belong to Chinese, while the first commercial quantum computer sale is from Canada, and the first widespread use of quantum cryptography in public is from Europe (Switzerland). Europe seems more concerned with China to compete with, while in US, China and EU are both mentioned as possible competitors in quantum technologies.

5.2 Data on Turkey

In this section of the study, quantitative and qualitative data on Turkey is provided. It constitutes the main ground on which the descriptive analysis and policy suggestions later are transpired upon. Some of the data presented here are given in greater length at Appendix E.

5.2.1 Quantitative Data

In this section, the data on Turkey is presented. This section contains data from strategic plans including TÜBİTAKs Vision 2023 document, State Planning Organization (DPT) spending, “Capabilities on Quantum Technologies” report, the draft of “Quantum Sciences and Technology Work Plan” and the National Thesis Center.

5.2.1.1 Strategic Plans and Vision 2023

Strategic plans obtained from the website[3] and the Vision 2023 document were covered for this section. There was only a single referral to quantum technologies in strategic plans of central organizations, which was in "National Boron Research Institute 2013-2017 Strategic Plan" as a reference to Vision 2023 document. The only explicit focus on quantum technologies in strategic plans of public universities was in "İzmir Institute of Technology 2014-2018 Strategic Plan" regarding the "Applied Quantum Research Center" in IZTECH.

The main focus on quantum information technologies was given under nanotechnology in Vision 2023 document, highlighting the importance of nanoscale quantum information processing. On the roadmap regarding the developments in nanotechnology, it was planned to develop basic quantum algorithms to control qubits built out of nanostructures until 2010, within the context of basic research. Similarly, it was planned to have nanoscale quantum cryptology systems ready to be employed for commercial and military use. Finally, supporting firms and SMEs in technoparks to be formed was also another goal for 2010.

Containing the focus on quantum information technologies under nanotechnology also reveals itself in "Turkish Nanotechnology Strategy and Action Plan (2017-2018)" published April 2017 as decision no 2017/23 on the Official Gazette. This document contains a detailed list of research centers and higher education programmes dedicated to nanotechnology in Turkey. Cross-referencing the list provided here with "University and Public Institutions Research Centers" document published in December 2010 by State Planning Organization, four centers contain the word 'quantum' in their description.

Table 5. 4: Institutions related to QIT mentioned in "Turkish Nanotechnology Strategy and Action Plan (2017-2018)"

Institutions	**Name of the Center**
Gazi University	Photonics Research Center
İstanbul University	Advanced Lithographic Techniques Laboratory
İzmir Institute of Technology	Applied Quantum Research Center
Selçuk University	Advanced Technology Research and Application Center

[3] http://www.sp.gov.tr/tr/stratejik-plan

Due to the distinction between quantum information technologies and technologies emanating from the first quantum revolution (such as laser, transistor etc.), this list should not be taken at its face value.

5.2.1.2 State Planning Organization Spending

The spending reports for projects obtained under State Planning Organization (DPT) regime were checked for this section. Two explicit mentions of centers related to quantum technologies are found. First one is BİLGEM (Informatics and Information Security Research Center) Quantum Cryptology Research Center where between 2009-2011 in total 5,38 million TL ($3.2 M)[4] is allocated towards and the second one is Applied Quantum Research Center at İzmir where 4,46 million TL ($2.67 M) is allocated in the same time period (DPT, 2010). Therefore, between 2009-2011 it can be seen that around 10 million TL ($6 M) from DPT sources were spent upon these centers.

5.2.1.3 Reports from TÜBİTAK

There are two reports from TÜBİTAK, "Capabilities on Quantum Technologies" is open access (BİLGEM, 2018) at MAM Library and the draft of "Quantum Sciences and Technology Work Plan", which is an in-house document not open to public access. The capabilities report shows two centers in TÜBİTAK, BİLGEM and UME, are invested in quantum technologies. BİLGEM is Informatics and Information Security Research Center and its interest toward quantum technologies is in cryptography. UME is National Metrology Institute and its focus is toward quantum metrology and SI units.

BİLGEM is part of a QuantERA project, which is an ERA-NET Cofund supported by EU and covers 32 organisations from 26 countries. In this framework, the SQUARE (Silicon Photonics for Quantum Fibre Networks) project has a seven partner consortium where TÜBİTAK BİLGEM is one of them. Main focus of Turkish side on this project is developing and demonstrating high speed quantum random number generators (QRNG) on a silicon chip. It can be seen from BİLGEMs website that an earlier version of QRNG (KRSU) is already available as a product, though its sale is only possible through permission of Ministry of National Defence.

The work plan report reveals there were in total six applications from three different institutions to QuantERA 2017 call. These institutions were BİLGEM, Bilkent University

[4] Calculations are made using the average exchange rate of 2011 (1 USD = 1.67 TL)

and Koç University, all are partners of previously mentioned “BİLGEM Quantum Cryptology Research Center” supported by DPT. A report titled “Quantum Cryptology Infrastructure Project Koç University Final Report” published at January 2012 reveals there were 11 participants from Koç University to this project at that time. A similar comprehensive report for Bilkent University could not be reached publicly however this project is listed within their list of “previously completed projects” for several researchers at Bilkent University.

5.2.1.4 National Thesis Center Data

In this part of the quantitative data section on Turkey, data obtained from National Thesis Center is introduced. The initial set of data is collected through applying the keywords provided in table 5.5 below. Theses that were completed abroad and uploaded to National Thesis Center were not included.

Table 5. 5: Keyword search on National Thesis Center with respect to related main field

Related Main Field	**Keywords searched (Eng)**	**Keywords searched (TR)**
Quantum Computation	Q. Computing Q. Circuit Q. Computer Q. Coding Q. Error Correction Q. Simulation Q. Algorithm	K. Hesaplama K. Devre K. Bilgisayar K. Hata Düzeltme K. Simulasyon K. Algoritma K. Kodlama
Quantum Communication	Q. Network Q. Channel	K. Ağ K. Kanal
Quantum Cryptography	Q. Cryptology Q. Key QKD (Q. Key Distribution)	K. Kriptografi K. Kriptoloji K. Anahtar K. Şifreleme
Quantum Information	Q. Teleportation	K. Bilgi K. Bilişim K. Telenakil K. Uzaktarım K. Işınlanma
Quantum Entanglement		K. Dolanıklık K. Dolaşıklık

Fields such as quantum thermodynamics, plasmonics, and spintronics were purposefully omitted to limit the range of data obtained strictly within fields directly related to quantum information theory. For the same reason, theses on single photon emission and absorption processes were not taken on face value. Out of four related theses two were already covered under quantum information and quantum communication searches. The other two were both from Koç University, and although related to quantum technologies they were mainly focused on material properties hence removed from this data set.

After obtaining an initial list through keyword search, other theses of each advisor was checked for potential related studies which might not contain any of the keywords in title, abstract or keywords. Finally, the same process was repeated for potential advisors of such theses. Names of these potential advisors were collected from previous KOBİT attendees, committee members and speakers, COST Action MCs, attendees of national roadmap brainstorming session at TÜBİTAK BİLGEM, and other minor sources.

As a result, there are 108 theses collected. Out of these, 77 are master's and 31 are doctoral degrees. The full list is available on Appendix E. Dataset at hand contains information on passed away and relocated advisors as well, therefore these should not be accepted as current situations, rather it can be seen as a historical accumulation of academic efforts. Middle East Technical University has the most (8) M.Sc. and Sabancı University has the most (5) Ph.D. degrees awarded in quantum information related fields. Tables E.1 and E.2 in Appendix E contains the number of master's and doctoral degrees awarded in all universities. Similar to the clustering of countries with respect to number of firms, universities are clustered with respect to the degrees they awarded in QIT related fields.

Finally, figure 5.6 below provide the number of master's and doctoral degrees awarded per year and in total on a national scale, together with a distribution of these theses in different fields related to QIT.

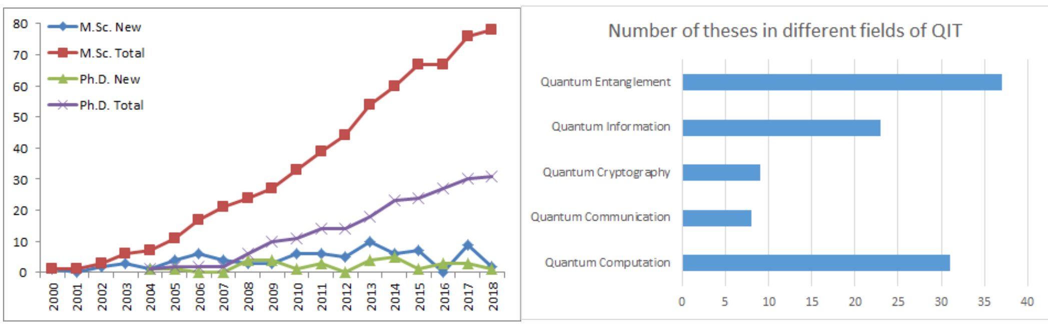

Figure 5. 6: Number of M.Sc. and Ph.D. degrees awarded in total and per year and theses in different areas of QIT on National Thesis Center

5.2.1.5 Web of Science Publications

In this part, the number of papers published that are covered by Web of Science database containing the keywords below are used. This section is added to the study around early March 2019 to double check whether the qualitative outcomes on Turkish academics collaboration habits indicating that they are somewhat different than countries with similar publication and population size.

The search query was for articles and proceedings published between 1945-2019 and containing the following keywords either in their titles or topics. Keyword query is given below.

> *quantum simulation, quantum imaging, quantum sensing, quantum sensor, quantum computing, quantum computation, quantum computer, quantum coding, quantum programming, quantum error correction, quantum error correcting, quantum circuits, quantum algorithm, quantum algorithms, quantum network, quantum networks, quantum channel, quantum channels, quantum cryptology, quantum cryptography, quantum key, quantum teleportation, quantum information, quantum technology, quantum technologies*

The purpose of this section was to see the differences in collaboration maps of different countries, rather than find the exact numbers of publications from each country on quantum information technologies in general. Therefore, it is assumed that the outcomes using keywords above are enough indicators for determining differences in collaboration behavior on national level.

For Turkey there were 152 publications. To list countries with similar number of publications a table is constructed and presented in Appendix E table E.2 containing the population and total gdp ranking of given countries as well. Out of the 12 countries with similar number of publications (between 100 and 200), two of them appear to have similar populations and GDP rankings with Turkey; Saudi Arabia, and South Africa.

To compare the network structures, publication data obtained from Web of Science was visualized using Pajek (Batagelj & Mrvar, 1998). The three maps, including Turkey, are provided below. Each node represent a person and the width of links between them represent how many times they appeared as co-authors on a paper. Names of the researchers are not given on the maps below to keep the graphs clean and to the point, however it should be noted that these maps cover foreign collaboration as well, therefore some of the nodes do not correspond to academics in given countries.

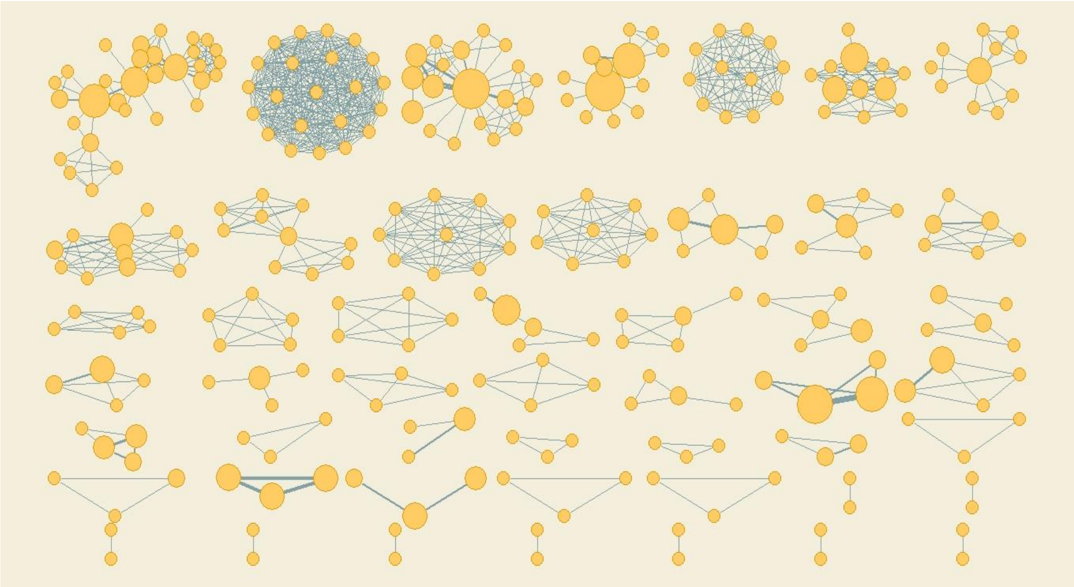

Figure 5. 7: Network map of Turkey

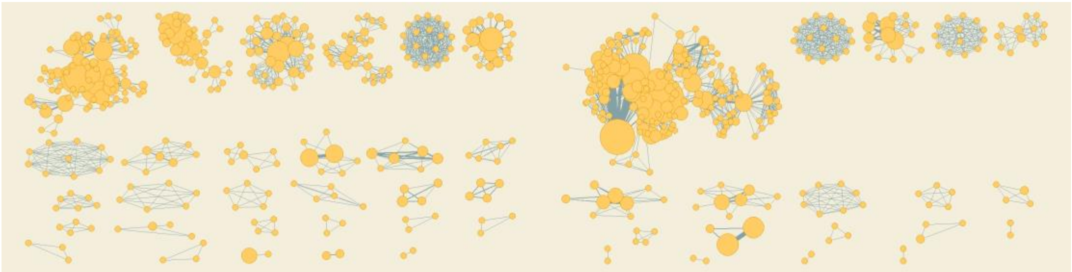

Figure 5. 8: Network maps of Saudi Arabia (left) and South Africa (right)

Out of the three network graphs, Turkey has the most fragmented collaboration map. Furthermore, even the strongest of Turkish collaborative actions (given at upper end of the graph) are smaller in size compared to other countries of Turkey's scale. This agrees with findings of qualitative section as well, and is discussed in the following chapter.

5.2.2 Qualitative Section

In this section, information and outcomes related to interviews is provided in a compact form. Only the clustered codes and important themes are highlighted here. Direct quotations are not invoked due to the fact that interviews were conducted in Turkish.

5.2.2.1 Interviews

For anonymity purposes, information such as gender, academic position, years of experience in quantum information, and cities of residence are given as distributions rather than specifically to each interviewee. Details on institution types and departments of participants can be found in table 4.3 under 'Qualitative Data Sections' part of Methodology chapter.

- In total there were 19 participants interviewed in three different cities, five in İzmir, seven in İstanbul and seven in Ankara.
- Out of 19, three were from private sector, 15 held academic positions and one was from a public institution with strong ties to academia.
- 16 of the participants held academic titles and positions, one was a Ph.D. candidate in their last year, one was a postdoc, two were assistant professors, six were associate professors and six were full rank professors.
- Out of 19 interviewees, only one had 'two years or less' experience, the bulk of participants (12 of them) had 5-15 years of experience, and three had 15+ years of experience in quantum information.
- Finally, two of the participants were women while 17 were men.

Interviews were transcribed into text form and later analyzed via QDA Miner. During the coding process no explicit theoretical bias was applied, codes were kept general. Later, themes and repeated points were gathered together and analyzed in the light of theoretical tools being utilized. Code clustering using code proximities and two sets of outcomes utilizing the theoretical background covered in previous chapters on "Systemic Problems in Turkey" and "Rationale for Public Intervention" are provided in detail on Appendix D. In general, the neutral form of unbiased code sequence analysis provided several key relations which can be summarized as following;

- "TÜBİTAK" is a central node in this discussion, both in terms of scientific research and commercialisation
- Participants believed that resources utilized for experimental purposes are lacking
- Quantum cryptology appear in a distinct manner than the other three areas of QT
- "Buyer Position" is an essential stance that participants believe Turkey has endorsed, which has consequences for research, funding, commercialisation and mindset

- Most of the participants note that Turkey has good theoreticians in quantum information theory, however one participant expressed that even though this is true, Turkey is not a trend setter in that sense but a close follower
- Commercialisation is accepted to have been focused on quantum computation by the participants, though especially experimental researchers are aware of commercial activity in their respective fields of quantum communication, metrology and cryptology
- Multidisciplinary nature of QT makes it additionally difficult for researchers to carve their way into Turkish academic system, which is seen as a disciplinary scene.

Table 5. 6: The summary of code clusters, themes and policy focuses

Codes	**Themes**	**Policy Focuses**
Cluster 1 - Tübitak - EU COST Actions - Academic Connections - Institutions Abroad *Cluster 2* - Ministries - Photonics - Quantum Cryptology - Quantum Sensing - Resources Utilized - Theoretical Aspect *Cluster 3* - Industry-Academia Partnership - Reasons of Collaboration - Effects of QT - Buyer Position - Obstacles (for commercialization) - Lacks in experimental fields *Cluster 4* - Scientific Meetings - QT Sharing Spaces - Obstacles (in general)	*Resource Management* - bureaucratic issues such as caps and delays - size problems and lack of variety in funding - mobility hindrances and access to international field *Strategic Thinking* - Short-term focus - Buyer position / lack of market formation - Rapidly changing priorities - Spillovers and learning processes are ignored *Trust* - Lack of collaboration - Increased uncertainty for prospective entrepreneurs - High risk for established commercial agents - Community based trust vs. institution based trust	*Resource Management* - Training a 'quantum aware' workforce - Expanding education - Focused R&D *Strategic Thinking* - Hybridization - Standardization - Integration to value chains and market formation - Prioritization *Trust* - Increased awareness on public, academia and industry scales - Centralization of authority and impact assessment - Creating fair competition - Supporting national and international collaboration

Using the clustered codes three themes are developed, and the policy suggestions focus on these themes. A brief overview of the continuity between codes, themes and policy focuses is summarized on Table 5.8.

Until this point in the chapter, data collected and generated through quantitative and qualitative sources on global and Turkey were presented. Findings reached till now lay the foundation of descriptive analysis formulated in the following section. The distinction between global and Turkey here were in order to distinguish the specifics of the Turkish case apart from general trends. Utilization of qualitative methods for Turkey helped to identify the location dependent issues in a clearer sense. On the next section, these individual findings are combined into general themes concerning both the Turkish and global cases.

5.3 Descriptive Analysis

In this section, a descriptive analysis of the national and global situation with regards to quantum technologies is given. Three themes per case are formulated. These themes are not necessarily the most dominant, but they are the most relevant ones for policy suggestions on the case of whether a developing nation (Turkey in this particular case) should attempt to start on a path to swing their entire economy upwards (Perez & Soete, 1988) using the window of opportunity presented due to the current technological revolution.

For all the six themes below, arguments provided contain analysis on quantitative and qualitative data from all the sources, global and national. Interview results are utilized directly in order to give examples and input from participants.

The main purpose of this section is to form the base on which policy suggestions are built upon. The themes highlighted for Turkey, (i) resource management, (ii) strategic thinking, and (iii) trust, are the ones most encountered in interview results. Issues of (i) lock-in, (ii) exploration-exploitation issues, and (iii) excessive focus on innovation/commercialization are considered as global trends. Although none of these are encountered in Turkey, for a country following the global trend they are sure to be imported if not ways of preemptive mitigation are developed early on.

5.3.1 Turkish Themes

Three of the most relevant themes covered here are resource management, strategic thinking, and trust. These themes are developed mainly using interview results and codes generated from them.

5.3.1.1 Resource Management

This theme is a central one to the Turkish case and contains several important issues. In this part, the main argument for resource management is actually given in the context of capability development, which is not a mission-oriented approach but can be considered as a pre-mission oriented one.

The most relevant resources in question here can be listed as human capital and infrastructure. Funding, or more bluntly money, is accepted by the interviewees as 'not a problem', however, accessing and utilizing those funds are. Institutional problems were presented as the primary factor of mismanagement or these resources.

Lack of infrastructure is also linked to the lack of human capital, especially in experimental areas by some interviewees. Others argue that on the contrary, lack of infrastructure hampers the accumulation of human capital. Interviewee 9 (i9) argued that Turkey is always ready to invest in buildings and equipment, the missing thing is people who can ask for it from the funding agencies in the right way. However, interviewee 2 (i2) expressed that it takes too long to set up a laboratory in Turkey with using the funding schemes available and what is understood as 'infrastructure' in Turkey is huge devices, therefore asking for 300.000 dollars to purchase a small sized oscilloscope is not an appealing option on projects.

Interviewee 7 (i7) expressed that because there are no local experimental groups, their work had to be implemented experimentally in other countries. Interviewee 8 (i8) mentioned that devices in quantum technologies are of high added value, therefore even buying back the knowledge they themselves shared to be translated into devices can be too expensive, and Turkey should begin commercialization to get its fair share of the knowledge it produces.

Interviewee 15 (i15) highlighted that Turkey lacks experience in production processes, which emanates from the lacks in human resources, production-related materials and machinery. Also, i15 noted that even the aluminum used in construction cannot be produced locally, therefore it would be a long way to produce stable aluminum alloys that can be used for physical realizations of quantum states.

Interviewee 12 (i12) argued that in Turkey, funds are granted to increase capabilities into new fields, however, the resources necessary to act on these capabilities are not utilized, which results in many idle infrastructure investments and dormant equipment or laboratories.

That argument can be taken in support for i9 proposing Turkey not being reluctant to invest in new infrastructure, though this enthusiasm causes funds from being used for the utilization of already existing infrastructure.

This also reveals itself in other forms as well. Interviewee 5 (i5) mentioned that although around 5 million TL ($3.2 M) from DPT sources were granted for infrastructure in BİLGEM, it's potential is not being realized because no additional support is provided. Furthermore, this issue of not maintaining the existing infrastructure surpasses equipment or devices, i5 noted in a laughing manner that even their university offices are too dirty to bring any colleagues and they don't know what to do if a collaborator from abroad needs to visit them.

Accessing funds to support graduate students to form the workforce necessary for research is another main pillar of this theme. Interviewee 10 (i10) stated that some universities do not have physics departments and the only way for them to reach graduate level researchers is through TÜBİTAK projects. On the same subject, i8 noted that finding graduate-level researchers is a problem in Turkey because there are few students focused on quantum mechanics and well-educated ones choose to continue their education abroad. The demand for these students is high in other countries, according to i8, and to compete with this they choose to train their students starting from undergraduate levels by themselves. Sometimes this is still not enough, due to high living costs in Turkey, especially in İstanbul, students are discouraged to continue their graduate level education here.

Scholarships are a huge point of discussion in this manner, however, most participants think that the level of financial support for a graduate-level researcher is too low to attract and keep well-educated students in Turkey. Unless they have other means of financial aid, such as research assistantships in public universities, finding students becomes an issue. Interviewee 3 (i3) noted that even though at the universities with graduate-level physics education, finding students without financial support is really difficult. According to i3, it would be unfair to expect intensive research for free from 24-25 year-old people, some of whom have financial responsibilities to their families. Even for students with other means of financial support, demanding their time and effort to be focused on thesis studies and research rather than their actual jobs is unrealistic.

In the group meeting, the levels of scholarship versus relative buying power were discussed and problems caused by TÜBİTAK's reluctance to update scholarship amounts were deemed as a problem. The meeting took place at early 2018 and the amounts have been updated since then, however, the idea participants focused upon has not been fully addressed, which is the volatility of Turkish Lira versus foreign currencies and its effect on income levels.

Several participants noted that although the amount these researchers receive must be increased, this increase should be limited to a certain degree. Both some participants from group meeting and i2 stressed that granting high-income scholarships to researchers in these areas would yield problems such as attracting the wrong kind of people and lowering the authority of principal investigators in the eyes of graduate students, due to similar income levels.

Another issue highlighted by interviewees is the caps imposed by TÜBİTAK, on the amount a researcher can earn and the number of projects a group leader can run simultaneously. A similar account to updating scholarships has been brought up in the group meeting regarding the funds for TÜBİTAK 1001 and 3501 programs, and small restrictions such as only 2.000 TL ($520)[5] for laptops or 10.000 TL ($2.600) for traveling abroad for scientific conferences. Since the time of that meeting, the upper limits of programs in TÜBİTAK are almost doubled, though again this does not address the problem of having these caps. The currency volatility is high in Turkey and in the time between applying for a grant and actually getting the funds to spend them can be rather long, causing serious delays or setbacks in certain projects.

Interviewee 6 (i6) noted that funding agencies and private actors from other countries want to support scientific and technological research on these fields in Turkey as well, but TÜBİTAK puts hard caps on the amounts researchers can receive from there. Similarly, there are serious problems in especially public universities about how the funds from abroad can be utilized. Some participants expressed that occasionally they cannot use their own funds due to university bureaucracies. On the group meeting, regulations imposed by TÜBİTAK on COST Actions were criticized. The delays on project assessment basically kills most projects aimed for COST Actions according to them because COST Actions are fast-paced programs with a couple of year of lifespans while TÜBİTAK's assessment of projects sometimes take more than a year, at which point the COST has already moved

[5] Calculations are made using the average exchange rate of March 2018 (1 USD = 3.80 TL)

forward to the second phase and opportunity is lost. Therefore, when people from TÜBİTAK complain that applications are low, they are not being sincere according to participants.

The issue of ‘critical mass’ is encountered in two individual interviews and the group meeting with exact same wording, implying that this issue might have been discussed by interested parties previously in private or could have been part of a non-public document. These participants expressed that to catch up in human capital, critical mass is an essential issue. The concept of critical mass here is used by the participants as not only the number of academics or researchers but also in conferences and activity in general. However, all participants focused on the lack of critical mass in experimental researchers. On a follow-up question on this subject, i9 elaborated that the brain drain occurring in the last two to three years and loss of charm in Turkey due to recent events, which had a negative impact upon progress being made in these areas. They noted that it has become exceedingly difficult to invite foreign researchers to come and conduct their research in Turkey, or even attend conferences when compared to earlier times. Though it would be necessary to note that this interview was held during January of 2018.

Final issue under this theme is mobility. It appeared as a serious problem on multiple accounts, especially under accessing and utilizing funds. Some participants noted that they have returned through TÜBİTAK’s 2232 program of ‘International Fellowship for Outstanding Researchers’. Under this programme, it is assumed and expected that these researchers should transfer their knowledge and provide linkages for their networks abroad. However, due to restrictions on mobility funds and administrative burdens, this is deemed to be not happening by interviewees.

One participant from the group meeting mentioned that their department head does not want them to travel for project-related purposes because it would disrupt departments flow. Therefore, there is a clear conflict of priorities for some institutions. Interviewee 4 (i4) stated that the administrative workload itself, even if the department is onboard with your research activities is really tiresome. To this end, the sabbaticals are brought up. In the group meeting, participants discussed that these one-year research-based intermissions can be guided towards visiting the institutions that are ahead in quantum information areas. A support structure aimed at this may overcome the conflict of interest situation since these sabbaticals are already established mechanisms to a certain extent.

Student mobility was a larger issue, especially the fate of students that went abroad for doctoral and post-doc studies. The issue has been brought up in several individual interviews and the group meeting, some participants shared stories of ill-fated researchers that they have heard or witnessed. It has been stressed upon that researchers returning to the country and spending so much time and effort to find posts is both a waste of energy and a source of discouragement, and the system should be organized in a better manner to suit both the needs of governmental institutes and researchers that were sent abroad on public funds.

Furthermore, mobility, in general, is argued to be important for many activities in academia. On the subject of accepting students, i5 noted that one of their post-doc from another country turned out to be mentally unstable and they regret accepting him without meeting face to face first. Several participants noted that face to face meetings are the points of first contact for collaboration and although follow up meetings can be performed on means of distant communication, these meetings in person are essential for networking and to build up trust. The caps imposed by TÜBİTAK on mobility funds, especially for students, are deemed problematic by several interviewees.

A connection is made by i4 between the issue of mobility and collaboration preference towards theoretical studies in Turkey over experimental ones. They noted that theoretical studies are “down-localized”, they are in the head of the researcher and can be transferred to someone abroad. Therefore, global collaborations where Turkish side acts as the theoretical input can be sustained. In contrast, for experimental studies, the researcher experiences a localization problem and becomes entrapped here, much like the collapse of a quantum state noted the interviewee by laughing.

All in all, the central theme of ‘resource management’ contain issues such as lack of infrastructure, human capital, and critical mass, meanwhile problems of mobility, and accessing/utilizing funds are acting as institutional issues contributing to the continuation of these lacks. Most participants believe that the funds to overcome some of these lacks are present but either not allocated for these purposes or not being utilized properly to improve the situation. However, several participants noted that lacking infrastructure such as cryogenics for quantum computation or expertise on high-grade materials cannot be overcome by basically spending money. There are certain areas that Turkey can catch up quickly, but in other areas, these lacks must be accepted as facts of state for the foreseeable future.

5.3.1.2 Strategic Thinking

Lack of resources and issues of accessing or utilizing funds point to a deeper theme, that is the strategic thinking behind initiatives in Turkey on quantum information technologies. In this part, the issues of short term thinking, buyer position stance, expectations of novelty, and discourse vs. factualities are discussed in the context of strategic thinking. The theme does not necessarily argue that there is no coherent strategic agenda on quantum technologies, but it suggests that there is an incoherence between published documents, expressed sentiments and actual efforts.

The first and maybe the most common issue encountered in interviews under this theme is the topic of short term thinking. The general expectation out of scientific projects is short termed in general, according to i6, and since quantum technologies won't be affecting everyday lives of citizens for quite some time, it is accepted as a purely scientific development rather than a technological one. On the same topic, i1, i5, i8, i10, i13, i15, and participants of the group meeting all commented on this issue. Some argued that firms avoid taking risks in Turkey, others noted that even ridiculously low amounts of money awarded by public institutions come with short term expectations attached to them.

A special focus was given to project lengths by i13, stating that achieving a final product for any projects with aims of high TRL (technology readiness level) takes around 10 years. For example, TRL 3 takes around 3 years according to i13, therefore a comprehensive project aiming for an end product should be 8 to 10 years in time. However, in Turkey, it is not possible to foresee what will change in 10 years or to predict a cost structure. Therefore, sticking to short term projects is not a mere risk-reward analysis but also a problem of uncertainty.

Interviewee 14 (i14) specifically noted that when dealing with government contracts, firms focus on risks rather than profit, and high risk - high reward scenarios are not appealing because "this is Turkey", indicating high uncertainty. Another participant from the private sector, i15, argued that the behavior of adhering to low-risk paths is common for academics as well and that is why there are so few experimental groups in these technologies locally. Finally, i13 distressed that there should be projects detached from individuals in charge, the main intention should not be publicity, and the government should be very clear about what is the expected outcome of any projects. They noted that there have been instances of changing the expectations midway through projects by public institutions, or withdrawals of funds when ‘the person in charge’ changes. Therefore, in addition to the uncertainty and all the lacks mentioned above, there is an extra layer of cultural risks for firms dealing with quantum technologies in Turkey, and probably for most high-tech fields as well.

In the group meeting, it has been expressed that there was and probably still is a critical team at BİLGEM. However, the problem with institutions like BİLGEM is that the personnel usually gets rotated between projects with outcomes in short term. This gets in the way of developing technologies requiring long term commitment since there is always something that requires immediate attention and has yields in short term. Participants argued that a publicly funded, long term and continuous project, which is being conducted at a dedicated center, is necessary to overcome these issues.

The issue of ‘buyer position’ is another central tenet to the Turkish approach to newly emerging technology fields according to several participants. Some interviewees noted this as a negative statement like it was an unintended consequence of other policies. Meanwhile, several interviewees mentioning this issue used neutral statements, indicating that this is not accepted as a negative situation by them but as a state of the matter. On this issue, i3 stated that Turkish society is not interested in how technology is developed only interested in using it, while i2 noted that the Turkish stance is waiting out the risks attached to the development and then buying the final products from abroad. On the same subject, i15 expressed that Turkish societies quickness to adopt new products open up a commercial landscape for applications, meanwhile setting local R&D in these fields back.

Not being on the developing side of technology means you are free of the risks attached to that process, however, you miss out all the experience, know-how and spillovers from those R&D processes. Some participants of the group meeting and several interviewees such as i2, i8, i12, i13, and i15 made comments on this topic. There were valued statements on both sides of the topic, whether this is an acceptable strategy or not, however, the consensus was that even if this is accepted as a general stance, certain exceptions must be made such as military and healthcare. Furthermore, it is noted that on these areas the importance of quantum technologies is not yet realized by neither the people in higher offices nor the public, which may eventually cause problems.

Another issue stressed by some participants is the difference between discourse and actual support given by public institutions. Even if the discourse is signaling investment into certain fields, the actual funding opportunities lie elsewhere. Therefore, it translates distrust to signals from public sources and gets in the way of sectoral alignment. Unless a very clear white paper comes out of a public institution with specific demands, it usually goes unnoticed.

Expectations of novelty from strategic projects was an interesting issue encountered during the interviews and it points to some evident institutional systemic problems about funding structures in TÜBİTAK. Two interviewees, i12 and i13, noted that they suffered from expectations of novelty by the judges at projects on strategic infrastructure or development. This issue was due to funds being diverted over TÜBİTAK and one of the criteria for the judges to check is novelty. Especially i12 stated that funding strategic projects through scientific funding structures, even if that strategic project has a high-tech element, causes serious problems. They joked that if Turkey wanted to build a fighter jet using TÜBİTAK funds, even the best projects would be turned down because there are other fighter jets around the world and it would not be counted as 'novel' by the judges.

At this point, it should be noted that TÜBİTAK's overall role as the main funding agency has been acknowledged by all the participants, and TÜBİTAK is also mentioned as the main supporter of activities in quantum information technologies. However, many participants came up with stories seemingly frustrated them at some point and therefore the main mentions of TÜBİTAK was not of great esteem but was considered as a nuance in order to achieve the necessary funding. Though most of the participants admitted that these regulations and rules are in place because of valid reasons, it does not make the process any less tiring just because the reasons are valid. Some participants noted that new funding mechanisms are necessary if any actual catching up is targeted, which was not the general expectation of participants.

Strategic policy papers are also brought up by participants in a negative sense. Some participants stated that these papers are either for public relations purposes or polishing certain people in power. Several participants noted that there is no coherence in strategy plans, and they feel reluctant to take them seriously because at the end the person in charge of a certain institution has the final say regardless of what strategy papers promised. As a general premise, i12 expressed that a strategy document should be precise and limited in content, meanwhile in Turkey, it is considered as a list of current important issues with hundreds of topics in them. Therefore, it loses focus and trails off the track, failing to guide or signal interested parties.

In conclusion, Turkish stance on developing technologies is generally accepted by the participants as targeting outcomes in short term, usually being at the buyer position for new technologies, not being consistent in planning, overly dependent on individuals, and public discourse not coinciding with actual plans or funding. Uncertainty seems to be a central topic in these discussions, where short term thinking, being at the buyer position, failing to follow plans, and being highly dependent on the current person in charge are all connected in one way or another to high uncertainty.

5.3.1.3 Trust

The final theme of this descriptive analysis of Turkey from interviews is 'trust'. It is also a central theme with important issues grouped under it such as collaboration, bureaucracy, risk and uncertainty, centralization and control. This theme is the one that is most heavily entrenched in societal, cultural and political matters, though it can be seen that some of these emanate from very material conditions such as lacking maintenance for experimental devices.

The first issue under this theme is collaboration, or more specifically how it is intertwined with trust. Several participants stated that trust is the key element in national partnerships, it surpasses the capabilities as the primary requirement for collaboration. This has been mentioned both by parties from academia and the private sector. In a particular example, i13 mentioned that unless the firm in question is a giant like TAI, they have to partner up with smaller firms to deliver what is expected, and unless they trust these other firms they won't take up the challenge because any failure on their part will translate to them. On the academic side, i5 stated that in Turkish academia a lot of people are angry at each other because of one or other failed partnership, therefore even if the opportunity to collaborate is present, it won't happen unless partners really trust each other.

Academic collaboration, especially on experimental projects requires an additional layer of trust because Turkey lacks proper maintenance on infrastructure. If a partner or a student of a partner breaks down a device, the repairs or necessary adjustments to make it work again would take a long time, causing other projects requiring that device to be stalled. In order to avoid that, owners of devices choose not to share them even if that means the devices won't be used for the better part of a year and lie dormant. The cost of breaking down a device is much greater than the possible reward of collaboration in many cases, which translates itself as a lack of infrastructure because even if the devices are present, they are inaccessible to most researchers other than the most trusted by the owners.

It has been witnessed that some experimental researchers share their infrastructure with others without going through official channels because it would take too long and cause a tedious bureaucratic inquiry, even if it is something small as a sensor or a laser source. Therefore, trust in this manner appears as a positive element reinforcing the way researchers operate and accelerating the process. However, since these are performed under the radar, it leaves the researchers in question to be vulnerable in case of any failure, therefore, this practice is expected to be rare.

It has been noted by some interviewees that the academic formation of Turkey works as a collection of 'feudalities' and if someone is an outsider, it is extremely hard for that person to get involved in any projects or research even if he or she is an expert on the subject. This is closely connected to trust, since the owner of laboratories decides who can perform which experiments mainly on their level of trust, they de facto gain authority over the research. Even if it is conducted on infrastructure built upon public funds, belonging to a public institution or university. This allows accumulation of power into individuals rather than institutions, allowing them to follow their own agendas disregard of strategy documents.

Several interviewees and participants of group meeting stated that individual authority over laboratories is a problem, and national laboratories similar to the ones in the US can provide institutional solutions. For example, i2 noted that there are some independent laboratories in Turkey acknowledged by Ministry of Development (now abolished), a similar initiative can be done in quantum technologies as well. However, this has been encountered as a double-edged sword, where on one hand it will strengthen the researchers that were unable to reach these infrastructures while on the other hand, it will bring forth many new issues due to systemic problems in Turkey.

Another issue mentioned by the participants is the division with respect to age. It has been noted by i5 that younger researchers want to collaborate with other young researchers because seniority in Turkey usually gets in the way of equal partnerships. The issue of age actually deserves an entire study on its own, it appears to be closely connected with the distribution of administrative burden, the formation of collaborations, exploration and exploitation of newly emerging funding tools (such as COST Actions), and so on.

The final connection between trust and collaboration can be stressed upon is on the in-person meetings. Formation of trust is deemed essential for collaboration. In-person meetings, short period visits, and social networking are brought up as matters of importance for the purposes of building trust. Therefore, mobility on both global and national scales play a central role for collaboration purposes. Even though there are examples of collaborators never meeting in person, several participants noted that spending time with a colleague in a scientific context is usually the way partnerships are formed.

The second issue under trust is the matter of bureaucracy. Many of the participants noted that bureaucratic drudgery is frustrating, causes delays and missed opportunities, costs too much time and effort, and so on. This appears out of a general assumption that academics or applicants to these funds are untrustworthy, and can only be awarded the necessary funds to conduct research after a tedious and somewhat lengthy elimination process, acting as an entry barrier to get rid of applicants with ill intentions. When elaborating on this topic, some participants suggested that centralization of funds around TÜBİTAK causes this situation and separation of funds according to different topics may allow more agility in these areas.

An observational anecdote from TÜBİTAK meeting in Gebze-BİLGEM on quantum information technologies in Turkey revealed that the amount of paperwork necessary is not clear to some higher officials in TÜBİTAK. This seems to be due to a disconnect between the researchers on the field applying for these funds, juries judging them, and designers of policies at TÜBİTAK. A certain document or report may not seem lengthy at first, but when a couple of these reports accumulate over projects, they cost a considerable amount of time for researchers, which could be used more effectively.

The third issue under trust is the relationship between risk, uncertainty and trust. Lack of trust in institutionalized support translates as increased risk for both academics and private agents according to participants. Institutions do not trust their applicants, and applicants are uncertain about the continuity of the institutions. During the period of interviews, many participants referred to the Ministry of Development, which is now transformed into another institution, that is not a Ministry anymore. One participant from the private sector stressed upon that Prime Ministers Office should act as the coordinator of activities in Turkey regarding quantum information technologies, which is also abolished now.

Several participants expressed that they don't know whether TÜBİTAK will be around in a couple of years, and even if so, whether the projects supported by TÜBİTAK will get continuous support or just stop at some point. These participants stated that the already passed projects were under re-evaluation during the time of interviews, because of political reasons. And although they understand why this process may be necessary, it surely hurt many projects and especially young researchers who were depending on the funds to support themselves.

Finally, the last issue under trust can be taken into regard as centralization and control. Many participants noted that creating one or several centers for quantum information theory is necessary and that these should be overseen by researchers trusted by the community. On this topic, i2 suggested that academics who are allocating funds should not be active researchers but retired or senior ones. Participants of the group meeting expressed that a center similar to Feza Gürsey Science Center in structure, which is disassociated from universities, would be well-directed towards product development in quantum technologies. On the same note, i11 mentioned that the issue of 'feudalities' arose at Feza Gürsey Science Center as well and similar mistakes should not be repeated in the case of a possible center for quantum technologies.

Centralization and control over the funds and activity were also considered under political concerns as well, some participants stated that these efforts should be coordinated at the 'highest order'. For example, i15 elaborated on this topic noting that it is not sufficient for YÖK, TÜBİTAK or any particular institution to take lead because it covers a wide range and only through coordination of many ministries and other institutions, a grand scale transformation can be accomplished, which can only be coordinated from above. On a contrary note, i13 stated that coordination of activities should be sector specific, for example topics falling under communication should be coordinated by BTK (Information and Communication Technologies Authority) and such.

To conclude, trust appeared as the third and final theme for the case of Turkey. Most of the issues encountered above under resource management or strategic thinking are closely correlated with this theme as well. Although, many participants used phrases indicating the situation is an inherent condition of Turkish society and culture, that it should be accepted as the precept rather than the exception, there have been many suggestions to mitigate the problems emanating from this theme

5.3.2 Global Themes

Three themes developed for this section are lock-in, exploration-exploitation issues, and excessive focus on innovation/commercialization. These are dominant global trends according to the data collected and generated in the previous sections, and they are relevant to the discussions being made in the next chapter on policy suggestions.

5.3.2.1 Lock-in

This theme is actually one of the most important, because any type of lock-in for the high-end of quantum technologies, that is quantum computing and what follows after, will have the highest societal impact on the way these technologies penetrate everyday lives of citizens. The issue of whether or not quantum computers themselves will be available to the public or just accessible through cloud depends on the hardware it is developed upon. Differences between how scientists and citizens will use these devices are already accepted being of societal importance in the literature (DiVincenzo, 2017).

One of the main technology used to construct qubits right now is superconductivity. These devices operate at near zero temperature, coldest places in the Universe only surpassed by some black holes, much colder than the empty space. They are expensive to build, maintain, and require lots of energy to be kept cold. A device like this, cannot be miniaturized to fit in a laptop, therefore a quantum computing industry built upon superconducting devices should operate strictly as a cloud service.

Formulation of an industry in that form means things cannot be decentralized like the current IT regime, cloud computing access to quantum computation would become the norm. This is already how supercomputing industry operates, therefore developing superconducting qubit based devices result in a certain way of industrial and market formation similar to supercomputer businesses.

There are other possibilities such as photonic or optical systems, ion-traps, atoms/molecules, graphene and else. None of these candidates have theoretical bounds preventing them from being the building blocks of next-gen quantum computers. Some of these also require cryogenic temperature, some have the promise of operating at room temperature, some has completely different set of requirements. Meaning, all in all, the future of quantum technologies heavily relies on which technology amongst the current contenders will be victorious against the others and rise up as the next ‘silicon-based transistor’-level disruption.

This issue has further relevance especially on the discussions concerning developed versus developing (in the IT paradigm) countries’ approaches to the risks they take and the problems they encounter. New and relatively smaller countries in the field, such as Austria and Australia are betting on firms such as Alpine Quantum Technologies and Silicon Quantum Computing because competing with giants like IBM, Intel or Google on superconducting qubits is not an appealing option. On the other hand, China, the US, and the EU are spending on developing multiple technologies in parallel to not miss any opportunity in the case of a technological breakthrough occurs in a different field.

Competing technologies approach (Arthur, 1988; 1989) is well equipped for dealing with this topic and further investigation of this subject can utilize the methods developed in that literature. Similar arguments can be developed for quantum sensing/imaging and communication as well, such as ‘what can be called as a quantum sensor’ or which technology amongst different types of quantum communication (land-based, satellite-based, repeaters with trusted nodes, repeaters without trusted nodes) will become the dominant one.

Locking-in to a primitive type of quantum communication infrastructure may cause some sunken cost expenses in the future if new cryptological methods are developed against quantum key distribution on such infrastructure. There have been some unexpected weaknesses discovered in earlier commercial quantum key distribution systems (Lydersen et al. 2010) by researchers focusing on ‘hacking’ these devices to explore security flaws. However, waiting for a highly advanced infrastructure may result in serious security breaches if a quantum computer capable of efficiently running Shor’s algorithm can be developed earlier than expected. There are currently many running quantum networks acting as test-beds for different algorithms and protocols, though no universal standards have been developed at this moment.

5.3.2.2 Exploration vs. Exploitation Issues

A possible quantum winter brought on by unfulfilled promises may be ahead in quantum computing due to the sector getting ahead of itself is an issue brought up on The Economist (2018). Data presented on quantum companies seem to confer this idea to a certain extent, there is an exponential growth in the numbers of firms and patents on applications. Considering that there is not a single commercially relevant algorithm performed on a quantum computer which outperforms the classical counterpart should be taken as a sign that the global trend is pushing on the exploration side hard.

Even for the more settled fields of quantum communication and sensing/imaging, the exploration mechanisms are far more favored than exploitation. This is expected due to being in the first phase of a new technological paradigm requires an exponential increase in the opportunity space and perceived understanding of what accounts as innovation. However, it should be noted by stakeholders that eventually exploitation mechanisms will kick in and firms not prepared for the competition are going to wither in this so-called quantum winter.

The title is purposefully chosen as issues since there are different approaches from different countries and parties. For example, EU Quantum Flagship mentions fostering supply chains (Riedel, 2019) for quantum technologies as an important matter that Europe should address. Meanwhile, the US is aiming to focus on a ‘science-first’ approach while simultaneously forming a stable marketplace for quantum information science and technology (Raymer & Monroe, 2019). UK (House of Commons, 2018) is discussing whether to include Innovation Centres to the extension of their national programme and supporting industrial activities in quantum technologies. Countries like Japan (Yamamoto et al., 2019), Canada (Sussman et al., 2019) and Australia (Roberson & White, 2019) are all actively pushing for new initiatives to increase the economic activity in their countries in these fields. Each country encounters different problems on issues such as regulations, standardization, supply chains, workforce training, and infrastructure. Learning from the experiences, successes, and failures of these countries’ efforts can be an invaluable tool for a developing nation to formulate its own solutions on how to tackle these issues when the need arises.

5.3.2.3 Excessive Focus on Innovation and Commercialization

As examples are given above, innovation and commercialization are excessively focused on reports and programs. Although large scale programs such as Quantum Flagship and US National Quantum Initiative gives room to basic science, their primary focuses are on applied research, innovation, and commercialization. Even the UK National Quantum Programme, which was more research and education oriented, is being transformed into a more industry-oriented form. The main issue on this is the lack of industry collaboration.

Quantum technologies is a new and high-risk area, even for somewhat settled fields like quantum communication. The main commercial activities in the field are related to exploring how these technologies can be utilized for industrial purposes, use cases of quantum technologies. Development of the field has been basic science driven, therefore other than a couple of highly expected commercial applications such as hack-proof quantum key distribution, extremely sensitive quantum gravity sensors, high precision atomic clocks for navigation systems, and quantum algorithms for unordered search and factoring, there are no current mid-tech applications ready to be utilized in the market.

This issue has been addressed at NAP Quantum Computing report (2018) with a reference to 'virtuous cycle' of classical computing where products using the new technology allowed the industry to make more money, which is then used to create newer technology. It has been stressed on the report that until such a cycle can be created for quantum computing, funding of an entire technological revolution through public funds is not feasible. Therefore, focusing on innovation and commercialization is deemed as essential for any developed country wishing to form a strong market for quantum technologies.

Another cause of this theme to emerge is something that can not be disregarded, the entrance of China to the field. The data on spending, publications, and patents all show that China had a relatively late entry to the field compared to US or Canada, however, the resources China utilized, both in terms of financial and human capital, have far surpassed either of these countries. This is frequently brought up in public documents and discussions from the US, sometimes equating the race for quantum technologies against China with the space race against the Soviet Union. Especially the patent frenzy of Chinese origin seems to have triggered a similar rise in the US and the fear of lagging behind in commercialization from other countries, particularly EU. The EU documents refer to the US and Chinese commercialization activities and argue that unless a similar path is followed, Europe will become a market follower except for some certain niche areas (EC COM 178, 2016).

Such a focus have effect on infrastructure development, workforce training, supply chains and so on. However, these are not issues related to scientific or even R&D problems, but market creation mechanisms. Therefore, there are billion dollar scale programs aiming both at tackling problems from basic science and market creation simultaneously. Different programs develop different approaches to this matter. US is dividing their activities and forming a Quantum Economic Development Consortium (QED-C) under National Institute of Standards and Technology (NIST) to tackle issues emerging during and after the prototyping process, leaving basic and application-oriented R&D for NQIA. EU Flagship has an Innovation Working Group dedicated to addressing them. UK and Canada have distributed these activities into their programmes. China is dealing with them through central coordination and strong public interference and guidance.

Unless policies are developed from scratch, which is rare, global trends in a field are reflected, even in implicit forms, at local policies. Therefore the themes highlighted here should be taken into notice before transferring any policy tools or ideas from abroad to Turkey or any other developing country. And even if policies are developed from the ground up, issues encountered by other countries can serve as examples on what lies ahead, and how they can be managed. Understanding the motivation behind a policy is as important as its tools of implementation, hence any policy tool to be adopted from these sources should be taken into consideration in the light of developments lead to it being formulated.

5.4 Cost of Entry Into a New Technology

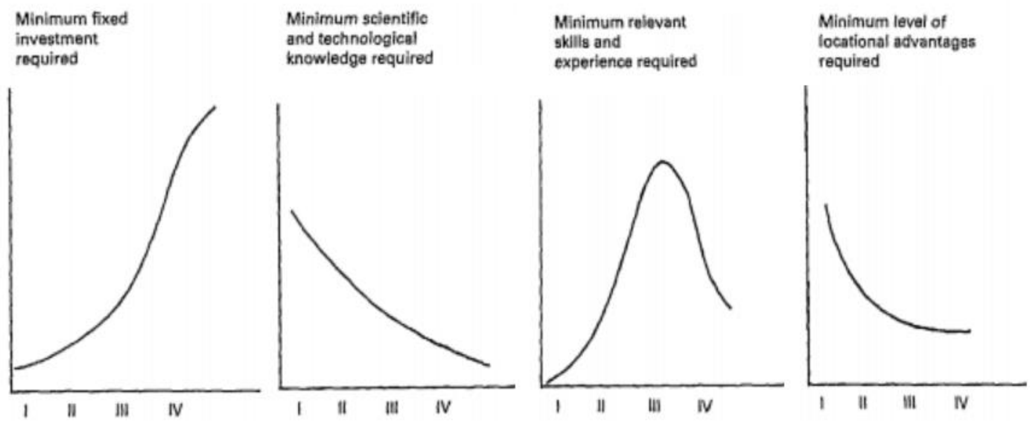

Fig 5.10: Minimum cost of entry for different phases into a techno-economic paradigm

In this section, a brief discussion on where Turkey stands regarding the four entry barriers described by Perez and Soete on the cost of entry into a new technology is presented for perspective.

It is assumed by most of the interviewees that Turkey does not have an investment problem especially in small scale when it comes to strategic technologies, however, there are serious systemic problems about the allocation of funds and their utilization according to some interviewees. Comments on investment co-occurred with the issue of short-term thinking repeatedly, both from academics and private sector participants. It seems to be a general assumption that investments in technology are accepted to have an outcome in ‘short-term’, otherwise, it is a failure. Therefore the fixed investment barrier heavily depends on strategic thinking entangled with resource management within the themes provided.

In Turkey, there are researchers invested in all fields of quantum technologies, especially in quantum communication and cryptography, with connections to institutes and knowledge sources abroad. However, technical knowledge is at a very low level in Turkey on quantum technologies. There are no trained technical personnel, support or maintenance structure except at some key institutes. Researchers either have to assume technical expertise on themselves or wait long times for technical assistance from supplier firms, which is also expensive.

There are no firms dedicated to quantum information technologies in Turkey. Most of the skills and experience accumulated in the country seems to be gathered around TÜBİTAK projects, which are short term and not continuous in their formatting. All of the three participants from private sector expressed their interest in quantum technologies as a far-future oriented form.

It is denoted by an interviewee at a public research institute that policies in Turkey are oriented toward supply, however without access to potential markets through mediums such as product fairs, without means of effective marketing and distribution, any commercial spark only counting on domestic demand would be extinguished, because it is limited to military and governmental sources which are not continuous or high in volume.

On the locational advantages side, being close to the European Research Area (ERA) seems to be a widely accepted locational advantage for interviewees. This allows Turkish researchers to be part of different support schemes such as the European Union’s COST (Cooperation in Science and Technology) Actions. A list of active COSTs and their respective Turkish management committee members are given on table E.3 in Appendix E.

Additionally, the country is between European and Asian markets, while also being closely related to US markets through many natural and historical links. Furthermore, due to socio-political reasons, it has close ties with many Middle Eastern and African countries. When combined together, Turkey has the potential of being a hub of technology transfer between these regions and more importantly, cultures.

Finally, due to its economic size, the Turkish domestic market can be cultivated to distribute at least some of the market creation cost towards national elements and domestic product cycles. All these require not just public intervention, but strong public leadership and command. No private actor, regardless of its size, can exploit these locational advantages without fully cooperating with the government and State in general. For a similar type of progress, the Chinese case can be taken into consideration (Sharma, 2018).

To conclude, the model developed by Perez and Soete suggests that the windows of opportunity for developing countries to catch up are phases I and IV. From the outcomes of this study, an attempt at catching up during phase I is a great and risky endeavor for Turkey. Under the current unstable political and economic conditions, any major attempts may fall short and cause severe setbacks to what could have been achieved otherwise. Public intervention is suggested only if public actors have or be able to acquire the ability to solve or mitigate systemic problems (Edquist, 2001; Chaminade & Edquist, 2006). The amount and types of systemic problems in Turkey are only solvable if the public actors set on a path to acquire the necessary abilities in a short period of time through great efforts.

Depending on the different barriers introduced by Perez and Soete on Fig. 5.10, and the current conditions of Turkey, it can be said that Turkey is not ready for a nationwide transformation on multiple fronts of quantum technologies. It may satisfy the other entry barriers, but lacking a critical mass in scientific and technological knowledge while simultaneously missing the necessary established infrastructure to gain that knowledge quickly is a strong entry barrier for Turkey into a phase I catching up effort. Even in the case of a strong will towards this direction, a focused and strategic approach to catch up in certain niche areas with necessary dedication may be the best course of action instead of an effort to upswing the entire economy over the second quantum revolution.

Entry at a later phase still requires great effort nonetheless. Different entry points on phases II, III or IV are possible. On a theoretical standpoint, Perez and Soete’s analysis suggests phases I and IV as the most suited ones for catching up. However, catching up to leading countries in a niche area has different requirements than upswinging an entire economy by utilizing the window of opportunity allowed by a technological revolution. In the following section, policy focuses and suggestions are provided towards that goal.

5.5 Conclusion

In this chapter, three themes for national and global cases are put forward to be operationalized for the next chapter. These themes are not the only ones emerging from data at hand, but they are taken as the most relevant ones for the research question on whether Turkey can use the window of opportunity caused by this technological revolution to catch-up. Issues given under these themes can be extended in number and depth as well, additional studies may reveal more complete pictures of the quantum technologies landscape. Further arguments are presented in the last section of this chapter on the path Turkey can follow regarding the entry barriers and phases of a techno-economic paradigm.

Combining local and global themes provide valuable insight. The global themes of (i) lock-in, (ii) exploration vs. exploitation issues and (iii) excessive focus on innovation and commercialization are not encountered in Turkey due to the problems emanating from the local themes, (i) resource management, (ii) strategic thinking, and (iii) trust. Therefore, if Turkey can overcome its systemic problems through successful policy implementations, it will encounter the issues covered under global themes.

Lack of lock-in into any of the existing hardware structures is both an opportunity and a huge risk. Committing limited resources to a field which may become irrelevant in a couple of years is not a risk that is suited for Turkey in most of QT, except maybe in some niche areas. Actively waiting out the developments, reinforcing its scientific and technical knowledge base to a point suited for quick adaption when lock-in does finally happen is a more attractive strategy for Turkey than to invest in several technologies simultaneously and hope that the right one is within those. Such an active form of waiting requires adjustment of strategic thinking and alignment of national capabilities into this line of thinking, which does not occur by itself and demands the use of different policy tools for signaling.

Exploration vs. exploitation issues and excessive focus on innovation and commercialization are strongly related to the formation of markets and generation of value chains. Either early integration to these chains or identifying the trends of development for entry at a later point is necessary to exploit the commercial outcomes of these technologies. Mapping of national capabilities, distribution of public resources to reinforce already existing capabilities, and creating a suitable environment for national and international collaborations are suitable paths forward that can be adopted in accordance with the national themes.

Lack of commercial activity in Turkey can be compensated through increasing scientific endeavors. It serves a double purpose of both allowing accumulation of scientific and technical knowledge while extending the base of trained professional which can translate their expertise into commercial enterprises at a desired later phase. Instead of expecting hasty commercialization on a domestic market that is almost non-existent, nourishing local capabilities while synchronously supporting the formation of this market can lead to much higher returns in the long run.

All in all, global themes can serve as both a projection of future issues that can be encountered locally and as targets of exploitation through which Turkey can attach itself to global value chains and benefit from the commercialization of these technologies. This is a long game with respect to Turkish standards of short-term expectations, therefore it requires a shift in mindset at least on long-term technologies such as quantum computation and simulation. For shorter-term results, somewhat established areas such as quantum sensing, imaging, cryptography, and communication are more suited. However, even markets in these fields are newly emerging and all of the global themes covered in this chapter apply to them as well. Therefore, short-term (5 years) commercial success from any local private actor in quantum technologies would not be a reasonable demand and set negative precedence for future entrepreneurs. On the next and final chapter of this study, policy suggestions that Turkey can adopt are discussed.

CHAPTER 6

DISCUSSION AND POLICY SUGGESTIONS

Until this point on the study, several arguments are established.

- Quantum Technologies has the potential to bring forth a new techno-economic paradigm through which upswing of an entire economy is possible.
- There are many countries around the globe with national and international initiatives, aiming at public intervention to the natural course of these technologies' direction to exploit the expected commercial advantages of them.
- The leadership role on a new paradigm is disputed, countries (US, China, UK, Canada) and regions (EU) are competing to attain a superior position through public policies.
- On overall, Turkey is not well-prepared for a hasty transition to these new set of technologies, however, there is room for development and an immediate paradigm shift is not expected globally.

Main global themes formulated in the previous chapter were, (i) lock-in, (ii) exploration vs. exploitation issues, and (iii) excessive focus on innovation and commercialization. The main themes for Turkey were, (i) resource management, (ii) strategic thinking, and (iii) trust. Global and local themes are used together on this chapter to formulate policy suggestions in order to utilize the data to its fullest extent.

6.1 Policy Focuses and Suggestions

Turkey lacks the infrastructure and previous investment in many fields in order to compete for the leadership position with countries like the US or China. However, it can still aim to utilize the opportunity window on niche areas suited for local strategic goals.

Two main areas Turkey can focus upon are quantum cryptography and quantum sensing. These hold the promise of being realized earliest due to their lower number of logical qubit requirements and there are already active global markets on both. Furthermore, Turkey has an extensive academic interest in photonics, on which the skills and experience developed can be translated to these two areas.

Quantum cryptography is a field that on strategic and academic level Turkey is already involved in, though commercially it is not an active player. Not being commercially involved in a field has severe negative feedback effects such as raising the cost of maintenance on infrastructure, lacking local value chains, and missing the spillover effects. Additionally, quantum cryptography is not expected to be a 'military only' technology, there will be widespread cross-sectoral market penetration due to critical infrastructure in energy grids, water distribution, avionics, e-government, and financial services.

In a similar sense, quantum sensing also aligns with Turkey's national interests not only in the defense industry but also in domestic appliances such as white goods. The following statement is taken from Bosch's website; "Quantum sensors will significantly improve future sensors and will be key to maintaining Bosch's world-market leadership in miniaturized sensor products". Sensors are important elements for many of the devices used on a daily basis, and quantum technologies promise to make them cheaper, more versatile and effective. Additionally, quantum sensing is a complementary technology to quantum cryptography in the sense that there are strong positive spillovers, developing improved sensors allow developing better cryptographic systems.

To achieve desired outcomes in any endeavors toward these areas, there needs to be a coordinated effort to tackle the national systematic problems. In regards to that, three focuses depending on national themes with their corresponding sub-focuses are provided on table 6.1.

Table 6. 1: Three sets of policy focuses

Resource Management - Training a 'quantum aware' workforce - Expanding education - Focused R&D *Strategic Thinking* - Hybridization - Standardization - Integration to value chains and market formation - Prioritization *Trust* - Centralization of authority and impact assessment - Supporting national and international collaboration - Increased awareness on public, academia and industry scales

6.1.1 Resource Management

One of the key findings of this study is that Turkey lacks a 'critical mass' of researchers in QT, especially in experimental fields. Misuse of resources at hand is a serious contributor to this lack of 'critical mass'. Difficulties of finding employment as academic staff, lack of continuous or long term researcher positions, underpayment problem of qualified technicians due to caps imposed by TÜBİTAK and other institutions are obstacles in front of increasing the number of experimental researchers in Turkey. These are all related to resource management.

Human capital, training and education, institutional and policy-based capabilities, physical infrastructure, and already established networks are all resources which are not managed or directed towards common strategic goals. Within this context three issues are, training a 'quantum aware' workforce, expanding education in related fields, and increasing focused R&D efforts.

Training a 'quantum aware' workforce requires exposure to these technologies. This can be attained through increased mobility of young researchers, possible entrepreneurs, and future workers in QT related sectors. One way is to establish internship programs focused on exchanging personnel with established firms in quantum technologies. Another is to increase international collaboration and be part of quantum consortiums through already established classical infrastructure (such as photonics) in order to elevate transfer of tacit knowledge through people and networks.

Expanding education in related fields is an essential subject according to participants of this study, and unanimous opinion is that quantum technologies require more attention to higher education level. On undergraduate and graduate levels, more courses dedicated to quantum information, quantum computing and quantum optics were mentioned by almost all participants as a necessary initial step. Many participants noted quantum technologies require its own dedicated graduate-level program or at least a joint program between different departments as soon as possible.

Expanding education may contain the goal of reaching a critical mass, supplying national efforts with young researchers, and attracting talent from other countries as well. Increased mobility opportunities can help foreign researchers from Middle Eastern and African countries to come and study in Turkey. Models like 'come, study and stay' through established funding schemes such as YTB (Yurtdışı Türkler ve Akraba Topluluklar Başkanlığı) Turkey Scholarships can be utilized to this end. There is already a considerable influx of foreign students, allocating funds to attract graduate-level students in these fields may provide fruitful results.

Finally, increasing focused research on any of the sub-fields of QT would also produce positive spillover effects on other fields. This can be achieved through removing caps, increasing size and variety of funding for a narrow field in accordance with strategic needs. Turkey does not possess the necessary resources to invest in multiple fields at once. Focusing R&D efforts have a better chance of producing tangible results rather than spreading the already limited resources even thinner.

6.1.2 Strategic Thinking

In terms of strategic thinking, the short-term investment mindset and limited duration of project periods appear as the main problem both on academic and private sector levels. Embracing the 'buyer position' makes Turkey passive in market creation processes, which in return causes a lack of strategic infrastructures in the long run. Things can change very rapidly, and every investment requires an immediate return which overlooks spillovers and learning processes. To overcome the negative effects caused by this, four issues can be focused upon are, hybridization, standardization, integration to value chains with market formation, and prioritization.

Hybridization is an issue brought up by i4 during the interviews. Quantum technologies will not take over and replace the entire infrastructure, and hybridization is a mechanism of negotiation for extending the current paradigm. There are already huge investments in current infrastructures both in physical and in skills and knowledge. Therefore maximizing the 'quantum advantage' while utilizing the previous investments appear as the main path forward globally. There are already many firms aiming at achieving efficient quantum communication over commercial fiber optic cables or developing integrable quantum processing units to already existing transistor based computer architecture.

This hybridization requires interdisciplinary research from different fields of engineering, basic sciences, and informatics. Currently, there are no such intersection points in Turkey, most academic events are either dominated by researchers from one field or another.

Creating these linkages and collaboration initiatives between different disciplines is a required first step toward exploiting the possible spoils of hybridization.

Standardization is another important issue in strategic thinking. Any large scale commercial investment requires the development of standards in a field such as cryptography and sensing. This is already a hot topic on both US and EU. In the US, the NQIA is a program being developed and run mainly in accordance with NIST. In Europe, The European Telecommunications Standards Institute (ETSI) has been involved in developing standards for quantum cryptography at least till 2015, and it is an active issue in the ongoing Quantum Flagship.

Integration to value chains is an essential part of any major commercialization endeavor, Developing skills and knowledge that can be easily and cheaply translated from other sources has a high opportunity cost for a country like Turkey where resource distribution is problematic. To forge ahead in any field, strategic planning on positioning the national value chain into global value chains play an important role. Inviting foreign investment in a field that may result in strong market stealing effects causes a setback in the local development of skills and knowledge. On the contrary, FDI that can fill a gap in the national value chain while providing positive spillovers in vertical linkages can accelerate market creation and formation greatly.

Finally, prioritization is the final issue under this theme. Rapidly changing priorities is a recurring theme brought up in interviews. This cannot be sustained within a catching up mentality. In the American NQIA program, a National Quantum Coordination Office under White House is established to coordinate the efforts on a national scale. A similar office can be formed under the Presidency of the Republic of Turkey. All of the items listed in this section are suited for oversight, requires extensive knowledge of the field and capable public servants who themselves are not researchers but are connected to interested parties in academia, industry, military and public institutions. Such nation-wide, cross-sectoral coordination cannot be accomplished under any sub-branch of TÜBİTAK or a singular Ministry (a list of potential shareholders of a national quantum programme are provided in Appendix F). Not being able to fund strategic priority projects due to lack of scientific novelty, which should not be a prerequisite of strategic projects, is a very practical example of why variety and oversight in funding mechanisms are needed. Establishing priorities and following up on their implementation through a central coordination mechanism is an effective way to tackle lacks in strategic thinking in QT if it is executed properly.

6.1.3 Trust

Lack of trust increases risk, therefore it makes dealing with high end R&D even more expensive and risky for firms and academics to invest in. Trust building occurs naturally in communities, however formation of these communities are rare due to lack of incentive. The collaboration networks in Turkey shown on Fig 5.X, which are few in number, are clustered around names either involved or related to the DPT project on quantum cryptography, which is the only area that Turkey has produced an end-user ready product. Three issues developed under this theme to tackle the problems emanating from it are centralization of authority and impact assessment, supporting national and international collaboration, increased awareness on public, academia and industry scales.

Centralization of authority is already covered under prioritization through formation of a national coordination office. However, the effectiveness of that office heavily relies on it being a trustworthy institution in the eyes of quantum community at large, both in Turkey and abroad since international collaboration is an important aspect of both knowledge transfer and market formation. To this end, transparent reporting of resources allocated on non-classified projects through mechanisms such as Turkish Court of Accounts (Sayıştay) and accessible impact assessment either performed by the coordination office or through a third party at the behest of the office would be positive steps towards establishing institutional trust into this newly formed body.

Supporting national and international collaboration is an effective method to foster community based trust formation. Groups working together developing trust through social and professional interactions can lead to follow up projects that otherwise would not have occurred. Collaboration has an initial cost on effectivity where collaborating groups suffer from adjustment period toward each others work, this can even be more severe on interdisciplinary efforts. Therefore, decisions on supporting national and international collaboration should account for the hidden benefits of trust formation, spillovers and learning processes.

Finally, increased awareness on public, academia and industry scales is closely related with lowering risk and uncertainty in general and hasten the trust formation processes. The word quantum is overused in a very negative context in Turkey. This affects private sector and even academics not involved with physics as well. The word awareness was usually understood as ‘public awareness’ by the participants in this study, however when a follow up question concerning the awareness of industry and government is asked, participants noted that awareness of quantum technologies is low on those levels as well. Therefore efforts of increasing awareness should not be limited to ‘public awareness’. Interviewee 12 mentioned publishing white papers is an effective way of increasing awareness at government level, they expressed that certain points highlighted in their own documents later return to them from unrelated sources as ‘points of interest’. This chaotic nature of information sharing on multiple levels should be accepted as a complex process in which evolutionary dynamics, such as diffusion, are better suited as tools of understanding.

Table 6. 2: Policy aims and corresponding policy tools

Policy Aims	**Policy Tools**
Increasing scientific knowledge base in Turkey	-Starting focused higher education programs -Supporting international collaboration projects -Founding focused public research institutions -Encouraging graduate studies into these topics
Increasing technological knowledge base in Turkey	-Funding internship programs in strategic fields -Expanding infrastructure and making it accessible -Employ public procurement to support firms -Support industry-academia collaboration efforts
Increasing awareness on quantum technologies	-Formulating public awareness programs -Supporting fairs, summer schools and competitions -Publishing white papers, books, academic journals -Bestowing awards of excellence in science on QT
Increasing interdisciplinary work	-Supporting interdisciplinary academic events -Starting interdisciplinary higher education programs -Prioritizing interdisciplinary projects in funding -Loosening disciplinary bounds on academic posts
Increasing commercialization efforts	-Formulating regulations for the market to emerge -Public standardization and certification of products -Supporting market exploration efforts of firms -Reinforcing commercial ecosystem formation

In this extent, summer schools, industry-academia events, internship opportunities and many other methods can be employed through related public institutions. However, this should not be expected as a voluntary option or a drudgery work for academics and researchers to comply. A well constructed awareness program with necessary funding, tailored for specific audiences and prepared according to the strategic goals of a national roadmap should be the path forward. On the table 6.2 a list of possible policy tools to be employed for different policy aims are provided.

6.1.4 Conclusion to Policy Suggestions

In this chapter, different sets of policy suggestions were presented based on arguments generated on previous chapter out of empirical data collected through several sources both locally and globally. It has been argued that Turkey should focus its research efforts into narrower fields with increased funding in size and variety, while simultaneously tackling the systemic problems through public intervention.

Although quantum technologies is a bundle of different fields which are complementary to each other on a great scale, they are not intertwined to the fullest extent. Focused research on one or several of these areas can be performed, and this would also produce some positive spillover effects on other fields.

On a national level, focused R&D in accordance with strategic needs can be a safe and easy to fund foundation to these efforts. It has already been accomplished once with limited resources (compared to investment in other countries), similar grand projects and infrastructure initiatives, such as national labs, can help accelerate development of these technologies on the domestic front.

Table 6. 3: Short term, mid-term and long-term policy milestones

Short term (within 5 years)	**Mid-term (5-20 years)**	**Long-term (20+ years)**
-National Quantum Coordination Office under the Presidency of the Republic of Turkey -Graduate level programs on quantum technologies -Mapping of national capacity and establishing a national mid-term roadmap -Awareness programs on public, academic and industry levels	-Several National Centers and Laboratories on central locations -Undergraduate programs on quantum technologies -Impact assessment mechanisms established -Industry involvement and first steps on the market formation (regulations, national standards, inviting FDI)	-Reformation of institutes established earlier (impact assessment) -Integration to global markets and value chains (customs agreements) -National quantum secure infrastructure -Industry clusters focused on quantum technologies

On table 6.3, three lists of practical suggestions for short, mid and long term policy actions are provided. It has to be kept in mind that any investment in quantum technologies should be considered as a long-term investment since Turkey needs to develop both exploration and exploitation mechanisms on these technologies, which will take time. Therefore, prioritizing strategic needs while facilitating overall progress in QT through training, education, and awareness on short term, and creating local infrastructure (physical and institutional) on mid-term, are necessary initial steps toward succeeding in long term.

6.2 Limitations of the Study

This thesis has been in the making for two years. Along this period, many things have changed in the field of quantum technologies. Quantum computing has become a hyped word, a strategic technology trend to be followed in 2019 according to Gartner (Cearley, 2018). Many of the national and international initiatives such as EU Quantum Flagship and U.S. National Quantum Initiative Act were signed into legislation within these two years. The number of firms dealing with QT has almost doubled. And many key research papers have been published that progressed the development in sub-fields of QT even further.

Still, the entire field of quantum technologies has little market share compared to classical technologies that dominate the current Information Age that we live in. And, even though quantum technologies promise development in many areas on several orders of magnitude, the foreseeable near term investment landscape will still be comprised of mainly classical technologies with simple quantum additions for a performance upgrade. This is the key point where developing countries, such as Turkey, can come into play and benefit by integrating themselves into this newly forming global value chain. However, even to obtain this supporting role there needs to be dedication and effort on a national scale.

The descriptive analysis of this study aims to highlight the systemic issues in Turkey, and the policy suggestion chapter is aimed towards generating improvements to these. It should be noted that both the identification of issues and the solutions to the problems arisen out of them is a continuous process, they shift as the opportunity landscape evolves. The goal of this thesis is performing these actions on the emergency phase of the oncoming paradigm, and it should be regarded within that historical context.

A great shortcoming of this study is that it lacks first-hand data from the defense industry in Turkey. During the interviews, there were participants that were involved with developing certain technologies for military and defense purposes, but they were either outside contractors or academics with research projects collaborating with defense industry sources. A set of interviews and surveys directed at Turkey's national defense industry can provide further insight into how quantum information technologies can be embodied into value chains regarding these industries. Additionally, such a study can help map the needs of the defense sector in terms of these newly emerging technologies.

Another limitation of the study is the language barrier. The interviews were conducted in Turkish and due to lack of agreed upon Turkish terms sometimes terms such as quantum computing and quantum information get mixed up (both are translated as 'kuantum bilişim' in the YÖK database). Through informing the Turkish and English versions of the terms used in the interview guide, this confusion did not constitute a severe problem. However, the lack of clear Turkish terminology is a limitation to be acknowledged for this study.

Similarly to the Turkish case, lack of documents in English from important players like China, Russia, Israel, Japan, and Korea has also affected this study and created a bias in data collection towards countries that are English oriented in their public documentation. Finding firms in China dealing with quantum technologies proved to be additionally difficult because not only small Chinese firms do not promote their efforts in proper English, but also they use different names for different markets. Hence, distinguishing firms from one another and identifying their actual area of business was somewhat more problematic than their Japanese counterparts for example.

The final limitation of this study should be noted as the lack of general consensus on what accounts as a 'quantum' technology. Different initiatives define quantum technologies differently, and it is in constant flux with new definitions or extensions arise each month. This limitation also translates itself into funding schemes globally, because identifying a technology as a 'quantum' technology makes it eligible to be supported from these exclusive funding schemes. In this study, the terms of quantum technologies and quantum information technologies are used interchangeably. This is not the original use of the term "quantum technologies", which accounts quantum information technologies as a sub-branch of QT but identifies others as well. The time, when the definitions will mature and consensus will be reached, is not yet here.

6.3 Conclusion to the Thesis

Key takeaways from this study can be considered on several levels. On a global level, Chinese race to topple U.S. hegemony on high-tech through developing quantum technologies can be clearly seen from both empirical data and statements from all the main players. European efforts should also be noted in this regard, though it seems the U.S. weighs developments in China as more noteworthy than Europe. Finally, the increase in the number of national initiatives, firms, patents, and research centers all indicate that the field will not suffer a 'quantum winter' at least in the near future.

On a national level, this study highlights the Turkish modus operandi of being a late follower in newly emerging high-tech fields. This general mindset is partially due to a lack of trust in people, institutions, and capabilities. However, the lack of trust is not just a mere cultural construct, very rapidly changing priorities and institutional landscape has also had an effect on investment priorities of agents both in terms of money and effort. Even public projects on high-tech areas focus on short term returns rather than longer-term public benefits. It is considered as a problem but also accepted as a fact by many of the researchers interviewed for this thesis. This fact, when compared with many systemic problems and hindrances, creates a negative feedback loop where even the most willing participants become reluctant to initiate any commercial activity.

The main finding of this study on a local level is that regardless of their position, public and private actors all demand public intervention to the field. Basically, nobody expects a natural market formation in Turkey regarding quantum technologies in the near future. The extent of intervention demanded, of course, varies from person to person. However, it is universal in the domain of this thesis that everybody expects intervention if these technologies are to be developed or utilized strongly in a national context.

Finally, this work can be extended in numerous ways. The academic aspect of this thesis is comprehensive in terms of data from National Thesis Center and Web of Science used for developing network maps. However, it is only partially representational on research centers and their activities. This can be a worthy effort in terms of mapping national capabilities in quantum technologies. A similar effort was carried on in TÜBİTAK's effort for a roadmap, but it was not completed.

Another way to further this study is a mapping of the commercial landscape in quantum technologies. There are 200 firms covered in this study, and the distribution of the number of firms seem in accordance with data from other sources. This is just a quantitative aspect and it can be improved greatly through adding a qualitative layer. Distinguishing the firms apart not only in size or years of activity but also in terms of future plans and root causes of formation would provide invaluable insight into how to kickstart commercial activity in Turkey or any other developing country. Such data can be generated through surveys, interviews, focus group meetings and other qualitative research methods, which probably requires an international collaboration of researchers to collect since the firms are spread out not only geographically but also culturally as well. For example, it would not be advisable to assess any firms' plans and causes in Germany without extensive knowledge of German regulations and laws concerning high-tech entrepreneurship.

The commercial landscape can also be extended into the innovation landscape as well. Listing the products and practices of active firms in quantum technologies to identify whether products are diverging or converging in design and supporting technologies would be an effective way to foresee possible trajectories. Similarly, it would help to identify value chains since products are actually developing interdependently. It is not just the computational devices but cables connecting them or refrigerators cooling them also are integral parts of this technological revolution that should be taken into consideration.

As a third option, this study can be extended in terms of policy suggestions and implementations. Global mapping of policy approaches through analysis of public documents, interviews with public officials, surveying of policy offices and other methods can be employed. Through this, common denominators and divergence points of national policies can be identified. Since quantum technologies is a newly emerging field, impact assessment of policies implemented is not present. Such a study can lay the foundation of developing benchmarks for certain common policy tools, investigating under which conditions it lays the relatively optimal outcome or through which mistakes it fails. Furthermore, such an analysis would allow identification of the countries that are actually investing in these technologies for the long run or to become leaders in certain sub-fields.

To sum up, although it is descriptive in nature, this thesis can also be accepted as an exploratory study into the field of quantum technologies through methods of science and technology policy studies. Outcomes can be utilized for policies to further development of

QT in Turkey or they can be employed in other academic or commercial studies to benefit from the empirical background provided here. Different theoretical frameworks can be used to analyze the same data here to enrich our understanding of what is going on globally in this field. Finally, this study can be considered as a tool for increasing awareness and introducing policymakers that are not familiar with quantum technologies to the field.

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APPENDICES

A. SPECIFIC QUANTUM TECHNOLOGIES

In this section several interesting and practical quantum technologies are going to be introduced that may be relevant to Turkey in near future.

A.1 Quantum Key Distribution (QKD)

This is one of the most famous applications of quantum cryptography that, in theory, promises 100% secure communication even on public channels. In August 2015, NSA released a statement announcing the need for post-quantum cryptography, and that none of the currently available cryptography algorithms can be guaranteed as 'secure' due to the possibility of quantum computers emerging in near future (Koblitz & Menezes, 2016). QKD, in this sense, is one of the original post-quantum cryptography methods.

There are different QKD protocols, some utilizing entanglement while others only rely on single photon generation and detection. The main concept relies on using a cryptographic method called one-time-pad, which means a single key with the same length of the message to be used for encrypting and decrypting the text. Since the key and the text are of the same length and the key is used only once, its security is guaranteed. However, the main problem with this method is secure distribution of keys. In that sense, using quantum correlations and uncertainty principle, QKD provides a solution and allows theoretical guarantee for the keys to be distributed securely.

Although it seems as a perfect solution to the ever-increasing need of secure encryption to the expanding cyber infrastructure, there are two main problems. Initially, one-time-pad itself is a costly method requiring high bitrates of key generation and distribution, which only becomes even costlier when accompanied with quantum devices. Therefore, the initial market volume is limited due to most data not being worth enough such high security. Secondly, in 2010 a group from Quantum Hacking Lab at University of Waterloo broke the encryption of a commercial quantum key distribution device (Lydersen et al. 2010) through side channel attacks that were not considered as a possibility before. Therefore, the science is still not settled on the subject as QKD being unbreakable.

Finally, the initial QKD setups required entirely new infrastructure which proved to be too costly for an overhaul of current systems. However, recently there have been many efforts and some successes (Zhang, 2017) to utilize QKD over existing commercial fiber cables. There are still many engineering and security problems, but QKD is an almost maturing technology with an already existing market volume. Even though it is still in its early stages and there are many issues to be tackled with, QKD is a milestone quantum technology which is only expected increase in market share. There is an extensive scientific knowledge base in Turkey on QKD, and some infrastructure through the previously mentioned "BİLGEM Quantum Cryptology Research Center". Therefore it can be counted as a possible quantum technology that Turkey can find itself a place on the global value chain.

A.2 Quantum Radar

This technology basically utilizes the quantum correlations caused by entanglement as a means to improve existing radars. One of the earlier works published on this topic was Seth Lloyd's (2008) who is also a pioneer in quantum information theory, and one of the first people to be awarded a DARPA project on quantum computation (Lloyd, 2016).

Quantum radar systems depend on generating a stream of entangled photons in the visible frequency spectrum. Half of them are transformed into microwave length scale and then proceed through normal radar system processes. The other half is kept as idle beam and used for comparison of received photons. Due to entanglement, quantum correlations are kept intact even if stealth measures are utilized on normal radar processes.

In practice, achieving such high precision entanglement generation, memory, and detection are huge engineering problems. However, the concept is accepted as feasible and there are many groups around the globe (especially in China and the US) that are working on this particular military technology.

A.3 Quantum Lithography

One of the pioneers of quantum lithography was Jonathan Dowling at JPL (Boto et al. 2000) who has also coined the terms second quantum revolution and quantum technologies. This method uses the non-classical properties of photons to overcome the Rayleigh diffraction limit.

At the first meeting of KOBİT-0 in Turkey on March 2016, the plenary speaker was M. S. Zubairy from Texas A&M and his talk was titled “Overcoming the Rayleigh limit in optical lithography”. There are researchers in Turkey who have researched this topic, and a general level of scientific knowledge base is already present.

Quantum lithography has many promises and practical use cases for industrial and commercial purposes. To obtain a higher resolution in any type of imaging and lithography, due to the Rayleigh limit, smaller wavelengths need to be utilized. Smaller wavelength in physics corresponds to higher energy waves, therefore to see or imprint on smaller objects one needs to apply high energy photons. For industrial purposes, being able to use less energetic lithography methods may allow sharper nano-fabrication with better quality products.

B. FIRMS ON QUANTUM TECHNOLOGIES

Table B.1: Information on firms covered in the dataset

Name of the firm	Origin Country	Field(s)	Start-up in QT (Yes/No)	Founded/QT dept. in (year)
1Qbit	Canada	quantum computing software	Yes	2012
A*Quantum Inc.	Japan	quantum computing applications	Yes	2018
Accenture	US-Global	consulting on quantum computing molecule design	No	2017
Acktar	Germany	quantum metrology (coating)	No	2016
Acronis	Global	quantum communication and memory	No	2014
Adcon Telemetry Gmbh	Austria	quantum sensing	No	2015
ADVA Optical Networking	Germany	quantum communication	No	2014
Airbus	France	quantum computing	No	2015
Alibaba	China	quantum computing	No	2015
Alpine Quantum Technologies, GmbH	Austria	quantum computing	Yes	2018
Amazon	US	quantum computing	No	2010
Anyon Systems	Canada	quantum computing	Yes	2014
AOSense	US	quantum sensing	Yes	2004
Apogee Instruments	US	quantum sensing	No	2017
Arqit	Sweden	quantum cryptography	Yes	2016
Artiste-qb	Canada	quantum computing software	Yes	2015
AT&T Foundry	US	quantum computing/communication	No	2011
Atom Computing	US	quantum computing hardware	Yes	2018
Atos	France	quantum computing/simulation	No	2016
Automatski	US	quantum computing applications	Yes	2017
Ayar Labs	US	electronic-photonic integrated circuits	No	2015
Baidu	China	quantum computing	No	2018
Beit.tech	Poland	quantum computing software	Yes	2016
Biogen	US	quantum computing application drug discovery	No	2017
Biospherical Instruments	US	quantum sensing	No	2011
Black Brane Systems Inc.	Canada	quantum computing software - machine learning	Yes	2016
Bleximo	US	quantum computing	Yes	2017
Bluefors	Finland	cryogenics	No	2007

Table B.1 (continued)

Name of the firm	Origin Country	Field(s)	Start-up in QT (Yes/No)	Founded/QT dept. in (year)
Bohr Technologies	Poland	quantum computing software	Yes	2017
Boxcat	Canada	quantum computing applications	Yes	2017
bra-ket Science	US	quantum computing hardware	Yes	2017
BraneCell	US	quantum computing hardware	Yes	2015
BT Group	UK	quantum communication	No	2014
Cambridge Quantum Computing	UK	quantum computing software / simulation	Yes	2014
China Aerospace Science and Industry Corporation	China	quantum sensing	No	2012
China Aerospace Science and Technology Corporation	China	quantum sensing	No	2009
China Electronics Technology Group	China	quantum sensing	No	2014
Commonwealth Bank of Australia	Australia	quantum computing (banking)	No	2017
Cryoconcept	France	quantum computing (cryogenics)	No	2001
Crypta Labs	UK	quantum cryptography (for IoT)	Yes	2014
Cyph	US	quantum cryptography	Yes	2014
D Slit Technologies	Japan	quantum computing applications	Yes	2018
D-Wave Systems	Canada	quantum computing (annealer)	Yes	1999
Dash Intelligence	Canada	quantum computing (artificial intelligence)	Yes	2018
Delft Circuits	Netherlands	quantum computing hardware	Yes	2017
DENSO	Japan	quantum computing application (traffic IoT)	No	2017
Digital China Information Service Company Ltd	China	quantum communication	No	2011
EDGC	South Korea	quantum computing application (medical)	No	2013
EeroQ	US	quantum computing hardware	Yes	2017
Element Six	UK	quantum sensing	No	2016

Table B.1 (continued)

Name of the firm	Origin Country	Field(s)	Start-up in QT (Yes/No)	Founded/QT dept. in (year)
Elyah	United Arab Emirates - Japan	quantum computing software	Yes	2018
Entanglement Partners	Spain	quantum cryptography (consultancy)	Yes	2016
Entropica Labs	Singapore	quantum computing software	Yes	2018
Everettian Technologies	Canada	quantum computing application (trade execution prediction)	Yes	2017
EvolutionQ	Canada	quantum computing (consultancy)	Yes	2015
Ford Motors	US	quantum computing application	No	2018
Fujitsu	Japan	quantum communication & computing (annealer)	No	2015
Gooch & Housego	UK	quantum devices	No	2016
Google	US	quantum computing/a.i.	No	2013
GTN	UK	quantum computing application (drug discovery)	Yes	2017
GWR Instruments	US	quantum sensing	No	2011
H-bar: Quantum Consultants	Australia	quantum computing (consultancy)	Yes	2016
Heisenberg Quantum Simulations	Germany	quantum simulation	Yes	2018
High Precision Devices	US	quantum computing (cryogenics)	No	2010
Honeywell (Quantum Solutions)	US	quantum computing	No	2018
Horizon Quantum Computing	Singapore	quantum computing software	Yes	2018
HP Labs	US	quantum computing	No	1996
HRL Laboratories	US	quantum computing	No	2008
Huawei	China	quantum communication and computing	No	2014
IBM	US	quantum computing	No	1990
ID Quantique	Switzerland	quantum communication/cryptography & sensing	Yes	2001
Impedans Ltd.	UK	quantum sensing	No	2014
Jiangsu Hengtong Photoelectric	China	quantum communication	No	2016
JoS Quantum	Germany	quantum computing applications (finance)	Yes	2018
Kaile Science and Technology Co Ltd	China	quantum communication	No	2011
Ketita Labs	Estonia	quantum computing software	Yes	2018

Table B.1 (continued)

Name of the firm	Origin Country	Field(s)	Start-up in QT (Yes/No)	Founded/QT dept. in (year)
KETS Quantum Security	UK	quantum cryptography	Yes	2018
Keysight Technologies	US	quantum computing (basic control hardware)	No	2013
Jiangsu Hengtong Photoelectric	China	quantum communication	No	2016
JoS Quantum	Germany	quantum computing applications (finance)	Yes	2018
KETS Quantum Security	UK	quantum cryptography	Yes	2018
Keysight Technologies	US	quantum computing (basic control hardware)	No	2013
Jiangsu Hengtong Photoelectric	China	quantum communication	No	2016
JoS Quantum	Germany	quantum computing applications (finance)	Yes	2018
KPN	Netherlands	quantum communication and cryptography	No	2016
Labber Quantum	US	quantum computing hardware	Yes	2018
LI-COR	US	quantum sensing	No	2015
Lightelligence	US	optical computing for machine learning	Yes	2017
Lightmatter	US	optical computing for machine learning	Yes	2017
LightOn	France	optical computing for machine learning	Yes	2016
Lockheed Martin	US	quantum computing hardware and application	No	2010
M Squared Lasers	UK	quantum sensing	Yes	2006
MagiQ Technologies Inc.	US	quantum communication/cryptography & sensing	Yes	1999
MDR Inc.	Japan	quantum computing hardware & software	Yes	2008
METER Group	US	quantum sensing	No	2017
Microsemi	US	quantum sensing	No	2014
Mitsubishi Electric	Japan	quantum cryptography	No	2010
Muquans	France	quantum sensing	Yes	2011
Nano-Meta Technologies	US	quantum computing and sensing	Yes	2010
NEC	Japan	quantum computing hardware	No	1998
NetraMark	Canada	quantum computing applications (medicine)	Yes	2015
Neuromorph Inc.	Canada	quantum computing application (medical)	Yes	2017
Nextremer	Japan	quantum computing applications	No	2017

Table B.1 (continued)

Name of the firm	Origin Country	Field(s)	Start-up in QT (Yes/No)	Founded/QT dept. in (year)
NKT Photonics	Denmark	quantum sensing and communication	No	2016
Nokia Bell Labs	US - Finland	quantum computing hardware	No	2006
Nordic Quantum Computing Group (NQCG)	Norway	quantum computing hardware & applications	Yes	2004
Northrop Grumman	US	quantum computing (annealer)	No	2007
NTT Labs	Japan	quantum computing hardware and communication	No	2002
Optalysys	UK	quantum (optical) computing	Yes	2013
Origin Quantum Computing	China	quantum computing	Yes	2017
Oxford Quantum Circuits	UK	quantum computing hardware	Yes	2017
Perspecta Labs	US	quantum sensing (LIDAR)	No	2018
Phase Space Computing	Sweden	quantum information - education	Yes	2017
PhaseCraft	UK	quantum computing software	Yes	2018
Photon Spot	US	quantum sensing	Yes	2010
PicoQuant	Germany	quantum sensing	No	2010
PQ Solutions	UK	quantum cryptography	Yes	2009
Princeton Lightwave	US	quantum communication	No	2005
ProteinQure	Canada	quantum computing application (drug discovery)	Yes	2017
PsiQuantum	US	quantum computing hardware	Yes	2016
Q-Ctrl	Australia	quantum computing software	Yes	2017
Q&I	UK	quantum technology (consultancy)	Yes	2017
Qasky	China	quantum cryptography	Yes	2009
Qbitlogic	US	quantum computing software	Yes	2014
QBRICS	US	quantum cryptography	No	2017
QC Ware	US	quantum computing software	Yes	2014
QEYNet	Canada	quantum cryptography	Yes	2017
Qilimanjaro Quantum Hub	Spain	quantum computing hardware & software	Yes	2018
Qindom	Canada	quantum computing (artificial intelligence)	Yes	2018
Qinetiq	UK	quantum sensing	No	2013
Quandela	France	quantum communication & hardware	Yes	2017
QuantiCor Security	Germany	quantum cryptography	Yes	2017
Quantika	US (?)	quantum (consultancy)	Yes	2017
Quantum Base	UK	quantum cryptography	Yes	2014

Table B.1 (continued)

Name of the firm	Origin Country	Field(s)	Start-up in QT (Yes/No)	Founded/QT dept. in (year)
Quantum Benchmark	Canada	quantum computing software - benching	Yes	2018
Quantum Biosystems	US-Japan	quantum computing software - dna sequencing	Yes	2013
Quantum Circuits	US	quantum computing	Yes	2015
Quantum Computing Inc	US	quantum computing hardware and application	Yes	2001
Quantum CTek	China	quantum cryptography	Yes	2009
Quantum Impenetrable	Scotland	quantum cryptography	Yes	2018
Quantum Lambda	US	quantum computing software	Yes	2018
Quantum Machines	Israel	quantum computing hardware & software	Yes	2018
Quantum Motion Technologies	UK	quantum computing hardware	Yes	2017
Quantum Opus	US	quantum sensing	Yes	2013
Quantum Phi	Czech Republic	quantum technology (consultancy)	Yes	2018
Quantum Sense	Canada	quantum computing application (text analysis)	Yes	2018
Quantum-Factory	Germany	quantum computing hardware	Yes	2018
Qubitekk	US	quantum computing/crpytography	Yes	2012
Qubitera	US	quantum computing (artificial intelligence)	Yes	2018
Quintessence Labs	Australia	quantum cryptography	Yes	2008
QuLab	US	quantum computing applications	No	2017
Qunnect	US	quantum communication	Yes	2017
QuNu Labs	India	quantum cryptography	Yes	2016
qutools	Germany	quantum devices	Yes	2005
QxBranch	US	quantum computing software	Yes	2014
Raytheon BBN Technologies	US	quantum sensing	No	2016
Rigetti	US	quantum computing	Yes	2013
RIKEN	Japan	quantum computing hardware	No	2005
River Lane Research	UK	quantum computing software	Yes	2017
RMY Electronics	China	supporting hardware	No	2018
S15 Space Systems	Singapore	quantum cryptography	Yes	2018
qutools	Germany	quantum devices	Yes	2005
QxBranch	US	quantum computing software	Yes	2014
Raytheon BBN Technologies	US	quantum sensing	No	2016
Rigetti	US	quantum computing	Yes	2013

Table B.1 (continued)

Name of the firm	Origin Country	Field(s)	Start-up in QT (Yes/No)	Founded/QT dept. in (year)
RIKEN	Japan	quantum computing hardware	No	2005
River Lane Research	UK	quantum computing software	Yes	2017
RMY Electronics	China	supporting hardware	No	2018
S15 Space Systems	Singapore	quantum cryptography	Yes	2018
Sanlux Co. Ltd.	China	quantum communication	No	2011
SAP	Germany	quantum computing	No	2017
Scontel	Russia	quantum sensing	Yes	2005
Sea-Bird Scientific	US	quantum sensing	No	2017
SeeQC	Italy	quantum computing hardware	Yes	2018
SeQureNet	France	quantum cryptograpgy	Yes	2010
Shangai Photon Technology	China	quantum sensing	Yes	2014
Siemens Healthineers	Germany	quantum computing application (medical imaging)	No	2018
Silicon Quantum Computing	Australia	quantum computing hardware	Yes	2017
Single Quantum	Netherlands	quantum sensing	Yes	2012
SK Telecom	South Korea	quantum communication	No	2011
Skye Instruments	UK	quantum sensing	No	2017
softwareQ	Canada	quantum computing software	Yes	2017
Solid State AI	Canada	quantum computing application (machine learning)	No	2017
Sparrow Quantum	Denmark	quantum technology hardware (photonics)	Yes	2016
Spectrum Technologies Inc.	US	quantum sensing	No	2011
Strangeworks	US	quantum computing software	Yes	2018
Teledyne e2v	UK	quantum sensing	No	2011
Tellus Matrix Group	UK	quantum computing (consultancy)	No	2016
Telstra	Australia	quantum computing	No	2017
Tencent	China	quantum computing	No	2017
Tokyo Quantum Computing	Japan	quantum computing software	Yes	2017
TOPTICA Photonics	Germany	quantum sensing and communication	No	2016
Toshiba	Japan	quantum cryptography and computing	No	2017
TundraSystems Global LTD	UK	quantum computing hardware (photonics)	Yes	2014
Turing Quantum	US	quantum computing software	Yes	2016
Universal Quantum Devices	Canada	quantum sensing	Yes	2010

Table B.1 (continued)

Name of the firm	**Origin Country**	**Field(s)**	**Start-up in QT (Yes/No)**	**Founded/QT dept. in (year)**
Virtual Cove	US	quantum computing applications	Yes	2016
Volkswagen	Germany	quantum computing software - traffic & car battery	No	2017
Xanadu	Canada	quantum computing hardware + applications	Yes	2016
Zapata Computing	US	quantum computing software	Yes	2017
ZheJiang Quantum Technologies Co.,Ltd	China	quantum communication	Yes	2012

C. REPORTS ON QUANTUM TECHNOLOGIES

In addition to the public documents listed in table 4.2, several market study and assessment reports were encountered and utilized on the course of this study. The list is provided in table C.1. It should be noted that the number of market reports is increasing steadily and there might be some companies exploiting the hype on quantum technologies by producing low quality reports. The list of 200 firms covered in this study is constructed using the encountered reports and many other sources. However, sector specific reports may contain valuable market analysis.

Table C.1: List of additional market study and assessment reports

Report Title	Institution	Year
Quantum cryptography 2014 market study & business opportunities assessment	University of Waterloo – Institute of Quantum Computing	2014
Industry Perspectives on Quantum Technologies	Industry Working Group (EU /pre-Quantum Flagship)	2015
The Quantum Age: technological opportunities	Government Office for Science (UK)	2016
The Commercial Prospects for Quantum Computing	Networked Quantum Information Technologies (under UKNQT)	2016
Assessment of the Future Economic Impact of Quantum Information Science	Science and Technology Policy Institute	2017
Quantum Information Technology Patent Landscape Reports	Patinformatics LLC	2017
Quantum Computing: Applications, Software And End-User Markets	CIR	2018
Quantum Sensors Market Research Report- Forecast till 2023	Market Research Future	2018
Global Quantum Sensors Market 2018-2022	Technavio	2018
Quantum Computing Market & Technologies - 2018-2024	Industry 4.0 Market Research	2018
Post-Quantum Cryptography: A Ten-Year Market and Technology Forecast	Inside Quantum Technology	2019
Quantum Cryptography Market by Component, Services, Security Type, Vertical & Region - Global Forecast to 2023	Research and Market	2019
Patent analysis of selected quantum technologies	JCR Technical Reports (EU)	2019

D. INTERVIEW GUIDE AND ADDITIONAL INFORMATION

Interview guide is provided below in Turkish on table D.1.

Table D.1: Interview guide

1- Kuantum Bilişim denilince aklınıza hangi teknolojiler geliyor? 2- Bu alanlarda çalışmalarınız var mı? Varsa nasıl çalışmalarınız var ve hangi açılardan ilgileniyorsunuz? Kaç yıldır bu alanda çalışma sürdürüyorsunuz? 2.1- Bu alanda ortaklık kurduğunuz kişi veya kuruluşlar var mı? 2.2- Bu kişi veya kuruluşları neden tercih ettiniz? 2.3- Çalışmalarınızda ne kadar mali ve insan kaynağı gerekliliği duyuyorsunuz ve bunları nasıl sağlıyorsunuz? 3- Alanınızda dünyada önemli gördüğünüz enstitüler, araştırma merkezleri, kurum ve kuruluşlar hangileridir? 3.1- Buralarla ortak bir çalışma yapmak için çabalarınız oldu mu? 3.1.1- Buralarla ortak bir çalışma yapabilmenin önünde engeller olduğunu düşünüyor musunuz? 3.2 - Alanınızda Türkiye'de önemli gördüğünüz enstitüler, araştırma merkezleri, kurum ve kuruluşlar hangileridir? 3.2.1- Buralarla ortak bir çalışma yapmak için çabalarınız oldu mu? 3.2.2- Buralarla ortak bir çalışma yapabilmenin önünde engeller olduğunu düşünüyor musunuz? 4- Kuantum Bilişim Teknolojilerinin ticarileştirilmesi hakkında ne düşünüyorsunuz? 4.1- Dünyada kuantum bilişim teknolojilerinin ticarileştirilmesi yönünde takip ettiğiniz gelişmeler var mı? 4.1.1- Bu alanda araştırma-geliştirme faaliyeti gösteren bildiğiniz yabancı firmalar var mı? 4.1.2- Bu alanda araştırma-geliştirme faaliyeti gösteren bildiğiniz yerli firmalar var mı?

Table D.1 (continued)

4.2- Kuantum bilişim teknolojilerindeki ticarileştirmenin bilimde ve pratik yaşamdaki etkileri sizce nelerdir? 4.2.1- Türkiye özelinde bu etkilerden söz etmek hangi bağlamda mümkündür? 4.3- Türkiye'de kuantum bilişim teknolojilerinin ticarileştirilmesinin önünde sizce engeller var mı? 4.4- Sizce Türkiye'de kuantum bilişim teknolojilerinin ticarileştirilmesinin ilerlemesi için pratik olarak neler yapılabilir? 5- Dünyayla kıyaslandığında Türkiye'de kuantum bilişim teknolojileri alanında nelerin öne çıktığını, nelerin geri planda kaldığını düşünüyorsunuz? 5.1- Peki sizce neden? 5.2- Türkiye'de kuantum bilişim teknolojilerine sizin bildiğiniz ne gibi destekler sağlanmakta? 5.3- Türkiye'deki teknolojik gelişim destekleri içinde kuantum bilişim teknolojilerine ne kadar yer verildiğiniz düşünüyorsunuz? Sizce yeterli mi? 5.4- Türkiye'de kuantum bilişim teknolojilerinin ticarileştirilmesi alanında neler yapılabileceğini düşünüyorsunuz? 5.5- Türkiye'de kuantum bilişim teknolojilerine dair farkındalığın arttırılması yönünde haberdar olduğunuz çalışmalar, uygulamalar veya programlar var mıdır? Bunlara dair görüşleriniz nelerdir? 6- Eklemek istediğiniz herhangi bir şey var mı?

D.1 Code Clusters

Code sequence analysis showed some clustering for codes. One cluster was for "QT Institutions", "Leading Countries" and "Important Names" which is expected. Disregarding the expected clustering of technical terms such as "quantum systems" with "NMR systems", and codes that naturally close such as "obstacles for commercialisation and "incentives for commercialisation", there were only a handful of significant codes that went together.

The code for "TÜBİTAK" was associated with the following codes in descending order; "EU Support/COST Action", "Academic Connections", "Universities-Institutions Abroad", "Ministries", "Photonics", "Industry-Academia Partnership" and "Resources Utilized".

“Resources Utilized” was most closely used with the code “Theoretical Aspect”, when checked it was revealed that in most cases this is where the interviewees mention theoretical work only requires minimal resources to be utilized; a modest computer, steady connection to internet, also a desk and a chair. The second in line for “Resources Utilized” was “Lacks in experimental fields”, where the resources deemed to be insufficient.

“Scientific Meetings” was mainly correlated with two codes, “QT Sharing Spaces” and “Obstacles”. The general consensus was even though internet and online tools are great, the important discussions and developments occur at scientific meetings, and it is hard to join these meetings due to “Obstacles”. The nature of obstacles varied from bureaucracy like visa difficulties to obscene regulations on funds that can be allocated towards mobility, to sheer lack of funding.

“Quantum cryptology” was correlated with “Institutions-Organisations”, which is mainly TÜBİTAK BİLGEM, also it was close with “Quantum metrology” due to TÜBİTAK UME (National Metrology Institute). Finally, “Photonics” and “Industry-Academia Partnership” are the other strong links for “Quantum cryptology” in the data.

“Industry-Academia Partnership” is close with “Reasons of Collaboration”, “Effects of QT” and “TÜBİTAK”. Where “Effects of QT” is most strongly correlated with “Buyer Position”, “Industry-Academia Partnership”, “Quantum Sensing” and “Cryptology”.

“Buyer Position” is a code worth noting, it came up in several of the interviews and is correlated with the following codes in descending order; “Obstacles for commercialisation”, “Effects of QT”, “Lacks in experimental fields” and “QT Sharing Spaces”. It is clearly noted by the interviewees that Turkey generally assumes a “Buyer Position” in face of developing technologies, and this attitude itself is an obstacle for commercialisation, it shapes the way public interacts with the technology and how it is affected by it. “Lacks in experimental fields” and not being able to easily access to “QT Sharing Spaces” reinforces this attitude, and is also are reinforced through it.

Two other important codes were “Where Turkey is lacking” and “Where Turkey is ahead”. Lacks are correlated with development strategies, experimental fields, developmental support, commercialisation, and quantum computation. The ‘ahead’ code is close with theoretical aspect and TÜBİTAK.

“Firms” code appear near codes related commercialisation, additionally “Quantum Computation” and “EU Support/COST Action”. Majority of the interviewees mentioned firms involving quantum computation when asked of examples, however during the interviews other firms such as IDQ, Toshiba, Thales and Bosch came up. It is noteworthy that when directly asked about whether they know any firms operating in quantum information technologies, almost all of the interviewees focused on firms dealing with quantum computation and only a few mentioned firms in other fields of quantum technologies.

“Obstacles” code came out related with “Multidisciplinarity”, “Scientific Meetings” and “Reasons for collaboration” in that order. This was another important code that yielded insight. Especially the multidisciplinary nature of quantum information field came out as a distinct obstacle in Turkey’s strong disciplinary academic environment. Finding suitable academic positions, being able to host multidisciplinary events, extensive disciplinary expectations from supervisors and lack of collaboration between disciplines all mentioned as obstacles in the development of quantum information technologies in Turkey.

E. ADDITIONAL DATA ON TURKISH ACADEMIA

Table E.1: Number of M.Sc. and Ph.D. degrees awarded in QIT fields per university

Number of M.Sc.s awarded in QIT	**Universities**
1	Dokuz Eylül University Erciyes University Eskişehir Osmangazi University Hacettepe University İstanbul Gelisim University İstanbul University Sakarya University
2	Ege University Gaziantep University Yıldız Technical University
3	Abant İzzet Baysal University Adnan Menderes University Bilkent University
4	İzmir Institute of Technology
5	Ondokuz Mayıs University TOBB University
6	Afyon Kocatepe University Ankara University Boğaziçi University İstanbul Technical University Koç University
8	Middle East Technical University
Number of PhDs awarded in QIT	**Universities**
1	Ankara University Çanakkale Onsekiz Mart University Dokuz Eylül University Eskişehir Osmangazi University Gaziantep University Hacettepe University İzmir Institute of Technology Koç University Marmara University Okan University TOBB University
3	Abant İzzet Baysal University Bilkent University Middle East Technical University
4	Ondokuz Mayıs University
5	Sabanci University

Table E.2: Countries with respect their numbers of publications in the search query, populations, and total GDP ranking

Country	# of publications	Population (Millions)	GDP Ranking
Turkey	152	83	20
Argentina	177	45	30
Chile	139	18	42
Egypt	190	101	44
Greece	164	11	52
Malaysia	128	32	35
Pakistan	109	205	43
Portugal	124	10	50
Romania	136	19	49
Saudi Arabia	196	34	18
Slovakia	128	5	61
South Africa	169	58	31
Ukraine	111	44	59

Table E.3: Information on COST Actions related to Quantum Information Technologies

Name of the Action	Code and Period	Website	Turkish MC(s)
Nanoscale Quantum Optics	MP1403 (2014-2019)	http://www.cost-nqo.eu/	Aykutlu Dana Serkan Ateş
Quantum structure of spacetime	MP1405 (2015-2019)	http://www.qspace-cost.eu	Aybike Özer Cemsinan Deliduman
Quantum Technologies in Space	CA15220 (2016-2020)	http://www.qtspace.eu/	Özgür Müstecaplıoğlu Serkan Ateş
Nanoscale Coherent Hybrid Devices for Superconducting QT	CA16218 (2017-2021)	http://nanocohybri.eu/	Cem Sevik Ali Gençer
QT with Ultra-Cold Atoms	CA16221 (2017-2012)	https://atomqt.eu/	Özgür Müstecaplıoğlu
Trapped Ions: Progress in classical and quantum applications	CA17113 (2018-2022)		

Table E.4: Information on theses collected through National Thesis Center Database

Advisor	Author	Type of Degree	University	Department
ABDULLAH VERÇİN	ERDEM AKYÜZ	Master	Ankara University	Physics and Physics Engineering
ABDULLAH VERÇİN	SOLMAZ YILMAZ	PHD	Ankara University	Physics and Physics Engineering
ABDULLAH VERÇİN	ADEM TÜRKMEN	Master	Ankara University	Physics and Physics Engineering
ABDULLAH VERÇİN	DURGUN DURAN	Master	Ankara University	Physics and Physics Engineering
ABDULLAH VERÇİN	ALİ ÜMİT CEMAL HARDAL	Master	Ankara University	Physics and Physics Engineering
AHMET ARİF ERGİN	MUSTAFA TOYRAN	PHD	Gebze Technical University	Electrical and Electronics Engineering
AHMET SERTBAŞ	SİNAN BUĞU	Master	İstanbul University	Computer Engineering
ALEXANDER S. SHUMOVSKY	SİNEM BİNİCİOĞLU ÇETİNER	PHD	Bilkent University	Physics
ALEXANDER S. SHUMOVSKY	ALPER DURU	Master	Bilkent University	Physics
ALEXANDER S. SHUMOVSKY	MUHAMMET ALİ CAN	Master	Bilkent University	Physics
ALEXANDRE KLYACHKO	EMRE ŞEN	Master	Bilkent University	Mathematics
ALİ BOZBEY	MUSTAFA EREN ÇELİK	Master	TOBB University	Electrical and Electronics Engineering
ALİ BOZBEY	SASAN RAZMKHAH	PHD	TOBB University	Electrical and Electronics Engineering
ALİ BOZBEY	KÜBRA ÜŞENMEZ	Master	TOBB University	Electrical and Electronics Engineering
ALİ BOZBEY	MURAT ÖZER	Master	TOBB University	Electrical and Electronics Engineering
ALİ BOZBEY	YİĞİT TÜKEL	Master	TOBB University	Electrical and Electronics Engineering
ALİ BOZBEY	UFUK YUMRUKAYA	Master	TOBB University	Electrical and Electronics Engineering
ALİ BOZBEY	EREN CAN AYDOĞAN	Master	TOBB University	Electrical and Electronics Engineering
ALİ ULVİ YILMAZER	İLHAM BOLATOĞLU	Master	Ankara University	Physics and Physics Engineering
ALİ ULVİ YILMAZER	OKAN ÇAMURSOY	Master	Ankara University	Physics and Physics Engineering
ALİ YILDIZ	SERKAN KARAÇUHA	Master	İstanbul Technical University	Physics and Physics Engineering
ALİ YILDIZ	SEÇGİN SEFİ	Master	İstanbul Technical University	Physics and Physics Engineering
ALİ YILDIZ	GÖKHAN TORUN	Master	İstanbul Technical University	Physics and Physics Engineering
ALİEKBER AKTAĞ	HÜNKAR KAYHAN	PHD	Abant İzzet Baysal University	Physics

Table E.4 (continued)

Advisor	Author	Type of Degree	University	Department
AZMİ ALİ ALTINTAŞ	VOLKAN EROL	PHD	Okan University	Computer Engineering
AZMİ GENÇTEN	DENİZ TÜRKPENÇE	Master	Ondokuz Mayıs University	Physics and Physics Engineering
AZMİ GENÇTEN	AHMET GÜN	PHD	Ondokuz Mayıs University	Physics and Physics Engineering
AZMİ GENÇTEN	SELÇUK ÇAKMAK	Master	Ondokuz Mayıs University	Physics and Physics Engineering
AZMİ GENÇTEN	SEVCAN ÇORBACI	Master	Ondokuz Mayıs University	Physics and Physics Engineering
AZMİ GENÇTEN	DENİZ TÜRKPENÇE	PHD	Ondokuz Mayıs University	Physics and Physics Engineering
AZMİ GENÇTEN	SELÇUK ÇAKMAK	PHD	Ondokuz Mayıs University	Physics and Physics Engineering
AZMİ GENÇTEN	ÇAĞDAŞ İLHAN	Master	Ondokuz Mayıs University	Physics and Physics Engineering
AZMİ GENÇTEN	VOLKAN DURAN	Master	Ondokuz Mayıs University	Physics and Physics Engineering
CEM SAY	ABUZER YAKARYILMAZ	PHD	Boğaziçi University	Computer Engineering
CEM SAY	UĞUR KÜÇÜK	Master	Boğaziçi University	Computer Engineering
CEM SAY	ELTON BALLHYSA	Master	Boğaziçi University	Computer Engineering
CEM SAY	DAMLA POSLU	Master	Boğaziçi University	Computer Engineering
CEM SAY	EVGENİYA KHUSNİTDİNOVA	Master	Boğaziçi University	Computer Engineering
CEM SAY	ABUZER YAKARYILMAZ	Master	Boğaziçi University	Computer Engineering
CEM SAY	FATİH MEHMET ATAK	Master	Boğaziçi University	Computer Engineering
CENK AKYÜZ	EMRAH KOCAARSLAN	Master	Adnan Menderes University	Physics
CENK AKYÜZ	YÜCEL BİLİR	Master	Adnan Menderes University	Physics
CENK AKYÜZ	ALEV ŞAHİNTAŞ	Master	Adnan Menderes University	Physics
EKREM AYDINER	CENK ORTA	Master	Dokuz Eylül University	Physics
EKREM AYDINER	CENK AKYÜZ	PHD	Dokuz Eylül University	Physics
EKREM AYDINER	SEYİT DENİZ HAN	Master	İstanbul University	Physics
EKREM YANMAZ	HÜSEYİN ULUCAN	Master	İstanbul Gelişim University	Mechatronics Engineering
FATİH DEMİRKALE	EDA YILDIZ	Master	Yıldız Technical University	Mathematics
İHSAN YILMAZ	MUSTAFA ŞAHİN	PHD	Çanakkale Onsekiz Mart University	Physics
İLHAMİ YAVUZ	SERHAN YARKAN	Master	İstanbul University	Computer Engineering
M. BÜLENT ÖRENCİK	MUSTAFA TOYRAN	Master	İstanbul Technical University	Computer Engineering
M. EMİN DALKILIÇ	GÜRKAN AYDIN ŞEN	Master	Ege University	Computer Engineering

Table E.4 (continued)

Advisor	Author	Type of Degree	University	Department
MEHMET ÖZEN	MURAT GÜZELTEPE	PHD	Sakarya University	Mathematics
MEHMET ÖZEN	FAİK CEM ERTUNÇ	Master	Sakarya University	Mathematics
MUSTAFA ALTUN	ÖMER CAN SUSAM	Master	İstanbul Technical University	Nano science
NAMIK KEMAL PAK	YUSUF GÜL	PHD	Middle East Technical University	Physics
NAMIK KEMAL PAK	CESİM KADRİ DUMLU	Master	Middle East Technical University	Physics
NAMIK KEMAL PAK	ENDERALP YAKABOYLU	Master	Middle East Technical University	Physics
NAMIK KEMAL PAK	ALİ CAN GÜNHAN	PHD	Middle East Technical University	Physics
OKTAY PASHAEV	AYGÜL KOÇAK	Master	İzmir Institute of Technology	Mathematics
OKTAY PASHAEV	ZEYNEP NİLHAN GÜRKAN	PHD	İzmir Institute of Technology	Mathematics
ÖMER FARUK DAYI	MELİS PAHALI	Master	İstanbul Technical University	Physics
ÖZGÜR BARIŞ AKAN	ÇAĞLAR KOCA	Master	Koç University	Electrical and Electronics Engineering
ÖZGÜR ÇAKIR	SEVİL ALTUĞ	Master	İzmir Institute of Technology	Physics
ÖZGÜR MÜSTECAPLIOĞLU	RAMAZAN UZEL	Master	Koç University	Physics
ÖZGÜR MÜSTECAPLIOĞLU	ALİ ÜMİT CEMAL HARDAL	PHD	Koç University	Physics
ÖZGÜR MÜSTECAPLIOĞLU	OMİD KHOSRAVANİ	Master	Koç University	Physics
ÖZGÜR OKTEL	MEHMET EMRE TAŞGIN	PHD	Bilkent University	Physics
ÖZGÜR OKTEL	BARIŞ ÖZTOP	PHD	Bilkent University	Physics
PARS MUTAF	BURCU KORKMAZ	Master	Ege University	Computer Science
RAMAZAN KOÇ	SHAKHAWAN SALİH ABDULLAH	Master	Gaziantep University	Physics
RAMAZAN KOÇ	MEHMET YAKUP HACIİBRAHİMOĞLU	PHD	Gaziantep University	Physics
RAMAZAN KOÇ	İBRAHİM NAZEM QADER AL-JAF	Master	Gaziantep University	Physics
RASİM DERMEZ	ABBAS ÇELİK	Master	Afyon Kocatepe University	Physics
RASİM DERMEZ	SONER ÖZEN	Master	Afyon Kocatepe University	Physics
RASİM DERMEZ	GÜLDEN NEVAL GÜNAYDIN	Master	Afyon Kocatepe University	Physics
RASİM DERMEZ	BEKİR DEVECİ	Master	Afyon Kocatepe University	Physics
RASİM DERMEZ	KEMAL KARA	Master	Afyon Kocatepe University	Physics
RASİM DERMEZ	MEHMET AKİF ÇAĞ	Master	Afyon Kocatepe University	Physics
RECEP TAPRAMAZ	MEHPEYKER KOCAKOÇ	PHD	Ondokuz Mayıs University	Physics

Table E.4 (continued)

Advisor	Author	Type of Degree	University	Department
RESUL ERYİĞİT	HÜNKAR KAYHAN	Master	Abant İzzet Baysal University	Physics
RESUL ERYİĞİT	ARZU KURT	Master	Abant İzzet Baysal University	Physics
RESUL ERYİĞİT	ARZU KURT	PHD	Abant İzzet Baysal University	Physics
RESUL ERYİĞİT	FERDİ ALTINTAŞ	PHD	Abant İzzet Baysal University	Physics
RESUL ERYİĞİT	FERDİ ALTINTAŞ	Master	Abant İzzet Baysal University	Physics
RÜYAL ERGÜL	ZUHAL KALE	Master	Middle East Technical University	Electrical and Electronics Engineering
SADİ TURGUT	ZEKİ CAN SESKİR	Master	Middle East Technical University	Physics
SADİ TURGUT	KIVANÇ UYANIK	PHD	Middle East Technical University	Physics
SADİ TURGUT	KIVANÇ UYANIK	Master	Middle East Technical University	Physics
SADİ TURGUT	ÖZENÇ GÜNGÖR	Master	Middle East Technical University	Physics
SADİ TURGUT	ÇAĞAN AKSAK	Master	Middle East Technical University	Physics
SADİ TURGUT	SEÇKİN KINTAŞ	Master	Middle East Technical University	Physics
ŞAHİN AKTAŞ	İZZET PARUĞ DURU	PHD	Marmara University	Physics
SELAMİ KILIÇKAYA	RASİM DERMEZ	PHD	Eskişehir Osmangazi University	Physics
SELAMİ KILIÇKAYA	VOLKAN ŞENAY	Master	Eskişehir Osmangazi University	Physics
SERKAN ATEŞ	NAHİT POLAT	Master	İzmir Institute of Technology	Physics
SERKAN ATEŞ	VOLKAN FIRAT	Master	İzmir Institute of Technology	Physics
SERKAN ÖZTÜRK	BİLGEHAN GÜRÜNLÜ	Master	Erciyes University	Computer Engineering
TEKİN DERELİ	AHMET TUNA BÖLÜKBAŞI	Master	Koç University	Physics
TEKİN DERELİ	İSMAİL ENES UYSAL	Master	Koç University	Physics
TEKİN DERELİ	UTKAN GÜNGÖRDÜ	Master	Koç University	Physics
YİĞİT GÜNDÜÇ	BUĞRA YILDIZ	Master	Hacettepe University	Physics and Physics Engineering
YİĞİT GÜNDÜÇ	RECEP ERYİĞİT	PHD	Hacettepe University	Physics and Physics Engineering
ZAFER GEDİK	İSKENDER YALÇINKAYA	PHD	Sabanci University	Physics
ZAFER GEDİK	BARIŞ ÇAKMAK	PHD	Sabanci University	Physics
ZAFER GEDİK	GÖKTUĞ KARPAT	PHD	Sabanci University	Physics
ZAFER GEDİK	ÖZGÜR BOZAT	PHD	Sabanci University	Engineering Sciences
ZEYNEL YALÇIN	HÜSNÜ KARA	Master	Yıldız Technical University	Physics

F. HUMAN SUBJECTS ETHICS COMMITTEE PERMISSION

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02 OCAK 2018

Konu: Değerlendirme Sonucu

Gönderen: ODTÜ İnsan Araştırmaları Etik Kurulu (İAEK)

İlgi: İnsan Araştırmaları Etik Kurulu Başvurusu

Sayın Doç.Dr. İbrahim Semih AKÇOMAK;

Danışmanlığını yaptığınız yüksek lisans öğrencisi Zeki Can ŞESKİR'in "**Kuantum Bilişim: Türkiye'deki Mevcut Durum ve Gelecek Beklentileri"** başlıklı araştırması İnsan Araştırmaları Etik Kurulu tarafından uygun görülerek gerekli onay **2017-SOS-215** protokol numarası ile **02.01.2018-28.08.2018** tarihleri arasında geçerli olmak üzere verilmiştir.

Bilgilerinize saygılarımla sunarım.

Prof. Dr. Ş. Halil TURAN
Başkan V

Prof. Dr. Ayhan SOL
Üye

Prof. Dr. Ayhan Gürbüz DEMİR
Üye

Doç. Dr. Yaşar KONDAKÇI
Üye

Doç. Dr. Zana ÇITAK
Üye

Yrd. Doç. Dr. Pınar KAYGAN
Üye

Yrd. Doç. Dr. Emre SELÇUK
Üye

G. TURKISH SUMMARY / TÜRKÇE ÖZET

TÜRKİYE'DE KUANTUM BİLİŞİM TEKNOLOJİLERİNİN
MEVCUT DURUMU

GİRİŞ

Araştırmanın Amacı ve Önemi

İkinci kuantum devrimi (Dowling & Milburn, 2003) ortaya sürüldüğü ilk yıllardan itibaren heyecan uyandıran bir kavram. Ancak kuantum teknolojilerinin bu kadar hızla ticari bağlamda bir popülerlik kazanacağı öngörülmemişti. 15 yıl önceye kıyasla kuantum teknolojileri alanına yapılan yatırımlar hızla arttı ve ülkeler geri kalmamak adına ardı ardına kendi ulusal ve uluslararası ortaklık girişimlerini oluşturmaya başladılar.

Bu tezin ana fikri 2016 ila 2017 seneleri arasında, alanın dünyada bu kadar hızlı yükselişe geçmesine karşın Türkiye'de yalnızca sınırlı sayıda insanın bu konuya ilgi göstermesi üzerine oluştu. Hali hazırda TÜBİTAK'ın 2004 yılında hazırladığı "Vizyon 2023" belgesinde bir stratejik hedef olarak var olan bir konuda dünyada bu kadar hızlı gelişmeler olurken Türkiye'nin atıl kalıp kalmadığı fikri tezin araştırma sorularının üzerine kurulacağı zemini oluşturdu.

Tekno-ekonomik paradigma yaklaşımı Perez ve Soete (1988) tarafından öne sürülen ve ekonomiyi dönüştürücü etkileri olan yenilik patlamalarının dönemsel olarak, tekno-ekonomik temellere dayanan düşünsel zeminler üzerine kurulduğunu öne süren bir kuramdır. Bu kuram çerçevesinde, gelişmekte olan ülkeler paradigma dönüşümlerine yol açacak olan teknolojik devrimleri bir yakalama mekanizması olarak kullanabilme imkanına sahip olabilmektedirler. Yani her teknolojik devrim, onu değerlendirmeyi bilen gelişmekte olan ülkeler için bir fırsat penceresidir.

Yukarıdaki iki konunun birleşiminden bu tezin araştırma soruları çıktı, Türkiye'de kuantum bilişim teknolojileri alanındaki mevcut durumun ortaya konulması ve gelişmekte olan bir ülke olarak Türkiye'nin değerlendirebileceği bir fırsat penceresinin gerçekten var olup olmadığının araştırılması. Takiben de bunların ışığında ortaya Türkiye'nin bu teknoloji alanında uygulayabileceği politika önerilerinin ortaya sunulması.

Politika önerileri oluşturabilmek adına öncelikli olarak cevaplanması gereken sorular bu tezin ana metnini oluşturuyor. Bu sorular sırasıyla kuantum teknolojilerinin gerçekten devrimsel bir niteliği olup olmadığı, küresel düzlemde bu teknolojilerin gelişmişlik düzeyi ve piyasanın durumu, son olarak da Türkiye'nin bu alanda ne durumda olduğu şeklinde sıralanabilir. Tezin öncelikli olarak amacı, eğer ortada yerleşik tekno-ekonomik paradigmayı dönüştürebilecek bir devrim varsa, dünya bu alanda henüz çok ilerlemediyse ve de Türkiye'de Perez ve Soete'nin öne sürdüğü fırsat penceresini değerlendirebilecek koşullar mevcutsa, bu fırsatı değerlendirmek amaçlı politikalar geliştirmekti. Aksi takdirdeyse eksiklerin giderilmesine ve kapasite geliştirmeye yönelik politikalar önermekti.

Ana Metnin Genel Akışı

İkinci bölümde kuantum bilişim teknolojileri üzerine odaklanıyor. Tüm tez boyunca kuantum teknolojileri ve kuantum bilişim teknolojileri kavramları eşanlamlı olarak kullanılıyor, ancak bu kavramların tekabül ettiği teknolojilerin tam uyuştuğu da söylenemez. Farklı belgelerin ve kurumların tanımlarına bu bölümde değiniliyor.

Üçüncü bölümde bu teknolojilere tekno-ekonomik paradigma yaklaşımı çerçevesinden bakabilmek adına önce kuram irdeleniyor. Bunu takiben herhangi bir teknoloji sistemi yaklaşımı altında kamu müdahalesi için hangi koşulların bulunması gerektiğine dair alan yazınsal tarama sunuluyor. Ardından bir fırsat penceresi olarak teknolojik devrimlerin kavramsallaştırılması ele alınıyor. Son olarak da kuantum teknolojilerinin neden bir teknolojik devrim sayılabileceği üzerine argümanlar sunuluyor.

Dördüncü bölüm metodolojinin ele alındığı kısım. Burada nicel ve nitel verilerin toplanma, üretilme ve analiz süreçlerine dair bilgi sunuluyor. Nicel veri kaynakları olarak kullanılan ulusal kurumların stratejik plan belgeleri, Ulusal Tez Merkezi'nde yapılan aramalar sonucu ulaşılan lisansüstü çalışmalar, ulusal ve uluslararası kurumlar tarafından yayınlanan yol haritaları ve firma, patent ve piyasa analizi verileri burada tanıtılıyor. Nitel veri kaynakları olaraksa yarı-yapılandırılmış görüşmeler ve etkinliklerde yapılan gözlemler ele alınıyor. Bunların nasıl toplandığı ve üretildiği, görüşmeler için katılımcıların hangi kriterlere göre ve nasıl süreçler sonunda seçildikleri burada ele alınıp okuyucuya aktarılıyor.

Beşinci bölümde ilk olarak veriler ve bulgular iki aşamalı olarak paylaşılıyor. İlk olarak küresel ölçekteki harcama, yayın, patent ve firma sayıları verileri ele alınıyor. İkinci kısımdaysa Türkiye üzerine nicel ve nitel bulgular tanıtılıyor. Stratejik planlar ve Vizyon 2023 belgesi, Devlet Planlama Teşkilatı destekli harcamalar, TÜBİTAK raporları, Ulusal Tez Merkezi'nde taranan tezler, Web of Science'dan elde edilen Türkiye'den yazarların da dahil olduğu akademik yayınlar ve son olarak görüşme çıktıları bu kısımda sunuluyor. Üçüncü kısımdaysa bu bulgulara dayanarak Türkiye ve küresel olarak üçer ayrı tema geliştiriliyor. Bu temalar hem politika önerileri kısmında kullanılmak üzere hem de betimsel analizin bir parçası olarak ele alınıyor.

Altıncı bölüm ise tezin son ve politika önerilerinin tartışıldığı bölümü. Burada bir önceki bölümde Türkiye üzerine ortaya konulan '*Kaynak Yönetimi', 'Stratejik Düşünme'* ve *'Güven'* üzerinden geliştirilen politika önerileri ortaya konuluyor. Türkiye'nin bu teknolojilere dair topyekun bir atak yapabilmek adına bilimsel ve teknik bilgi bağlamında geride olduğu, özellikle deneysel alanlardaki araştırmacı sayılarının kritik kitlenin altında kaldığına ve yetersizliğine vurgu yapılıyor. Öte yandan, Türkiye'nin kuantum kriptografi ve algılama alanlarında önceki yatırımları, yetişmiş insan gücü ve stratejik hedefleriyle uyumluluğu öne çıkarılıp Türkiye'nin kuantum bilgisayım veya bütünsel bir kuantum teknolojileri hamlesinden ziyade özelleşmiş bir alanda stratejik hamleler yapmasına yönelik öneriler sunuluyor. Bunların yanında geleceğe yönelik, kuantum teknolojileri alanında daha genel bir kapasite geliştirme çabası içinde uygulanabilecek politika önerileri ve kısa-orta-uzun vadeli hedefler ortaya konuluyor.

Bölüm 2: Kuantum Bilişim Teknolojileri

Bu bölümde birinci kuantum devrimi olarak ele alınan transistör ve lazer üzerine kurulan Bilişim Çağı'nın neden bir kuantum yükseltmeye ihtiyacı olduğu tartışılıyor. Giderek küçülen mikroçip boyutlarından kaynaklı kuantum etkilerin hesaba katılmaya başlanmak zorunda kalınması, iletişim için gittikçe daha az sayıda fotona bilgi kodlamanın ve kontrol edebilmenin gereklilik haline gelmeye başlaması gibi argümanlar burada irdeleniyor. Temel teknolojileri fiziksel sistemlerin manipülasyonuna dayalı ürünlerin çalıştığı rejim değiştikçe (boyutlar küçüldükçe, sayılar azaldıkça) üzerine kuruldukları fiziksel kuramı da değiştirmek zorunda kalacakları açıklanıyor. Burada pratik bir örnek olarak sunulan kuantum internet ile bugünkü internet arasındaki ilişki, kuantum yükseltmenin eski sistemleri devre dışı bırakmayacağına ancak bugün sahip olmaları mümkün olmayan bazı yetiler kazandıracağı fikri değerlendiriliyor.

Kuantum teknolojilerinin alt alanları ve farklı tanımlara da bu bölümde değinilip ardından ülkelerin ulusal ve uluslararası girişimlerine dair bilgiler sunuluyor. Özellikle de Amerika'daki Ulusal Kuantum Girişimi (NQIA, 2018) ve Avrupa'daki Kuantum Amiral Gemisi (Quantum Flagship) üzerinden dünya genelinde devletler tarafından giderek artan yatırım miktarlarına dikkat çekiliyor. Bu iki proje de bir milyar avro ölçeğine sahip.

Bölüm 3: Tekno-Ekonomik Paradigma Yaklaşımı Çerçevesinde Kuantum Bilişim Teknolojileri

Tekno-ekonomik paradigmaların safhaları bu bölümde tanıtılıyor. Her paradigmanın dört safhadan oluştuğu kurgulanan bu yaklaşımda ilk aşamanın keşif, ikinci ve üçüncü aşamanın hızlanan ve yavaşlayan artışlar, son aşamanınsa dengeye gelme ve doyuş olarak alındığı açıklanıyor. Yazarların (Dosi, 1982; Perez & Soete, 1988) kuramsal çerçevesine göre gelişmekte olan bir ülkenin bir tekno-ekonomik paradigmaya en rahatça uyum sağlayıp bunu genel bir ekonomik atılım amaçlı kullanabileceği iki fırsat penceresi bulunmakta. Bunların ilki denge aşamasında, standart iktisadi kurallara göre, ucuz işgücü ve potansiyel pazar vaadiyle sermaye çekip teknoloji transferiyle üretimin yerlileştirilip ardından ihracata evrilmesi şeklinde tezahür eden süreç. Bunu yazarlar statükoyu koruyucu olması ve aslında bir alandaki liderliğin el değişmesine izin vermeyecek bir süreç olduğu için optimal bir yakalama mekanizması olarak görmüyorlar.

Diğer fırsat penceresiyse bir önceki paradigma sonlanıp yeni paradigma başlarken olarak görülüyor. Yeni paradigmanın üzerine kurulacağı alana dair yüksek bilimsel ve teknolojik bilgiye, uygun konumsal avantajlara ve gereken yatırım sermayesi gücüne sahip gelişmekte olan ülkelerin bunları kullanarak yeni paradigmada ekonomilerine topyekun bir yükseliş için fırsatı bulabilecekleri öne sürülüyor. Buradaki en önemli ayrıntıysa kuramın bu fırsatın varlığı için koyduğu koşulların fırsatın başarıyla değerlendirilebilmesini garanti etmedikleri. Yaklaşımın öne sürdüğü koşullar (Perez, 2010) yalnızca bir ülkenin yeni paradigmanın birinci safhasını fırsat penceresi olarak kullanabilmenin alt koşullarını sağlayıp sağlayamadığı üzerinde duruyor. Yani yarışa girebilmek için gerekli olan minimum gereklilikleri ortaya koyuyor, ancak kazanmak için izlenmesi gereken politikaları kesin hatlarıyla belirlemiyor.

Bu bağlamda bir sonraki kuramsal çerçeve olarak sistemik problemler yaklaşımı (Edquist, 2001; Chaminade & Edquist, 2006) ele alınıyor ve hangi problemlerin varlığının kamu müdahalesini, hangi koşullar altında gerektirdiğine dair arka plan anlatılıyor. Alan yazında taranmış ve tanımlanmış sistemik problemler burada sunuluyor. Ayrıca kamunun bu problemlere müdahale edebilmesi adına gerekli olan koşullar da, (i) özel aktörlerin bu sorunları kendi başlarına çözemeyecek olmaları ve (ii) kamu aktörlerinin bu sorunları çözebilecek kapasiteye sahip veya bu kapasiteyi edinebilir olmaları, burada tanıtılıyor.

Son olarak da kuantum teknolojilerinin neden altıncı teknolojik devrim olarak ele alınabileceğine dair fikirler burada sunuluyor. Kontradieff (1935) dalgalarına dayanan ve döngüsel ama değişimci bir tarihsellik çerçevesine dayanan argümanlarla yeni bir teknolojik devrimin hem tarihsel, hem fiziksel, hem de ekonomik gerekliliklerinin oluştuğu öne sürülüyor. Elbette yine de tarihin önceden bilinemezliği not edilerek yeni oluşacak olan tekno-ekonomik paradigmanın en belirleyici öğesinin kuantum teknolojileri olmasının gerekmediği belirtilirken ne olursa olsun kuantum teknolojilerinin bir şekilde çok önemli bir rol oynamak zorunda olacakları ikinci bölümde sunulan genel akışla birleştirilerek aktarılıyor.

Bölüm 4: Metodoloji

Nicel ve nitel yaklaşımların ikisinin de kullanıldığı bu çalışmanın metodoloji bölümünde hem tezin amacına yönelik nasıl bir veri toplama ve üretme süreci işlendiği, hem de bu süreçlerde kullanılan yöntemlerin ne şekilde ele alındığı irdeleniyor. Karma yöntemin kullanılmasının, alandaki ilk çalışma olarak tezin bulgularını güçlendireceğine vurgu yapılıyor. Nicel verilerin nitel araştırma için destekleyici, nitel çıktıların da nicel analize tamamlayıcı olması tez sürecinde önemli ve değerli bir yöntemsel yaklaşıma tekabül ediyor.

Tezin nicel kısmında öncelikle Türkiye'deki kurumların stratejik planları arasında[6] *"kuantum, kuvantum, bilgi güvenliği, bilişim"* anahtar kelimeleri kullanarak aramalar yapıldı. Orijinal kullanım olarak yalnızca iki belgede kuantum/kuvantum kullanımlarına rastlanıldı. Bunlardan birisi ve en yoğun kullanılanı "Vizyon 2023" belgesi, diğeriyse "İYTE 2014-2018 Stratejik Planı" idi. Bunun yanında Ulusal Tez Merkezi ve Web of Science taramalarının bilgileri, faydalanılan yan dokümanların listeleri de nicel kısımda veriliyor.

Nitel araştırma kısmı içinse yapılan 15 birebir ve bir adet dört katılımcılı grup görüşmesi bu bölümde ele alınıp kurum ve uzmanlık alanı dağılımları burada sağlanıyor. Ayrıca gözlem gerçekleştirilen altı etkinlik ve gözlemsel verinin kullanımına dair bahisler de bu kısımda

[6] www.sp.gov.tr/tr/stratejik-plan

yapılıyor. Son olarak da nicel ve nitel yaklaşımın yöntemleri ve ne için gerçekleştirildiklerine dair bir tablo sunularak bölüm kapatılıyor.

Bölüm 5: Veriler ve Bulgular

Tezin bu bölümü üç temel başlığa ayrılıyor. Küresel ve ulusal verilerle bulguların ortaya konulması ilk iki başlığı, betimsel analiz ise üçüncü başlığı oluşturuyor. Küresel ve ulusal başlıklarsa kendi altlarında nicel ve nitel veriler ve bunlardan elde edilen bulgular şeklinde alt başlıklara ayrılıyorlar.

Küresel veriler yoğunluklu olarak nicel kaynaklara dayanıyor. Bu kısımdaki veriler genel olarak ikinci el kaynaklara dayanarak sunuluyor. Harcama miktarları, akademik yayınlar, patent sayılar ve kurulan firma sayıları küresel ölçekteki nicel verileri oluşturuyor. Bunların arasında 200 firmadan oluşan veri seti onlarca farklı kaynaktan derlenmiş, bu tez için orijinal bir veri seti. Bu set aynı zamanda ekler arasında (Appendix B) faydalanmak isteyen araştırmacılar için açık olarak verilmiş durumda. Firmalara dair verilerin web bazlı kaynakları da aslında orijinal veri setinin içinde yer alıyor ancak tezin yazılı formatına uymadıkları için açık erişim listeden çıkarıldılar.

Küresel ölçekteki nitel verilerse katılınmış olan etkinliklerdeki gözlemsel veriye ve takip edilen yurtdışı kaynaklarından (YouTube veya kurum paylaşımlarından izlenilen videolar, okunulan raporlar vbg.) yapılan betimsel çıkarımlara dayanıyor. Etkinliklerdense özellikle Viyana'daki Kuantum Amiral Gemisi Açılışı gibi politika tartışılan mecralardan yapılan gözlemler de burada yansıtılıyor.

Nicel ve nitel küresel verilerden yapılan temel çıkarımlar da burada paylaşılıyor. Ülkelerin harcama, yayın, patent ve firma sayıları arasındaki tutarlılık, kuantum teknolojilerinin alt başlıkları arasında ülkelerin karşılaştırmalı pozisyonlarına dair yorumlar (Çin'in kuantum kriptografide, Amerika'nın kuantum bilgisayımda ileri olması gibi) da bu verilerden elde edilen bulgular olarak ortaya konuluyor. Özellikle patent ve firma sayılarındaki artışlar burada göze çarpıyor.

Ülkelerin firma sayılarına göre kümelenmesi G.1 tablosunda verilmiş durumda. Bu kümelenme aşağı yukarı ülkelerin birbirlerine göre ticari gelişmişlik düzeylerine tekabül ediyor. Ancak burada önemli bir kısıtlama olarak Çin, Rusya, Japonya, Güney Kore, İsrail gibi bu alanda aktif ancak ticari etkinliklerini kendi dillerinde gerçekleştiren ülkelerdeki tekno-girişimci firmaların bilgilerine erişememek. Tabloda harcama, yayın ve patent sayılarıyla tutarlı pozisyona sahip olmayan tek ülkeyse Çin. Bunun ise olası iki açıklaması olabileceği düşünülüyor, ilki yukarıda bahsedilen dil bariyeri ve girişim kültürünün Batı'dan farklı olması. İkincisiyse Çin'de bu alanda faaliyet gösteren firmaların genelde çok büyük boyutlu ve devlet destekli firmalardan oluşmaları. Çin'in kuantum teknolojilerini öncelikli bir atılım alanı olarak gördüğünü göz önüne alırsak (Sharma, 2018), Çin'de bu teknoloji alanını küçük girişimcilere örtük biçimde kapatmış olma ihtimali de olasılık dahilinde.

Tablo G.1: Ülkelerin kuantum bilişim teknolojileri alanında var olan firma sayılarına göre kümelenmesi

Veri setindeki firma sayıları (200)	**Ülkeler**
1-4	Avusturya, Çek Cumhuriyeti, Danimarka, Estonya, Finlandiya, Hindistan, İsrail, İtalya, Norveç, Polonya, Rusya, İskoçya, Singapur, Güney Kore, İspanya, İsveç, İsviçre, BAE
5-9	Avustralya, Fransa, Hollanda
10-19	Almanya, Japonya, Çin
20-39	Kanada, Birleşik Krallık
40+	Amerika Birleşik Devletleri

Ulusal ölçekteyse nicel verilere giriş stratejik planlar, Vizyon 2023, DPT harcama verileri, TÜBİTAK raporları taramaları üzerinden gerçekleştiriliyor. Bunu takiben Ulusal Tez Merkezinde anahtar kelime ve danışman akademisyenler odağında yapılan taramadan çıkan 77 adedi yüksek lisans 31 adedi doktora çalışması olmak koşuluyla 108 lisansüstü tez çalışmasına dair çıktılar paylaşılıyor. Bu orijinal veri seti de eklerdeki Tablo E.4'te (Appendix E) ilgili araştırmacılara açık. Veri setinin kendisinde tez çalışmalarının başlıkları da yer alıyor ancak tezin sayfa formatından ötürü bu başlıklar da paylaşılan formatta çıkarılmış durumda.

Ulusal nicel veri kapsamında son olarak da Web of Science'dan kuantum bilişim bilimi alanında yapılan ve indekslerde taranan akademik çalışmaların incelenip, içlerinde Türkiye'den de en az bir yazar olan grupların ağ modeli haritalandırılması yapılıyor. Aynı model Türkiye ile benzer yayın ölçeğinde (100-200 arası yayın) olan diğer 12 ülke için de yapılıyor. Tez çalışmasındaysa bu 12 ülke içerisinde hem GSYİH (Gayri Safi Yurt İçi Hasıla) hem de nüfus bakımından Türkiye'ye en yakın örnekler olmalarından ötürü karşılaştırma amaçlı Suudi Arabistan ve Güney Afrika ele alınıyor.

Türkiye'ye dair nicel verilerden elde edilen en temel iki bulgu şu şekilde sıralanabilir. Öncelikle, Türkiye'de yurtiçinde bu alandaki aktivite düzeyinde bir artış gözlenemiyor, son 13 senedir yıllık ölçekte neredeyse aynı sayıda yüksek lisans ve doktora tezi yayınlanıyor. Taranan akademik makale sayılarında da benzer bir davranış dikkat çekiyor. Dolayısıyla dünyada her sene yeni üretilen akademik sayısı artarken Türkiye'de sabit kalıyor, bu da toplam ürün sayısında küresel üretim üstel artış gösterirken ulusal üretimin lineer artış göstermesine sebebiyet veriyor ve seneler geçtikçe makas açılıyor. İkinci temel bulguysa Türkiye'den yazarların dahil oldukları bilimsel ortaklıkların boyutlarının benzerlerine (Suudi Arabistan ve Güney Afrika) göre dikkat çekici ölçüde parçalı olması ve en büyük konsorsiyumların bile diğer ülkelere kıyasla küçük kaldığı gerçeği. Çalışmanın bu kısmı nitel verilerden gelen "Türkiye'de kimse birbirine güvenmiyor" donesinin üstüne gerçekleştirildiği için bir nevi tamamlayıcı rol oynamış oluyor ve *'Güven'* temasının betimsel analizde yer almasında rol oynuyor.

Ulusal düzeyde nitel veriler ise yüz yüze görüşmeler ve gözlemsel verilerden oluşuyor. Görüşmeci veri setinde Ankara, İstanbul ve İzmir'den 15'i akademisyen, biri kamu görevlisi, üçü özel şirket mensubu olmak üzere toplamda 19 katılımcı bulunuyor. Bu katılımcıların seçimi kartopu modeliyle gerçekleştirilmiş olup tüm görüşmeler yüz yüze, ya görüşmecinin ofisinde ya da dışarıda bir kahvecilerde yapılmış durumda. Veri toplama sürecinin 2018'in ilk birkaç ayında gerçekleştirilmiş bulunuyor, bu nedenle bazı bilgilerin ve sayıların güncellenmesi veya dönemine uygun kullanımı gerektiği yerlerde belirtilmiş durumda (döviz kuru, TÜBİTAK destek miktarları gibi). Görüşmelerden elde edilen kayıtların transkripsiyonu yapıldıktan sonra QDA Miner programı yardımıyla kodlanmalarına binaen benzerlik, yakınlık gibi analizler yapılıp bunların sonuçları paylaşılıyor. Yarı yapılandırılmış görüşmeler için oluşturulan görüşme kılavuzu ve analizlerden çıkan kodların kümelenmeleri ekler (Appendix D) kısmında sunuluyor.

Bu bölümün son kısmı olan betimsel analizdeyse ulusal ve küresel ölçekte temalar çıkartılıyor. Türkiye için bu temalar '*Kaynak Yönetimi', 'Stratejik Düşünme'* ve *'Güven'* iken küresel ölçekte *'Kitlenme (Lock-in)', 'Keşif ve Değerlendirme Meseleleri (Exploration vs. Exploitation Issues)'* ve *'Yenilik ve Ticarileştirmeye Aşırı Odaklanma (Excessive Focus on Innovation and Commercialization)'* olarak ortaya konuluyor. Küresel temalar özellikle Türkiye'nin ileride içine düşebileceği potansiyel durumlar olarak ele alınıyor ve politika önerilerine bu ışık altında yansıtılıyor.

Aslında bu temaların (Türkiye özelinde) birbirlerini destekledikleri görülüyor. İşbirliği eksikliği görüşmelerde sürekli ortaya sürülüyor ve arttırılması gerektiği söyleniyor, ancak kimsenin birbirine güvenmediği belirtiliyor. Güvenmemenin bir sebebi olarak paylaşılan deneysel ekipmanların bozulmasının diğer projeleri aksattığı belirtiliyor, bu da aslında altyapının ve bakım hizmetlerine ulaşmanın pahalı ve zor olmasından kaynaklanıyor, yani bir kaynak yönetim problemi. Bu kaynakların yönetilemiyor olmasının arka planındaysa hızlı değişen kurumsal öncelikler, fonlamanın süreksizliği ve kısa vadeli olması yatıyor, yani stratejik düşünmedeki hatalı süreçlerle örtüşüyor. Fakat bu stratejik önceliklerin belirlenmesindeyse önceki kaynak yönetimi hatalarının giderilmesi amacı büyük rol oynuyor, bu kaynak yönetiminin başarısız idare edilmiş olmasıysa güven problemlerinden kaynaklı olarak yoğun bürokrasiye ve işbirliği noksanlığına bağlanıyor. Kısacası bu üç ana tema, bazı yerlerde ayrı ayrı kendilerini ihtiva etseler ve açıklayıcı etkiye sahip olsalar da aslında bir nevi dolanık durum gibi birlikte düşünülmelerini gerektiriyorlar.

Son olarak da bu bölümde tekno-ekonomik paradigma yaklaşımında yeni bir teknolojiye giriş yapabilmenin minimum düzeylerini ortaya koyan kısa bir kısım yer alıyor. Burada da kısaca Türkiye'ye dair eldeki bulgularla kuramda belirtilen koşullara uyup uymadığımız tartışılıyor. Sonuç olaraksa Türkiye'nin erken dönem (keşif safhasında) kuantum teknolojilerine topyekun bir giriş yapmak için yeterli teknolojik bilgi birikimine sahip olmadığı, ancak kuantum kriptografi ve algılama gibi Türkiye'nin ulusal çıkarları ve stratejik hedefleriyle uyuşan alt alanlarda bunun sağlanabileceği öne sürülüyor. Ayrıca ülkedeki ilgili devlet kurumlarının kısa vadeli getiri ve görüşmeciler tarafından 'satın alıcı pozisyonu' olarak tasvir edilen tutumlarından ötürü getirileri orta vade ve üstündeki teknolojilerde şimdiden yoğun bir girişim başlatabilmenin zorluğuna vurgu yapılıyor. Ek olarak da Türkiye'nin Asya ile Avrupa arasında olması, Avrupa Araştırma Alanına (ERA) entegre olması, Afrika, Orta Doğu ve Orta Asya gibi pazarlarla kültürel bağları olması da konumsal avantaj olarak ele alınıyor.

Bölüm 6: Tartışma ve Politika Önerileri

Son bölüm olan altıncı bölüm çalışmanın şimdiye kadarki temel bulgularını özetleyerek başlıyor.

- Kuantum teknolojileri, bütün bir ekonominin yükselişinin mümkün olabileceği yeni bir tekno-ekonomik paradigma ortaya koyma potansiyeline sahiptir.

- Bu teknolojilerin doğal seyrini kamu müdahalesi yoluyla ticari avantajlarından yararlanmak amacıyla kendi lehine değiştirmeye yönelik ulusal ve uluslararası girişimleri olan dünya çapında birçok ülke var.
- Yeni bir paradigmada liderlik rolü tartışılmakta, ülkeler (ABD, Çin, İngiltere, Kanada) ve bölgeler (AB) kamu politikaları yoluyla üstün bir pozisyona ulaşmak için yarışmakta
- Genel olarak, Türkiye bu yeni teknolojilere hızlı bir geçiş için hazır değil, ancak gelişebilmek için fırsatlar var ve acil bir paradigma değişimi küresel olarak beklenmiyor.

Türkiye'nin halihazırda kuantum teknolojilerine yapmış bulunduğu (ilgili dönemlerin kurlarıyla hesaplandığında) en az 6 Milyon $ yatırım bulunmakta. Bunların kuantum kriptografi ve kuantum algılama alanlarında yapıldığı, bu alanların küresel ölçekte teknolojik gereksinimlerinden kaynaklı en hızlı ticarileşecek alanlar oldukları ve de Türkiye'nin ulusal güvenlik ve baskın sanayi altyapısı türleri göz önüne alınacak olursa stratejik olarak bu alanların bir tekno-ekonomik paradigma değişiminde, erken safha dahiliyet adına kalan alanlardan ticarileşme adına daha uygun görünmekte oldukları düşünülmektedir.

Tablo G.2: Üç politika seti odakları

Kaynak yönetimi - Bir "kuantum farkında" işgücünün eğitimi - Eğitimin genişletilmesi - Odaklanmış Ar-Ge *Stratejik düşünme* - Hibridizasyon - Standardizasyon - Değer zincirlerine entegrasyon ve pazar oluşumu - Önceliklendirme *Güven* - Otoritenin merkezileştirilmesi ve etki değerlendirmesi - Ulusal ve uluslararası işbirliğini desteklemek - Kamu, akademi ve sanayi ölçeğinde farkındalık arttırma

Bunların dışında kuantum teknolojilerinin Türkiye'de gelişebilmesi adına tablo G.2'de verilen, tema bazlı politika amaç setleri geliştirilmiştir. Bunlara olarak da tablo G.3'te sunulan kısa-orta-uzun vadeli hedefler belirlenmiştir.

Table G.3: Kısa, orta ve uzun vadeli politika hedefleri

Kısa vade (5 yıl içinde)	**Orta vade (5-20 yıl)**	**Uzun vade (20+ yıl)**
-Türkiye Cumhuriyeti Cumhurbaşkanlığı Altında Ulusal Kuantum Koordinasyon Ofisi açılması -Kuantum teknolojileri üzerine yüksek lisans programları -Ulusal kapasitenin düzenlenmesi ve ulusal orta vadeli bir yol haritasının oluşturulması - Kamu, akademik ve endüstri seviyelerinde farkındalık programları	- Merkezi konumdaki çeşitli Ulusal Merkezler ve Laboratuvarlar -Kuantum teknolojileri üzerine lisans programları - Etki değerlendirme mekanizmaları kuruldu -Sanayi katılımı ve pazarın oluşumuna ilişkin ilk adımlar (düzenlemeler, ulusal standartlar, DYY davet edilmesi)	-Daha önce kurulan enstitülerdeki reformlar (etki değerlendirmesi) - Küresel pazarlara entegrasyon ve değer zincirleri (gümrük anlaşmaları) -Ulusal kuantum güvenli altyapı - Endüstriyel kümelenmeler kuantum teknolojilerine odaklandı

Bu çalışmadan elde edilen temel çıktılar birkaç düzeyde düşünülebilir. Küresel düzeyde, Çin'in kuantum teknolojileri geliştirerek yüksek teknolojide ABD hegemonyasını devirme yarışı, hem ampirik verilerden hem de tüm ana oyuncuların ifadelerinden açıkça görülebilir. ABD'nin Çin'deki gelişmeleri Avrupa'dan daha fazla dikkate almasına rağmen, Avrupa'nın bu çabalarına da dikkat edilmesi gerekiyor. Son olarak, ulusal girişimlerin, firmaların, patentlerin ve araştırma merkezlerinin sayısındaki artış, alanın en azından yakın bir gelecekte 'kuantum kışı' yaşayamayacağını göstermektedir.

Ulusal düzeyde, bu çalışma Türkiye'nin yeni ortaya çıkan yüksek teknoloji alanlarında geç bir takipçi olma şeklindeki davranış modelini vurgulamaktadır. Bu genel zihniyet kısmen insanlara, kurumlara ve yeteneklere duyulan güven eksikliğinden kaynaklanmaktadır. Bununla birlikte, güven eksikliği sadece kültürel bir yapı değil, çok hızlı değişen önceliklere ve kurumsal ortamın, hem para hem de çaba açısından yatırım önceliklerini de etkilemiştir. Yüksek teknoloji alanlarındaki kamu projeleri bile uzun vadeli kamu yararlarından ziyade kısa vadeli getirilere odaklanmaktadır. Bu genelde otomatikman bir problem olarak kabul edilir, ancak bu tez için görüşülen araştırmacıların çoğu tarafından bunun verili bir gerçek olarak kabul edildiği görülmektedir. Bu gerçek, birçok sistemik problem ve engelle karşılaştırıldığında, en istekli katılımcıların bile herhangi bir ticari faaliyeti başlatmak konusunda isteksiz hale geldiği bir negatif geri besleme döngüsü yaratmaktadır.

Bu çalışmanın yerel düzeyde temel bulgusu, konumlarına bakılmaksızın, kamu ve özel aktörlerin hepsinin sahaya kamu müdahalesi talep etmeleridir. Temel olarak, hiç kimse Türkiye'de yakın gelecekte kuantum teknolojileri konusunda doğal bir piyasa oluşumu beklememektedir. Elbette talep edilen müdahalenin kapsamı kişiden kişiye değişmektedir. Ancak, bu teknolojinin ulusal bağlamda güçlü bir şekilde geliştirilmesi veya kullanılacak olması için herkesin müdahale beklentisi bu tez kapsamında tüm katılımcılarda gözlemlenmiştir.

Sonuç olarak, bu tez tanımlayıcı nitelikte olmasına rağmen, bilim ve teknoloji politikası çalışmaları yoluyla kuantum teknolojileri alanında keşifsel bir çalışma olarak da kabul edilebilir. Türkiye'de kuantum teknolojilerinin daha da geliştirilmesine yönelik politikalar için sonuçlar kullanılabilir veya burada verilen ampirik arka plan akademik veya ticari çalışmalarda kullanılabilir. Bu alanda küresel olarak neler olup bittiğine dair anlayışımızı zenginleştirmek için aynı verileri analiz ederken buradakinden farklı teorik çerçeveler kullanılabilir. Son olarak, bu çalışma, farkındalığın arttırılması ve kuantum teknolojilerine aşina olmayan politika yapıcıların bu alana tanıtılması için bir giriş aracı olarak düşünülebilir.

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