Technology Assessment for Quantum Computing in the Energy Sector

TOM ESSERS, University of Twente, The Netherlands

Consultancy companies forecast that, in the energy sector, quantum computing will see commercial applications by 2030, allowing businesses to solve business problems that are computationally unsolvable for classical computers. These forecasts suggest that the energy sector will be one of the most impacted sectors seeing high increases in operational income. This paper aims to, by performing a technology assessment, validate the accuracy of the forecasts of these consultancy companies. We start by classifying the business problems that quantum computers can potentially solve into four different categories. Then we will present multiple scenarios that depict the possible evolution of quantum computing. For each scenario, we determine whether quantum computers will be able to solve these problems, determine their benefits and costs, and present the impacts they will have on businesses. We show that while the forecasts of the consultancy companies are indeed a scenario that could unfold, it is not a guaranteed outcome, as we are still unsure of the level of technology maturity and level of adoption that quantum computing will have.

Additional Key Words and Phrases: Quantum Computing, Technology Assessment, Energy

1 INTRODUCTION

Quantum computing uses quantum mechanics, allowing it to solve mathematical problems faster than any classical computer can [1–4]. This is because the core of the classical computer, the bit, is replaced by a quantum bit, referred to as a qubit. Quantum computers with only several hundred of these qubits are estimated to have more computational power than a classical computer with as many bits as atoms in the universe [1].

Quantum computers have such a high computational power that they could allow businesses to solve business problems that would have previously not been possible to solve. The energy sector, which is the main focus of this paper, could use quantum computing to, for example, increase the efficiency of energy resources [5, 6]. Other sectors, such as the financial sector, could use quantum computing for improving market simulations [7]. Big corporations such as IBM, Google, and Microsoft, which are currently investing billions into quantum computing, justify their R&D investments by claiming that it could solve such business problems [8]. Additionally, the amount of startups has seen a massive increase in the last couple of years, indicating that many other parties also see big potential in quantum computing [9].

Consultancy companies estimate that by 2030 a few thousand quantum computers will be operational, while quantum systems that can tackle the most complex problems might start rolling out in 2035 and later [10]. They estimate that the energy sector will be one of the most affected sectors, and will see big increases in operating incomes [10–12]. To validate whether these estimations are accurate, a technology assessment (TA) needs to be conducted. TA is a way to, in an early stage, identify and assess the eventual impacts of a technology performed to enhance decision-making [13]. It can assist in, among other methods and tools, identifying potential applications, determining possible future scenarios, and comparing the benefits to the costs quantum computing will bring.

In this research, a technical assessment of quantum computing will be performed and it will be evaluated how accurately quantum computing will be able to solve the business problems it suggests. It will identify business problems that can currently not be solved by classical computers in the energy sector, conduct a technical assessment of quantum computing in this sector, and present how accurate predictions of quantum computing are compared to the outcome of the technical assessment.

The remainder of this paper is structured as follows: In Section 2 we provide the problem statement, in Section 3 we discuss related works, in Section 4 we discuss the methodologies used for the research, in Section 5 we present the findings of the research, in Section 6 we conclude the results, and in Section 7 we discuss the results and provide directions for future research.

2 PROBLEM STATEMENT

There is an abundance of research in the field of quantum computing explaining how it works, the kind of algorithmic problems it could solve, and what sectors it could impact. However, a critical validation of whether the technology actually has the potential to solve business problems is still lacking at this moment. This paper will attempt a technology assessment by critically reviewing existing literature to assess whether quantum computing has the potential to solve business problems in the energy sector.

2.1 Research Question

The problem statement has led to the following research questions. Main research question: *How accurate are current quantum computing forecasts, and can they address business problems in the energy sector?*

This research question will be answered using the following set of sub-questions:

(1) *How can we classify computationally unsolvable business problems in the energy sector that are difficult to be solved using classical computers?*
(2) *What technology assessment methods can be used to evaluate the potential of solving business problems with quantum computing in the energy sector?*
(3) *How accurate are the technology forecasts of how quantum computers can solve these business problems in the energy sector?*

3 RELATED WORK

To find existing literature in the relevant field for this research, Semanticscholar, Google Scholar, Scopus, and IEEE were used.

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Quantum computers can potentially solve complex computationally hard problems [1–4, 14]. This allows them to assist in solving business problems across multiple sectors [5, 7, 10, 15, 16]. One of these sectors is the energy sector [5, 6, 17, 18]. Especially [1] properly defines the stage of quantum computing we are in right now, and possible future directions are presented by [19].

Research is primarily focused on finding new applications for quantum computers. However, there is a gap in research that focuses on critically validating whether quantum computers will actually be useful for businesses. Therefore the goal of this research will be to find whether it will be useful, and what problems it will be able to solve in the energy sector.

4 METHODOLOGY

4.1 Sub-research question 1

The first research question will be answered using a literature study. Different existing papers will be analyzed to find out what types of problems exist in the energy sector that can currently not be solved using classical computers and require the assistance of more powerful devices.

4.2 Sub-research question 2

This paper uses [20] as its headline for performing the technology assessment. Together with other literature about technology assessments, these will form the basis of the technology assessment and determine what methods will be used to answer the main research question.

4.3 Sub-research question 3

To answer this sub-research question the methods that have been determined in sub-research question 2 will each be fully worked out. Using the results of these methods, it will be determined how accurate predictions of quantum computing are.

5 FINDINGS

Each of the sub-research questions will be answered separately and will be combined to answer the main research question. In Section 5.1 we discuss what quantum computing is, in Section 5.2 we discuss problems that quantum computers can solve, that are unsolvable on classical computers, in Section 5.3 we present these problems applied to the energy sector, in Section 5.4 we will explain what a technology assessment is and what methods will be discussed in this research, and finally in Sector 5.5 the technology assessment will be performed.

5.1 What is quantum computing?

Classical computers operate using bits, which are transistors that are either on ('1') or off ('0'). Quantum computers operate using qubits, which can be represented as an electron, photon, or a different physical system. Qubits can take a value of '0', '1', or anything in between. When the latter occurs, a qubit is said to be in superposition, a fundamental property of quantum computing. Unlike bits, qubits, therefore, have a probability of becoming '0' or '1'. Another fundamental property of quantum computing is entanglement, which occurs when two qubits act as if they are connected, despite them being physically distant from one another [2, 19]. This means that we can predict the value of one qubit, using the other qubits which are entangled to it. These, among other, properties allow quantum computers to behave differently from classical computers.

There are different types of quantum computers that work differently. One way such a computation could work is, for example, by starting with assigning the same probability to all possible outcomes of the computation. Once the computation begins, the computer follows a set of calculations that have been created by the developer of the program. The machine will then utilize the superposition and entanglement, by giving higher probability to desired outcomes, and a lower probability to other outcomes. A quantum computer will always return this outcome as '0's and '1's [19]. This way we can read the output with a classical computer and interpret the result.

5.2 What problems can we solve on a quantum computer which are unsolvable on a classical computer

Classical computers are slow in solving complex mathematical problems. This is especially the case for problems that are classified as being NP-hard (nondeterministic polynomial time). NP-hard problems are decision problems that are computationally challenging to solve, and the solution time often grows exponentially as the input size grows. Efficient algorithms to solve NP-hard problems do not currently exist, meaning that getting a solution to such a problem on a classical computer could take a long time. Building bigger and faster classical computers or supercomputers to solve these NP-hard problems is no longer an option, as computer parts are approaching the size of atoms, and classical computers would require too many bits to solve such problems [1]. Quantum computers have more computational power than classical computers, as for quantum computers, unlike classical computers, the computational space grows exponentially as the number of qubits inside the computer grows [10]. This increase in computational power means that quantum computers will be able to solve some NP-hard problems, that classical computers cannot [18].

Combinatorial optimization problems are problems that attempt to find the optimal solution from a set of all possible solutions. These are often NP-hard [21]. There are many practical examples of these NP-hard combinatorial optimization problems for businesses that can potentially be solved by quantum computers, such as vehicle routing [22], electric vehicle charging schedules [23], and quadratic assignment [18]. The latter can be applied to the energy sector and further explained in Section 5.3.

Quantum computers can also assist in solving problems that require data processing. These problems are not necessarily NP-hard problems, as the solution time does not grow exponentially, but are rather time-consuming for classical computers. Especially fields such as artificial intelligence and machine learning could benefit from this, as the data sets to power these technologies can be huge [7, 10, 15].

Finally, quantum computers can improve simulations that run the behavior of quantum systems. These simulations are used for finding new materials, drug development, and in chemistry. For classical computers running these simulations is difficult and is currently mostly based on estimations and approximations of real interactions

[6]. To describe a quantum system, we use the Schrödinger equation, a function that describes how the wave function of a system evolves over time. As the amount of particles in the quantum system increases, the size of this wave function grows exponentially [24, 25] making it intractable for classical computers to solve the equation for large systems [26]. To mitigate this problem, approximation functions such as the Hatree-Fork methods are used, although these lower the accuracy and reliability [17]. Quantum computers show potential in being able to calculate and store those wave functions allowing for accurate calculations of the Schrödinger equation [17].

5.3 What problems occur in the energy sector?

In the energy sector, business problems that are hard for classical computers to solve can also occur. We classify these business problems into four categories: optimization, data processing, simulations, and cybersecurity [5, 6, 17, 18, 23, 25]. These will now be discussed individually and an example of each will be given.

5.3.1 Optimization. Examples of optimization problems in the energy sector are the planning of generating energy, transportation, resource allocation, engineering design, and the power grid [18]. Many of these problems are NP-hard combinatorial optimization problems. An example given in section 5.2 was the quadratic assignment problem, which can in the energy sector directly be mapped to a facility location-allocation problem [18]. This problem attempts to calculate optimal locations for energy facilities such as wind farms, to maximize the inputted energy to these sources. This is an NP-hard problem, as the time it takes to calculate the optimal solution exponentially increases as the number of facilities increases.

A power grid is responsible for distributing energy from the producers to its customers, balancing the demand and supply. It has to deal with many different optimization problems such as optimizing power flow [6, 23], optimizing unit commitment [18], and long-term resource planning. Many of these problems are also NP-hard [27].

5.3.2 Simulations. Simulating the behavior of quantum systems is used in the energy sector for finding new or improving existing sustainable energy sources [17], in chemistry to improve existing energy-storing solutions such as batteries [6], and more. Improving the efficiency of the way we generate and store energy is important as it can assist in lowering carbon dioxide emissions [28].

5.3.3 Data-processing. The energy sector applies machine learning in designing materials [17], for designing, modeling, and operating smart energy systems [23], and forecasting in the power grid [29]. These machine learning and artificial intelligence algorithms are trained by large data sets that can be computationally complex, and as these sets are getting larger we are approaching the limit of how much data classical computers can process [30]. For making forecasts in the power grid alone, weather forecasts need to be made to calculate the amount of energy generated by energy sources such as solar panels and windmills, and predictions to calculate the demand for energy for the upcoming period [29].

5.3.4 Cybersecurity. Some functions of cryptography, a fundamental pillar in cybersecurity, exploit that classical computers are slow at certain computations. One well-known example of such a problem is the factorization of two prime numbers of a very large composite integer, an algorithm used in cryptography to, for example, encrypt messages and other data [14]. Faster computers will be a threat to cybersecurity, as they have enough computational power to break certain encryption algorithms [16]. Such algorithms are also used for communication within the power grid, and will therefore impact the energy sector [31].

5.4 What is a technology assessment?

A technology assessment is used to help identify existing and possible impacts of technologies. In the 1980s, technology assessment was recognized as a professional activity and discussions regarding the environmental effects of technologies contributed to this [13]. It is now widely used in different contexts, such as on a project level, business level, and for political decision-making. For this research, a technology assessment will be conducted on a sector-specific level, meaning that the acceptability, and impact of quantum computing will be determined for the energy sector [13].

5.4.1 Technology assessment methods. Methods lay the foundation of a technology assessment. They can be used for a variety of reasons and should be selected individually for the problem at hand. There is a big diversity in these different methods, and depending on the technology assessment, already existing methods can be chosen. Methods can also be tailored by combining multiple methods, or by creating new ones [32, 33].

For this technology assessment, the following methods have been selected:

(1) *Scenario modeling/monitoring*
(2) *Cost-benefit analysis*
(3) *Cross-impact matrix analysis*

5.5 Scenario modeling

[20] expresses that a projection of feasible future paths is important to make predictions of the impact technology might have. This is referred to as technology forecasting, which is one of the first steps of a technology assessment. It starts by presenting a comprehensive description of the state-of-the-art of the technology, followed by a scenario modeling, a method used to forecast different future scenarios [33, 34].

In our scenario modeling, we will present scenarios based on the level of adoption, and the level of technology maturity of quantum computing. For both of these variables, we present four milestones, labeled 1, 2, 3, and 4. These milestones will be explained in 5.5. We will elaborate on four different scenarios, where the level of adoption and level of technology maturity are at their lowest (1) and highest (4).

5.5.1 Cost-benefit analysis. The cost-benefit analysis is an economic analysis that compares the benefits gained from a new piece of technology against the costs it brings. It is important, as a piece of technology that is not economically profitable rarely receives further consideration [20]. Costs and benefits are often expressed as monetary values and result in profit or loss, however, in the scope of technology assessment for a sector, can also be expressed qualitatively [20]. For this research, therefore, the costs and benefits will be expressed qualitatively.

The cost-benefit analysis will be integrated into the four scenarios created in the scenario modeling. This way for each of the scenarios it will be possible to determine whether quantum computing is economically valuable.

5.5.2 Cross-impact matrix analysis. The cross-impact analysis is performed to discover the factors that have an impact on the new technology, as well as what impact the new technology has on the factors. A cross-impact matrix has *n* factors. With these factors, it is possible to create an $n*n$ matrix that assigns a probability to the impact that one factor will have on another factor.

The cross-impact matrix analysis will also be integrated into the scenarios created by the scenario modeling. This way it is possible to determine the probability of the impacts of quantum computing for each scenario. The factors that we use are 'Quantum Computing', 'Energy Businesses', and 'Energy Computational Problems'. The impact that these factors have on one another, will be expressed as a statement. These statements will be given a probability of likelihood of occurring. The scale used for this is 1 (very low) to 5 (very high).

5.6 Technology assessment

In this Section, we perform the technology assessment using the methods mentioned in the Subsection above.

The first concepts of quantum computing were presented in the early 1980s and since then businesses and researchers have been busy improving the hard- and software. Research about how these systems should theoretically work rolled out in the next 15 years, and the first quantum computers with just a few qubits were operating in the late 1990s and early 2000s. An overview of all achievements that quantum computing has had over the years are presented in *Table 1.* The goal of these businesses and researchers was to attempt to achieve Quantum Supremacy, which occurs when quantum computers perform computational tasks that no classical computer can or will (in the foreseeable future) be able to solve [1]. The first instance of such quantum supremacy was shown in 2019 by [35] on Google's sycamore quantum computer, which had 54 qubits.

The period that we are currently situated in can be described as the NISQ-era which stands for Noisy Intermediate-Scale Quantum era. This indicates that we are in an intermediate-scaled stage where we have access to some quantum computers which could outperform classical computers in very specific problems, as shown by [35]. However, we will still have imperfect control over qubits, making them unusable for now to solve business problems, hence the "noisy" part [1].

To present the possible scenarios of quantum computing, we created a model based on the level of adoption, and the level of technological maturity.

The level of adoption for quantum computing explains the level of investments done into the technology, how much potential is seen, and how heavily it is used. A high adoption indicates that businesses are actively investing in quantum computing, see high potential in the technology, and that the technology is used, where possible,

Year	Achievements
1976	Roman Stanislaw Ingarden publishes - "Quantum Information Theory"
1981	Richard Feynman put forth the concept of quantum computation
1988	Yoshihisa Yamamoto and Kazuhiro Igeta proposes the first physical quantum computer by using photons and atoms
1992	"Deutsch's problem"(the very first calculation that a quantum computer would be able to solve more efficiently than a classical machine) was outlined by David Deutsch and Richard Jozsa
1994	Shor's algorithm was introduced, suggesting that quantum computing may break much of modern cryptography. A quantum logic gate using cold trapped ions was proposed by Peter Zoller and Ignacio Cirac
1995	Christoper Monroe and David Wineland created the first quantum logic gate at NIST
1997	IBM develops the first working 3-qubit NMR computer
1998	Experimentalists at UC Berkeley demonstrated the first working 2-qubit nuclear magnetic resonance computer.
1999	A superconducting circuit is harnessed as a qubit.
2000	IBM implements part of Shor's algorithm from 5-qubit and 7-qubit NMR computer
2006	12-qubit quantum computer developed.
2011	The first commercially available quantum computer which costs $10m released by D-Wave.
2016	A hydrogen molecule simulated by Google using an array of superconducting qubits. IBM Q Experience which is an online public interface to its quantum processors was released by IBM
2017	A 17-qubit computer and 50-qubit computer gets built by IBM.
2018	"Tangle Lake," a 49-qubit superconducting chip released by Intel. "Bristlecone," a 72-qubit quantum chip released by Google.
2019	Google claims to have achieved quantum supremacy with sycamore which has 54 qubits.
2020	Increase in quantum volume and major quantum algorithm breakthrough.

Table 1. Achievements in quantum computing over the years from [36]

throughout the sector to perform various tasks. Low adoption indicates that the investments in the technology are low, businesses lack to see the potential for the technology, and it is barely used to perform any tasks.

The level of technological maturity explains the potential speedup of the quantum computer, compared to the classical computer, to what extent it can solve business problems that were not possible to be solved by classical computers, and the level of error rates. A high technological maturity indicates that quantum computers will be able to computationally outperform classical computers, allowing them to perform calculations impossible for classical computers, with low error rates. A low technological maturity indicates that quantum computers might be able to slightly outperform classical computers, allowing them to solve some algorithms quicker, but barely solve any problems that were impossible to solve for classical computers, also due to high error rates.

The results are presented in a model in *Figure 1.*

Milestones 1 to 4 are found on both axes of the model. For the level of adoption, these milestones are defined as follows:

1 - The technology is barely used by any businesses and investments are low

2 - The technology is used by the biggest multinational corporations such as Google, IBM, and Microsoft and they are actively investing in it

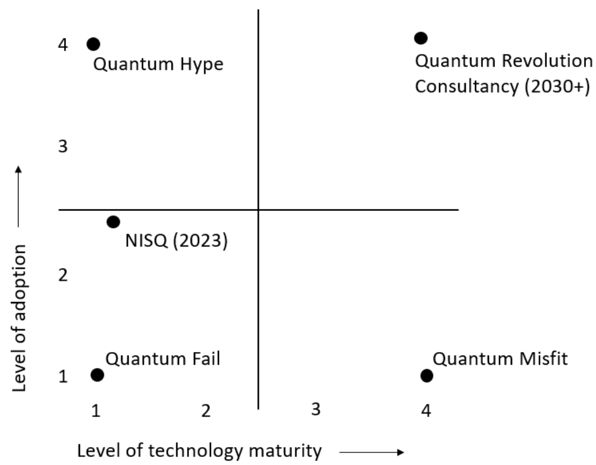

Fig. 1. Quantum computing scenarios

3 - The technology is used by large businesses in the sector that can utilize it, and investments are significant
4 - The technology is used by almost all businesses in the sector that can utilize it, with high investments

The milestones for the level of technology maturity are defined as follows:
1 - The technology can barely solve any problems that cannot be solved by classical computers
2 - The technology can solve a few problems that cannot be solved by classical computers
3 - The technology can be used to solve some problems that cannot be solved by classical computers, and showing some speedups
4 - The technology can be used to solve many problems that cannot be solved by classical computers, and showing big speedups

We will now elaborate on the scenarios where the level of adoption and level of technology maturity are at their lowest and highest. We call these scenarios 'Quantum Fail' (1,1), 'Quantum Misfit' (4,1), 'Quantum Hype' (1,4), and 'Quantum Revolution (4,4). We will explore these scenarios in the energy sector and see how quantum computing fits into each one. Each of the scenarios will be accompanied by a cost-benefit analysis and a cross-impact matrix analysis. We present the cross-impact matrix with all statements in Table 2. Each statement is represented by a letter. In the text, we will use these letters to refer to the statement.

5.6.1 Quantum fail. In this scenario quantum computing has a low technology maturity, meaning that it can barely solve any problems that cannot be solved by classical computers. Businesses no longer see a reason to invest in the technology as they do not see any potential for the technology. This scenario could occur, if researchers do not manage to get control over the qubits of the quantum computer, and lower the level of error rates [36].

5.6.2 Quantum fail - Cost-benefit analysis.

Benefits:
- Although this scenario has a low technology maturity, quantum computing simulations will still probably be one practical use of quantum computers [19]. Quantum computers might assist classical computers for specific simulations in an algorithmic hybrid approach using Variational Quantum Eigensolvers (VQE). These algorithms require quantum computers with 100 to 1000 qubits, which is likely to be possible within the next 5 years [6]. These simulations can assist in improving energy efficiency, and maybe even finding new more efficient energy sources. The improvement in energy efficiency results in more energy being generated, resulting in higher operating incomes for businesses.

Costs:
- Billions have been invested in research and development of quantum computers by big corporations.
- As quantum computers are expensive to build, they will likely be available through the cloud provided by big corporations. Energy companies using hybrid simulations will have to pay to make use of these systems.

In this scenario, it is likely that the billions invested in developing quantum computing will not be earned back by the few specific applications in the energy sector. Although specific hybrid simulations would allow for new insights into the material design, which can help improve energy efficiency.

5.6.3 Quantum fail - Cross-impact matrix analysis.
A - 1 (very low). As the level of adoption is low in this scenario, it is highly unlikely that businesses in the energy sector will be using quantum computers.
B - 2 (low). As the level of technology maturity is low, quantum computers are unlikely to solve many problems that are unsolvable by classical computers in the energy sector. Quantum computers are unlikely to assist in optimization problems [1]. Quantum computers might be able to, with a hybrid approach, help in data processing [19]. Quantum computers are likely to assist in running hybrid simulations [6, 19]. Using quantum computing for quantum encryption is at an early stage [19].
C - 1 (very low). As the level of adoption is low, researchers and businesses have stopped investing in the research and development of quantum computing. It is likely that the error rates are too high, and a way to control the qubits has not been found [36].
D - 4 (high). Researchers and businesses are already looking for different methods of improving energy efficiency. IoT, AI, and blockchain are technologies that can be used to create smart energy systems, which can generate more revenue, and improve energy efficiency [23, 37].
E - 1 (very low). Other technologies can be used to improve energy efficiency, and quantum computing is unlikely to assist in problems that are computationally unsolvable for classical computers.
F - 3 (moderate). As running simulations to simulate the behavior of quantum systems is crucial for material design, and quantum computing will only provide hybrid systems in this scenario [6], businesses in the energy sector could be looking for different alternatives.

	Quantum Computing	Energy businesses	Energy computational problems
Quantum computing	X	A: Quantum computing will be used by businesses in the energy sector	B: Quantum computing will be able to solve computational unsolvable problems in the energy sector
Energy businesses	C: Businesses will invest in research and development of quantum computing to attempt to improve its usability	X	D: Businesses in the energy sector are looking for ways to solve problems that are computationally unsolvable
Energy computational problems	E: Computationally unsolvable problems in the energy sector thrive the need to create quantum computers	F: Computationally unsolvable problems will be a problem for businesses in the energy sector	X

Table 2. Cross-impact matrix

5.6.4 Quantum Misfit. In this scenario quantum computing has achieved a high technology maturity, meaning that it is possible to accomplish computational tasks a classical computer would not. Businesses in the energy sector, however, do not see potential in quantum computing, as its applications might not be relevant enough. Because of this, there will barely be any practical uses, while quantum computers theoretically could outperform classical computers.

5.6.5 Quantum Misfit - Cost-benefit analysis.
Benefits:
- Quantum computing simulations will probably already, as explained, be used within 5 years [6]. As quantum computers improve, more complex simulations can be run to ensure even more energy efficiency. These simulations will give new bigger insights into material design, thus resulting in higher operating incomes for businesses.
- Quantum computers have enough computational power to decrease time to solve optimization problems and find better solutions. It is possible, however, that, especially for NP-hard problems, these turn out to not be much more accurate than the approximations that are currently used [1]. Quantum computers might therefore result in slightly improving energy efficiency.

Costs:
- Billions have been invested in research and development of quantum computers by big corporations.
- Energy companies using quantum for simulations, or specific optimization problems will have to pay for using the quantum systems.

Some businesses in the energy sector might utilize quantum computers to run simulations or solve specific optimization problems. These few businesses will see benefits in simulations and some specific optimization problems. Quantum computers, however, might be expensive to use. The billions that have been invested will probably not be earned back.

5.6.6 Quantum Misfit - Cross-impact matrix analysis.
A - 2 (low) As the level of adoption is low in this scenario, it is unlikely that businesses in the energy sector will be using quantum computers. There will be some instances where quantum computing will be used to solve specific problems.
B - 4 (high) As the level of technology maturity is high, quantum computers are likely to be able to solve problems that are unsolvable by classical computers in the energy sector. Optimization problem calculation times can be decreased and solutions are more accurate [18]. More complex simulations can be run [19]. Quantum computers have the potential to assist in machine learning [30], though it might need more research. New quantum encryption methods such as QKD might be possible [19].
C - 2 (low) As the level of adoption is low, researchers and businesses are no longer actively investing in the research and development of quantum computing. However, as the technology maturity is high, it is possible that the need for quantum computers could change in the future.
D - 2 (low) Approximation algorithms that are currently in use and can run on classical computers seem to be accurate enough, businesses, therefore, are not actively looking for ways to solve computationally unsolvable business problems.
E - 2 (low) The need for quantum computing to solve problems that are computationally unsolvable for classical computers seems low.
F - 2 (low) Businesses in the energy sector already have good enough approximations and can rely on other technologies such as IoT, AI, and blockchain, as explained before, to improve energy efficiency.

5.6.7 Quantum Hype. In this scenario quantum computing has a low technology maturity, meaning they are not yet useful to solve business problems and are still error-prone. Businesses and researchers still, however, see potential in the technology, meaning investments are still high and hard- and software is being improved. This scenario is what most closely resembles the NISQ-era that we currently find ourselves in [1].

5.6.8 Quantum Hype - Cost-benefit analysis.
Benefits:
- Quantum computers with 100-1000 qubits could be used to run simulation algorithms as a hybrid approach. These could lead to some new insights into material design [6].

Costs:
- Billions have been invested in research and development of quantum computers by big corporations.
- As businesses and researchers see big potential in quantum, more time and money will be invested into researching and developing better quantum computers.
- Businesses using hybrid quantum computers to run simulations will have to pay for using them.

Researchers and businesses in the energy sector are actively looking for applications of quantum computers. The costs of research and development, and paying for the use of quantum computers still strongly outweigh the benefits, as quantum computers cannot yet help in increasing operating incomes.

5.6.9 Quantum Hype - Cross-impact matrix analysis.
A - 2 (low). As quantum computing is still being researched and developed its usage will still be low. It is likely that once developed, hybrid simulations will already be run [6]
B - 2 (low) As it is yet to determine whether we will get full control over the qubits [36], it is not possible to determine whether quantum computing will solve these problems in the future. In this scenario, however, quantum computers do not yet assist in optimization problems [1]. Quantum computers are likely to assist in running hybrid simulations [6, 19]. Quantum computers might be able to, with a hybrid approach, help in data processing [19]. Researchers might be busy with breaking existing encryption, but using quantum computing to improve encryption is at an early stage [19].
C - 4 (high) In this scenario researchers and businesses in the energy sector see big potential in quantum computing. Therefore investments are made to improve the technology maturity.
D - 4 (high) Businesses in the energy sector are looking for ways to solve optimization problems that can assist in improving energy efficiency [17]. As the level of adoption is high, researchers and businesses are actively looking for ways to solve these problems.
E - (unknown) As it is yet unclear whether the business problems that are unsolvable for classical computers can be solved by quantum computers, it is not possible to assign a probability to this impact.
F - 3 (moderate) There exist optimization and simulation problems which are still unsolved by businesses that could potentially improve their energy efficiency.

5.6.10 Quantum Revolution. In this scenario quantum computing has achieved high technology maturity, meaning that it is possible to accomplish computational tasks a classical computer can not. Businesses see the potential that it can help them solve problems, which is why they are using it where possible and are investing in finding new algorithms that can help them even more. This scenario is being adopted by consultancy companies as a highly possible future for quantum computing, while the duration to get to this scenario varies between them [12, 38].

5.6.11 Quantum Revolution - Cost-benefit analysis.
In this scenario, we find the most benefits of quantum computing, as the technological maturity and adoption of businesses are at their highest.

Benefits:
- Quantum computers will have access to way more than 1000 qubits, and as a result, bigger and more complex simulations can be run. These new insights may contribute to creating new combinations of materials, which can improve energy efficiency, and lower carbon dioxide emissions [17, 28]. The improvement in energy efficiency results in more energy being generated, resulting in higher operating incomes for businesses.
- Quantum computing can decrease, or in some cases even fully remove the gap between estimations and the optimal solutions in optimization issues. Because of this, optimization problems will get better solutions. In the energy sector, this can among others lead to improvement of the power grid [18], and improving facility allocation, which can both lead to higher energy efficiency, and thus higher operating incomes.
- Quantum computing can assist in processing data for machine learning. For large data sets to be processed by quantum computers we would need millions of qubits [3]. When this is realized, it is possible to more accurately predict weather conditions, to which we can adjust our energy sources, such as wind turbines [6].
- In Section 5.3.4 we discussed how faster computers could act as a threat to cryptography. However, quantum computing's potential impact on cryptography can besides being a challenge also severely improve our security. Protocols such as quantum key distribution (QKD) have the power to generate theoretical unbreakable end-to-end security. These algorithms would no longer work by the computational complexity of the algorithms, but rather the presence of a physical property to be decrypted [3]. It will take some time before post-quantum cryptography will become a reality though, as these systems still have serious impediments, as well as the big need for testing before these systems are deployed [3, 19]. Still, businesses in the energy sector using quantum cybersecurity therefore can potentially create a level of security that would outperform current security measures. This could benefit the energy sector, as it is one of the most targeted sectors for cybercrime, costing businesses millions [39].

Costs:
- Billions have been invested in research and development of quantum computers by big corporations.
- As businesses and researchers see big potential in quantum, more time and money will be invested into researching and developing better quantum computers.
- Businesses using quantum computers will have to pay for using

them.

Businesses are actively using quantum computers to solve business problems, resulting in an increase in operating income. This increase will over time probably outweigh the costs of research and development.

5.6.12 Quantum Revolution - Cross-impact matrix analysis.

A - 5 (very high) Level of adoption and level of technology maturity are at their highest. This means that quantum computing will be used across the energy sector wherever the technology gives an advantage.

B - 5 (very high) If quantum computing reaches high technology maturity, it will be able to solve business problems. Therefore, quantum will be able to fully solve optimization problems quicker than any classical computer, or make quicker approximations [18]. Complex simulations can be run [17, 28]. Quantum computers will assist in data processing [30]. New more secure quantum encryption methods will be created [3, 19].

C - 4 (high) Businesses are likely to keep investing in quantum computing to improve the existing systems. Researchers could keep looking for ways to make algorithms faster and improve quantum computers.

D - 3 (moderate) Quantum computers already are able to solve many of the problems that were previously unsolvable. However, the most difficult NP-hard problems will still probably remain a challenge [1] and might keep businesses busy to solve these problems.

E - 2 (low) In this scenario, quantum computers are already used to solve these problems.

F - 2 (low) Some NP-hard problems will remain a challenge, and might not be solved by quantum computers [1].

6 CONCLUSION

In this paper, we performed a technology assessment to determine the impact that quantum computers will have, and the benefits that they could bring.

We used scenario modeling, a technology assessment method, to show that various scenarios on quantum computing in the energy sector can unfold, depending on the level of adoption, and the level of technology maturity that quantum computing achieves. Using these two variables, we created a model that allows us to track the scenario that we are currently situated in. We explained that throughout the development of quantum computing, these scenarios will change, and proposed 4 different milestones for each variable to make it easier to track in which scenario we are. We elaborated on the four distinct scenarios, with the lowest and highest level of adoption and level of technology maturity, 'Quantum Fail', 'Quantum Misfit', 'Quantum Hype', and 'Quantum Revolution'. Inside each of these scenarios, we performed a cost-benefit analysis to determine the economic impact of quantum computing on business. Additionally, for each scenario, we also performed an impact analysis to determine the impact of quantum computers on business problems and businesses.

We applied this model to the energy sector, a sector that can potentially benefit from quantum computing. We classified computationally complex business problems that quantum computing can solve into four different categories, namely optimization problems, simulations, data processing, and cybersecurity. The Quantum Fail scenario will bring minimal benefits, have a limited impact on businesses in the energy sector, and will solve the least of these computationally complex business problems. The Quantum Revolution scenario will bring the most benefits, showing a significant impact on energy businesses, and has the potential to solve a wide range of the problems mentioned above.

7 DISCUSSION

Consultancy companies forecast that quantum computing will substantially impact the energy sector, resulting in significant increases in operational incomes. They estimate that by 2030 a few thousand quantum computers will be operational, and from 2035 and later, they will be able to tackle the most complex computational problems.

In this study, we showed that this is indeed a scenario that can unfold. We showed that this scenario would be most beneficial for businesses in the energy sector as it would allow quantum computers to solve many business problems. However, the model that we proposed also showed that while the forecast of the consultancy companies is indeed a possibility, this outcome is not guaranteed, as we cannot yet forecast the level of adoption and level of technology maturity quantum computing will have. It is too early to determine whether we will ever get full control over qubits, and lower error rates enough to make quantum computers useful.

To track the development of quantum computers, we proposed a model with clear milestones, making it possible for researchers and business managers to follow the scenarios in which quantum computers can evolve. It can help managers determine how far along the development of quantum computing we are, and get insight into if the scenario that is forecasted by consultancy companies is indeed unfolding.

We applied the model we created to the energy sector. Researchers can utilize our model in future research to determine how other sectors will be impacted and can benefit from quantum computing.

Furthermore, future studies can increase the reliability of the cross-impact matrix analysis by performing expert interviews. These can help in assigning more accurate probabilities to the impacts of the factors on one another. Additionally, future studies could express both costs and benefits in the cost-benefit analysis as monetary values. This can help in determining the profitability of quantum computers on a business level. To accomplish this, the gap between approximated solutions on classical computers should be compared to the solutions provided by the quantum computer, from which it is possible to determine the increase in operational costs. Researchers can also utilize other technology assessment methods such as risk assessment, decision analysis, and market analysis [32, 33], to further understand the impact of quantum computing. By doing this, we can get a clear overview of what impact it will have, and how we can fully utilize it.

REFERENCES

[1] John Preskill. Quantum Computing in the NISQ era and beyond. 2018. doi: 10.22331/q-2018-08-06-79.

[2] Vikas Hassija, Vinay Chamola, Vikas Saxena, Vaibhav Chanana, Prakhar Parashari, Shahid Mumtaz, and Mohsen Guizani. Present landscape of quantum computing. *IET Quantum Communication*, 1(2):42–48, 12 2020. ISSN 26328925. doi: 10.1049/IET-QTC.2020.0027.

[3] Yoshito Kanamori and Seong-Moo Yoo. Quantum Computing: Principles and Applications. *Journal of International Technology and Information Management*, 29(2):43–71, 1 2020. ISSN 1941-6679. doi: 10.58729/1941-6679.1410. URL https://scholarworks.lib.csusb.edu/jitim/vol29/iss2/3.

[4] Todd A. Brun. Quantum Computing. *Computer Science*, pages 295–347, 2011. doi: 10.1007/978-1-4614-1168-0{_}14. URL https://link.springer.com/chapter/10.1007/978-1-4614-1168-0_14.

[5] Anand Singh Rajawat, Chetan Chauhan, S B Goyal, Pawan R Bhaladhare, Dillip Rout, and Abhay R Gaidhani. Utilization Of Renewable Energy For Industrial Applications Using Quantum Computing. *SSRN Electronic Journal*, 8 2022. doi: 10.2139/SSRN.4187814. URL https://papers.ssrn.com/abstract=4187814.

[6] Annarita Giani and Zachary Eldredge. Quantum Computing Opportunities in Renewable Energy. 2:393, 2021. doi: 10.1007/s42979-021-00786-3. URL https://doi.org/10.1007/s42979-021-00786-3.

[7] Andrey Saltan and Sami Hyrynsalmi. The Business Perspective of Quantum Computing: An Overview. *CEUR Workshop Proceedings*, 3316, 2022. ISSN 16130073.

[8] IBM Quantum Computing. URL https://www.ibm.com/topics/quantum-computing.

[9] Evan R MacQuarrie, Christoph Simon, Stephanie Simmons, and Elicia Maine. The emerging commercial landscape of quantum computing. *Nature Reviews Physics*, 2022. doi: 10.1038/s42254-020-00247-5. URL https://doi.org/10.1038/s42254-020-00247-5.

[10] Alexandre Ménard, Ivan Ostojic, Mark Patel, and Daniel Volz. A game plan for quantum computing. 2020.

[11] Vidyut Navelkar, Sridhar CV, and Godfrey Mathais. Quantum Computing Applications: Evolution & Potential Impact. URL https://www.tcs.com/what-we-do/pace-innovation/white-paper/quantum-computing-technology-applications.

[12] Matt Langione, Amit Kumar, Corban Tillemann-Dick, and Vikas Taneja. Where Will Quantum Computers Create Value—and When? URL https://www.bcg.com/publications/2019/quantum-computers-create-value-when.

[13] Arie Rip. Technology Assessment. *International Encyclopedia of the Social & Behavioral Sciences: Second Edition*, pages 125–128, 3 2015. ISSN 1090-3941. doi: 10.1016/B978-0-08-097086-8.85036-9.

[14] Peter W Shor. Polynomial-Time Algorithms for Prime Factorization and Discrete Logarithms on a Quantum Computer *. *† AT&T Research*, pages 124–134, 1995.

[15] Andreas Bayerstadler, Guillaume Becquin, Julia Binder, Thierry Botter, Hans Ehm, Thomas Ehmer, Marvin Erdmann, Norbert Gaus, Philipp Harbach, Maximilian Hess, Johannes Klepsch, Martin Leib, Sebastian Luber, Andre Luckow, Maximilian Mansky, Wolfgang Mauerer, Florian Neukart, Christoph Niedermeier, Lilly Palackal, Ruben Pfeiffer, Carsten Polenz, Johanna Sepulveda, Tammo Sievers, Brian Standen, Michael Streif, Thomas Strohm, Clemens Utschig-Utschig, Daniel Volz, Horst Weiss, and Fabian Winter. Industry quantum computing applications Quantum Technology and Application Consortium-QUTAC. *EPJ Quantum Technol.*, 8:25, 2021. doi: 10.1140/epjqt/s40507-021-00114-x. URL https://doi.org/10.1140/epjqt/s40507-021-00114-x.

[16] Francesco Bova, Avi Goldfarb, and Roger G Melko. Commercial applications of quantum computing. *EPJ Quantum Technol.*, 8(2), 2021. doi: 10.1140/epjqt/s40507-021-00091-1. URL https://doi.org/10.1140/epjqt/s40507-021-00091-1.

[17] Akshay Ajagekar and Fengqi You. Quantum computing and quantum artificial intelligence for renewable and sustainable energy: A emerging prospect towards climate neutrality. *Renewable and Sustainable Energy Reviews*, 165:112493, 2022. ISSN 1364-0321. doi: https://doi.org/10.1016/j.rser.2022.112493. URL https://www.sciencedirect.com/science/article/pii/S1364032122003975.

[18] Akshay Ajagekar and Fengqi You. Quantum computing for energy systems optimization: Challenges and opportunities. 2019. doi: 10.1016/j.energy.2019.04.186. URL https://doi.org/10.1016/j.energy.2019.04.186.

[19] Sukhpal Singh Gill, Adarsh Kumar, Harvinder Singh, Manmeet Singh, Kamalpreet Kaur, Muhammad Usman, and Rajkumar Buyya. Quantum computing: A taxonomy, systematic review and future directions. 2021. doi: 10.1002/spe.3039. URL https://onlinelibrary.wiley.com/doi/10.1002/spe.3039.

[20] Alan L. Porter. A Guidebook for technology assessment and impact analysis. page 510, 1980. URL https://books.google.com/books/about/A_Guidebook_for_Technology_Assessment_an.html?id=0Z9RAAAAMAAJ.

[21] Sanjeev Arora. Approximability of NP-hard problems. *Conference Proceedings of the Annual ACM Symposium on Theory of Computing*, pages 337–348, 1998. ISSN 07349025. doi: 10.1145/276698.276784. URL https://dl.acm.org/doi/10.1145/276698.276784.

[22] Stuart Harwood, Claudio Gambella, Dimitar Trenev, Andrea Simonetto, David Bernal, and Donny Greenberg. Engineering quantum Transactions on IEEE Formulating and Solving Routing Problems on Quantum Computers. doi: 10.1109/TQE.2021.3049230.

[23] Ning Zhao, Haoran Zhang, Xiaohu Yang, Jinyue Yan, Fengqi You, and Robert Frederick. Emerging information and communication technologies for smart energy systems and renewable transition. *Advances in Applied Energy*, 9:100125, 2023. doi: 10.1016/j.adapen.2023.100125. URL https://doi.org/10.1016/j.adapen.2023.100125.

[24] Iulia Buluta and Franco Nori. Quantum Simulators. Technical report, 2009. URL https://www.science.org.

[25] Ronald De Wolf. The potential impact of quantum computers on society. *Ethics and Information Technology*, 19:271–276, 2017. doi: 10.1007/s10676-017-9439-z. URL http://homepages.cwi.nl/~rdewolf/.

[26] Yudong Cao, Jonathan Romero, Jonathan P. Olson, Matthias Degroote, Peter D. Johnson, Mária Kieferová, Ian D. Kivlichan, Tim Menke, Borja Peropadre, Nicolas P.D. Sawaya, Sukin Sim, Libor Veis, and Alán Aspuru-Guzik. Quantum Chemistry in the Age of Quantum Computing. *Chemical Reviews*, 119(19):10856–10915, 10 2019. ISSN 15206890. doi: 10.1021/ACS.CHEMREV.8B00803/ASSET/IMAGES/LARGE/CR8B00803{_}0003.JPEG. URL https://pubs.acs.org/doi/full/10.1021/acs.chemrev.8b00803.

[27] Rozhin Eskandarpour, Kumar Jang Bahadur Ghosh, Amin Khodaei, Aleksi Paaso, and Liuxi Zhang. Quantum-enhanced grid of the future: A primer. *IEEE Access*, 8:188993–189002, 2020. ISSN 21693536. doi: 10.1109/ACCESS.2020.3031595.

[28] Kelvin O Yoro, Michael O Daramola, Patrick T Sekoai, Uwemedimo N Wilson, and Orevaoghene Eterigho-Ikelegbe. Update on current approaches, challenges, and prospects of modeling and simulation in renewable and sustainable energy systems. *Renewable and Sustainable Energy Reviews*, 150:111506, 2021. ISSN 1364-0321. doi: https://doi.org/10.1016/j.rser.2021.111506. URL https://www.sciencedirect.com/science/article/pii/S1364032121007851.

[29] Andreea Claudia Serban and Miltiadis D. Lytras. Artificial intelligence for smart renewable energy sector in europe - Smart energy infrastructures for next generation smart cities. *IEEE Access*, 8:77364–77377, 2020. ISSN 21693536. doi: 10.1109/ACCESS.2020.2990123.

[30] Aishwarya Jhanwar and Manisha J. Nene. Enhanced Machine Learning using Quantum Computing. *Proceedings of the 2nd International Conference on Electronics and Sustainable Communication Systems, ICESC 2021*, pages 1407–1413, 8 2021. doi: 10.1109/ICESC51422.2021.9532638.

[31] Chih-Che Sun, Adam Hahn, and Chen-Ching Liu. Cyber security of a power grid: State-of-the-art. 2018. doi: 10.1016/j.ijepes.2017.12.020. URL https://doi.org/10.1016/j.ijepes.2017.12.020.

[32] Thien A. Tran. Review of methods and tools applied in technology assessment literature. *Portland International Conference on Management of Engineering and Technology*, pages 1651–1660, 2007. doi: 10.1109/PICMET.2007.4349490.

[33] Thien A. Tran and Tugrul Daim. A taxonomic review of methods and tools applied in technology assessment. *Technological Forecasting and Social Change*, 75(9):1396–1405, 11 2008. ISSN 0040-1625. doi: 10.1016/J.TECHFORE.2008.04.004.

[34] Armin Grunwald. Technology Assessment: Concepts and Methods. *Philosophy of Technology and Engineering Sciences*, pages 1103–1146, 1 2009. doi: 10.1016/B978-0-444-51667-1.50044-6.

[35] Frank Arute, Kunal Arya, Ryan Babbush, Dave Bacon, Joseph C. Bardin, Rami Barends, Rupak Biswas, Sergio Boixo, Fernando G.S.L. Brandao, David A. Buell, Brian Burkett, Yu Chen, Zijun Chen, Ben Chiaro, Roberto Collins, William Courtney, Andrew Dunsworth, Edward Farhi, Brooks Foxen, Austin Fowler, Craig Gidney, Marissa Giustina, Rob Graff, Keith Guerin, Steve Habegger, Matthew P. Harrigan, Michael J. Hartmann, Alan Ho, Markus Hoffmann, Trent Huang, Travis S. Humble, Sergei V. Isakov, Evan Jeffrey, Zhang Jiang, Dvir Kafri, Kostyantyn Kechedzhi, Julian Kelly, Paul V. Klimov, Sergey Knysh, Alexander Korotkov, Fedor Kostritsa, David Landhuis, Mike Lindmark, Erik Lucero, Dmitry Lyakh, Salvatore Mandrà, Jarrod R. McClean, Matthew McEwen, Anthony Megrant, Xiao Mi, Kristel Michielsen, Masoud Mohseni, Josh Mutus, Ofer Naaman, Matthew Neeley, Charles Neill, Murphy Yuezhen Niu, Eric Ostby, Andre Petukhov, John C. Platt, Chris Quintana, Eleanor G. Rieffel, Pedram Roushan, Nicholas C. Rubin, Daniel Sank, Kevin J. Satzinger, Vadim Smelyanskiy, Kevin J. Sung, Matthew D. Trevithick, Amit Vainsencher, Benjamin Villalonga, Theodore White, Z. Jamie Yao, Ping Yeh, Adam Zalcman, Hartmut Neven, and John M. Martinis. Quantum supremacy using a programmable superconducting processor. *Nature 2019 574:7779*, 574 (7779):505–510, 10 2019. ISSN 1476-4687. doi: 10.1038/s41586-019-1666-5. URL https://www.nature.com/articles/s41586-019-1666-5.

[36] Ayekpam Malemnagnbi Chanu and Vinod Kumar. Quantum Supremacy: How far along are we on the journey? *2021 Asian Conference on Innovation in Technology, ASIANCON 2021*, 8 2021. doi: 10.1109/ASIANCON51346.2021.9544619.

[37] Tanveer Ahmad and Dongdong Zhang. Sustainable Cities and Society 68 (2021) 102783 Using the internet of things in smart energy systems and networks. 2021. doi: 10.1016/j.scs.2021.102783. URL https://doi.org/10.1016/j.scs.2021.102783.

[38] Kasey Panetta. The Cios Guide To Quantum Computing. URL https://www.gartner.com/smarterwithgartner/the-cios-guide-to-quantum-computing.

[39] Sampath Kumar Venkatachary, Jagdish Prasad, and Ravi Samikannu. International Journal of Energy Economics and Policy Economic Impacts of Cyber Security in Energy Sector: A Review. *International Journal of Energy Economics and Policy |*, 7(5):250–262, 2017. ISSN 2146-4553. URL http:www.econjournals.com.