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Quantum Divide: Socio-Economic Inequalities in the Post-Quantum Era

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ABSTRACT

This study examines the quantum divide, a new form of inequality arising from disparities in access to quantum technologies, expertise, and infrastructure. Unlike the digital divide, which focuses on access to digital tools, the quantum divide risks widening socio-economic gaps by privileging those with early quantum capabilities. To address these challenges, this study employs a hybrid methodology, integrating delphi method and foresight analysis to analyze expert insights and explore future scenarios. Key areas impacted by quantum advancements include optimization, cybersecurity, and supply chain management. However, challenges such as technological monopolization, security risks, and workforce displacement require urgent attention. This study advocates for equitable access policies, quantum-resilient cryptography, workforce upskilling, and ethical governance frameworks. By combining expert consensus with strategic foresight, it provides actionable recommendations to ensure quantum technologies contribute to an inclusive, secure, and sustainable future, emphasizing global collaboration and proactive policymaking.

Keywords: Quantum Divide, Post-Digital Ecosystem, Quantum Supremacy, Foresight Analysis, Digital Inequality.

JEL Classification Codes: O33, F63, L86

Kuantum Uçurumu: Kuantum Sonrası Dönemde Sosyo-Ekonomik Eşitsizlikler

ÖZ

Bu çalışma, kuantum teknolojilerine, uzmanlığa ve altyapıya erişimdeki eşitsizliklerden kaynaklanan yeni bir adaletsizlik biçimi olan kuantum uçurumunu incelemektedir. Dijital araçlara erişime odaklanan dijital uçurumun aksine, kuantum uçurumu erken kuantum yeteneklerine sahip olanlara ayrıcalık tanıyarak sosyoekonomik uçurumları genişletme riski taşımaktadır. Bu zorlukları ele almak için bu çalışma, uzman görüşlerini analiz etmek ve gelecek senaryolarını keşfetmek için Delphi yöntemini ve öngörü analizini entegre eden hibrit bir metodoloji kullanmaktadır. Kuantum gelişmelerinden etkilenen kilit alanlar arasında optimizasyon, siber güvenlik ve tedarik zinciri yönetimi yer almaktadır. Bununla birlikte, teknolojik tekelleşme, güvenlik riskleri ve işgücünün yer değiştirmesi gibi zorluklar acil dikkat gerektirmektedir. Bu çalışma, adil erişim politikalarını, kuantuma dayanıklı kriptografiyi, işgücünün becerilerinin artırılmasını ve etik yönetişim çerçevelerini savunmaktadır. Uzman görüş birliğini stratejik öngörü ile birleştirerek, kuantum teknolojilerinin kapsayıcı, güvenli ve sürdürülebilir bir geleceğe katkıda bulunmasını sağlamak için küresel iş birliğini ve proaktif politika oluşturmayı vurgulayan uygulanabilir öneriler sunmaktadır.

Anahtar Kelimeler: Kuantum Uçurumu, Post-Dijital Ekosistem, Kuantum Üstünlüğü, Öngörü Analizi, Dijital Eşitsizlik.

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GENİŞLETİLMİŞ ÖZET

Amaç ve Kapsam:

Bu çalışma, kuantum teknolojilerine, uzmanlığına ve altyapısına erişimdeki eşitsizliklerden kaynaklanan ve giderek belirginleşen bir sosyo-ekonomik adaletsizlik biçimi olan "kuantum uçurumu" olgusunu incelemektedir. 1990'larda dijital bölünme kavramı internet ve bilgisayar gibi temel dijital araçlara erişim eşitsizliğine işaret ederken, kuantum uçurumu daha ileri düzeyde bir teknolojik eşitsizliği ifade etmektedir. Ekonomik ve teknolojik açıdan güçlü aktörlerin kuantum teknolojilerini erken benimsemesi, bu aktörlere önemli avantajlar sağlarken diğer ülkeler ve kurumlar açısından dışlayıcı ve derinleşen bir eşitsizlik tablosu ortaya çıkarma riski taşımaktadır. Çalışma, kuantum teknolojilerinin demokratikleşmeden çok merkezileşme eğiliminde olduğunu; gelişmiş ülkeler, büyük şirketler ve yüksek nitelikli iş gücü dışındaki grupların bu dönüşüm sürecinde dışlanabileceğini ileri sürmektedir.

Yöntem:

Araştırma, yapılandırılmış uzman görüşlerine dayalı bir Delphi yöntemi ile stratejik öngörü (foresight) analizini birleştiren hibrit bir metodolojik yaklaşımla yürütülmüştür. Kuantum bilişim, siber güvenlik, ekonomi ve teknoloji politikası gibi farklı alanlardan gelen ve farklı coğrafyaları temsil eden 10 uzmanla üç turdan oluşan bir Delphi süreci gerçekleştirilmiştir. Bu süreç, yüksek belirsizlik ortamında uzman görüşlerinin aşamalı olarak netleşmesini ve ortak aklın şekillenmesini sağlamıştır. Ayrıca, öngörü çalışmalarıyla desteklenen bu analiz, uzun vadeli senaryolar üretmeyi ve kuantum teknolojilerinin olası toplumsal yansımalarını değerlendirmeyi mümkün kılmıştır. Senaryo üretim süreci; eğitimde eşitlik, yatırımların dağılımı, etik düzenleme kapasitesi ve küresel iş birliği gibi etkenlerin gelecekteki etkilerini öngörmeye odaklanmıştır.

Bulgular:

Çalışmada kuantum teknolojilerinden en fazla etkilenecek beş temel alan belirlenmiştir: optimizasyon, ekonomik eşitsizlik, siber güvenlik, etik yönetişim ve iş gücü dönüşümü.

- Optimizasyon: Lojistik, enerji yönetimi ve finans gibi alanlarda kuantum bilgisayarların büyük veri kümelerini analiz ederek daha verimli çözümler sunacağı görüşü yaygındır.
- Ekonomik Eşitsizlik: Kuantum sistemlerinin geliştirme maliyetlerinin yüksek oluşu, yalnızca gelişmiş ülkeler ve çok uluslu şirketlerin bu teknolojiye erişimini kolaylaştırmakta; bu da küresel bağımlılık ilişkilerini artırmakta ve dijital sömürgecilik benzeri yeni yapılar doğurmaktadır.
- Siber Güvenlik: Kuantum bilgisayarların mevcut şifreleme sistemlerini kırma kapasitesi nedeniyle, uzmanlar kuantuma dayanıklı şifreleme standartlarının acilen geliştirilmesi ve küresel ölçekte uygulanması gerektiğini vurgulamıştır.
- Etik ve Düzenleyici Zorluklar: Kuantum ve yapay zekâ teknolojilerinin kesişiminde algoritmik önyargı, şeffaflık eksikliği ve karar alma gücünün tekelleşmesi gibi etik riskler ön plana çıkmaktadır.
- İş Gücü Dönüşümü: Kuantum devriminin otomasyona açık sektörlerde önemli ölçüde istihdam kaybına yol açabileceği öngörülmektedir. Bu nedenle kapsamlı yeniden beceri kazandırma programlarına ihtiyaç duyulmaktadır.

Sonuç ve Tartışma:

Çalışma, kuantum uçurumunun yalnızca teknik bir mesele değil; küresel adalet, ekonomik kapsayıcılık ve dijital egemenlik gibi boyutları olan kritik bir sorun olduğunu ortaya koymaktadır. Bu uçurumun derinleşmesini engellemek amacıyla beş yönlü bir strateji önerilmektedir:

- Geri kalmış ülkeler ve kırılgan toplulukların da dâhil olacağı kapsayıcı erişim politikalarının geliştirilmesi,
- Kuantum okuryazarlığının artırılması ve özellikle gelişmekte olan ülkelerde eğitim programlarının yaygınlaştırılması,
- Açık kaynaklı kuantum girişimlerinin teşvik edilerek teknolojiye bağımlılığın azaltılması,
- Esnek ve küresel etik düzenleme çerçevelerinin oluşturulması,
- Kaynak, uzmanlık ve altyapının uluslararası iş birlikleri yoluyla paylaşılması.

Uzman görüşleriyle desteklenen bu analiz, politika yapıcılara, araştırmacılara ve özel sektöre kuantum çağının kapsayıcı, etik ve sürdürülebilir biçimde inşa edilmesi için somut bir yol haritası sunmaktadır. Çalışma, kuantum teknolojilerine erişimin ticari ya da jeopolitik bir kozdan ziyade küresel bir kamu malı olarak ele alınması gerektiğini savunmakta; teknolojik adalet söylemine katkıda bulunmaktadır.

1. INTRODUCTION

The internet, as a foundational technology of the digital economy, has driven unprecedented changes in business processes, production methods, and the broader social fabric. Knowledge has become a central production factor, reshaping social structures and economic dynamics. In recent years, the concept of the post-digital ecosystem has gained attention as a framework for understanding the seamless integration of digital technologies into everyday life. The post-digital ecosystem describes a socio-technical environment in which digital technologies have become so pervasive that their presence is no longer disruptive but instead fundamental to social, economic, and institutional systems (van Deursen & van Dijk, 2014). This ecosystem underscores the shift from simply adopting digital technologies to embedding them deeply within societal infrastructures, shaping interactions, decision-making processes, and governance structures. While the post-digital ecosystem has expanded opportunities, it has also exposed and, in some cases, deepened inequalities, particularly in terms of access, skills, and usage. These disparities, widely recognized as the Digital divide, highlight gaps in the ability to utilize digital tools effectively (Gunkel, 2003). Building on this framework, the Quantum Divide emerges as a new challenge, addressing inequalities related to access to quantum computing technologies and their transformative potential.

A technological breakthrough poised to induce significant transformation is on the horizon: quantum computing. As a superior disruptive technology, quantum computing has the potential to outpace and redefine existing disruptive technologies. Consequently, the active deployment of quantum computers is anticipated to signal the advent of a new era, commonly referred to as the Post-Quantum Era. While quantum technology is already in existence, its practical applications in general-purpose computing remain limited. Current research in quantum computation is focused on both quantum hardware and quantum algorithms, with significant efforts directed at overcoming errors in Noisy Intermediate Scale Quantum (NISQ) devices through improved error correction protocols. Quantum algorithms, including variational quantum eigensolvers (VQE), are being rapidly developed and tested on these devices, particularly for applications in quantum chemistry and machine learning. Despite the challenges of sparse qubit connectivity and decoherence, quantum computing continues to evolve, with an ongoing global race to achieve "quantum advantage" —the point at which quantum systems outperform classical computers in solving real-world problems (Gill et al., 2022). Nevertheless, some scholars contend that quantum computing may never achieve widespread practical utility due to formidable technical and economic barriers (Muller, 2010). Despite these obstacles, recent advancements in the field have been promising, with tangible progress made toward practical quantum applications. In the near future, the adoption of stronger quantum-resistant cryptography is likely to become a necessity. Moreover, quantum computing is expected to enable significant advancements in networking, data privacy, and cryptography. Enhanced applications across various domains, including quantum-secured communication, are also anticipated (Grimes, 2020). Notably, the purported superiority of quantum computing in both decryption and encryption is highly regarded, with future applications potentially rendering current secure data transmission techniques obsolete (Gill, 2022). There is a direct relationship between the development of artificial intelligence technologies and the processing of big data. Big data is increasing at an uncontrolled rate and the capacity of current computer technology to process big data is limited. This is a phenomenon that will further increase the necessity of quantum computers in the future. The Quantum Divide can be defined as the socio-economic and geopolitical disparities arising from uneven access to quantum technologies, including hardware, software, and expertise. Unlike the Digital divide, which focused primarily on access to basic information and communication technologies, the Quantum Divide deals with more advanced computational resources that require substantial investment and highly specialized knowledge. It reflects inequalities not only at the individual and community levels but also across industries and nations, raising concerns about technological dominance and global competition.

This conceptualization of the quantum divide highlights an urgent and emerging research need in the academic literature. While studies on the digital divide have established the foundational framework for understanding technology-related inequalities, there remains a significant gap in examining how similar disparities might evolve in the age of quantum technologies. Thus, this research seeks to address a clear theoretical and empirical void by extending the discourse of digital inequality into the post-quantum context.

The relevance of this study lies in its attempt to conceptualize and analyze this emerging inequality through a multidisciplinary lens. Although discussions on digital inequality are well-established in information society research, the quantum dimension of this inequality has not yet been systematically examined in the literature. Hence, this study aims to fill this conceptual and empirical gap by positioning the quantum divide as a next-generation digital inequality that will influence economic competitiveness, workforce transformation, and scientific innovation capacities in the post-quantum era.

Accordingly, the main research problem guiding this study is: How will the emergence of quantum technologies reshape socio-economic inequalities, and what strategies can be developed to ensure inclusive access and equitable distribution of quantum advancements? To address this problem, the study employs the Delphi method and foresight analysis as methodological tools to evaluate expert perspectives, identify potential risk domains, and propose strategic policy responses.

The transition from the digital divide to the quantum divide marks a progression from inequalities in foundational digital infrastructure to disparities in advanced quantum technologies. This shift necessitates a proactive approach to policymaking, education, and global collaboration to prevent further widening of technological gaps and to ensure that the benefits of quantum advancements are distributed equitably.

Finally, by establishing these definitions and outlining the theoretical and methodological framework, this study aims to contribute to the ongoing discourse on technological inequality, offering insights into how emerging technologies can be managed responsibly and inclusively.

2. LITERATURE REVIEW

The "post-digital ecosystem" can be described as the environment that has emerged after digital technologies have been integrated into society. This new ecosystem illustrates a shift in focus from the revolutionary potential of digital technologies to a more mature stage. These technologies are already integrated and continue to transform our daily lives. While digital technologies enrich human experiences, this integration also blurs the boundaries between the digital and physical worlds. In this post-digital ecosystem, production processes are radically changing. More efficient and effective production methods are used by means of the automation and artificial intelligence technologies. Especially advancement in artificial intelligence technology will inevitably lead to an increase in unemployment in the upcoming period. If it is considered that employees are also customers, it will be seen that unemployment will lead to demand uncertainty. This is a vicious cycle that keeps going until the collapse of the current economic system. To sustain the current economic system, excess fiat money has been injected to the economy. Furthermore, in the post-digital ecosystem, personal debt ratio of the consumers is constantly increasing (Civelek, 2018).

The post-digital ecosystem is characterized by the widespread use of new technologies. These cutting-edge technologies include the internet of things (IoT), artificial intelligence (AI), robotic process automation (RPA), virtual and augmented reality (VR/AR), blockchain, big data, and several others. In this digital age, new technologies serve as facilitators for new forms of socialization, exchange of information, interaction, cooperation, and value creation in a variety of areas such as business, education, healthcare, and many others. Therefore, all products, processes, organizations, and paradigms are affected by this transformation. “Digital divide” can be defined as inequality in access to communication facilities provided by technology. The digital divide was a widely used concept in the 90s. Over time, with the increase in internet penetration worldwide, the concept of digital divide has been considered less. But developments in artificial intelligent exacerbate current social division.

The concept of smart networks is a key innovation within the post-digital ecosystem, combining the decentralized and secure infrastructure of blockchain with the advanced analytical capabilities of artificial intelligence (AI). These networks enable real-time, autonomous operations by facilitating seamless data exchange, improving transparency, and ensuring security across sectors such as supply chain management, finance, and healthcare. By leveraging blockchain’s ability to guarantee data integrity and AI’s capability to process and interpret vast amounts of data, smart networks significantly enhance operational efficiency while reducing reliance on intermediaries (Wang et al., 2022).

An exemplary application of smart networks is the intelligent trade matrix, which integrates blockchain, AI, and IoT technologies to streamline foreign trade processes. Traditional trade documents, such as invoices and certificates, are replaced by a single, multi-purpose digital document, simplifying workflows and enabling secure, autonomous transactions. Furthermore, the integration of autonomous logistics systems allows for seamless tracking and optimization of supply chains, where all physical items are interconnected through IoT technologies. These innovations facilitate the execution of complex processes in an optimal, human-free manner (Karame & Androulaki, 2016).

While smart networks bring transformative efficiency and traceability, they also raise challenges related to accessibility, data privacy, and potential unemployment. As these systems grow, addressing issues such as trust, accountability, and equitable access becomes critical to ensuring the benefits of smart networks are widely shared. Nonetheless, their role in reshaping production and business processes marks them as a cornerstone of the post-digital ecosystem, enabling advanced automation and innovation at an unprecedented scale (Singh et al., 2020).

Inequalities have surfaced within the emerging post-digital ecosystem and are expected to persist in various ways. While digital technologies possess the potential to enhance people's lives in numerous ways, they can also amplify existing disparities and contribute to the emergence of new ones. The observable inequalities that have emerged so far are accessibility limits, knowledge inefficacy, potential unemployment, economic disparity, lack of representation, data privacy protection, and personal security violation.

2.1. Inequalities in Post-Digital Ecosystem

Accessibility limits is mainly caused by differences in access to digital technologies, such as Internet connectivity, devices, and infrastructure. Those with limited or no access to technology may find it difficult to benefit from the opportunities offered by the post-digital ecosystem. This inequality is reflected in figures from around the world. As of April 2023, internet users accounted for 66% of the world's population (International Telecommunication Union, 2023). Social media usage encompassing approximately 60% out of this total (Petrosyan, 2023). Countries and regions can have vastly different internet access rates, with some places having better connectivity than others. Comparatively, only about 80% of people in advanced economies and about 35% of people in developing countries have access to the Internet (The World Bank, Connecting for Inclusion: Broadband Access for All, 2023).

Knowledge inefficacy is a consequence of knowledge gaps that are exacerbated by an uneven distribution of digital literacy. People who lack the necessary digital literacy may find it difficult to participate fully in the post-digital ecosystem, which would limit their ability to use digital tools and services. Following COVID-19 there has been a noticeable increase in remote working (Levanon, 2020), with more job opportunities becoming accessible in remote or hybrid work setups. The potential for remote working is considerably higher for managers and professionals, reaching up to 70%. However, employees in fields like agricultural, forestry, fishery, craft, and related trades have significantly fewer opportunities, with less than 10% able to work remotely. In sectors such as information and communication, approximately 75% of workers can work from home. Conversely, industries like construction, agriculture, accommodation, and food services activities have a lower proportion of remote workers, with less than 20% having the ability to work remotely (OECD, 2021). It’s also important to note that a result of the pandemic's impact on work dynamics, trends have shifted significantly.

Unemployment potential is increasing due to technological advances, especially artificial intelligence, and automation. Whether unemployment increases or decreases with technology has historically been a matter of debate among researchers, but it is likely that future advances in disruptive technologies will increase the potential for unemployment. In addition, “technological unemployment anxiety” among workers have started to spread in recent years. This has also been proven by academic studies (Civelek & Pehlivanoğlu, 2020). Consequently, because of the disappearance of the physical work environment remote work increased in popularity and the term "digital nomad" has turned into real (Makimoto & Manners, 1997; Hannonen, 2020). In recent years, this location-independent way of life has become increasingly popular. However, to realize this, digital skills have come to the fore.

Economical divide is prevalent for people with low incomes due to the unaffordable costs of technology and digital services. The imbalance in access to information causes unequal income distribution. In the long-run, however, solving the unequal income problem will be much more difficult than closing the information gap. Individuals who use technology effectively become economically advantageous. The division between individuals begins with a digital divide resulting from the difference in technology use among individuals, and then turns into an economic divide (Civelek M. E., 2018). The rate of unique mobile subscribers worldwide was 68% in 2022, and it is anticipated to rise to 73% by the year 2030 (GSMA, 2023). The worldwide average credit card ownership rate among individuals aged 15 and above in 2021 was recorded at 24.5% (The World Bank, 2023). This means that about one-fifth of the population in these countries had credit cards. Also, digital platforms and similar business models have the potential to widen the economic divide by reducing the opportunities for new entrepreneurs to emerge. In 2021, Alibaba accounted for approximately 24% of the global e-commerce market share in terms of gross merchandise volume, while Amazon held a 13% share. The combined online sales of just two companies accounted for 37% of the total global e-commerce market (Coppola, 2022). The presence of many dominant sellers in these marketplaces makes the trading environment difficult for new entrepreneurs.

Lack of representation is caused by digital representation inequalities. Some people or groups may face difficulties in being heard and may experience social and cultural inequality due to biased algorithms. In certain countries, there are limitations or outright blocking of popular platforms like Facebook and Twitter (Zandt, 2022; Barry, 2022). Such restrictions often stem from political motivations.

Data privacy protection is emerging due to the limited digital awareness or control of people or communities over their personal data. Some individuals or groups are more likely to be being monitored or exploited. Devices that people use in their daily lives constantly collect personal information. With the spread of systems such as the social scoring system implemented in China, these data can be used as a social control tool on society.

Personal security unlash stems from the negligence of people about online security. Trust in the digital age relies heavily on the importance of digital security. While some people can resolve their digital security through their personal relationships and financial strength, it may be difficult for others to deal with it on their own. This situation brings a number of grievances.

Today, digital divide is transforming into artificial intelligence gap. This transformation will become more evident as the use of artificial intelligence increases. Those who specialize in prompt engineering will stand out from the rest. Moreover, with the use of quantum computing technology, this gap will be opened to never close.

2.2. Quantum Divide

The post-digital ecosystem has brought many changes to the world. However, humanity is likely to face even more significant changes with the Quantum Divide. The preconception setting was described in the previous sections. What is known about the emergence of this new concept is limited. It is a concept that has been introduced for the first time in the literature by this article. Therefore, the new concept needs to be well understood with extensive research.

Within the framework of the developments that have been observed so far, quantum computing appears as the key pillar of the Quantum Divide. Quantum computing leverages the principles of quantum mechanics to execute computations, enabling simultaneous execution of multiple calculations. Quantum computers possess superior information processing and manipulation capabilities compared to conventional computers. They can demonstrate noteworthy aptitude in machine learning and tackle intricate problems (Gill and Buyya, 2024). Despite being a promising field with immense potential, quantum computing is still in its nascent phase of advancement, and research efforts are ongoing. The fact that highly developed computers powered by artificial intelligence are so deeply ingrained in human life and have attained an impressive position has both positive and negative aspects (Rieffel et al., 2024).

The Quantum Divide represents the emerging disparities in access to quantum technologies and the socio-economic benefits they promise. While building on the foundations of the Digital divide, the Quantum Divide brings forth a new layer of inequality tied to advanced technological capabilities. To understand its implications fully, it is necessary to define the Quantum Divide, differentiate it from similar concepts such as the Digital divide, and establish its place within the existing body of literature.

Although it is not possible to predict exactly what Quantum Divide will bring to human life, it can be predicted that it will cause inequality in the world, just like the digital divide. The fact that quantum computers are expensive and advanced technology is the main reason for inequality. It is inevitable for countries that do not have quantum computers to suffer from cyber security vulnerabilities. The quantum divide can be defined as the inequality that arises between countries that have quantum computing technology and others. The use of this technology by companies that have personal data of many people will accelerate artificial intelligence studies. This will deepen humanity's lack of privacy problem. The lack of privacy, which is likely to become even more acute, will be a concern for humans on a scale that cannot be foreseen now.

The digital divide, a term that gained prominence in the mid-1990s, focuses on disparities in access to foundational digital technologies, such as the internet and computers (National Telecommunications and Information Administration [NTIA], 1999). While the Digital divide emphasizes access to basic IT infrastructure, the Quantum Divide highlights disparities in access to cutting-edge technologies and the expertise required to utilize them effectively. As shown in Table 1, the comparison between the Digital divide and the Quantum Divide highlights the shift from addressing basic technological access to managing more complex inequalities related to advanced computational resources and expertise.

Table 1. Comparison of the Digital Divide and the Quantum Divide

Dimension	Digital Divide	Quantum Divide
Scope	Access to basic IT tools and internet	Access to quantum computing infrastructure and expertise
Primary Challenge	Bridging gaps in digital literacy and infrastructure	Overcoming economic, educational, and geopolitical barriers
Impact Scale	Individual and community levels	Global, industrial, and geopolitical levels
Temporal Context	Emerged in the 1990s	Emerging in the 21st century as quantum technologies advance

Source: Created by the authors based on insights from the literature.)

The quantum divide extends the discourse on technological inequality into a new technological frontier. Early studies on the digital divide emphasized the importance of equitable access to digital technologies to prevent broader societal disparities (Gunkel, 2003). As digital technologies matured, research shifted focus to usage inequality, where differences in digital skills and applications reflected broader socio-economic divides (van Deursen & van Dijk, 2014).

The quantum divide builds on foundational insights into technological inequality, offering a more nuanced understanding of emerging disparities in the quantum era. One of the primary issues it addresses is skill and educational disparities. The effective utilization of quantum technologies demands highly specialized knowledge, which remains predominantly concentrated in elite institutions and technologically advanced nations. This concentration limits the accessibility of quantum expertise to a select group, thereby creating significant barriers for less developed regions to participate in the quantum revolution (Coates, 1985). Without deliberate efforts to expand quantum education and training, these disparities are likely to widen, further entrenching global inequality.

In addition to educational barriers, the Quantum Divide highlights the unequal distribution of power on a global scale. The high economic and technical thresholds required to enter the quantum technology arena place developing countries at a severe disadvantage. Quantum infrastructure—comprising expensive hardware, cutting-edge research facilities, and a well-trained workforce—demands substantial investment, which only a few nations can afford. Consequently, the dominance of wealthier nations in quantum innovation risks perpetuating existing global inequities (Gunkel, 2003). This imbalance raises concerns about technological hegemony, as countries with early access to quantum capabilities may wield disproportionate influence in international relations.

Moreover, the socio-economic implications of the Quantum Divide cannot be overlooked. Advanced technologies often mirror and magnify pre-existing inequalities unless proactive measures are implemented to counteract these effects. As seen with earlier digital technologies, quantum advancements could exacerbate socio-economic disparities by favoring those already equipped with the resources and infrastructure necessary to harness their potential. Without well-designed policies to ensure equitable access and foster inclusive participation, the benefits of quantum technologies may remain concentrated among a privileged few, leaving others further behind (van Deursen & van Dijk, 2014).

By drawing attention to these critical dimensions—educational disparities, global power dynamics, and socio-economic implications—the concept of the Quantum Divide underscores the urgent need for global collaboration, equitable policymaking, and investment in inclusive quantum education. These efforts are essential to prevent the deepening of technological inequality in the quantum era and to ensure that the transformative potential of quantum technologies can be shared widely across societies.

3. METHODOLOGY

This study employs a hybrid methodological approach, integrating the Delphi method and foresight analysis to systematically assess the quantum divide and propose strategic recommendations. The Delphi method was selected for its ability to gather expert insights and build consensus on emerging and complex topics, while foresight analysis provided a structured framework for exploring long-term scenarios and strategic implications. The integration of these two methodologies offered a balanced framework for addressing the multifaceted challenges of the quantum divide. While the Delphi method provided focused, expert-driven insights into immediate risks and priorities, foresight analysis expanded the analytical lens to account for broader uncertainties and long-term implications. Together, these methodologies enabled a comprehensive understanding of the technical, ethical, economic, and geopolitical dimensions of quantum technologies. As noted by Martin (1996), this integrated approach ensures that research not only identifies current challenges but also develops strategies to manage future risks and leverage opportunities.

3.1. Delphi Method

The Delphi Method was selected for its systematic and iterative approach to gathering expert opinions, particularly in areas where empirical data is scarce (Dalkey & Helmer, 1963). This method is well-suited for studying emerging technologies like quantum computing, which are in their early stages and lack substantial historical data. By facilitating structured consensus building, the Delphi Method collects expert insights anonymously over multiple rounds, allowing for a refinement of perspectives and minimizing bias (Linstone & Turoff, 1975).

In this study, the Delphi Method focused on evaluating specific challenges related to quantum technologies, such as risks of inequality, cybersecurity vulnerabilities, and economic competition. Experts were tasked with assessing these issues and providing practical recommendations to mitigate inequalities and foster equitable access to quantum advancements. The iterative nature of the method enabled the identification of short-term priorities and strategies, particularly in areas like educational preparedness and quantum-resilient cybersecurity. This process emphasized actionable outcomes, aligning with the objective of developing targeted policies to address immediate concerns (Rowe & Wright, 1999).

A panel of ten experts participated in the Delphi process, comprising six academics and four industry professionals with expertise in quantum technologies, digital policy, and socio-economic strategy. This number aligns with methodological conventions, which typically recommend 10–20 participants to ensure expert diversity without compromising consensus quality (Linstone & Turoff, 2002; Rowe & Wright, 1999). The Delphi study was conducted over three iterative rounds between March and May 2025. In the first round, participants provided open-ended assessments of the risks and opportunities associated with the quantum divide. The second round refined these insights into structured statements rated on a five-point Likert scale, and the third round sought convergence on priority areas and strategic actions.

To evaluate consensus reliability, Kendall's W coefficient of concordance was calculated for each round. The W value increased from 0.58 in the second round to 0.76 in the third, indicating a high degree of agreement among experts (Von der Gracht, 2012; Landeta & Lertxundi, 2024). As the coefficient surpassed the commonly accepted threshold of 0.70 for strong consensus, the process was concluded after the third round, since additional iterations were unlikely to yield significant new insights.

3.2. Foresight Analysis

Foresight Analysis complemented the Delphi Method by extending the study's scope to explore long-term uncertainties and develop strategic plans for addressing the challenges of the Quantum Divide. As defined by Coates (1985), foresight is a systematic process of envisioning potential futures, identifying risks, and recognizing strategic opportunities. This approach not only aligns with traditional planning but also expands its focus to proactively address uncertainties.

Drawing on Martin (1995) this study employed foresight to construct plausible scenarios that analyzed the broader socio-economic impacts of quantum technologies. These scenarios allowed the exploration of alternative technological trajectories and their implications. The methodology also facilitated strategic planning, helping to identify proactive measures to guide the development of quantum technologies in ways that promote equity and sustainability. Popper (2008) highlights the value of foresight in scenario development and strategic adaptability, which proved crucial for preparing stakeholders to navigate unpredictable technological shifts.

The foresight approach emphasized adaptability, recognizing that quantum technologies will likely evolve in ways that are difficult to anticipate. Miles (2010) notes the importance of flexibility in foresight methodologies, which ensures that policy recommendations remain robust and actionable in dynamic environments. By integrating this long-term perspective, the study provided insights that complemented the expert-driven precision of the Delphi Method.

3.2.1. Delphi Method Implementation

The Delphi method was conducted in three iterative rounds, with structured surveys designed to progressively refine expert insights. A total of 10 experts from diverse backgrounds, including quantum computing, artificial intelligence, cybersecurity, and socio-economic policy, participated in this study.

The Delphi process in this study was conducted in three iterative rounds, ensuring a structured refinement of expert insights and consensus-building on the key challenges, opportunities, and policy implications related to the quantum divide. This method allowed for a progressive narrowing of focus, ultimately leading to a well-supported synthesis of expert opinions that informed both immediate policy decisions and long-term strategic planning.

In the first round, a questionnaire with 10 open-ended general questions was distributed to all 10 experts. These questions aimed to identify the primary concerns, opportunities, and inequalities expected to emerge with quantum technologies. The responses were collected, analyzed, and categorized to identify recurring themes and points of divergence among expert perspectives.

The second round built upon the insights from the first phase, refining the areas of focus through a second questionnaire containing 10 more specific questions. This round was designed to narrow down critical issues, clarify expert perspectives, and elicit more detailed policy recommendations. Participants were also invited to provide additional comments or modifications, ensuring that evolving viewpoints were incorporated into the discussion.

In the third round, rather than maintaining a question-based approach, the insights gathered from previous rounds were consolidated into five key categories that encapsulated the core themes identified by the experts. Instead of responding to a new set of questions, experts were asked to validate these five conceptual categories, assess their relative importance, and refine the final strategic recommendations. This shift from a question-based format to a category-based validation process ensured that the study's conclusions were structured around the most pressing and consensus-driven issues.

By the end of the third round, a structured synthesis of expert insights had been achieved, forming the basis for the key findings and recommendations presented in Table 2. This iterative process ensured that the conclusions drawn were rigorously debated, critically examined, and validated through expert consensus, reinforcing the study's methodological robustness.

- Exploring Long-Term Scenarios: Foresight analysis enabled the identification of possible future trajectories of quantum technologies and their societal impact.
- Contextualizing Expert Insights: Instead of focusing solely on current concerns, foresight provided a structured future-oriented perspective, allowing the study to develop anticipatory strategies rather than just reactive solutions.
- Enhancing Policy Relevance: The integration of foresight analysis helped frame policy recommendations within broader strategic foresight models, ensuring that solutions remain adaptable to evolving quantum developments. If the reference is taken from a web site and the author is known, reference should be made like periodic publications. If the date of the downloaded source is not given, access date should be used. If the date of the downloaded source is not given, date of access should be used. Also, if no publisher name is available, use the name of website and data of access.

By combining precision with adaptability, this integrated methodological approach equipped policymakers and stakeholders with robust tools for navigating the evolving landscape of quantum advancements. The study effectively addresses the complex interplay of short-term actions and long-term goals, reinforcing the importance of proactive governance, ethical technology development, and equitable access strategies to mitigate the risks of the quantum divide.

3.2.2. Expert Selection and Criteria

To ensure a diverse and well-rounded perspective, 10 experts from the United States (2), Europe (2), and Türkiye (6) were selected based on their academic and professional expertise in quantum computing, artificial intelligence, cybersecurity, and technology policy. The selection criteria ensured that the study incorporated insights from both technologically leading nations and developing economies, where access to quantum technologies may be limited.

Experts were chosen through a structured selection process to balance academic and industry perspectives. Six academic researchers specializing in quantum computing, AI, and the socio-economic impact of emerging technologies were included, along with four industry professionals working in private sector organizations developing quantum technologies, cybersecurity solutions, or involved in technology policy advisory roles.

Each expert met at least one of the following criteria. First, advanced academic and professional qualifications were considered, including holding a Ph.D. or equivalent expertise in quantum computing, artificial intelligence, cybersecurity, or technology governance, as well as demonstrated contributions to research or policy development in emerging technologies. Second, sectoral and disciplinary diversity was ensured by selecting participants from physics, computer science, cybersecurity, economics, and public policy to capture multi-dimensional perspectives on the quantum divide. Third, geographical representation was maintained by including participants from the United States, Europe, and Türkiye, providing a mix of global and regional perspectives and ensuring the inclusion of viewpoints from both quantum technology leaders and regions where access remains a challenge.

4. FINDINGS AND DISCUSSION

This study employed a hybrid methodological approach, integrating Delphi method and foresight analysis to assess the societal and technological impacts of the quantum divide. Through structured engagement with 10 experts from academia and industry, five key areas were identified: optimization, economic inequalities, cybersecurity risks, ethical concerns, and workforce adaptation. Optimization was recognized as the first major application of quantum technologies, particularly in logistics, energy, and finance, while economic inequalities were highlighted as a risk, favoring developed economies and widening the quantum divide. Cybersecurity threats, especially quantum computing's potential to break encryption, underscored the need for quantum-resilient cryptography and global cooperation. Ethical concerns related to AI-quantum integration emphasized the importance of regulatory frameworks, while workforce displacement due to automation called for reskilling initiatives. The Delphi method ensured expert consensus on immediate priorities, while foresight analysis expanded discussions to long-term strategic implications, equipping policymakers with actionable insights for an inclusive and secure transition into the quantum era.

The Delphi process engaged 10 experts, which is consistent with established methodological standards emphasizing expertise diversity over numerical size (Linstone & Turoff, 2002; Rowe & Wright, 1999). Delphi studies commonly employ panels of 10–20 experts, as the objective is to achieve informed consensus rather than statistical generalization. The participants represented a balanced mix of academic and industry backgrounds, ensuring multidimensional perspectives. Reliability and consensus levels were evaluated at the end of each Delphi round using Kendall's W coefficient of concordance. By the third round, the coefficient indicated a level of agreement above the generally accepted threshold for consensus in Delphi studies, suggesting that expert opinions had converged and that additional rounds would yield diminishing returns (Von der Gracht, 2012; Landeta & Lertxundi, 2024). Therefore, the process was concluded after the third iteration.

Table 2. Foresight Analysis Results

Key Findings	Details	Strategic Recommendations
Optimization as the Gateway to Quantum Applications	Optimization identified as the primary area where quantum technologies will initially demonstrate utility. Key applications include logistics, energy management, and financial modeling. Experts emphasized its potential to transform various industries.	Foster partnerships between quantum technology providers and industries. Support research initiatives to refine and expand quantum optimization algorithms.
Economic Inequalities and Access Challenges	Quantum technologies may exacerbate global inequalities due to resource-intensive infrastructure. Expertise favoring developed economies increases the risk of widening the 'Quantum Divide'. Bridging this divide requires international collaboration.	Develop global partnerships for equitable access. Facilitate collaborations between quantum technology developers and industries reliant on optimization.
Cybersecurity and Data Privacy Risks	Quantum computing poses significant cybersecurity risks by potentially compromising existing encryption methods. Quantum-resistant encryption and international cooperation are critical to ensure data security.	Prioritize quantum-resilient encryption development and deployment. Promote cross-border collaboration on cybersecurity frameworks.
Ethical and Regulatory Frameworks	The integration of quantum computing with AI raises ethical concerns. Key issues include transparency, accountability, and equitable decision-making. Global ethical guidelines and adaptable regulatory frameworks are needed.	Formulate global ethical guidelines for quantum technologies. Establish adaptable regulatory policies for quantum and AI integration.
Workforce and Societal Adaptation	Quantum-enhanced automation may displace traditional roles, necessitating workforce preparation. Reskilling, upskilling, and public engagement are essential to societal adaptation.	Launch comprehensive reskilling and upskilling programs. Increase public engagement through educational initiatives to foster understanding and acceptance.

4.1. Optimization as the Gateway to Quantum Applications

Experts unanimously identified optimization as the initial gateway for quantum technologies, with significant potential in logistics, energy management, and financial modeling. Quantum optimization's superior computational power enables faster and more precise solutions to complex problems, enhancing resource allocation, supply chain management, and operational efficiency across industries. Recognizing its foundational role, fostering strategic partnerships between quantum technology providers and industries is crucial for accelerating adoption. Additionally, continued research on refining quantum optimization algorithms will expand their applicability, ensuring adaptability to diverse industrial needs. By prioritizing quantum optimization, stakeholders can facilitate the practical integration of quantum technologies, paving the way for broader advancements and socio-economic impact.

4.2. Economic Inequalities and Access Challenges

Experts warned that quantum technologies could exacerbate global economic inequalities due to the resource-intensive infrastructure and specialized expertise required for their development. Developed economies, with greater capacity to invest in quantum research, are likely to gain early advantages, widening the quantum divide and limiting access for developing nations. To mitigate this risk, international collaboration is essential to promote equitable access and prevent quantum technologies from becoming exclusive to wealthier countries. Establishing global partnerships and fostering cooperation between quantum technology providers and industries can accelerate adoption and ensure broader socio-economic benefits. Addressing these disparities requires targeted investments, knowledge-sharing initiatives, and policy interventions to make quantum advancements accessible to a wider range of societies, rather than a privileged few.

4.3. Cybersecurity and Data Privacy Risks

Experts highlighted the cybersecurity risks of quantum computing, particularly its ability to break existing encryption methods, posing threats to sensitive data, critical infrastructure, and global information systems. As quantum technologies advance, the need for quantum-resistant encryption becomes urgent to prevent current security protocols from becoming obsolete. Addressing these vulnerabilities requires more than technological solutions; it demands international collaboration to establish global cybersecurity standards and ensure a coordinated response to emerging threats. Developing and deploying quantum-resilient encryption technologies, alongside cross-border cooperation, is crucial for safeguarding digital security and maintaining trust in information systems as quantum computing evolves.

4.4. Ethical and Regulatory Frameworks

Experts emphasized the ethical challenges of quantum technologies, particularly when integrated with artificial intelligence, raising concerns about transparency, accountability, and equitable decision-making. As these technologies become more embedded in societal functions, ensuring ethical deployment is essential to prevent bias, inequalities, and unintended consequences. To address these risks, experts called for global ethical guidelines that align with societal values and promote trust in quantum and AI systems. Additionally, adaptable regulatory policies are needed to keep pace with rapid advancements while maintaining oversight. A dual approach—combining ethical standards with flexible regulations—will be crucial for guiding quantum technology development in a way that prioritizes societal well-being and global inclusivity. Proactively establishing ethical and regulatory frameworks will help mitigate risks and ensure that the benefits of quantum advancements are equitably distributed (World Economic Forum, 2024).

4.5. Workforce and Social Adaptation

Experts emphasized the need to prepare the workforce for the transformations brought by quantum technologies, as quantum-enhanced automation may displace traditional roles, widening socio-economic inequalities if proactive measures are not taken. To address this challenge, experts advocated for comprehensive reskilling and upskilling programs focused on quantum technology, artificial intelligence, and automation, ensuring workers remain competitive in a rapidly evolving job market. Beyond technical training, fostering interdisciplinary skills is crucial to help professionals navigate both the technological and societal implications of quantum advancements. Additionally, public engagement through educational initiatives was identified as essential for increasing awareness, fostering trust, and promoting inclusive participation in shaping the quantum-driven future. A multifaceted approach, combining education, skill development, and public outreach, is necessary to mitigate workforce disruptions and ensure that quantum advancements benefit society equitably rather than deepening existing inequalities (OECD, 2025; World Economic Forum, 2024).

In summary, this study demonstrates that while quantum technologies hold transformative potential, their benefits and risks must be carefully balanced. Insights from the experts have provided actionable strategies to address the concerns outlined in the quantum divide while maximizing the societal and technological advantages of quantum computing. These findings further emphasize the necessity for collaborative efforts and strategic planning to ensure an equitable and responsible quantum future.

5. CONCLUSION

This study aimed to analyze the socio-economic and technological inequalities emerging from the quantum divide and provide strategic policy recommendations for ensuring equitable access to quantum technologies. To achieve this, a hybrid methodological approach was employed, combining the Delphi method and foresight analysis to systematically collect and refine expert insights. The Delphi process allowed for the identification and prioritization of key concerns through iterative rounds of expert consultation, while foresight analysis contextualized these findings within broader long-term technological and policy implications.

The findings of this research highlight five major areas where quantum technologies are expected to have the most profound impact: optimization, economic inequalities, cybersecurity risks, ethical concerns, and workforce adaptation. Optimization was identified as the initial gateway through which quantum technologies will demonstrate their utility, particularly in logistics, energy management, and financial modeling. Economic inequalities emerged as a significant concern, with the risk that early access to quantum technologies will favor developed economies, widening the quantum divide. Cybersecurity risks were underscored due to the potential of quantum computing to break existing encryption methods, necessitating quantum-resilient encryption solutions and international cooperation. Ethical concerns regarding transparency, accountability, and AI-quantum integration called for the establishment of global ethical guidelines and adaptive regulatory frameworks. Lastly, workforce adaptation was identified as a critical challenge, requiring comprehensive reskilling and public engagement initiatives to mitigate potential job displacement and ensure a smooth transition to the quantum era.

The anticipated issues arising from the post-digital ecosystem are expected to have far-reaching implications for individuals, institutions, and global governance structures. Given the complexity and transformative potential of quantum technologies, a multifaceted approach is needed to address the inequalities and risks associated with their development and deployment. Ensuring fair access to quantum infrastructure, promoting digital literacy, investing in workforce upskilling, and strengthening cybersecurity measures will be essential in mitigating the negative consequences of the quantum divide. The findings of this study emphasize that without proactive intervention, the rapid adoption of quantum technologies may deepen existing socio-economic inequalities, leaving certain regions, industries, and populations disadvantaged.

Despite these challenges, the quantum era presents unprecedented opportunities for scientific breakthroughs, economic growth, and technological innovation. If managed effectively, quantum advancements can enhance global productivity, optimize resource management, and foster collaboration across disciplines and industries. The insights gained from this study highlight the importance of maintaining a human-centered approach in shaping the quantum era—one that prioritizes ethical considerations, inclusivity, and long-term societal well-being.

To navigate this transition, global collaboration, strategic policymaking, and continuous investment in research and education will be crucial. Stakeholders—including governments, research institutions, industry leaders, and civil society—must work collectively to develop inclusive frameworks that maximize the benefits of quantum technologies while minimizing their risks. The more this emerging phenomenon is understood, the better equipped decision-makers will be to guide its trajectory toward an equitable and sustainable future.

DECLARATION OF THE AUTHORS

Declaration of Contribution Rate: The authors contributed equally to the study (25%).

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