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# Full-Stack Quantum Computing and Distributed Systems: A Community-Centric Approach

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**Abstract.** Quantum computing is considered a promising future technology for addressing complex societal and technical challenges. However, it is still in an experimental early stage. This article takes a full-stack perspective and advocates for a community-driven, interdisciplinary development of quantum computing. First, the importance of close collaboration across different scientific and technical disciplines is emphasized. It is then shown that long-term scalable quantum computers can only be realized through distributed architectures, and the resulting technical and organizational requirements are discussed. Using concrete application examples from the fields of energy, logistics, mobility, and network analysis, the paper illustrates where quantum computing could create real societal value in the future. Finally, a roadmap is presented with short-, medium-, and long-term actions addressing technological, infrastructural, and educational aspects. At the core of this message is the idea that open communities, transparent standards, and interdisciplinary knowledge exchange are essential for the sustainable development and broad adoption of quantum-based technologies.

**Keywords:** Full-stack quantum computing · Distributed architectures · Community-driven innovation

## 1 Quantum Computing as an Interdisciplinary Collaboration

Quantum computing is one of the most promising future technologies, offering enormous potential to address complex technological and societal challenges. However, this technology is still at an early stage of its development cycle. To fully unlock its potential, quantum computing requires close collaboration across multiple scientific and technical disciplines, as well as among research institutions, industry, and educational organizations. The following sections will elaborate that successful progress in quantum computing can only be achieved through interdisciplinary and collaborative efforts. Thus, the core message of this article is: quantum computing is a community-driven journey centered around people.


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### 1.1 Interdisciplinarity is Key

Quantum computing is not a field that can develop in isolation. Due to the complexity and multi-layered nature of quantum computer technology, close cooperation among various scientific and technical disciplines is essential. Each discipline involved contributes knowledge and skills crucial for the practical and meaningful use of quantum computing. The following list (see also Fig. 1) is not intended to be exhaustive, but rather serves as a positive example.

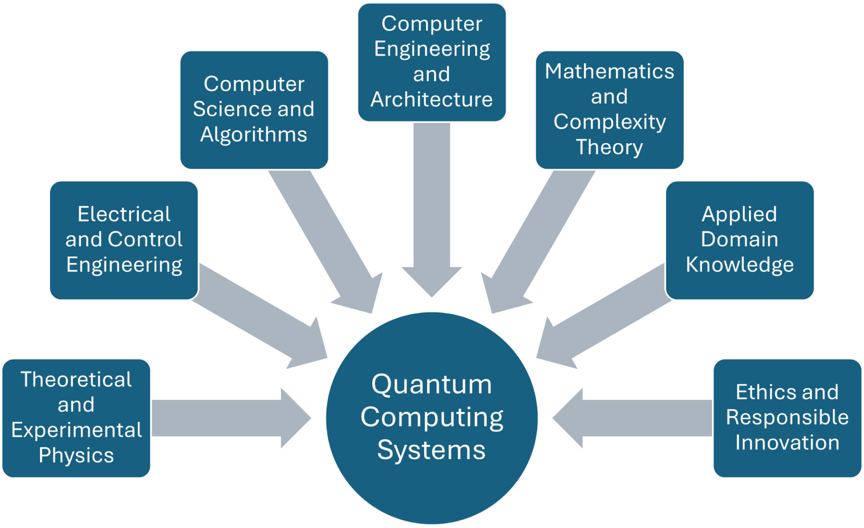


**Fig. 1.** Interdisciplinary collaboration in quantum computing

*Physicists* (both theoretical and experimental) lay the foundations for the theory and hardware implementation of quantum computers. They research and develop qubits, improve the stability of quantum states, extend coherence times, and work on realizing and characterizing quantum gates and quantum processors. *Engineers* ensure the reliability, integration, and scalability of the systems. They develop control and cooling technologies, technical infrastructure, and solutions for integrating quantum and classical computing components. *Computer scientists* design and optimize quantum algorithms, software frameworks, middleware, and efficient compiler technologies to maximize the practical usability and performance of quantum hardware. *Mathematicians* develop the theoretical foundations of quantum algorithms and analyze their properties within complexity theory, thereby making the theoretical advantages of quantum-based approaches measurable and understandable. *Domain experts*, such as specialists from chemistry, biology, logistics, the energy industry, and many other fields, ensure the practical relevance of quantum solutions. They define realistic application scenarios and assess the outcomes regarding their actual added value for their specific industry.

Each of these competencies is essential for the practical application of quantum computing. Without physicists, reliable hardware would not exist; without computer scientists, efficient software would be lacking; without engineers, scalable systems would not be achievable; and without domain experts, even the best technological solutions would fail to find practical use.

## 1.2 Community-Driven Frameworks and Tools

The experience from classical computing communities, especially in the fields of hardware acceleration [50,58] (e.g., GPUs and FPGAs) and distributed systems [82], can provide proven approaches that quantum computing can build upon. Best practices developed over decades, such as those from design automation [76], compiler techniques [1], modularity [66], standardization [26], or software abstraction layers [36], serve as foundations for current quantum computing developments. However, completely "recycling" this knowledge is not possible, as quantum computing has several fundamental differences compared to classical computing [64]. Perhaps the most basic of these differences originate from the underlying physics, such as the No-Cloning theorem [94], which states that it is impossible to copy an unknown quantum state.

Nevertheless, the quantum computing community strongly relies on open and collaborative initiatives. Well-known open-source platforms such as Qiskit (IBM) [45], Cirq (Google) [22], and Pennylane (Xanadu) [9] publicly provide algorithms and simulation tools to promote innovation. The importance of transparency provided by open-source concepts [92] should also not be underestimated. Furthermore, benchmarking – including its standardization – is another essential, community-driven area [12,19,74]. Benchmarking is necessary because quantum hardware significantly differs in underlying technology (e.g., superconducting qubits, photonics, ion traps) and current performance capabilities. This variability not only complicates comparisons between different quantum technologies but also makes evaluating quantum-based solutions against the current state-of-the-art classical computing technologies especially challenging. Such comparisons often seem unfair, given that quantum computers are still at an early stage of development and compete directly against classical systems that have been established and highly optimized for decades. Nonetheless, this comparability is essential for documenting measurable progress and clearly managing expectations. Typical benchmarks range from component-specific tests (e.g., gate error rates), system metrics (e.g., Quantum Volume [19], CLOPS [14]), to application-oriented scenarios [56,57,77], designed to reflect realistic usage scenarios.

## 1.3 Education and Competence Development

To achieve sustainable success in quantum computing, a broad educational initiative is essential. Just a few years ago, specialized courses existed at individual universities; today, these have evolved into comprehensive, independent degree programs, including specialized Bachelor's and Master's programs. Examples include Quantum Information Science and Technology (TU Delft, University of Leiden, Netherlands) [83], Quantum Science and Technology (TU Munich, LMU Munich, Germany) [62], Quantum Engineering (ETH Zurich, Switzerland) [95], Quantum Technology (RWTH Aachen, Germany) [90], and many others. Additional specialized educational programs exist and continue to emerge globally [79,88,89].

Moreover, there is growing importance of non-commercial, community-driven educational and outreach initiatives, particularly student-led and NGO-managed projects that help "democratize" access to quantum computing. Examples of such initiatives include Quantum Open Source Foundation [31], QWorld [75], Quantum Universal Education [25], as well as initiatives like OneQuantum [65] or Women in Quantum Development [72].

## 2 Scaling Through Distributed Architectures

In the previous section, we discussed that interdisciplinary collaboration and community-driven efforts are essential prerequisites for sustainable innovation in quantum computing. However, to implement scalable and powerful quantum computers in practice, an additional step is necessary: the explicit transition to distributed architectures.

### 2.1 Technical Limitations of Monolithic Systems and the Necessity of Distributed Approaches

Current monolithic quantum computers, where a single processor or chip provides all the quantum computing power, face several technical challenges [70]. In particular, high error rates and limited coherence times significantly restrict scalability when increasing the number of qubits [5]. Controlling increasingly large qubit systems also requires complex error-correction procedures, adding further complexity [32]. Additionally, there are physical limitations, for example, in cooling large monolithic quantum processors, especially in superconducting systems. As the processor size increases, demands for cooling power, thermal stability, and mechanical isolation significantly rise, approaching the limits of current technology [51]. Another issue is the complexity of managing the qubits themselves. Centralized control and signal processing of densely integrated qubit systems lead to increasingly complicated electronic control structures, causing issues related to stability, synchronization, and scalability [5].

These challenges alone illustrate that scaling quantum computers to hundreds or thousands of qubits – let alone millions required for fault-tolerant applications – is unlikely achievable using only monolithic architectures. Distributed architectures, where several smaller and more easily controllable quantum processors are interconnected, appear to be a practical approach to achieving true scalability. However, it is not simply a choice between monolithic or modular approaches. Technological advancements will improve both the performance of individual quantum processors and the efficiency of their interconnection. Ultimately, both approaches will be necessary to achieve scalable and powerful quantum computing.

## 2.2 Local and Global Distribution

To realize distributed quantum architectures, there are essentially two approaches: local and global distribution (see also Fig. 2).

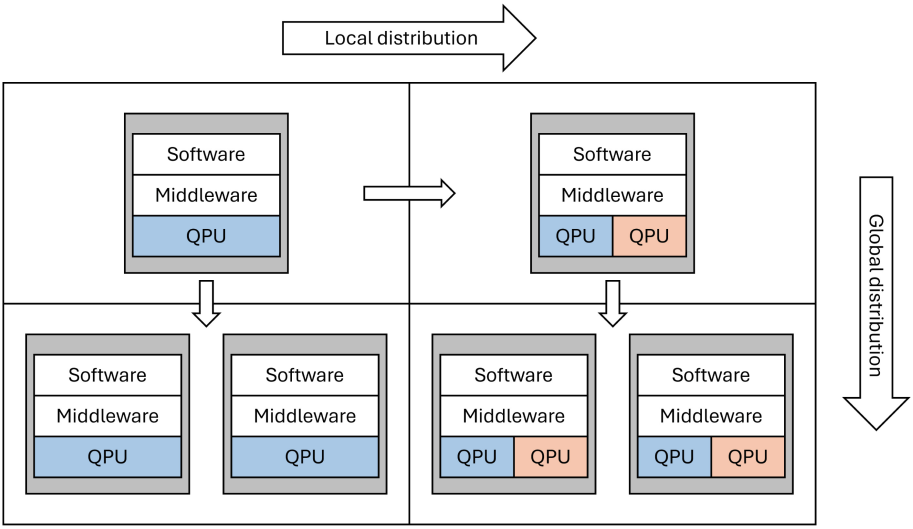


**Fig. 2.** Local and global distribution approaches

In *local distribution*, multiple smaller quantum processors are closely interconnected within a single location [60]. The central idea is that a quantum computer performs calculations using a "multi-core QPU" (see Fig. 2, the evolution from top-left to top-right, but also in bottom-right). Typical implementations of such systems are based on superconducting qubits that communicate locally through microwave coupling or integrated photonic networks [49].

Key advantages of distributing similar technologies within close proximity include reduced overall system complexity and better controllability, enabling targeted error correction strategies, and reduced communication latency (compared to global distribution, discussed below). Processors that are close together and technologically homogeneous can transfer information quickly and efficiently.

*Global distribution* is based on geographically separate locations, in which quantum processors (monolithic or locally distributed systems) communicate via photonic connections (see Fig. 2, the evolution from top to bottom). This approach is also referred to as Distributed Quantum Computing [16,55] or Quantum Internet [24,93].

The intended advantages of global distribution differ from those of local distribution. The primary goal here is massive scalability, as geographic separation allows virtually unlimited expandability across multiple locations. It also permits integrating different hardware types, combining the best properties of various technologies (e.g., photonics, superconducting systems, ion traps, and more). Additionally, geographic distribution enhances resilience against local disruptions or technical failures by avoiding dependency on a single central infrastructure.

However, implementing distributed quantum architectures also brings technical challenges. These can be specific to quantum technologies but also resemble challenges encountered in classical distributed systems. Examples include precise synchronization and timing of distributed components, development of scalable resource management and scheduling methods, and error correction over spatial distance and heterogeneous systems [15]. Thus, there is potential to transfer experience from classical distributed systems and high-performance computing infrastructures (HPC) [78]. For instance, research already exists on applying proven communication standards, such as MPI, within quantum systems [40].

Open testing platforms and community-driven benchmarking initiatives also play an essential role in this context. Communities such as the Quantum Internet Alliance [73] or Quantum Benchmarking Initiative [21] develop standards to ensure interoperability, comparability, and ultimately, quality assurance of distributed quantum systems.

### 2.3 Full-Stack Quantum Computer Architecture

Regardless of the chosen distribution approach, a comprehensive view of all system layers simplifies the successful implementation of (distributed) quantum computer systems. Numerous models and architectures exist for organizing both classical and quantum-based computer systems [6,20,34,43,47,59,91]. The primary goal is always to introduce a certain level of abstraction to simplify system development and operation. Typically, these architectures consist of three main layers.

The *hardware layer* deals with various physical technologies such as photonics, superconducting qubits, ion traps, and neutral atoms. One of the most significant technical challenges here lies in developing standardized interfaces and transmission protocols, such as those needed for transferring entangled quantum states or integrating photonic interfaces [54]. The *middleware layer* primarily handles the efficient distribution and management of quantum-mechanical resources. Challenges at this level include developing distributed compiler technologies, efficient scheduling methods, and robust communication protocols [18]. As previously mentioned, there is potential to adapt established classical methods from distributed systems, such as MPI or containerization. The *software or application layer* often includes frameworks, programming models, and applications explicitly optimized for (distributed) quantum architectures [41]. A major research focus here is minimizing communication overhead and intelligently distributing computations across spatially separated processors.

## 3 Quantum Computing Empowering Communities

The previous section discussed why distributed architectures are essential for scaling quantum computers. Now, we present specific application scenarios where quantum computing is expected to provide real societal value in the future. The focus is on community services, which is why we take a closer look at use cases in the areas of energy, logistics, mobility, and network or community analysis (see also Fig. 3). At the same time, we apply a clear and deliberately conservative expectation management, as we are still far from practical applicability due to major technical and algorithmic challenges. Nevertheless, it already makes sense to explore – based on the currently available quantum systems – which application domains and optimization problems might offer the most promising potential for quantum-based solutions in the future.

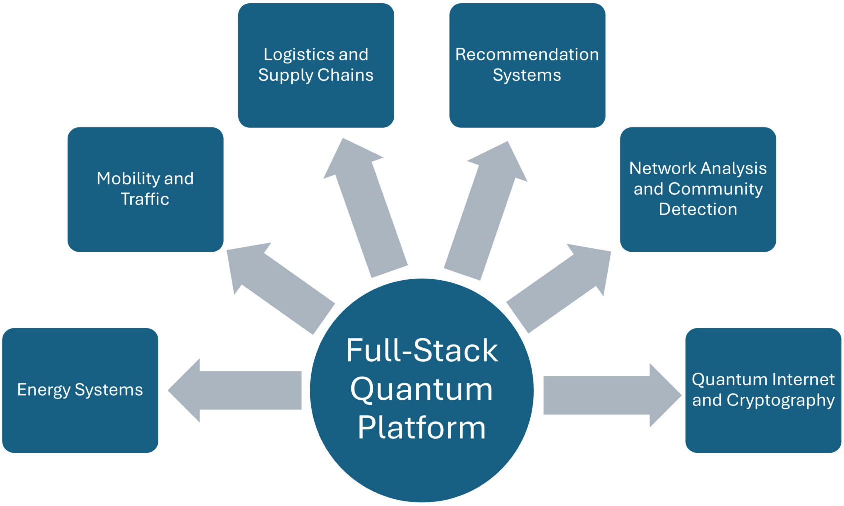


**Fig. 3.** Potential application areas of quantum computing in the domain of community services

### 3.1 Quantum-Based Optimization for Energy Systems and Infrastructure

The domains of energy supply and infrastructure planning face numerous complex challenges that could be supported by quantum computing technologies [3,61,67]. In particular, applications involving combinatorial optimization problems may benefit from quantum technologies such as Quantum Annealing [46] or the Quantum Approximate Optimization Algorithm (QAOA) [29]. Both methods aim to find approximate solutions to NP-hard problems, where classical exact algorithms no longer scale efficiently. Beyond these, current research also explores algorithmic strategies such as VQE-based optimization [84], dynamic quantum walks [42], and the Quantum Alternating Operator Ansatz [39], a generalization of QAOA.

In the context of *smart grids* [87], quantum-enhanced algorithms could improve the optimization of electricity distribution in intelligent power networks. Potential applications include load balancing for renewable energy and intelligent battery storage planning. In *energy network resource allocation* [11], quantum optimization might enable more efficient handling of dynamic consumption patterns as well as decentralized energy input (e.g., via solar panels) and storage. The goals are improved energy efficiency and increased resilience of supply networks. In the field of *infrastructure planning* [35], quantum methods could support the selection of locations and capacity planning for critical infrastructure, such as charging stations for electric vehicles or decentralized generation and storage facilities.

Currently, quantum-based approaches in the energy sector are mostly at the level of pilot studies and feasibility analyses, typically based on simplified models with a limited number of nodes. A large-scale deployment of quantum solutions is not yet foreseeable under the current state of technology. Nonetheless, the potential of these technologies should not be dismissed, especially since even minor improvements in optimization can have significant cumulative effects in long-running energy systems. Achieving practical impact, however, will require substantial advances both in algorithm development and quantum hardware capabilities.

### 3.2 Quantum Technologies for Logistics, Traffic, and Mobility

The domains of traffic and logistics are characterized by complex optimization problems where fast and flexible decision-making is essential [68,81]. In the long term, quantum-based methods could support such processes, provided that scalable algorithms and tight integration with sensor data can be achieved.

One possible application is *adaptive traffic control* [44], where dynamic traffic light coordination and load management could be implemented more efficiently in (near) real time, aiming to reduce congestion and emissions. Another area is *route planning and resource management* [8], particularly in situations involving short-term or critical events such as accidents, traffic jams, or disasters, where quantum-enhanced algorithms may enable faster response and better adaptability.

As in the energy sector, current approaches in logistics, traffic, and mobility are mostly limited to proof-of-concept studies with restricted scope. Initial results suggest promising directions, but practical advantages over established classical methods have not been demonstrated so far. Future progress will strongly depend on advances in quantum algorithm design, hardware capabilities, and integration with classical systems, especially in real-time scenarios.

### 3.3 Graph-Based Quantum Algorithms for Network Analysis and Community Detection

Many real-world problems from various domains, such as social networks, technological infrastructures, or epidemiological systems, can be modeled using graph-based algorithms [13,63]. Quantum approaches to graph analysis are currently being explored as potentially promising methods, although their practical applicability is still mostly limited to small or idealized networks.

In the area of *community detection and clustering* [2,4,28], quantum algorithms could help accelerate or refine the identification of communities or clusters in large datasets, what is an essential subtask in analyzing social or infrastructure networks. Similarly, *resilience analysis* [33,86], such as identifying critical nodes in power grids, transportation systems, or communication networks, could become more robust and efficient through quantum-enhanced techniques. This is especially relevant for pattern recognition in dynamic scenarios like epidemics or crisis events.

Although early approaches appear promising, the use of quantum graph algorithms remains largely at a theoretical or early experimental stage. Their practical utility is, for now, mostly demonstrated in simplified models. Achieving real impact in large-scale, real-world networks will require further advancements in both algorithm design and quantum hardware.

### 3.4 Further Application Areas

The examples discussed so far represent only a subset of the diverse application possibilities of quantum computing. Moreover, the selected examples were deliberately focused on community services. In reality, there are virtually no limits to the imagination when it comes to identifying quantum use cases.

In practice, however, identifying suitable use cases remains an active area of research and development. The "special tool" that is the quantum computer must be carefully tailored to a specific problem domain. Only when the strengths (and weaknesses) of quantum approaches are clearly understood, and the real "pain points" of an application area are well defined, can quantum computing offer concrete added value. At present, hybrid approaches, where quantum algorithms are embedded into classical systems, represent a particularly promising path for combining the best of both worlds [17].

Beyond the areas mentioned so far, additional fields of application are emerging where quantum technologies could also benefit community services. One notable example is the *quantum internet* [24,93], which is gaining attention as a means for secure communication, for example, through the use of quantum key distribution (QKD) [53]. Closely related is the field of *quantum-based cryptography* [10,38,69], which enables secure and decentralized transactions.

Although current hardware resources remain limited, initiatives and research projects in areas such as the quantum internet and quantum cryptography are steadily growing. This trend highlights the strong interest from academic institutions, government bodies, and industry in protecting security-critical infrastructures and driving forward the broader digital transformation.

# 4 Roadmap for a Sustainable Quantum Computing Ecosystem

The previous section discussed potential application areas of quantum computing in energy systems, logistics, mobility, and network analysis. However, in order for today's still limited and experimental quantum-based solutions to become practically relevant, a number of technical, organizational, and educational challenges must first be addressed. These challenges, along with concrete measures and a corresponding timeline, form the core of the chapter that follows.

## 4.1 Technical Challenges

Despite significant progress, fundamental technical limitations still persist. The most critical factor remains the limited physical scalability of current systems [52]. The number of reliably controllable qubits is still low, and they continue to suffer from short coherence times and high error rates. However, quantum algorithms operating at realistic problem scales typically require thousands, or even millions, of error-corrected qubits [37]. Another major issue concerns interoperability and interfaces. Different quantum hardware platforms, such as photonic systems, superconducting qubits, or ion traps, require standardized interfaces and protocols to work together efficiently. Lastly, one of the most pressing challenges is the seamless integration of quantum computers into existing high-performance computing (HPC) infrastructures. As a result, hybrid HPC-QC approaches have become an increasingly active area of research [78].

In addition, the development of quantum software remains a key challenge [7,30,80]. Scalable and robust algorithms that can demonstrably outperform optimized classical methods are still rare and require systematic development and validation. This also applies to evaluation and benchmarking efforts [71,85]. Currently, there is a lack of widely accepted standards and methods to objectively assess quantum-based solutions.

These challenges reflect the current state of a still-emerging technology field. The following section outlines a roadmap toward a broadly usable and sustainable quantum computing ecosystem, structured into three successive phases, each with distinct focus areas.

In the *early phase*, the focus is on establishing the fundamental technical and methodological foundations. This includes the development of standardized evaluation frameworks for quantum algorithms and their integration into existing HPC benchmarking suites. In parallel, initial hybrid pilot projects are being implemented (e.g., EuroHPC-Quantum initiatives [27]), in which quantum processors are coupled with classical high-performance computing systems. This phase is characterized by high uncertainty, experimental approaches, and intensive foundational research.

As the technologies mature, the *scaling phase* shifts the focus toward systematic upscaling and industrial testing. Middleware and compiler technologies that enable efficient integration of quantum and classical systems become increasingly important. Concrete application projects emerge in data centers and industrial settings, where quantum solutions are embedded into existing workflows. Interoperability between different quantum platforms becomes a key concern.

In the *established phase*, a stable technological and organizational framework evolves, in which quantum computing becomes an integral part of digital infrastructures. During this phase, global quantum communication networks are established, and quantum processors are integrated as standard resources within supercomputing and cloud platforms.

### 4.2 Organizational and Infrastructural Challenges

In addition to technical issues, organizational and infrastructural aspects also pose significant challenges on the path toward a functioning quantum computing ecosystem.

One major challenge is the lack of universal standards for evaluating and comparing quantum computing systems. The development of realistic and application-oriented benchmarks, both at the component and system levels, is therefore of central importance. Another important aspect is the creation of collaborative test platforms and supporting structures. International, open testbeds and experimental environments, such as the Quantum Internet Alliance [73], are essential for practically testing and validating distributed and hybrid quantum solutions. The development in this area can also be structured into several successive phases.

In the *early phase*, the focus lies on building foundational structures for collaboration, standardization, and infrastructure development. There is an urgent need for jointly funded, open test platforms that can be shared by research institutions, industry, and public agencies. In parallel, the creation or strengthening of central standardization bodies (e.g., within IEEE, ACM, or ETSI) should be pursued to establish binding evaluation criteria and benchmarking standards for quantum computing systems at an early stage [23].

In the *scaling phase*, international cooperation and the operation of large-scale testbeds become increasingly important. The goal is to provide realistic, scalable, and interoperable quantum infrastructures. At the same time, formal quality standards and certifications for quantum hardware and software can be developed, similar to certification processes in classical IT systems. Institutional collaboration becomes more professionalized, and integration into existing research policies and innovation programs continues to advance.

In the *established phase*, long-term international cooperation structures are set up to secure global standards and ensure long-term interoperability. A stable regulatory and financial framework supports the sustainable development, deployment, and advancement of quantum technologies. Public and private stakeholders routinely access standardized quantum resources that are fully integrated into the broader digital infrastructure.

### 4.3 Challenges in Education and Skills Development

The long-term success of quantum technologies will depend heavily on broad-based, interdisciplinary skills development. A sustainable integration of quantum computing into science, industry, and society requires not only technological maturity, but also a qualified workforce capable of connecting complex concepts from physics, computer science, and engineering [48]. Once again, this area can be structured into three developmental phases.

In the *early phase*, the focus is on creating low-barrier, accessible educational offerings. These include new certificate programs, hands-on workshops, and the provision of free online courses (e.g., MOOCs) aimed specifically at professionals and decision-makers in industry, government, and research. The goal is to convey basic knowledge and spark broad interest in quantum technologies.

Once foundational knowledge is established, the *scaling phase* involves building structured educational programs with greater academic depth. Interdisciplinary master's and PhD programs involving multiple fields (physics, computer science, engineering, business, and more) are introduced. In parallel, exchange formats and doctoral networks are developed to strengthen knowledge transfer between research and industry.

In the *established phase*, quantum computing becomes an integral part of technical and scientific higher education. Continuing education programs for working professionals are systematically implemented and become a regular component of vocational training and upskilling initiatives.

## 5 Conclusion

The previous section not only identified challenges but also presented realistic and concrete measures to make quantum computing practically viable in the future. Now we are going to summarize the key contributions of this article.

Section 1 positioned quantum computing explicitly as an interdisciplinary collaborative effort. It became clear that sustainable and practice-oriented quantum computing solutions are only possible when experts from different fields work closely together. In addition, Sect. 2 highlighted that long-term scalable quantum computers can only be realized through distributed architectures. Both technical challenges, such as the physical limitations of monolithic systems, and potential solutions using local and global distributed architectures were discussed. Section 3 used concrete applications, especially in the areas of energy, logistics, traffic control, and network analysis, to illustrate where quantum technologies could potentially address real-world problems. At the same time, realistic expectations were managed by explicitly pointing out the current experimental nature and future potential of these solutions. Finally, Sect. 4 presented practice-oriented recommendations for action. These include short-, medium-, and long-term measures outlining concrete steps toward a sustainable and practically applicable implementation of quantum computing technologies.

The core message of this article is the importance of community: quantum computing is a community-driven journey with people at its center. Open communities, transparent standards, and interdisciplinary collaboration are not only desirable but essential for broad acceptance and sustainable use of quantum-based technologies.

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