The Integration of High-Performance Computing and Quantum Computing: A Theoretical Review and Recent Developments

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ABSTRACT
This review entails an in-depth study of the integration between quantum computing and high-performance computing (HPC), looking at recent breakthroughs, challenges, and future directions. It analyses the basic theoretical challenges in developing software and hardware platforms and explores the stability and scalability issues that emerge when quantum modules are embedded into classical supercomputing environments.

Based on a wider scope of literature reviews, the study examines both the conceptual frameworks and real-world deployments of combining quantum and HPC systems. Case studies in areas such as simulation for drug discovery and risk analysis in financial services illustrate where quantum-enhanced frameworks are expected to help, in terms of execution speed and resource utilisation. The results, which are analytical and drawn from the cited literature, indicate the potential of quantum and HPC hybrids to improve computational power; no new measurements are reported, and measured gains in speed, resource utilisation and energy efficiency remain to be demonstrated. Finally, the paper emphasises the necessity of closer collaboration between academic researchers and industry practitioners, highlighting the main technical and organisational roadblocks and outlining promising paths for collaborative evolution.

Keywords
Quantum Computing, High-Performance Computing (HPC), Framework

1. INTRODUCTION
The integration of high-performance computing and quantum computing technologies is being seen as an emerging research area and is ready to change how complex challenges are addressed across diverse fields. Gill et al. [1] suggest that quantum computing gives a clear platform to show the fundamental limitations of classical machines, providing an entirely new layer of processing power. By providing previously unheard-of speed and efficiency in processing enormous volumes of data, this combination intends to solve issues in domains that cover medicine development, weather forecasting, encryption, and economic modelling. Nonetheless, there are other obstacles to overcome before quantum-enhanced HPC computers can be used in practice, which involve hardware integration, error correction, and the creation of quantum-classical combined algorithms [2].

One goal of quantum computing is to accelerate processes that are most suited to its characteristics instead of replacing traditional computing; hence, it is necessary to integrate it alongside its conventional counterparts, especially high-performance computing. It is anticipated that in the near future, quantum machines will cohabit alongside traditional supercomputer systems, utilising their distinct benefits to improve processing power. The complexity of quantum techniques necessitates the use of advanced corrective techniques [3]. In order to create, test, and debug quantum algorithms in a safe, error-free setting, scholars rely heavily on quantum simulators. When physical quantum resources are limited, they increase accessibility, making them an essential instrument for furthering studies on quantum computing.

The study examines the state of high-performance computing and quantum computing integration today, looking at new developments, difficulties, and potential paths forward. This study delivers an exhaustive survey of the fusion between quantum computing and high-performance computing, evaluating real-world implementations and pioneering solutions to assess their transformative impact on both scientific research and industrial practices.

Central to this work is the design of a resource management schema that both simplifies deployment and boosts real-time performance and throughput. This architecture forms the foundation for seamless interoperability between quantum processors and classical supercomputing systems.

The manuscript unfolds as follows. First, it reviews the foundational concepts and technical mechanisms involved in marrying high-performance architectures with quantum computing. Next, it presents an integration paradigm that guides the subsequent discussion. A comprehensive literature

survey then situates the proposed framework within the context of existing scholarship.

Building on that review, the paper's main contribution emerges: a detailed integration framework that specifies the model's components and workflows. Following this, a high-level overview of the integration process examines current trends, application domains, and the primary challenges practitioners face.

Figure 2 offers an initial schematic of the framework's overall structure, with an in-depth analysis deferred to Section 5. Finally, the paper concludes with a concise summary, highlights promising avenues for future research, and delivers closing reflections.

2. BACKGROUND AND TECHNICAL FOUNDATION

Grasping how quantum computing can revolutionise high-performance computing starts with the essentials of quantum information processing.

The fundamental unit in this domain is the quantum bit, or qubit. In stark contrast to a classical bit, which must settle on either 0 or 1, a qubit can inhabit both states at once thanks to superposition. This feature is typically expressed by writing the qubit's state as a linear combination of the basis vectors $|0\rangle$ and $|1\rangle$, as given in Equation (1).

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle \quad (1)$$

Quantum computing architectures depart from classical designs by enabling the simultaneous exploration of many computational states, which can yield quadratic speedups for specific algorithms. This multidimensional parallelism accelerates the simulation of quantum systems and enhances the efficiency of solving complex optimisation problems within HPC environments [4].

In the integration framework under review, quantum processors act as standalone modules that mesh with existing HPC infrastructures, supporting both cloud-based (off-premises) and locally hosted (on-premises) configurations. Unlike off-site quantum access via remote data centres, the on-premises approach embeds quantum hardware directly in HPC facilities, linking them to conventional systems through shared file systems and high-speed networks (Figure 1). Developing a dedicated resource manager for this local integration harnesses HPC's strengths for quantum simulations while offering a cohesive management layer for hybrid deployments [5]. By reducing implementation complexities and improving execution, the framework is made to enable smooth transitions from simulation backends to actual quantum hardware.

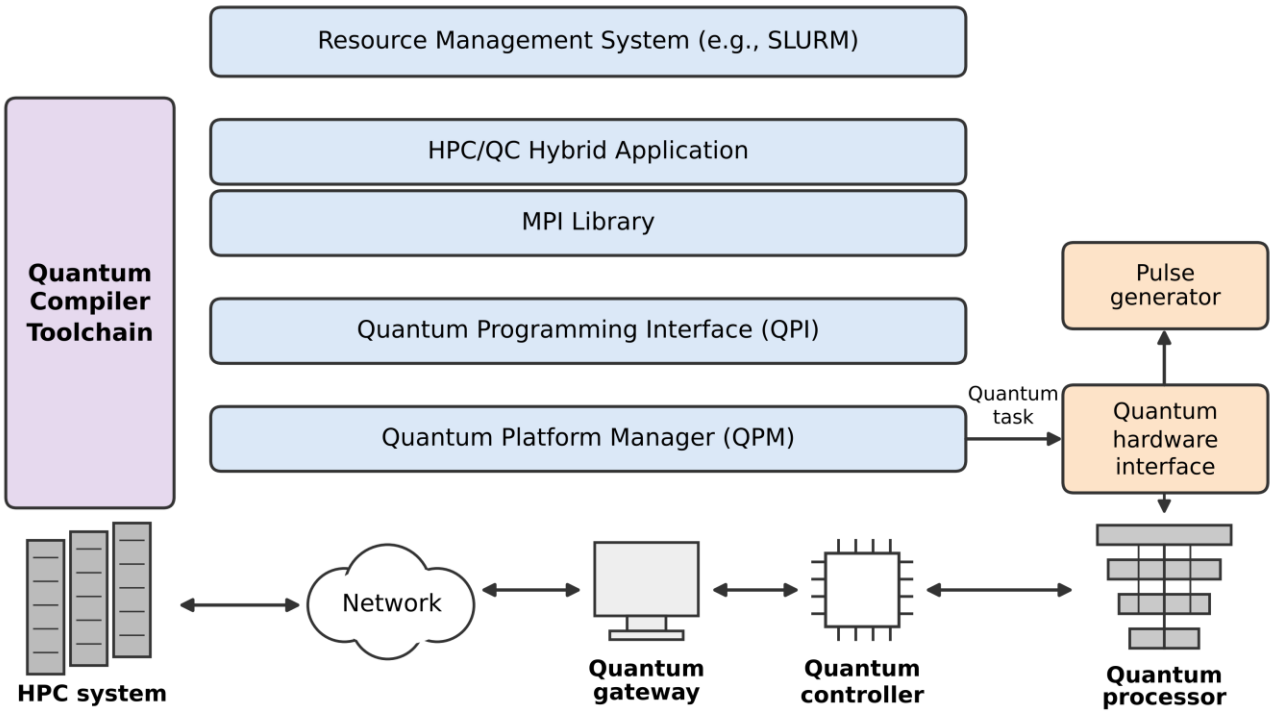

Fig 1: An overview of the physical aspects of QC/HPC convergence [6].

3. LITERATURE REVIEW

Although there has been a lot of research and alliances in the past few decades, the field investigating quantum computing fusion with current high-performance computing power is still in its infancy. Among these are theoretical illustrations of the QHPC interface [7]. A group of Bavarian universities and research institutions called the Munich Quantum Valley [8] is working to create a single software stack for the HPC-QC ecosystem, and ORNL is attempting to integrate quantum runtimes in parallel with other accelerators onto CPUs and GPUs within a well-known task-based kernel framework, IRIS [9].

Some multinational collaboration, nevertheless, emphasises how crucial it is to pursue strong integration initiatives and offer frameworks for successfully improving traditional computation. Funded by the European Union, HPC-QS plans to introduce an open European federated hybrid infrastructure and integrate and combine two quantum simulation machines with two current European Tier-0 supercomputers [10]. In a recent partnership with the RIKEN Quantum Computing Centre [11], IBM agreed to co-locate and integrate the Fugaku supercomputer with the IBM system, which is powered by a 133-qubit IBM Quantum Heron processor. Furthermore, they plan to connect quantum and classical computing resources for HPC processes by creating an integrated framework for

programming based on Qiskit with Pasqal [12].

Last but not least, IQM and Hewlett-Packard Enterprise (HPE) recently teamed up to develop their own form of quantum-HPC integration [13]. Additional advancements in the sector, such as Riverlane's Deltaflow and Nvidia's CUDA-Q, may make hybrid QC-HPC more successful [6].

4. METHODOLOGY

Usually, conventional and quantum logic are combined in the integration of HPC and QC. Building, compiling, optimising, and executing quantum jobs on either real quantum hardware or a quantum simulator are necessary for this integration.

Combining the simulation tool with processes on compute nodes is the current state-of-the-art for integrating quantum simulators in HPC settings. The current strategy of integrating GPUs for speed is similar to this per-process quantum simulator paradigm. Computation unit over-subscription, underutilisation, and a lack of large circuit parallelisation are some of this algorithm's drawbacks.

The purpose of the Quantum Framework (QFw) is to improve the utilisation of HPC resources for quantum simulations. The QFw makes it possible for mixed systems to smoothly switch from simulation backends to actual devices. To control interaction and the completion of quantum jobs, the framework comes with a Quantum Task Manager (QTM) and a Quantum Platform Manager (QPM). The architecture overview of the quantum framework in HPC environments is shown in Figure 2. In order to facilitate the concurrent use of many quantum services, the QFw manages numerous QPMs. It offers a backend for transforming native quantum circuit architectures into QASM 2.0 and enables programs to separately determine the HPC resources needed for classical and quantum logic. Platform-specific processes are used by the QPM to carry out responsibilities, whereas the QTM uses processes like circuit reduction for jobs and consolidation of outcomes.

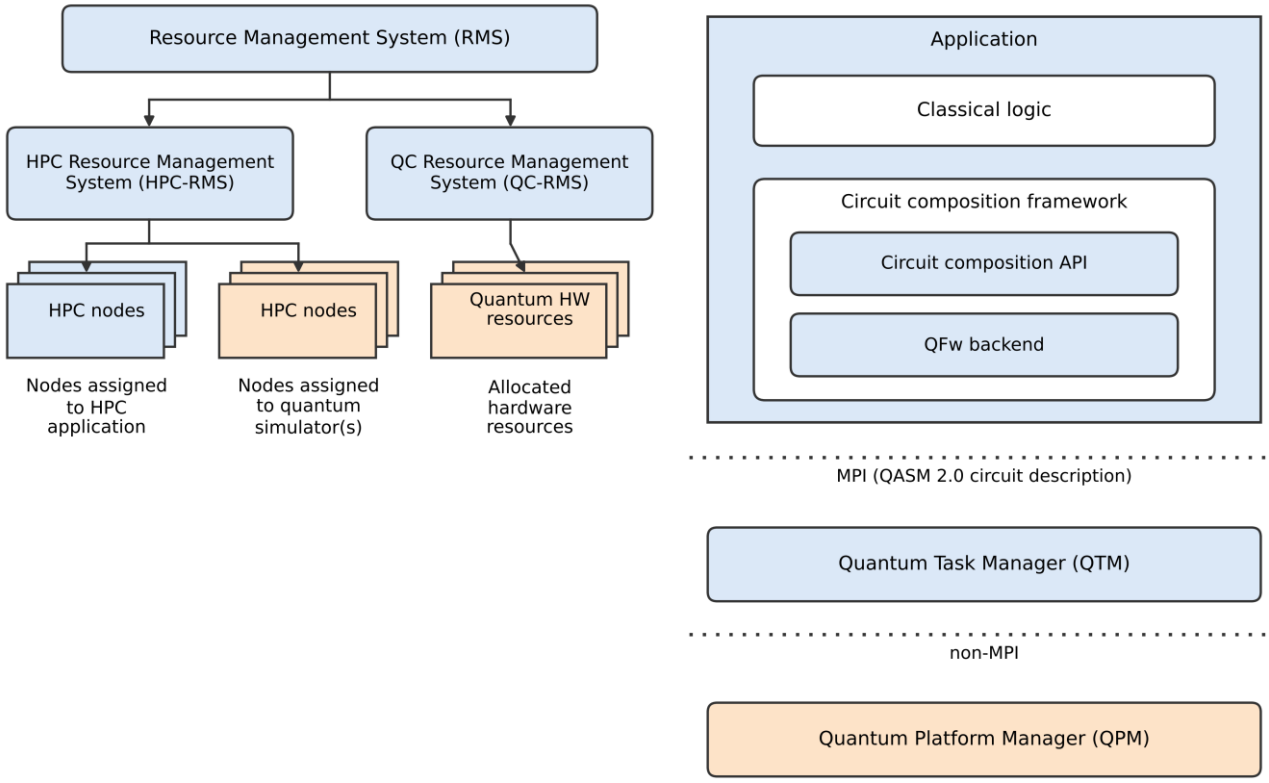

Fig 2: An overview of the quantum framework's architecture for HPC systems

5. INTEGRATION FRAMEWORK

There is a rising movement to develop mechanisms for integrating the expanding QC capacities into HPC settings [14]. A resource management system is still required to coordinate access to the QPU or simulators. The resources that the application requests are scheduled and allocated by this system. For instance, SLURM (Frontier) and IBM Platform LSF (Summit) are currently widely used frameworks for job scheduling in OLCF HPC systems. Nonetheless, in order to guarantee the best possible use of the QC/HPC system, jobs that closely combine classical and quantum workloads need to be co-allocated and co-scheduled. Therefore, one important component of system integration will be the creation of a QC-aware resource management system.

5.1 QC/HPC Integration Models

To meet the above-mentioned hybrid QC/HPC application usage patterns, the framework suggests supporting both a per-job QC model and a single QC resource model. The single-simulation resources, such as the previously described ATOS system and real quantum hardware, are supported by the single QC model. HPC workloads can reserve this one QC resource together with traditional HPC resources to meet the needs of the hybrid application. The per-job QC model allocates a certain amount of quantum resources to each classical HPC job. This method can be used for simulation, but at this point in the development of QC technology, it is not practical with actual quantum hardware. Every hybrid QC/HPC job in this architecture receives two simultaneous HPC node allocations: one is used to simulate quantum circuits, and the other is used to execute the hybrid application's classical logic. Because both allocations can be set separately, different kinds of hybrid applications can have customised resource assignments.

Two essential levels of resource allocation and work scheduling are involved in the QC/HPC integration: (a) The workflow management system parses and compiles workflows as part of the higher-level task scheduling. (b) Job definitions are acquired from the workflow management system at the HPC/QC resource layer, after jobs and their dependencies are assessed for parallel execution and eligible tasks are delivered to HPC/QC resource managers for scheduling. Workflow orchestration tools adjust how finely tasks are subdivided based on user-defined settings, whereas resource schedulers—such as SLURM and PBS—handle the allocation of compute resources among users.

6. RESULTS

This section surveys pivotal breakthroughs in quantum computing that are redefining its synergy with high-performance computing. It emphasises cutting-edge quantum algorithms, as well as the high potential of hybrid quantum-classical architectures, which are seeing improvements in this direction.

Through leveraging quantum physics effects such as superposition and entanglement, these techniques solve specific problem domains faster than conventional technologies. In the context of high-performance computing usage, a lot of these quantum methods have already emerged as promising techniques:

6.1 Shor's Algorithm for Factorisation

In 1994, Shor's algorithm changed the factorisation of big integers by increasing its speed exponentially, as compared with most classical algorithms. Its tendency to possibly compromise public-key cryptosystems is a result of quantum computing advancements. In the scope of high-performance computing, Shor's algorithm sheds light on how quantum computers could handle tasks that are beyond the capabilities of traditional computers.

6.2 Grover's Algorithm for Database Search

Lov Grover came up with this search algorithm in the year 1996 to suggest a quadratic improvement for processing unstructured datasets. This algorithm has been applied in the fields of cryptanalysis, advanced code optimisation, and data mining. Grover's framework can shorten processing time for search and optimisation processes in high-performance computing and quantum computing applications.

6.3 Quantum Approximate Optimization Algorithm (QAOA)

The quantum approximate optimization algorithm integrates quantum and traditional processing to build an approximate model for advanced combinatorial optimisation tasks. It has demonstrated effectiveness in areas such as machine learning model training, network architecture design, and supply chain logistics. Because QAOA runs on today's intermediate-scale quantum processors, it can be readily integrated into existing high-performance computing environments. More broadly, the fusion of quantum computing modules with traditional HPC infrastructures represents a major trend in boosting overall computational power.

6.4 Architectural Overview

In most hybrid setups, a classical computing system is paired with a quantum processor: the quantum unit handles the execution of specialised circuits, while the classical host manages data preprocessing, orchestrates job scheduling, and performs post-run processing.

6.5 Performance Analysis and Benchmarking

The advent of hybrid computing platforms has made rigorous benchmarks and transparent performance metrics indispensable. To completely understand the difference between quantum computing and classical computers across a range of use cases, researchers assembled trustworthy benchmarking models. These benchmarking models put together values including quantum volume, maximum circuit depth, and error-correction efficiencies to present an overall view of each system's capabilities. The ideal model for combining quantum computing and high-performance computing frameworks is the use of a hybrid quantum–conventional computer.

6.6 Comparative Analysis of the Surveyed Algorithms

Table 1 compares the three algorithms discussed above on the problem addressed, the scaling reported in the original sources, and the role each plays in hybrid QC/HPC workflows. All entries are taken from the cited sources and from the preceding sections; no new measurements are reported in this table.

Table 1. Comparison of the algorithms discussed in this section

Algorithm	Problem addressed	Classical reference point	Quantum scaling reported in the source	Role in hybrid QC/HPC use (this paper)
Shor [15]	Integer factorisation and discrete logarithms	Generally thought to be hard on a classical computer	Running time polynomial in the input size	Shows tasks beyond the reach of classical computers; a possible threat to public-key cryptosystems
Grover [16]	Search of an unstructured database of N items	Order N steps	Order √N steps (quadratic improvement)	Shortens search and optimisation processes
QAOA [17]	Approximate solutions to combinatorial optimisation problems	Not compared in the source	Approximation quality improves as the number of levels p increases; circuit depth grows linearly with p (at worst, times the number of constraints)	Combines quantum and classical processing; suited to current intermediate-scale processors

Several differences follow from Table 1. Shor's algorithm [15] is the only one of the three whose reported advantage concerns a change in how the running time grows with input size: it is polynomial for a problem that is generally believed to be hard classically. Grover's algorithm [16] gives a quadratic reduction in the number of steps, not an exponential one, which limits the benefit available to HPC workloads that are dominated by unstructured search. For QAOA [17], solution quality depends on the number of levels p, and circuit depth grows with p, so a better approximation requires a deeper circuit. In a hybrid system, the classical side of the workflow performs the preprocessing that the algorithm requires [17].

6.7 Scaling of Search Effort: Classical Search versus Grover's Algorithm

Grover's algorithm is the one for which the step count is a simple closed-form function of problem size, so its scaling can be compared directly. Table 2 lists the classical order-N and quantum order-√N step counts for database sizes from 10^2 to 10^{12}, and Figure 3 plots the same quantities on logarithmic axes. The values are analytical: constants are omitted, and each step is counted as one query to the database.

Table 2. Number of search steps (constants omitted) for an unstructured database of N items

Database size N	Classical search, order N	Grover's algorithm, order √N	Ratio N / √N
10^2	10^2	10^1	10^1
10^4	10^4	10^2	10^2
10^6	10^6	10^3	10^3
10^8	10^8	10^4	10^4
10^{10}	10^{10}	10^5	10^5
10^{12}	10^{12}	10^6	10^6

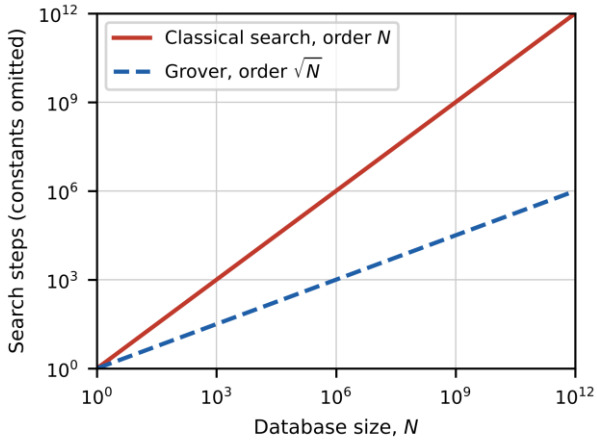

Fig 3: Number of search steps against database size N for classical exhaustive search (order N) and Grover's algorithm (order √N). Analytical curves with constants omitted; no measured data.

On the logarithmic axes of Figure 3, the two curves are straight lines with slopes 1 and 1/2, so the gap between them widens as N grows. At $N = 10^6$ the step counts are 10^6 and 10^3, and at $N = 10^{12}$ they are 10^{12} and 10^6. The ratio equals √N, so the relative benefit increases with problem size. Two limits apply to this reading. First, the comparison counts steps and omits the cost of carrying out each step on real hardware, including the error-correction and hardware-integration obstacles noted in the Introduction, so wall-clock times cannot be inferred from Figure 3. Second, the figure covers unstructured search only; problems that have structure may admit classical algorithms that do better than order N.

6.8 Resource Allocation Models for Hybrid QC/HPC Jobs

Table 3 sets the two resource-allocation models of the integration framework side by side, using the description given in the section on QC/HPC integration models.

Table 3. Comparison of the per-job QC model and the single QC resource model

Attribute	Per-job QC model	Single QC resource model
Quantum resource assigned	A certain amount of quantum resources is allocated to each classical HPC job	One QC resource, such as a single-simulation resource (the ATOS system) or real quantum hardware
How the resource is obtained	Allocated together with the classical HPC job	HPC workloads reserve the QC resource together with conventional HPC resources
HPC node allocations	Two simultaneous allocations: one to simulate quantum circuits, one for the classical logic of the hybrid application; each can be set separately	Not described separately in the framework
Applicability	Simulation; not practical with real quantum hardware at the current stage of QC technology	Both single simulation resources and real quantum hardware

The per-job model gives every classical job its own quantum allocation. This is workable when the quantum resource is a simulator running on ordinary HPC nodes, but it is not practical for physical devices at present. The single-resource model corresponds to a shared device and requires the QC resource to be co-allocated with HPC resources, which is the co-allocation and co-scheduling need identified in the section on the integration framework.

6.9 Summary of Reported Integration Initiatives

Table 4 lists the integration initiatives described in the literature review, together with the integration approach reported for each.

Table 4. Integration initiatives described in the literature review

Initiative	Partners or region	Reported integration approach	Source
Munich Quantum Valley	Bavarian universities and research institutions	Munich Quantum Software Stack (MQSS): a single software stack for HPC–quantum integration, validated within the initiative	[8]
IRIS	Oak Ridge National Laboratory	Quantum runtimes integrated alongside other accelerators, on CPUs and GPUs, within a task-based kernel framework	[9]
HPC-QS	European Union funded	Open European federated hybrid infrastructure combining two quantum simulation machines with two European Tier-0 supercomputers	[10]
RIKEN–IBM	RIKEN Quantum Computing Centre and IBM	Co-location and integration of the Fugaku supercomputer with an IBM system powered by a 133-qubit IBM Quantum Heron processor	[11]
IBM–Pasqal	IBM and Pasqal	Integrated Qiskit-based programming framework linking quantum and classical resources	[12]
IQM–HPE	IQM and Hewlett-Packard Enterprise	Collaboration and joint demonstration of quantum–HPC integration (classical and quantum hardware running integration software) at ISC High Performance 2024	[13]
Deltaflow; CUDA-Q	Riverlane; Nvidia	Further developments that may make hybrid QC–HPC more successful	[6]

Table 4 shows that the initiatives address the problem at different levels: software stacks and runtimes (Munich Quantum Valley, IRIS, IBM–Pasqal), federated infrastructure (HPC-QS), and physical co-location of a quantum system with a supercomputer (RIKEN–IBM). The descriptions in the cited sources are qualitative, so Table 4 does not rank the initiatives. The tables and Figure 3 in this section were compiled from the cited sources and from analytical expressions; no new experiments on quantum hardware or simulators were run for this review, and measured benchmarks of a specific QC/HPC system remain a task for future work.

7. DISCUSSION

In many fields, the integration of quantum algorithms into high-performance computing is eventually producing important progress. This section gives well-structured examples and case studies showing how HPC and quantum computing help in finding solutions to problems faced by the world.

7.1 Financial Modelling and Risk Analysis

Using quantum machines and a conventional, powerful computer is promising to redirect economic prediction, notably in cases that demand huge numerical computations and optimisations. For instance, in the finance sector, risk analysis and evaluation of reports rely mainly on the traditional Monte Carlo sampling. The Quantum Approximate Optimization Algorithm is being used to speed up searches to allocate resources.

7.2 Drug Discovery and Molecular Modelling

Quantum machines are exceptionally well-suited for drug development and pharmacological studies because they can natively emulate quantum mechanical processes. Accurately predicting molecular conformations is vital for understanding how drug candidates interact and for designing new therapeutic agents.

8. RESEARCH GAPS AND INNOVATION OPPORTUNITIES

Quantum computing and high-performance computing can enhance computing power, but there still exist some gaps to resolve. A deeper look into research gaps and opportunities is examined below in the process of integrating QC and HPC.

8.1 Hardware Integration Issues

Integrating Quantum Computing (QC) with conventional High-Performance Computing (HPC) frameworks has seen a setback in terms of hardware issues.

Quantum computers need to be at normal level temperatures. High-performance computing computers do not have advanced algorithmic standards to level the temperature in terms of hardware. Another issue is that the movement of the qubit states to and from the traditional computers needs shielding, timing controls, and noise suppression to overcome decoherence.

8.2 Software Compatibility and Development Tools

Developing programs that can use quantum and conventional processors remains a challenge in the field. Researchers are working on compiler infrastructures that can generate, optimise, and schedule instructions across quantum and classical units in a single workflow. The inherently probabilistic outputs of qubits make it hard to build deterministic validation suites and interactive debuggers for hybrid algorithms, complicating error diagnosis and performance tuning.

8.3 Scaling Quantum Systems to HPC Levels

Bringing quantum architectures up to the throughput of modern HPC systems uncovers two fundamental scaling challenges:

- Growing qubit populations: Ramping up the total count of qubits is essential, yet doing so without sacrificing coherence, gate fidelity, or precise control over each element remains a central engineering obstacle.
- Expanding interconnect infrastructures: Designing

network topologies and communication channels that can reliably tie together hundreds—or eventually thousands—of qubits is critical for building quantum machines with HPC-level performance.

8.4 Optimisation Strategies for Large-Scale Quantum-HPC Systems

To unlock the full potential of expansive hybrid quantum–classical platforms, entirely new, inventive approaches must be developed to boost their overall efficiency and performance.

- Workload Distribution: There is an ongoing study into the best ways to divide computational jobs between quantum and classical resources in a hybrid system.
- Resource Allocation: There are particular difficulties in creating algorithms for the effective distribution of both quantum and conventional resources in a shared HPC environment.
- Energy Efficiency: For large-scale deployments, controlling the energy usage of quantum-enhanced HPC systems is crucial, especially in light of the power needs of cryogenic cooling.

Quantum physicists, computer scientists, electrical engineers, and HPC specialists must collaborate across disciplines to deal with these issues. Once these obstacles are removed, combining quantum computing with high-performance computing (HPC) could transform processing power in a number of science and industrial fields.

For some issues, better conventional methods have been developed as a result of insights gained through quantum techniques. For algorithmic studies, this "quantum inspiration" is a rich field. Finding quantum algorithmic methods that can be applied to traditional computing to improve HPC execution is a further goal, especially in fields like machine learning and optimisation.

9. CONCLUSIONS

Combining quantum computing and high-performance computing (HPC) is a scientific technology field that has the ability to completely change how challenging issues are addressed in a variety of fields. This paper has examined the basic ideas of quantum computing, recent developments in quantum algorithms, integration frameworks, and hybrid quantum-classical systems, as well as the major obstacles that need to be addressed in the areas of software development, hardware integration, and scalability. Even though the topic is still in its infancy, the quick development of quantum technology, along with creative studies of quantum algorithms and error correction, suggests that in the future, quantum-enhanced HPC systems may be able to solve problems that were previously unsolvable. Continued industry-academia cooperation, funding for quantum-HPC testbeds, and the creation of a trained labour force able to bridge the gap between quantum and classical computing paradigms are all necessary to realise this promise. Given that HPC is on the verge of a quantum revolution, it is obvious that the ensuing decades will bring about innovative discoveries that have the potential to revolutionise entire sectors, speed up scientific research, and expand knowledge of the cosmos.

The study paves openings for potential advances in processing powers by providing researchers, engineers, and industry professionals with a useful platform for comprehending and utilising the interaction between quantum computing and HPC.

10. RECOMMENDATIONS

The combination of quantum computing and high-performance computing (HPC) creates fascinating new research and development opportunities as the area develops further.

By taking advantage of the characteristics of unusual quantum states of matter, topological quantum computing holds out the possibility of more stable qubits. Current quantum systems may be able to overcome some of their decoherence issues with this method. Further work should focus on creating useful topological qubit implementations and incorporating them into scalable quantum processors that work with high-performance computing (HPC) frameworks.

Increasing the effectiveness of single-photon sources and detectors and creating photonic circuits that can carry out intricate quantum processes to a significant degree is a field that can be researched further.

11. DECLARATIONS

All authors declare that they have no conflicts of interest.

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