



QC Next Innovation Project Final Report

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Comment

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1 Management Summary

Quantum computing (QC) is considered a future key technology on both national and EU levels. The immense potential of this technology can have a disruptive impact on the economy and thus on German and EU sovereignty.

This report highlights aspects for strengthening the German quantum computing ecosystem. The focus is on the digital infrastructure. It summarizes the results of the *QC Next innovation project* on the *quantum computing software stack*. This project was conducted by an interdisciplinary science and industry consortium as part of the *Digital Technology Development* funding program of the German Federal Ministry for Economic Affairs and Climate Action (BMWK).

The purpose of this project was to determine the scientific and technical status of the German quantum computing software infrastructure and to develop an innovation concept building on this.

Part I of this document is a retrospective work report, summarizing the results achieved during the funding period as the basis for the QC Next innovation concept. This part was based on the work package structure of the conceptualizing project (see Figure 1) and especially covers the following key analysis areas:

Conceptual/scientific approaches (Work Package 2): Investigation of quantum computing software stack concepts commonly used in the literature as a basis and starting point. The result is a synthesized representation of the quantum computing software stack, supplemented with missing elements. This serves as the technical basis for the QC Next innovation concept.

Technology/infrastructure analysis (Work Package 3): Identification of existing quantum computing software components and their integration in the developed stack. This analysis serves as an application-oriented starting point for the QC Next innovation concept.

Organizational structures and Governance (Work Package 7): Research and analysis of suitable organizational structures and governance mechanisms based on technical literature and existing flagship projects. Derivation of recommended, useful structures and processes for implementing and continuing the innovation concept in a flagship project.

Part II builds on these results, is forward-looking and presents the QC Next innovation concept. It deals with necessary subsequent innovative steps to strengthen the competitiveness of the German quantum computing software ecosystem in comparison with international competitors. This includes strategic approaches, objectives and added value as well as the organizational structures of a targeted flagship project. Involved are, among other things, the consolidation and networking of existing software components along the stack to enable more efficient instantiation of a comprehensive reference architecture and its derivatives.

Taken together, these two sections comprise both the report on completed work and progress achieved as well as the vision and recommendations for next steps. A coherent and feasible path is presented towards the development and sustainable provision of a quantum computing software stack for future end users from science and industry. Hence, it will contribute to strengthening the future key technology of quantum computing and thus German and European sovereignty.

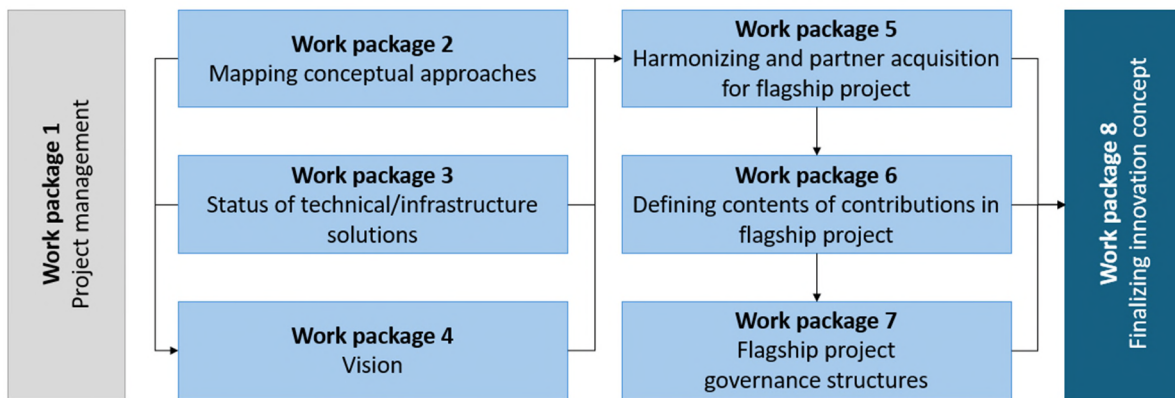


Figure 1: Overview of work packages from overall project description

Part I

Work report

2 Initial situation, research and results

Quantum computing is one of the most promising technologies of the 21st century in terms of economic potential. Though it is not yet powerful enough to provide any immediate economically relevant added value, the race is on to capitalize on this future key technology.

In January of 2025, the European Quantum Industry Consortium (QuIC) published its second report on patent applications in the field of quantum technology.¹ Patents are just one indicator highlighting the race for this technology. However, the patent situation is symbolic for the current state of German quantum computing research and development (R&D): looking at the ranking of the 50 stakeholders with the most patents, there is a single European company, in 50th place. China and the USA head the list. It is also noteworthy that the EU is the only region listed in this ranking that does not dominate its own domestic market in terms of patent applications. In other words, more patents in Europe are filed by foreign companies than by European companies. The first EU company in the ranking of patent applications in the EU is in 9th place, while the first German company on the list is the Fraunhofer Gesellschaft, in 24th place. The authors of the QuIC report stress the negative economic and innovative consequences that this distribution entails for Europe. Overall, the report supports the need for consistent and targeted efforts to achieve competitiveness in quantum computing and to ensure independent sovereignty.

2.1 Initial funding policy situation

In the *Quantum Technology Action Plan* adopted in April of 2023, the German federal government assigned a central role to the development of this future technology (German Federal Ministry of Education and Research (BMBWF) 2023)². Quantum computing (QC) has been attracting significant attention from politicians and investors in recent years. Accessibility to QC resources continues to grow and is becoming increasingly heterogeneous in terms of the underlying hardware. Especially the emulation of quantum computers with conventional processors and integration into high-performance computing (HPC) clusters are contributing to the development of this technology. The development of application software is thus facilitated and further accelerated by projects for developing software tools for high-level programming.

The number of quantum computing use cases for which proof-of-concepts are being provided continues to rise steadily. Hardware and software development in Germany is currently driven primarily by government funding. The German federal government intends to invest three billion euros in developing quantum technologies and implementing these in applications by 2026. This places Germany first in Europe and second worldwide after China. Funding is still relatively high in comparison with the forecast market volume by 2030 for QC in general and application software in particular. There are now dedicated networks in six federal states pooling regional expertise, connecting stakeholders from science and industry in QC and other quantum technologies and supporting them with state funding. These include the German federal states of Lower Saxony, North Rhine-Westphalia, Bavaria, Hamburg, Berlin and Baden-Württemberg.³

¹ [A Portrait of The Global Patent Landscape in Quantum Technologies 2025](#)

² [Handlungskonzept Quantentechnologien der Bundesregierung](#)

³ [Quantencomputing – Markt, Zugang, Perspektiven \(Technologieprogramm des BMWK\)](#)

However, Germany and the EU are lagging in private investments. The report on EU competitiveness published by former ECB President Mario Draghi in September 2024 also lists quantum computing as a key future technology. However, it also presents a sobering picture: Measured by investment volume, five of the ten largest quantum technology companies, including quantum computing, are already based in the USA, with four more in China and not even one in the EU.

The American companies that emerged from the first digital revolution currently dominate the market and the development of quantum technology. Their technical expertise in digitalization and artificial intelligence acquired over the last two decades, combined with high capital strength, gives these companies a comparative advantage in developing quantum computing solutions.

In late October 2024, a group of experts from the EU Commission came to a similar conclusion to that of the Draghi Report: "*The EU is comparatively weaker than the US and China when it comes to introducing, commercializing and scaling new technologies.*"⁴

Research activities in the field of quantum computing are funded by programs such as *Digital Technology Development* from the German Federal Ministry for Economic Affairs and Climate Action (BMWK) or *Application-Oriented Quantum Computing* from the German Federal Ministry of Education and Research (BMBF).

Quantum computing software development has already been actively pursued in Germany for several years. In the PlanQK joint research project *Platform and Ecosystem for Quantum Applications* (2020-2023), the BMWK especially funded the development of an open platform enabling developers and users to access and collaborate on application-oriented software for quantum computing⁵. This grant initiative thus represented an important building block in establishing sovereign quantum computing structures in Germany and Europe in order to ensure access to QC software and QC computing power for SMEs and to develop corresponding expertise. The subsequent funding program (2021-2025) *Quantum Computing - Applications for the Economy, Platforms, Tools and Methods for the Development and Integration of Quantum Computing Applications* further promoted the development of platforms, tools and methods for economic development and integration of quantum computing applications. The EniQmA⁶, Qompiler⁷ and QCHALLENGE⁸ funding projects from this program are scheduled to continue until mid-2025. In addition to already completed projects such as AutoQML⁹ or SeQenC¹⁰, these projects address the various layers of the quantum computing software stack, where the individual software components are rarely coordinated/standardized.

Apart from these developments, the BMBF has also funded various projects based on quantum computing software, such as the QCStack project for developing cross-technology middleware¹¹ and the QuCUN project, which is developing a software platform giving users access to a library

⁴ Commission: Directorate-General for Research and Innovation, Align, act, accelerate – Research, technology and innovation to boost European competitiveness, Publications Office of the European Union, 2024

⁵ [PlanQK - Plattform und Ökosystem für Quantenapplikationen](#)

⁶ [EniQmA - Ermöglichung hybrider Quantum-Anwendungen](#)

⁷ [Qompiler - Standardisierter Quanten Software Stack](#)

⁸ [QCHALLENGE - Quantum-Classical Hybrid Optimization Algorithms for Logistics and Production Line Management](#)

⁹ [AutoQML – Neue Potenziale für automatisiertes Machine Learning mit Quantencomputing](#)

¹⁰ [SeQenC - Souveränität für Quantenlösungen in der Cloud](#)

¹¹ [Projekt QCStack - Zentraler Softwarestack für Quantencomputer](#)

with implementations and explanations of standard use cases and to quantum computing resources¹².

The research landscape in Germany is characterized by a high degree of fragmentation, and R&D projects are also largely autonomous. The pooling of resources and expertise will therefore play a key role in maximizing innovation potential.

Based on the initial situation outlined above, the BMWK has entrusted the consortium of Fraunhofer IAO, KIT and Kipu Quantum with developing an innovation concept to determine the need for further funding for the quantum computing software stack and its harmonization.

This final report summarizes the results of the QC Next project. This project entailed an in-depth analysis of conceptual approaches and an inventory of technical and infrastructure solutions relating to the quantum computing software stack. Building on this, the report contains an innovation concept defining specific measures for the targeted further development of German quantum computing software solutions. This includes the development of a reference architecture and various reference implementations, approaches to strengthen the quantum software ecosystem and standardization considerations. This approach to a comprehensive quantum computing software stack solution intends to accelerate the *lab to fab* transition.

2.2 Funding policy objectives

The project implemented several funding policy goals. These are listed in Table 1 below.

Objectives of tender	Goal fulfillment in project
Digital transformation to improve international competitiveness of the German economy in the provision and use of digital technology.	<ul style="list-style-type: none"> ▪ Investment in research and development and supporting SMEs ▪ Expanding the ecosystem ▪ Knowledge transfer to industry
Addressing current trends and developments, specific digitalization needs of the economy and the market, including timely implementation.	<ul style="list-style-type: none"> ▪ Analysis of requirements from science and industry
Expansion and strengthening of future technology, digital innovation and infrastructure.	<ul style="list-style-type: none"> ▪ Contribution to quantum awareness and quantum readiness in Germany and Europe ▪ Expanding the ecosystem
Contribution to strengthening sovereignty and maintaining German and European competitiveness.	<ul style="list-style-type: none"> ▪ Development of a resilient framework concept for the quantum computing software stack ▪ Promotion of orientation, systematization and connectivity
Reducing development risks in market-oriented research.	<ul style="list-style-type: none"> ▪ Development of a resilient framework concept for the quantum computing software stack
Exploiting spillover effects.	<ul style="list-style-type: none"> ▪ Integrating science and industry and jointly elaborating relevant requirements

¹² [QuCUN - Das Quantum Computing User Network in Deutschland](#)

	<ul style="list-style-type: none"> ▪ Knowledge transfer to industry ▪ Further development of initiatives and networks ▪ Follow-up projects and investments
Achieving sustainability goals	<ul style="list-style-type: none"> ▪ Highly qualified employees in the workplace (%)
Spotlighting solutions developed in projects for the professional community and for society	<ul style="list-style-type: none"> ▪ Publications ▪ Presentation of the funding program at trade fairs, conferences and workshops ▪ Ecosystem & outreach

Table 1: Funding policy objectives and their fulfillment in the QC Next innovation project.

2.3 Scientific and conceptual goals

The purpose of the project was to formulate an innovation concept for the quantum computing software stack. This innovation concept (see Part II of this report) is intended to serve as the basis for the design and implementation of a flagship project. Existing conceptual approaches and infrastructures were first mapped and analyzed to establish a solid basis for development of the innovation concept. The interdisciplinary consortium then developed a vision for the future quantum computing software stack, in which a consistent reference architecture strengthens dynamic innovation in quantum computing and specifically expands Germany's technological sovereignty.

The early involvement and broad participation of the community promote acceptance of the planned reference architecture and supports the transfer of technology from the research environment to practical applications (*lab to fab*). The underlying work and the resulting conclusions and vision were therefore presented to representatives from industry and research in workshops and discussed with them to promote acceptance, obtain feedback and initiate partnerships for future projects.

Key research questions were also defined to serve as the basis for further developments. These elements were formulated in the *QC Next innovation concept*, which is presented in Part II of this final report.

2.4 Current scientific and economic status

Implementation of quantum algorithms. The quantum hardware currently available consists of a limited number of noisy qubits (in order of 10-1000) with shallow circuit depth and limited connectivity between the qubits (NISQ hardware) [1]. Examples of industry-specific applications include simulating molecules by Variational Quantum Eigensolver (VQE) [2] methods, which is the most widely implemented NISQ algorithm [3]. This has already been successfully demonstrated for small chemical molecules using various hardware architectures [4, 5].

However, the approaches first used have demanding hardware requirements [6, 7]. The system sizes available to date are too small to compete with conventional methods [8].

In contrast to current noisy hardware, error-corrected systems can execute significantly longer and more complex circuits. This is achieved by interconnecting multiple physical qubits with error correction codes to form logical qubits. Significant progress in this direction has recently been demonstrated [9] and several quantum hardware companies (e.g. Xanadu, QuEra) are working

intensively on implementing error-corrected hardware [10, 11]. One of the algorithms that can only be executed on error-corrected hardware is the Quantum Phase Estimation algorithm (QPE) [12], which is also used in Shor's factoring algorithm, for example [13]. Qubitization [15] or other approximations to the time evolution operator [16] can be used to represent the Hamilton operators as a unitary matrix on quantum computers in order to use QPE.

Quantum software platforms. Initiatives in software platform development cover different areas of use for quantum computers. Platforms for solving specific problems are covered by providers such as PLANQK [17], as well as by D-Wave and Quantagonia [18], which enable users to specify mathematical problem formulations and solve them with simulators, quantum annealers, as well as on true quantum computers. The quantum layer is generally treated as a 'black box' in this case. The user therefore does not have to (and cannot) inspect and understand these in detail and must accept predefined use cases and limited transferability when using them. Users wishing for greater insight when selecting their solution approaches must currently still implement these themselves. Specially developed frameworks are available for this, such as IBM's Qiskit algorithms [19] or the Qrisp framework developed by Fraunhofer FOKUS [20]. These, however, require a high degree of expert knowledge. Yet, there is no generally applicable toolbox with reusable and adaptable quantum algorithmic methods for (partial) optimization problems, nor any combined solution approaches for complex optimization problems.

Quantum computing software stacks. The most established quantum computing software stacks are strongly monolithic in design and closely coupled with specific hardware manufacturers. They include a suitable runtime infrastructure and tend to form closed ecosystems. Several current research projects have the goal of more modular software stacks in combination with extendable runtimes that can decouple the various layers in the stack. Examples of this are the Munich Quantum Software Stack [21], the Quantum Delta software from the Technical University of Delft and the Superstaq from the University of Chicago, which is now supported by Infleqtion [22].

3 Scientific and technical results

3.1 Mapping conceptual approaches

The first basic step in designing a robust innovation concept for the quantum computing software stack was a systematic literature review of existing concepts for quantum computing software stacks. This yielded a detailed overview of quantum computing software stacks. The project consortium focused on identifying and analyzing key definitions, recurring components and patterns of architecture in academic, commercial and theoretical quantum computing software stacks. The primary goal was to extract these conceptual approaches and to understand how different software stacks are aligned or complement each other.

The results of this study provide insights into the similarities and differences between the quantum computing software stacks investigated. The findings also provided the basis for workshops and the design of potential partnerships enabling the development of a comprehensive quantum software ecosystem.

The scientific publications offer various perspectives on quantum software stacks. The following section summarizes their most important aspects: Definitions, layers and recommendations or requirements.

3.1.1 Defining the quantum computing software stack:

Although there is no strict, generally accepted definition, scientific literature describes quantum computing software stacks as a structured approach to bridging the gap between high-level quantum algorithms and the physical implementation of quantum computers. Quantum computing software stacks provide a multi-layered framework, often inspired by classical computer architectures. They include all software – and sometimes hardware components – required to develop, compile and execute quantum algorithms on quantum devices.

Some studies describe quantum software ecosystems, which is a broader concept encompassing not only the actual stack but also the surrounding stakeholders, tools and interactions. This includes aspects such as algorithm design, results processing tools, compiler optimization, integration with classic HPC environments and user access models.

3.1.2 Layers in the quantum computing software stack

The individual layers and their internal structure can vary in different studies, reflecting the historical development of quantum computing software stacks. However, common themes can be identified:

- 1. Application layer:** This layer represents the highest level of abstraction, where users define problems and algorithms without the need for in-depth knowledge of the underlying quantum mechanics or hardware. This layer includes the following:
 - *Applications:* User-side software that uses QC for specific tasks.
 - *Algorithms:* Methods for solving computational problems using quantum principles.
 - *High-level programming languages:* Tools for expressing quantum algorithms in a human-readable format, such as Quipper, Scaffold and Q#.
 - *Quantum software development kits (SDKs):* Frameworks such as Cirq and Qiskit that simplify the development and execution of quantum circuits.
- 2. System layer:** This layer acts as an intermediary between the application layer and the physical hardware and performs tasks such as compilation, optimization and resource management. The components include the following:
 - *Compilers:* These translate high-level code into low-level instructions for execution by quantum processors.
 - *Runtimes:* A runtime environment, possibly in the form of a virtual quantum machine, is required to execute the compiled quantum programs and integrate these into non-quantum systems.

- *Quantum instruction set architecture*: Defines the basic operations that a quantum processor can execute and other figures of merit¹³ that are relevant for providing circuits (gate sets, coherence times, etc.).

3. Physical layer: This layer is the physical implementation of quantum calculation. These include:

- *Quantum error correction*: Methods for reducing the noise and errors in current quantum devices.
- *Control electronics*: Generation of signals for manipulating and measuring qubits to bridge the gap between classical control systems and the quantum device.
- *Quantum hardware*: This comprises the physical qubits, their control and measurement systems and the underlying technology (e.g. superconducting transmon qubits or trapped ions).

4. Cross-layer aspects: Some aspects are not exclusively limited to a single layer of the quantum computing software stack, or they represent useful, but not essential, extensions of the stack. Examples:

- *Quantum/classic splitting*: Many applications involve a hybrid approach where classical computers perform preprocessing and postprocessing tasks, while quantum computers execute specific calculations. The stack must facilitate communication and data transfer between these domains.
- *Hardware models and error models*: Although characterizing the specific properties and limitations of the underlying quantum hardware is critical to the development of effective compilation and error-correction strategies, it is difficult to limit this to a specific layer.
- *Verification and benchmarking*: New tools are needed to check the correctness of quantum software and to evaluate the performance of different hardware platforms.

Figure 2 presents the first draft for a prototypical quantum computing software stack. This is based on analyses of scientific publications, discussions within the consortium and expert assessments in the community workshop. While this "proto-stack" largely follows the above findings, it goes beyond the state of the art (and the state of technology) in two aspects. First, the translations that are structured in the system level in the literature are arranged laterally over several layers here, as they form the transformation between multiple layers. Also, many scientific publications lack an explicit approach to how the different layers interact with each other. This requires the definition of corresponding interfaces, which are represented by the interface symbols on the right of the prototypical stack.

¹³ Hardware parameters such as coherence or connectivity.

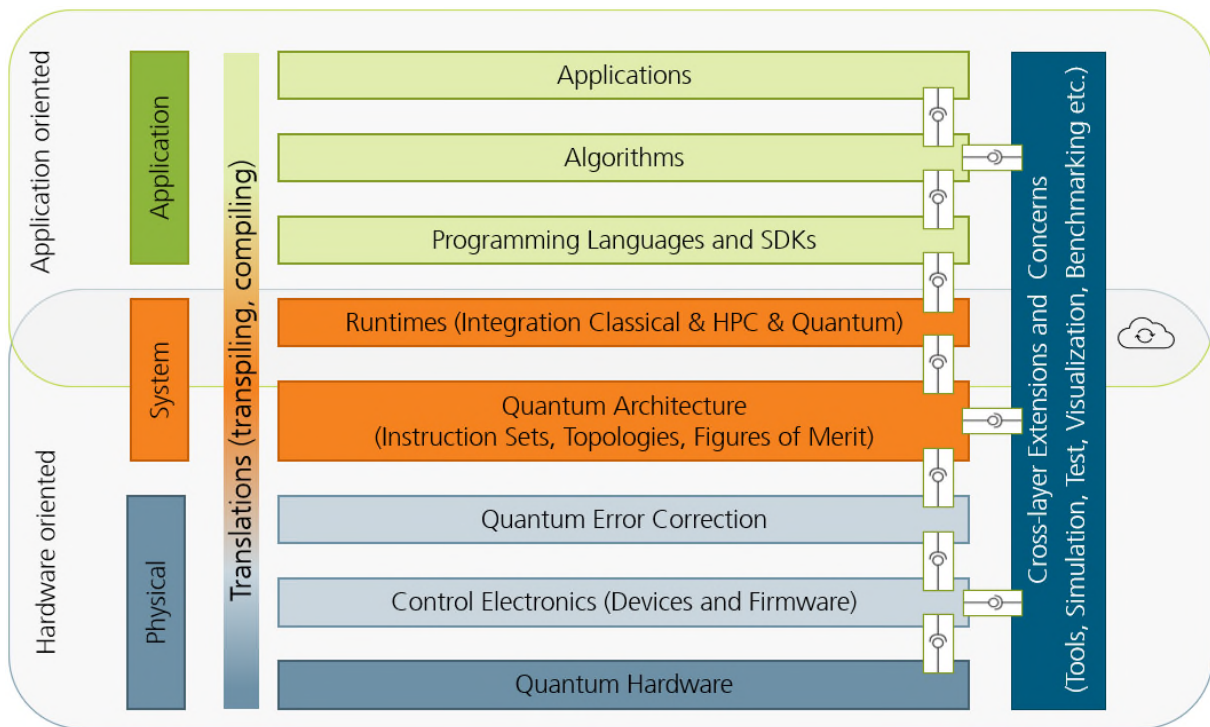


Figure 2: Software stack

3.1.3 Recommendations and requirements

The publications list several recommendations and requirements for creating effective quantum software stacks. A common theme is that quantum software stacks are not simply about replicating classic architectures. Instead, they require new approaches, abstractions and tools to effectively harness the computational power of quantum hardware:

1. **Agnosticism and compatibility:** Ideally, the quantum computing software stack must support multiple quantum hardware platforms and programming languages to enable flexibility and prevent vendor lock-in.
2. **Coexistence with classical computing:** Seamless integration with existing high-performance computing (HPC) systems is critical to enabling hybrid workflows and leveraging the strengths of both classical and quantum resources.
3. **Multi-layered abstraction and modularity:** A clear separation of requirements between the individual layers enables independent development and optimization of the various components.
4. **Efficient resource management:** Quantum resources are scarce and expensive. The stack should optimize their allocation, planning and use.
5. **Error handling and fault tolerance:** With the noisy nature of current quantum hardware, robust error models and mitigation strategies are of critical importance.
6. **User-friendliness and accessibility:** Abstracting complexity and providing intuitive interfaces for different user groups (e.g. algorithm developers, application programmers) are crucial for broader acceptance.
7. **Tool support for verification, validation and testing:** Specialized tools absolutely must be developed to ensure the quality and correctness of quantum software.

8. **NISQ-ready and FTQ-proof:** The stack must be designed for applicability in the current NISQ era, while being robust enough to remain viable in fault-tolerant quantum computing with few adjustments.

3.2 Status of technical/infrastructure solutions

The second fundamental step in designing a robust innovation concept for the quantum computing software stack was a systematic examination of the solutions available on the market and their position in the prototypical stack developed in the first step. The results of research into commercial offerings and open source implementations (see Figure 3) from quantum computing research projects reveal significant differences in the objectives and maturity of the solutions. While commercial offerings usually seek to provide market-ready, immediately applicable solutions, research projects focus more on the development of basic technologies and experimental approaches.

Analyzing the commercial offerings clearly shows that these are often developed as proprietary, i.e. manufacturer-specific, systems in the form of black boxes. This means that the underlying software stack is not transparent to users. However, many solutions offer a certain degree of flexibility, such as by supporting multiple hardware providers. This is accompanied by the provision of SDKs and APIs, most of which are open source.

In contrast, the open source implementations from research projects focus on investigating and providing new tools that address more general requirements such as error correction, simulation, traceability, reproducibility and benchmarking. These tools provide essential support for complex development steps in quantum computing but often take on the form of prototypical solutions. Research results are often isolated and are less geared towards collaboration or market adaptation. However, the use and provision of open source technologies are highly important for providing access to the results for the scientific community and for promoting further development.

In summary, the research shows that despite progress in commercial solutions and funded research projects, there is a significant need for harmonization. The potential of quantum computing in Germany could be significantly increased by a stronger connection between market-ready and experimental approaches and a focus on standardized and interoperable solutions. Important keys here are cooperation between industry and research and a focus on open source development.

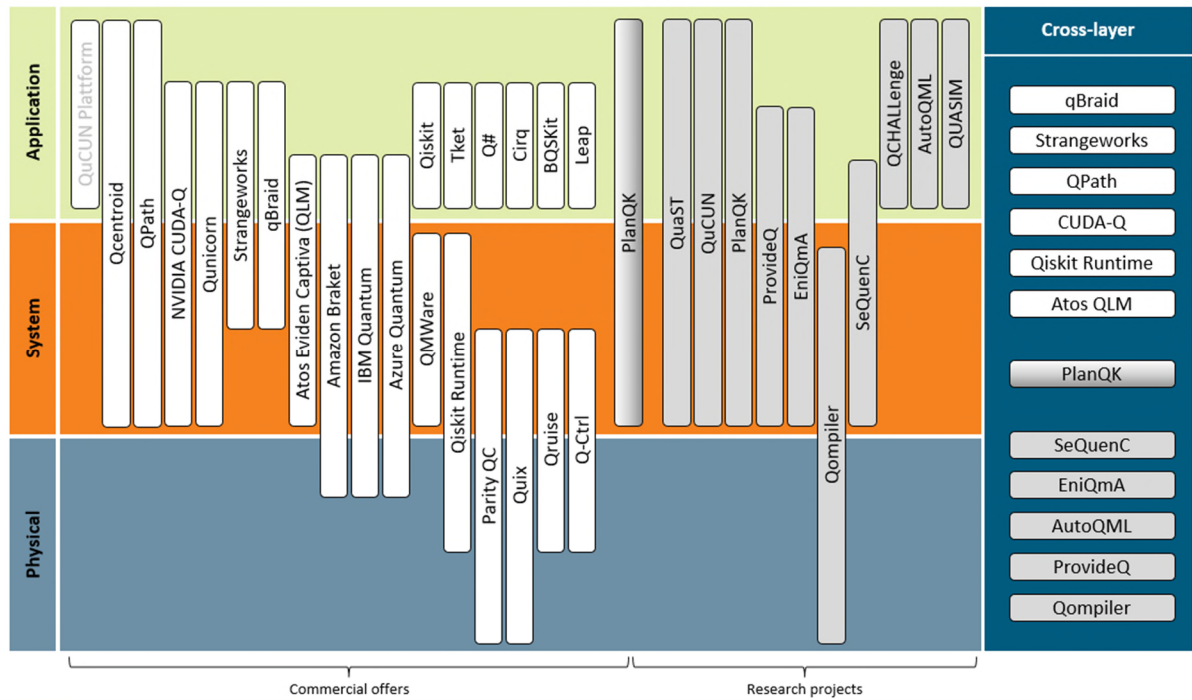


Figure 3: Commercial offers and research projects along the defined software stack.

3.3 Vision and governance for flagship projects

Building on the results of the conceptual approaches and technical/infrastructure solutions, the third step was to develop a vision for the QC Next project. A workshop was held among the consortium partners for this purpose. This workshop presented the results of the previous analyses and the approach for developing the vision. The steps to develop the vision were implemented together within the specified content framework.

The steps involved in developing the vision followed a proven generic approach:

1. **Analysis of status quo:** Joint evaluation of the current state of the art, existing challenges and opportunities to establish a technically sound and clearly defined starting point.
2. **Definition of target perspective:** A long-term vision for addressing a QC Next flagship project was developed.
3. **Identification of key building blocks:** The key content and principles of the vision were defined based on the results of the analyses, the discussed future prospects and the long-term goals.
4. **Development of guiding principles:** Guiding principles and higher-level values were formulated to strategically align the vision. For orientation and inspiration, a best-practice collection of vision texts was used, drawn from the contexts of companies, organizations and major projects.
5. **Iterative refinement:** The modules developed were discussed in an iterative process, further specified and developed in a consistent vision text.

The result is the following vision for the QC Next innovation concept:

"We accelerate and optimize the development and application of quantum computing through a comprehensive and consistent reference architecture.

The time to market for quantum solutions will be significantly reduced, the creation of efficient QC value chains will be promoted, and the technological sovereignty of the German economy will be strengthened."

In addition to the aforementioned steps in vision development we explored how governance can be structured in terms of managing a multi-stakeholder constellation to implement the QC Next innovation concept. We drew on findings from the literature on the subject and two qualitative interviews with knowledge carriers from projects of a similar size and constellation. The findings are summarized here and presented in Part II of this document as a proposed organizational chart.

The development of quantum computing technologies ranks among the most ambitious and promising projects in research and development. The field is characterized by significant technical complexity, dynamic scientific progress with a high degree of uncertainty, public funding and global competition. It also entails pronounced interdisciplinary aspects requiring cooperation between different stakeholders from universities, companies and public institutions. Expectations are high not only to achieve technological and scientific breakthroughs, but also to transfer these to the economy to solve relevant and ultimately also societal problems. The design and implementation of contemporary structures, processes and artifacts for governance in the sense of harmonizing project management of autonomous and indispensable partner organizations is challenging. For the QC Next innovation concept, we define *governance* as the holistic management and organization of the collaborative effort in a consortium of research institutions and companies with different specialist backgrounds in a complex and dynamic field such as quantum computing. Specifically, governance encompasses the structural, procedural and normative regulations that provide the best possible support for the collective elements in achieving the objectives of the project. It promotes transparency, efficient knowledge transfer, targeted integration of knowledge and strategic utilization of the results while simultaneously complying with legal and ethical standards and ideally also promoting trust and acceptance. A balance must be struck between proven and established mechanisms of control and new elements that are suitable for supporting coordinated and collaborative action by numerous stakeholders from different knowledge domains and with different, sometimes diverging interests.

In the present case, governance can be broken down in three key dimensions:

1. **Structural dimension:** This includes the clear allocation of roles and responsibilities among stakeholders involved such as universities, companies and public institutions as well as the establishment of decision-making and steering committees to enable smooth coordination.
2. **Procedural dimension:** This includes mechanisms for communication, conflict resolution and decision-making, including regular reporting cycles and milestone checks to monitor project progress and keep it on track.

3. **Normative dimension:** This dimension focuses on promoting transparency, ethics and compliance, especially in handling public funding, to ensure the trust of those involved and the public.

A modern governance approach also integrates the principles of the platform economy to improve the efficiency and flexibility of R&D projects. In this context the term *platform* is understood in a broader sense: Here, a platform is not a digital solution in the narrower sense, but rather the platform concept refers to the actual desired multi-stakeholder project structure itself. The governance structure therefore accounts for the points listed below within the framework of the QC Next innovation concept.

- *Interoperability through clear interfaces:* Defined processes and standardized handovers establish synergy, promote collaboration and minimize redundancy.
- *Networking effects:* Workshops and exchange formats strengthen interaction and knowledge transfer and contribute to sustainable anchoring of results.
- *Participative governance:* Involving the various stakeholders in decision-making processes distributes responsibility and promotes acceptance and innovative management approaches.
- *Flexible resource allocation:* Dynamic prioritization and targeted incentives enable a rapid response to changes. This will only be possible to a limited extent in a public funding context and is reflected in the structure of the satellite projects.
- *Transparency and trust:* Open communication structures and regular reporting strengthen cooperation and trust between those involved.
- *Shared values and goals:* A clear list of goals integrating technological and economic priorities, and not least the vision already presented, ensure coherence and orientation.

It is clear from the literature and from two qualitative best practice analyses that the major challenge in designing suitable governance lies in striking a balance between clear control structures and the necessary agility in day-to-day working practice. The proven mechanisms include the following:

- A clearly defined leading *instance of overall control* representing and integrating the consortium or collective.
- *Consortium contracts:* Clear contractual regulations defining rights and responsibilities as well as mechanisms for conflict resolution.
- *Transparent decision processes:* Implementation of clear decision-making processes and competence regulations.
- *Regular communication:* Processes and tools for continuous exchange, such as digital collaboration tools. It is important to account for the fact that this is a voluntary association of autonomous organizations on a temporary basis and with only some of their resources, each bound to their own processes, instruments and usual practices.
- *Evaluation mechanisms:* Milestone checks and indicators for assessing progress.
- *Adaptive governance:* A certain degree of flexible structures enabling dynamic adaptation to changes.

These considerations form the basis for designing a governance structure, presented as an organizational chart in Part II of this report.

3.4 Concluding remarks for Part I

The results of the content-specific and technical research, the specially developed quantum computing software stack and the vision were presented to the quantum computing community at a workshop designed and organized by the project consortium in Berlin. This provided feedback and strengthened the collective understanding of the objectives. The fact that the workshop was fully booked, as well as the high attendance at a second workshop open to the community in March 2025, underscore the interest of science and industry in this topic. In this reflection of the proto-stack, the vision, and the content focus in the community, no fundamental concerns or reservations were expressed about the stack. This indicates that the project is realistic.

The second part of this final report which follows is the QC Next innovation concept, which is based on the work done and the results achieved. It outlines the necessary innovative steps to be taken in response to the R&D results presented here. It explains how the pooling of expertise, the activation of established networks and cooperation with industrial partners can generate spillover effects contributing to the establishment of a sustainable ecosystem for quantum computing in Germany over the long term.

Part II

QC Next innovation concept

The task of the project, which was reported on in the previous chapters, was to develop an innovation concept for future quantum computing software stack instantiations. This innovation concept forms the basis for the design of a downstream QC Next flagship project. The innovation concept recommends the development of a widely accepted reference architecture with stable interface definitions, modular building blocks and reference implementations in each layer, which are to be validated in proof-of-concept form. Implementing the QC Next innovation concept provides the following added value for developing and applying quantum computing solutions:

1. **Consolidation and reducing fragmentation** A reference architecture for the quantum computing software stack, including open source interface definitions between all layers, standardizes the highly fragmented landscape of quantum computing solutions and establishes a clear structure for interoperable developments.
2. **Modularization and interchangeability** A modular stack design enables the integration and exchange of components - both from the open source community and from commercial providers.
3. **Efficiency and effectiveness** Together with specific blueprints, the reference architecture enables various user groups to simplify and accelerate the development of quantum computing software, saving time and resources.
4. **Standardization** The framework forms a basis for establishing formal institutional standardizations for interfaces and processes on the national and international level (e.g. DIN, CEN-CENELEC, OASIS) that promote seamless cooperation and compatibility.
5. **Accessibility and availability** Git repositories and other platforms give developers and end users easy access to the tools, frameworks and best practices, enabling them to actively contribute to their further development.

A QC Next flagship project implementing these points accelerates the structured and cooperative development of quantum computing solutions and establishes a sustainable basis for innovation and growth. As a result, the time to market for quantum solutions will be shortened, efficient value chains will be facilitated, and Germany's technological sovereignty will be strengthened.

The goal of the innovation concept presented here is to identify the necessary innovative steps in a flagship project to decisively advance the development and application of quantum computing (QC). These steps are formulated below.

4 Necessary innovative steps

The QC Next innovation concept recommends subdividing a downstream QC Next flagship project into four key areas that together establish a sound and comprehensive basis for the development and application of software-based quantum computing solutions. The following subsections summarize these four key areas.

4.1 Reference architecture and process models

The individual layers of the stack must dovetail seamlessly together in order to develop the full performance potential and versatility of quantum computers. The interaction of the individual components must be efficient, effective and open to innovation. The goal is to establish a standardized and clearly defined structure for the layers and especially to create open source interfaces between all layers of the quantum computing stack. Clearly defined interface specifications are critical for stack consistency. Robust interfaces provide investment security, enable modularity and interchangeability and can also contribute to quasi-standardization within the stack.

The reference architecture for the quantum computing software stack to be developed in the project represents a standardized, modular structure covering all essential layers from the hardware layer to the application layer. In the future, this should help project managers, software developers, IT architects and IT managers to collaborate and communicate effectively as part of a QC implementation project. Among other things, the reference architecture should anticipate and answer frequently asked questions, supplemented by a process model. The goal of this reference architecture, in combination with the process model, is to simplify the development and integration of quantum computing solutions, promote interoperability and establish a long-term basis for standardization.

4.1.1 Reference architecture and interface definitions

The basis for this architecture is the proto stack developed in the upstream innovation project (see Figure 2). In addition to further elaborating and specifying the individual application, system and physical layers, the interface definitions are of critical importance. The project aims to define standardized open-source interfaces along the stack. This allows users and programmers to link the required software systems and tools with their own applications. Vendor lock-in effects, i.e. dependence on individual companies should thus be avoided.

The interface definitions are based on precise specifications that enable reliable communication between the individual layers. The interfaces are designed to be modular to facilitate integration or replacement of individual components. Special attention is given here to the provision of open-source reference implementations for these interfaces to ensure transparency and traceability.

A well-defined reference architecture provides numerous advantages that sustainably strengthen further software development. The uniform structure provides for consolidation, significantly reduces the existing fragmentation of approaches and establishes a common basis for researchers, developers and users. The modularized instantiation of the stack based on the reference architecture enables the interchangeability of elements and extensibility of the stack.

With clearly defined interfaces, individual modules can be flexibly updated, replaced and expanded without compromising the stability of the overall system.

Smaller companies in particular benefit from this architecture, as they can focus on specific parts of the quantum computing software stack instead of having to implement the entire stack themselves. This makes it easier for them to get started in quantum computing, as they can draw on modules already available on the market and focus more on their specific areas of interest. Furthermore, simplified access to this highly complex technology should also motivate smaller stakeholders to greater innovation.

The reference architecture also forms a basis for standardization, promoting interoperability and compatibility between different implementations in the long term. The provision of building blocks and reference implementations in open source repositories also accelerate the development of quantum computing solutions. Open sourcing not only establishes transparency and trust but also promotes knowledge transfer and gives broad user base access to fundamental technology, strengthening the entire ecosystem.

4.1.2 Process model

Fully exploiting the advantages of a reference architecture requires the use of suitable process models to define the development and application processes. Experience in classic software engineering has shown that process models are essential when planning software development projects. They structure software development projects by separating them into distinct phases and defining the activities that take place within each phase. Furthermore, they improve communication by fostering a common understanding of tasks and responsibilities. Established process models facilitate project control and the harmonization of expectations for project results.

While the reference architecture of the quantum computing software stack describes which components have to be taken into account when developing a quantum computing solution, a QC Next flagship project must also indicate how the stack can be used efficiently. Only in this way can we ensure that it is actually used by the community. One result from the workshops held in the innovation project is that such a process model must distinguish between the business perspective (end user) and the technical perspective (developer).

From a business perspective, the focus is particularly on finding a methodical answer to the question of when a quantum computing solution makes economic sense for a company. Every company, regardless of its size, is confronted with this question when considering the use of a quantum computing solution. From a business perspective, it is especially important to demonstrate how classic practical problems can be translated into process-specific requirements and formulations for a QC solution. This is the only way to adequately assess the costs and benefits of their implementation and to improve investment security. If necessary, new evaluation categories and methods should be developed with which to extend common calculation methods (e.g. Total Cost of Ownership [TCO]).

The technical perspective of the process model must especially identify the processes required for efficiently implementing a quantum computing solution in the specific business environment in conjunction with the quantum computing software stack. Two further results of the workshops held while elaborating the innovation concept are the need for technical process models designed for assembling or instantiating a stack on the one hand and for integrating it

into the company's existing IT landscape on the other. The first aspect deals with questions relating to the necessary components for a specific use case when instantiating the stack, as well as their technical combination. The purpose of the latter aspect is to integrate a quantum computing solution in software engineering process models and IT landscapes already in use in the company to create hybrid systems. This must be based on the current state of research in quantum software engineering. Any blind spots identified must be addressed. Development processes, modeling or validation procedures from classic software development must be adapted to the development of quantum computing solutions as required. The goals should be methodical conception, implementation, adaptation and reuse of quantum computing solutions. The perspectives described above must be integrated in a quantum computing software lifecycle that should result from the QC Next flagship project. Both the quantum computing software stack and the lifecycle are being evaluated in a QC Next flagship project together with use cases from industrial partners (*vertical slice*).

4.2 Reference implementation and layer design

Building blocks and reference implementations are developed for each layer of the software stack, based on the reference architecture as the conceptual framework for the stack. The structure follows the logic of the developed prototypical stack (see Figure 2):

1. *Application layer*: Building blocks for developing and using quantum algorithms and applications.
2. *System layer*: Components for controlling and optimizing quantum resources.
3. *Physical layer*: Implementation of interfaces with hardware and control systems.
4. *Cross-layer concerns*: Topics such as security, fault tolerance and benchmarking, accounted for across all layers.

A central component of the flagship project will be the development of reference implementations and building blocks for the quantum computing software stack. The goal must be to support the layers and interfaces defined in the reference architecture with operational modules that can serve both as a proof of concept for the architecture and as the basis for integration in real applications. A systematic approach is followed, based on a suitable process model, to build on existing solutions, create new implementations and define specific functions both logically and technically.

Each stack layer, from the application to the system to the physical layer, is specifically investigated in view of the requirements of the respective use cases to develop customized solutions. Functions for developing and using quantum algorithms in the application layer, mechanisms for controlling and optimizing quantum resources in the system layer and access to hardware components and control systems in the physical layer are regarded as key components. The requirements of these layers are analyzed with a view to specific use cases for targeted implementation in functional modules. Potential for improvement in the individual layers must be fed back into the reference architecture. The quantum computing software stack is thus undergoing continuous development as part of the flagship project.

Clearly defined interfaces from the reference architecture are highly important for interoperability between the layers. Modules for these interfaces are implemented with a combination of various approaches. Wherever possible, existing solutions are integrated directly,

while in other cases wrappers are developed to ensure the compatibility of existing software elements. New implementations are developed for areas where no existing solutions are available. This applies in particular to the area of compilers and transpilers enabling the smooth translation of quantum programs across different layers, as well as error correction modules or specific hardware drivers. The focus for compilers should also be on reusing or extending existing solutions in order to keep the development effort lean and economical.

All reference implementations are provided in open source repositories to promote acceptance and further development of the modules. This open approach ensures transparency, thereby promoting acceptance, facilitating knowledge transfer and offering the developer community the opportunity to provide feedback and actively participate in further development. Onboarding programs with training and documentation should be offered in parallel with this to facilitate access to the developed modules.

Another key aspect to which effort must be applied is maintenance. Existing components must be continuously maintained to prevent *legacy code* and to ensure a living, long-term functioning software stack. This may be necessary for reasons such as new releases of included software packages. Maintenance is ideally conducted implicitly in stabilizing the stack or the components. However, this aspect must be explicitly accounted for in the initial development phases and for components developed by research institutions.

The building blocks are validated in practical applications that must be defined as part of the project. Specific use cases serve as a test environment for checking the overall interaction and practical suitability of the developed reference implementation while simultaneously identifying potential for improvement. Continuous testing and further development of the modules ensure that they meet the requirements of real applications and contribute to further strengthening the quantum computing ecosystem.

The development of these reference implementations and building blocks establishes a solid basis for practical application of the reference architecture. The combination of existing and new software then promotes interoperability and modularity and accelerates the development of innovative quantum computing solutions.

4.3 Blueprints as a concept for specific stack instantiations

Companies must be able to rely on scalable, flexible and implementable software stacks that meet the specific requirements of quantum computing in order to exploit the potential of quantum computing. The reference architecture developed in the project serves as the foundation for this. For actual implementation, however, it must also be considered how the reference architecture can be transferred and instantiated for specific application scenarios. The partner workshops have already identified three areas of application – high-performance computing centers (HPC), cloud providers and on-site deployments in corporate IT landscapes – for which efficient use necessitates a transfer of the reference architecture, including compilation of the necessary software components along an integration concept. In addition to these application scenarios, typical application domains for quantum computing also play a role and dictate the targeted interaction of software components in the reference stack. Examples include , the application domains of optimization and quantum machine learning as quantum computing can be expected to become usable in these fields in the near future in the regime of

early error-corrected quantum computers. In the QC Next flagship project, so-called *blueprints* must therefore be developed as preconfigured use case-specific instantiations of the reference architecture for relevant deployment scenarios and application domains.

4.3.1 Use of blueprints to adapt the reference architecture to various application scenarios

Blueprints are a widely used concept in areas such as software development, the deployment of software systems with a large number of variants and the management of corporate IT landscapes. They offer a systematic approach to adapting complex software systems to specific requirements and environments. A blueprint is a prepared template that includes both technical and organizational details and is therefore closely related to the technical process model. It offers a basic configuration tailored to the respective target environment and contains mechanisms for simple scaling and further adaptation.

For example, a blueprint for the quantum computing software stack reference architecture to be developed in the flagship project, can include the following elements adapted to specific use cases:

- *Basic architectural structure*: Predefined layers and modules adapted to specific hardware, middleware and application requirements.
- *Configuration data*: Settings for hardware integration, performance optimization and quantum algorithms.
- *Compatibility requirements*: Specifications for IT infrastructure, operating systems and networks.
- *Automation scripts*: Tools for rapid implementation, instantiation and deployment of a prepared part of the reference stack in the target environment.
- *Scenarios for error management and security*: Standards and protocols for protecting sensitive data and dealing with hardware weaknesses.

This modular approach means that the reference architecture can be implemented more quickly without the need for completely new developments. In particular, the automated provision and integration of interlocking software components ensure efficient usability of the quantum computing software stack. The specific design of the blueprints is determined by the requirements of the respective application scenario.

4.3.2 Example application scenarios and specific requirements

High-performance computing centers (HPC) HPC environments are characterized by massive computing capacity and specialized hardware. Integrated quantum computing solutions in HPC centers require the following:

- Hybrid architectures with seamless interaction of quantum and conventional processors.
- Optimized middleware layers for distributing workloads between quantum hardware and existing HPC resources.
- Scalable control systems operating with a high degree of parallelism and efficiency.

For example, a quantum computing blueprint for HPC systems could have the goal of integrating existing high-performance network infrastructures and providing special optimizations for hardware error correction in intensive use. This is implemented using integration tools connecting quantum control and middleware with existing HPC orchestration software.

Cloud providers Cloud providers typically enable access to quantum computing resources in a *pay-as-you-go* model. The key challenges here are in the multi-tenant infrastructure, availability and seamless integration of classic and quantum-based services. A blueprint could include the following:

- APIs and SDKs for developers to create cloud-based quantum algorithms.
- An abstracted hardware layer which requires no specific skills or knowledge of quantum hardware on the part of the customer.
- Security protocols and access control mechanisms to separate data from different cloud tenants.

A typical blueprint for cloud providers would also rely on cloud-native orchestration and execution environments such as Kubernetes to run quantum applications in a highly dynamic environment.

On-site solutions in corporate environments Companies that integrate quantum computing directly into their local IT infrastructure (on-premise) usually face other challenges, such as embedding it into existing networks and ensuring data protection and compliance requirements are met. A blueprint could include the following:

- Minimum hardware requirements for future on-site installation of quantum computing.
- Standardized interfaces for connection to existing company software such as ERP or CRM systems.
- Security solutions accounting for on-site requirements such as firewalls, data access rights and physical security.

Blueprints adapted for industrial use can therefore be designed to give companies access to a prefabricated architecture that both facilitates entry and supports subsequent scaling.

4.3.3 Dissemination and acceptance of the software stack through blueprints

The use of blueprints enables significant promotion of acceptance and widespread use of the quantum computing software stack to be developed in a downstream flagship project by realizing key benefits. Providing prefabricated models and preconfigured solutions greatly reduces development complexity. This significantly reduces both the required time as well as costs. The blueprint approach simultaneously offers a high degree of scalability, enabling companies, research institutions and data centers to start with a simple basic configuration and gradually adapt this to their individual and growing requirements. Furthermore, interoperability as a result of defined standards and interfaces ensures seamless integration with existing systems, significantly increasing compatibility and possible applications. A further benefit is time savings, as automated processes and tools significantly shorten implementation cycles. Overall, the use of blueprints democratizes the provision of instances of the developed reference

architecture oriented to target groups by reducing entry barriers for companies and thus giving organizations of all sizes access to this pioneering technology.

4.4 Activating the ecosystem: A common guiding principle for a strong community

Further key aspects of the downstream QC Next flagship project are communication, knowledge integration and the positioning and integration of stakeholders in the quantum computing ecosystem. The previous section already touched on the importance of acceptance of the developed quantum computing software stack. The community plays a central role in this regard.

The term »community« here refers to all stakeholders who contribute to research and development along the stack and its use for further development. This encompasses all layers and stakeholders – from hardware developers to end users. The active involvement of the latter is essential. Interests, needs, and mutual requirements must be communicated openly. The added value of a closely networked community includes knowledge sharing and reduced development risks, enabled, for example, by continuous course corrections through feedback loops. In addition, economies of scale can be generated: a community whose products and services are compatible and coordinated can generate greater added value for end users and thus gain acceptance and relevance.

The term »community building« refers to a method that connects stakeholders in an industry through various channels to discuss topics, exchange ideas, interact, and support each other. Especially in a young and dynamic environment such as quantum computing software development, close and constant exchange between all participants is essential to bring together the knowledge, skills, and experience of different groups. Strengthening the interconnections within the industry helps to promote synergies in the form of compatibility along the value chain and avoid silo developments.

Research and development in the field of quantum computing are currently characterized by a large number of more or less isolated initiatives. In order to make technological advances usable in the long term, it is necessary to bring together a critical mass of players and establish a comprehensive reference architecture. The defined software stack forms the central technological reference point for this, and the aim is for its conceptual development and implementation to become a quasi-standard for quantum software development. One of the biggest challenges in bringing the community together is to promote acceptance and intrinsic motivation with regard to the design of the stack to ensure broad and sustainable participation.

Sustainable participation requires that technological developments are not only technically excellent, but also designed to be usable, relevant, and interoperable in the long term. In addition, effective knowledge transfer plays a crucial role in accelerating competence building and promoting use within the community. The consolidation of the quantum computing software community is based on the principle that consortium partners and other interested parties act as multipliers. Three central guiding elements are anchored in this approach:

1. **Establishing a common exploitation strand:** Pooling expertise generates synergies, avoids the duplication of development work and drives targeted progress in quantum software development.
2. **Motivation for compatibility of individual developments:** The reference architecture provides a framework like a system of building blocks to enable seamless integration of different components.
3. **Technical implementation and provision:** The reference architecture is implemented in practical and accessible software solutions. A functional, well-documented infrastructure provides the foundation for transparency, widespread acceptance and long-term usability within the community.

Particularly with regard to the definition and provision of hardware-agnostic or standardized open interfaces, the community's awareness, acceptance, and active participation are required. To achieve this, various approaches can be pursued, which, orchestrated by a project office, will lead to the necessary acceptance of the QC Next concepts. Some of these are listed below.

National approaches

- Increasing the number of use case partners in the project who test the end-to-end software chain along the interfaces to be defined.
- An industry advisory board or, alternatively, regular exchange with the QUTAC consortium to promote awareness and acceptance among German DAX companies.
- Regular hackathons with industry participation and mini reference implementations.

European approaches

- Networking with IBM Working Groups to improve visibility.
- Networking with the CEN/CLC/JTC 22 standardization group (WG1 Strategic Advisory Group and WG3 Quantum Computing and Simulation). Initiating the formulation of a DIN-SPEC on the national level if necessary.

International

- As one of the most respected non-profit standards bodies in the world, *OASIS Open* offers a path to standardization and legal approval for projects, including open-source projects, as a reference in international policy and procurement.

The objective is to implement the project results for broad long-term use in the quantum computing community.

With this approach, the downstream flagship project combines technological excellence with broad community involvement for sustainable and targeted promotion of quantum computing.

4.4.1 Procedure and measures

The project relies on continuous measures in target group definition, transparency, training and feedback mechanisms to promote broad acceptance and identification within the community.

Target group-specific content Active involvement of the community is essential to increase awareness of the stack and ensure its acceptance. If possible, active participation should be motivated by suitable mechanisms (badges in forums, mentions of contributors in social media posts, etc.). The specific definition of target groups and their assignment to the functional layers of the QC Next prototype stack enables the structured involvement of various stakeholder groups. This facilitates targeted collaboration and strengthens the overall exchange of information within the community.

Regular provision of relevant content is also essential for establishing an active community. It is important here that the content be specific and sufficiently technical in nature. The goal is to introduce new topics and discuss ideas. Marketing and *vendor biases* must be avoided so as not to undermine the credibility and acceptance of the formats.

Transparency and communication In order to anchor the project idea firmly in the community, a coherent corporate design/branding will be developed and accompanied by targeted communication measures. Existing formats of the consortium partners will be opened to enable broader participation. The aim is to bring the community together at a higher level in order to achieve the necessary critical mass, connect individuals closer, and promote professional exchange. Merging formats with similar content and coordinating their timing can also contribute to this.

New formats should only be created if they bring real innovation or fill existing gaps, as otherwise they could contribute to further fragmentation of the community. In addition, the provision of a central information and knowledge platform offering a comprehensive overview of the community's current activities can be considered.

Training and multiplication Customized stack training formats will be provided for both the end-user and developer target groups to promote acceptance and use of the QC software stack. Stakeholders are thus familiarized with the concept of the stack and the components and interfaces relevant to them (onboarding).

This includes creating and providing technical documentation, user guides, tutorials and training courses to enable efficient use and further development of the stack.

Participation and feedback integration A key element is early involvement of the users through targeted feedback mechanisms. Feedback on technical and user-related design can be gathered via comment functions directly in Git, in a developer forum and in systematic user surveys for active integration in the design of the prototypical stack.

This approach can succeed in unifying the quantum computing software community on the topic of the quantum computing software stack, consolidating it as a reference architecture over the long term. The targeted tight dovetailing of technical innovation, collaborative development and active knowledge transfer establishes the basis for an internationally competitive quantum computing software landscape that is viable for the future.

It is recommended that a project office be established to coordinate and implement the above points. This ensures a unified external presence and serves as a central contact point for quantum computing software topics, thereby creating additional visibility for the project.

Interorganizational coordination and cooperation on the funding side are also desirable. This refers specifically to networking activities by the various ministries responsible.

5 Transfer strategies: From concept to implementation

The QC Next innovation concept proposes the development of an open, interoperable and future-proof reference architecture for quantum computing software. It thus provides a key contribution to promoting quantum technology in Germany and in Europe. The purpose of the proposed architecture is to strengthen technological sovereignty, reduce dependency on non-European solutions and open up strategic markets in the field of quantum computing.

The QC Next innovation concept simultaneously formulates the goal of broad integration and acceptance within quantum computing and the quantum community with a flagship project. Close cooperation between science, industry and policy will establish a sustainable innovation platform that promotes technology transfer, accelerates the commercial use of quantum computing technology in Germany and in Europe and creates strategic added value.

5.1 Challenges of flagship project governance

Implementing the QC Next innovation concept in a flagship project requires efficient governance enabling both strategic management and agile, operational collaboration. Governance must coordinate, set priorities, distribute resources efficiently and ensure the transfer of knowledge. It must also remain sufficiently flexible to react to new developments and scientific breakthroughs. The following aspects are essential here:

- **Strategic control:** A dedicated project management team comprising representatives from all involved partners and the funding body designs and manages the implementation of the strategic objectives. This ensures efficient use of resources and the clear allocation of roles and responsibilities within the project.
- **Process control:** Clear communication and decision-making processes promote the transfer of knowledge and continuous development. The application of agile methods and digital tools promotes collaboration within the project and enables rapid adaptation to new challenges.
- **Normative framework:** Transparency, open communication and accessibility are essential principles for cooperation based on trust. These aspects improve acceptance of the developed architecture and establish a common understanding among project participants.
- **Community building:** Sustainable project success requires networking among relevant stakeholders beyond the consortium. Workshops, open standards, and exchange formats promote interoperability between different technologies and organizations, creating synergies.

5.2 Organizational structure of a flagship project

Given the governance challenges for a QC Next flagship project, a structure is recommended that combines clear management principles with flexible, interdisciplinary and interorganizational cooperation. This structure is shown in Figure 4.

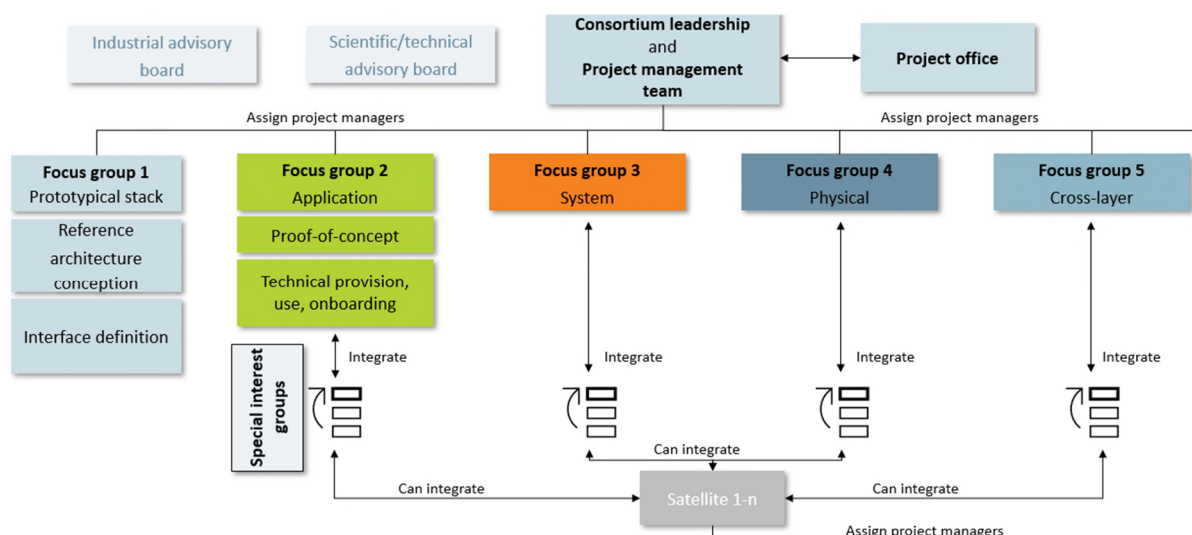


Figure 4: Proposed governance structure in the QC Next lead flagship project.

Central control level. A project management team forms the central steering committee. This consists of the leading stakeholders from all focus groups and satellite projects. Consortium leadership assumes a moderating role, bringing together different perspectives, structuring discussions, making well-founded decisions in keeping with strategic objectives and representing the flagship project in its overall external communications.

The formation of a scientific and technical advisory board and an industrial advisory board can be considered. These can support the project in an advisory capacity. The advisory boards can provide impetus, reflect on research progress and present accomplishments to ensure the achievement of technical and application-specific milestones.

Focus groups and special interest groups for key development topics. The focus groups are organized as corner stones along the proto-stack presented in this innovation concept. They fully reflect its components. Under the collegial leadership of the consortium partners, the focus groups work on key technical, scientific, and application-oriented issues. The focus groups are divided into the following development areas:

- Focus group 1: QC software stack reference architecture
- Focus group 2: Application layer
- Focus group 3: System layer
- Focus group 4: Physical layer
- Focus group 5: Cross-layer considerations

The special interest groups can be flexibly defined from the focus groups and enable specific in-depth study of selected topics for a limited period of time. Strong networking ensures the smooth integration of work results: The combination of focus group management and representation in the project management team ensures strategic upward consolidation of the components. In the other direction, the focus groups ensure the establishment of special interest groups and integration of their results in the overall architecture. This promotes close coordination and synergistic cooperation between both specialized and more general levels.

Project office. It is not a mere administrative body, but rather a central interface for knowledge transfer, networking, and internal and external communication. In close coordination with the consortium leadership and project management team, it ensures a structured flow of information between focus groups and satellite projects, coordinates processes, and supports the integration of work results. As a point of contact for the leading players, it facilitates cooperation and promotes strategic control. It also strengthens external communication by helping to make the project's successes visible and supporting dialogue with the community and politicians. In this context, it will also be significantly involved in event management.

Specialized satellite projects. Satellite projects are independently funded projects with topics aligned with the objectives and requirements of the flagship project and contribute their results to its overall structure. They operate independently but are committed to the flagship project and make a targeted contribution to further development of its content. Satellite projects are required to provide a lead person for the project management team and maintain contact with the project office for better coordination. This ensures integration of their work results. If interested, stakeholders from the satellite projects also have the opportunity to become involved in specific technical developments through the special interest groups and to exploit the potential synergy with the focus groups in the flagship project.

Performance measurement. It is recommended that an extended orientation with qualitative and user-centered key performance indicators (KPI) be developed to supplement the usual definition of milestones. These should go beyond strictly technical progress measurements and account for aspects such as accessibility for and use by developers and end users, clarity and understandability of the architecture as well as integrability in existing systems and existing elements. For open source components, examples of these could be Git-based indicators (number of stars, contributors, etc.). Reliable provision and sustainable maintenance of the quantum computing software stack as a knowledge product are additional key factors. A co-design approach in development should also be established as a measurable criterion to ensure close integration between hardware, software and applications.

6 Final evaluation

Quantum computing has the potential to become a key technology of the future. In comparison with the USA, where high levels of investment are already being made by industry, especially by companies such as Google, Amazon, IBM etc., Germany and the EU are lagging behind in the race for this key technology. The statement by IBM, one of the leading hardware manufacturers, that it will demonstrate the first quantum advantages for some specific industrial problems within the next two years highlights the momentum that the quantum computing industry is currently facing.

In her inaugural speech in November 2024, Henna Virkkunen, Vice-President of the European Commission for Technological Sovereignty, Security and Democracy, stressed the critical importance of quantum technology for the EU's sovereignty, competitiveness and defense capability. European researchers have the necessary talent, but a more comprehensive common approach is now needed, says Virkkunen.

The necessary digital infrastructure, in this case the software stack, must be developed and provided in addition to the underlying hardware in order to fully exploit the potential of quantum technology. A demand supported by the Quantum Industry Consortium (QuIC) in its latest report.¹⁴

This report presents the current state of the German quantum computing software ecosystem. The innovation concept in this report also presents the steps needed to establish a comprehensive reference architecture. This report thus takes the first step towards the necessary comprehensive joint approach. It shows how existing expertise and resources can be coordinated and bundled to achieve the necessary critical mass.

Various expert reports^{15,16} have highlighted the need for scientific and innovative excellence and the relevance of research and innovation initiatives for industrial competitiveness. The value of a strong European R&D ecosystem of institutions, investors, infrastructures, innovators and entrepreneurs in transferring breakthrough research and innovation to global markets was also stressed.

The application potential of quantum computing is heavily dependent on the underlying hardware. However, this must be complemented by providing the necessary software infrastructure to deliver quantum benefits for end users. Leadership in these areas is based on scientific excellence combined with the ability to establish strong integrated software platforms and create a significant, scalable and efficient computing infrastructure.¹⁷ Existing interactions between stakeholders should be strengthened to enable the requirements to be met and to overcome existing silos.

The approach outlined in this document would provide a strong impetus towards the implementation and commercialization of concepts and applications in quantum computing in Germany and Europe. On the other hand, a delay or lack of investment in this future key technology would increase the risk of being left behind in this international race and solidify the position of non-European suppliers. This would result in new dependencies and pose a threat to German and European sovereignty. Decisive action must be taken to counteract this.

¹⁴ [Recommendations from the European Quantum Industry Consortium \(QuIC\) for the EU Quantum Strategy](#)

¹⁵ [Align, act, accelerate - Publications Office of the EU](#)

¹⁶ [Gutachten zu Forschung, Innovation und Technologischer Leistungsfähigkeit Deutschlands 2025](#)

¹⁷ [Artificial intelligence and quantum computing white paper](#)

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8 Annex

A. Lead institutions

The **Fraunhofer Institute for Industrial Engineering IAO** with the Quantum Computing team led by Dr. Tutschku in the Digital Business research department headed by Dr. Renner, is already playing a central role in expanding and strengthening the quantum computing ecosystem through its role in the *Baden-Württemberg Quantum Computing Competence Center (KQCBW)*, in the *QuantumBW Initiative* and by offering the first non-university quantum computing training program in Baden-Württemberg. Frameworks and methods for classical computing with artificial intelligence have already been developed, piloted and evaluated with industry partners in artificial intelligence projects such as *SmartAIwork* or *KI Ultra*.

At the **Karlsruhe Institute of Technology (KIT)**, Prof. Schaefer's research group is investigating various questions in quantum software engineering. This group has been working intensively on improving the applicability of quantum computing since 2020, especially in the development of benchmarking tools (BMBF QuBRA project) and on hybrid quantum/algorithmic toolbox (BMWK ProvideQ project). The ProvideQ toolbox combines classical mathematical optimization methods with novel quantum algorithms and enables users to apply hybrid quantum solution methods with the help of this toolbox for specific use cases.

Kipu Quantum is a German startup company that develops software solutions for quantum computers (QC). This company was founded in 2021 by the three managing directors, Dr. Daniel Volz (CEO), Prof. Enrique Solano (Chief Visionary Officer) and Dr. Tobias Grab (Chief Strategy Officer) to commercialize Prof. Solano's research results on quantum algorithmic compression methods. It should thus be possible, within the next few years, to offer solutions providing end users with real benefits in industrial applications. The Kipu Quantum team draws on 25 years of research experience in quantum algorithms and quantum computers. The combined knowledge of hardware and compressed algorithms enables Kipu Quantum to offer solutions tailored to the specific application as well as to existing quantum hardware. Kipu Quantum ranks among the leading providers in digital, analog and digital/analog quantum algorithms. Kipu's algorithms are in use in a wide variety of industrial sectors, such as pharmaceutical and chemical manufacturing, as well as the manufacturing industry (automotive, aerospace, etc.), banking and insurance. Those use cases are especially emphasized that are based on optimization tasks.

With its many projects and networking activities, the consortium can draw on a broad pool of potential partners from various sectors. This ensures good access to other partners and their early involvement in the flagship project to be planned.