VQ Among Machine-Checked Quantum Program Systems

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Abstract

VQ combines Lean 4 syntax for unitary circuits, reversible circuits, and hybrid quantum–classical programs with exact semantics and syntax-derived resource reports. The comparison covers VQ, QWIRE, SQIR/VOQC, Qbricks, CoqQ, Qafny, qrhl-tool, and QBlue under separate criteria for semantics, program logic, compilation, equivalence, resources, mixed-state models, execution, and applications. SQIR/VOQC and Qbricks verify optimization or end-to-end algorithm results. CoqQ and qrhl-tool provide general program logics, Qafny provides automated program verification, and QBlue verifies Hamiltonian compilation. VQ connects generated reversible or measured component syntax, cleanup, logical resources, and a paper-specific elliptic-curve audit. Its general program logic, terminal probability, approximation, and external execution coverage remain limited.

1 Systems with checked program obligations

A system must expose quantum-circuit or quantum-program syntax, or a compiler over such syntax, and must connect at least one semantic, logic, compilation, equivalence, resource, or application claim to a proof assistant or deductive verifier. It must also have an original paper and a public source artifact or official project page, and its checked obligation must overlap directly with a VQ obligation. These conditions define the comparator set.

The rule excludes general quantum-mathematics libraries whose public interface does not include programs or compilation, including finite-dimensional information-theory and error-correction libraries. It also excludes quantum software development kits (SDKs), simulators, testing systems, and stand-alone equivalence checkers unless a proof assistant or deductive verifier checks their correctness argument. CertiQ and similar compiler analyses remain relevant prior work, but this survey does not include them because the public materials inspected here did not expose the proof-assistant artifact required by the rule [18].

VQ supplies the baseline for every comparison. Its public reports describe exact dyadic-cyclotomic circuit semantics, reversible basis-permutation semantics, measurement and feed-forward branch semantics, relational component specifications, and resource functions over circuit and program syntax constructed by its generators [20, 21]. Revision `cdb8db8` supplies the inspected source artifact, including the paper-specific elliptic-curve work that determines the scope of its checked claims [19].

2 Checked-claim criteria

The semantic criterion, S, requires a machine-checked theorem that connects program syntax to a denotational or operational meaning. The logic criterion, L, requires checked, reusable precondition, postcondition, or relational rules. The compilation criterion, C, requires a checked source-to-target semantic-preservation result, while equivalence, E, requires a checked reusable transformation, normalization procedure, equivalence method, or relational equivalence rule.

The resource criterion, R, requires a theorem that connects the syntax under study to a width, gate-count, depth, or asymptotic bound. The mixed-state criterion, M, requires density-operator or superoperator semantics. The execution criterion, X, requires checked theorems connecting syntax to an external executable circuit or compiler output. The application criterion, P, requires a checked implementation of a named algorithm or cryptographic protocol that composes multiple operations and has an end-to-end functional, probability, or security specification. The survey reports approximation bounds and physical-noise models separately because neither follows from mixed-state semantics.

Symbol K means that the public paper and artifact identify a checked reusable result for the criterion, while A means that a checked result exists only for a named application or restricted component. Symbol T means that a tool or translation is public but the inspected sources do not identify an end-to-end correctness theorem, and – means that the survey located no qualifying claim.

System	S	L	C	E	R	M	X	P
VQ	K	A	A	A	K	–	–	A
QWIRE	K	A	T	A	–	K	T	A
SQIR/VOQC	K	–	K	K	A	K	K	K
Qbricks	K	K	K	A	K	–	K	K
CoqQ	K	K	–	K	–	K	–	K
Qafny	K	K	T	–	–	–	T	K
qrhl-tool	K	K	–	K	–	K	–	K
QBlue	K	A	K	–	–	–	T	A

Table 1: Public checked coverage under the criteria defined in the text.

VQ models measurement branches with amplitudes and classical records but has no density-operator library or physical-noise model, so it does not meet M. Its reversible-to-unitary compilation, circuit-to-program embedding, and component equations satisfy restricted instances of C and E. The repository has no general verified optimizer or external code generator [21, 19].

3 Typed semantics and verified compilers

QWIRE embeds a typed circuit language in Coq using higher-order abstract syntax and linear wire types. Its denotation interprets circuits as superoperators on density matrices, and its examples prove an adder, Deutsch variants, teleportation, and circuit equations for the published examples [9, 17]. The current repository also contains a quantum assembly language (QASM) printer, but its own file guide says that `Composition.v` admits compositionality lemmas used by later files. The inspected artifact therefore does not justify closed compilation and compositionality proofs [5].

QWIRE provides typed circuit construction with density-matrix semantics. VQ provides selected component theorems linking generated syntax, cleanup, and resource reports without admitted lemmas. The inspected QWIRE papers and repository provide no syntax-derived resource theorems. QWIRE's QASM output serves execution experiments. The VQ repository provides an internal evaluator and verifier interface.

SQIR gives low-level Coq syntax and unitary, density-matrix, nondeterministic, and sampling semantics. VOQC defines verified peephole, cancellation, rotation-merging, nonunitary, layout, and routing transformations over that syntax, then extracts the verified functions to an OCaml library with a Python wrapper [4, 6]. The same repository contains checked Grover search, quantum phase estimation, teleportation, Simon's algorithm, and Shor factorization developments, so its compilation and algorithm coverage share a public Coq base.

SQIR/VOQC verifies optimization, architecture mapping, mixed-state semantics, and external compiler execution. Its Shor development also proves an end-to-end success bound and an Open Quantum Assembly Language (OpenQASM) gate-count upper bound [10]. VQ checks measurement-assisted arithmetic, cleanup whose restored ancillas do not depend on the measurement record (record-independent cleanup), reversible register placement, and a point-addition schedule with width 758 for an elliptic-curve discrete-logarithm problem (ECDLP) construction. The inspected SQIR/VOQC sources claim none of these properties [20, 19].

Qbricks represents parametric circuit families with parametrized path sums and generates first-order Why3 obligations through its Hybrid Quantum Hoare Logic. The 2021 paper reports checked parametric implementations of the quantum Fourier transform (QFT), Grover search, quantum phase estimation (QPE), and Shor order finding, including functional behavior, probability requirements, and polynomial circuit complexity [1]. The current project repository adds a formally verified transformation for circuits without ancillas to OQASM, the project's low-level target circuit representation, together with an extracted output generator [15, 16].

Qbricks uses path-sum specifications, resource properties, and Why3 automation to prove the stated QFT, Grover, QPE, and Shor properties. The 2021 paper excludes classical–quantum interaction and probabilistic measurement side effects. VQ verifies measured uncomputation, reset, feed-forward, and record-independent cleanup. Both systems connect functional and resource properties to generated syntax for different program classes.

4 Program logics in CoqQ, Qafny, qrhl-tool, and VQ

CoqQ builds a quantum-while language, density-operator semantics, and a quantum Hoare logic on MathComp and MathComp Analysis. Coq proves the logic sound, and the repository includes local and parallel rules, a refinement calculus, weakest-liberal-precondition and strongest-postcondition results, program laws, and normal forms [28, 3]. Its checked examples cover the Harrow–Hassidim–Lloyd (HHL) algorithm, Grover search, QPE, hidden subgroup algorithms, QFT, the hidden linear function problem, and a quantum error-correction example.

CoqQ provides general mixed-state program reasoning, compositional Hoare rules, and refinement laws. VQ proves relational component specifications and predicates stating that a circuit's input and output registers satisfy those relations, without a general soundness theorem for a program logic. The inspected CoqQ material exposes no syntax-derived gate or depth report and no verified external compiler. VQ relates generated syntax to gate and depth functions and provides executable circuit generators.

Qafny uses a flow-sensitive typed language whose proof system treats quantum operations as aggregate operations over classical array-like representations. Coq checks type soundness, proof-system soundness, and relative completeness. The implementation translates Qafny programs and specifications to Dafny for automated verification [8, 13]. The 2025 Dafny embedding reports 37 verified programs and states a goal of separating verified source reasoning from later circuit execution [2].

Qafny checks high-level functional properties through automated Dafny obligations. Its paper distinguishes the verified proof-system metatheory and Dafny obligations from the tested Qafny-to-SQIR-to-OpenQASM translation sequence, so the public evidence does not support a verified quantum compiler claim under criterion *C*. VQ checks cleanup, register placement, and resource reports computed from the circuit syntax. The inspected Qafny artifact does not claim those properties.

qrhl-tool implements quantum relational Hoare logic for pairs of classical–quantum programs and delegates general mathematical obligations to Isabelle/HOL. The logic expresses equality and other relations between two program runs, supports local variables and adversary rules, and uses the Isabelle Complex_Bounded_Operators development for its operator model [22, 23, 26, 27]. Published applications include teleportation and a post-quantum Fujisaki–Okamoto proof, and the current repository includes an Isabelle-checked one-way-permutation game example [24, 25].

qrhl-tool checks relational security proofs and adversarial program transformations. VQ's checked cryptographic results cover circuit and program semantics, cleanup, probability, and logical resources, but its current logic has no quantum relational Hoare rules or adversarial security theorem [21]. qrhl-tool does not connect its proofs to circuit generation or logical gate resources, which VQ uses for concrete ECDLP estimates.

5 QBlue Hamiltonian-compilation verification

QBlue defines a typed language for second-quantized Hamiltonians and a compiler to digital and analog quantum-circuit models. Its Rocq development checks the language, type system, static and dynamic semantics, and end-to-end compilation correctness, including backend-specific approximation bounds [7, 14]. The paper's checked application compiles a typed Hamiltonian example. It does not include a general cryptographic or arithmetic circuit library.

QBlue checks a source-level Hamiltonian program compiled through particle transformations to digital or analog simulation. VQ's public approximation interfaces lack the theorems that connect generated circuits to complex-valued semantics and bound their approximation error, and it has no analog target [20]. VQ checks exact reversible arithmetic, ancilla cleanup, measurement-assisted programs, and syntax-derived logical resources. The inspected QBlue paper and artifact do not claim those properties.

6 Resource, probability, noise, and execution claims

Only VQ, SQIR/VOQC, and Qbricks meet the resource criterion in the inspected materials. VQ proves reusable resource functions and component-specific exact or bounded reports, SQIR/VOQC proves an application-level Shor gate bound, and Qbricks includes parametric width, gate, ancilla, and polynomial-size properties in its specification logic [20, 10, 1]. These results use logical gate models, so none establishes a physical-qubit, fault-tolerance, scheduling, or device-cost theorem.

Probability coverage also has distinct meanings across the set. SQIR/VOQC proves an end-to-end Shor success theorem, and Qbricks proves probability requirements from unitary path-sum semantics. VQ proves finite conditional probability bounds for named arithmetic events and preserves total mass for its branch semantics, but its reports state no terminal algorithm success theorem and no theorem transferring the arithmetic-event bounds from the modeled input distribution to the full ECDLP algorithm's input distribution [20].

Density-matrix support does not establish a noise theorem. QWIRE, SQIR, CoqQ, and qrhl-tool provide mixed-state or superoperator models that can express nonunitary behavior, while VQ and Qafny give measurement semantics over pure-state representations. The inspected papers and current documentation do not identify a checked physical-noise model or fault-tolerant implementation theorem for any system in the set.

Only SQIR/VOQC and Qbricks meet criterion X in the inspected sources. SQIR/VOQC extracts verified Coq transformations to OCaml, and Qbricks documents a checked OQASM transformation and output generator. The QWIRE printer emits QASM, but its authors state no end-to-end semantic theorem for the emitted circuits. The Qafny implementation translates programs to SQIR before generating OpenQASM, but its authors state no end-to-end theorem for that translation sequence. The inspected papers and artifacts for VQ, CoqQ, qrhl-tool, and QBlue contain only internal program or target models. Their authors report no checked external translation.

7 Recent public development records

A project counts as current when an official repository, release record, artifact, paper, or project page shows a public change between 16 August 2025 and 16 August 2026. A project with no qualifying event receives "no recent public evidence." This label records the result of the public-source search within the stated interval.

Project, named developers, and public location	Dated evidence and documented goal	Result under rule
VQ. Jamie Stephens. `jsmorph/vq`.	Revision `cdb8db8`, 16 August 2026. Goals: terminal probability, phase estimation, approximation, and end-to-end algorithm theorems.	Current
QWIRE. Jennifer Paykin, Robert Rand, Dong-Ho Lee, and Steve Zdancewic. `inQWIRE/QWIRE`.	Latest inspected default-branch commit, 11 May 2025. Documentation covers typed circuits, superoperator proofs, and QASM output.	No recent public evidence
SQIR/VOQC. Kesha Hietala, Robert Rand, and inQWIRE contributors. `inQWIRE/SQIR`.	Latest inspected default-branch commit, 30 July 2025. Goals: verified algorithms, optimization, mapping, and extracted libraries.	No recent public evidence
Qbricks. Sébastien Bardin, Benoît Valiron, Christophe Chareton, and the Qbricks team at CEA LIST and LMF Paris-Saclay. `Qbricks/qbricks.github.io`.	Repository change, 14 May 2026. Goals: hybrid Qbricks 2, certified compilation, path-sum rewriting, and error correction.	Current
CoqQ. Li Zhou, Gilles Barthe, Pierre-Yves Strub, Junyi Liu, and Mingsheng Ying. `coq-quantum/CoqQ`.	Latest inspected default-branch commit, 28 December 2024. Goals: quantum information, program laws, refinement, and Dirac-expression decisions.	No recent public evidence
Qafny. Liyi Li, Feifei Cheng, and contributors. `qafny/qafny_impl`.	Paper, 9 October 2025. Repository change, 2 February 2026. Goal: expanded Dafny-backed verification.	Current
qrhl-tool. Dominique Unruh, University of Tartu. `dominique-unruh/qrhl-tool`.	Checked one-way-permutation example, 24 May 2026. Goal: computer-aided quantum and post-quantum security proofs.	Current
QBlue. Mark Gordon, Liyi Li, Fenfen An, Federico Zahariev, and the Iowa State and Ames Laboratory team. Q-Blue pages and Zenodo artifact.	Compiler paper, 23 September 2025. Project outcome, December 2025. Goal: hardware, compiler, and scientific-application co-design.	Current

Table 2: Named developers, official development locations and goals, and observable public activity evidence, accessed 16 August 2026.

The developer entries name the authors or maintainers responsible for each mutable source. The location entries give the repository or project page inspected on 16 August 2026 and where a later survey can check changes. The goal phrases paraphrase official documentation [5, 6, 16, 28, 3, 13, 2, 22, 26, 11, 12].

8 Limits of public artifacts and cross-system comparison

The survey compares stated and inspectable checked coverage, not every theorem that a repository might contain. A missing entry can mean that no result exists, that documentation does not identify it, or that the result lies on an uninspected branch or artifact. In particular, GitHub metadata recorded an SQIR repository push in April 2026, but the inspected public branch heads did not reveal a qualifying commit after 30 July 2025, so Table 2 does not treat the metadata timestamp as technical development evidence.

The systems have different trusted computing bases. Coq, Lean, and Isabelle developments rely on their kernels and declared axioms, Why3 delegates obligations to configured provers, and Dafny translates verification conditions to automated solvers. A K entry therefore states that the system's documented checking procedure accepted the result, without asserting equal trusted code bases or equal resistance to specification mistakes.

Application totals do not support a quality ranking because an end-to-end Shor proof, a library of high-level examples, a cryptographic relational proof, and a detailed arithmetic audit answer different questions. Each comparison above therefore names a use case and its checked property. Breadth, automation, and repository activity describe separate properties.

Formal quantum-information libraries, verified error-correction developments, and ZX-calculus proof systems address other verification problems. Automata-based program verifiers, stand-alone circuit equivalence tools, and verified classical control software also fall outside the selection rule. The conclusions apply to the selected public evidence on 16 August 2026.

9 Compiler, program-logic, circuit-language, and VQ results

SQIR/VOQC, Qbricks, and QBlue check compiler or end-to-end algorithm properties for their named use cases. CoqQ, Qafny, and qrhl-tool check general, automated, or relational program properties. QWIRE supplies a typed higher-order circuit language and mixed-state semantics. The inspected artifact contains admitted compositional lemmas and no syntax-derived resource theorem.

VQ combines checked component semantics with syntax-derived resource theorems. It connects generated reversible and measured syntax to exact action, cleanup, placement, and logical resources, then applies the component semantics and resource theorems to the audit of the width-758 point-addition schedule for the ECDLP construction. A general program logic, verified optimization and export, density-operator or noise semantics, approximation-error theorems for generated circuits, and terminal algorithm probability would let VQ satisfy the use cases that the comparator systems already check separately.

References

[1] Christophe Chareton, Sébastien Bardin, François Bobot, Valentin Perrelle, and Benoît Valiron. An automated deductive verification framework for circuit-building quantum programs. In *Programming Languages and Systems*, volume 12648 of *Lecture Notes in Computer Science*, pages 148–177, 2021.

[2] Feifei Cheng, Sushen Vangeepuram, Henry Allard, Seyed Mohammad Reza Jafari, Alex Potanin, and Liyi Li. Embedding quantum program verification into Dafny. *Proceedings of the ACM on Programming Languages*, 9(OOPSLA2):2981–3007, 2025.

[3] CoqQ contributors. CoqQ repository and documentation. GitHub repository, 2026. Accessed 16 August 2026; latest inspected default-branch commit b169ea4, 28 December 2024.

[4] Kesha Hietala, Robert Rand, Shih-Han Hung, Xiaodi Wu, and Michael Hicks. A verified optimizer for quantum circuits. *Proceedings of the ACM on Programming Languages*, 5(POPL):1–29, 2021.

[5] inQWIRE contributors. QWIRE repository and documentation. GitHub repository, 2026. Accessed 16 August 2026; latest inspected default-branch commit 6cb3e5a, 11 May 2025.

[6] inQWIRE contributors. SQIR and VOQC repository and documentation. GitHub repository, 2026. Accessed 16 August 2026; latest inspected default-branch commit 134fb94, 30 July 2025.

[7] Liyi Li, Fenfen An, Federico Zahariev, Zhi Xiang Chong, Amr Sabry, and Mark S. Gordon. A verified compiler for quantum simulation. arXiv:2509.18583, 2025.

[8] Liyi Li, Mingwei Zhu, Rance Cleaveland, Alexander Nicolellis, Yi Lee, Le Chang, and Xiaodi Wu. Qafny: A quantum-program verifier. In *38th European Conference on Object-Oriented Programming*, volume 313 of *Leibniz International Proceedings in Informatics*, pages 24:1–24:31, 2024.

[9] Jennifer Paykin, Robert Rand, and Steve Zdancewic. QWIRE: A core language for quantum circuits. In *Proceedings of the 44th ACM SIGPLAN Symposium on Principles of Programming Languages*, pages 846–858, 2017.

[10] Yuxiang Peng, Kesha Hietala, Runzhou Tao, Liyi Li, Robert Rand, Michael Hicks, and Xiaodi Wu. A formally certified end-to-end implementation of Shor's factorization algorithm. *Proceedings of the National Academy of Sciences*, 120(21):e2218775120, 2023.

[11] Q-Blue Quantum team. Q-Blue Quantum people, 2026. Accessed 16 August 2026.

[12] Q-Blue Quantum team. Q-Blue Quantum project and outcomes, 2026. Accessed 16 August 2026.

[13] Qafny contributors. Qafny compiler repository and documentation. GitHub repository, 2026. Accessed 16 August 2026; repository change fe8d6f7, 2 February 2026.

[14] QBlue authors. A verified compiler for quantum simulation: Artifact. Zenodo, 2025. Rocq artifact; accessed 16 August 2026.

[15] Qbricks contributors. Qbricks source repository. GitHub repository, 2026. Accessed 16 August 2026; repository change e00fc97, 14 May 2026.

[16] Qbricks team. Qbricks project documentation, 2026. Accessed 16 August 2026.

[17] Robert Rand, Jennifer Paykin, and Steve Zdancewic. QWIRE practice: Formal verification of quantum circuits in Coq. In *Proceedings of the 14th International Conference on Quantum Physics and Logic*, volume 266 of *Electronic Proceedings in Theoretical Computer Science*, pages 119–132, 2018.

[18] Yunong Shi, Runzhou Tao, Xupeng Li, Ali Javadi-Abhari, Andrew W. Cross, Frederic T. Chong, and Ronghui Gu. CertiQ: A mostly-automated verification of a realistic quantum compiler. arXiv:1908.08963, 2019.

[19] Jamie Stephens. VQ: Formal verification artifact. Git repository, revision `cdb8db8`, 2026. Accessed 16 August 2026.

[20] Jamie Stephens. VQ: Kernel-checked semantics and resource certification for quantum programs. marXiv:2608.00023, 2026.

[21] Jamie Stephens. VQ system design: Connecting quantum programs, proofs, and resource reports. marXiv:2608.00030, 2026.

[22] Dominique Unruh. Quantum relational Hoare logic. *Proceedings of the ACM on Programming Languages*, 3(POPL):33:1–33:31, 2019.

[23] Dominique Unruh. Local variables and quantum relational Hoare logic. arXiv:2007.14155, 2020.

[24] Dominique Unruh. Post-quantum verification of Fujisaki–Okamoto. In *Advances in Cryptology—ASIACRYPT 2020*, 2020.

[25] Dominique Unruh. Added one-way permutation example. Git commit 328ad96, 2026. 24 May 2026; accessed 16 August 2026.

[26] Dominique Unruh. qrhl-tool: Interactive theorem prover for qRHL, 2026. Accessed 16 August 2026.

[27] Dominique Unruh. qrhl-tool source repository. GitHub repository, 2026. Accessed 16 August 2026.

[28] Li Zhou, Gilles Barthe, Pierre-Yves Strub, Junyi Liu, and Mingsheng Ying. CoqQ: Foundational verification of quantum programs. *Proceedings of the ACM on Programming Languages*, 7(POPL):833–865, 2023.