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. This survey compares VQ with 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 provide stronger checked coverage for verified optimization or end-to-end algorithm proofs, CoqQ and qrhl-tool provide stronger general program logics, Qafny provides broader automated program verification, and QBlue proves Hamiltonian compiler correctness that VQ lacks. VQ's distinctive coverage connects generated reversible or measured component syntax, cleanup, logical resources, and a paper-specific elliptic-curve audit, while its general program logic, terminal probability, approximation, and external execution coverage remain narrower.

1 The comparison includes systems with checked program obligations

The comparison set follows four inclusion conditions. 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 select seven comparators without turning the survey into a catalogue.

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 is the baseline rather than another entry chosen by the rule. 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 Eight criteria distinguish checked claims from tool functions

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 rather than isolated functional theorems. 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, not only pure-state measurement branches. 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.

Table 1 uses three evidence levels. 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. The table records evidence scope rather than implementation quality.

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 QWIRE checks typed semantics while SQIR/VOQC and Qbricks verify 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].

For typed circuit construction with density-matrix semantics, QWIRE covers a use case that VQ does not. For a closed theorem set linking generated syntax, cleanup, and resource reports, VQ provides stronger public evidence because its selected component theorems do not depend on the admitted QWIRE lemmas and the QWIRE papers and repository provide no syntax-derived resource theorems. QWIRE's QASM output serves execution experiments, while the VQ repository provides only an internal evaluator and judge 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 provides stronger coverage than VQ for 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. These results exceed VQ's present coverage because VQ has no terminal success theorem or full-algorithm gate 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].

For automated proofs about parametric unitary circuit builders, Qbricks provides stronger coverage than VQ because its path-sum specifications, resource properties, and Why3 automation prove the QFT, Grover, QPE, and Shor properties stated above. The 2021 paper explicitly excludes classical–quantum interaction and probabilistic measurement side effects, so VQ provides stronger coverage for measured uncomputation, reset, feed-forward, and record-independent cleanup. Both systems connect functional and resource properties to generated syntax, but they cover different program classes.

4 Program logics separate CoqQ, Qafny, and qrhl-tool from 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.

For general mixed-state program reasoning, compositional Hoare rules, and refinement laws, CoqQ provides stronger coverage than VQ. VQ instead 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, so VQ provides stronger coverage for theorems that relate generated syntax to gate or depth functions, as well as for 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, while 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 current goal of separating verified source reasoning from later circuit execution [2].

For high-level automated functional verification across the reported 37-program suite, Qafny provides stronger coverage than VQ. 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 provides stronger checked coverage for cleanup, register placement, and resource reports computed from the same circuit syntax, properties absent from the inspected Qafny artifact.

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].

For relational security games and adversarial program transformations, qrhl-tool provides stronger coverage than VQ. VQ contains a Lean model of an Elliptic Curve Digital Signature Algorithm (ECDSA) verification game, but its design report records no theorem connecting adversarially supplied signature data to that game. It also has no quantum relational Hoare logic rules [21]. qrhl-tool does not connect its proofs to circuit generation or logical gate resources, which are the parts of VQ relevant to concrete ECDLP estimates.

5 QBlue verifies Hamiltonian compilation across digital and analog targets

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 rather than a general cryptographic or arithmetic circuit library.

For a source-level Hamiltonian program compiled through particle transformations to digital or analog simulation, QBlue provides stronger coverage than VQ. 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 provides stronger evidence for exact reversible arithmetic, ancilla cleanup, measurement-assisted programs, and syntax-derived logical resources, which the inspected QBlue paper and artifact do not claim.

6 Resource, probability, noise, and execution claims remain separate

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. QWIRE and Qafny emit QASM or translate programs to SQIR, but their inspected sources do not state an end-to-end semantic theorem for that output. 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 Five projects show public work in the preceding year

This survey classifies development with a dated evidence rule. 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 only 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 and location entries identify who publishes each mutable source and where a later survey can inspect changes. The goal phrases paraphrase official documentation rather than infer private plans [5, 6, 16, 28, 3, 13, 2, 22, 26, 11, 12]. Each location identifies the repository or project page inspected on 16 August 2026.

8 Public artifacts limit completeness and cross-system conclusions

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 counts do not support a quality ranking. One end-to-end Shor proof, a library of 37 high-level examples, a cryptographic relational proof, and a detailed arithmetic audit answer different questions. The meaningful comparison names a use case and its checked property, as the preceding sections do, rather than treating breadth, automation, or repository activity as a single score.

The selection rule omits adjacent work that a broader survey should cover. Formal quantum-information libraries, verified error-correction developments, ZX-calculus proof systems, automata-based program verifiers, stand-alone circuit equivalence tools, and verified classical control software all meet needs that the eight systems address only partly. The conclusions apply to the selected public evidence on 16 August 2026 and do not constitute a comprehensive survey of formal quantum software.

9 Compilers, program logics, and VQ components check complementary properties

SQIR/VOQC, Qbricks, and QBlue provide the strongest compiler or end-to-end algorithm coverage for their named use cases. CoqQ, Qafny, and qrhl-tool provide the strongest general, automated, or relational program reasoning. QWIRE supplies a typed higher-order circuit language and mixed-state semantics whose published compositional proofs and resource theorems remain narrower under the criteria used here.

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.

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