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 complete algorithm proofs, CoqQ and qrhl-tool provide stronger general program logics, Qafny provides broader automated program verification, and QBlue verifies a Hamiltonian-compilation path 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 SDKs, simulators, testing systems, and stand-alone equivalence checkers unless their correctness argument passes through a proof assistant or deductive verification development. 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 authoritative syntax [20, 21]. Revision `cdb8db8` supplies the inspected source artifact, including the paper-specific elliptic-curve work that motivates its evidence boundaries [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 a checked route to an external executable circuit or compiler output, and the application criterion, P, requires a checked nontrivial algorithm or cryptographic protocol. Approximation bounds and physical-noise models are reported 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

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.

component. Symbol T means that a tool or translation is public but the inspected sources do not identify a checked correctness chain, and – means that no qualifying claim was located. The table records evidence scope rather than implementation quality.

The VQ entry needs two qualifications. Its program semantics represents measurement branches by amplitudes and classical records, but it does not provide a density-operator library or a 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, but the repository has no general verified optimizer or external code generator [21, 19].

3 Circuit semantics and compiler proofs divide QWIRE, SQIR, and Qbricks

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 small circuit equations [9, 17]. The current repository also contains a QASM printer, but its own file guide says that `Composition.v` admits compositionality lemmas used by later files, so the inspected artifact does not justify a closed compilation or compositional proof chain [5].

For typed circuit construction with density-matrix semantics, QWIRE covers a use case that VQ does not. For a closed theorem chain linking generated syntax, cleanup, and resource reports, VQ provides stronger public evidence because its selected component endpoints do not depend on the admitted QWIRE lemmas and QWIRE publishes no syntax-derived resource layer. QWIRE's QASM output also serves execution experiments, while VQ currently stops at its internal evaluator and judge interface.

SQIR gives low-level Coq syntax 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, phase-estimation, teleportation, Simon, and Shor 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 OpenQASM-gate-count upper bound, which exceeds VQ's present algorithm-level probability and resource closure [10]. VQ provides a different checked path for measurement-assisted arithmetic, record-independent cleanup, reversible register placement, and an audit of a specific low-resource ECDLP construction, none of which the inspected SQIR/VOQC sources claim.

Qbricks represents parametric circuit families with parametrized path sums and generates first-order Why3 obligations through its Hybrid Quantum Hoare Logic. The ESOP paper reports checked parametric implementations of QFT, Grover, QPE, and Shor order finding, including functional behavior, probability requirements, and polynomial circuit complexity [1]. The current project repository adds a formally verified circuit transformation to OQASM for circuits without ancillas and 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 reach complete named algorithms. 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. The two systems both 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 HHL, Grover, 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 direct relational specifications and realization predicates for circuit components, 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 logical resource provenance and 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 QafnyC work 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 a broad 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 execution path, 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-native VECDSA game, but its design report records that no hostile-submission adapter closes that game to an external candidate, and it has no qRHL-style relational program logic [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 complete complex-semantic and approximation endpoints needed for an analogous compiler theorem, 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 fall outside QBlue's stated simulation goal.

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 a complete Shor success theorem, and Qbricks proves probability requirements from unitary path-sum semantics. VQ proves finite conditional

Project	Dated public evidence and development location	Result under rule
VQ	Source revision `cdb8db8`, 16 August 2026, in `jsmorph/vq`. The report states terminal-probability, phase-estimation, approximation, and complete-algorithm goals.	Current
QWIRE	`inQWIRE/QWIRE`. Latest inspected default-branch commit, 11 May 2025.	No recent public evidence
SQIR/VOQC	`inQWIRE/SQIR`. Latest inspected default-branch commit, 30 July 2025.	No recent public evidence
Qbricks	`Qbricks/qbricks.github.io`. Repository change, 14 May 2026. Project documentation names hybrid Qbricks 2, certified compilation, path-sum rewriting, and error correction.	Current
CoqQ	`coq-quantum/CoqQ`. Latest inspected default-branch commit, 28 December 2024.	No recent public evidence
Qafny	`qafny/qafny_impl`. OOPSLA paper, 9 October 2025, and repository change, 2 February 2026. Current work expands Dafny-backed verification.	Current
qrhl-tool	`dominique-unruh/qrhl-tool`. One-way-permutation example committed 24 May 2026.	Current
QBlue	Zenodo Rocq artifact and Iowa State Q-Blue pages. Compiler paper posted 23 September 2025, and project outcome recorded in December 2025.	Current

Table 2: Observable public development evidence, accessed 16 August 2026.

probability bounds for named arithmetic events and preserves total mass for its branch semantics, but its reports state that terminal algorithm probability and the input-law transfer for its ECDLP audit remain open [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.

External execution has a similar boundary. SQIR/VOQC extracts verified Coq transformations to OCaml, and Qbricks documents a checked OQASM transformation and output generator. QWIRE and Qafny emit QASM or pass through SQIR, but their inspected sources do not state the end-to-end semantic theorem required by criterion X. VQ, CoqQ, qrhl-tool, and the public QBlue artifact stop at internal program or target models.

7 Five projects show public work in the preceding year

Current development uses 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," which says nothing about private work or the project's technical value.

The named developers and sites follow the official papers and current project pages. Jennifer Paykin, Robert Rand, Dong-Ho Lee, and Steve Zdancewic developed QWIRE in the inQWIRE repository, while Kesha Hietala and Robert Rand serve as the primary SQIR/VOQC contacts with contributors from the University of Maryland, University of Chicago, Columbia University, and related groups [5, 6, 10]. Their current documentation continues to describe typed circuits for QWIRE and verified algorithms, optimization, mapping, and extracted libraries for SQIR/VOQC, even though the survey found no qualifying change in the activity window.

CEA LIST and Laboratoire Méthodes Formelles at Université Paris-Saclay develop Qbricks. Its page names Sébastien Bardin, Benoît Valiron, Christophe Chareton, and the current project team [16]. Li Zhou, Gilles Barthe, Pierre-Yves Strub, Junyi Liu, and Mingsheng Ying develop CoqQ through the `coq-quantum` repository, whose documentation lists quantum information theory, program laws, refinement, and Dirac-decision procedures as its active technical directions [28, 3]. The absence of a recent CoqQ repository event under the rule does not show that those directions have ended.

The current Qafny repository names Liyi Li and Feifei Cheng as primary contacts and records contributors from Iowa State, Maryland, and the Australian National University [13, 2]. Dominique Unruh at the University of Tartu develops qrhl-tool in its eponymous GitHub repository, with the stated goal of computer-aided quantum and post-quantum security proofs [22, 26]. The Iowa State and Ames National Laboratory Q-Blue group, led by Mark Gordon and including Liyi Li, Fenfen An, and Federico Zahariev, develops QBlue as part of a hardware, compilation, and scientific-application co-design project [11, 12].

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 also use different trust boundaries. 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 path 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 should not be read as an exhaustive map of formal quantum software.

9 No system dominates all eight obligations

The comparison separates three clusters of stronger coverage. SQIR/VOQC, Qbricks, and QBlue lead for their named compiler or complete algorithm use cases, while CoqQ, Qafny, and qrhl-tool lead for general, automated, or relational program reasoning. QWIRE supplies a typed higher-order circuit language and mixed-state semantics whose public proof chain and resource coverage remain narrower under the criteria used here.

VQ occupies the component-verification and evidence-provenance intersection. It connects generated reversible and measured syntax to exact action, cleanup, placement, and logical resources, then applies those objects to a low-resource ECDLP audit. Extending VQ with a general program logic, verified optimization and export, density-operator or noise semantics, complete approximation theorems, and terminal algorithm probability would move it into the stronger coverage already demonstrated separately by the comparator systems.

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