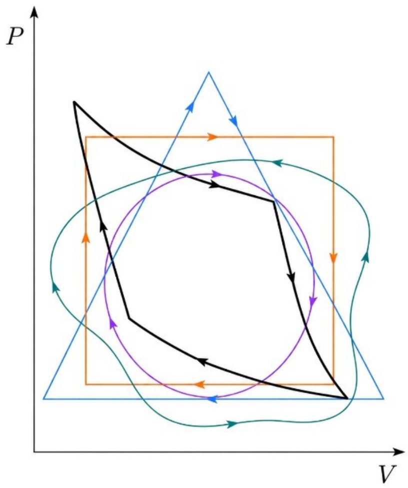
THERMODYNAMICS PUBLICATION PROGRAMME

Extending the Foundations of Thermodynamic Heat–Work Conversion in Cycles

Operationalizing the Carnot and Clausius Reversible-Cycle Equalities for Process-Specific Thermodynamic Benchmarks

Scientific Executive Summary of the Generalized Reversible-Cycle Framework



Carnot as a Special Case
Clausius as the Parent Reversible-Cycle Benchmark Framework

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Developed within Unified Energy B.V.

Scientific Executive Summary · Direct Public Download · Specialist Review and Publisher Orientation
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01 | Introduction

Background, purpose and the role of the Formal Core

CENTRAL ACADEMIC-REVIEW PROPOSITION. Can the established Clausius equality be operationalized systematically as the parent cycle-level constraint for qualified process-specific reversible benchmarks while recovering Carnot exactly in its reversible two-isothermal domain?

Background. Classical cycle theory commonly presents reversible heat-engine, heat-pump and refrigerator performance through the familiar Carnot efficiency and COP formulas. Those formulas are exact for a completely reversible cycle whose external heat exchange is confined to one high-temperature and one low-temperature isothermal interaction. They are not general formulas for cycles with multiple or continuously changing boundary temperatures.

PURPOSE. The Formal Core examines whether the established First-Law cycle balance, classical Carnot relations and Clausius reversible-cycle equality can be organized into a complete, configurable architecture for constructing process-specific reversible-cycle benchmarks.

GOVERNING FORMAL-CORE STATEMENT
“This paper does not introduce a new thermodynamic law and does not replace Carnot or Clausius. ‘Modernization of thermodynamic cycle theory’ is used as a concise framing term for the proposed systematic operationalization of established reversible-cycle equalities across a broader family of known-data selections, target quantities, configuration variables, cycle functions, and heat–temperature representations.”
Formal Core R175-L15, §1.2 — reproduced verbatim.

Role of the Formal Core. The Formal Core is the governing scientific and review specification. It supplies the definitions, derivations, representation rules, residual formulations, closure requirements, admissibility conditions, benchmark procedure, appendices, evidence boundaries and implementation governance that cannot be reproduced fully in this summary. The proposal is deliberately conservative in its thermodynamic foundations but potentially broad in its operational consequences.

The contribution submitted for review

The proposed contribution is organized into four connected elements that together define the scope submitted for scientific and editorial review.

- Algebraic reconstruction and complete operationalization of the Carnot reversible-isothermal cycle equality.
- Complete operationalization of the Clausius reversible-cycle equality for exact discrete, exact continuous and mixed heat–temperature structures.
- One configurable benchmark architecture spanning known data, targets, variables, closure, solution, admissibility, qualification and reporting.
- Exact recovery of Carnot as the two-isothermal specialization of the Clausius parent framework.

SCOPE BOUNDARY. The equalities alone do not establish uniqueness, a complete internal architecture, technical constructability, or experimentally validated performance.

02 | Scientific basis

Established foundations and the proposed operational hierarchy

The scientific ingredients are established; their proposed systematic organization and constructive use form the review object. The Carnot relations are retained exactly. The Clausius equality is adopted as the broader parent constraint for complete reversible cycles. Equations (SES-1) and (SES-2) state the governing forms summarized in Figure SES-1.

MEANING OF OPERATIONALIZATION. In this framework, mathematical operationalization does not mean merely restating or algebraically rearranging an established equality. It means converting the equality into an explicit and configurable constraint architecture in which the heat–temperature representation, known data, target variables, unresolved quantities, residual formulation, supplementary closure relations, solution routes and admissibility conditions are declared. Complete operationalization additionally specifies sufficiency, qualification and reporting, so that the equality can be used constructively to configure and assess a process-specific reversible benchmark rather than only being checked a posteriori.

LOCATION OF THE PROPOSED CONTRIBUTION. The Carnot and Clausius equalities, the First-Law cycle balance and the classical Carnot performance relations are established thermodynamics. The proposed contribution lies in the claimed completeness and unified organization of their operational use: a configurable four-variable architecture for the Carnot reversible-isothermal equality, a corresponding discrete, continuous and mixed architecture for the Clausius reversible-cycle equality, exact nesting of Carnot within the Clausius parent framework, and a common procedure for closure, solution, admissibility, qualification and reporting. Novelty is not claimed for the established equalities or for individual algebraic transformations considered in isolation.

$$\frac{Q_H}{T_H} = \frac{Q_L}{T_L} \qquad \text{(SES-1)}$$

Carnot reversible-isothermal cycle equality for exactly two isothermal interactions.

$$\oint \frac{\delta Q_{rev}}{T_b} = 0 \qquad \text{(SES-2)}$$

Established Clausius reversible-cycle equality in continuous cycle form.

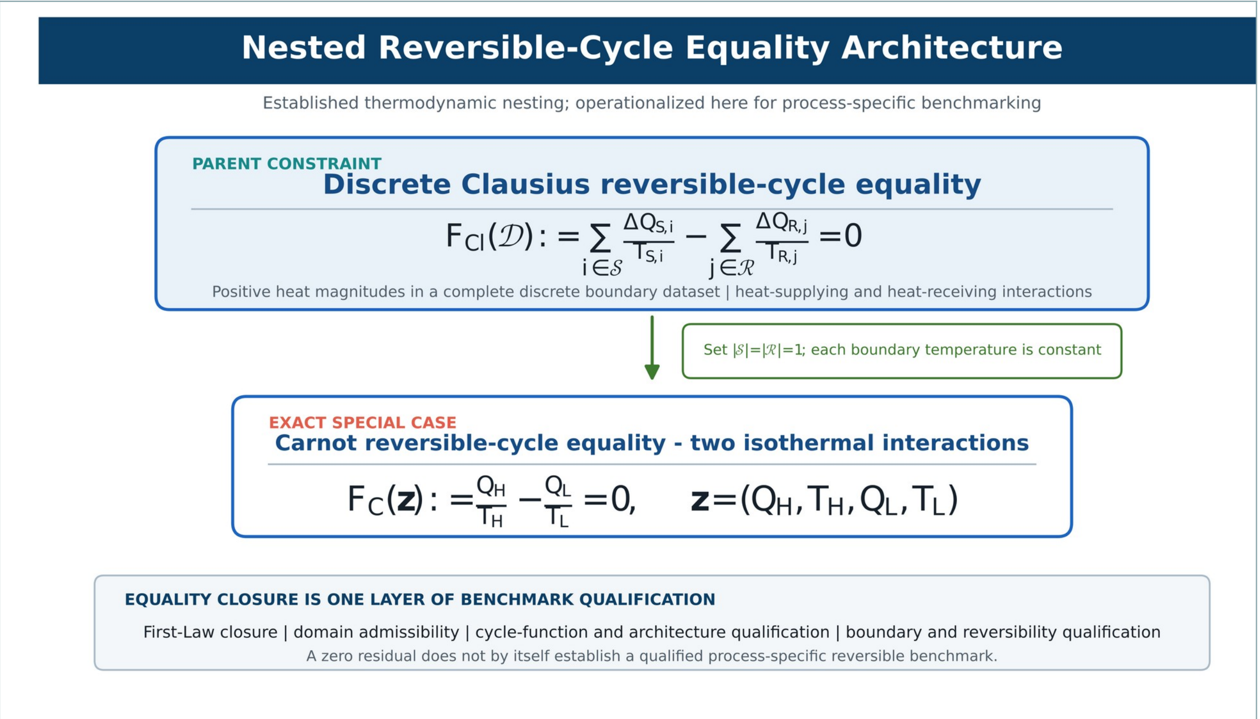

Figure SES-1. Nested reversible-cycle equality architecture. The discrete Clausius reversible-cycle equality is shown as the parent boundary constraint; the two-isothermal Carnot equality is recovered exactly by restricting the complete heat–temperature dataset to one supplying and one receiving interaction at constant boundary temperatures. The lower qualification layer emphasizes that equality closure is necessary but not sufficient for a qualified process-specific reversible benchmark.
Source: Reproduced unchanged from Formal Core R175-L15, Figure 12.

EXACT NESTING. Set one heat-supplying and one heat-receiving interaction, each at a constant relevant boundary temperature. The discrete Clausius equality then reduces exactly to the Carnot equality; First-Law closure recovers the classical Carnot performance relations.

03 | Two-isothermal domain

Complete operationalization of the Carnot equality

The proposed modernization returns to the four-parameter heat–temperature basis of the classical performance formulas and makes all problem roles explicit. Equations (SES-3) to (SES-5) state that operational basis.

> **GOVERNING FORMAL-CORE STATEMENT**
> "More fundamentally, the Carnot performance relations quantify the performance of an already qualified reversible two-isothermal cycle. They are exact downstream performance projections within that domain; they do not by themselves define the complete physical conditions under which a candidate cycle qualifies as reversible."
> *Formal Core R175-L15, §3.1 — reproduced verbatim.*

$$\eta_{engine,max}=1-\frac{T_L}{T_H},\quad COP_{H,max}=\frac{T_H}{T_H-T_L},\quad COP_{L,max}=\frac{T_L}{T_H-T_L} \tag{SES-3}$$

$$z=(Q_H,T_H,Q_L,T_L),\quad F_C(z):=\frac{Q_H}{T_H}-\frac{Q_L}{T_L}=0 \tag{SES-4}$$

> **GOVERNING FORMAL-CORE STATEMENT**
> "Complete operationalization means more than knowing, expressing, or rearranging an equality. The equality may be checked after a calculation for consistency; within the proposed methodology, it is also used constructively as one constraint in a sufficiently specified benchmark problem."
> *Formal Core R175-L15, Preface — From special-case formulas to a parent reversible-cycle framework — reproduced verbatim.*

Operational content

The six steps below summarize the proposed operational workflow for using the Carnot reversible-isothermal cycle equality within a sufficiently specified benchmark problem. Together they connect the declared heat–temperature boundary record to variable allocation, target selection and solution, closure, admissibility and qualified reporting.

01 Declare the boundary record. Use the complete pair set Biso = {(QH, TH), (QL, TL)} with positive heat magnitudes and positive absolute temperatures.

02 Allocate variable roles. Identify fixed known data K, the requested target, unresolved variables, configuration variables and any genuinely free degrees of freedom.

03 Select the target route. Solve QH, QL, TH or TL directly from the other three, or compute work, efficiency, COP or another qualified target using additional definitions.

04 Close the problem. Combine FC(z) = 0 with the First-Law cycle balance, the performance definition and any constitutive, state, comparison or selection conditions.

05 Test admissibility. Verify cycle function, directions, temperature ordering, positive magnitudes, finite work, cycle closure and the complete applicable reversibility conditions.

06 Qualify and report. Distinguish an equality-satisfying candidate from a qualified process-specific reversible benchmark cycle and state its domain.

Four additional reversible-isothermal solve-for relations

Besides the familiar Carnot engine-efficiency relation and the equivalent Carnot heat-pump and refrigeration COP relations in (SES-3), complete operationalization exposes four direct reversible-isothermal cycle relations. With any three of QH, QL, TH and TL specified, the fourth quantity can be solved as shown in (SES-5), subject to First-Law closure and physical admissibility. These four formulas are operationally useful rearrangements of the same four-parameter Carnot equality; they are not four new thermodynamic laws or four independent equalities.

Thermodynamic and mathematical status. These four relations do not represent a less ideal or approximate cycle. Subject to the same completely reversible two-isothermal cycle conditions, positive absolute temperatures, First-Law closure and physical admissibility, they are exact solve-for forms of the same Carnot equality that—together with the applicable performance definition and First-Law balance—underlies the classical maximum engine-efficiency and reversible heat-pump and refrigeration COP relations. Their mathematical status is therefore exact algebraic equivalence within that domain, and their thermodynamic status is the same reversible-isothermal ideal benchmark. Unlike the $\eta_{\max}$ and $COP_{\max}$ relations, however, they solve directly for a heat quantity or boundary temperature rather than expressing a performance ratio.

$$Q_L = Q_H \frac{T_L}{T_H}, \quad Q_H = Q_L \frac{T_H}{T_L}, \quad T_L = T_H \frac{Q_L}{Q_H}, \quad T_H = T_L \frac{Q_H}{Q_L} \tag{SES-5}$$

WHAT IS COMPLETE HERE. The equality is operationalized as a configurable four-variable constraint supporting multiple known-data/target allocations, direct and indirect solutions, composite targets and qualified reporting.

04 | General reversible-cycle domain

Complete operationalization of the Clausius equality

The same operational logic is extended from exactly two isothermal interactions to complete cycles with more than two discrete heat–temperature records, continuously varying boundary-temperature trajectories, or a mixed structure. Table SES-1 distinguishes the exact governing representation for each declared structure.

$$\sum_{i \in S} \frac{\Delta Q_{S,i}}{T_{S,i}} = \sum_{j \in R} \frac{\Delta Q_{R,j}}{T_{R,j}} \tag{SES-6}$$

$$\int_S \frac{\delta Q_S}{T_{S,b}} = \int_R \frac{\delta Q_R}{T_{R,b}} \tag{SES-7}$$

Table SES-1. Thermal-interaction structures and governing representations.

Thermal-interaction structure	Governing representation	Qualification
Exactly two isothermal interactions	Carnot equality	Exact finite specialization
>2 finite isothermal interactions	Discrete Clausius equality	Exact for the declared piecewise structure
Continuously varying boundary trajectory	Continuous Clausius integral	Exact; segmentation requires demonstrated convergence
Discrete + continuous interactions	Mixed sum/integral form	Each contribution retains its physical representation

$$F_{Cl}(D) := \sum_{i \in S} \frac{\Delta Q_{S,i}}{T_{S,i}} - \sum_{j \in R} \frac{\Delta Q_{R,j}}{T_{R,j}} = 0 \tag{SES-8}$$

Constructive benchmark use

The residual may check a completed dataset a posteriori. Within the proposed methodology it is also used constructively as one governing constraint within a sufficiently specified benchmark problem. Let K contain the fixed data and x only the declared unresolved variables:

$$D = D(K, x), \quad F_{Cl}(K, x) := F_{Cl}(D(K, x)) \tag{SES-9}$$

REPRESENTATION DISCIPLINE. Every heat increment remains paired with its applicable boundary temperature. Replacing a temperature-resolved trajectory by one average, maximum or minimum temperature defines a different dataset unless thermodynamic equivalence is demonstrated.

Operational content

The seven steps below make the corresponding Clausius operational workflow explicit. Together they connect a declared complete heat–temperature representation to variable allocation, residual construction, closure, solution, admissibility, exact special-case recovery and qualified reporting.

01 Declare the complete thermal-interaction record. For a discrete structure, state every heat–temperature pair; for a continuous structure, state the complete boundary-temperature trajectory; for a mixed structure, preserve both parts explicitly.

02 Select the exact governing representation. Use the applicable discrete sum, continuous cycle integral or mixed form, retaining every heat increment with its relevant boundary temperature.

03 Allocate variable roles. Identify the fixed data K, requested target, unresolved variables x, configuration variables and any genuinely free degrees of freedom.

04 Construct the residual and close the problem. Form the applicable Clausius residual and combine it with the First-Law cycle balance and the required boundary, constitutive, state, process, working-medium, comparison and selection conditions.

05 Select the solution route. Determine whether the configured problem is a direct analytical relation, scalar root problem, coupled nonlinear system, conditional solution or admissible solution family.

06 Test sufficiency and admissibility. Verify representation completeness, closure, cycle function, sign convention, finite quantities, physical ordering and all applicable complete-cycle reversibility conditions.

07 Verify specialization and qualify the result. Under the restriction to two constant-temperature heat interactions, recover the Carnot equality exactly; otherwise report the declared domain, assumptions, residual status, solution status and qualification boundary.

> **WHAT IS COMPLETE HERE.** The Clausius equality is operationalized as a representation-aware parent constraint for discrete, continuous and mixed complete-cycle data, supporting configurable variable allocation, residual construction, supplementary closure, multiple solution routes, admissibility testing, exact Carnot recovery and qualified reporting.

05 | Carnot–Clausius unification

Two development routes, one benchmark architecture

The Formal Core supports a Carnot-first review route and a Clausius-first general route. Both converge on the same hierarchy: established equalities, explicit representation, complete operationalization, configured benchmark construction and exact Carnot recovery within the two-isothermal domain.

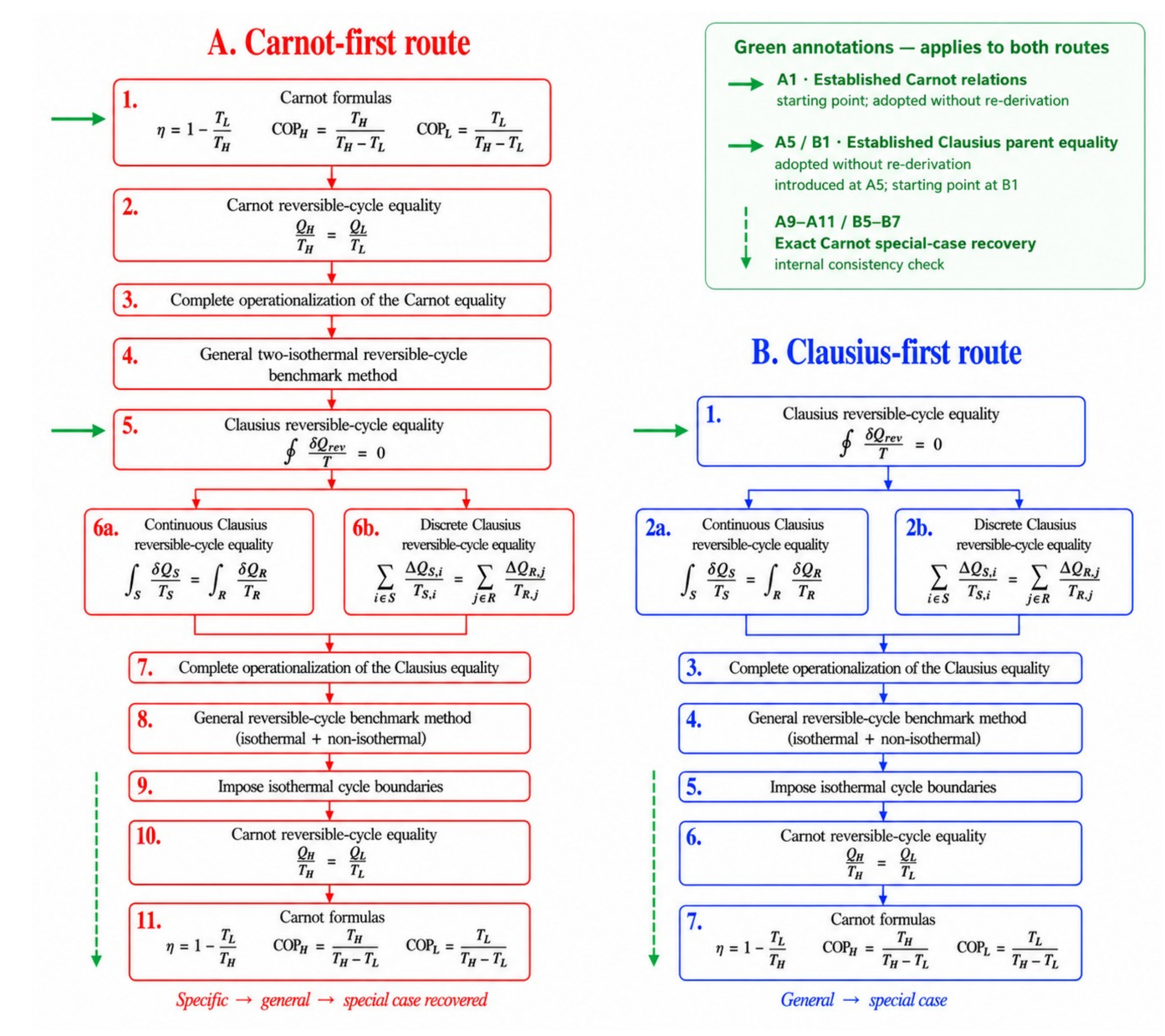

Figure SES-2. Carnot-first and Clausius-first development routes through one benchmark architecture. The two routes differ in development sequence, not in scientific hierarchy: both retain the established Carnot relations, use the Clausius equality as the broader parent constraint, and recover the same two-isothermal special case.
Source: Reproduced unchanged from Formal Core R175-L15, Figure 1a.

How to read Figure SES-2

Purpose of the figure. Figure SES-2 is a roadmap of two logically equivalent development routes through the same proposed benchmark architecture. The red Carnot-first route begins with the familiar performance formulas and exposes the reversible two-isothermal equality that underlies them before moving to the broader Clausius framework. The blue Clausius-first route begins directly with the established Clausius reversible-cycle equality and then specializes it to the Carnot domain. The arrows indicate dependency and specialization, not a historical sequence and not a claim that one route replaces the other.

A. Carnot-first route. The left-hand route starts at A1 with the established efficiency and coefficient-of-performance relations for an already qualified reversible cycle exchanging heat at exactly two constant boundary temperatures. A2 makes their four-quantity heat–temperature basis explicit through the Carnot reversible-isothermal cycle equality. A3 is the proposed complete operationalization: known data, target variables, closure, admissibility, solution and qualification roles are made configurable instead of leaving the equality as a single textbook relation. A4 packages that structure as a two-isothermal benchmark method. At A5-A8 the route adopts the established Clausius equality as the parent cycle constraint, distinguishes its discrete and continuous representations and extends the same operational logic to general heat–temperature structures.

B. Clausius-first route. The right-hand route begins at B1 with the established Clausius reversible-cycle equality. B2 separates the continuous boundary-temperature form from the discrete form for finite heat–temperature records; mixed cases retain both representations. B3 and B4 then apply the proposed operational architecture and benchmark procedure directly at this general level. When the declared cycle boundary is subsequently restricted at B5 to one heat-supplying and one heat-receiving isothermal interaction, the Clausius constraint reduces at B6 to the Carnot equality and yields the classical formulas at B7. Thus the general route does not discard Carnot; it contains Carnot as its exact two-isothermal specialization.

Why the routes converge. The green annotations identify the common scientific anchors. The classical Carnot relations and the Clausius equality are established thermodynamics and are adopted rather than presented as new laws. The proposed contribution lies in organizing those relations into one explicit, configurable and qualified workflow. Convergence means that the Carnot-first route can be generalized without contradicting its starting point, while the Clausius-first route must recover the same Carnot equality and performance formulas when the two-isothermal conditions are imposed. Equation (SES-10) summarizes this nesting as a domain relation: the reversible-isothermal Carnot cycle domain is a special subset of the wider Clausius reversible-cycle domain.

Scientific interpretation and limit. Exact Carnot recovery is an internal consistency requirement and a finite review test. It shows that the proposed general architecture preserves the classical limiting case under its stated conditions. The figure does not by itself prove that the operationalization is complete, novel, uniquely formulated, practically useful or independently validated. Those questions require separate review of the definitions, algebra, representation choices, closure and admissibility conditions, reproducibility and prior-art position in the Formal Core. Nor does every Clausius-compatible mathematical record automatically constitute a physically qualified reversible cycle; cycle closure, boundary consistency and the full reversibility conditions remain separate requirements.

$$\text{Carnot reversible-isothermal cycle domain} \subset \text{Clausius reversible-cycle domain} \quad \text{(SES-10)}$$

06 | Configuration and qualification

From equality to a qualified process-specific benchmark

A zero residual is one necessary layer, not the final benchmark. Table SES-2 separates four controlled stages and requires the governing equality to be embedded in a closed, admissible and reviewable problem. In Equation (SES-11), K denotes the known-data set, x_{rev} the solved reversible variables, and Π_{rev} the reported reversible benchmark performance.

Table SES-2. Controlled stages from benchmark definition to a qualified cycle.

Stage	Required scientific content
1. Benchmark problem	Function, system boundary, comparison purpose and requested result.
2. Configuration	Fixed data K, target, unresolved x, comparison class, equalities, closure, admissibility and selection conditions.
3. Solution	A solved parameter set or admissible solution set satisfying the complete configured constraint system.
4. Qualified benchmark cycle	A complete, closed and thermodynamically admissible reversible cycle for the stated problem.

$$K \rightarrow x_{rev} \rightarrow \Pi_{rev} \tag{SES-11}$$

Depending on the allocation of known and unresolved variables, the configured result may be a direct analytical relation, scalar root problem, coupled nonlinear system, conditional solution or admissible solution family. Closed-form availability belongs to the complete problem, not to the equality in isolation.

From parent constraint to configured benchmark families

Figure SES-3 illustrates the second stage of the proposed operational architecture. The Clausius reversible-cycle equality supplies the governing parent constraint for reversible cyclic heat–work conversion, but it does not by itself generate a unique named-cycle relation or determine a realizable machine architecture. A particular reversible benchmark formulation emerges only after the applicable boundary data, heat–temperature representation, constitutive and state relations, working-medium and process restrictions, closure conditions, reversibility requirements and admissibility conditions have been imposed.

The two-isothermal branch recovers the Carnot reversible-isothermal cycle equality exactly, together with the familiar efficiency and COP relations and the other operational rearrangements of the four-parameter equality. Other configurations require different supplementary conditions. Linear temperature glides combined with appropriate constitutive and process assumptions may produce Lorenz-type benchmark relations. Coupled glides satisfying the relevant ideal reversed Brayton/Joule conditions define another specialized branch. General piecewise or continuously non-isothermal boundaries instead lead to process-specific benchmark relations configured from their actual heat–temperature structure.

The branches are illustrative rather than exhaustive. They do not imply that the Clausius equality alone derives every named cycle, or that a cycle-family label automatically fixes its external heat-interaction structure. The system boundary and declared thermodynamic conditions remain decisive. Equality satisfaction therefore remains distinct from uniqueness, realizability, constructability and independently validated performance.

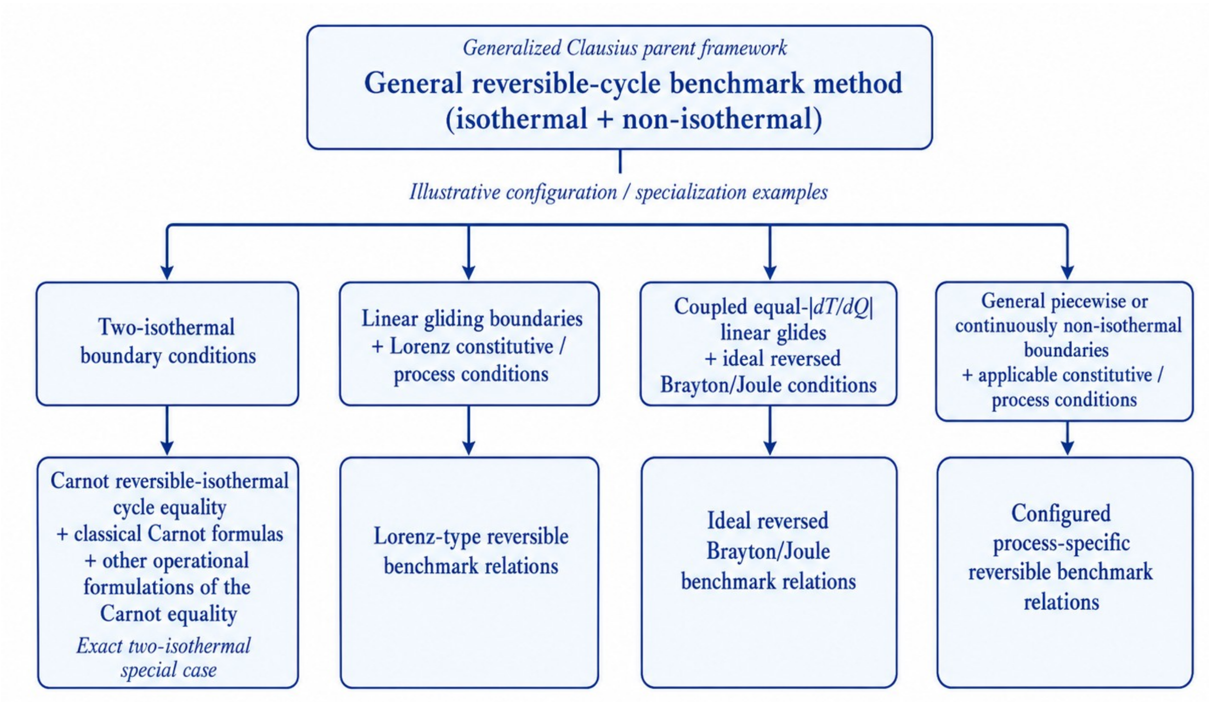

Figure SES-3. Illustrative specialization of the generalized reversible-cycle benchmark framework. The Clausius equality acts as the parent reversible-cycle constraint. Carnot, Lorenz-type, ideal reversed Brayton/Joule and general non-isothermal benchmark relations arise only after the additional conditions defining the applicable thermal and cycle model are imposed. The branches are illustrative and not exhaustive.
Source: Reproduced unchanged from Formal Core R175-L15, Figure 1b.

Figure SES-4 then isolates a complementary qualification issue: satisfying the governing equality identifies an equality-closed candidate, not automatically the separately conditioned admissible reversible subset. The visual uses signed heat quantities ($Q_k > 0$ into the cycle and $Q_k < 0$ out of the cycle), whereas Equations (SES-4) and (SES-5) use positive heat magnitudes. The conventions are equivalent through $Q_{L,signed} = -Q_{L,mag}$.

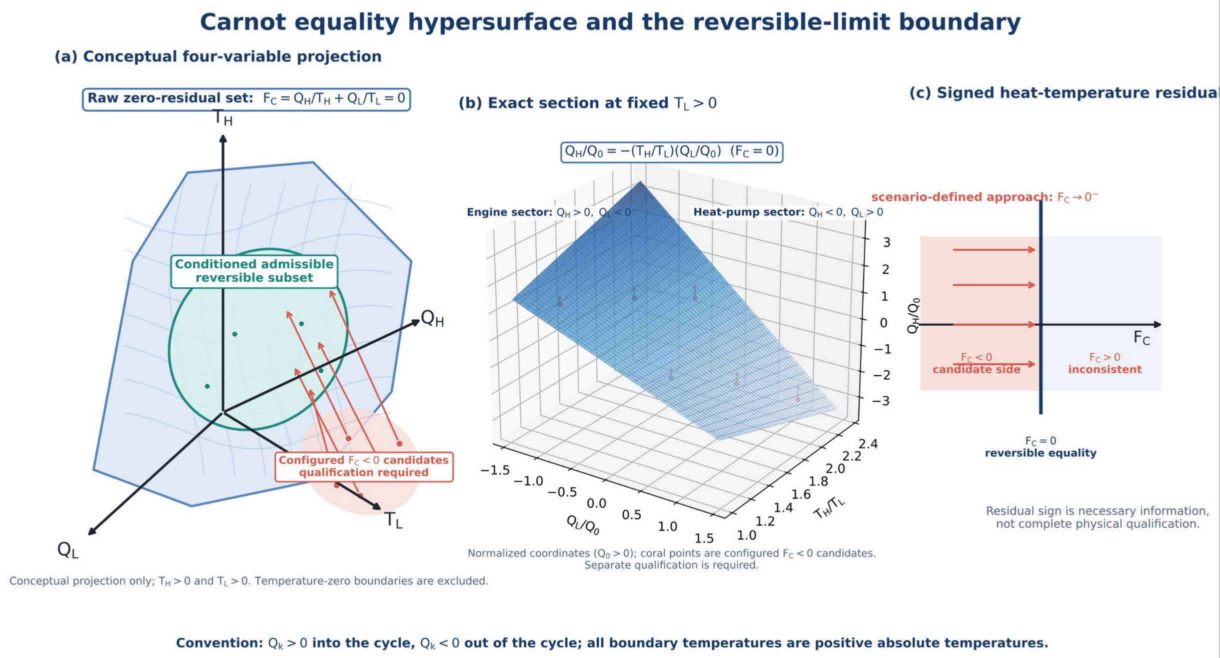

Figure SES-4. Equality closure and the separately conditioned admissible reversible subset. A zero Carnot residual establishes equality closure only; First-Law closure, domain admissibility, cycle-function and architecture qualification, complete-cycle reversibility, uniqueness and constructability require separate findings.
Source: Reproduced unchanged from Formal Core R175-L15, Figure 13.

07 | What follows — and what does not

Formal consequences, relevance and scientific status

Direct formal consequences within the declared method

Within the declared method, the proposed organization yields the following direct formal consequences. They apply within the stated thermodynamic domains and qualification conditions; they are not claims of experimental validation or universal engineering applicability.

- Carnot is recovered exactly and retained as the simplest two-isothermal specialization.
- Finite multi-isothermal, continuous non-isothermal and mixed heat–temperature structures can be configured without forcing them into a two-temperature Carnot representation.
- Known-data, target-variable, closure, direct/indirect solution, admissibility and qualification roles become explicit and programmable.
- A qualified reversible benchmark can serve independently or as the corresponding reversible counterpart of an actual irreversible-cycle problem under a declared comparison class.

Evidence and claim-status boundary

To prevent established thermodynamics, the proposed operational organization and downstream applications from being conflated, Table SES-3 separates the principal claim layers and their present evidential status.

Table SES-3. Evidence and claim-status boundaries.

Claim layer	Current status
Established thermodynamics	First Law; classical Carnot relations; Clausius equality; established reversibility principles.
Algebraic organization	Derived and substantiated in the Formal Core; open to independent formal checking.
Proposed operationalization	Complete configurable architecture submitted for independent scientific review.
Method-enabled applications	Supported in principle; system-specific models, feasibility assessment and validation remain required.
Research extensions	Hypotheses or research directions; not consequences established by the equalities.
CarnotX	Optional implementation layer; intended, implemented, verified and validated capability must be reported separately.

WHY THIS MAY MATTER. Many heat engines, heat pumps, refrigeration cycles and thermal processes exchange heat over multiple or changing temperatures. A process-specific reversible benchmark can retain that temperature-resolved structure instead of reducing it automatically to one hot and one cold temperature. This can make assumptions, comparison boundaries, theoretical limits and locations of thermal mismatch more explicit. It does not by itself establish realizable energy savings, technical feasibility or validated device performance.

POTENTIAL METHODOLOGICAL SIGNIFICANCE. If the architecture is found correct, sufficiently complete and reproducible, it could support a substantial shift in analytical practice: from treating the familiar two-temperature Carnot formulas as the default reversible reference towards configuring process-specific reversible benchmarks from the applicable heat–temperature structure. This would concern the organization and use of established theory, not replacement of its foundations. Mathematical consistency still does not by itself establish novelty, usefulness or validated performance.

Engineering relevance and programme aim

Central to this programme aim is the proposed shift from using the familiar two-temperature Carnot formulas as the default reversible reference to using the Clausius equality as the parent constraint for a broader configurable benchmark architecture, while retaining Carnot exactly within its two-isothermal domain. Subject to independent scientific confirmation and application-specific validation, the programme aims to accelerate the international development and use of temperature-resolved, process-specific reversible-cycle benchmarks for combustion engines, power plants, heat pumps, refrigeration systems and related thermal technologies. The anticipated engineering value is not a predetermined performance gain, but a more complete basis for defining comparison limits, locating thermal mismatch, evaluating design alternatives and guiding optimization. These are programme objectives and potential consequences of the proposed operationalization, not presently validated universal outcomes.

CARNOTX IMPLEMENTATION LAYER. CarnotX is the developing computational, analytical and learning platform intended to translate selected parts of the framework into configurable calculations, model libraries, demonstrations and visual interpretation, including reversible-cycle benchmarking, temperature-resolved non-isothermal analysis and Thermal Matching studies. Companion publications, implementation and demonstrations remain in development; broader implementation is intended, not completed adoption. CarnotX is not evidence of scientific correctness: intended, implemented, verified and independently validated capabilities remain separately identified.

Representative textbook impact — the Moran case

WHY THIS TEXTBOOK CASE. Appendix D uses the Moran engineering-thermodynamics textbook family as a bounded representative case. Moran is selected because it is a rigorous, widely used treatment containing the established ingredients at issue: reversible processes, Carnot relations, the Clausius relation, entropy, exergy, named power and refrigeration cycles, and conventional engineering applications. The assessment does not argue that Moran teaches incorrect thermodynamics. It asks which established reversible-cycle relations are converted into complete, configurable problem-solving procedures.

TITLE AND EDITION BOUNDARY. The directly inspected source is M. J. Moran and H. N. Shapiro, Fundamentals of Engineering Thermodynamics, 5th edition, SI version (2006). The detailed source-manuscript assessment concerns M. J. Moran, H. N. Shapiro, D. D. Boettner and M. B. Bailey, Moran's Principles of Engineering Thermodynamics, SI Version, Global Edition, 9th edition (2018), for which direct edition verification remains pending. These are bibliographically distinct titles in the same textbook lineage: the later possessive "Moran's" identifies that lineage and does not name a separate thermodynamic principle; "Principles" likewise does not imply replacement of the established laws discussed here. The 8th edition, SI version (2015), is retained only as a distinct curriculum reference. Edition-specific chapter, equation and wording references must be checked against the licensed edition before external publication.

THREE DISTINCT GAPS. The bounded assessment distinguishes: (i) a definition-and-qualification gap—no equivalent consolidated cycle-level procedure was identified for establishing whether a candidate physical cycle satisfies the complete applicable equality, heat–work, closure, physical-reversibility, state/process, constitutive and admissibility conditions; (ii) a Carnot-operationalization gap—the familiar efficiency and COP formulas are directly calculable, but no complete known-data/target-variable architecture was identified for the underlying four-quantity Carnot equality; and (iii) a Clausius-parent gap—no equivalent configurable workflow was identified for discrete, continuously varying and mixed heat–temperature structures.

GOVERNING FORMAL-CORE STATEMENT
"This distinction is essential: 'no formula erratum' does not mean 'no textbook consequence.' The proposed development is a structural modernization of how established relations are organized and operationalized, not a replacement of the First Law, Second Law, Carnot theorem, entropy, exergy, or conventional named-cycle analysis."
Formal Core R175-L15, Appendix D.2.6 — reproduced verbatim.

Table SES-4. Bounded textbook-impact map for the representative Moran case.

Consequence category	Count	Bounded interpretation
Formula corrections or established errata	0	The existing Carnot and Clausius relations remain valid.

Consequence category	Count	Bounded interpretation
Domain and interpretation qualification	1	State the exact two-isothermal comparison class of the principal Carnot efficiency and COP limits.
Operational additions	9	Add complete Carnot- and Clausius-based data, closure, solution, admissibility and qualification procedures.
Total necessary intervention types	10	Minimum structural consequence, conditional on scientific acceptance.
Desirable editorial harmonizations	3	Align terminology, hierarchy and cross-chapter presentation.
Desirable application and implementation additions	5	Add T–Q visualization, actual/reversible comparison, loss analysis, Thermal Matching, application cases and software-supported exercises.
Total necessary and desirable	18	Illustrative integration depth in this case—not a universal textbook statistic.

PUBLISHER AND REVIEWER SIGNIFICANCE. For publishers, the bounded result supports evaluating a coordinated scientific and educational architecture, not an isolated formula amendment. Reviewers should test whether the three gaps exist, whether the architecture resolves them correctly and completely, and whether the intervention categories are justified.

EVIDENCE BOUNDARY. This source-bounded case demonstrates possible integration depth, not prevalence across textbooks, editions, institutions, countries or curricula. Publication consequences remain conditional on independent review; broader conclusions require wider corpus and pedagogical research.

08 | Specialist review route

Review priorities and relationship to the Formal Core

PROGRAMME PROVENANCE. The CarnotX programme was initiated and is led by Casper Helder within Unified Energy B.V., which provides the scientific-method, software and intellectual-property foundation. CarnotX Academy provides access to publications, academic engagement and professional learning. Dialogue, review, co-authorship, software contribution and engineering collaboration are role-specific; they do not imply endorsement, independent validation or institutional adoption. Contributors and institutions are associated only with confirmed roles, while application-specific engineering routes require their own models, evidence and validation.

This summary enables initial specialist assessment; it does not replace review of the governing specification. The Formal Core remains controlling for scientific meaning, equation scope, sign conventions, qualification boundaries, references, appendices and reproducible implementation details.

Finite review decomposition

Independent assessment can be organized as a finite sequence of review objects rather than as a single all-or-nothing judgement. Table SES-5 identifies five tests spanning exact Carnot recovery, mathematical and thermodynamic correctness, architectural completeness, reproducibility and adequate distinction from established theory and prior work.

Table SES-5. Finite review decomposition.

Test	Primary review object
1	Exact Carnot recovery under the declared two-isothermal conditions.
2	Thermodynamic and mathematical correctness of the discrete, continuous and mixed Clausius formulations.
3	Completeness of data, target, closure, sufficiency, admissibility and qualification architecture for the claims made.

Test	Primary review object
4	Reproducibility of configured benchmark construction within each declared domain.
5	Adequate distinction between established theory, the proposed operational organization, prior work and downstream validation.

University-first international dissemination route

Technical universities are the intended first institutional route because they combine independent scientific scrutiny with the education of the engineers who will design and improve future energy systems. Following scientific review, the programme seeks international integration through thermodynamics courses, textbooks, software-supported exercises, student projects, theses and research collaborations, followed by transfer into professional engineering practice. This staged route is an implementation objective; it does not imply current institutional endorsement, curriculum adoption or validated engineering impact.

Document layers and access routes

The publication programme uses three document layers with different audiences and access routes. Table SES-6 clarifies their respective roles while preserving the Formal Core as the governing technical source.

Table SES-6. Document layers and access routes.

Layer	Role and access route
Public Overview	Freely accessible overview; non-specialist orientation.
Scientific Executive Summary	Direct PDF download; specialist orientation and review.
Formal Core R175-L15	Controlled scientific or editorial review; governing technical source.

Scientific source and access

Scientific source basis. Operationalizing the Carnot and Clausius Reversible-Cycle Equalities for Process-Specific Thermodynamic Benchmarks, Formal Core Specification, revision R175, layout edition L15, Editorial and Academic Review Copy, August 2026.

Selected source lineage retained from the Formal Core: Carnot (1824); Clausius (1867); Callen (1985); Moran and Shapiro (2006); Moran et al. (2018). Consult the Formal Core for the complete references and source-status distinctions.

Programme context and access route: CarnotX Academy, https://carnotx.unified-energy.com

> **CONTROLLING SOURCE.** If this summary and the governing Formal Core differ, the Formal Core determines the scientific meaning, scope and qualification boundary.

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