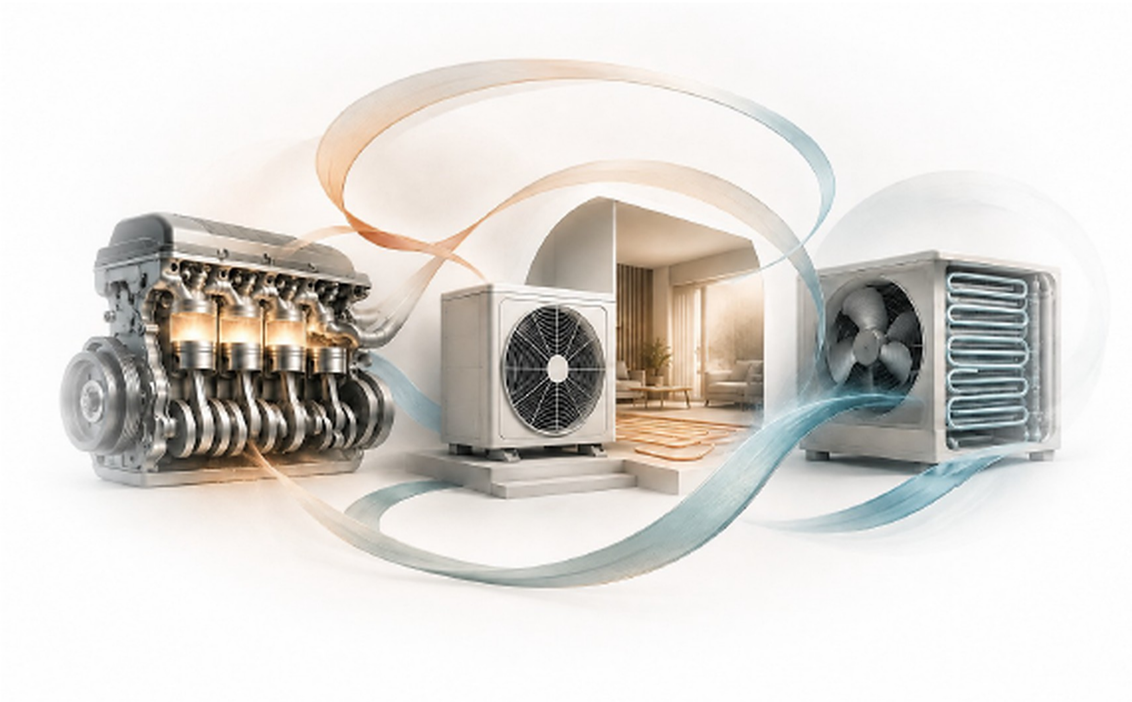
THERMODYNAMICS PUBLICATION PROGRAMME

Extending the Foundations of Thermodynamic Heat–Work Conversion in Cycles

IMPACT, APPLICATIONS & RESEARCH OPPORTUNITIES REPORT

What Becomes Possible Beyond the Two-Isothermal Carnot Benchmark?

Impact, Applications and Research Opportunities of Process-Specific Reversible-Cycle Benchmarking



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Developed within Unified Energy B.V.

Scientific source basis: Formal Core R180-L15

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Impact, applications and research opportunities - a reader-facing route through the report.

NAVIGATION NOTE

The report is intentionally impact- and application-focused. Formal derivations, qualification workflows and the complete operational method remain in the Formal Core, the Scientific and Methodological Source Document.

| Report at a Glance

More than two centuries after Carnot's 1824 analysis, the familiar Carnot efficiency relation remains perhaps the most widely recognized formula for reversible heat-work conversion:

$$\eta_{Carnot} = 1 - \frac{T_L}{T_H}$$

With T_H and T_L denoting absolute boundary temperatures, this relation and the analogous heat-pump and refrigerator COP expressions have long supported education, theoretical analysis and performance benchmarking. Its exact domain is the reversible two-isothermal case: heat is supplied at one constant boundary temperature T_H and rejected at another T_L. Many systems instead exchange heat at multiple or continuously varying temperatures. One selected temperature pair then does not generally represent the complete heat-temperature structure or automatically provide a qualified process-specific reversible benchmark.

Classical thermodynamics already provides entropy balances, exergy analysis and specialized non-isothermal methods. The narrower gap addressed here is that the familiar Carnot formulas do not by themselves provide an explicit, configurable and reproducible cycle-level method for constructing and qualifying benchmarks across discrete, continuous and mixed thermal-interaction structures.

The First Law, the Carnot relations and the Clausius reversible-cycle equality are established thermodynamics. The proposed modernization has two linked layers: first, scope-bounded operationalization of the Carnot reversible-isothermal cycle equality within its exact two-isothermal domain, beyond the familiar efficiency and COP projections; second, operationalization of the Clausius reversible-cycle equality as the parent cycle-level benchmark relation for admissible isothermal, piecewise-isothermal, multi-temperature, continuously non-isothermal and mixed cycles. This report examines the resulting potential for explanation, quantification, comparison and optimization. Within the declared scope, the framework is intended to determine qualified process-specific reversible limits—engine efficiency, heating COP or refrigeration COP—for sufficiently specified and admissible cycles; maxima remain dataset- and comparison-class-specific.

Impact logic

TWO-ISOTHERMAL CARNOT BENCHMARK
Exact special case
↓

PROPOSED CLAUSIUS-PARENT REVERSIBLE-CYCLE BENCHMARK FRAMEWORK
Broader process-specific benchmark architecture
↓

EXPLANATION | QUANTIFICATION | COMPARISON | OPTIMIZATION
Potential capability
↓

ENGINEERING | SCIENCE | EDUCATION
Potential impact domains

SCIENTIFIC STATUS AND SOURCE BOUNDARY

Established: First Law; Carnot relations; Clausius reversible-cycle equality. **Proposed here:** systematic operationalization into a Clausius-parent process-specific benchmark framework. **Impact status:** applications and research extensions have different levels of development and validation. **Scientific source:** Formal Core R180-L15.

What This Report Does - and Does Not Do

PURPOSE AND DISCLOSURE BOUNDARY

This report examines potential impact, applications and research opportunities arising from the scientific and methodological architecture developed in the Formal Core. It describes the proposed benchmark framework conceptually. It does not reproduce the formal derivations, complete operationalization, qualification workflow, residual or solver architecture, or a reconstructable computational method.

The scientific and methodological source for this report is the Formal Core, Operationalizing the Carnot and Clausius Reversible-Cycle Equalities for Process-Specific Thermodynamic Benchmarks, revision R180-L15. The Formal Core contains the formal derivations, benchmark architecture, qualification framework, worked verification cases and scientific-status boundaries underlying the perspectives discussed here.

TERMINOLOGY NOTE

The underlying modernization/framework does not yet have an official proper name. The preferred descriptive term in this report is the proposed Clausius-parent reversible-cycle benchmark framework. CarnotX is the wider Unified Energy Group programme for research, publication, education, software, product and service activities surrounding the proposed modernization; it is not the name of the underlying theory or methodological framework. CarnotX Software is an early implementation and learning layer. CarnotX Academy is the programme's publication, communication and education channel, not a scientific validation authority.

Questions Beyond the Two-Isothermal Carnot Benchmark

- Which refrigerant and temperature glide best match a specified heat-pump source and sink?
- What is the minimum reversible work required to heat or cool a finite body through a specified temperature range?
- How much useful-work opportunity is lost when two streams at different temperatures exchange heat directly or are mixed?
- How does the reversible work potential of the same quantity of heat change when that heat is supplied through different temperature trajectories?
- Can the mechanically unrecovered work of a cyclically loaded solid be compared with a qualified reversible thermomechanical counterpart?
- Can distributed natural or planetary systems with coupled heat and mechanical-energy conversion be given a common process-specific reversible benchmark without replacing their domain-specific physics?

COMMON THERMODYNAMIC FEATURE

These questions arise in different disciplines, but they share a thermodynamic feature: the relevant heat interactions cannot be represented completely by one constant high temperature and one constant low temperature. The proposed modernization asks whether the established Clausius reversible-cycle equality can provide the common parent benchmark layer needed to address such problems while retaining the Carnot relations exactly in their two-isothermal domain.

01 | Why Established Knowledge Can Gain New Explanatory Power

Reorganization can change what a scientific framework makes visible and usable.

Scientific advances do not always begin with a new physical law. They can also arise when established knowledge is reorganized into a structure with greater explanatory and operational power. Euclid's organization of geometry and Mendeleev's ordering of the chemical elements illustrate how relationships, gaps and new questions can become visible once known knowledge is placed within a more coherent framework. The proposed modernization of reversible-cycle theory is advanced in this more limited sense: not as a replacement for established thermodynamics, but as an attempt to organize and operationalize its reversible-cycle relations into a broader benchmark architecture. If successful, the gain is not only formal: it can increase explanatory power - why different systems behave differently; benchmark power - what a qualified reversible counterpart would be; and operational power - what can then be quantified, compared and optimized.

CONCEPTUAL CAPABILITY **EXPLANATORY POWER** Connects apparently different heat-work problems through a common thermodynamic comparison structure while leaving their local governing physics intact.	FORMAL-METHOD CAPABILITY **BENCHMARK POWER** Constructs a process-specific reversible reference for declared multi-temperature or varying-temperature heat interactions.
METHOD-ENABLED CAPABILITY **OPERATIONAL POWER** Turns the benchmark into calculation, actual/reversible comparison, work-unit penalties, configuration studies and optimization objectives.	RESEARCH OPPORTUNITY **TRANSFER POWER** Allows the same thermodynamic layer to be used alongside domain models in thermal engineering, process engineering, materials science and selected natural systems.

Why potentially broad impact can follow from one benchmark change

Thermodynamic benchmarks sit upstream of many engineering decisions. A change in what can be benchmarked changes what can be compared; a change in what can be compared changes what can be quantified; and a change in what can be quantified changes what can be optimized. This is why a reorganization of established thermodynamic relations can have consequences far beyond the number of equations that are altered - even when no physical law is altered at all.

IMPACT BOUNDARY

The analogy concerns the epistemic mechanism - organization of existing knowledge - not a claim that this programme has the historical magnitude of Euclid or Mendeleev. The extent of scientific and engineering impact remains subject to independent review, application-specific modelling and validation.

02 | The Benchmark Limitation of the Classical Two-Isothermal Carnot Case

Carnot remains exact; the limitation appears when the boundary-temperature structure becomes richer.

The classical Carnot relations are exact within their two-isothermal domain - but that exactness can obscure an important limitation. Once heat is supplied or rejected over multiple or continuously varying temperatures, the familiar Carnot formulas no longer contain the complete thermal boundary information needed for a process-specific reversible benchmark.

$$\frac{Q_H}{T_H} = \frac{Q_L}{T_L}$$

Recognition anchor: reversible two-isothermal Carnot equality (positive heat magnitudes).

What the two-temperature representation does exceptionally well

For a completely reversible cycle with exactly one high-temperature and one low-temperature isothermal external heat interaction, the two boundary temperatures determine the familiar reversible efficiency or COP once the cycle function is fixed. These familiar expressions are the simplest two-reservoir performance projections of the Carnot reversible-isothermal cycle equality; they do not exhaust its direct solve-for content or all admissible reversible isothermal-boundary configurations.

What it does not retain

A two-temperature representation does not preserve a cooling finite body, a heating water stream, a condensing zeotrope with glide, a sensible exhaust stream, several separate heat sources, or a distributed heat-addition trajectory. Replacing such structures by one average, maximum or minimum temperature defines a different benchmark dataset unless equivalence is demonstrated.

PROBLEM STATEMENT

If the generic reversible benchmark used in education and engineering is exact only for the two-isothermal case, what benchmark should be used when the temperature trajectory itself determines the thermodynamic opportunity?

The stronger programme-level claim

The programme addresses a narrower methodological gap: the familiar Carnot formulas do not by themselves provide a generic, configurable and process-specific cycle-level architecture for constructing and qualifying reversible benchmarks across multiple or continuously varying heat-transfer temperatures. In the sources examined for the Formal Core, an equivalent integrated architecture was not identified. Broader Second-Law, entropy, exergy and domain-specific analysis methods do exist and remain essential, but they serve partly different analytical purposes.

This is a corpus-bounded programme conclusion, not proof of universal historical absence or priority. Variable-temperature, multi-reservoir, Lorenz-type, finite-source/sink, heat-exchanger, pinch and temperature-glide methods predate this programme. Independent prior-art and priority review therefore remain necessary before uniqueness, prevalence or historical-first claims are made.

02 | The Benchmark Limitation of the Classical Two-Isothermal Carnot Case

From one generic benchmark tradition to a fragmented explanatory landscape.

From discipline-specific models to a common thermodynamic benchmark layer

Consequently, physics, chemical and process engineering, materials science and planetary science often address complex thermal and dissipative systems through discipline-specific theories, constitutive models, empirical correlations and semi-empirical descriptions. These approaches can be indispensable for prediction and design, but they do not generally provide one common reversible-cycle benchmark layer retaining the complete heat-temperature boundary structure.

The result can be a fragmented explanatory landscape: local behaviour may be modelled very effectively while system-level thermodynamic comparison, achievable reversible performance and benchmark-relative lost work remain disconnected. The proposed Clausius-parent reversible-cycle benchmark framework is intended to provide such a common thermodynamic layer without replacing the governing physics of the individual disciplines.

Table 2.1. Established analysis traditions and the distinct function of the proposed common benchmark layer.

Analysis tradition	Primary strength	What remains distinct from the proposed common benchmark layer
Classical Carnot formulas	Exact reversible efficiency/COP for two isothermal interactions	Do not by themselves configure multiple or varying heat-temperature interactions.
Entropy / entropy-generation analysis	Second-Law process accounting and irreversibility quantification	Different output and workflow; does not by itself define the same process-specific reversible counterpart.
Exergy analysis	Reference-dependent useful-work potential and work-equivalent irreversibility	Requires reference environment/temperature and serves a different comparison interpretation.
Named-cycle / component models	Rich architecture-, fluid- and process-specific prediction	Highly valuable but not one common parent benchmark layer across thermal structures.
Transport / constitutive / CFD / materials models	Mechanism-specific and local predictive detail	Remain essential; the proposed benchmark layer does not replace them.

A representation issue, not a rejection of classical thermodynamics

The proposed modernization changes the hierarchy and operational use of established relations. Carnot remains the exact two-isothermal specialization. The Clausius equality is used as the broader parent reversible-cycle relation, combined with the First Law and the boundary, constitutive, closure, admissibility and qualification conditions needed for a meaningful benchmark.

NO NEW LAW

The proposal is intentionally conservative in physical foundations: no new First Law, Carnot theorem, Clausius equality, entropy law or exergy law is claimed. The review object is the completeness, correctness, scope, reproducibility and usefulness of the proposed operational organization.

03 | What the Proposed Modernization Adds

A parent benchmark relation, a complete boundary record and a configurable problem architecture.

The proposed architecture first makes the Carnot reversible-isothermal cycle equality operational across its declared two-isothermal solve-for domain, beyond the familiar efficiency and COP projections. It then treats the Clausius reversible-cycle equality as the established parent constraint for broader admissible heat-temperature structures. Together with the First Law and the required boundary, closure, constitutive, admissibility, selection and complete-system reversibility conditions, these two layers are intended to support a broader thermodynamic capability for explanation, benchmarking, quantification, comparison and optimization.

$$\oint \frac{\delta Q_{rev}}{T_b} = 0$$

Recognition anchor: established Clausius reversible-cycle equality; T_b *denotes the applicable absolute boundary temperature.*

The conceptual shift

The central shift is from treating a reversible benchmark mainly as a named formula to treating it as a configured thermodynamic problem. The relevant heat quantities remain paired with their applicable boundary temperatures. For continuously varying interactions, the complete temperature trajectory remains part of the benchmark data.

DIRECT FORMAL CONSEQUENCE

COMPLETE HEAT-TEMPERATURE STRUCTURE

Finite heat-temperature pairs, continuous trajectories and mixed structures can be retained instead of forced into one T_H and one T_L.

DIRECT FORMAL CONSEQUENCE

CONFIGURABLE TARGETS

The benchmark can target work, efficiency, COP, a missing heat quantity or temperature, or another closed application-coupled quantity when sufficient relations are supplied.

PROPOSED OPERATIONAL CAPABILITY

QUALIFIED REVERSIBLE COUNTERPARTS

A benchmark can stand alone or be configured as the corresponding reversible counterpart of an actual irreversible cycle under a declared comparison class.

IMPLEMENTATION OPPORTUNITY

PROGRAMMABLE WORKFLOWS

The architecture can be expressed in analytical, numerical, software and experimental-model workflows without the software becoming part of the thermodynamic validity claim.

CENTRAL ENGINEERING CAPABILITY

Within the declared benchmark-construction scope, the proposed Clausius-parent reversible-cycle benchmark framework is intended to configure and solve process-specific reversible benchmarks for sufficiently specified and admissible heat engines, heat pumps, refrigerators and other heat–work cycles. Once a valid benchmark has been established, the corresponding reversible efficiency, heating COP or refrigeration COP can be determined. A maximum designation applies only where the fixed dataset, target and comparison class establish that extremum.

KEY QUALIFICATION

A Clausius equality value of zero is one necessary layer, not a complete benchmark. First-Law closure, domain admissibility, cycle function, process and state closure, constitutive sufficiency, complete-cycle reversibility and other applicable conditions remain separate requirements.

03 | What the Proposed Modernization Adds

From a wider benchmark domain to new engineering questions.

Four practical consequences

1. More faithful reversible limits

A finite source, sensible stream, multi-source system or temperature glide can retain the boundary structure that actually defines the thermodynamic opportunity.

2. Better actual-to-reversible comparison

An actual cycle can be compared with a specifically matched reversible counterpart rather than with an unrelated generic two-temperature reference.

3. New optimization variables become thermodynamic variables

Working-medium composition, pressure levels, mass flows, heat-capacity rates, staging, regeneration and heat-release trajectories can be studied through their effect on the complete temperature path.

4. A common comparison language across disciplines

Domain models can remain local and detailed while the thermodynamic benchmark layer provides a common cycle-level reference and work consequence.

Illustrative non-isothermal heat-pump benchmark

A Formal Core example specifies a reversible heat-pump benchmark with an isothermal low-temperature interaction at 263.15 K and a high-temperature interaction containing an isothermal segment at 373.15 K followed by a linear temperature glide in T–Q space to 423.15 K. With normalized high-side heat $Q_{H,tot} = 1$ and a fixed 0.58/0.42 heat partition, the Clausius reversible-cycle equality gives $\frac{Q_L}{Q_{H,tot}} = 0.687$. First-Law closure then gives $\frac{W_{\text{in}}}{Q_{H,tot}} = 0.313$, $COP_{H,rev} = 3.195$ and $COP_{L,rev} = 2.195$.

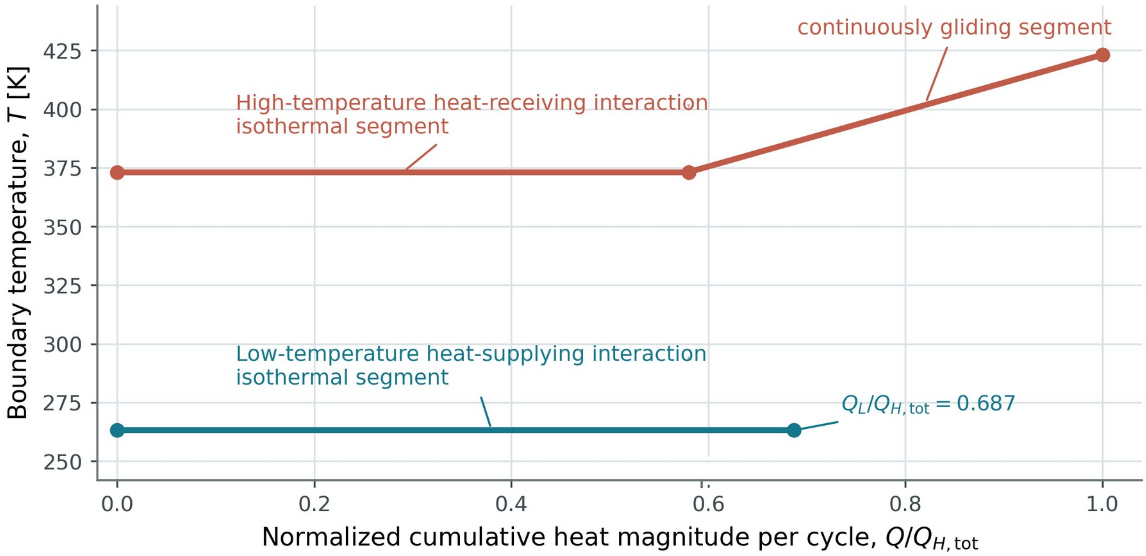

Figure 3.1. T–Q representation of the illustrative non-isothermal heat-pump benchmark. The high side combines a 0.58 isothermal fraction at 373.15 K and a 0.42 linear glide to 423.15 K; the low side is isothermal at 263.15 K. For QH,tot = 1: QL/QH,tot = 0.687, Win/QH,tot = 0.313, COPH,rev = 3.195 and COPL,rev = 2.195. Separate branch origins are used; the horizontal-length difference is normalized work input. This is a candidate cycle-level benchmark only; admissibility and constructability are not established.

Source: Reproduced from Formal Core R178-L16, Figure 5.

WHY THE EXAMPLE MATTERS

The result is not a claim of a constructible heat pump or a universal optimum. It shows something narrower and important: once part of the heat interaction glides in temperature, the reversible benchmark depends on the complete prescribed heat-temperature structure and cannot be recovered from the classical two-temperature Carnot COP formula alone.

Scientific status architecture

Table 3.1. Scientific-status architecture used in this report.

Layer	Status in this report
Carnot relations, Clausius equality, First Law	Established thermodynamic basis
Complete configurable benchmark operationalization	Proposed operational methodology; independently reviewable
Thermal Matching, direct benchmark-relative work comparison, HEX-LWR, CFQM	Proposed engineering methods / method-enabled applications
Solids, distributed natural systems, planetary tidal extensions	Research extensions; separate modelling and validation required

04 | From Reversible Benchmarking to Direct Lost-Work Quantification

A process-specific reversible counterpart turns irreversibility into a direct work comparison.

Once a corresponding reversible benchmark has been qualified, an actual heat engine and its reversible counterpart can be compared directly in work units. For heat pumps and refrigerators the analogous quantity is excess work input when useful heating or cooling duty is held fixed.

$$W_{lost,b} = W_{rev,b} - W_{actual}$$

Recognition anchor for a heat-engine comparison. The benchmark subscript denotes the declared comparison class.

What is distinctive about the direct route

The direct benchmark-relative route does not require a separately selected environmental dead-state temperature. It is not temperature-free or context-free: the reversible benchmark still requires the applicable heat-temperature boundary structure, fixed comparison data, target definition and adjustable-variable selection. Its practical distinction is that the cycle-level penalty is reported directly in work/energy units from an explicit actual-versus-reversible comparison.

Table 4.1. Complementary thermodynamic perspectives on irreversibility and work consequence.

Quantification perspective	Principal output	Reference requirement	Engineering interpretation
Clausius-entropy-based irreversibility	Irreversibility measure, J/K	No additional work-reference temperature	Thermodynamic irreversibility in entropy units.
Exergy / Gouy-Stodola	Work-equivalent quantity, J	Reference environment or reference temperature	Environment-relative useful-work potential / work-equivalent irreversibility.
Direct benchmark-relative lost/excess work	Work difference, J	Qualified reversible counterpart + comparison class	Actual work opportunity lost, or excess work input, for the declared comparison.

COMPLEMENTARY, NOT COMPETING

The three perspectives should not be presented as mutually exclusive theories. Entropy generation and exergy analysis remain established and powerful. The direct benchmark-relative route offers a different operational comparison, especially when the process-specific reversible counterpart itself is the engineering object of interest.

04 | From Reversible Benchmarking to Direct Lost-Work Quantification

A concrete work-unit example and the measurement boundary.

Illustrative 50 kJ benchmark-relative lost-work case

A Formal Core example considers an actual heat engine with two heat-supplying interactions: 600 kJ at 600 K and 300 kJ at 450 K. Heat rejection is 550 kJ at 300 K, so First-Law closure gives 350 kJ of work output. A corresponding reversible comparison holds the two heat inputs and all three boundary temperatures fixed and solves for the reversible heat-rejection quantity. The reversible value is 500 kJ, giving 400 kJ of work output.

Table 4.2. Illustrative actual-to-reversible heat-engine comparison under a declared common basis.

Declared comparison	Actual cycle	Qualified reversible comparison
Heat supplied	600 kJ @ 600 K + 300 kJ @ 450 K	same
Low-side temperature	300 K	same
Heat rejected	550 kJ	500 kJ
Work output	350 kJ	400 kJ
Difference	-	50 kJ benchmark-relative lost work

EXPERIMENTAL RELEVANCE

Actual shaft work, electrical work input/output, heat-transfer quantities and temperatures can be measured or reconstructed experimentally. The ideal reversible counterpart is ordinarily a calculated benchmark rather than a physically realized perfect machine. The direct work difference is therefore experimentally testable through measured actual-cycle data plus a qualified reversible benchmark; this does not by itself constitute completed independent validation.

What lost work does not tell you

An aggregate work penalty does not identify where the responsible irreversible processes occur, which mechanisms are active, or how the total should be allocated. Local balances, heat-transfer diagnostics, pressure-loss models, reacting-flow models, field descriptions, constitutive relations, entropy-generation analysis, exergy analysis and experiments remain necessary for mechanism attribution and component design.

Why this matters for optimization

For Thermal Matching, benchmark-relative lost or excess work can serve as a common cycle-level objective while local temperature differences, pinch points, OHTC or UA, pressure loss and geometry remain diagnostics and constraints. A finite-conductance optimum may retain non-zero local temperature differences; a global minimum is global only within the declared variables and constraints.

05 | Engineering Questions and Applications

Selective depth: representative cases that show different kinds of benchmark value.

Across the cases below, the governing capability is the same: once a sufficiently specified and admissible reversible benchmark is qualified, the applicable limiting heat-engine efficiency, heating COP or refrigeration COP can be determined for the declared boundary dataset and comparison class.

PROPOSED ENGINEERING METHOD

Zeotropic water-water heat pumps and Thermal Matching

QUESTION. Which refrigerant composition and temperature glide best match the source-water and sink-water trajectories over both evaporator and condenser?

LIMIT OF TWO-ISOTHERMAL BENCHMARK. One T_H and one T_L do not preserve the four relevant temperature trajectories or reveal where a refrigerant glide improves one branch but worsens the other.

PROPOSED CAPABILITY. Treat refrigerant composition, pressure levels and other cycle variables as trajectory-shaping design variables; construct a common process-specific benchmark and compare COP or excess work under the same external duty and constraints.

POTENTIAL IMPACT. A more explicit route for refrigerant screening and system optimization. Phase equilibrium, pressure drop, heat-transfer coefficients, safety, environmental constraints and compressor limits remain separate requirements.

A quantitative heat-pump reference - not a zeotrope performance claim

The Formal Core also provides a separate finite-temperature-difference heat-pump illustration with external reservoirs at 373.15 K and 263.15 K. Under the stated internally reversible medium-side temperatures, the illustrative heating COP is 2.947 compared with the external-reservoir Carnot maximum of 3.392; the cooling COP is 1.947 compared with 2.392. This is an illustrative benchmark-gap example under a tightly defined model, not a measured device result and not a claimed zeotropic gain.

STATUS SAFEGUARD

The zeotropic application is a proposed optimization route, not a validated universal refrigerant-selection procedure. The use of temperature-glide matching and T–Q profile plots is established; the programme contribution is the proposed integration of those trajectories into one process-specific reversible benchmark and cycle-level work objective.

05 | Engineering Questions and Applications

Finite bodies, sensible streams and temperature-glide heating or cooling.

PROPOSED DIRECT FRAMEWORK APPLICATION

Minimum reversible work through a temperature glide

QUESTION. What reversible work input is associated with heating or cooling a finite body or stream whose temperature changes throughout the process?

LIMIT OF TWO-ISOTHERMAL BENCHMARK. A fixed-temperature Carnot COP cannot retain the complete temperature history of the body or stream. A mean temperature defines a different approximate benchmark problem.

PROPOSED CAPABILITY. Represent the complete heat-temperature trajectory and construct the corresponding process-specific reversible heat-pump or refrigeration benchmark. The target may be reversible work, COP, terminal temperature, mass-flow-related quantity or another sufficiently closed result.

POTENTIAL IMPACT. More relevant ideal comparisons for process heating, district heating, sensible cooling, thermal storage and finite-capacity sources/sinks.

Where this application family appears

- heat engines supplied by cooling finite bodies, gas streams, liquid streams, solar or industrial waste-heat sources;
- heat pumps serving water or other streams with substantial temperature rise, including process heating and simultaneous heating/cooling;
- thermal-storage charging/discharging when the store temperature changes materially;
- cycles coupled to sensible-heating or sensible-cooling streams;
- multi-source and multi-sink systems where one pair of fixed reservoir temperatures does not preserve the boundary dataset.

05 | Engineering Questions and Applications

Direct heat exchange, mixing, heat exchangers and work opportunity.

PROPOSED ENGINEERING METHOD

Direct mixing, heat exchange and foregone work opportunity

QUESTION. How much useful-work opportunity is foregone when heat is allowed to flow directly between bodies or streams at different temperatures?

LIMIT OF TWO-ISOTHERMAL BENCHMARK. The Carnot formula alone does not configure the actual finite trajectories or define which alternative reversible comparison keeps the relevant inlet states, terminal conditions, duty and boundaries equivalent.

PROPOSED CAPABILITY. For a declared comparison class, construct a reversible counterpart or external-boundary-mimicking heat-engine benchmark between the complete hot- and cold-side trajectories and report the corresponding work opportunity.

POTENTIAL IMPACT. A possible work-based comparison of heat-exchanger configurations, stream routing and Thermal Matching decisions, complementary to effectiveness, pinch, conductance, pressure-drop, entropy and exergy measures.

Proposed Heat-Exchanger Lost-Work Rating (HEX-LWR)

For a passive heat exchanger with no net shaft work, the reversible comparison work is not work produced by the actual exchanger. It represents foregone work opportunity only within the explicitly matched comparison class. Because adding reversible work changes the energy balance, inlet states, outlet states, heat duty and benchmark work cannot all be fixed independently. A valid comparison must declare what remains fixed and what is permitted to change.

District-heating mixing and heat-pump integration

Passive mixing of district-heating streams is an irreversible open-flow process and should not be relabelled as a complete thermodynamic cycle. Established open-system energy, entropy and exergy balances remain primary. Where a heat pump or other explicit heat-work cycle is part of the configuration, the proposed framework can add a process-specific reversible benchmark for stream routing, avoidance or relocation of mixing, staging, temperature levels, mass-flow distribution and control.

ELECTRICITY-SAVING BOUNDARY

A benchmark-relative lost/excess-work result is a thermodynamic potential or penalty within its comparison class. It is not automatically a realizable electricity saving. Actual savings require an explicit alternative configuration with actual COP, pressure losses, pumping energy, pinch constraints, temporal source/demand availability, component limits and technical feasibility.

05 | Engineering Questions and Applications

Non-isothermal heat supply, combustion trajectories and cycle architecture.

PROPOSED ENGINEERING METHOD

Non-Isothermal Combustion-Fuel Quantification Method (CFQM)

QUESTION. How does the reversible work potential of the same total heat input change when that heat is made available over different temperature trajectories?

LIMIT OF TWO-ISOTHERMAL BENCHMARK. Total heat input, heating value, firing temperature or one representative temperature do not preserve how energy is distributed over temperature during a non-isothermal heat-addition process.

PROPOSED CAPABILITY. Retain a temperature-resolved heat-supply trajectory and compare admissible cycle configurations against a process-specific reversible benchmark. Thermal Matching can be studied from the cycle side, the heat-release side, or both. For direct-fired turbines, it concerns coordinated reaction, mixing, dilution, residence time, pressure evolution and heat-release shaping rather than a separate source-to-medium heat exchanger.

POTENTIAL IMPACT. A common comparison layer for Brayton/gas-turbine studies, waste-heat use, staged heat addition, recuperation and other non-isothermal heat-engine configurations.

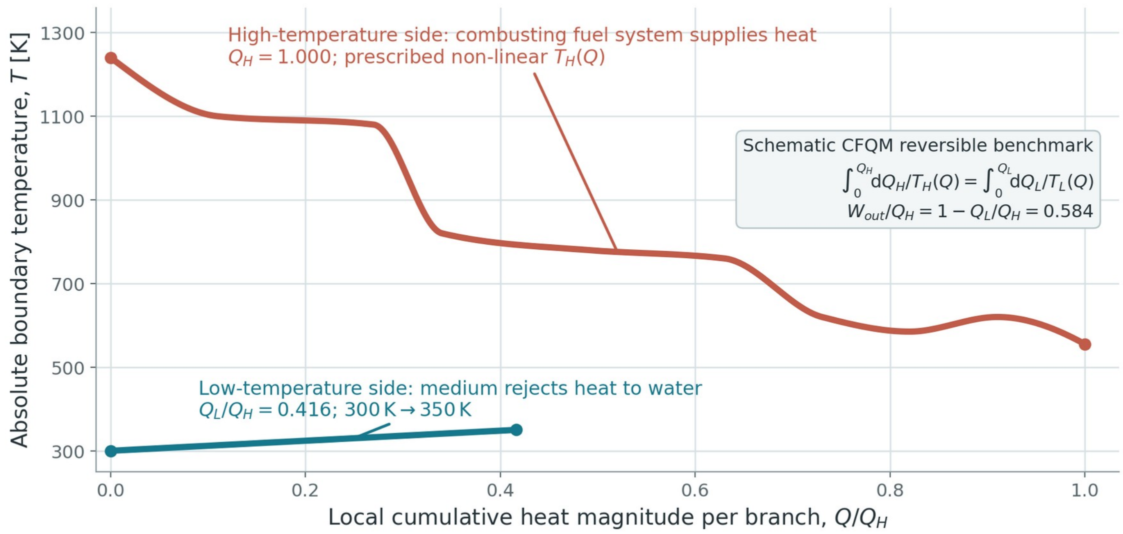

Figure 5.1. Schematic T–Q representation of the proposed Non-Isothermal Combustion-Fuel Quantification Method (CFQM). A prescribed non-linear combustion-source trajectory supplies normalized heat QH = 1.000; a linear water-sink trajectory receives QL/QH = 0.416 while warming from 300 K to 350 K. The configured reversible benchmark gives Wout/QH = 0.584. The result characterizes maximum heat-to-work conversion for the declared trajectory and comparison conditions; it is not an intrinsic fuel property, a complete chemical-exergy value or a validated finite-rate combustor result.

Source: Reproduced from Formal Core R178-L16, Figure 21.

What this does not claim

It does not claim that a particular fuel, combustor, gas-turbine architecture or lower-temperature heat release is universally superior. Combustion kinetics, chemical exergy, emissions, evaporation, mixing, dilution, flame stability, pressure loss, cooling, turbine-entry-temperature distribution, component life and technical realizability remain additional engineering requirements.

Related cycle families

- Brayton/Joule, Rankine-family, regenerative and recuperative configurations under explicitly stated external heat-temperature conditions;
- Lorenz-type benchmark configurations with gliding external temperatures;

- cascade and multistage systems;
- multi-source, multi-sink and polygeneration systems;
- industrial heat integration and waste-heat recovery;
- refrigerant or working-medium screening where the medium changes the shape of the heat-temperature trajectory.

ARCHITECTURE RATHER THAN NAMED-CYCLE HIERARCHY

A named cycle does not by itself determine the benchmark class. The external heat-interaction structure, system boundary, regeneration assumptions, constitutive relations and comparison purpose determine whether the classical Carnot benchmark is complete or whether a broader Clausius-based benchmark route is required.

06 | Applications Across Scientific Disciplines

One thermodynamic comparison layer; different local physics.

The proposed framework is most credible when it is treated as an additional thermodynamic layer rather than a substitute for the theories of other disciplines. The same benchmark logic can be placed alongside detailed domain models: the domain model describes the mechanism and local fields; the benchmark layer asks what reversible counterpart is appropriate and what work consequence follows under a declared comparison class.

DIRECT + PROPOSED METHODS

MECHANICAL & ENERGY ENGINEERING

Heat engines, heat pumps, refrigeration, thermal storage, heat exchangers, waste heat, district heating, working-medium screening, Thermal Matching and cycle optimization.

METHOD-ENABLED APPLICATIONS

CHEMICAL & PROCESS ENGINEERING

Process heating/cooling, multi-stream integration, polygeneration, non-isothermal heat supply, phase-change trajectories and coupled process constraints.

RESEARCH EXTENSION

MATERIALS SCIENCE

Thermoelastic damping, cyclic solids, hysteresis, self-heating, high/low damping design, mechanocaloric cooling and work recovery questions.

RESEARCH EXTENSION

PHYSICS & NATURAL SYSTEMS

Distributed heat-to-mechanical-energy pathways, convection, temperature fields, mechanical-energy production/dissipation and reversible-counterpart questions.

RESEARCH EXTENSION

PLANETARY / ASTROPHYSICAL

Cyclic tidal deformation, internal heating, orbital/rotational mechanical-energy dissipation and possible thermomechanical benchmark layers.

ADOPTION OPPORTUNITY

EDUCATION & COMPUTATION

Textbooks, courses, benchmark-construction exercises, numerical tools, design workflows and integration into existing engineering software.

CROSS-DISCIPLINARY RULE

The farther an application moves from conventional closed heat-engine, heat-pump or refrigeration cycles, the more important it becomes to establish a valid system boundary, cycle or stationary representation, heat and work interactions, constitutive models and independent validation. Shared benchmark language does not create shared mechanism physics.

06 | Applications Across Scientific Disciplines

Table 6.1. Application map - direct and method-enabled domains.

Application family	Primary discipline(s)	Benchmark relevance	Status
Finite-body / finite-stream heat engines	Thermal / mechanical engineering	Cooling source trajectory determines reversible work opportunity	Proposed direct framework application
Solar and industrial waste-heat recovery	Energy / process engineering	Heat availability spans temperature; one source temperature may be inadequate	Proposed direct framework application
Water-water heat pumps	Thermal engineering	Source and sink glides define a process-specific reversible comparison	Proposed direct framework application
District-heating heat-pump interfaces	Energy systems	Multiple streams, mixing, staging and heat-pump temperature lifts interact	Method-enabled application
Process heating and simultaneous heating/cooling	Chemical / process engineering	Useful duty and temperature trajectories can be benchmarked together	Method-enabled application
Zeotropic refrigerant mixtures / natural-refrigerant systems	Refrigeration / chemistry	Composition changes evaporation/condensation trajectories and matching	Proposed engineering method
Superheating, subcooling, transcritical rejection	Refrigeration	Distributed heat-transfer segments require explicit trajectory treatment	Proposed direct framework application
Lorenz-type configurations	Thermodynamics	Continuously varying external temperatures require a broader reversible reference	Proposed direct framework application
Rankine / Brayton / regenerative / recuperative cycles	Power engineering	Benchmark class follows declared external heat interactions, not cycle name alone	Proposed direct framework application
Cascade and multistage systems	Refrigeration / energy	More than two distinct external heat interactions may require discrete/mixed Clausius route	Proposed direct framework application
Multi-source / multi-sink / polygeneration	Energy systems	Multiple boundary interactions cannot be compressed to one high/low temperature pair without loss of structure	Proposed direct framework application
Thermal storage	Energy systems	Charge/discharge temperature trajectories affect reversible work or minimum-work benchmark	Proposed direct framework application

06 | Applications Across Scientific Disciplines

Table 6.2. Optimization, implementation and research gateways.

Application family	Primary discipline(s)	Benchmark relevance	Status
Integrated cycle-heat-exchanger studies	Thermal / process engineering	Separates conductance limitation from structural temperature-trajectory mismatch	Proposed engineering method
Thermal Matching	Thermal engineering	Aligns medium and external-system temperature trajectories; lost/excess work can be cycle objective	Proposed engineering method
HEX-LWR	Heat transfer	Rates foregone work opportunity under an explicit comparison class	Proposed engineering method
Combustion-fuel quantification / heat-release shaping	Power / combustion	Retains temperature-resolved heat-release trajectory as design/comparison information	Proposed engineering method
Sensitivity / optimization / verification targets	Engineering computation	Provides qualified reference targets for analytical, numerical and software models	Method-enabled application
High-damping materials / vibration attenuation / impact / noise	Materials / mechanical	Potential cycle-level mapping of unrecovered work and thermal fields	Research extension
Low-damping resonators / precision structures / sensors	Materials / applied physics	Potential reversible-reference and lost-work perspective	Research extension
Fatigue, hysteresis, cyclic self-heating	Materials science	Connects work loops, thermal redistribution and mechanism-specific models	Research extension
Elastocaloric / mechanocaloric cooling	Materials / refrigeration	Specified solid cycles may admit heat-pump/refrigeration benchmarking if heat transfers are demonstrated	Research extension
Rayleigh–Bénard / distributed natural thermo-fluid systems	Physics / geophysics	Candidate connection between heat supply, mechanical-energy generation/dissipation and reversible counterpart	Research extension
Atmospheric, oceanic, planetary-interior and stellar convection	Physics / planetary science	Related distributed systems may benefit from a thermodynamic energy-conversion layer; they are not automatically heat engines	Research opportunity
Solid-body tidal dissipation	Planetary / astrophysical / materials	Candidate thermomechanical pathway from cyclic deformation to heat and benchmark-relative lost work	Research extension
Textbooks, curricula, engineering workflows, software	Education / industry	Turns scientific capability into repeatable practice and computation	Adoption opportunity

COVERAGE PRINCIPLE

The application map is intentionally broader than the detailed cases in this report. It preserves consistency with the current Formal Core by naming the material application families there identified, while leaving detailed models, calculations and validation to later domain-specific work.

07 | Research Extensions and New Questions

When the framework moves beyond conventional thermal machinery, scientific status becomes the central design constraint.

RESEARCH EXTENSION - INDEPENDENT VALIDATION REQUIRED

Dynamically loaded solids and thermoelastic damping

QUESTION. Can an actual irreversible thermomechanical cycle in a solid be mapped to a qualified reversible counterpart and benchmark-relative lost work?

LIMIT OF TWO-ISOTHERMAL BENCHMARK. The classical Carnot formulas do not describe cyclic stress-strain work, spatial thermoelastic temperature fields or internal heat conduction in a solid component.

PROPOSED CAPABILITY. Use established thermoelastic/constitutive physics to define the actual cycle, heat transfer and work; then investigate whether the process-specific benchmark architecture provides a useful cycle-level reversible reference.

POTENTIAL IMPACT. Potentially links material damping, hysteresis-loop work, local thermal fields, high/low damping design and durability questions within one thermodynamic comparison layer.

Established physics is retained

Classical thermoelastic-damping theory links cyclic deformation, temperature gradients and irreversible internal heat conduction (Zener, 1937, 1938; Lifshitz & Roukes, 2000). Viscoelastic relaxation, defect and dislocation motion, interfacial friction, microplasticity, phase transformation, damage and other mechanisms also have established or widely used models. The research extension does not claim that material damping is wholly empirical or that one mechanism has already been shown to explain all hysteresis.

Potential material and component questions

- design for intentionally high damping, vibration attenuation, impact mitigation and noise control;
- design for intentionally low damping and high quality factor in resonators, precision structures and sensors;
- separate and compare thermoelastic, viscoelastic, defect-mediated, interfacial and phase-transformation contributions;
- treat geometry, microstructure, thermal conductivity, heat capacity, thermal expansion, frequency and amplitude as coupled design variables;
- investigate cyclic self-heating, heat redistribution, hysteresis and possible links to durability/fatigue models;
- benchmark adequately specified elastocaloric or other mechanocaloric solid-state cooling cycles.

07 | Research Extensions and New Questions

Distributed natural systems and planetary thermomechanics.

RESEARCH EXTENSION - INDEPENDENT VALIDATION REQUIRED

Rayleigh–Bénard and distributed thermo-fluid systems

QUESTION. Can a distributed system with heat transport, buoyancy-driven motion and mechanical-energy dissipation be given a qualified cycle-level thermodynamic benchmark?

LIMIT OF TWO-ISOTHERMAL BENCHMARK. A distributed temperature field and internal circulation do not automatically define a heat-engine cycle or a net work interaction. Classical Carnot formulas do not encode the complete spatial/temporal boundary heat structure.

PROPOSED CAPABILITY. Combine the proposed benchmark layer with the governing Navier–Stokes/Oberbeck–Boussinesq, stability, scaling, DNS/CFD/LES and energy-budget models after a valid boundary and cycle or statistically stationary representation has been defined. Rayleigh (1916) and Shraiman & Siggia (1990) provide foundational and modern contextual lineage for this convection problem.

POTENTIAL IMPACT. Could connect local flow physics to system-level heat-to-mechanical-energy conversion and benchmark-relative work opportunity in engineered and natural convection.

Planetary tidal dissipation - a more speculative extension

Solid-body tidal dissipation is already modelled through celestial mechanics, Love numbers, quality factors, phase lags and viscoelastic/anelastic rheologies (Kaula, 1964; Efroimsky & Lainey, 2007). The proposed programme explores whether cyclic deformation, thermoelastic temperature fields, internal heat conduction and incomplete mechanical-work recovery can also be organized in a physics- and thermodynamics-explicit cycle-level architecture.

STRONG HYPOTHESIS BOUNDARY

The strongest single-cause hypothesis - that deformation-induced internal heat conduction is the universal underlying cause of intrinsic mechanical-energy dissipation in an otherwise solid tidally deformed body - is not established. Existing literature recognizes multiple viscoelastic, anelastic, defect-mediated and grain-boundary mechanisms. Any exclusivity claim requires dedicated derivation, laboratory testing, planetary-data comparison and independent validation.

Why the research direction can still matter

Even without the strongest hypothesis, a common benchmark layer could be useful if it makes the pathway from forcing and deformation to temperature fields, heat redistribution, unrecovered mechanical work and cumulative orbital/rotational energy loss more explicit. Similar logic may be explored for atmospheric, oceanic, geophysical, planetary-interior and stellar convective systems, while preserving their domain-specific physics.

08 | From Scientific Capability to Education, Methods and Engineering Practice

A scientific capability becomes broadly useful only when people learn to apply it and tools make it routine.

Scientific capability becomes engineering capability only when it is taught, translated into methods, and embedded in the tools and workflows used by engineers and scientists.

Educational implication

The practical impact of a broader reversible-cycle benchmark architecture will depend on whether future engineers and scientists learn the governing hierarchy explicitly: the Clausius reversible-cycle equality as the parent cycle-level benchmark relation, the Carnot relations as its exact two-isothermal specialization, and process-specific benchmark construction as an applicable skill for multi-temperature and varying-temperature heat-work problems.

This does not require abandoning Carnot-first teaching. A Carnot-first route can remain a familiar bridge, while a Clausius-first route can make the scientific hierarchy explicit earlier. Both routes should converge on the same benchmark and qualification logic.

FROM CAPABILITY TO ADOPTION

A scientific capability that is not taught cannot readily become an engineering capability. Broad impact therefore depends on independent scientific assessment, textbooks and curricula, worked methods, professional training, software and integration into ordinary design and analysis workflows.

Methods and software ecosystem

If adopted, the proposed framework is software-independent. It could enter dedicated calculation tools, optimization routines, digital models, simulation environments, digital twins and modules within existing thermodynamic and engineering-design systems. It could also generate new discipline-specific methods whose names and implementations need not be tied to one software platform.

CarnotX Software is being developed as one early educational and engineering implementation of this broader capability. It is not the name of the underlying framework and is not required for scientific validity. Its current status is an early implementation layer; it does not by itself constitute independent scientific validation or a general deployment-readiness claim. Its future product trajectory is not the subject of this report.

Foundational book and wider readership

The first proposed foundational book is intended to make this hierarchy teachable to readers across physics, chemistry/chemical engineering, mechanical and energy engineering, and related physical sciences. Later application-focused publications can carry the same benchmark logic into deeper engineering and research domains without changing the Formal Core's role as the scientific and methodological source.

09 | Impact Boundaries, Validation and Outlook

Potentially broad consequences require claim-specific evidence.

The potential significance of the proposed Clausius-parent reversible-cycle benchmark framework lies not in replacing established thermodynamics, but in extending what established reversible-cycle relations can explain, benchmark, quantify and support in engineering practice. If the framework withstands independent scientific scrutiny and is subsequently incorporated into education, methods and engineering tools, its impact could extend well beyond conventional heat engines, heat pumps and refrigeration to a wider range of problems across engineering and the physical sciences.

Table 9.1. Current claim status and remaining assessment requirements.

Claim layer	What can be said now	What still requires assessment
Established thermodynamic basis	Carnot, Clausius, First Law, reversible-cycle and conventional irreversibility principles remain established.	No revalidation is implied by this report.
Proposed benchmark operationalization	The formal architecture is developed and documented in Formal Core R180-L15.	Independent review of correctness, completeness, reproducibility, scope and prior-art position.
Method-enabled engineering applications	Supported in principle by the architecture.	Device/process models, feasibility, numerical/experimental validation and comparison against existing methods.
Research extensions	Defined as hypotheses or candidate research architectures.	Constitutive models, causal testing, experiments, domain-specific validation and independent review.
Education, software and adoption	Plausible implementation routes.	Pedagogical effectiveness, software verification, institutional adoption and market relevance.

What should happen next

- Independent scientific review of the formal benchmark architecture and exact Carnot recovery.
- Application testing on representative non-isothermal heat-engine, heat-pump, refrigeration and heat-exchanger problems.
- Comparison of direct benchmark-relative lost/excess work with established entropy-generation and exergy routes under thermodynamically compatible boundaries.
- Numerical and experimental assessment of Thermal Matching and the proposed engineering methods.
- Separate research programmes for cyclic solids, distributed natural thermo-fluid systems and planetary thermomechanics.
- Assessment by universities and publishers of how the Clausius-parent / Carnot-special-case hierarchy can be incorporated into foundational thermodynamics education.

CLOSING PERSPECTIVE

The next step is not acceptance by assertion, but examination: scientific review of the framework, testing against representative problems, and assessment of how its benchmark hierarchy could be incorporated into university education and engineering practice.

Scientific Source Basis, Status and Public-Use Notice

Scientific source basis

Operationalizing the Carnot and Clausius Reversible-Cycle Equalities for Process-Specific Thermodynamic Benchmarks, Formal Core R180-L15, Editorial and Academic Review Copy, September 2026. This Formal Core is the Scientific and Methodological Source Document for the present report.

If wording in this report differs from the current controlled Formal Core, the Formal Core determines scientific meaning, equation scope, definitions, applicability and qualification boundaries. The Scientific Positioning and Terminology Standard v4.1 governs compatible terminology and claim-status distinctions for downstream documents.

Selected source lineage retained from the Formal Core

- Carnot, S. (1824). Reflections on the Motive Power of Fire.
- Clausius, R. (1867). The Mechanical Theory of Heat.
- Callen, H. B. (1985). Thermodynamics and an Introduction to Thermostatistics.
- Moran, M. J., Shapiro, H. N., et al. Engineering thermodynamics textbook lineage used as a bounded representative educational case.
- Zener (1937, 1938); Lifshitz & Roukes (2000) and later coupled-thermoelastic work for thermoelastic damping.
- Rayleigh (1916); Shraiman & Siggia (1990) for Rayleigh-Benard and distributed convective-system context.
- Kaula (1964); Efroimsky & Lainey (2007) and later rheological literature for tidal-dissipation context.
- Li, Hua & Sun (2023) for an example of continuous elastocaloric solid-state cooling.

Consult the Formal Core for the complete reference list, bibliographic details, source-status distinctions and application-specific evidence boundaries.

Document identity and access

Table S.1. Document control and programme identity.

Item	Current status
Report	What Becomes Possible Beyond the Two-Isothermal Carnot Benchmark?
Version	v1.5 - 3 September 2026
Document type	Public Impact, Applications & Research Opportunities Report
Scientific source basis	Formal Core R180-L15
Author and principal developer	Casper Helder
Developed within	Unified Energy B.V.
Publication / education channel	CarnotX Academy
Programme context	https://carnotx.unified-energy.com

Public-use and rights notice

SCIENTIFIC-STATUS SAFEGUARD

Public availability does not strengthen a scientific claim. Established thermodynamics, Formal-Core interpretation, proposed operational methods, illustrative calculations, research extensions and independently validated results remain distinct claim categories.