

Thermodynamics and energy accounting

Juan Segurola

Core question

How did nineteenth-century work on heat and engines create a general science of energy, conversion, entropy and limits on what physical processes can accomplish?

Historical and evolutionary context

Steam engines were commercially important before a satisfactory theory of heat and work existed. Engineers could improve machines empirically while natural philosophers debated caloric theories and mechanical accounts of heat. Thermodynamics emerged when engine analysis, calorimetry, mechanics and mathematical idealisation were brought into a common accounting framework.

What could communities know before this transition?

Artisans and engineers could compare fuel use, pressure, expansion and machine performance. Physicists could measure temperatures and heat capacities. The limitation was the absence of a general conserved quantity connecting mechanical work, heat and other physical changes, together with a principled account of why some conversions have unavoidable directionality and loss of useful work.

What changed?

Carnot separated ideal limits from particular engines

In 1824, Sadi Carnot analysed heat engines through an ideal reversible cycle. Although he worked within a caloric framework, his reasoning introduced a powerful distinction between contingent engineering details and limiting relations imposed by temperature differences.

Joule and others connected heat with work

Mayer's 1842 argument, Joule's experiments through the 1840s, and Helmholtz's 1847 synthesis supported quantitative equivalence between mechanical work and heat and a broader conservation principle. Energy conservation became a cross-domain bookkeeping principle rather than a property of one specific machine.

Clausius and Kelvin introduced directionality

Rudolf Clausius in 1850 reformulated Carnot's insights on the basis of heat-work equivalence and in 1865 introduced the term entropy. William Thomson proposed an absolute temperature scale in 1848 and articulated a second-law formulation in 1851. Thermodynamics therefore combined conservation with asymmetry: total energy is conserved, yet not every energy transformation is equally available for work.

Why could this capability emerge?

Industrial engines created practical pressure to understand efficiency, while precision calorimetry, mechanics and mathematical physics supplied quantitative tools. The transition required both workshop knowledge and abstract idealisation. No single experiment or theorist produced thermodynamics in finished form.

What later forms of knowledge did it enable?

Thermodynamics became foundational in chemistry, phase equilibria, statistical mechanics, engines, refrigeration, atmospheric science and later information theory. Energy accounting also supplied a common language across previously separate physical processes.

New limits and risks

Thermodynamic variables are coarse-grained descriptions. Treating equilibrium relations as universally instantaneous can hide kinetics, fluctuations and spatial gradients. Industrial mastery of heat engines also intensified fossil-fuel extraction and combustion, creating environmental consequences that thermodynamic efficiency alone does not evaluate.

What changed in the architecture of knowledge?

Physical change became subject to **conservation plus constraint**. Investigators could track energy across transformations while distinguishing possible processes from impossible idealisations and reversible limits from real irreversible behaviour.

Loss, exclusion and uncertainty

Heroic accounts often separate engineering from theory too sharply. Engine builders, instrument makers and industrial practice supplied essential knowledge before formal thermodynamics. Historical labels such as first and second “laws” were stabilised after contributions by Carnot, Clapeyron, Joule, Mayer, Helmholtz, Clausius, Kelvin and others. Their roles should not be collapsed into one discovery moment.

Dependency map

- DIRECT ← PIO-057 Steam engines: when technology preceded theory
- INDIRECT ← PIO-053 Newton, mechanics and universal gravitation
- INDIRECT ← PIO-054 Calculus, limits and infinitesimals
- INDIRECT ← PIO-059 Lavoisier and quantitative chemical transformation
- INDIRECT → PIO-083 Nuclear physics, nuclear energy and dual-use knowledge
- INDIRECT → PIO-091 Climate science and knowledge of a coupled planet

References

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3. Clausius, R. “On the moving force of heat, and the laws regarding the nature of heat itself which are deducible therefrom.” *The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science*, Series 4, 2, 1–21 and 102–119 (1851). DOI: 10.1080/14786445108646819; 10.1080/14786445108646840.
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