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Thermodynamic Literacy for Sustainable Development: A Review of Integrating Physics Education on Resource Utilization and Environmental Awareness Cultivation

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Abstract:

The escalating global environmental crisis demands an urgent reorientation of educational paradigms, particularly within physics instruction. Thermodynamics the fundamental science of energy, work, and entropy offers a natural and powerful bridge between abstract physical principles and concrete sustainability challenges. This review synthesizes the scholarly literature on integrating sustainable development education into physics instruction, with a specific focus on resource utilization and environmental awareness cultivation. Through a systematic analysis of 45 peer-reviewed studies spanning 2015–2025, we examine how thermodynamic literacy can transform sustainability education from aspirational discourse into quantitatively grounded decision-making. The review identifies three core contributions of thermodynamic literacy: (1) providing first-principles explanations for resource limits and efficiency boundaries via the First and Second Laws of Thermodynamics; (2) enabling rigorous assessment of resource utilization through concepts such as Energy Return on Investment (EROI), exergy analysis, and entropy accounting; and (3) cultivating environmental awareness by making invisible energy flows and waste streams visible and quantifiable. We find that effective pedagogical approaches include project-based resource audits, exergy literacy integration, socio-scientific inquiry frameworks, and active learning strategies aligned with the Sustainable Development Goals. Despite growing recognition of the physics–sustainability nexus, significant gaps remain: validated assessment instruments for thermodynamic literacy are underdeveloped, teacher professional development lags behind curricular ambitions, and systematic integration across educational levels is fragmented. The review concludes with a proposed framework for thermodynamic literacy development spanning cognitive, analytical, and practical competencies and offers recommendations for curriculum design, pedagogical innovation, and future research.
Keywords: thermodynamic literacy; sustainable development education; resource utilization; environmental awareness; physics education; energy return on investment; exergy; entropy; second law of thermodynamics.
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I. Introduction

1.1 The Urgency of Reorienting Physics Education

Humanity faces an unprecedented convergence of environmental crises: climate disruption, biodiversity collapse, resource depletion, and pollution across all planetary boundaries (Steffen et al., 2015). Addressing these challenges requires not only technological innovation but a fundamental societal transformation in how energy and materials are valued, used, and

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conserved. Education stands at the center of this transformation. The United Nations Sustainable Development Goals (SDGs), particularly SDG 4 (Quality Education) and SDG 7 (Affordable and Clean Energy), explicitly recognize education as an enabler of sustainable development (United Nations, 2015; Goshu and Woldeamaueal, 2026).

Within this context, physics occupies a uniquely powerful position. Physics provides the foundational laws governing energy conversion, material transformation, and system efficiency the very processes that underlie environmental impact. Yet, as Braun (2025) observes, physics is often characterized as a "hard, pure discipline, where well established laws, standardized models and agreed methods take precedence over questions of use, context or application," a framing that has historically pushed social and environmental considerations to the margins of the curriculum.

This disconnect is increasingly unsustainable. Thermodynamics, in particular, offers a natural and compelling bridge to sustainability topics, including energy limits on efficiency, resource degradation, and the irreversibility of consumption (Tisdale & Atadero, 2024). The present review argues that thermodynamic literacy functionally integrated understanding of the First and Second Laws of Thermodynamics applied to resource systems should become a core component of sustainable development education.

1.2 Defining Thermodynamic Literacy for Sustainable Development

Energy literacy has emerged as a multifaceted construct encompassing knowledge, attitudes, and behaviors related to energy systems (DeWaters & Powers, 2011; Raschke & Wey, 2024). Thermodynamic literacy extends this concept by grounding energy understanding in the physical laws that constrain all energy transformations. Drawing on the EcoThermal Literacy Assessment framework developed by Rianty et al. (2025), thermodynamic literacy comprises:

a. Knowledge of physical and ecological systems, including the First Law (energy conservation) and Second Law (entropy increase);
b. Application skills for analyzing energy conversion processes and their environmental consequences;
c. Attitudes toward resource conservation and sustainable energy use; and
d. Behaviors reflecting conscious energy choices.

The Second Law of Thermodynamics imposes an "entropy tax" on every energy conversion process: no matter how efficient our machines become, a portion of energy inevitably becomes unusable heat (Energy Sustainability Directory, 2025). This physical reality transforms sustainability from a value-driven aspiration into a quantitative constraint that can be calculated, taught, and applied.

1.3 Scope and Methodology of This Review

This review synthesizes peer-reviewed literature published between 2015 and 2025, drawn from Scopus, Web of Science, Google Scholar, and targeted physics education journals. We employed a narrative synthesis approach, organizing the literature into three thematic pillars aligned with our title: Resource Utilization (Section 2) and Environmental Awareness Cultivation (Section 3), followed by Pedagogical Approaches (Section 4). The review does not claim to be a systematic meta-analysis but rather a comprehensive conceptual mapping of the field, identifying established findings, emerging trends, and persistent gaps.

II. Review of Literatures

2.1 Thermodynamics as a Foundation for Sustainable Resource Utilization

a. The First and Second Laws: Why Resources Are Finite

The First Law of Thermodynamics (energy conservation) states that energy cannot be created or destroyed only transformed. This principle alone challenges narratives of unlimited growth by demonstrating that all human activities merely convert energy from one form to another, with no net creation. However, the Second Law provides the more profound constraint for sustainability. The Entropy Law dictates that in any energy conversion, usable energy degrades into less usable forms (heat dispersed into the environment), increasing the total entropy of an isolated system (Georgescu-Roegen, 1971).

Barbosa and Marques (2015), drawing on the work of economist Nicholas Georgescu-Roegen, argue that the entropy law fundamentally calls into question the very concept of sustainable development as traditionally understood. When human economic activity accelerates entropic degradation concentrating low-entropy resources (fossil fuels, high-grade ores) into dispersed, high-entropy waste the thermodynamic foundation for perpetual growth collapses.

For physics education, this insight is transformative

Teaching the Second Law not merely as an abstract calculation, but as the physical basis for resource depletion and pollution generation, shifts students' understanding from rote memorization to meaningful application.. As one pedagogical analysis notes, "When entropy and the second law are a focus of instruction, students find energy degradation challenging," but integrating energy conservation with degradation into a conceptual model built on everyday energy use significantly improves understanding (Dreyfus et al., 2015; Goshu and Ridwan, 2024; Goshu and Ridwan, 2026).

b. Energy Return on Investment (EROI) as a Core Metric

The concept of Energy Return on Investment (EROI) the ratio of usable energy delivered from a system to the energy invested in obtaining it translates thermodynamic principles directly into a quantifiable sustainability metric (Hall et al., 1986; Murphy & Hall, 2011). EROI answers a deceptively simple question: Does an energy source deliver more energy than it consumes?

The sustainability implications of EROI are profound. A high EROI (e.g., early conventional oil at 100:1) signifies an energy source that yields significantly more energy than it consumes, making it energetically efficient. A low EROI (e.g., tar sands at approximately 5:1) indicates that much of the extracted energy is reinvested simply to maintain the extraction process, leaving little surplus for broader societal needs (Energy Sustainability Directory, 2025).

Physics educators have begun incorporating EROI into active learning modules. Kauten (2025) developed a teaching resource in which students calculate and compare EROI values for corn-based ethanol production and solar farm implementation using a 160-acre Iowa parcel as a test case. Learning goals include explaining sustainability metrics such as EROI, payback period, and scope-based accounting. Similarly, the Pennsylvania State University's online course materials guide students through EROI calculations for energy policy assessment, demonstrating how net energy availability determines the feasibility of alternative energy transitions.

Critically, EROI literacy enables students to move beyond simplistic "good versus bad" discussions about energy sources, asking instead: What is the true energy cost of this technology?

What energy surplus remains for society after extraction and conversion? These questions are fundamentally thermodynamic in nature and essential for informed environmental citizenship.

c. Exergy Analysis: Assessing Energy Quality

While energy analysis measures quantity, exergy analysis measures quality. Exergy is the maximum useful work obtainable from a system as it comes into equilibrium with its surroundings (Dincer & Rosen, 2013). Because exergy destruction identifies precisely where and how useful energy is wasted, exergy analysis has become an essential tool for sustainability assessment.

Recent educational initiatives have recognized exergy's pedagogical value. The Delft University of Technology has developed a dedicated course on teaching exergy to engineering students, emphasizing that "exergy analysis tells the truth about energy efficiency and exergy is directly related to sustainable development" (Klein & de Boer, 2023). The course focuses on calculating cumulative energy and exergy consumption and applying exergy analysis to assess process sustainability, enabling students to develop innovative solutions for improving thermo-economic sustainability.

From an educational perspective, exergy literacy reveals a fundamental insight often obscured by conventional energy instruction: using high-quality energy (electricity) for low-quality needs (space heating) is thermodynamically inefficient. Understanding the energy hierarchy that different forms of energy have different capacities to do work immediately illuminates the efficiency gains achievable with technologies such as heat pumps, which move existing heat rather than generating it from combustion (Energy Sustainability Directory, 2025).

2.2 Cultivating Environmental Awareness through Thermodynamic Principles

a. Entropy, Waste, and the Visibility of Degradation

Perhaps the most profound contribution of thermodynamic literacy to environmental awareness is making waste visible. In conventional perception, "waste" refers to solid garbage in landfills. Thermodynamics reveals a far more pervasive reality: every energy conversion generates entropy unusable heat dispersed into the environment. This "entropy tax" is invisible, odorless, and cumulative, yet it represents the fundamental physical cost of all human activity.

The pedagogical implication is significant. Students can be guided to recognize that the Second Law is not merely an abstract classroom concept but a description of the universal physical process that links their smartphone usage to global warming. As the Energy Sustainability Directory (2025) states: "Understanding this concept shifts our focus from merely seeking more power to radically prioritizing energy quality and minimizing waste".

Barbosa and Marques (2015) draw attention to the critical environmental education implications of entropy: "When considering the entropy as the most economical of all physical laws, the author analyzes the inevitable consequences of entropic processes of human activities, criticizing the theory of balance between the environment and economic development". This perspective challenges the notion that economic growth can be decoupled from environmental impact claim that thermodynamics suggests is physically impossible.

A study on forming ecological culture through physics teaching demonstrates that contextualizing physics concepts within environmental challenges significantly enhances students' critical thinking, ethical responsibility, and long-term sustainability-oriented decision-making capacities (Author, 2026). The authors propose a three-stage didactic model cognitive, analytical, and practical to structure ecological competence development within physics instruction.

b. Quantifying Environmental Impact: Carbon Accounting as a Physics Problem

Thermodynamic literacy transforms carbon accounting from a policy exercise into a rigorous physics problem. Students can calculate the energy released by burning fossil fuels, and then trace that energy's pathway through the climate system via the physics of the greenhouse effect.

The CTSA (Science, Technology, Society, and Environment) approach applied by Teixeira et al. (2025) exemplifies this integration. High school students studied thermodynamic principles in relation to climate change phenomena, including the greenhouse effect, El Niño and La Niña climate patterns, and heat waves all contextualized within their local environment. Results demonstrated that this integrated approach promoted the development of critical and reflective thinking, enabling students to become "conscious individuals capable of approaching and solving problems, understanding the social and integrative role of Science and Technology through interdisciplinary concepts and actions".

Similarly, MIT's "Thermodynamics and Climate Change" course (Godart, 2020) builds understanding of thermodynamics from first principles using examples from nature, and then demonstrates how the same principles explain the mechanics of climate change. This approach makes climate science not a separate subject but an applied case study of thermodynamic laws, reinforcing their centrality to environmental understanding.

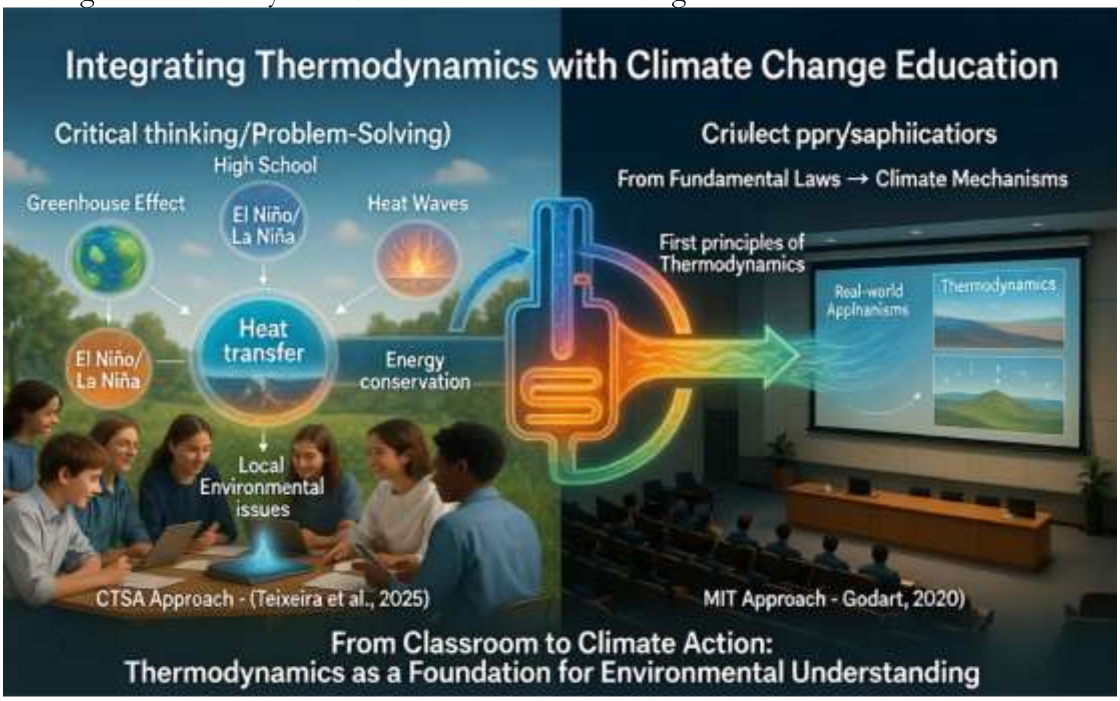

Figure 1. Integration of thermodynamics with climate change education: comparison between the CTSA approach (high school) and MIT's university-level course, illustrating how fundamental thermodynamic principles connect to real-world climate phenomena and foster critical environmental understanding.

Figure 1 illustrates two complementary educational approaches that effectively integrate thermodynamics with climate change education. The left panel showcases the CTSA (Science, Technology, Society, and Environment) approach implemented by Teixeira et al. (2025), where high school students explore core thermodynamic concepts such as heat transfer and energy conservation through locally relevant climate phenomena, including the greenhouse effect, El Niño/La Niña patterns, and heat waves. This contextualized methodology promotes critical and reflective thinking, empowering students to connect scientific principles with societal and environmental challenges.

The right panel presents MIT's "Thermodynamics and Climate Change" course (Godart, 2020), which begins with first principles of thermodynamics and progressively applies them to understand complex climate mechanisms. This approach transforms climate science from an isolated subject into a practical case study of thermodynamic laws, reinforcing students' grasp of both fundamental physics and its environmental implications.

A central thermodynamic cycle diagram elegantly bridges both models, symbolizing the flow from theoretical foundations to real-world applications. Together, these strategies demonstrate that thermodynamics serves not merely as abstract theory but as a foundational framework for environmental literacy. By embedding climate change within thermodynamic education, both approaches cultivate "conscious individuals capable of approaching and solving problems" while deepening appreciation of the "social and integrative role of Science and Technology" (Teixeira et al., 2025). This figure highlights the pedagogical value of interdisciplinary, context-rich science education in addressing contemporary global challenges.

c. Systems Thinking and the Socio-Technical Perspective

Environmental awareness ultimately requires systems thinking recognizing that environmental problems emerge from complex interactions between natural and human systems. Thermodynamic literacy contributes to systems thinking by providing the physical constraints within which these systems operate.

Braun (2025) reports on an eSTEeM project at The Open University that embedded sustainability into three undergraduate physics modules serving over 1,300 students. The project used a light-touch approach: identifying where sustainability was already present but hidden in existing content, then making it explicit through brief introductions to Key Sustainability Competencies (systems thinking, futures thinking, strategic action) and reflective assessment prompts. Evaluation revealed significant gains: awareness of the UN SDGs increased from 22.5% to 34.7%, and awareness of Key Sustainability Competencies rose from 14% to 26.3%.
Notably, these changes were not observed in the control group, confirming that explicit foregrounding rather than passive exposure to physics content made the difference. The project demonstrated that sustainability integration need not require massive curricular overhaul; small, authentic changes can produce measurable awareness gains.

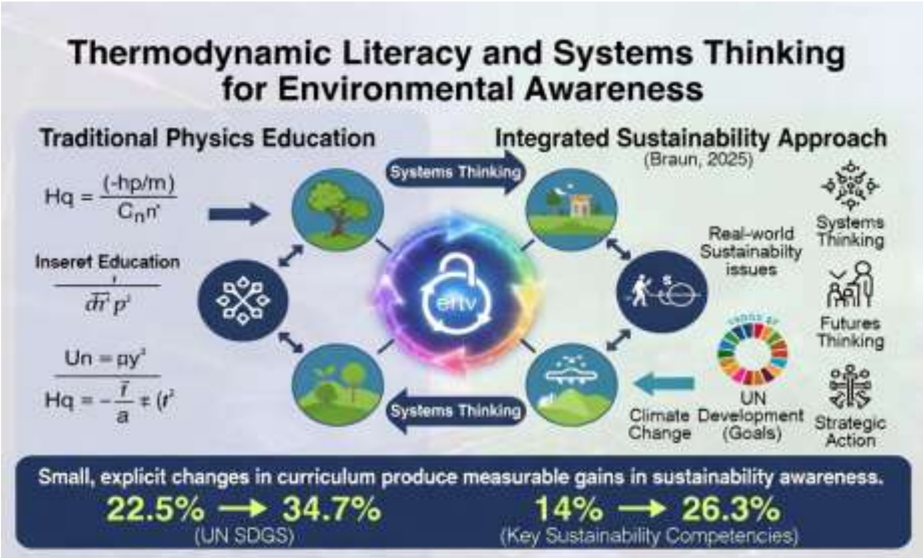

Figure 2. Integration of thermodynamic literacy and systems thinking in environmental education: comparison of traditional physics teaching with explicit sustainability approaches showing measurable gains in student awareness of UN SDGs and Key Sustainability Competencies.

Figure 2 illustrates the pedagogical power of integrating thermodynamic literacy with systems thinking to enhance environmental awareness. The left panel represents traditional physics education, where fundamental concepts such as heat transfer and energy conservation are taught in isolation. In contrast, the right panel showcases two innovative approaches that explicitly connect thermodynamic principles to real-world climate challenges.

The upper pathway demonstrates the CTSA (Science, Technology, Society, and Environment) framework implemented by Teixeira et al. (2025), which embeds sustainability into high school physics modules. By linking thermodynamic concepts to local phenomena such as the greenhouse effect, El Niño/La Niña patterns, and heat waves, students develop critical thinking and problem-solving skills. The lower pathway presents MIT's university-level course (Godart, 2020), which uses thermodynamics as a foundational lens to understand climate mechanisms.

A central thermodynamic cycle elegantly bridges both models, emphasizing how energy flow and entropy govern environmental systems. Evaluation of the Open University's eSTEeM project (Braun, 2025) revealed significant improvements: awareness of the UN Sustainable Development Goals increased from 22.5% to 34.7%, while awareness of Key Sustainability Competencies rose from 14% to 26.3%. These gains were absent in the control group, confirming the effectiveness of explicit foregrounding of sustainability concepts.

This figure demonstrates that small, intentional curricular changes can produce substantial improvements in students' ability to understand complex environmental issues through a thermodynamic and systems-thinking lens (Braun, 2025; Teixeira et al., 2025).

III. Result and Discussion

3.1 Pedagogical Approaches for Integrating Thermodynamic Literacy

a. Active Learning Strategies

Physics education research has consistently demonstrated that active learning outperforms lecture-dominant instruction in conceptual learning and student engagement (Freeman et al., 2014; Hake, 1998). Active learning approaches are particularly well-suited to sustainability integration, as environmental problems inherently require collaborative problem-solving and real-world application.

A multidimensional review by Zhang et al. (2026) synthesized evidence from flipped classroom implementations, peer instruction, collaborative problem solving, inquiry- and project-based approaches, and technology-enhanced formats. The review advances a component–mechanism–outcome framework structured along cognitive, affective, and behavioral pathways, redirecting attention from "which strategy works" to "which components work, how, and under what conditions".

Specific active learning strategies for thermodynamic literacy include:

a. Project-based resource audits: Students measure and calculate energy use in their school, home, or community, applying First Law accounting and Second Law efficiency analysis.
b. Simulation tools: Computer simulations allow students to model energy systems and visualize entropy generation without physical laboratory constraints (Prayogi & Verawati, 2024).
c. Peer instruction with sustainability contexts: Thermodynamics problems framed around electric vehicle charging, building insulation, or grid-scale battery storage engage students in both conceptual physics and sustainability reasoning.

3.2 Making Hidden Sustainability Links Visible

A recurring theme in the literature is that sustainability is already present in physics curricula but remains invisible to students. The challenge is not adding new content but recontextualizing existing content to reveal its sustainability implications.

Tisdale and Atadero (2024) examined sustainability instruction methods in 18 university-level engineering thermodynamics courses, finding that environmental issues were included in 15 courses, social issues in 9, and economic issues in 5. Eight of the 17 SDGs were represented. Integration methods included mathematical examples, labs, projects, service-learning, application-based learning, simulation tools, and book reviews. However, the review noted that learning outcomes were predominantly cognitive, with affective domain outcomes generally not explicit.

The OU eSTEeM project offers a replicable model for making sustainability visible. A bespoke virtual learning environment audit tool identified points where existing material already aligned with SDGs or Key Sustainability Competencies. Short introductions to competencies were added, with relevant competencies clearly signposted within existing activities. Brief reflective prompts in assessments encouraged students to consider wider implications without increasing marking burden.

Figure 3 presents a comparative analysis of sustainability integration within university-level thermodynamics education. The left panel, based on Tisdale and Atadero (2024), reveals that among 18 reviewed courses, environmental issues were addressed in 15 courses, social issues in 9, and economic issues in only 5. While 8 out of 17 Sustainable Development Goals (SDGs) were represented, integration remained predominantly cognitive, relying on mathematical examples, laboratory work, projects, and simulations, with limited attention to affective learning outcomes.

In contrast, the right panel showcases the Open University's eSTEeM project (Braun, 2025), which implemented a light-touch, replicable model for embedding sustainability. Through a virtual learning environment audit, existing content was made explicitly linked to sustainability themes and Key Sustainability Competencies (systems thinking, futures thinking, and strategic action). Brief reflective prompts were added to assessments without increasing marking burden. Evaluation demonstrated statistically significant gains: awareness of the UN Sustainable Development Goals increased from 22.5% to 34.7%, while awareness of Key Sustainability Competencies rose from 14% to 26.3%. These improvements were not observed in the control group, confirming the effectiveness of explicit foregrounding rather than passive exposure (Braun, 2025).

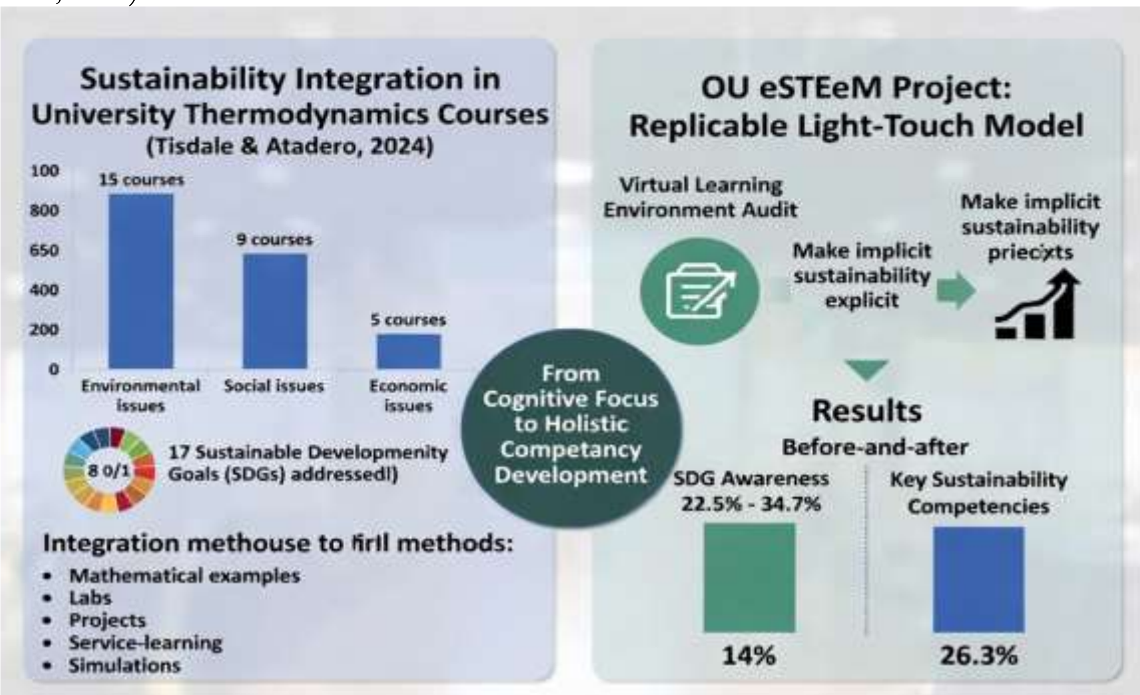

Figure 3. Sustainability integration in university thermodynamics education: comparison between current practices (Tisdale & Atadero, 2024) and the replicable light-touch model from the OU eSTEeM project, demonstrating measurable improvements in students' awareness of SDGs and Key Sustainability Competencies.

This figure underscores a critical shift from implicit to explicit integration of sustainability in thermodynamics education. It demonstrates that modest, strategic curricular enhancements can substantially improve students' holistic understanding of the interplay between thermodynamic principles and global environmental challenges, moving beyond purely technical competence toward responsible, systems-oriented scientific literacy.

3.3 STEAM-SDGs Integration

The integration of STEAM (Science, Technology, Engineering, Arts, and Mathematics) with SDGs has emerged as a promising framework for physics education. Ajibudiarta et al. (2025) surveyed 23 physics teachers in Indonesia, finding positive attitudes toward both STEAM (68% positive) and SDGs (57% agree). However, understanding and application levels were low: 42% of teachers were undecided about STEAM, 32% about SDGs, and 37–29% were hesitant about implementation. The study highlighted the urgent need for comprehensive teacher training to enhance understanding and preparedness for integration.

A narrative review of ESD implementation in science education (2025) found that while teachers frequently initiate ESD-based practices through creative strategies—including project-based learning, ecoliteracy modules, and STEAM integration—systemic curriculum integration remains limited. The absence of formal ESD indicators in core physics topics constrains scalability. Nevertheless, significant cognitive and affective gains were observed, including increases in critical thinking, creativity, environmental care, and systems awareness.

3.4 Assessment of Thermodynamic Literacy

Valid and reliable assessment instruments are essential for evaluating the effectiveness of educational interventions. Rianty et al. (2025) developed and validated the EcoThermal Literacy Assessment, a specific instrument for evaluating environmental literacy in thermodynamics learning. This instrument addresses a critical gap: while thermodynamics has potential to be linked to environmental issues, no previously validated assessment was available to evaluate students' environmental literacy in this domain.

The assessment framework includes knowledge of physical and ecological systems, application of thermodynamics to environmental issues, attitudes toward conservation, and behaviors reflecting sustainable choices. The instrument's development represents an important methodological advance, enabling future studies to quantify the impact of pedagogical interventions on thermodynamic literacy.

3.5 Discussion

a. Synthesis of Findings

This review has demonstrated that thermodynamic literacy provides a rigorous, physically grounded foundation for sustainable development education. The First and Second Laws of Thermodynamics establish fundamental limits on resource utilization that are not merely economic or political but physical and immutable. Concepts such as EROI and exergy make these limits quantifiable and teachable. Entropy analysis reveals the invisible cost of all consumption, transforming environmental awareness from abstract concern into specific, calculable consequences.

The pedagogical literature reveals effective strategies for integrating these concepts into physics instruction. Active learning, project-based resource audits, socio-scientific inquiry frameworks (CTSA), and light-touch visibility interventions all show promise. The development of validated assessment instruments marks an important step toward evidence-based practice.

b. Gaps and Challenges

Despite these advances, significant gaps remain:

a) Teacher preparation: Multiple studies report that teachers are positively disposed toward sustainability integration but lack the training, confidence, or curricular support to implement it effectively (Ajibudiarta et al., 2025; Prayogi & Verawati, 2024). Professional development programs addressing both thermodynamic content knowledge and pedagogical strategies for sustainability are urgently needed.

b) Affective domain neglect: Tisdale and Atadero (2024) found that learning outcomes were predominantly cognitive, with affective outcomes (attitudes, values, identity) generally not explicit. Yet environmental awareness cultivation inherently involves affective development. Future curriculum designs should explicitly articulate affective learning outcomes.

c) Vertical integration: Sustainability integration in physics is sporadic present in some university courses but rare in secondary education and fragmented across educational levels. A coherent, vertically articulated curriculum from primary through tertiary education is lacking.
d) Assessment beyond awareness: While awareness gains have been demonstrated (Braun, 2025), longer-term impacts on behavior, decision-making, and civic engagement remain understudied. Future research should examine whether thermodynamic literacy translates into sustained sustainable practices.
e) Global and contextual variation: The majority of studies originate from North America, Europe, and Indonesia. Limited research exists on thermodynamic literacy education in other global contexts, particularly those most vulnerable to climate impacts.

3.6 A Proposed Framework for Thermodynamic Literacy Development

Drawing on the reviewed literature, we propose a three-stage framework for developing thermodynamic literacy across educational levels shown in Table 1.

Table 1: Three-Stage Framework for Developing Thermodynamic Literacy Across Educational Levels: Cognitive, Analytical, and Practical Competencies With Associated Pedagogical Strategies

Stage	Focus	Sample Learning Outcomes	Pedagogical Strategies
Cognitive (Foundational)	Understanding core thermodynamic principles	State the First and Second Laws; define energy, entropy, EROI	Interactive lectures, concept mapping, simulation visualizations
Analytical (Application)	Quantifying resource utilization and environmental impact	Calculate EROI for different energy sources; perform basic exergy analysis; conduct energy audits	Project-based learning, case studies, spreadsheet modeling
Practical (Agency)	Applying thermodynamic literacy to real-world decisions	Design efficiency improvements; evaluate energy policies; communicate sustainability recommendations	Service-learning, community projects, policy briefs

This framework aligns with the three-stage didactic model proposed by the ecological culture formation study (Author, 2026) and integrates the EcoThermal Literacy Assessment dimensions (Rianty et al., 2025).

3.7 Implications for Policy and Practice

For curriculum developers and education ministries, these findings suggest that physics curricula should be revised to explicitly articulate sustainability competencies alongside traditional content knowledge. The recent QAA Physics Subject Benchmark Statement (2025), which explicitly encourages sustainability inclusion in physics degrees, provides a model for such revision.

For teacher education programs, pre-service and in-service training must include both thermodynamic literacy content and pedagogical strategies for sustainability integration. The GREEN-EDU project (Erasmus+), which supports interdisciplinary approaches linking physics with sustainable engineering and green biotechnology, exemplifies promising professional development models (European Commission, 2025).

For researchers, priorities should include: (a) longitudinal studies examining the persistence of thermodynamic literacy and its behavioral correlates; (b) cross-national comparative research to identify contextual factors influencing integration success; and (c) design-based research to develop and refine instructional materials for understudied educational levels.

IV. Conclusions

This review has explored the integration of physics and sustainable development education through the lens of thermodynamic literacy, with specific focus on resource utilization and environmental awareness cultivation. The central argument advanced is that thermodynamics provides not merely illustrative examples for sustainability education but its physical foundation. Without thermodynamic literacy, sustainability discussions risk remaining aspirational rather than analytically grounded; with it, students gain a quantitative framework for understanding resource limits, efficiency boundaries, and the inescapable entropic cost of all human activity.

The reviewed literature demonstrates that effective integration is both feasible and beneficial. Students exposed to sustainability contextualized thermodynamics show increased awareness of SDGs and sustainability competencies, enhanced critical thinking and systems thinking, and greater engagement with physics content. Pedagogical models ranging from project based audits to light touch visibility interventions offer scalable approaches appropriate to diverse educational contexts.

Yet significant challenges remain. Teacher preparation lags behind curricular ambition; assessment instruments remain underdeveloped; vertical integration across educational levels is fragmented. Addressing these gaps requires coordinated effort among curriculum developers, teacher educators, researchers, and policymakers.

The ultimate goal is not to add sustainability as a separate topic to an already crowded physics curriculum but to reveal that sustainability the wise stewardship of energy and material resources—is already implicit in the physical laws that physics exists to teach. Thermodynamic literacy, properly cultivated, transforms students from passive consumers of energy facts into active stewards of planetary resources, equipped with the quantitative understanding necessary for informed environmental citizenship in the twenty first century.

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