

Re-centering Energy Learning Progressions on the Work–Energy Relation: A Review of the Instruction–Assessment Chain

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Abstract: Learning progressions (LPs) are widely used in science education to describe how students develop understanding of core concepts, yet research on energy learning progressions (ELPs) has yielded inconsistent findings. This review argues that such inconsistency cannot be explained solely by differences in instruments or samples, but should also be understood through the instruction–assessment chain. Drawing on a synthesis of prior research together with textbook materials from China, the United States, and Germany, the paper advances the interpretive claim that current energy instruction and ELP-based assessment together form a terminology-centered rather than mechanism-centered closed loop. Within this loop, instruction and assessment are organized primarily around descriptive categories such as forms, transfer, transformation, dissipation, and conservation, while work is not systematically positioned as the mechanistic core for explaining energy change. To address this problem, the paper argues for re-centering energy learning progressions on the work–energy relation and for reorganizing energy knowledge into a coherent causal chain linking energy terms, change of energy, and conservation of energy. This reinterpretation offers a mechanism-oriented direction for future assessment and instruction, while also requiring further empirical validation across contexts and educational levels.

Keywords: learning progressions; energy learning progressions; work–energy relation; instruction–assessment chain; mechanism-centered understanding

1. Introduction

Over the past two decades, learning progressions (LPs) have attracted increasing attention in science education as frameworks for describing how students develop in their understanding of core scientific concepts (Duncan & Hmelo-Silver, 2009; Lee & Liu, 2010; Neumann et al., 2013; Stevens et al., 2010) and in their participation in scientific practices (Gotwals et al., 2012; Schwarz et al., 2009). LPs are generally regarded as empirically grounded structures that can represent trajectories of conceptual development and directly inform the design of assessments aligned with those progressions (Brewer, 2011; Duncan & Hmelo-Silver, 2009; Jonassen et al., 2005).

As LP research has continued to evolve, it has gradually incorporated several new features, including greater attention to interrelationships among concepts, the use of modern assessment tools, and the inclusion of authentic task contexts (Duschl et al., 2011). However, these advances have not eliminated concerns regarding the validity and applicability of LPs. Many scholars have pointed out potential

problems associated with adopting progressions without sufficient validation. First, LPs often presuppose that student learning proceeds along an ordered and cumulative pathway; yet empirical research has shown that learning processes are frequently non-linear and discontinuous (Wyrwich et al., 2025; J.-X. Yao et al., 2017; J. Yao et al., 2017). Such oversimplification may lead to misinterpretations of students' learning trajectories (Duncan & Hmelo-Silver, 2009). In addition, the construction of LPs is often grounded in researchers' theoretical assumptions validated only within limited regions, and their scientific validity and generalizability may become highly contested when applied across contexts with substantial cultural and background differences (Alonzo & Gotwals, 2012). LPs may also "discipline" teachers' practice by confining it within predetermined frameworks, thereby reducing the flexibility of both teaching and learning (Duschl et al., 2011). Therefore, in contemporary educational contexts that place greater emphasis on student individuality and diversity in teaching practice, the approach of depicting learning pathways on the basis of conceptual learning outcomes—that is, modeling pathways by evaluating outcomes with reference to LPs—deserves renewed scrutiny.

Energy is commonly defined as a physical quantity that represents an object's capacity to do work and is widely recognized as a core concept in science education (National Research, 2012). However, owing to characteristics inherent to energy as a physical concept, most learners fall far short of achieving a robust understanding of it (Duit, 1987; Tong et al., 2023). More specifically, energy is highly abstract, and students often hold a wide range of alternative conceptions about it (Nordine et al., 2024; Watts, 1983). Moreover, energy is inherently interdisciplinary (Opitz et al., 2015), which creates additional challenges for students in establishing connections among energy-related ideas across disciplinary contexts. Consequently, these characteristics make not only the learning of energy highly difficult but also the assessment of students' understanding of energy particularly challenging (Duit, 1987). To address these issues, many scholars have attempted, under existing instructional conditions, to use a variety of methods to assess and analyze students' learning outcomes in the domain of energy (Herrmann-Abell & DeBoer, 2018; Lee & Liu, 2010; Tong et al., 2023), while also working toward the development of a more coherent framework for energy (Wyrwich et al., 2025; J.-X. Yao et al., 2017).

Energy Learning Progressions and Their Inconsistencies

Because LPs can represent relationships among concepts and propose possible learning sequences, many studies have treated them as effective tools for conducting in-depth evaluations of student learning outcomes in the domain of energy (Herrmann-Abell & DeBoer, 2018; Lee & Liu, 2010; Neumann et al., 2013). The development of the energy learning progression (ELP) originated from early studies on the order in which students acquire energy-related concepts. Driver et al. (2004) were among the first to outline an initial developmental sequence in students' scientific conceptions of energy. Building on this work, Liu and McKeough (2005) proposed five hierarchical stages: (1) viewing energy as activity or the ability to do work (Activity/Work), (2) identifying multiple forms and sources of energy (Form/Source), (3) understanding energy transfer and transformation (Transfer/Transformation), (4) recognizing energy degradation (Degradation), and (5) mastering the principle of energy conservation (Conservation). Using TIMSS data, Liu and McKeough (2005) provided early evidence for the hypothesis that understanding becomes more sophisticated with age and further suggested that key concepts (form/source, transfer/transformation, degradation, and conservation) may be acquired in sequence. These studies on conceptual ordering gradually gave rise to an assessment framework for the ELP. On this basis, Lee and Liu (2010), from a knowledge integration perspective, validated the sequence through which students acquire source, transformation, and conservation; from this version onward, work was removed from the ELP as an independent stage. Subsequently, Neumann et al. (2013) empirically tested a broader four-stage ELP sequence: (1) Form/Source, (2) Transfer/Transformation, (3) Degradation/Dissipation, and (4) Conservation.

This has since become the most widely used stage classification. Although later studies have continued to refine the model, these four stages are generally regarded as the four core sub-concepts of energy. For example, J.-X. Yao et al. (2017) evaluated this four-stage sequence from a cognitive-developmental perspective, whereas Herrmann-Abell and DeBoer (2018) elaborated the four core sub-concepts into 14 specific ideas and, overall, supported a model of conceptual growth from form and transformation to transfer and then to conservation.

Although established ELPs are often treated as valid models, no consensus has yet been reached regarding the sequence of specific sub-concepts within the energy domain. More specifically, Liu and McKeough (2005) found no significant difference in students' performance on conservation and degradation, suggesting that the acquisition of these two ideas may not follow the linear process presupposed by the progression. Neumann et al. (2013) reported no significant difference in difficulty between transfer/transformation and degradation, indicating that students' learning of these two components may likewise not follow the prescribed ELP order. In contrast to these findings, although J.-X. Yao et al. (2017) supported the view that students' knowledge development is constrained by cognitive developmental theory, they found no evidence that students progress step by step according to the conceptual order proposed in the ELP. The findings of Herrmann-Abell and DeBoer (2018) were similar to those of Neumann et al. (2013). Overall, a growing body of research has revealed a fundamental inconsistency in existing ELP-based assessments.

2. The Instruction–Assessment Loop

It is important to note that some studies focusing specifically on assessment validity have argued that inconsistencies in assessment results may stem from more objective factors, such as differences in measurement instruments and regional variation among tested populations (Drasgow, 1987; Kane, 2013). However, the explanations offered by these studies are often fragmented and do not provide a unified and convincing account of why measurements of the same body of knowledge can differ so substantially. Building on the widely accepted view that learning progressions are descriptions of instructional performance (Duncan & Hmelo-Silver, 2009), we therefore shift the focus from “inconsistency in assessment” to “how instruction shapes what is assessed.” From this perspective, it is necessary first to examine how energy is currently taught and then to offer an integrated explanation along the instruction–assessment chain.

To this end, we analyzed energy-related content in widely used elementary science and secondary physics textbooks in China, the United States, and Germany (CK-12 Foundation, 2018; Kultusministerkonferenz (KMK), 2020; Ministry of Education of the People's Republic of China, 2022; National Research, 2012; People's Education Press Curriculum & Textbook Research Institute, 2022; People's Education Press Editorial Office, 2020; Urone, 2022). Overall, these sources display a broadly similar organizational pattern. Along the “energy” strand, textbooks and classroom instruction primarily cultivate students' ability to describe energy phenomena, including identifying forms of energy, tracking “transfer,” “transformation,” and “dissipation,” and determining whether energy is conserved (CK-12 Foundation, 2018; People's Education Press Curriculum & Textbook Research Institute, 2022; People's Education Press Editorial Office, 2020; Verlag, n.d.). Another theme related to energy is work. Although work is addressed at the secondary level, it is typically treated as a means of analyzing kinematics and mechanics problems. This means that “energy” and “work” are organized as two parallel strands in the curriculum, rather than positioning work as an integrative mechanism across contexts (CK-12 Foundation, 2018; People's Education Press Curriculum & Textbook Research Institute, 2022; People's Education Press Editorial Office, 2020; Verlag, n.d.).

In textbooks, energy is typically introduced along a recurring trajectory. In the lower grades, students first learn basic forms of energy and encounter terms such as “energy transfer” and “energy transformation.” In the upper grades, instruction expands to conservation, efficiency, energy use and saving, and other applied or societal contexts. This pathway extends from elementary school through secondary education and aligns closely with the four themes commonly adopted in existing energy learning progressions: form and source, transfer and transformation, dissipation, and conservation. From a relatively early stage, students are required to use these standardized terms to track what “happens” to energy, and proficiency is often operationalized as mastery of this descriptive vocabulary rather than as the ability to explain the underlying mechanism responsible for energy change. Even in textbooks that invoke work in the definition of energy—for example, by defining energy as the “ability to do work”—subsequent instruction rarely mobilizes work to explain why energy changes or to unify analysis across different contexts. Instead, energy instruction tends to emphasize phenomenological descriptions—where energy comes from, where it goes, in what form it appears, and whether it is conserved—rather than mechanism-based explanation.

Work, by contrast, provides a key mechanism for explaining energy change, yet it typically appears at a later stage, in secondary mechanics or kinematics units. It is introduced as the product of force and displacement and is then used to analyze force and motion, the work–kinetic energy theorem, and the conservation of mechanical energy. Along this pathway, work is framed primarily as a computational tool for solving mechanics problems and is associated mainly with kinetic energy and mechanical energy. This treatment remains largely confined to mechanical contexts and is only rarely extended to non-mechanical domains such as thermal phenomena or electricity. After the mechanics unit ends, work is seldom recalled as an overarching idea for analyzing energy, which further reinforces the separation between the two strands.

The textbook analysis thus shows that current instruction and the thematic sequence of learning progressions closely correspond to one another: both instruction and assessment are organized around the same four conceptual themes. At the same time, however, we also observe that instruction in the energy domain places greater emphasis on terminological “description and tracking” than on mechanistic understanding of energy knowledge. Moreover, much like the content organization of learning progressions, work is not systematically incorporated into the energy unit itself but remains relatively separate within the broader curriculum structure.

At the same time, this instructional arrangement also reveals a series of problems. A substantial body of scholarship has argued that current energy instruction does not genuinely promote deep understanding. First, current instruction relies heavily on defining terms for different forms of energy and, on this basis, introduces verbs used to describe energy change (Fiedler et al., 2025). From this perspective, energy appears in different forms—such as kinetic energy, chemical energy, and elastic potential energy—and is transformed from one form into another in observable phenomena. However, when instruction emphasizes terminology without providing the underlying mechanisms that support those terms and the processes they describe, students often remain at the level of memorizing labels while overlooking their physical meaning (Falk et al., 1983; Quinn, 2014). In addition, teaching that emphasizes a chain of energy-related terms has been criticized for encouraging students to apply labels mechanically while failing to grasp the physical causal relations that connect them (Millar, 2014).

Furthermore, many of the terms commonly used in current instruction—such as “transfer,” “transformation,” and “degradation/dissipation”—belong to everyday language used to describe properties of material objects. This may unintentionally lead students to treat energy as if it were a substance-like entity, which is ontologically inappropriate. Warren (1983) argued that treating energy as a quasi-material substance is a fundamental error: it introduces terms that lack rigorous definition while failing to reveal or convey the essential nature of energy. Substance-based metaphors are also limited in

their ability to support the tracing of energy flow between objects and may therefore hinder deeper understanding of the energy concept (Duit, 1987). Although the substance metaphor can be intuitively appealing in introductory instruction, it often leads students to misconstrue energy as a tangible entity, thereby obscuring its abstract nature and its conservation (Scherr et al., 2012).

Taken together, the patterns observed in instruction and in ELP-based assessment reveal a clear chain of relations. Current instructional organization corresponds closely to ELP-based assessment, yet the former may fail to foster deep understanding of physical knowledge, and the latter may fail to reflect students' mechanistic grasp of energy knowledge. When instruction does not support mechanism-oriented understanding and relies primarily on conceptual definitions, students are likely to fall back on terminological memorization and word associations centered on those terms. Because terminological memory is not constrained by the underlying regularities of the knowledge itself, its development does not necessarily follow a fixed sequence and is highly susceptible to individual differences and instructional variation. On this basis, existing ELP measurements are more likely to be describing instructional output. Accordingly, the inconsistencies found in these results largely stem from students' memory-based knowledge systems—systems that are non-sequential and highly sensitive to item context and instructional differences. In conjunction with the evidence from textbook analysis, this points to a more serious conclusion: current instruction and ELP-dominated assessment together form a closed loop that is centered on terminology rather than on the mechanism of energy knowledge. This loop may be internally coherent, but from the standpoint of the nature of knowledge, it deviates substantially from the physics view of energy and, in practice, obstructs students' genuine mastery of energy knowledge.

3. The Work–Energy Relation

Based on the terminology-oriented closed loop revealed in the preceding instruction–assessment chain, we argue that the core problem does not lie merely in differences in instruments or samples, but rather in a disconnection from the physical nature of energy knowledge. In other words, the root of the problem is more likely to lie in how knowledge is defined and organized than in any single assessment step itself. The next step, therefore, is to return to the nature of the knowledge involved and reexamine the energy concept at the mechanistic level, using the work–energy relation as the central thread for exploring the structure of energy knowledge.

Why the Work – Energy Relation Matters

From a physics standpoint, the key question is not “where did the energy go,” but why energy changes. Its causal structure is revealed by the work–energy relation (Russ et al., 2008; Tong et al., 2023; Tong et al., 2025): in classical mechanics, when a force acts through a displacement on a system, the work done by that force equals the change in the system's energy (Mungan, 2005; Taylor, 2005; Tong et al., 2023). Hence, changes in energy can be viewed as the outcomes of concrete interactions; “conservation” is understood as redistribution of energy between a system and its environment rather than “disappearance” or “exhaustion” (Daane et al., 2015; Mungan, 2005). The work–energy relation not only explains the causes of energy change in specific situations, it also unifies seemingly disparate phenomena—e.g., heating during deceleration, frictional heating, and Joule heating in circuits—within a single mechanistic account. In what follows, our use of the work–energy relational perspective refers to a quantitative–causal description centered on $W=\Delta E$ together with system boundaries and interaction conditions, and, on that basis, to organizing the internal connections among terms, processes, and conservation.

Prior Evidence for a Work-Centered Approach

It should also be noted that existing research has accumulated evidence in support of a teaching orientation anchored in work. Warren (1983) argued that energy education should not be confined to

terminology instruction, but should instead be grounded in work and force so as to support students' understanding of the mechanistic basis of the energy concept. As a physical quantity, energy represents an object's capacity to do work, while the work–energy theorem reveals the basic mechanism of energy change (Hecht, 2019). This internal relation highlights the commonality underlying energy-related phenomena. Accordingly, rather than continuing to fit students' performance to a rank order of terminological displays, it is more productive to return to the causal chain represented by work and energy and reconsider what should be learned, how it should be assessed, and how it should be taught. A number of scholars have further examined the pedagogical role of work in energy instruction. For example, Jewett (2008) showed that introducing the energy concept through work can encourage students to analyze energy problems from a systems perspective. Lindsey et al. (2009, 2012) similarly found that emphasizing work helps students address friction-related energy problems from a thermodynamic standpoint. Podschuweit and Bernholt (2018) reported that designing energy instruction around work can reduce cognitive load. Likewise, Hecht (2019) proposed a work-centered model of energy transformation that explicitly connects force, work, and energy. Taken together, these studies indicate that anchoring instruction in work can provide cross-contextual coherence at the levels of concepts, representations, and reasoning.

However, most of the existing evidence consists of individual cases demonstrating the effectiveness of organizing instruction around work, while relatively few studies have systematically clarified the structural pathway through which work can organize energy-related knowledge. For this reason, the present article does not propose an entirely new theory from scratch. Instead, drawing on existing research and textbook evidence, it adopts a knowledge integration perspective to synthesize and reinterpret the energy concept in a mechanism-oriented way (Bao & Fritchman, 2021; Dai et al., 2019; Linn, 2005; Liu et al., 2022; Shen et al., 2017; Tong et al., 2023; Xu et al., 2023). More specifically, we propose the work–energy theorem as the central idea and place terminology (representation/fact), change (process/interaction), and conservation (outcome/constraint) within a single causal chain, thereby providing an operational pathway for instructional intervention. In the following sections, we present only an outline of this framework and its alignment logic, without elaborating all details, and on that basis derive testable expectations for assessment and instruction.

Reorganizing the ELP Themes

The purpose of this section is to bring these previously dispersed elements together within the same work–energy chain and to provide an alignment description comparable to the themes used in existing ELPs. Based on the preceding synthesis of literature and textbook materials, we identify work and the work–energy theorem it entails as the central idea of the broad energy concept—that is, as the mechanistic process underlying all energy phenomena. On this basis, we reorganize the commonly used ELP themes into an alignment that is centered on the work–energy relation. This framework is specifically designed to establish a comparable mapping to the four stages of existing ELPs: (1) form/source, (2) transfer/transformation, (3) degradation/dissipation, and (4) conservation. We reorganize these four stages into three subdomains—Energy Terms, Change of Energy, and Conservation of Energy—and integrate them into a coherent knowledge system under the central idea of the work–energy theorem. In doing so, we emphasize the causal sequence of terms–process–constraint and explicitly show how work mechanistically connects the three subdomains and their more specific elements.

Given that work is the mechanism of energy change (Warren, 1983), its effects are manifested in changes in energy forms and in the system under consideration. Some previous studies have in fact approached energy problems from the perspectives of energy forms and systems (Fiedler et al., 2025; Nordine et al., 2018). On this basis, and in conjunction with the central idea of the present study, we argue that changes in form and system can be understood as contextualized manifestations of the mechanism of work in the process of energy change. From this perspective, most of the terms used in current instruction

describe different aspects of these physical processes, while changes in form and system serve as a bridge between work and the phenomena denoted by those terms.

Energy Terms. This category includes terms that mark different energy forms and energy sources (systems). Energy forms include kinetic energy, potential energy, thermal energy, and so forth; energy sources refer to the systems in which energy resides, which may be single objects (such as a spring or a chemical substance) or systems composed of multiple objects (such as a charge distribution). In existing curricula, the meanings of these terms tend to be relatively static and factual. This subdomain corresponds to the “form/source” stage in the ELP, but in our framework it is further assigned a representational and factual cognitive status. Importantly, once a work-centered mechanistic perspective is introduced, definitions such as kinetic energy, potential energy, and thermal energy can all be seen as extensions and derivations of the work–energy theorem in different micro- and macro-level contexts. Their connection to work provides these definitions with a mechanistic basis and thus shifts learning from term memorization to meaning construction.

Change of Energy. This domain integrates the ELP categories of “transfer/transformation” and “degradation/dissipation” into a single process-oriented concept—change—and explains it from a mechanistic perspective. For example, transfer can be understood as a change in energy between two or more objects or systems while the energy remains in the same form, as in the transfer of kinetic energy between objects during a collision. Transformation, by contrast, refers to change between different forms of energy within or between systems, as when kinetic energy is transformed into potential energy or thermal energy. As for degradation/dissipation, its literal wording may misleadingly suggest that energy “disappears,” which conflicts with conservation of energy. In the present framework, it can instead be understood as a negative change in one or more forms of energy within a given object or system. In short, transfer, transformation, and degradation/dissipation can all be unified as changes in energy, and their underlying mechanism is explained by the work done by interaction forces at the micro- or macro-level.

Conservation of Energy. Although this domain retains the same label as the ELP category of “conservation,” in our framework it is presented as the outcome component of the “Change of Energy” subdomain. According to the work–energy theorem, in an isolated system the algebraic sum of all changes in energy across forms and processes is zero, and the total energy of the system remains constant. Unlike existing curricula, which often present the law of conservation as a fact to be memorized, the present framework treats it as a necessary consequence of work and energy change, thereby providing a mechanistic and intelligible basis for its existence.

In sum, the three components organized around the central idea of the work–energy theorem form a highly integrated knowledge system. This system not only provides meaningful support for the definition of terms, the description of change processes, and the statement of the conservation law, but is also readily applicable in instruction. More specifically, with the help of terminology and work-based processes, students can distinguish and define relevant energy forms and systems and thereby describe energy change both qualitatively and quantitatively. The work-centered mechanistic perspective helps explain problems involving energy change, while the mechanism-based view of conservation of energy ensures that, even as forms, systems, and processes change, total energy remains constant as long as the system is isolated. In this sense, conservation can also serve as a convenient quantitative tool for solving problems involving energy change.

4. Implications

Scope, Evidence, and Future Validation

First, it is important to restate the scope and evidentiary boundaries of this article. Through a systematic review of the literature and textbook materials, we advance the interpretive claim that, with respect to the energy concept, the instruction–assessment chain has formed a terminology-centered rather than mechanism-centered closed loop. To strengthen the external validity and persuasiveness of this claim, future research should conduct multi-site replication and reproducibility tests on a broader empirical basis. More specifically, existing ELP instruments should be administered across samples spanning multiple countries, regions, and educational levels, accompanied by measurement invariance analyses based on item response theory (IRT) or structural equation modeling (SEM), including stepwise tests of configural, loading, and intercept equivalence. These analyses should be supplemented by differential item functioning (DIF) and mixed IRT/latent class analyses to identify potential differences in subgroup structure, so as to distinguish whether apparent sequence inconsistency arises from participant differences, contextual transfer, or instrument properties. At the same time, response-process evidence and indicators of knowledge organization should be incorporated to test, through multi-source triangulation, whether students solve problems through terminological association or through mechanistic reasoning. Relevant evidence may include think-aloud protocols and semi-structured interview data, classroom observation records, visual modeling of semantic/conceptual networks and representational transformation pathways, and traceable coding of the mechanistic chain of system boundary–interaction–work–energy change–conservation constraint. To improve comparability and reproducibility, research designs should adopt preregistration and open materials/open data practices, include anchor items and linking studies, and combine rater reliability and generalizability theory (G-theory) to evaluate the robustness of explanatory responses.

Implications for Assessment

In assessment, the focus should shift from “describing current learning outcomes” to “measuring genuine mastery of energy knowledge.” Existing studies have already shown that conceptual frameworks can effectively support assessment design and better reflect students’ authentic learning (Ding et al., 2024; Liu et al., 2022; Lu et al., 2023; Tong et al., 2023; Xie et al., 2021; Xu et al., 2020; Ye et al., 2024). One operational pathway is to organize knowledge around a central idea, which is closely related to the work–energy relation-centered mode of construction proposed in this article. Future work may therefore develop corresponding models and design assessments to examine students’ knowledge integration by placing the work–energy relation, together with system boundaries and interaction conditions, at the organizational core of progression-based assessment, and by constructing contextualized tasks that simultaneously test the internal connections among terms–process–constraint. Concretely, such assessment may require students, across multiple contexts such as mechanics, thermodynamics, and electricity, to define the system and surroundings, determine the direction and source of work, explain changes in energy form through the work–energy chain, and return to conservation constraints. At the item level, explanatory responses may be paired with high-quality contextualized multiple-choice items, while cognitive diagnostic models can be used to disentangle key attributes such as systems thinking, interaction identification, work–energy linkage, and conservation constraint. In reporting results, the emphasis should be placed on indicators of mechanistic evidence rather than merely terminological scores. At the same time, log data, process traces, and diagrams such as energy bar charts, energy flow diagrams, and work arrows may be integrated to enhance interpretive power and support instructional feedback. As evidence accumulates, item banks, scoring rubrics, and interpretive frameworks should be progressively shared and standardized, thereby fostering a cumulative research ecosystem that can operate across teams, languages, and curriculum standards.

Implications for Instruction and Future Research

In terms of instructional improvement, strengthening students' mechanistic understanding should become an explicit goal of curriculum and classroom practice. The framework proposed here offers a translatable organizational approach for instruction: by treating work as the general mechanism of energy change, the traditional phenomenological sequence of form–transfer–transformation–dissipation–conservation can be reconstructed into a causal chain of terms (representation/fact)–process (interaction/change)–constraint (conservation/boundary condition), thereby aligning both the hierarchy of knowledge and the learning sequence with the physical nature of the concept. At the level of design strategy, cross-domain bridging tasks may be used to explain, through the same work–energy chain, phenomena such as heating during braking, frictional heating, and Joule heating in circuits. This can be combined with translation across multiple representations (text–diagram–equation–context), diagrammatic tools for system boundaries and energy flow, and inquiry activities in which mechanism takes priority over terminology. Such approaches may help students move from a descriptive mode of “memorizing terms and tracking where energy goes” to an explanatory mode of “analyzing interactions, determining work, identifying change, and constraining it through conservation.” In terms of implementation, design-based research (DBR) cycles are recommended to iteratively refine meso-level instructional sequences and micro-level task structures in authentic classrooms, while teacher professional development can support the instructional transition toward using work to unify multiple contexts. It should be emphasized that foregrounding work does not imply a drift toward formula-centered instruction. Through contextualized analyses of force–displacement–energy change and shifts between qualitative and quantitative representations, it is possible to avoid the mechanical substitution of $W=F \cdot s$ and instead ensure that the mechanistic chain remains understandable and transferable. From the perspective of equity and accessibility, a mechanism-oriented approach may also reduce the disadvantage imposed by heavy terminological demands on language learners and students from different cultural backgrounds, and may provide a more inclusive learning pathway through diagrams, operational tasks, and causal explanation.

Finally, the judgments and methodology developed in this study are not limited to the domain of energy alone, but also have implications for other core concepts in physics and STEM education. A growing consensus in related fields is that instructional effectiveness should not be judged by whether students can reproduce terminology, but by whether they can draw on core disciplinary mechanisms to explain phenomena and predict system behavior. On this basis, future review and empirical work may extend this paradigm shift from terminology orientation to mechanism orientation to concepts such as momentum–impulse, entropy–irreversible processes, and electric potential–energy density, thereby building a cross-concept, cross-level research–practice community anchored in the nature of knowledge itself. At the same time, we acknowledge the limitations of the present study. As a review, its evidentiary chain relies primarily on secondary sources and textbook analysis; moreover, the construct validity, predictive validity, and usability of the proposed framework still need to be tested through larger-scale systematic assessment and classroom intervention. We therefore call for the establishment of open item and data-sharing mechanisms and for continued cross-checking across multilingual, multi-standards, and multicultural contexts, so that the evidentiary base for a mechanism-oriented approach can be broadened and strengthened and ultimately translated into sustainably improved teaching and assessment.

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