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RESEARCH ARTICLE

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What affects the continued learning about energy? Evidence from a 4-year longitudinal study

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Abstract

Energy is a central concept across the sciences and an important goal of science education is to support all students so that they develop a full understanding of the energy concept. However, given the abstract and complex nature of the energy concept, only a few students develop an understanding so that they can use energy ideas to make sense of phenomena. Research into energy learning progressions aims at developing models of learning about energy to guide instruction so that students can be best supported in developing competence and has provided a rich model of how students' understanding of energy develops over time. Being largely based on cross-section data, however, the extent to which this model can guide instruction is limited, especially concerning the continued learning of students about energy. To address this gap—the limited evidence regarding what supports students' continued learning about energy—it was investigated how holding non-normative ideas and the integratedness of students' energy knowledge affect students' continued learning about energy. Drawing on data from a 4-year longitudinal study covering Grades 6–9 on students' learning about energy, diagnostic classification models were used to characterize students' non-normative idea profiles and the integratedness of their knowledge and then related both to their continued learning. The results suggest no detrimental effects of holding non-normative ideas and strong positive effects of holding integrated knowledge for students' continued learning about energy. Implications for teaching and future research are discussed.

KEYWORDS

diagnostic classification models, energy, learning progressions, longitudinal

Energy is a central concept across the sciences (Chen et al., 2014) and is also central to global challenges such as climate change or the energy transition. Thus, an important goal of science education is to support all students in developing a full understanding of the energy concept, that is, an understanding that allows them to apply core ideas about energy—ranging from manifestations of energy to conservation of energy—to make sense of phenomena. Few students, however, develop such an understanding (Herrmann-Abell & DeBoer, 2017; Lee & Liu, 2010; Liu & McKeough, 2005; Neumann et al., 2013).

Research on the energy learning progression has aimed at developing models of learning about energy with the aim to subsequently guide instruction in middle and high school. Drawing primarily on cross-sectional designs, this research has repeatedly found that across middle school, students' learning typically progresses along a set of normative core ideas about energy; from manifestations of energy, through transfer/transformations and degradation, to conservation (e.g., Neumann et al., 2013) while at the same time developing connections between these ideas, that is, developing an integrated understanding about energy (e.g., Lee & Liu, 2010). More recent studies have added a finer grain size, for example, differentiating between different manifestations of energy (e.g., Herrmann-Abell & DeBoer, 2017) and extending the age range (ibid.). The understanding of the energy learning progression has been further supported by research that has investigated students' non-normative ideas about energy so that an overview of typical student conceptions about energy is available (e.g., Lancor, 2015). In sum, research into the energy learning progression and students' conceptions of energy has provided a rich model of the central steps in learning about energy that can help guide curriculum planning and sequencing (Duschl et al., 2011).

The extent to which this model—as it is largely based on cross-sectional data—can guide instruction remains limited. As Duschl et al. (2011, p. 172) point out, "[…] longitudinal studies of students' learning are critically important to advance our understanding of assisting learning." Thus, to effectively support students, a better understanding of what factors support the continued learning about energy is needed. Based on the current understanding of the learning progression, two issues stand out: (1) While it is known that students who hold non-normative ideas often struggle to make sense of phenomena when they hold these ideas, the effects of holding non-normative ideas on the continued learning about energy remain largely unknown. In consequence, it remains hard to provide guidance for instruction: should these ideas be engaged (Wiser & Carey, 2014), seen as stepping stones (Duncan & Rivet, 2018), or should a more asset-oriented approach be taken (National Academies of Sciences, Engineering, and Medicine, 2018)? (2) While having an integrated knowledge of energy is a learning goal as it is required to make sense of phenomena using energy ideas, it remains unclear to what extent having an integrated knowledge supports continued learning. Again, different instructional approaches seem feasible: one could first focus on learning about different aspects of energy and then emphasize integration or try to facilitate integration throughout the course of instruction. What is more effective, however, remains an open question.

As answering these questions can have important implications for guiding instruction, informing the development of effective support systems, and helping to further refine the energy learning progression, the goal of the present study is to investigate these questions by analyzing longitudinal data on students' learning about energy during 4 years in middle school.

1 | BACKGROUND

1.1 | The energy concept

Energy is a core idea across the sciences. This is reflected in its role as a Disciplinary Core Idea (DCI) in the US Framework for K–12 Science Education (National Research Council, 2012) or as *Basiskonzept* in the German science standards (Sekretariat der ständigen Konferenz der Kultusminister der Länder in der Bundesrepublik Deutschland, 2020) which is similar to a DCI. One of the defining qualities of energy is that it is a conserved quantity, that is, whenever energy is transferred between systems or changes its manifestation in the world through a transformation, the total amount of energy remains the same. Although the total amount of energy remains the same as it is transformed or transferred, some of the energy is dissipated or degraded, that is, it spreads out through space and becomes less usable for technical applications. In sum, this leads to four core ideas about energy: (1) energy manifests itself in various forms, such as kinetic energy or thermal energy; (2) energy can change its manifestation, that is, forms of energy can be transformed into each other, and energy can be transferred between systems; (3) some of the energy is degraded whenever it is transformed or transferred; (4) the overall amount of energy remains conserved during transformations or transfers (Duit, 1986, 2014). These four core ideas also reflect a hierarchy or inner logic, for example, the idea of transformation is rather meaningless if one does not also have ideas about manifestations of energy that undergo these transformations (Coopersmith, 2015). In consequence, there is a principal consensus among researchers that a full understanding of the energy concept encompasses the four core ideas and how they are related to each other (Doménech et al., 2007; Duit, 2014; Neumann et al., 2013). In other words, students do not only need to acquire knowledge about these core ideas but also develop connections between core ideas to develop understanding (Lee & Liu, 2010; Yao et al., 2017). Finally, it is important to note that for each of the four core ideas, there are multiple subideas, for example, the definitions of the different forms of energy, for example, kinetic energy is proportional to the mass and the square of the velocity of an object, are subideas of the manifestations core idea.

1.2 | The energy learning progression

The field's current understanding of how students can be supported in learning about energy is synthesized in the energy learning progression. Learning progressions describe "successively more sophisticated ways of reasoning within a content domain that follow one another as students learn" (Smith et al., 2006, p. 1). To do so, learning progressions identify steps of intermediate stages of understanding from a lower anchor, representing students understanding upon entering the learning progression, and an upper anchor, representing mastery of the domain or an aspect thereof. The intermediate steps represent idealized trajectories of learning as a means for aligning instruction and assessment (Duncan & Rivet, 2018; Duschl et al., 2011). These trajectories are hypothetical in nature and need empirical validation (Duschl et al., 2011; Jin et al., 2019). Empirically validating learning progressions has triggered much debate (Shavelson & Kurpius, 2012; Steedle & Shavelson, 2009), mostly revolving around how individual learners' trajectories align with the hypothesized one and adequate research designs (Duschl et al., 2011; Lehrer & Schauble, 2015). More specifically, Duschl et al. (2011) point out key issues with studies that use a cross-sectional design or only focus on short durations of instructions (e.g., single units): such studies cannot—by design—provide information about learners' developmental pathways toward long-term learning goals (the kind of learning goals, that learning progressions are developed for). In consequence, Duschl et al. (2011) conclude that to better understand learners' pathways, longitudinal studies across several grade levels are needed. Such an approach can also help to disentangle the messy middle, that is, students understanding at the intermediate steps of the progression (Gotwals & Songer, 2009), where mixed or indiscriminate results about the order of the different steps may be attributed to a variety of alternative individual pathways. Without longitudinal data, however, the relative effectiveness of alternative pathways cannot be assessed, limiting the functionality of the learning progression to guide instruction.

Figure 1 summarizes the current knowledge about the energy learning progression relative to the four core ideas: manifestations, transformation, degradation, and conservation. Let me unpack what is represented here:

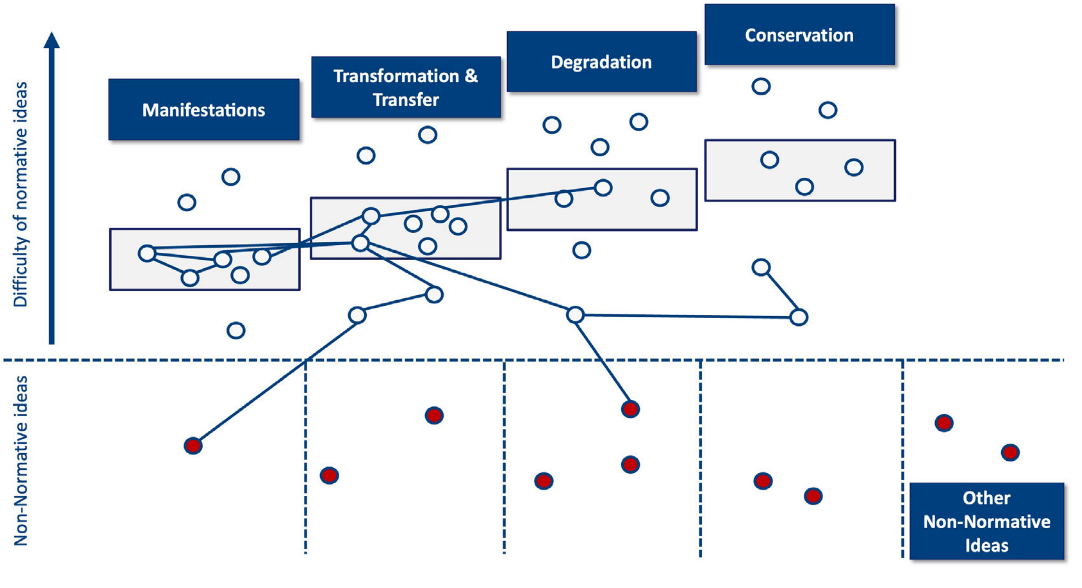


FIGURE 1 Summary of energy learning progression.

The blue boxes represent an understanding of the four core ideas. The progression from manifestations at the lower anchor, conservation at the upper anchor, and transformation and degradation as intermediate steps has been reported in a range of studies focusing on middle and high school (Dawson-Tunik, 2006; Herrmann-Abell & DeBoer, 2017; Liu & McKeough, 2005; Neumann et al., 2013; Yao et al., 2017). The blue circles below the boxes represent normative ideas, that is, ideas are ideas that are aligned with the scientific consensus on a finer grain size that make up the core ideas, for example, different manifestations of energy such as electric or kinetic energy. The red circles represent non-normative ideas. Two features about the normative ideas stand out: these ideas vary widely in difficulty and there is substantial overlap in difficulty across the core ideas. Both features are frequently found in the literature, for example, Neumann et al. (2013) report standard deviations of the item difficulties for the four core ideas in the range of the differences in mean item difficulty between adjacent core ideas and Yao et al. (2017) report very similar difficulties for the easiest forms, degradation, and conservation items. Herrmann-Abell and DeBoer (2017) provide even more detail on the ordering of the difficulty of specific ideas within the four core ideas, for example, they found ideas about kinetic energy—on average—to be easier than ideas about thermal energy. With this wide variation and overlap in difficulty between different energy ideas one may wonder how the progression from manifestations to conservation was established. The order is established based on the average difficulty of test items that are assigned to one of the four core ideas—in Figure 1, this is represented by the gray boxes around the circles.

Figure 1 also shows lines that connect circles. These lines represent—in an exemplary manner for a hypothetical student—the findings from studies informed by a knowledge integration perspective. In short, the knowledge integration perspective emphasizes that to use knowledge in a domain to make sense of phenomena, students do not only need to hold ideas but also develop connections between ideas (the blue lines) so that they develop well-organized knowledge structures organized around central ideas (Linn, 2006; see also Bransford, 2000). Using this perspective, Lee and Liu (2010) found that higher steps in the learning progressions require higher levels of knowledge integration. This suggests that developing well-organized connections between ideas is a goal for energy instruction. In this context, well-organized is not clearly defined as there are potentially different ways to develop a well-organized knowledge base around energy: Nordine et al. (2011) and Fortus et al. (2019) found that students who are developing well-organized knowledge around the core energy ideas emphasized in the respective instructional approach they studied (energy transformation vs. energy transfer) supported students in making sense of phenomena. Furthermore, Nordine et al. (2011) provide preliminary evidence—in alignment with theoretical models such as coordination class theory (Bransford, 2000; DiSessa & Wagner, 2006; Linn, 2006; National Academies of Sciences, Engineering, and Medicine, 2018)—that suggests that having a (more) integrated knowledge also supports continued learning about energy. More specifically, Nordine et al. (2011) found that students who were in a unit that emphasized knowledge integration learned more about energy in later instruction compared to students in a unit that did not emphasize knowledge integration. However, the analyses that Nordine et al. (2011) present do not directly disentangle the amount of knowledge that students had about energy and the integratedness of that knowledge. Similarly, the studies by Fortus et al. (2015) and Fiedler et al. (2023) found that earlier learning about energy supports continued learning about energy. However, in both cases, it also remains unclear whether this is due to the amount of knowledge that students held about energy, the extent to which their knowledge was integrated, or an interaction of the amount of knowledge and its integration. In sum, being able to use energy ideas to make sense of phenomena requires that students not only learn about certain energy ideas—rather, they also need to connect ideas in alignment with the instructional approach—to develop an integrated knowledge. Furthermore, some preliminary evidence suggests that having (more) integrated knowledge may also support continued learning about energy, although the specifics remain unclear.

While empirical evidence about the extent to which having better-connected ideas about energy, that is, more integrated knowledge, supports continued learning is still preliminary, Nordine et al. (2011) provide compelling evidence that having connections to non-normative ideas (represented by the lines connecting clue circles to red circles in Figure 1) about energy such as associating energy with activity only or thinking of energy as some kind of fuel is detrimental to being able to make sense of phenomena using energy ideas. Non-normative is used as an umbrella term for all ideas about energy that students may hold that reflect some sort of misconception or alternative view of energy, for example, confusing energy with a kind of fuel, associating energy with activity or living things, or confusing energy with force (Lancor, 2015; Watts, 1983). While non-normative ideas can be categorized in different ways, for example, alternative conceptions of energy or misconceptions about the core ideas of energy, it is hard to consider them in an overarching framework as they can also be highly context-specific. In Figure 1, this is reflected by vertical dashed lines that map non-normative ideas to normative ideas on the upper part of the figure and the additional area on the right of the figure with the box "other non-normative ideas." While there is a rich literature that has investigated students' non-normative ideas about energy and strategies to engage them (e.g., Driver & Warrington, 1985; Kesidou & Duit, 1993; Lancor, 2015; Watts, 1983), little is known about how students' non-normative ideas influence students' continued learning over time. Such information would be valuable for guiding instruction, especially in light of contradictory evidence about the long-term impact of non-normative ideas (see also Hammer & Sikorski, 2015; Schwartz & Martin, 2004). While some research suggests that holding non-normative ideas, such as confusing energy with a fuel-like substance, is detrimental to learning about conservation (e.g., Chen et al., 2014) other research suggests that even experts hold non-normative ideas but are able to inhibit them (Brault Foisy et al., 2015; Mason et al., 2019). In consequence, the field's current understanding of the role of non-normative ideas in learning about energy struggles to provide guidance for practice: should non-normative ideas be actively engaged (Vosniadou & Skopeliti, 2019; Wiser & Carey, 2014), is it more productive to think of them as stepping stones (Castro-Faix et al., 2020; Duncan & Rivet, 2018; Roseman et al., 2008), or should instruction focus on students assets (National Academies of Sciences, Engineering, and Medicine, 2018)?

2 | RESEARCH QUESTIONS

Research on students' learning about energy has provided a rich model to describe how students' learning about energy progresses across K–12. As this research either drew on cross-section designs (e.g., Neumann et al., 2013) or on relatively short longitudinal designs across single units (Bächtold, 2018; Fortus et al., 2019; Nordine et al., 2011), important questions about students' long-term progress toward an understanding of energy remain unanswered. It remains unclear to what extent holding non-normative ideas about energy at one point influences long-term continued learning about energy. Furthermore, while research has shown that to make sense of phenomena using energy ideas, students do not only need to hold these ideas but also need to integrate them, it remains unclear to what extent having an integrated understanding promotes continued learning. We address these gaps by asking the following research questions:

Research Question 1. To what extent does holding non-normative ideas about energy at one point influence students' continued learning about energy?

Research Question 2. To what extent does having an integrated knowledge about energy support the continued learning about energy?

3 | METHODS

Both research questions target different aspects of how students continue to learn about energy based on what ideas about energy they hold and to what extent those ideas are integrated. This requires a longitudinal data set that allows us to characterize what ideas about energy students hold—both normative and non-normative—and how those ideas are integrated. As long-term longitudinal data is challenging to collect, I address the research question by reanalyzing an existing dataset spanning 4 years. To characterize what ideas students hold and how they are integrated, I use a combination of traditional Rasch techniques and diagnostic classification models (DCMs).[1] In the following, I will first describe the data set and instrument before diving into the analyses. Limitations arising from addressing our research question by reanalyzing an existing data set are considered in the discussion section.

3.1 | Dataset

The dataset (data and materials can be found here: https://osf.io/t5hva/) is a longitudinal extension of the cross-sectional data set used in Neumann et al. (2013). For all analyses, I focus on the data from $N = 289$ students that completed the Energy Concept Assessment (ECA) (Neumann et al., 2013) once in each grade at the end of the school year from Grades 6 (data collected in 2009) to 9 (data collected in 2012), that is, without missing any of the measurements. Data from students that missed any of the measurements was not considered as the reasons for missing measurements could no longer be reconstructed, making appropriate choices for imputation methods challenging. Furthermore, preliminary analyses show no significant correlation between missingness and available scores, suggesting the absence of selection effects. Data on further background variables (socioeconomic status, ethnicity, grades, etc.) was not collected due to privacy concerns.

Students studied in four different *Gymnasiums* in North Rhine-Westphalia, the most populous state in Germany. The *Gymnasium* is the most academic of the German school tracks, with most students continuing their education to earn a university degree, that is, a relatively homogenous student population. In all schools, instruction followed the state science curriculum of North Rhine-Westphalia.

The state science curriculum emphasizes the idea of organizing instruction around core ideas such as energy (Sekretariat der ständigen Konferenz der Kultusminister der Länder in der Bundesrepublik Deutschland, 2004) to help students build competency over time, similar to the emphasis on developing DCIs over time in the US *Next Generation Science Standards* (NGSS Lead States, 2013). This is implemented in the form of a spiral curriculum that emphasizes energy between grades 5 and 10 and is based on the energy ideas manifestations of energy, transfer and transformations of energy, degradation of energy, and conservation of energy. During three 2-grade periods (5/6, 7/8, 9/10), schools have to cover energy but are free to choose when in the period they cover energy, for example, some schools may cover energy in Grades 5, 7, and 10, and some in 6, 7, and 9. In Grades 5/6, the four ideas are all introduced with an emphasis on transfer, transformations, and degradation while conservation is addressed qualitatively. In Grades 7/8 and 9/10, energy is addressed in numerous different contexts, and in Grades 9/10, quantitative elements come into focus.

What does this curriculum imply for developing integrated knowledge? The curriculum emphasizes that students should develop connections between energy manifestations and energy transformations as transformations describe changes in how energy is manifest in the world, and without an idea of manifestations of energy, transformations of energy are somewhat meaningless. As a next step, students may connect these ideas to the concept of degradation, emphasizing that during energy transformations, part of the energy is degraded. Finally, the ideas of manifestations, transformations, and degradation need to be connected to the idea of conservation, emphasizing that during transformations, the total amount of energy is conserved. Alternatively, students could first connect the ideas of manifestations and transformations to energy conservation and then establish the connection that although energy is conserved during transformation, it is still degraded.

3.2 | Instrument

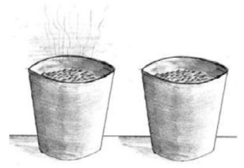
The ECA consists of 120 multiple-choice tasks, each emphasizing one of the four core ideas: manifestations of energy, transfer and transformation of energy, energy degradation, or energy conservation (see Table 1 for details). Note that especially tasks that emphasize higher steps in

TABLE 1 Categories of normative ideas with definitions (adopted from Neumann et al., 2013).

Category	Definition	Example
Manifestation	Students are expected to understand that the amount of energy in a particular manifestation depends on indicators and factors.	*A moving car has kinetic energy because it has a non-zero mass and is moving at a certain speed.*
Transformation	Students are expected to understand that each transformation process includes the reduction of energy in one form and the increase of energy in another form.	*A deflected pendulum has greater potential energy because of its height, that is transformed into kinetic energy when the pendulums is swinging down, resulting in a reduced height, but increased velocity and* vice versa.
Degradation	Students are expected to understand that the degradation of energy means that all processes will stop in the long run if no additional energy is provided to keep them running.	*If the wind stops blowing a wind mill will stop even if no electrical energy is consumed.*
Conservation	Students are expected to understand that whenever it seems that energy is not conserved, energy was transformed into a form that is not considered.	*When a swinging pendulum stops, the energy originally available was transformed into thermal energy.*

Example ECA task.

On a table one glass is filled with cold milk and one glass is filled with hot milk. There is the same amount of milk in each glass.



Which statement about the energy of the cold and hot milk is correct?

a) ☐ The cold and the hot milk possess thermal energy. However, the cold milk possesses less thermal energy than the hot milk.

b) ☐ The cold and the hot milk possess the same amount of thermal energy. However, the hot milk has a higher temperature than the cold milk

c) ☐ Only the hot milk possesses thermal energy. The cold milk does not possess any thermal energy at all.

d) ☐ Neither the hot nor the cold milk possess thermal energy. Only moving things possess energy.

FIGURE 2 Example Energy Concept Assessment task.

the learning progression, such as energy degradation, may also require knowledge about lower steps, such as manifestations of energy and transformations of energy. The tasks draw on numerous real-world contexts, for example, a skateboarder riding in a half-pipe or shooting an arrow. Figure 2 shows an example task emphasizing forms of energy. The distractors were designed to capture non-normative conceptions of energy from the literature. In this way, chosen distractors can provide information about non-normative ideas about energy. Overall, Neumann et al. (2013) report that the instrument works well for the purpose of investigating students' average ability across grades. For more details on the instrument, see Neumann et al. (2013).

To obtain reliable measures from students in different grades, specific booklets with 40 tasks from the ECA item pool were designed for each grade, adjusting the difficulty of the items in accordance with grade level. To allow the comparison of students across grades, a vertical linking method was used throughout, that is, booklets for consecutive grades share 20 tasks. Students were given 45 min to answer the tasks.

3.3 | Analyses

3.3.1 | Research Question 1: Non-normative ideas and continued learning

To answer this research question, I first used DCMs to characterize what profiles of non-normative ideas students held at each of the measurement time points and then investigated how having a certain non-normative idea profile in Grade X is related to students' continued learning about energy in Grade X + 1.

Non-normative idea profiles

To create these profiles, I used DCMs (Rupp & Templin, 2008). DCMs estimate profiles that describe what ideas an individual likely holds based on their answers to a series of tasks and a *Q-Matrix* that describes about what ideas these tasks provide evidence. The following example shows how this principle can be applied to the ECA data to investigate non-normative ideas about energy students hold: If a student answered the task in Figure 2 incorrectly by choosing answer (d), this constitutes a piece of evidence that the student holds the non-normative conception that energy is primarily associated with activity (Lancor, 2015; Watts, 1983). Iterating this principle, formalized in a statistical model, across all the tasks students answered provides profiles of what non-normative ideas students likely hold.

The information that maps the distractors of the items to non-normative ideas is provided in the form of a so-called Q-Matrix. To create this matrix, I initially drew on the information provided by the designers of the ECA (Viering & Neumann, 2012). However, the information the designers provided does not cover every task and resolves students' non-normative ideas on a grain size far too detailed to handle with the available data. Thus, I grouped the non-normative ideas in the ECA into four broad categories based on the literature on students' non-normative ideas about energy (e.g., Watts, 1983) and the supporting information in Viering and Neumann (2012). With *activity* and *fuel*, the non-normative ideas in Table 2 include two of the non-normative ideas for which (Nordine et al., 2011) found detrimental effects on students' ability to make sense of phenomena using energy ideas. Based on the definitions in Table 2, the author and a trained student independently coded all distractors to one of the categories. A first round of coding led to substantial agreement (Cohen's $\kappa = 0.81$) between the two raters, indicating sufficient agreement. Afterward, the remaining conflicting assignments were analyzed and resolved. In the resulting Q-Matrix, 70% of the items load on the "other" category, 10% load on the "Confused with other science idea" category, 10% load on the "fuel" category, and 10% load on the "activity" category.

With the Q-Matrix at hand, non-normative idea profiles were estimated. R (R Development Core Team, 2008) and the CDM package (George et al., 2016) were used to estimate the MC-DINA Model (de la Torre, 2009). The CDM package provides various functions for estimating and diagnosing DCMs. The MC-Dina model is a form of DCM tailored to situations where students have to choose between multiple different options. Unlike traditional assessment models that often classify a student's response as simply right or wrong, the MC-DINA provides more detailed information about students' responses, such as what specific knowledge elements or skills a student may have demonstrated. When students answer the ECA, they are presented with one correct answer and three distractors that are mapped onto non-normative ideas as designated by the Q-Matrix. If students choose the correct answer, the model interprets this as evidence that the students do not hold any of the non-normative ideas that the distractors represent. If students choose a distractor, the model interprets this as evidence that the students hold the respective non-normative idea. While goodness-of-fit measures can, in principle, be calculated for the MC-DINA model, the relatively small sample in this study prohibits a meaningful goodness-of-fit test (de la Torre, 2009).

Relating non-normative idea profiles to continued learning

With non-normative idea profiles for all students and all time points at hand, I investigated how having a certain non-normative idea profile in Grade X is related to students' continued learning about energy in Grade X + 1. As a measure of students' continued learning about energy, I followed Neumann et al. (2013) and scaled the ECA data using the Rasch Model

TABLE 2 Categories of non-normative ideas with definitions and examples.

Category	Definition	Example
Activity	Energy is conceptualized as obvious activity. Includes relating energy to living things.	*In physics, one says the arrow has no energy because the arrow is* ***not a living thing****.* *Neither the hot nor the cold milk possess thermal energy. Only* ***moving things possess energy****.*
Fuel	Energy is conceptualized as some kind of fuel. This includes the idea of energy being used up in processes.	*One can assign gravitational energy to the skater that he* ***got from eating food****.* *The total energy decreases. This is because* ***the kinetic energy of the car gets lost*** *after the car is stopped by the wall.* *Kinetic* ***energy from food is burned up*** *in your muscles. Afterward, pedals and chain transfer kinetic energy to you and your bike.*
Confused with other science idea	Energy is confused with another science idea (force, momentum, friction, etc.) or another science idea is emphasized in the answer.	*The gymnast must jump on the trampoline with emphasis to* ***overcome friction****. After having* ***overcome frictio****n the gymnast can jump more easily. The gymnast does not loose kinetic energy.* *The total energy remains the same. The car's kinetic energy is transformed completely into kinetic energy of the wall. However, since the* ***wall is much more massive than the car, the wall does not move****.*
Other	This category mostly contains distractors that are wrong because forms of energy are confused (potential energy is stated to depend on speed) and any other distractors that did not fit the above categories.	*In physics one would say the arrow has gravitational energy because of the arrow if flying quickly.* *Gravitational energy of the skater is transformed into kinetic energy while the skater is moving up the walls of the half-pipe. This kinetic energy of the skater is transformed when the skater is moving down the walls of the half-pipe.*

(DeMars, 2010). The Rasch model was used to accommodate the design of the test booklets, that is, booklets used at different time points had a portion of shared items but also a portion of changing items in alignment with the curriculum. The model was estimated with all data simultaneously and time in latent regression to calculate weighted likelihood estimates (WLEs) using TAM (Robitzsch et al., 2021). The use of WLEs is sensible because they provide more accurate and individualized estimates of a student's ability level by giving greater weight to items that are more informative for that particular student. This provides a measure of students' energy competence for each measurement point (all following references to students' scores or competence in figures or the text refer to WLE scores). The infit and outfit of all items were in the satisfactory range between 0.86 and 1.22 (Wright et al., 1994) and the WLE person separation reliability was 0.56.

Lacking a strong hypothesis about the relation between students' non-normative ideas and continued learning, I did an exploratory analysis: using the WLE scores, I ran ANOVAs to estimate the effects of all possible profiles of non-normative ideas in Grade X on students' competence as measured by the EAC in the consecutive Grade X + 1. Then, I used post hoc Tukey tests to look for any statistically significant influences on the profiles of non-normative ideas.

3.3.2 | Research Question 2: Integrated knowledge and continued learning

To answer this research question, I generally proceeded similarly to research question one: first, I used DCMs to characterize to what extent students had integrated knowledge at each of the measurement time points and then investigated how having integrated knowledge in Grade X is related to students' continued learning about energy year X + 1.

Integrated knowledge

To assess to what extent students had an integrated knowledge about energy, I first used DCMs to estimate knowledge profiles and then classified these knowledge profiles as either reflecting integrated knowledge or not. The following example shows how the ECA items can provide evidence about the normative energy ideas that students and the ideas that students connect. If a student answered the task in Figure 2 correctly by choosing answer (a), this constitutes a piece of evidence that the student holds ideas about manifestations of energy. Furthermore, if a student answered the task in Figure 3 correctly by choosing answer (a), this constitutes a piece of

Example ECA task.

You pick up a stone and let it fall.

How could you describe the stone as it moves using the term energy?

a) ☐ Before the stone is let go, it possesses gravitational energy. When the stone is moving downward its gravitational energy is transformed into kinetic energy.

b) ☐ Before the stone is let go it possesses no energy. After the stone is let go it possesses kinetic energy.

c) ☐ Before the stone is let go it possesses kinetic energy. When the stone is moving its kinetic energy is transformed into speed.

d) ☐ Before the stone is let go it possesses kinetic energy. When the stone is falling down its kinetic energy is transformed into gravitational energy.

FIGURE 3 Example Energy Concept Assessment task.

evidence that the students used ideas about the manifestation of energy and transformation of energy together. This can be interpreted as evidence of having connections between these ideas in the sense of integrated knowledge (Fortus et al., 2019; Gombert et al., 2023; Kubsch et al., 2019). Iterating this idea across all tasks, students answered, formalized in a statistical model, provides profiles of students' normative ideas that also reflect connections between ideas.

Again, the information that maps the different normative ideas to the items needed to be encoded in a Q-Matrix. To create the Q-Matrix, I used the ECA technical handbook (Neumann et al., 2013). Next, I estimated what profiles of normative ideas students most likely hold, given their answers to the ECA. I used R (R Development Core Team, 2008) and the CDM Package (George et al., 2016) and ran a DINA (Deterministic Input Noisy "And" Gate) model (Haertel, 1989). The important property of the DINA model is that it is not compensatory, that is, students cannot compensate for the lack of one idea needed to answer a task with another idea. This reflects the assumption that answering an item that maps onto more than one idea can provide evidence that students connect these ideas. As criteria for model fit, I drew on the item pairwise χ^2 by Chen et al. (2013) and the standardized root mean square residual (SRMSR) (Maydeu-Olivares, 2013). While the p value of the maximal item pairwise χ^2 ($\max(\chi^2)$) <0.01 indicates questionable model fit, the SRMSR of 0.014 indicates at least satisfactory model fit (Maydeu-Olivares, 2013; see also George & Robitzsch, 2015).

The last step in assessing the integratedness of students' knowledge was to categorize the profiles of normative ideas as reflecting integration—in the sense of being well-organized—or not. Table 3 shows which of the possible energy idea profiles can be considered as integrated: Profile 2 having ideas about manifestations and transfer/transformation, Profile 3 having ideas about manifestations, transfer/transformation, and degradation, Profile 4 having ideas about manifestations, transfer/transformation, and conservation, and Profile 5 having ideas

TABLE 3 Profiles of energy ideas and integratedness.

	Energy ideas					
Profile	Manifestations	Transformation	Degradation	Conservation	Integrated	No. of items
1	×					31
2	×	×			×	20
3	×	×	×		×	19
4	×	×		×	×	2
5	×	×	×	×	×	8
6	×		×			6
7	×			×		11
8		×				4
9			×	×		1
10				×		3
11				×		3
12			×			1
13		×				4

Note: × indicates that an idea is present.

about manifestations, transfer/transformation, and degradation, and conservation. These four profiles reflect the inner logic of the energy concept from a physics perspective (Coopersmith, 2015), making them well-organized. Furthermore, these profiles align with the connections that students are supposed to make between energy ideas as intended by the curriculum (see Section 3.1). Overall, items were distributed across the booklets and measurement time points so that students could realistically fall into all possible profiles denoted in Figure 3.

Relating integrated knowledge to continued learning

Having characterized students' knowledge about energy as integrated or not, I now investigated the effect of having integrated knowledge in Grade X was related to students' continued learning about energy in Grade X + 1. As a measure of students' continued learning about energy, I used the same WLEs scores reflecting students energy competence as in the analysis for Research Question 1. Now, I used a series of linear models to estimate the effect of having an integrated on students' competence as measured by the EAC in the consecutive Grade X + 1 while adjusting for students' competence in Grade X. To use the full potential of the 4-year longitudinal data, I also used linear models to investigate how students who had an integrated profile throughout all 4 years compared to students who had an unintegrated profile at least once with respect to their continued learning about energy.

4 | RESULTS

4.1 | Research Question 1: Non-normative ideas and continued learning

Before examining how non-normative idea profiles are related to students' continued learning about energy, I present what profiles of non-normative ideas were found and how they developed over time. Figure 4 shows students' profiles of non-normative idea shifts across Grades 6–9. Across all grades, the majority of students hold multiple non-normative ideas, although the proportion of students that hold multiple non-normative ideas decreases from 87% ($N = 247$) in Grade 6 to 53% ($N = 150$) in Grade 9. Furthermore, the number of students who do not hold any non-normative ideas increases from 3% ($N = 9$) in Grade 6 to 21% ($N = 60$) in Grade 9. The remaining groups of students who hold single non-normative ideas (activity, fuel, confused with other science ideas, and others) all start with similar sizes in Grade 6. Across the remaining grades, students who confuse energy with other science ideas remain the largest group, which is also relatively stable in size. At the same time, the number of students who relate energy with activity increases slightly but consistently, while the number of students whose single non-normative idea falls in the "Other" category decreases in the same way. In contrast, the number of students that consider energy as some kind of fuel is relatively small and stable across Grades 6–8 and then quadruples in the transition from Grade 8 to 9. This may potentially be explained by the nature of contexts in which energy is explored in Grade 8.

Across all grades, complex trajectories can be observed. Students may hold no non-normative ideas at one point but later develop non-normative ideas or students may oscillate between ideas, that is, they hold a certain non-normative idea at one point, hold another at the next point, and go back to the first one. Furthermore, the number of students that transition from multiple non-normative ideas to no non-normative ideas is always larger than the number of students that transition from single non-normative ideas to no non-normative ideas.

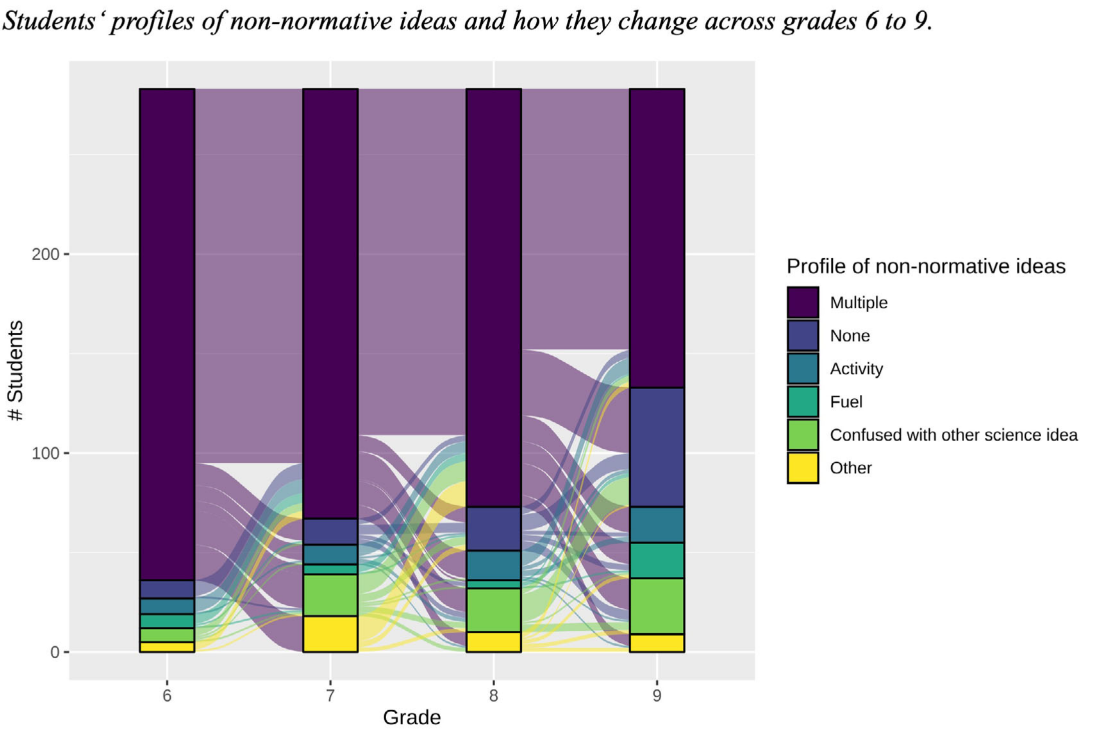


FIGURE 4 Students' profiles of non-normative ideas and how they change across Grades 6–9.

The results of the exploratory ANOVAs show a statistically significant relation between the profile of non-normative ideas in Grade X and ECA score on Grade X + 1 for Grades 7 $F_{15,276} = 2.144$, $p < 0.01$ and 8 $F_{15,276} = 1.748$, $p < 0.05$ but not for Grade 6 $F_{15,276} = 1.172$, $p > 0.05$. However, post hoc comparisons between the different profiles of non-normative ideas were all statistically nonsignificant for all grade levels. Online Supporting Information S1 provides descriptive plots of the differences between the profiles of non-normative ideas.

In sum, the results show complex trajectories of transitions between holding no, one, or even multiple non-normative ideas. However, no detrimental relationship between holding one or more non-normative ideas and the continued learning about energy was found.

4.2 | Research Question 2: Integrated knowledge and continued learning

Figure 5 shows how the integratedness of students' normative idea profiles changes across Grades 6–9. Over time, the number of students' whose profiles of ideas are integrated increases from 16% ($N = 46$) in Grade 6 through 21% ($N = 63$) and 27% ($N = 81$) in Grades 7 and 8, respectively, to 40% ($N = 115$) in Grade 9. Furthermore, some students (5% ($N = 16$)) have integrated profiles across all time points, whereas other students transition from integrated profiles to unintegrated profiles and then back to integrated profiles that encompass more ideas than before, that is, students transition to profiles that reflect more integration through intermediate stages of less organization.

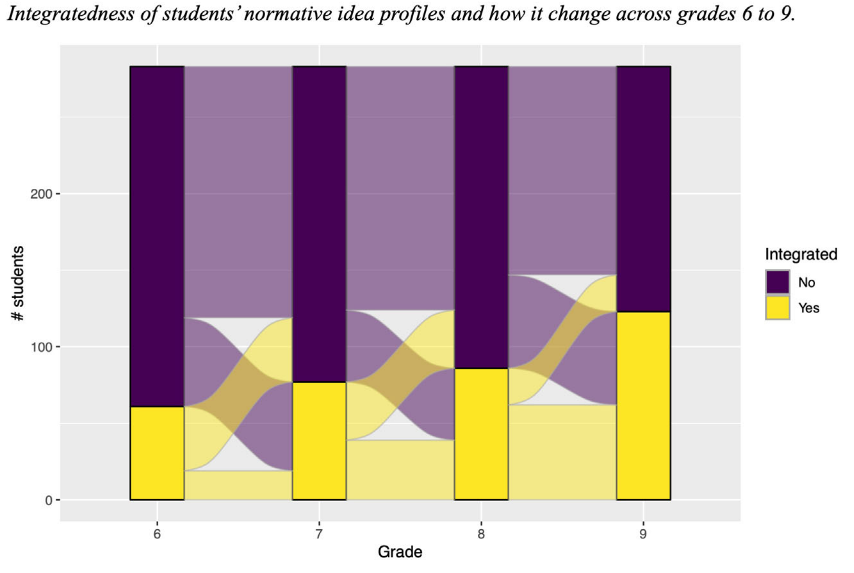


FIGURE 5 Integratedness of students' normative idea profiles and how it change across Grades 6–9.

TABLE 4 Linear models predicting students' ECA score in Grades 7–9 based on their ECA score and integratedness of their profile of ideas in the previous grade.

Predictor \ Outcome	Score in Grade 7			Score in Grade 8			Score in Grade 9		
	β	SE	*p* Value	β	SE	*p* Value	β	SE	*p* Value
Integrated profile of ideas[a]	0.38	0.17	0.0279	0.66	0.16	<0.001	0.38	0.14	<0.01
Prior ECA Score	0.11	0.06	0.10	0.19	0.07	<0.01	0.47	0.06	<0.001
R^2	0.04			0.17			0.36		

Note: Score and integratedness of students' profile of ideas were measured in the respective previous grade.
[a]Dichotomously coded (0 = no, 1 = yes).

In Table 4, the results of three linear models are presented where the outcome was students' ECA score in Grade X + 1 and the predictors were students' ECA score in Grade X and the integratedness of their normative ideas profile. The large, positive, and statistically significant coefficients of the "integrated" variable show that having integrated knowledge supports the continued learning about energy above and beyond the amount of knowledge one has.

A comparison of the models with their respective baseline versions that do only predict the score in 1 year based on the score in the previous year is shown in Table 5.

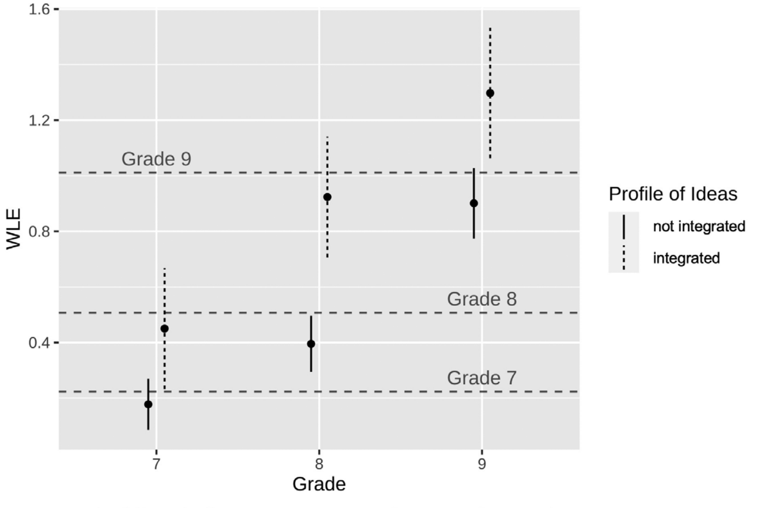
It indicates that whether students' profile of ideas are integrated or not accounts for an additional, statistically significant portion of variance. Figure 6 depicts how the effect of having a profile of normative ideas about the energy that is integrated plays out for an average-scoring student across the grades. While the mean ECA score increases from Grades 7 to 9 irrespective of the integratedness of students' profile of ideas, the mean ECA score of students that have integrated profiles of ideas is statistically significantly higher (about half a standard deviation

TABLE 5 Comparison of nested linear models predicting students ECA score in Grades 7–9 based on their ECA score and integratedness of profile of ideas in the previous grade.

Model	R^2	F-test	AIC
Score Grade 7 ~ score Grade 6	0.03	$F_{1,288} = 4.88$, $p < 0.05$	822.55
Score Grade 7 ~ score Grade 6 + ideas Grade 6[a]	0.04		822.22
Score Grade 8 ~ score Grade 7	0.12	$F_{1,288} = 16.76$, $p < 0.01$	794.48
Score Grade 8 ~ score Grade 7 + ideas Grade 7[a]	0.17		780.02
Score Grade 9 ~ score Grade 8	0.34	$F_{1,288} = 6.94$, $p < 0.01$	711.56
Score Grade 9 ~ score Grade 8 + ideas grade 8[a]	0.36		706.63

[a]Codes whether profile of ideas in respective grade is integrated, dichotomously coded (0 = no, 1 = yes).

Means and 95% confidence intervals of students ECA scores in grades 7 to 9 marginalized over the average ECA score in the respective previous grade and integratedness of their profile of ideas.



Note. Dashed lines indicate average score in respective grade.

FIGURE 6 Means and 95% confidence intervals of students Energy Concept Assessment (ECA) scores in Grades 7–9 marginalized over the average ECA score in the respective previous grade and integratedness of their profile of ideas.

on the scale of the test) in Grades 8 and 9 than the mean ECA score of students whose profile of ideas is not integrated.

Finally, Table 6 shows the results of two linear models with students' EAC score at the end of grade nine as the dependent variable. Both models show increasingly large and statistically significant effects of time. Furthermore, the large and statistically significant predictor “integrated throughout” in Model 2 shows that students who have integrated profiles of ideas through Grades 6–9 learn substantially more than students who do not have integrated profiles at least once. Finally, Model 2 explains statistically significant more variance than Model 1.

TABLE 6 Linear models predicting students learning at the end of Grade 9.

	Model 1		Model 2	
Variable	β	p Value	β	p Value
Time 1	0.05	0.31	0.01	0.82
Time 2	0.22	<0.001	0.18	<0.001
Time 3	0.55	<0.001	0.47	<0.001
Time 4	1.02	<0.001	0.97	<0.001
Integrated throughout[a]	–		1.12	<0.001
R^2	0.32		0.37	
ΔR^2	0.05[b]			

[a]Dichotomously coded (0 = no, 1 = yes).
[b]$F_{1,1150} = 74.53$, $p < 0.001$.

In sum, the results indicate that having an integrated knowledge about energy, that is, well-organized knowledge, supports the continued learning about energy above and beyond the amount of knowledge that students hold.

5 | DISCUSSION

In this study, I investigated students' continued learning about energy as a function of their knowledge profiles, focusing on the role of non-normative ideas and knowledge integration. Regarding students' non-normative ideas, I found enormous variation and—somewhat surprisingly—no effects on students' learning. Regarding the integratedness of students' knowledge, I found that having an integrated knowledge supports students' continued learning about energy. In the following, I will discuss these results in more detail.

5.1 | Research Question 1: Non-normative ideas and continued learning

Generally, the results align with findings from the energy misconceptions literature (e.g., Watts, 1983) and newer research into the metaphors that students use in the context of energy (Lancor, 2015) but extend them as they provide a longitudinal perspective and relate non-normative ideas to the continued learning about energy.

Trajectories that transition between stages of having non-normative ideas and having no non-normative ideas underline research from cognitive science that indicates that certain non-normative ideas may only be inhibited (Brault Foisy et al., 2015; Masson & Brault Foisy, 2014; Masson et al., 2014), that is, instruction does not "replace" these ideas with more normative counterparts but rather favors the activation of normative ideas. In consequence, non-normative ideas may resurface in new contexts, as the students that transition from no non-normative ideas in Grade 8 to a fuel conception of energy in Grade 9 indicate. Overall, I was surprised by the results as having non-normative ideas is typically considered detrimental to learning, both in the teaching and learning of energy (e.g., Nordine et al., 2011; Watts, 1983) and generally (Masson & Brault Foisy, 2014; Vosniadou & Skopeliti, 2019). While one could argue that some non-normative ideas can serve as stepping stones and thus still be productive (e.g., Castro-Faix et al., 2020; Roseman et al., 2008), the non-normative ideas considered in this study do not fall into this category in contrast to, for example, the non-normative idea that energy has substance-like properties (Brewe, 2011; Kubsch et al., 2021; Reiner et al., 2000; Swackhamer, 2005). More specifically, Nordine et al. (2011) found a substantial negative correlation between fuel conception and students' knowledge about energy where no such effect was observed in this study. In conclusion, does this mean that the role of non-normative ideas in hindering learning about energy has been overestimated in the past? I warrant over-interpretation of this result as the analysis of students' non-normative ideas suffers from some methodological limitations. A consequence of reanalyzing an existing data set is that the instrument was not designed to be analyzed with DCMs and the goal of estimating profiles of non-normative ideas. In consequence, these findings can be considered as calling for more research that examines how non-normative ideas influence continued learning. In this future work, students' non-normative ideas should be assessed on a finer grain size to better distinguish different non-normative ideas and with a higher temporal resolution. A higher temporal resolution would allow us to better understand when and how students' non-normative ideas change as a function of instruction.

Due to the dataset used, there is another limitation to the current study: normative and non-normative ideas were analyzed in septate models. For future work it would be interesting to analyze these ideas together as this could help to answer questions regarding the co-development of normative and non-normative ideas, for example, what non-normative ideas actually can function as stepping stones and which not.

5.2 | Research Question 2: Integrated knowledge and continued learning

The findings show that having an integrated knowledge supports the continued learning about energy. This results add further weight to preliminary evidence from previous studies by Nordine et al. (2011) and Fortus et al. (2015) that suggested that students' knowledge about energy at one time supported their continued learning but struggled to disentangle whether this effect was primarily due to the amount of knowledge, the structure of this knowledge, or a combination of both. This study clearly demonstrates that beyond the amount of knowledge (as measured by the ECA score), the structure of students' knowledge—its integratedness—supports the continued learning about energy. Furthermore, these findings support theoretical perspectives such as coordination class theory that suggest that having integrated knowledge can support continued learning (DiSessa & Wagner, 2006). A limitation of this finding is that evidence for the integratedness of students' knowledge hinges on the theoretical argument that ideas that are used together can be considered connected. While valid evidence for this argument exists (Fortus et al., 2019; Gombert et al., 2023; Kubsch et al., 2019), future research would profit from additional data sources—qualitative or quantitative—to triangulate claims about the integratedness of students' knowledge with more diverse evidence.

5.3 | Implications for teaching about energy

What implications do these results have for the classroom? It is hard to make any clear-cut recommendations regarding non-normative ideas as it is not clear what moderating role instruction played for students' continued learning. However, the findings show that in regular classrooms and without specific interventions, having non-normative ideas at one point had no detrimental effects on the continued learning about energy. In consequence, when non-normative ideas show up in the classrooms, teachers and students should have some confidence that they have the means to productively continue to learn. Regarding the role of integrated knowledge, the results are clearer, as having integrated knowledge was related to more productive continued learning. Thus, teachers may be encouraged to use instructional materials and strategies that support knowledge integration by emphasizing core ideas and generally coherent instruction (e.g., Reiser et al., 2021).

6 | CONCLUSION

This study offers significant insights into students' continued learning about energy, particularly in relation to their non-normative ideas and the integration of their knowledge. Notably, the presence of non-normative ideas did not impede students' learning about energy, a finding that contrasts with previous research. This raises questions about the historical understanding of the role of non-normative ideas in obstructing learning about energy. Nonetheless, caution is advised in interpreting these findings due to methodological limitations, emphasizing the need for further research. On the other hand, the benefits of integrated knowledge are clear: it plays a pivotal role in supporting the continued learning about energy. This underscores the importance of instructional strategies that foster knowledge integration, highlighting the significance of coherent instruction and core ideas.

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ENDNOTE

[1] Diagnostic classification models (DCMs) and cognitive diagnostic models (CDMs) are essentially different terms that refer to the same conceptual framework in educational assessment. Both DCMs and CDMs focus on providing detailed insights into students' cognitive strengths and weaknesses by analyzing their responses to test items. These models go beyond traditional scoring methods by identifying specific knowledge components or skills that students have mastered or need improvement in. In essence, whether termed as DCMs or CDMs, these models share the common goal of offering a more nuanced understanding of student learning for targeted instructional strategies.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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