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Telling the energy story: Design and results of a new curriculum for energy in upper elementary school

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Abstract

We describe the development, design, implementation, and preliminary classroom results of an innovative curriculum, *Focus on Energy*, that supports learning about energy in Grades 4–5. The curriculum is grounded in the concepts of science as practice, model-based reasoning, and learning progressions, and builds on students' pre-existing ideas and resources. We illustrate how students gradually develop the ability to track energy forms, transfers, and transformations in increasingly complex scenarios. We present evidence, using a quasi-experimental design, that students who completed the curriculum were significantly more adept at these skills than students in comparable classrooms who experienced their districts' existing energy-related physical science curricula. Important features of the curriculum include: the careful selection of a limited set of concepts chosen to provide a sound foundation for future learning; a consistent conceptual framework (the Energy Tracking Lens) within which the students have agency to build and refine a model of energy; engaging hands-on activities that steadily build in complexity; accessible and versatile semi-quantitative representations that support reasoning and communication; individual, small-group and large-group meaning-making; and training and support for the teachers.

KEYWORDS
curriculum development, energy, model-based reasoning, physics, upper elementary

1 | INTRODUCTION

Energy is a central concept in all fields of science and engineering, and a sound basic understanding is essential for informed citizenship. Energy is thus widely acknowledged as a vital topic for K-12 science education (Duit, 2014; Jin & Anderson, 2012; National Research Council, 2012). It is mentioned more than 300 times in the Next Generation Science Standards (NGSS), including in standards for the elementary grades (NGSS Lead States, 2013). Yet existing instructional approaches largely fail to bring students to the kind of integrated understanding that they need to apply energy ideas meaningfully in either scientific or practical contexts (Driver & Warrington, 1985; Duit, 2014; Herrmann-Abell & DeBoer, 2017; Liu & McKeough, 2005; Neumann et al., 2013).

An extensive literature documents the problem, cataloging the inadequacies of students' understandings, critiquing existing curricular approaches, and suggesting alternatives (Brook & Wells, 1988; Hecht, 2019; Millar, 2005; Solomon, 1985, 1992; J. W. Warren, 1983; Watts, 1983). The *K-12 Framework for Science Education* (National Research Council, 2012) presents an ambitious new vision for science education. It promotes science learning as a developmental progression "so that students continually build on and revise their knowledge and abilities over multiple years" (p. 2), beginning in elementary school. The science standards (NGSS Lead States, 2013), reflecting this vision, require a basic conceptual understanding of how energy behaves, including energy transfer, by the end of elementary school. This requirement poses a significant instructional challenge. Energy is abstract; we are asking young children to reason about something they cannot see, touch, or even measure directly. Furthermore, energy reasoning is fundamentally a matter of accounting for gains and losses, so children with limited mathematical skills need appropriate tools for representing and tracking amounts. There is little empirical literature, particularly for the elementary grades, exploring how children's ability to reason about energy could develop more productively, or what kind of curriculum can effectively support them in developing that ability.

Given these challenges, it is fair to question whether energy should be taught in the elementary grades at all. The utility of a scientific concept of energy, how to describe it, and how to use it, are far from obvious, as evidenced by the hundreds of years that elapsed from Newton's elucidation of the concepts of force and momentum to the emergence of a clear understanding of energy (Elkana, 1974). Further, there is no accepted definition of energy that is both scientifically accurate and pedagogically useful, particularly for young children (Bächtold, 2018). The content of the standards, however, dictates that it will be taught. Moreover, even young children know and use the word "energy," and attach meaning to it in ways that are loosely aligned with the scientific concept—for example, third-graders often associate energy with certain forms of motion, and with batteries (Lacy et al., 2014). There is therefore reason to investigate whether and how meaningful learning about the scientific concept of energy might take place in these early grades. This study shows that such learning can occur and presents a model for how it can be fostered.

We describe here the development, design, implementation, and preliminary classroom results of an innovative curriculum, *Focus on Energy* (TERC, 2017), aimed at students in Grades 4–5. We show that students develop the ability to track energy forms, transfers, and transformations in increasingly complex scenarios, and we present evidence that students who completed the curriculum were significantly more adept at these skills than comparable students who experienced standard curricula. We address the following research question:

- To what extent, and in what ways, did elementary-grade students completing the *Focus on Energy* curriculum gain skills in identifying, tracking, representing, and reasoning about forms and flows of energy?

We are also interested in exploring what aspects of the *Focus on Energy* curriculum seem to foster those gains. Since we have not compared versions of the curriculum incorporating or omitting different features, we cannot make conclusive causal statements about which aspects are more or less helpful. We will, however, highlight the aspects that seem to us to be important, based on our observations and reports from participating teachers.

2 | THEORETICAL FRAMEWORKS

Our approach to teaching and learning about energy in the upper elementary grades draws on research relating to three key conceptual strands: (1) Learning progressions for energy; (2) Science as practice; and (3) Modeling-based teaching and learning.

The theory of learning progressions (Alonzo & Elby, 2019; Corcoran et al., 2009; Herrmann-Abell & DeBoer, 2017; Jin & Anderson, 2012; Jin et al., 2019; Lacy et al., 2014; Neumann et al., 2013; Nordine et al., 2011; National Research Council, 2007; Schwarz et al., 2009; Yao et al., 2017) posits that the learning of complex scientific ideas, such as energy, occurs in stages and often over periods of years. In a previous publication, we have outlined a vision for an elementary-level energy learning progression, grounded in both theoretical considerations and empirical research on children's ideas about energy (Lacy et al., 2014). Researchers in energy teaching and learning have typically identified four key conceptual themes that must be mastered for an adequate understanding of energy as a scientific concept: Forms, Transfers and Transformations, Dissipation and Degradation, and Conservation. (There is some debate surrounding the concepts of forms and transformations, which we discuss below.) These ideas, however, are interdependent and cannot be learned sequentially or in isolation (Duit, 2014; Goldring & Osborne, 1994; Herrmann-Abell & DeBoer, 2017; Lacy et al., 2014; Neumann et al., 2013; Papadouris & Constantinou, 2016; Yao et al., 2017). In particular, students are unlikely to understand the principle of energy conservation—certainly the most important aspect of the energy concept—without an understanding of dissipation, which in turn cannot be understood without a clear conception of forms, transfers, and transformations, and at least a tentative belief in conservation itself. Further, using the energy concept to trace energy flow in real systems, which usually involve multiple components and energy forms, and are almost always dissipative, requires that these four themes be integrated into a coherent model of how energy behaves, and how it is related to observable aspects of the phenomena (Jin & Anderson, 2012; Lee & Liu, 2010; Nordine et al., 2011).

Learning progressions for energy, therefore, do not move sequentially from one theme to the next but rather start from students' pre-existing ideas—such as that batteries have energy, and a willingness to accept that moving objects have energy (Lacy et al., 2014)—and systematically develop their understanding of all the themes together, accompanied by a growing ability to integrate and apply them successfully to phenomena of increasing complexity (Jin & Anderson, 2012; Lacy et al., 2014; Neumann et al., 2013; Nordine et al., 2011). This approach is embodied in the sequence of investigations in *Focus on Energy*. We introduce, at an age-appropriate level, elements of all four themes and focus not just on identifying specific forms and processes but on tracking energy flow in phenomena of increasing complexity. As Papadouris and Constaninou (2016) argue, from a study with slightly older students, such an approach can lead to "coherent qualitative understandings [that] can serve as a robust foundation for subsequent refinements as well as for constructing meaningful quantitative accounts." (p. 140)

The concept of science as practice (Lehrer & Schauble, 2006b; NGSS Lead States, 2013; National Research Council, 2007, 2012; Stroupe, 2014), emphasizes that the teaching and learning of science content should be integrated with a developing understanding and experience in science practices, leading to an understanding of science as a way of knowing rather than a fixed body of facts. Beyond students' engagement in specific practices, however, this vision also involves students acting as epistemic agents "who take, or are granted, responsibility for shaping the knowledge and practice of a community" (Stroupe, 2014). The *Focus on Energy* curriculum is designed to guide students through a sequence of investigations to collectively build, revise, and learn to use a working model of energy.

Our work builds on research about modeling-based teaching and learning (Acher et al., 2007; Etkina et al., 2006; Forbes et al., 2015; Gilbert & Justi, 2016; Hestenes, 1987; Lehrer & Schauble, 2006a; Louca & Zacharia, 2012; Manz, 2012; Passmore et al., 2009; Schwarz & White, 2005; Schwarz et al., 2009; Ward, 2016; Windschitl et al., 2008). While "developing and using models," is listed as just one of the eight Science and Engineering Practices in the NGSS (NGSS Lead States, 2013), it is arguably of both special importance and of special difficulty. Since the ultimate goal of science is to explain natural phenomena using valid and reliable evidence and reasoning, the practices of developing and using models, constructing explanations, and engaging in argument from evidence have been identified as the culmination of the practice of science, with all other science practices serving as supports (Pasley et al., 2016). And since the construction of explanations generally depends on the development and use of models, the practice of model-based reasoning is particularly crucial (Gilbert & Justi, 2016; Lehrer & Schauble, 2006a; National Research Council, 2007; Pasley et al., 2016; Passmore et al., 2009; Texley, 2014; Windschitl et al., 2008). Yet modeling practices tend to be underemphasized in school science, particularly in the elementary grades (Forbes et al., 2015; National Research Council, 2007; Schwarz et al., 2009; Windschitl et al., 2008).

The inherently abstract nature of energy means that tracking energy flow in all but the simplest systems requires both reasoning from observable evidence and arguing by inference from a model of energy (Tobin et al., 2018). For example, we cannot see directly that a battery contains energy. But when we connect it to a bulb and the bulb lights up, we can infer that the battery must have had energy to transfer it to the light bulb—if we have a model that requires that a gain of energy in one place must be accompanied by a loss somewhere else. The *Focus on Energy* approach seamlessly weaves the investigation of specific, concrete phenomena with their interpretation in terms of an evolving, student-generated, model of energy. As we have argued elsewhere (Tobin et al., 2018), the study of energy requires model-based reasoning, and, at the same time, provides a powerful context in which to build students' facility in the essential scientific practice of creating and using models, even in relatively early grades.

3 | DESIGN OF THE CURRICULUM

The *Focus on Energy* instructional program, based on our previously proposed learning progression (Lacy et al., 2014), includes newly developed hands-on investigations and curricular materials supported by a teacher professional development (PD) program, teacher support materials, and formative and summative assessment tools. It was developed, through an iterative process of Design Research (Collins et al., 2004) by a project team that included research physicists, education researchers, former elementary school science teachers, and experts in curriculum design and teacher training, most with experience in teaching energy concepts. Our strategy is to use a carefully scaffolded set of activities and questions to guide the students toward the beginnings of a scientific model of energy, starting from their productive prior ideas. In the process, they begin to experience how to explore and understand energy flow in a broad range of phenomena. The approach is "top-down," in the sense that the activities, tasks, prompts, representational tools, and learning goals are predetermined, based on the standards and decisions of the design team. But it is also "bottom-up," in that the students themselves, starting from their own ideas and observations, develop and refine a general working model of energy and, within that general model, create and refine models of the energy flow in increasingly complex scenarios. Beginning with students' intuitive idea that objects in motion have energy (Lacy et al., 2014), they "bootstrap" ideas of transfer, transformation, and the existence of other forms of energy through their ability to transform into known forms.

The curriculum provides ongoing opportunities for students to link their pre-existing experiences, language, and ideas to their classroom work. In the first class session, students share ideas about what the word "energy" means to them, watch a short video montage (available as Supp_video.mov in the Supporting Information accompanying the online article) that includes 12 real-world scenarios—a teapot boiling, a child riding a bicycle, a plant—where energy may be present in various forms. They share their ideas about which ones represent energy, and what they notice that suggests the presence of energy. They return to these scenarios and other everyday situations throughout the curriculum as they learn to reason with energy ideas and representations. After investigating "When a ball causes another ball to move, does it always lose some of its own energy?", students consider the question, "Can you think of an example from your everyday life where there's a loss of energy somewhere and a gain of energy somewhere else?" When they investigate "Can a paint paddle gain energy?", students look for elastic objects and evidence of elastic energy in their surroundings. Investigations about energy in electrical phenomena begin with an elicitation of student ideas about the flow of energy in the context of a familiar electric fan. Students reason about energy in these contexts independently in their student notebooks, collaboratively in small groups, and in all-class discussions.

Classroom activities, along with related materials, such as student notebooks and formative assessments, were tested and refined through three cycles of summer workshops and classroom implementations for three separate groups of teachers. In each cycle, we collected data from direct observation, student notebooks and other written work, and from reports from teachers in professional learning community (PLC) meetings. Based on that feedback, we adjusted the activities and materials. In the first year of classroom testing, project staff regularly visited the classrooms and actively assisted and advised the teachers. In the second year, staff visits were less frequent and less active. Finally, in the third year, the third group of teachers taught the curriculum without intervention from project team members (except for occasional observations by the external evaluator, described below). The student results presented are from that final year of implementation.

3.1 | Learning targets—What to include and what to leave out

Initially, the project team selected concepts to be learning targets for students (Table 1) as well as concepts that would be deferred for later grades. We also identified teacher targets, to be addressed either in the PD workshop or with online resources, that would provide teachers with necessary background and prepare them for possible student questions.

Since the research literature on energy instruction in the elementary grades is limited, our initial choices were based on our collective knowledge and experience as well as consideration of the Framework for K-12 Science Education (National Research Council, 2012) and published proposals for energy learning progressions (Jin & Anderson, 2012; Lacy et al., 2014; Neumann et al., 2013; Nordine et al., 2011). We identified targets for the general, interdependent ideas of forms, transfer, transformation and flow, and then context-specific targets in the areas of motion energy, elastic energy, thermal energy, and energy in electrical phenomena. Our goal was that students would become adept at using these energy ideas to describe and explain increasingly complex real-world scenarios, rather than learning disconnected energy facts or vocabulary.

We agreed that conservation of energy as a fixed principle was *not* a learning goal at this grade level and would not be explicitly taught. Research suggests that it can be ineffective to teach children to recite the mantra that "energy is neither created nor destroyed" before they have enough experience in tracking energy to give the idea meaning (Driver & Warrington, 1985; Liu & McKeough, 2005; Solomon, 1992; Tobin et al., 2019). In *Focus on Energy*, students use representations that implicitly incorporate energy conservation, with the goal that by the end of the curriculum they will be comfortable with that idea, be able to give it meaning, and find it at least plausible. Other important ideas that were not included in the learning targets for students include gravitational potential energy; energy degradation (Second Law of Thermodynamics); the dependence of motion (kinetic) energy on mass; and the distinction between thermal energy and temperature.

Some have argued that the ideas of forms and energy transformation should be avoided (Ellse, 1988; Falk et al., 1983; Millar, 2005; National Research Council, 2012; Quinn, 2014), and there is empirical evidence that both approaches using forms (Nordine et al., 2011; Papadouris & Constantinou, 2016) and a "transfer-only" approach (Fortus et al., 2019; Kubsch et al., 2021; Nordine et al., 2018) can be successful at the middle school level. A

TABLE 1 Examples of student learning targets addressed within the curriculum

Nature of Energy	Energy is associated with objects, including inanimate objects, but is not an object. Energy cannot be directly observed, but can be inferred from observable indicators. Energy can take different forms. Energy can transfer between objects and/or change form.
Conservation of Energy	Correlation of gains and losses. Implicit idea of conservation through energy cubes.
Motion Energy (*ME*)	All moving objects have ME. Speed is an indicator of presence and amount of ME. ME can be transferred through interactions like pushes, pulls, and collisions.
Potential Energy (*PE*)	Elastic objects and elastic energy. Deformation is an indicator of presence and amount of elastic energy. Elastic energy can be transformed into ME, and vice versa, through pushes, pulls, etc. An object can have both ME and elastic energy at the same time.
Thermal Energy (*TE*)	Temperature is an indicator of presence and amount of TE. TE can be transferred between objects via contact. TE flows from higher temperature to lower temperature objects.
Electrical Energy	Batteries have electrical energy. There is no easily perceptible indicator for electrical energy. The presence of electrical energy can be inferred by its transformation into another form (e.g., ME or TE). Electrical energy can be transferred through wires. Motors transform electrical energy into ME. Generators transform ME into electrical energy. Electrical energy can be stored in a capacitor for later use.
Dissipation and Degradation	ME can be transformed into TE through rubbing and deformation. When a moving object slides or rolls, some of the ME is transformed into TE of the object and the surface. Some of the thermal energy of a warm object is transferred to the environment. Small amounts of TE added to the environment may not cause a detectable temperature change.

challenge to the transfer-only approach in the early grades, however, is that abstract, non-localized fields, and a particle model of matter, must be invoked to account for the energy associated with such phenomena as elastic deformations, thermal phenomena, chemical reactions, and changes of height in the presence of gravity.

Rather than abandoning "forms" and "transformations" entirely, we chose to construct activities that emphasize the underlying unity of these apparently disparate manifestations (Lacy et al., 2014). In our approach, the naming of forms is never an end in itself; it is always in the service of "telling the energy story"—tracking the flow of energy in a system during some process and associating that flow with observable, or inferable, changes in the system (Lehavi & Eylon, 2018; Nordine et al., 2018). We share the view of Papadouris and Constantinou (2016) that this is "an epistemologically and conceptually coherent framework that renders energy accessible to students at a fairly early stage." (p. 140)

We made a conscious decision not to use the terms "kinetic energy" and, especially, "potential energy." The latter is particularly misleading, as it is often understood to mean "having the capacity to acquire energy," rather than denoting a form of energy associated with the configuration of an object or system (Cooper & Klymkowsky, 2013; Lindsey et al., 2012). To introduce forms of energy that a physicist would term "potential," we introduce elastic energy (of a bent piece of wood and a twisted rubber band) and electrostatic energy stored in a capacitor—contexts in which the energy can be meaningfully associated with an individual object.

We also confined the investigations to physical science cases in which *energy* undergoes transfers and transformations, but there are no transfers or transformations of *matter*. Notably, we excluded the important cases of food and fuel, in which the transformation of chemical energy into other forms is accompanied by complex changes in materials. In part this choice may reflect the physics-centric composition of our team, but it also reflects our judgement that a focus on physical science cases can provide a strong foundation for future learning about more complex scenarios involving chemical transformations. While the curriculum does not explicitly introduce these energy forms, teachers report students initiating and productively engaging in conversations about chemical and gravitational energy. The curriculum encourages the construction of a flexible model for energy in which new energy forms can be identified and added as needed, and we have observed students "inventing" new (to them) forms when the phenomenon and their model of energy require them (Tobin et al., 2018).

Our goal in this winnowing process was to leave the students with a set of experiences and understandings that can provide a firm foundation for future learning about energy. While those understandings are certainly incomplete, and in some respects may be canonically incorrect (e.g., if students still confound temperature and thermal energy), we sought to avoid leaving them with ideas that we believed would present serious impediments to their future progress. We do not claim that our choices are the only viable ones or are necessarily optimal. We do argue that such choices are unavoidable in teaching a complex concept such as energy; it is not realistic to expect students to leave fifth grade with a fully formed and complete understanding.

3.2 | Analytical framework: The energy tracking lens

Energy ideas provide a powerful analytical tool in all fields of science and engineering but, as with any tool, training and experience in its use are essential. Learning facts, definitions, rules, and categories about energy is of little value, unless students also discover what kinds of questions energy reasoning can (and can't) address, and how to use energy arguments to analyze and interpret real-world phenomena. In *Focus on Energy*, students learn to use the "Energy Tracking Lens" (ETL), shown in Table 2 (Crissman et al., 2015; Lacy et al., 2014).

The ETL encapsulates, at an age-appropriate level, the way scientists use energy reasoning to think about phenomena. Throughout the curriculum, it provides a consistent framework for constructing and using a model of energy (Tobin et al., 2018). It represents a subtle but critical epistemic shift, from defining what energy *is* to focusing on what kinds of *questions* the concept of energy enables us to ask and answer. As students ask and begin to answer these questions, they develop skill at using all four key conceptual energy themes together.

We choose the term "lens" to signal that energy is not a discrete topic, but an analytical stance that provides partial but powerful insights into many topics in science and society. It is distinct from, and complementary to, a mechanistic lens that focuses attention on *how* things work (Tang et al., 2020). In using the energy lens, we elide specific mechanisms to determine which processes are possible and which are not. It allows us to understand that plants require sunlight to live and grow, or where the energy for an electric car comes from, without either requiring, or contributing to, an understanding of how photosynthesis works or how electric cars are built (Lacy et al., 2014).

TABLE 2 Elements of the Energy Tracking Lens (ETL)

Part 1. Describe what you observe.
Part 2. Tell the energy story.
• What components are involved?
• Form(s) of energy?
• Increases and decreases in amounts of energy?
• Energy transfers?
• Change of energy from one form to another?
• Where does the energy come from and where does the energy go?
Use observations to support your energy story.

The analytical framework (ETL) and the representational tools (see below) afford the students considerable agency in how they model energy flow in any given scenario: which objects to include, at what points in the process to start and stop the representation, and what amounts and forms of energy to assign to each object at each point. This modeling process parallels the practice of science and engineering professionals, who typically work within well-established theories, using available analytical and experimental tools, but exercise judgement and agency in modeling their specific problems. We have elaborated and analyzed the role of model-based reasoning in this curriculum elsewhere (Tobin et al., 2018).

3.3 | Representational tools

To use the ETL to reason about and communicate the flow of energy through a system, students need tools and methods for representing relative amounts of energy associated with different objects, and in different forms, at different points in the evolution of the system. Students first use Energy Bars (Crissman et al., 2015)—similar to the segmented bars used in many digital displays to show things like battery charge—to represent relative amounts of energy in different objects at different points during a scenario. As the scenarios become more complex, we introduce Energy Cubes (Scherr et al., 2012; Seeley et al., 2014, 2021; Tobin et al., 2018). Objects in the scenario are represented by circles on a whiteboard. Units of energy are represented by small cubes similar to dice. Sides of the cubes are marked to represent different energy forms. Students decide which components to include and enact their model of the energy flow by (1) moving cubes between circles to represent energy transfer and (2) flipping the cubes to represent energy transformation. In this process, the students are simultaneously creating, refining, and communicating a model for the flow of energy in the particular scenario under consideration (Tobin et al., 2018). Figure 1 shows students tracking energy flow using Energy Cubes. Teacher reports and classroom observations provide evidence that both students and teachers found these representations intuitive and engaging, and they quickly became fluent in using them—both as tools to reason with, and as a way to communicate their ideas to one another. As one teacher told us, “the energy cubes … really helped them explain what they were thinking because the cubes were concrete and tangible.”

Importantly, the energy cube representation builds in the idea of conservation, without asserting it as a principle, because the number of cubes is fixed, and all the cubes must always be placed somewhere on the board. If energy seems to appear or disappear (e.g., when all motion comes to a stop), the students are forced to reckon with the challenge of where to put the cubes. Sometimes their solution is a circle labeled “Unknown.” In this way the energy cubes act as a precursor or foundation to the principle of energy conservation.

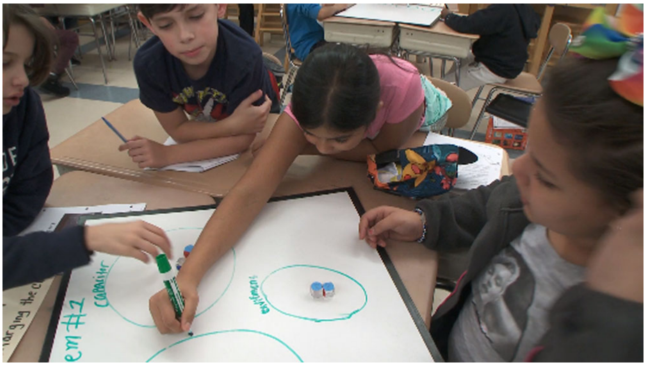


FIGURE 1 Students using Energy Cubes to track energy flow

3.4 | Classroom activities

Over a series of 14 50–60 min lessons, students learn to ask the ETL questions, and at least tentatively answer them, in the context of hands-on investigations involving mechanical, thermal, and electrical phenomena. The activities are designed to be simple to use and engaging, with each new activity raising a new challenge or question. Over the course of the curriculum, the activities involve more objects; more, and more subtle, forms of energy; more instances of transfer and transformation; and more need to draw on both observation and model-based inference to reason about energy. Table 3 lists the investigation question and the phenomenon that students investigate for each lesson.

The goal of each investigation is to tell the “energy story” of a scenario. By using the word “story,” we evoke what children know about narratives: In a story, something happens, there is a beginning and an ending, and the task of the storyteller is to provide a coherent account of how and why the story evolves as it does. Similarly, the analytical power of the energy concept appears when it is used to analyze a process in which something is happening—not, for example, just to identify the presence of energy in a static situation. By emphasizing that it is an *energy* story, we highlight that we're trying to tell the story of the energy—which is different, for example, from a mechanistic explanation of what happens to the objects. By insisting that it be a *scientific* story, we require that the

TABLE 3 Sequence of curriculum activities

Session/Investigation question	Phenomenon investigated
1. Anchoring/elicitation phenomena	Videos of everyday situations
Motion energy	
2. What can motion tell us about energy?	Ball rolling on a track
3. Can a ball cause another ball to move AND not lose any of its own energy?	Balls colliding on a track
4. Can a paint paddle gain and lose energy?	Paint paddle launcher sending a pompom flying into the air.
5. What's the energy story of the paint paddle and pompom?	
6. What's the energy story of the propeller?	Rubber band untwisting and propeller spinning
Thermal energy	
7. What can temperature tell us about energy?	Room temperature rock submerged in warm water.
8. What's the energy story of the rock in the water?	
9. What's the energy story of the rock in the water?	
10. Where does the thermal energy go?	Cup of warm water in closed box
Energy in electrical phenomena	
11. What is the flow of energy when the propeller spins?	Hand-cranked generator driving motor and propeller
12. What if there's no wind? Can we store energy?	Hand-cranked generator storing energy in a capacitor, capacitor driving motor and propeller
13. Solar panels: Where does the energy come from and where does the energy go?	Solar cell storing energy in a capacitor, capacitor driving motor and propeller
14. Solar panels: Where does the energy come from and where does the energy go?	
15. What is the flow of energy when the propeller spins?	

narrative be consistent both with the observable evidence and with our understanding of how energy is related to observable phenomena (e.g., changes in the speed or temperature of an object), and with our model of how energy behaves (e.g., gains and losses must be correlated).

The lessons follow a consistent structure. Each begins with an *Investigation Question*, such as “When a ball causes another ball to move, does it always lose some of its own energy?” The teacher leads an *Elicitation* activity, in which students give their initial ideas about the question. Then the class moves to a hands-on *Investigation*, in which the students work in small groups, doing first-hand investigations to gather evidence, and using representations to collaboratively test and revise their ideas. The investigations are mostly qualitative and only loosely scripted, and the students are free to try things on their own initiative, and to return to the materials to repeat experiments or try new ones while they are working to interpret the results. They document their observations and ideas in science notebooks. Finally, the class gathers in a circle for an all-class *Meaning-Making Discussion* in which they reflect on and discuss their activities and their ideas. The combination of small-group work, individual work in science notebooks, and all-class discussion ensures that each investigation incorporates multiple opportunities for sense-making.

Through this repeated cycle of investigation, scaffolded reasoning, and individual and group storytelling, the class collectively builds and revises an emerging, and increasingly broad and sophisticated conceptual model of energy—one that is still incomplete but that can provide tentative explanations and serve as a sound basis for future learning. The emerging model of energy is recorded on posters that include statements elicited from the class, not provided by the teacher or dictated by the curriculum materials. The teacher is encouraged to write down the students' suggestions, even if they are incomplete, inaccurate, or not part of what a scientist would call a model. The class revisits the posters repeatedly during the course of the curriculum, adding new ideas and revising or crossing out old ones that have been superseded or found to be faulty. This process highlights the nature of scientific models as the products of inquiry, rather than authoritative dogma, and as always subject to revision (Gilbert & Justi, 2016; Lehrer & Schauble, 2006a; Louca & Zacharia, 2012; Schwarz & White, 2005; Schwarz et al., 2009; Tobin et al., 2018; Ward, 2016; Windschitl et al., 2008). Figure 2 shows posters summarizing one class's emerging model near the conclusion of the introductory unit on motion and elastic energy. This is a snapshot at one relatively early point in the development of the provisional model, not a final product (in model-based reasoning there is never really a final product).

Each learning experience builds on the ones before, so that students systematically become more skillful at engaging in argument from evidence and using their model of energy to tell an energy story. An acceptable energy story for a scenario needs to be compatible with the model of energy as the class understands it. But as the scenarios become more complex, it becomes impossible to accommodate them within the students' model—for example, perhaps a new form of energy is needed that hasn't previously been identified. Periodically, then, the class revisits the model, adding new ideas and solidifying, refining, generalizing, or in some cases deleting previous ones.

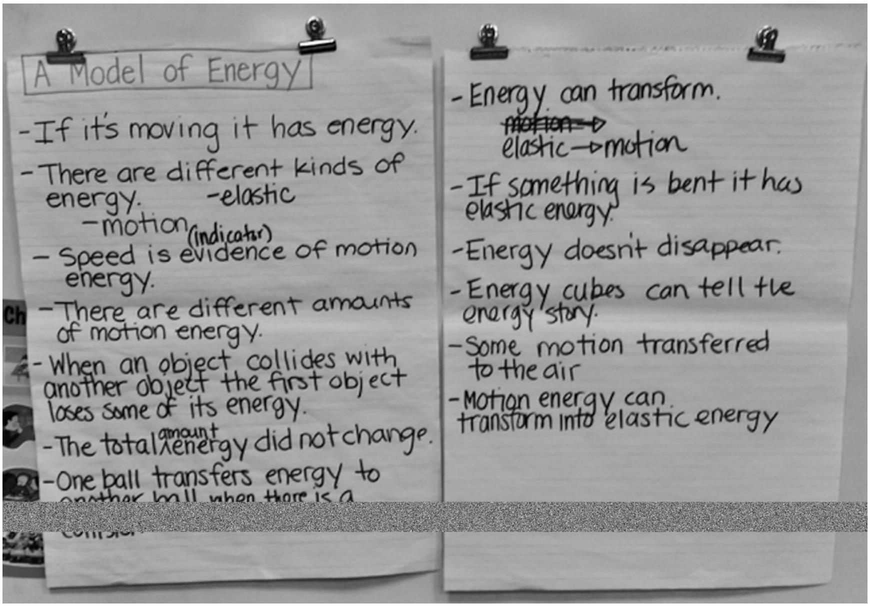
4 | EXAMPLE ACTIVITIES AND STUDENT WORK

In this section, we present and discuss three examples of student work that illustrate the kind of tasks posed during the curriculum, and how students' ability to reason about energy flow can develop as they progress through the curriculum and become adept at using the ETL framework, representational tools, and energy ideas. Artifacts like these, along with classroom observations, were also primary tools that the teachers used for formative assessment of their students' progress. The examples presented here are merely illustrative and are not intended as evidence of the curriculum's efficacy. They were selected primarily because the students' work was clear and legible. They are not exceptional—many students, of diverse backgrounds and socioeconomic status, exhibited similar growth in the sophistication of their energy reasoning. Systematic data on students' progress is presented in Section 6 below.

4.1 | Motion energy story: An early investigation of a simple system

In Lesson 2 of the introductory Motion Energy unit, students roll one ball along a track to collide with a ball that is initially at rest. They explore the question, "When a ball causes another ball to move, does it always lose some of its own energy?" In three consecutive trials, students record their observations of the motion of the individual balls just before and after the collision (ETL Part 1) before describing energy changes. The student notebook page (Figure 3) provides a scaffolded context for students to begin to distinguish the observable motion of the ball from the energy of the ball, which is not observable, taking their first step in building a model of energy.

In this rudimentary energy story, students are prompted to focus on two parts of the ETL: "What components are involved?" and "Increases and decreases in amounts of energy?" Below a sketch of the balls, the notebook prompts students to use "energy bars" to represent amounts of energy of each ball, allowing them to track and communicate energy gains and losses during the collision and to convey the idea of energy as a quantity (Crissman et al., 2015). They use the observable evidence of energy—speed—to decide how many energy bars to color in. In Figure 3, both students check the Energy Change boxes noting Ball 1's energy loss and Ball 2's energy gain in the

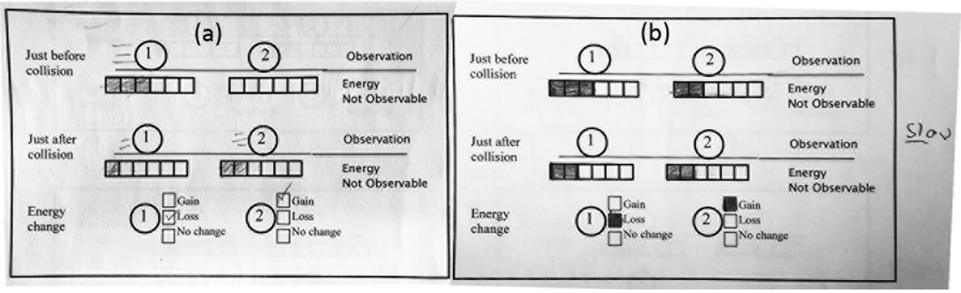


A Model of Energy

- If it's moving it has energy.
- There are different kinds of energy. -elastic -motion
- Speed is (indicator) evidence of motion energy.
- There are different amounts of motion energy.
- When an object collides with another object the first object loses some of its energy.
- The total amount energy did not change.
- One ball transfers energy to [redacted]

- Energy can transform. ~~motion →~~ elastic → motion
- If something is bent it has elastic energy.
- Energy doesn't disappear.
- Energy cubes can tell the energy story.
- Some motion transferred to the air
- Motion energy can transform into elastic energy

FIGURE 2 Model of energy generated by one class, near the end of the first unit, on motion and elastic energy



(a)

Just before collision ① ② Observation
Energy Not Observable

Just after collision ① ② Observation
Energy Not Observable

Energy change ① ☐ Gain ☑ Loss ☐ No change ② ☑ Gain ☐ Loss ☐ No change

(b)

Just before collision ① ② Observation
Energy Not Observable

Just after collision ① ② Observation Slow
Energy Not Observable

Energy change ① ☐ Gain ■ Loss ☐ No change ② ■ Gain ☐ Loss ☐ No change

FIGURE 3 Two examples of student notebook pages for ball collisions collision. Student (a) has "conserved" the number of bars, although that is not required by the ETL or the representation. Student (b), like many students at this stage, does not show the same number of total bars before and after the collision.

When asked to use their data to answer the investigation question and explain their reasoning, student (b)'s response (not shown here) indicates that he has begun to associate a loss of energy with a gain of energy: "*What we found out was that when one ball collides with another ball the first ball losses some of it's own energy depending on the speed while it give energy to the other ball. I think it makes sense because one ball gained energy and the other one lost energy.*" In response to the prompt: "Can you think of an example from your everyday life where there's a loss of energy somewhere and a gain of energy somewhere else?" student (b) writes: "*My example is when you play soccer and you kick the ball and you give it energy from you kicking the ball while your leg losses some energy.*" Student (a), on the other hand, does not (yet) associate energy gains with losses in the same system: "*When someone pushes a shoping cart it gain energy. When a computer battery is about to did [die] it has less energy as before*."

Already these students have used the ideas of "form" (motion energy), indicator (speed) of changes in the amount of energy, and the key idea that an energy gain in one part of the system is accompanied by an energy loss somewhere else. It is not clear, however, whether, at this stage, they were making a conceptual distinction between motion itself and motion energy—what we are calling "energy bars" they could very well have been interpreting as "speed bars."

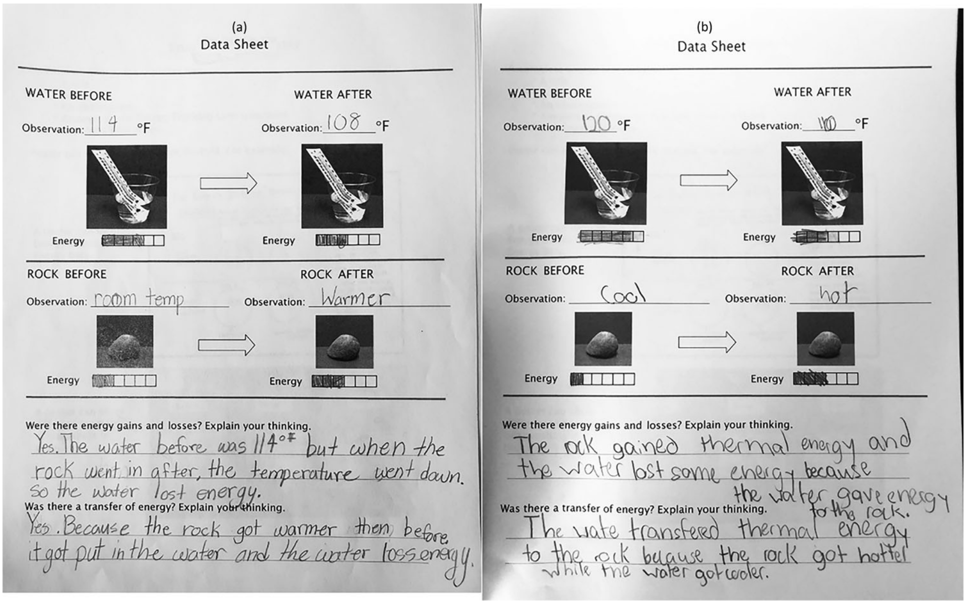
4.2 | Thermal energy story: Adding energy forms and representations, and removing scaffolds

After the five-session Motion Energy unit, students investigate a new energy form: Thermal Energy. In the second thermal activity, students put a room-temperature rock into a cup of warm water and work in small groups to address the question "What's the energy story of the rock and the water?"

The notebook page for the investigation (Figure 4) prompts students to record changes in the measured temperature of the water and the felt temperature of the rock (ETL Part 1) and fill in energy bars to show energy changes. The two examples in Figure 4 show the number of energy bars of the water decreasing, corresponding to a decrease in water temperature. The students' written responses show them using the ETL: They associated changes in an observable property, temperature, with changes in the amount of energy. They noted that when one part of the system, the water, lost thermal energy, another part, the rock, gained energy. In Figure 4b, the student also identified a form of energy (thermal energy) and used the idea of energy transfer or flow from one component to the other ("*the water gave energy to the rock*").

After completing their individual notebook pages for this activity, students worked in small groups, using Energy Cubes, previously introduced in the Motion Unit, to represent and reason about the energy story of the rock in warm water. They needed to decide for themselves which system components to represent, moving and flipping cubes to represent energy transfer and transformation, while holding themselves and one another responsible for consistency both with their observations and with their overarching model of energy. Once a group agreed on the story, they were given a blank piece of paper and asked to create a poster to tell the energy story in a way that would be clear to someone who never saw the investigation.

Figure 5 shows what one group of students was able to do when the scaffolds provided by the science notebook were withdrawn. They used three different representations—writing, energy bars, and energy cubes—to describe energy changes in the system from just before the rock is placed in the water to just after the rock is removed from the water. They described their observations separately from their inferences about energy: "*Before the rock was put in the water it* [the water] *was 114 °F. The rock before it was put in the water it was 82 °F. After the rock was put in the water, it was 100 °F. The water after the rock was put in it was 108 °F.*" Then, in their energy story, they identified two relevant components, the water and the rock, which they represented as circles. (They omitted,



(a)
Data Sheet

WATER BEFORE
Observation: 114 °F
Energy

WATER AFTER
Observation: 108 °F
Energy

ROCK BEFORE
Observation: room temp
Energy

ROCK AFTER
Observation: Warmer
Energy

Were there energy gains and losses? Explain your thinking.
Yes. The water before was 114°F but when the rock went in after, the temperature went down. So the water lost energy.

Was there a transfer of energy? Explain your thinking.
Yes. Because the rock got warmer then before it got put in the water and the water loss energy.

(b)
Data Sheet

WATER BEFORE
Observation: 120 °F
Energy

WATER AFTER
Observation: 110 °F
Energy

ROCK BEFORE
Observation: Cool
Energy

ROCK AFTER
Observation: hot
Energy

Were there energy gains and losses? Explain your thinking.
The rock gained thermal energy and the water lost some energy because the water gave energy to the rock.

Was there a transfer of energy? Explain your thinking.
The wate transferd thermal energy to the rock because the rock got hotter while the water got cooler.

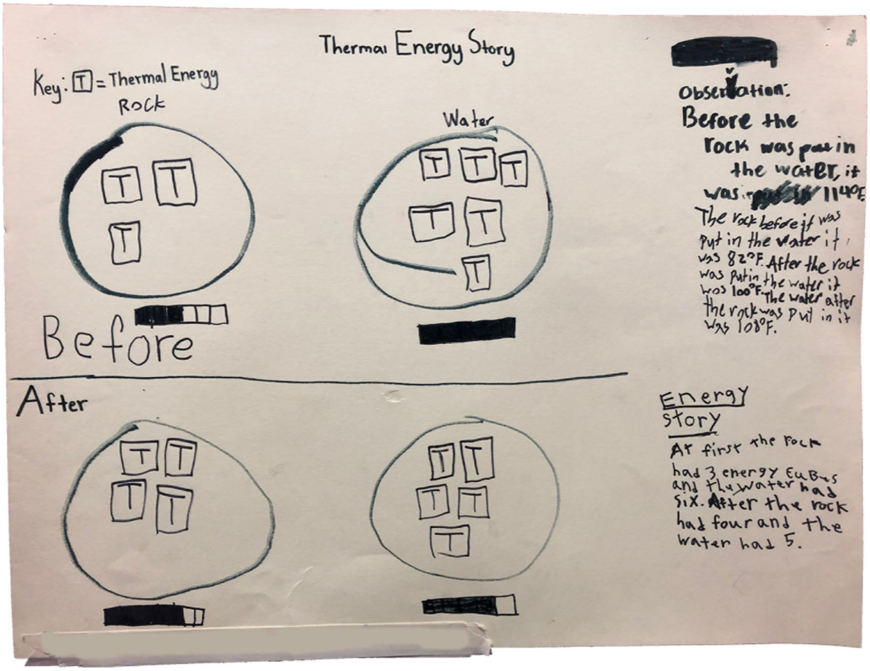
FIGURE 4 Individual notebook pages for the rock in water activity.
Student (a) text: Yes. The water before was 114 °F but when the rock went in after, the temperature went down so the water lost energy. Yes. Because the water got warmer then before it got put in the water and the water loss energy.
Student (b) text: The rock gained thermal energy and water lost some energy because the water gave energy to the rock. The wate transferred thermal energy to the rock because the rock got hotter while the water got cooler

e.g., the cup and the thermometer, as not relevant to the energy story they were telling—this was often a subject of discussion among the students.) They identified the form of energy: thermal energy. The energy bars, cubes, and words "*At first the rock had 3 energy cubes and the water had six. After the rock had four the water had 5*" show they were aware of energy increases and decreases. This poster does not, however, show clear evidence that, at this point in the curriculum, the group thought of the energy gained by the rock as the same energy lost by the water.

4.3 | Electrical energy story: The last investigation

In the final unit, students track energy in the context of electrical phenomena. In the very last investigation, they (1) use a solar panel to charge a capacitor and then (2) connect the charged capacitor to a motor and propeller system to make the propeller spin. (A capacitor is an electronic component that can store and release electric charge and electrical energy, similar to the behavior of a rechargeable battery.) After using Energy Cubes to dynamically track energy flow, each small group of students uses annotated drawings to tell the energy story in the two situations. Figure 6 shows the work of one group.

By this last investigation, these students could answer all six ETL questions without specific prompting and could tell a coherent energy story about a complex scenario that involves several components, multiple energy forms, and transformation as well as transfer. These students have decided to end their story once the propeller is spinning—the poster doesn't indicate what happens when all the capacitor's energy is discharged and the system comes to a halt—and they have not included the wires or the environment as relevant objects. Other student groups made different choices. This illustrates the extent of authentic model-based reasoning and epistemic agency shown by these young students by the end of the curriculum.



[redacted]

Observation: Before the rock was put in the water, it was 114°F

The rock before it was put in the water it was 82°F. After the rock was put in the water it was 100°F. The water after the rock was put in it was 108°F.

Energy Story

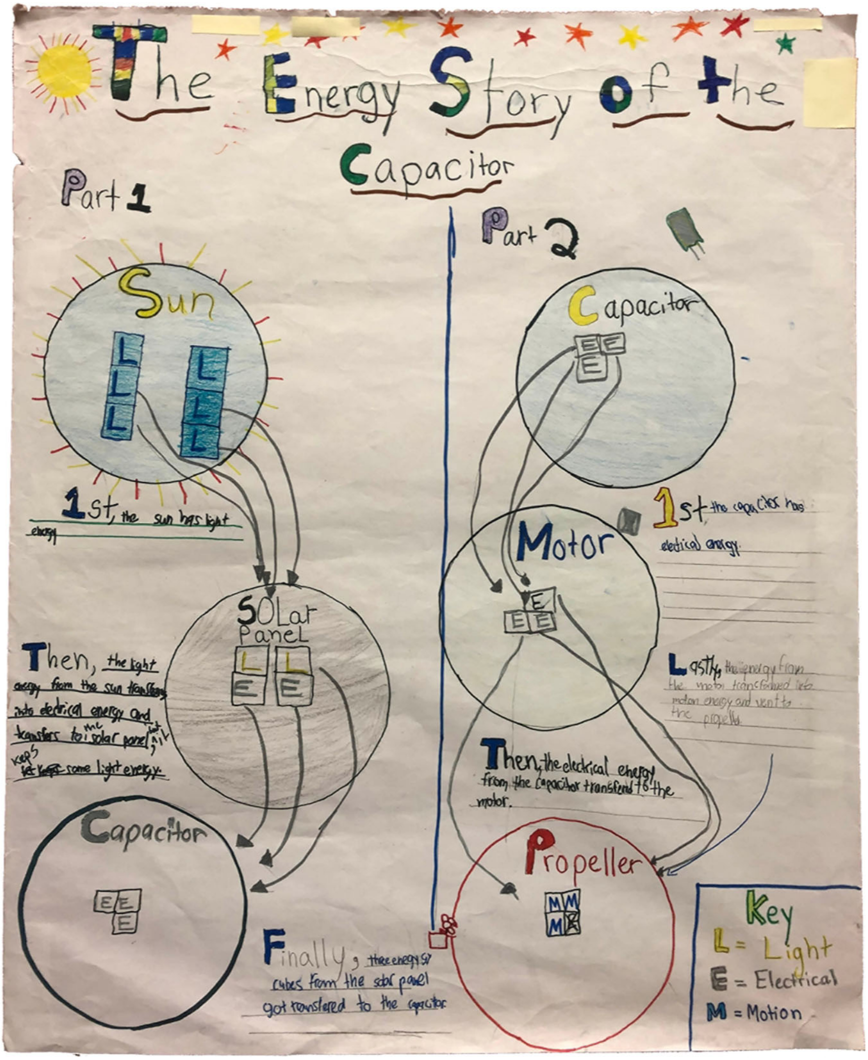
At first the rock had 3 energy CuBes and the water had six. After the rock had four and the water had 5.

FIGURE 5 Small-group poster for the rock in water activity.
Student text: Observation: Before the rock was put in the water, it was 114 °F. The rock before it was put in the water it was 82 °F. After the rock was put in the water it was 100 °F. The water after the rock was put in it was 108 °F. Energy Story: At first the rock had 3 energy cubes and the water had six. After the rock had four and the water had 5

The poster shows evidence that these students understood that energy not only increases and decreases in different objects, but flows from one object to another, and transforms from one form to another. This interpretation is suggested by the arrows showing the motion of the cubes from one object to another, and from phrasing like "the electrical energy *from the capacitor* transferred to the motor." [Emphasis added]

This student poster is unclear about where the changes of form occur—within or outside of the solar panel or the motor. This imprecision is typical and unsurprising given how little information young students have about the sun, the nature of light and electrical energy, and the mechanism of a solar panel or a motor. We consider unresolved questions to be indicative of authentic scientific engagement. Science can resolve questions, but it also refines questions and raises new ones. This student group did not explicitly follow the ETL instruction to "Use observations to support your energy story." In this scenario, there are no detectable changes in the sun, the panel, the wires or the capacitor that students can use as indicators of energy flow. Only when the capacitor is connected to the motor, making it spin, is there an observable indicator of energy flow; these students showed they were able to develop the chain of model-based inference leading back to the sun, even if it was not fully articulated.

The poster in this example shows that these students had become adept at using energy cubes to reason about a complex system involving multiple components and multiple forms of energy. They could move and flip the cubes in ways that make sense to someone with a clear understanding of energy, but did they really understand them as representing energy as a scientist would understand it? Or are the cubes just tokens in an elaborate board game? We do not know what the students were thinking, but we can say from the evidence that these students described the cubes as representing something they called energy. Their use of the cubes showed it to be something that is quantifiable (represented by the number of cubes in a particular circle and labeled as a particular form), associated



1st, the sun has light energy

Then, the light energy from the sun transforms into electrical energy and transfers to the solar panel, but it ~~let keeps~~ keeps some light energy.

Finally, three energy cubes from the solar panel got transfered to the capacitor

1st the capacitor has electical energy.

Then, the electrical energy from the capacitor transferd to the motor.

Lastly, the energy from the motor transformed into motion energy and went to the propeller

FIGURE 6 Small-group poster for the solar panel activity addresses multiple ETL questions: *Components*: Sun, solar panel, capacitor, and propeller; *Forms*: Light, electric, and motion energy; *Gains and losses*: Individual cubes move; *Transfer*: Arrows and words; *Transformation*: Words; *Where does the energy come from and go*: Arrows and words Student text: **Part 1** 1st, the sun has light energy. Then, the light energy from the sun transforms into electrical energy and transfers to the solar panel but it keeps some light energy. Finally, three energy cubes from the solar panel got transfered to the capacitor. **Part 2** 1st the capacitor has electical energy. Then, the electrical energy from the capacitor transferred to the motor. Lastly, the energy from the motor transformed into motion energy and went to the propeller

with objects and systems (by being placed in a particular circle), and that its presence and amount can be related to observable phenomena like motion, deformation or temperature. It (they) moved from one object to another and changed from one form to another, moving through a system, but the total amount didn't change. The same cube that represented light energy in the sun also represented electrical energy in the capacitor and motion energy in the propeller. And the story that they constructed accords well with the physical changes they observed in the system, and with the energy story that a scientist might tell. Whatever mental construct they had in mind, it has many of the attributes of the scientific entity called "energy."

5 | ASSESSMENT METHODOLOGY

When we began this project, it was not clear whether it was even possible to develop meaningful energy-reasoning skills in these early grades. Our project was not a systematic efficacy study, but rather a development project and, we hoped, a proof-of-principle demonstration. We took a quasi-experimental approach to investigate how the *Focus on Energy* program affected student learning outcomes. We developed and used a scored, open-ended pre-post assessment to quantify some aspects of students' gains, and to compare *Focus on Energy* classes with similar classes that used existing curricula.

5.1 | Participants

Our data come from fifteen (15) "Treatment" teachers and their students from public schools in the Boston area, and in greater metropolitan Seattle, who completed intensive professional development (PD) and implemented the *Focus on Energy* curriculum in their classrooms. Three (3) additional teachers completed the PD workshop and implemented the curriculum, but did not provide completed research instruments; those classes are not included in our analysis. Participating teachers were volunteers, recruited through local science coordinators, word of mouth, and a website. They received a stipend and earned professional development credits. Their teaching experience ranged from 0 to 25 years, with a median of 12 years.

The PD program was designed to incorporate key components of effective professional learning (Borko, 2016; Gilbert & Justi, 2016): Teacher workshop sessions were content-focused and student-focused, provided opportunities for the teachers to participate and collaborate as active learners; and were ongoing, including a week-long summer workshop and a series of three PLC meetings during the school year. In the summer workshop, teachers experienced the *Focus on Energy* curriculum as science learners, building their own understanding of energy as a scientific concept and as an analytical tool for reasoning about diverse phenomena and experiencing modeling- and practices-based pedagogy. They also had opportunities to observe and build on students' energy ideas through use of classroom video and student work and received guidance in facilitating student learning—particularly in the area of creating and using models—through the use of the *Focus on Energy* activities and the ETL questions. Participating teachers received an annotated teacher guide to the curriculum and, during PLC meetings, they had opportunities to discuss their classroom experiences and questions with each other and with the development team.

To compare *Focus on Energy* with existing, "business as usual" instruction, we collected pre- and post-tests, described below, from students in six "Comparison" classrooms in the same Boston area districts as the Treatment classrooms, with students from similar backgrounds. Comparison teachers were identified by local science coordinators. They received a stipend for collecting student data and were offered the opportunity to receive all curriculum materials, classroom kits, and an abbreviated implementation workshop at the end of the study. In these classes, teachers taught their existing energy-related physical science curriculum with no new supports. Three teachers taught the STC Electrical Circuits unit (National Academy of Sciences, 2002) that was in place before the introduction of the new standards. They supplemented the curriculum with district-created lessons about magnets and discussions about forms of energy and where energy comes from. The three other teachers taught an 8–10 session unit developed by the district science coordinator to address the new standards, focusing on light, sound, heat, electrical and kinetic energy. Because of the small numbers, and possible variation in how the materials were taught, we could not analyze the data for differences among the curricula used in the comparison classes.

Table 4 summarizes characteristics of the classrooms studied. The schools were in urban and suburban settings and included students from diverse socioeconomic backgrounds and many English language learners. Class sizes ranged from 15 to 32 (mean 23.7, median 25). While the comparison and treatment groups were similar in grade level and drawn from some of the same districts as the treatment classes, the Comparison set included a slightly larger proportion of 5th graders and a slightly smaller proportion of Title I schools than the Treatment classes.

5.2 | Classroom implementation

The participating (Treatment) teachers taught the *Focus on Energy* curriculum without further intervention from the research team. During implementation, the project's external evaluator conducted fifteen classroom visits in the Boston-area treatment classrooms over a six-month period. Six classrooms were observed twice, and three were observed once. The evaluator usually sat in the back of the room and took notes on what the teacher and the students were doing throughout the lesson. When the students were working in small groups (Investigation phase) the evaluator walked around the room, first just watching and listening to each group, and later asking them to briefly explain what they understood about the investigation. While this interaction could be considered an intervention, we believe any effect on achievement would be small.

The evaluator's observations provide some indication of the extent to which the teachers implemented the curriculum as designed. Table 5 summarizes the number of observed classes in which various key aspects of the lesson structure were observed. If a particular activity was not observed, it does not necessarily mean that it was absent from that classroom, only from the observed lesson. We would not expect, for example, that every class would include an explicit discussion of the ETL. In the PLC meetings, teachers often reported running out of time for the group meaning-making discussion, and moving it to the beginning of the next class.

Overall, the observations suggest generally faithful adherence to the curriculum design, with all of the classes following the basic lesson structure of Elicitation-Investigation-Discussion and most of the key features present in the large majority of the classes observed. The evaluator noted, however, that some classes were more teacher-led than the curriculum envisions.

TABLE 4 Characteristics of the classrooms studied

	Title I classrooms			Non-title I classrooms			
	Grade 4	Grade 4/5	Grade 5	Grade 3	Grade 4	Grade 5	Total
Treatment							
Seattle Area	1	1	2	1	0	1	6
Boston Area	7	0	1	0	1	0	9
Comparison							
Boston Area	0	0	2	0	3	1	6

TABLE 5 Number of observed classes (out of 15) in which various aspects of the lesson structure were observed

Tally	Behavior observed
13	Teacher poses the investigation question, gives directions for the investigation
15	Students do the first-hand investigation
15	Students complete the items in their student notebook
11	Student groups use representation to reason about energy flow
13	Students have meaning making discussions in their small groups
15	Students are able to describe the energy story of the investigation to the evaluator
10	Teacher and students discuss the *Energy Tracking Lens*
13	All-class meaning-making discussion

In every class observed, all of the small student groups were able to articulate to the evaluator an energy story for the activity. This included students who had limited English-speaking skills and students in special education inclusion classrooms. The evaluator also recorded all students as being fully engaged in the activities and/or small-group discussions, across all the classrooms, based on his close observation of whether students appeared to be paying attention to one another and to the activity—as opposed to looking away, doodling, or otherwise physically manifesting lack of participation or interest.

5.3 | Scored pre-/post-assessment

Since reasoning about energy demands both knowledge about an abstract concept and the ability to integrate and apply that knowledge meaningfully, a useful practical assessment tool must go beyond multiple-choice items to see not just what students *know*, but what they can *do* with that knowledge (Lee & Liu, 2010). We developed an open-ended assessment of energy knowledge and reasoning that can be scored quickly and reliably, and probes both students' basic knowledge about energy and their ability to use that knowledge to track energy flow in a real system. Because we wanted it to be accessible to students before energy instruction, and to students experiencing other energy curricula, it was not designed as a comprehensive assessment of our learning goals, but rather as a gauge of knowledge and reasoning about energy that might be expected from any elementary-school energy curriculum.

To establish face validity, the assessment was reviewed by the project's external advisory board, an independent panel of experts in science and science education, with backgrounds in various disciplines, who agreed that it was a fair measure of important knowledge about energy, and not biased towards our specific curriculum. The assessment was given to one college physics professor and several physics graduate students, unaffiliated with the project, to verify that it would evoke appropriate and complete responses from experts. We did not test it with scientists from other disciplines; however, Park and Liu, in a study of college students, found strong correlation in understanding of energy concepts across disciplines, concluding that “discipline effects, taken as a whole, are not significantly related to students' understanding of the energy concept” (Park & Liu, 2016, p. 508).

The instrument is an open-ended paper-and-pencil probe looking at the energy story of a wind-up toy (Figure 7) known as Sparklz™ (Kikkerland Design Inc., 2018). After being wound up and released, the toy wobbles around, makes a whirring noise, and generates sparks by rotating an arm fitted with flints over a piece of sandpaper. Its mechanism is fully visible. Neither this toy nor any similar device is used in any of the curricular activities.

Pairs of students are given an opportunity to play with and examine the toy. The first page of the assessment sheet shows pictures of the toy from two angles, along with a Word Bank listing the names of components, and asks the students to identify those components in the picture. This page is not scored, but it stimulates the students to closely examine the mechanism and gives them words to use in their subsequent descriptions. The second page (Figure 8), which is scored, asks them first to describe the changes they see when the toy is set in motion, and second to describe how energy flows and changes during that process. Students are free to choose or combine verbal, pictorial or diagrammatic representations, and to decide for themselves what aspects of the scenario to include. (Teachers report that this flexibility is particularly helpful for English-language learners and other children for whom extended writing is a challenge.) The page also includes a checklist of aspects of the energy story, including identifying forms, transfer and transformation, and energy gains and losses, but there is no requirement that it be used. Examples of student responses are presented in Section 6 below.

A scoring rubric, summarized in Table 6, assigns scores in five areas: Forms; Transfer and Transformation; Flow; Dissipation; and Overall Quality and Coherence. The first four are scored on a 0-2 scale, while the last uses a 0-3 scale. The “Overall” category is not based on a sum of the scores in the other categories; it is a separate evaluation category of its own, intended to evaluate the general quality of energy reasoning. The assessments were scored by

FIGURE 7 Sparklz™ wind-up toy

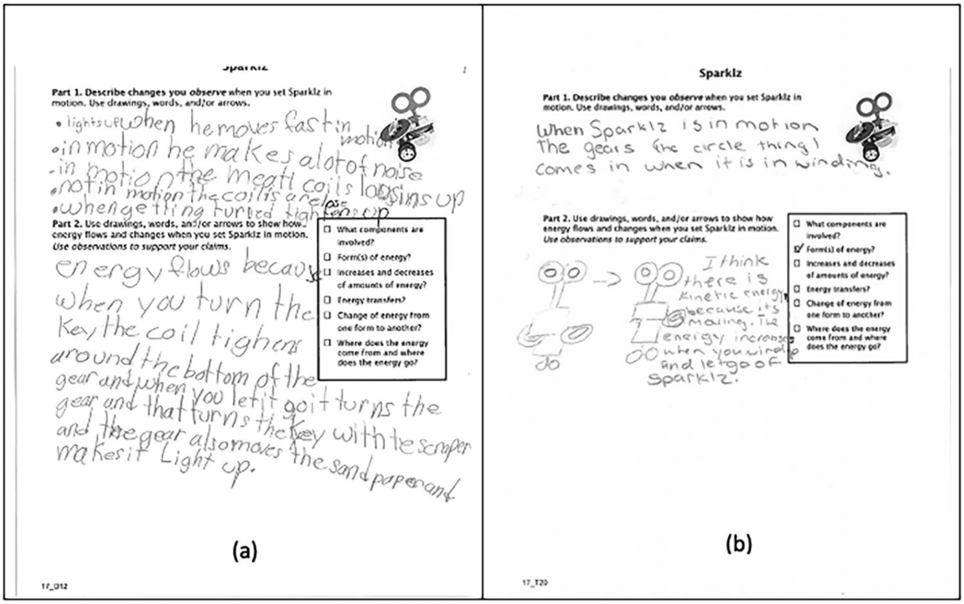
two student assistants. Interrater reliability was checked for a sample of 20 posttests. Percent agreement in the various categories ranged from 0.69 (Overall Coherence) to 0.90 (Forms) with a mean of 0.81. Similarly, values of Gwet's AC1 coefficient (Gwet, 2008)—which is more stable than Cohen's Kappa in a case such as this with a high degree of trait prevalence—ranged from 0.63 (Overall Coherence) to 0.88 (Forms) with a mean of 0.76. Since it represents a holistic judgement of quality, it is not surprising that the Overall Coherence category is subject to higher interrater variability, and measurements in that category should accordingly be viewed with somewhat more caution than in the others.

Importantly, the rubric focuses on what the student *knows* and *is able* to do, rather than on what is missing or incorrect. It is designed to capture the knowledge and intellectual resources relating to energy that a student brings to bear on a new, complex, and unfamiliar situation. Because the assessment is open-ended, the absence of an idea in an answer doesn't necessarily mean the student lacks that idea. In particular, nothing in the assessment cues attention to what happens to the energy when the toy stops, so students who mentioned dissipation did so entirely on their own initiative. It is possible that other students would have included dissipation if prompted.

6 | RESULTS AND DISCUSSION

6.1 | Scored pre-/post-assessment

The Sparklz scored assessment was administered to students in both Treatment and Comparison classrooms, both before and after the completion of their energy-related physical science unit. Its purpose was to assess the curriculum, not to grade individual students, and individual assessment scores were not shared with students or teachers. Many students with little or no knowledge about energy provided thoughtful and detailed answers like those shown in Figure 8. Before instruction, however, their answers usually described what the toy does, or tried to explain its mechanism, but said little or nothing about energy. There is great value in mechanistic analysis (Tang et al., 2020), but our rubric focuses specifically on the use of energy ideas, so even



Sparklz

Part 1. Describe changes you *observe* when you set Sparklz in motion. Use drawings, words, and/or arrows.

• lights up when he moves fast in motion
• in motion he makes alot of noise
- in motion the meatl coils loosins up
• not in motion the coil is are lose
• when getting turned tighten up

Part 2. Use drawings, words, and/or arrows to show how energy flows and changes when you set Sparklz in motion. ***Use observations to support your claims.***

☐ What components are involved?
☐ Form(s) of energy?
☐ Increases and decreases of amounts of energy?
☐ Energy transfers?
☐ Change of energy from one form to another?
☐ Where does the energy come from and where does the energy go?

energy flows because when you turn the Key the coil tighens around the bottom of the gear and when you let it go it turns the gear and that turns the Key with te scraper and the gear also moves the sand paper and makes it Light up.

(a)

17_O12

Sparklz

Part 1. Describe changes you observe when you set Sparklz in motion. Use drawings, words, and/or arrows.

When Sparklz is in motion The gears (the circle thing) comes in when it is in winding.

Part 2. Use drawings, words, and/or arrows to show how energy flows and changes when you set Sparklz in motion. ***Use observations to support your claims.***

☐ What components are involved?
☑ Form(s) of energy?
☐ Increases and decreases of amounts of energy?
☐ Energy transfers?
☐ Change of energy from one form to another?
☐ Where does the energy come from and where does the energy go?

I think there is kinetic energy because it's moving. The energy increases when you wind up and letgo of Sparklz.

(b)

17_T20

FIGURE 8 Two examples of student responses before instruction about energy. The answers show engagement in the task and careful attention to how the toy works, but very little understanding of energy ([a] received scores of zero in all categories; [b] received scores of 1 for forms and overall quality and coherence—because it associates energy with motion and with the winding of the spring—and zero in all other categories)
Student (a) text: Part 1. ●lights up when he moves fast in motion ●in motion he makes a lot of noise ●not in motion the coils are lose ●when getting turned tightens up Part 2. Energy flows because when you turn the key the coil tightens around the bottom of the gear and when you let it go it turns the gear and that turns the key with the scraper and the gear also moves the sand paper and makes it Light up.
Student (b) text: Part 1. When Sparklz is in motion the gears (the circle thing) comes in when it is in winding. Part 2. I think there is kinetic energy because its moving. The energy increases when you wind up and letgo of Sparklz

an excellent and detailed explanation of the mechanism would receive a low score if it lacked evidence of energy concepts.

Figure 9 shows an above-average student paper from a Comparison (business-as-usual) classroom at the conclusion of that class's energy unit. This student shows considerable ability to identify multiple forms of energy and uses words ("went from") that suggest an awareness of transfer and transformation, and so it received maximum scores (2/2) in those categories. There is less clarity about the idea of a given amount of energy flowing through the system as the toy operates, so this paper received scores of 1/2 for flow, and 1/3 for overall quality and coherence. There is no mention of dissipation, so it received 0/2 for that category.

Figure 10 shows two posttests from students in Treatment classrooms. These students conveyed their energy stories in very different ways. Student (a) built the explanation around a sketch of the toy, with very few words and none of the representational tools used in the curriculum. Nevertheless, by using labels for energy forms and arrows and stars for energy transfer and transformation, this student showed recognition of two energy forms, clear instances of transfer and transformation, a sense of the flow of energy from the handle through the mechanism, and a reasonably coherent, though not entirely complete (there is no recognition of the stored elastic energy in the spring, e.g.) energy story. Student (b) used the energy cubes representation, supplemented by a verbal description, and gave a substantially complete and accurate energy story. In particular, student (b) seems to understand energy as something that flows through the toy from one part to another, and in

TABLE 6 Scoring rubric for Sparklz assessment

1. Forms

0: No evidence that student appropriately identifies any forms of energy.

1: Evidence that student appropriately identifies 1 or 2 forms of energy, even if nonstandard terms are used.

2: Evidence that student appropriately identifies 3 or more forms of energy, even if nonstandard terms are used.

2. Transfer and Transformation

0: No evidence that student appropriately identifies any instances of energy transfer or transformation.

1: Evidence that student appropriately identifies instances of either transfer or transformation of energy between system components and/or between forms, but not both.

2: Evidence that student appropriately identifies instances of both transfer and transformation of energy between system components and between forms.

3. Flow of Energy

0: No instances of transfer or transformation identified.

1: Instances of transfer/transformation are identified, but there is not clear evidence that student understands the instances as involving a flow of energy from one component/form into another.

2: Evidence that student understands the instances of transfer/transformation as involving a flow of energy from one component/form into another (e.g. via arrows, labels or wording such as "gives some of *its* energy to …").

4. Dissipation

0: No evidence that student is aware that energy is dissipated into the environment/air/surroundings.

1: Evidence that student is aware that energy is dissipated into the environment/air/surroundings.

2: Evidence that student understands that eventually ***all*** the energy in the system is dissipated into the environment/air/surroundings.

5. Overall quality and coherence

0: Description is primarily mechanistic, with little or no evidence of energy reasoning (even though energy-related vocabulary may be present).

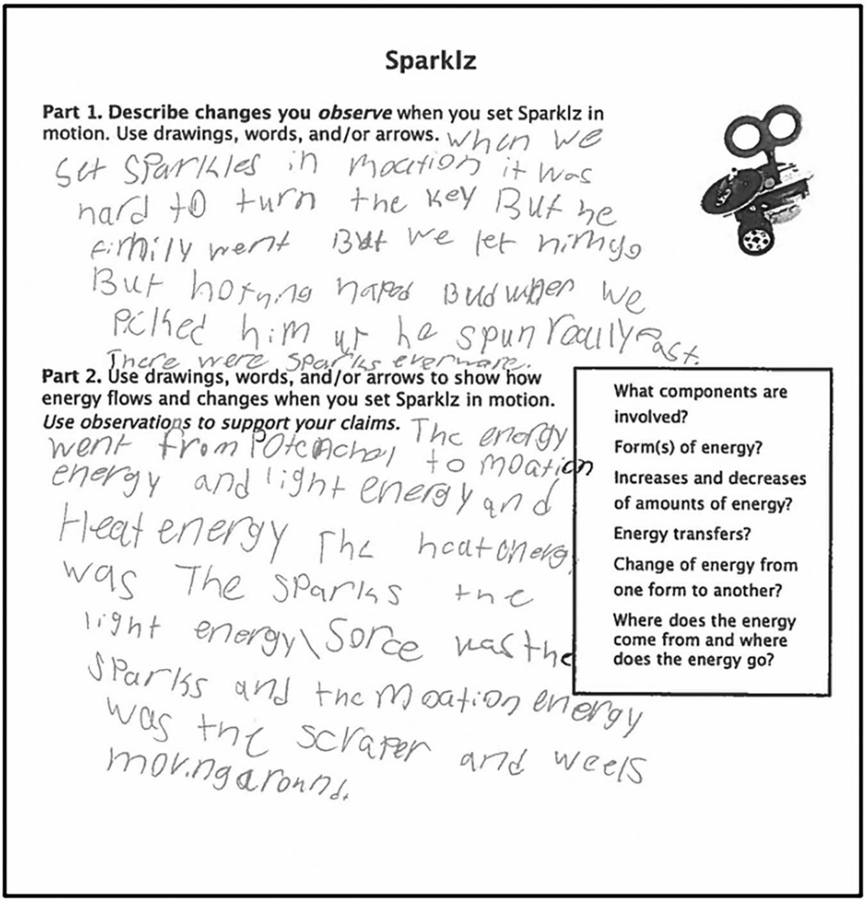
1: Energy ideas are present primarily in the sense of presence or absence of energy and/or the identification of forms of energy, but without evidence of reasoning about the flow of energy associated with the observed behavior of the system.

2: Evidence that student appropriately traces flow of energy through the system but the description has significant gaps or errors.

3: Evidence of a substantially accurate and complete understanding of the flow of energy through the system.

the process changes form several times, while maintaining the same total amount. Their scores are given in the caption.

These examples illustrate how the assessment and scoring rubric capture important aspects of students' energy reasoning, even though the students use very different forms of expression, and may or may not use the vocabulary and representational tools of the *Focus on Energy* curriculum. In Figure 10b, for example, the student never uses the words "transfer" or "transform," instead using terms like "goes into," "changes," and "turns to" to express the same ideas. Compared to the same students' pretests (not shown), all three of these posttests exhibit strong growth in energy knowledge and reasoning ability. The two Treatment examples, however, are stronger than the Comparison example in Flow and Overall Coherence—the categories that focus most on the ability to *use* energy ideas to track energy in a scenario.



Sparklz

Part 1. Describe changes you *observe* when you set Sparklz in motion. Use drawings, words, and/or arrows. when we set Sparkles in moation it was hard to turn the key But he finily went But we let him go But nothng haped Bud when we picked him up he spun really fast. There were sparks everware.

Part 2. Use drawings, words, and/or arrows to show how energy flows and changes when you set Sparklz in motion. *Use observations to support your claims.* The energy went from POtenchal to moation energy and light energy and Heat energy The heat energy was The Sparks the light energy\Sorce was the Sparks and the moation energy was the scraper and weels moving around.

What components are involved?

Form(s) of energy?

Increases and decreases of amounts of energy?

Energy transfers?

Change of energy from one form to another?

Where does the energy come from and where does the energy go?

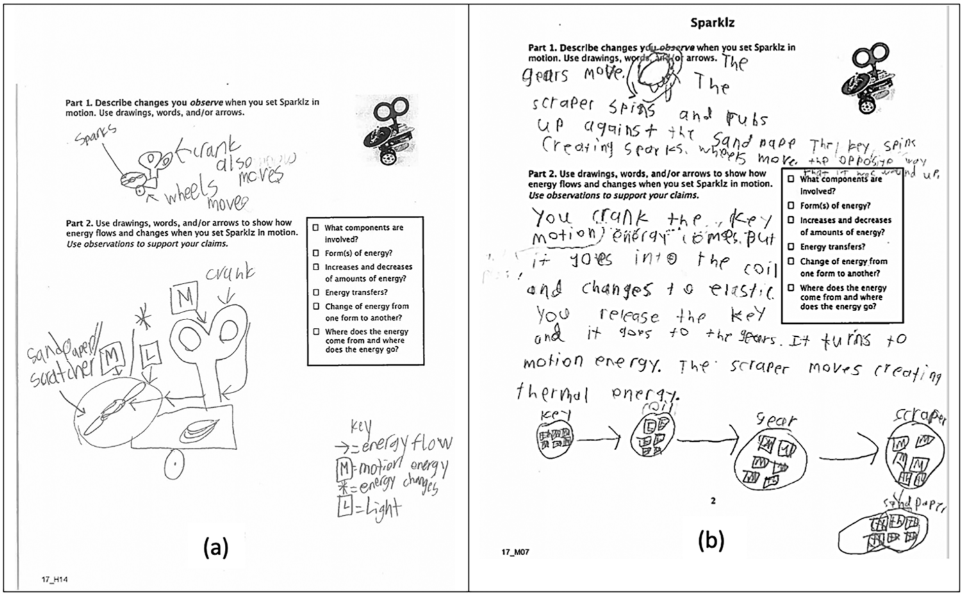
FIGURE 9 Posttest from a comparison classroom. It received scores of 2 (of 2) for forms and transfer and transformation, 1 (of 2) for flow, 0 (of 2) for dissipation, and 1 (of 3) for overall quality and coherence
Student text: Part 1. When we set Sparkles in motion it was hard to turn the key But he finily went But we let him go But nothng haped Bud when we picked him up he spun really fast. There were sparks everware. Part 2. The energy went from POtenchal to moation energy and light energy and Heat energy The heat energy was The Sparks the light energy\sorce was the sparks and the moation energy was the scraper and weels moving around

6.2 | Quantitative analysis

A systematic quantitative analysis of student learning gains confirms that the *Focus on Energy* curriculum was substantially more effective than business-as-usual instruction in developing not only students' knowledge about energy (such as the ability to identify forms), but their ability to track energy flow in a complex real-world scenario.

Figure 11 compares pre- and post-instruction classroom average scores in each scoring category, for both Treatment and Comparison classes. On average:

- Pre-instruction scores are very low, and similar in Comparison and Treatment classes.
- Both Comparison and Treatment classrooms show large gains following instruction in all categories, except for Comparison classrooms in the Dissipation category.
- Treatment classes show larger gains than Comparison classrooms across all categories.



Part 1. Describe changes you *observe* when you set Sparklz in motion. Use drawings, words, and/or arrows.

Part 2. Use drawings, words, and/or arrows to show how energy flows and changes when you set Sparklz in motion. *Use observations to support your claims.*

- ☐ What components are involved?
- ☐ Form(s) of energy?
- ☐ Increases and decreases of amounts of energy?
- ☐ Energy transfers?
- ☐ Change of energy from one form to another?
- ☐ Where does the energy come from and where does the energy go?

(a)

17_H14

Sparklz

Part 1. Describe changes you *observe* when you set Sparklz in motion. Use drawings, words, and/or arrows.

The gears move. The scraper spins and rubs up against the sand pape Thr key spins Creating sparks. wheels move. the opposite way that it was wound up.

Part 2. Use drawings, words, and/or arrows to show how energy flows and changes when you set Sparklz in motion. *Use observations to support your claims.*

- ☐ What components are involved?
- ☐ Form(s) of energy?
- ☐ Increases and decreases of amounts of energy?
- ☐ Energy transfers?
- ☐ Change of energy from one form to another?
- ☐ Where does the energy come from and where does the energy go?

You crank the key motion energy comes. But it goes into the coil and changes to elastic. You release the key and it goes to the gears. It turns to motion energy. The scraper moves creating thermal energy.

2

(b)

17_M07

FIGURE 10 Two examples of posttests from *Focus on Energy* classrooms. (a) received scores of 1 for forms, 2 for transfer and transformation, 2 for flow, and 2 for overall quality and coherence. (b) received maximum scores (2,2,2,3) in all categories except dissipation. Both papers received scores of zero for dissipation
Student (b) text: Part 1. The gears move. The scraper spins and rubs up against the sand paper The key spins creating sparks. Wheels move the opposite way that it was wound up. Part 2. You crank the key motion energy comes. But it goes into the coil and changes to elastic. You release the key and it goes to the gears. It turns to motion energy. The scraper moves creating thermal energy

A more detailed statistical analysis (available, in Suppinfo.pdf, as supplementary material accompanying the online article) confirms these conclusions and verifies that the increased gains in the Treatment classrooms are not only large in magnitude, but highly statistically significant ($p < 0.01$) in every category except Forms (perhaps because traditional energy instruction often focuses strongly on identifying and naming energy forms).

There was, however, variation among classrooms. Figure 12 shows the average posttest scores for individual classrooms. While the Treatment classes overall do outperform the Comparison classes, in every category there are exceptions.

Multi-level (hierarchical) analyses account for nonrandom assignment to Treatment condition and other class-to-class differences in teaching and relevant background variables, and differentiate *within*-class from *between*-class variance so that the Treatment condition is, appropriately, modeling the class-to-class component of the variance (Raudenbush & Bryk, 2002).

Sixty-two percent of Treatment students ($N = 257$) and 77% of Comparison students ($N = 115$) completed both the pretest and posttest. Among those who completed at least one test, there was no significant difference in completion rates (Treatment 86%, Comparison 89%, χ^2 ($df = 1$)= 0.20, $p = 0.65$). For students who had both pretest and posttest scores, we analyzed the difference score in each scoring category.

Examining pretest scores with multiple analysis of variance (MANOVA) techniques confirms that scores *before instruction* were very low and finds *no significant difference in prior preparation between Comparison and Treatment classes*. There was significant variation among different classes only in the categories of Forms ($F(20,333) = 2.20$, $p = 0.002$) and Overall Coherence ($F(20,333) = 2.30$, $p = 0.0014$), but in these cases the variation was not correlated with Comparison/Treatment condition (Forms: $t_{\text{Treatment}} = 1.37$, $p = 0.17$; Overall: $t_{\text{Treatment}} = 1.59$, $p = 0.11$).

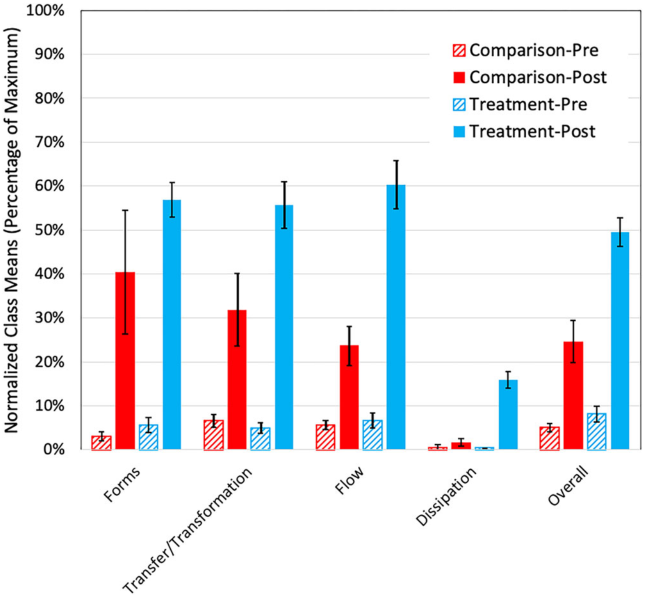


FIGURE 11 Average pre- and post-instruction scores in each scoring category for Comparison (*N* = 6) and Treatment (*N* = 15) classrooms. All values are expressed as a percentage of the maximum score in the category (3 for Overall, 2 for all other categories). The unit of analysis is the classroom. Bar heights represent the arithmetic mean of the mean scores for the individual classrooms; error bars represent one standard error of the mean. In the Comparison classrooms 133 students completed the pretest and 104 completed the posttest; the corresponding numbers were 240 and 238 for the Treatment classrooms

Table 7 summarizes the results of our hierarchical modeling. Columns 1, 3, 5, 7, 9 show a null model that treats all classes as equivalent, distinguishing *between-class* from *within-class* variance in student gains. As shown by the intraclass correlation (ICC), only 7% (Dissipation) to 33% (Forms) can be attributed to differences between classes, with a mean of 20%. Our analysis asks how much of that class-to-class variation can be attributed to the curriculum (Treatment/Comparison). We did not include any student-level predictors.

The hierarchical analysis confirms the tentative conclusions drawn from Figure 11: That there are significant gains from instruction for both Treatment and Comparison classes, but that the gains are significantly greater for the Treatment classes. Columns 2, 4, 6, 8, and 10 reflect a model that compares Treatment and Comparison classes. The values in the “Constant” row represent the gain from business-as-usual instruction, and values in the “Treatment” row indicate *additional* gains for students in Treatment classrooms. The “Constant” values demonstrate significant learning in business-as-usual classes, except in Dissipation. The “Treatment” values are large and, except in the Forms category, highly statistically significant ($p < 0.01$).

Since the comparison classrooms were all in the Boston area, we checked for differences between the Boston and Seattle Treatment classes, to see whether the greater gains in the Treatment category could be due to higher achievement in the Seattle schools. Pre-test scores were significantly higher than those in Boston for Forms and Overall Coherence, suggesting some regional difference in energy education in the early grades. Posttest scores and gains, however, did not differ significantly between the two regions, so our conclusions are not an artifact of regional differences. We also explored models that included grade level and Title 1 status as variables, but the small number of classrooms in some of the categories makes any interpretation questionable, since the influence of an individual teacher or school environment could dominate the results.

These analyses show that, on average, students in *Focus on Energy* classrooms exhibited gains in all five of the categories of the Sparklz assessments that were both large in magnitude and, except for Forms,

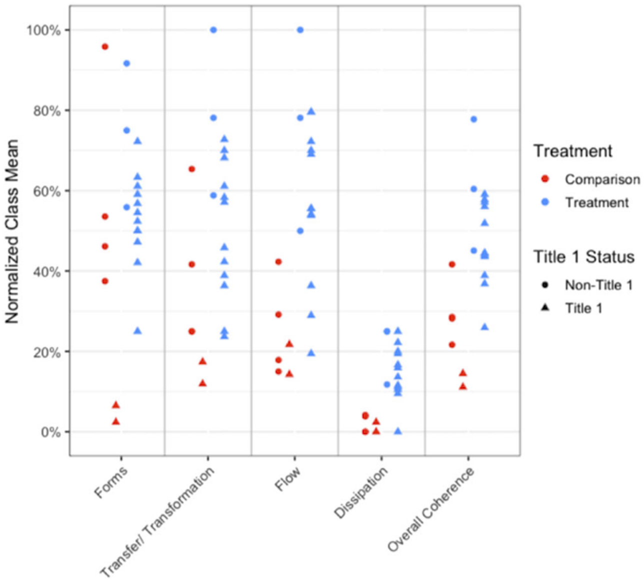


FIGURE 12 Normalized mean scores (percent of maximum possible) for individual classrooms on post-instruction assessments, showing variability within Treatment and Title 1 groupings

TABLE 7 Results of hierarchical modeling

	Forms		Transfers/ Transformations		Flow		Dissipation		Overall Coherence	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Constant	0.94***	0.73***	0.85***	0.44**	0.85***	0.33*	0.22***	0.01	1.04***	0.55***
Treatment		**0.31**		**0.56****		**0.73*****		**0.29*****		**0.68*****
	Model Fit and Variance Components									
AIC	644	644	832	825	867	855	493	481	804	794
BIC	655	659	843	840	878	870	505	496	815	809
Intercept	0.18	0.16	0.14	0.07	0.18	0.06	0.02	0.00	0.19	0.08
Residual	0.37	0.37	0.68	0.69	0.76	0.76	0.25	0.25	0.62	0.62
ICC	0.33	0.31	0.17	0.10	0.19	0.07	0.07	0.01	0.23	0.12
Explained compared to null		0.12		0.49		0.66		0.84		0.57

Note: All measures on a 2-point (0,1,2) scale except Overall which is a 3-point (0,1,2,3) scale. Differences can range from −2 to 2 or −3 to 3. There are 324 student difference scores for each variable, grouped into 21 classrooms. Columns 2, 4, 6, 8, and 10 compare gains in Treatment classrooms with those in Comparison classrooms.

$^{*}p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$.

significantly greater than those in business-as-usual classes. Students using our curriculum showed much higher ability to identify instances of transfer and transformation, and to track the flow of energy. Only in the Treatment classes did any significant number of students show awareness of energy dissipation (Tobin et al., 2019).

7 | CONCLUSIONS

The concept of a Learning Progression anticipates that understanding of a complex concept, such as energy, develops over time, starting from students existing resources, and implies that curriculum design should support that gradual development (Jin et al., 2019; National Research Council, 2007). In the case of energy, the ideas of forms, transfer, transformation and flow are interdependent, and must develop in parallel (Lacy et al., 2014; Neumann et al., 2013; Papadouris & Constantinou, 2016). But there has been little empirical evidence of what that progression might look like in the elementary grades or how a curriculum might support it. This study supports that model of gradual learning by providing evidence for the success of one innovative curriculum based on a Learning Progression framework. Our results also offer some illustrations of the richness of student reasoning that the curriculum promotes.

The *Focus on Energy* curriculum was carefully designed and iteratively revised to support growth in elementary students' understanding of energy ideas, their ability to work with them to track energy flow in complex real-world situations, and their ability and agency in building and applying a scientific model of energy. These gains in understanding and skill were observed in diverse student populations, and the quantitative data show that, on average, they were significantly greater than for comparison students receiving standard energy-related physical science instruction.

Even in the classrooms in which the teacher did not follow all aspects of the intended pedagogical approach, students were able to articulate the energy story of the phenomenon under investigation. The curriculum provides multiple channels for building students' reasoning about energy and skills in the practices of science, and multiple contexts in which sensemaking can occur. This multiplicity of supports may help students with various learning styles and backgrounds, and may also provide some degree of robustness when teachers have varying degrees of comfort with a more student-centered instructional approach or latitude to adopt such an approach. Since the completion of this pilot project, we have provided one-day training (in contrast to the week-long workshop experienced by the self-selected teachers in this study) to all grade-level teachers in several communities that have implemented the curriculum district-wide. In consultation with the treatment teachers, we identified and developed additional resources to support teachers who would not have the opportunity to participate in a summer workshop. These include a suite of resources (TERC, 2017) about using energy representations as pedagogical tools, classroom activity set-up videos, and classroom video illuminating content that we observed was pedagogically challenging, including small group learning, how to start the model of energy, introducing energy cubes, and introducing additional forms of energy. While we have not been able to conduct a systematic assessment, reports from the districts, and qualitative examination of samples of student work, are encouraging, suggesting that much of the student progress reported here is also observed in those classrooms.

We do not have comparative data that would allow us to isolate the key curricular elements that are responsible for these positive results. Based on our observations and feedback from teachers, we suggest that essential features include:

- Carefully designed and sequenced activities that are simple without being simplistic, provide opportunities for student exploration and investigation, and gradually increase in complexity and sophistication;
- A consistent lesson structure, analytical framework (ETL), and language used throughout the curriculum;
- A modeling-based stance that supports reasoning both from observation and by inference from the model, and that empowers students to construct, reason with, and revise their own models, rather than relying on authority to provide the “right” answer;
- Consistent and repeated use of versatile and accessible representational tools (energy bars and cubes, as well as oral and written communication);
- Multiple opportunities and modalities for individual, small-group, and all-class meaning-making;

- Integrated professional development that includes close attention to both the science and the pedagogical approach, supplemented by ample support materials. It has been our experience that adult teachers often share many of the same ideas about energy held by their students, and benefit from experiencing the same curriculum – the same activities, representational tools, group work, meaning-making, model-building, etc. At the same time, however, we also devoted explicit attention to how the curriculum is constructed and presented, and how they can do an effective job of leading it themselves. To support them when they returned to the classroom, we created on online library of written and video resources.

Another important characteristic is the conscious decision not to try to do everything. In this project we chose to omit important energy concepts, including gravitational potential energy, energy degradation, energy conservation as an explicit principle, and chemical energy associated with foods and fuels. Other choices are certainly possible, and a curriculum more oriented towards the life sciences or engineering might well take a different approach, but bounding the content and goals is crucial.

This list of characteristics is not novel, or specific to energy instruction; it is consistent with general principles of high-quality, practice-based science instruction and reflects the research about modeling-based teaching and learning cited in the theoretical framework section. Our work contributes a specific example of how those principles can be implemented in the particularly challenging context of an elementary school energy curriculum—one that is age-appropriate, scientifically sound, pedagogically effective, and feasible for teachers in diverse classrooms. Our work may also offer a model for a process of developing and assessing such curricula in other subject areas.

This project was a development initiative, not an efficacy study. We used a quasi-experimental design, with a limited number of schools and classrooms. Some of the positive effects observed may be due simply to greater time-on-task in the classroom. We do not have detailed information about the curricula used in the Comparison classes, or to what extent energy concepts were emphasized (as opposed, e.g., to principles of electrical circuits). The Treatment teachers—volunteers who received an intensive week-long PD workshop and ongoing PLC support—may also have been more committed both to teaching energy ideas and to the assessments. A much more extensive study would be needed to assess how well these results would stand up if the curriculum were adopted on a wide scale.

Our results also raise many questions for further investigation: What do students understand the energy cubes, and their manipulation of them, as representing? To what extent can and do they use the Energy Lens in other contexts, both in school and in everyday life? What kind of curriculum in later grades would build effectively on the foundation established in this project? How can this approach be extended to energy in chemistry and biology, where transfer and transformation of energy is often accompanied by transfer and transformation of matter?

Notwithstanding these limitations, this study extends our understanding of what energy learning is possible in elementary school. There has been debate about the readiness of elementary students to learn about energy (Koliopoulos et al., 2009, Papadouris & Constantinou, 2016; Solomon, 1986; Trumper, 1993; Van Hook & Huziak-Clark, 2008; J. Warren, 1986). Because energy is an abstract concept, reasoning about it requires sophisticated science practices, particularly in the area of model-based reasoning. Moreover, since energy reasoning is fundamentally a matter of quantitative accounting, it was far from clear that children in fourth or fifth grade, with a limited mathematical toolkit, could engage in it successfully. Our results provide strong evidence that, with appropriate guidance and support, and adequate teacher preparation, elementary students of diverse backgrounds can and do engage effectively in those practices and make striking gains in understanding and using key foundational energy ideas. We anticipate that the strong foundation in energy reasoning developed in *Focus on Energy* will provide students with the groundwork to master those concepts in future grades, but additional research will be needed to confirm that expectation.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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SUPPORTING INFORMATION

Additional supporting information may be found in the online version of the article at the publisher's website.

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