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RESEARCH ARTICLE

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Model-based reasoning about energy: A fourth-grade case study

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Abstract

We report a case study of model-based reasoning in which a small group of fourth-grade students analyzes the energy flow when a solar panel is used to power an electric motor that spins a propeller. In developing their explanation of energy flow, the students draw on a general model of energy developed collectively by their class in the course of an experimental classroom curriculum led by a trained teacher. They also construct a model-based representation of the specific system under study. Their investigation and reasoning process exhibit all the features of authentic scientific model-based inquiry, including the revision of their models to incorporate new information. In the course of their work the students recruit and seamlessly integrate nearly all of the practices of science designated in the Next Generation Science Standards. This case study provides an example of what modeling-based teaching and learning can look like in an elementary school classroom. It also suggests that the study of energy offers a particularly promising context for developing students' use of science practices, especially the practice of developing and using models.

KEYWORDS
energy, scientific modeling, scientific practice, student learning

1 | INTRODUCTION

There is by now an extensive literature persuasively advocating a central role for model-based reasoning in science instruction at all grade levels (Gilbert & Justi, 2016; Lehrer & Schauble, 2006a; Louca & Zacharia, 2012; Passmore, Stewart, & Cartier, 2009; Schwarz et al., 2009; Windschitl, Thompson, & Braaten, 2008; among many). Yet it is clear that effectively implementing modeling-based teaching and learning, especially in the early grades, is challenging for teachers, teacher educators, and curriculum designers. Moreover, only a few empirical studies report on modeling-based teaching and learning in the elementary grades (Acher, Arcà, & Sanmartí, 2007; Forbes, Zangori, & Schwarz, 2015; Forbes, Vo, Zangori, & Schwarz, 2015; Kenyon, Schwarz, & Hug, 2008; Lehrer & Schauble, 2004; Manz, 2012; Schwarz et al., 2009).

This study adds to and enriches that work by providing an in-depth look at model-based reasoning as practiced by fourth-grade students in the context of energy. We present a close analysis of a selected case study in which a small group of fourth grade students analyzed the energy flow that occurs when a solar panel powers a motor to spin a propeller. Since modeling is a complex practice that can be manifested in many disparate forms and representations, it is valuable to develop and document a diverse set of cases, across multiple content areas. Further, this "thick" case-study approach enables us to examine the students' complex verbal and nonverbal interactions for manifestations of key aspects of modeling-based reasoning, and for evidence of the other practices of science that undergird that reasoning. We find evidence that the students' work includes all the key characteristics of authentic scientific modeling, in an informal and qualitative form appropriate to their grade level. In support of their inquiry, they use and integrate almost all of the NGSS practices of science (NGSS Lead States, 2013) to construct a model-based explanation of energy flow.

2 | BACKGROUND AND CONCEPTUAL FRAMEWORK

The student activity that we focus on in this study took place in the context of *Focus on Energy*, an experimental program of instruction and professional development aimed at teaching scientific concepts of energy to fourth- and fifth-grade students and their teachers. Thanks to its conceptual importance in all fields of science and engineering, and its relevance to important societal issues, energy is widely acknowledged as a vital topic for K-12 science education (Duit, 2014; Jin & Anderson, 2012; National Research Council, 2012), and is mentioned more than 150 times in the Next Generation Science Standards (NGSS Lead States, 2013). At the same time, numerous assessments have shown that existing instructional approaches are largely ineffective in bringing students to the kind of integrated understanding of energy that is needed for the meaningful application of energy ideas (Duit, 2014; Herrmann-Abell & DeBoer, 2017; Liu & McKeough, 2005; Neumann, Viering, Boone, & Fischer, 2013).

Our novel approach to teaching and learning about energy in the early grades draws on three key conceptual strands, relating to (1) our overall approach to the design of science curricula in general; (2) our approach to the specific challenge of teaching and learning about the concept of energy in elementary school; and (3) our approach to modeling-based teaching and learning, both as a part of the curriculum and as a subject for analysis. This article is concerned primarily with the third strand, so it will be discussed in some detail. For contextual purposes, however, we first provide brief discussions of the first two.

Our overall approach to designing science curriculum centers on the concept of science as practice (Lehrer & Schauble, 2006b; National Research Council, 2007, 2012; NGSS Lead States, 2013; Stroupe, 2014), emphasizing that the teaching and learning of the content of science should be integrated with a developing understanding and experience in the practices of science, leading to an understanding of science as a way of knowing rather than as a fixed body of facts. The structure of the *Focus on Energy* curriculum calls upon the students to engage in nearly all of the NGSS science practices. Beyond students' engagement in specific practices, however, the vision of science as practice also involves students acting as epistemic agents "who take, or are granted, responsibility for shaping the knowledge and practice of a community" (Stroupe, 2014). In the *Focus on Energy* curriculum students collectively build and learn to use a working model of energy through a sequence of guided investigations, and their sense of responsibility and empowerment for sense-making is manifest in this case study.

The second strand is the theory of learning progressions (Corcoran, Mosher, & Rogat, 2009; Herrmann-Abell & DeBoer, 2017; Jin & Anderson, 2012; Lacy, Tobin, Wiser, & Crissman, 2014; National Research Council, 2007; Neumann et al., 2013; Nordine, Krajcik, & Fortus, 2010; Schwarz et al., 2009), which emphasizes that the learning of complex scientific ideas like energy occurs in stages and often over periods of years. Researchers in energy teaching and learning have 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. These ideas, however, are interdependent and cannot be learned sequentially or in isolation (Duit, 2014; Herrmann-Abell & DeBoer, 2017; Lacy et al., 2014; Neumann et al., 2013). In particular, energy conservation, which is the ultimate goal of energy education, cannot be understood or believed without an understanding of dissipation, which in turn cannot be understood without a clear conception of forms, transfers, and transformations—and indeed without at least a tentative belief in conservation itself. Further, using the energy concept requires integration of these themes in order to trace energy flow in real systems that usually involve multiple components and are almost invariably dissipative (Jin & Anderson, 2012; Lee & Liu, 2009; Nordine et al., 2010).

Learning progressions for energy, therefore, do not move sequentially from one theme to the next but rather focus on systematically developing students' 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., 2010). 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.

The third strand, and the one that is the primary focus of this article, is that of modeling-based teaching and learning (Acher et al., 2007; Etkina, Warren, & Gentile, 2006; Forbes, Zangori, et al., 2015; Gilbert & Justi, 2016; Hestenes, 1987; Krajcik & Merritt, 2012; Lehrer & Schauble, 2006a; Louca & Zacharia, 2012; Manz, 2012; Passmore et al., 2009; Schwarz & White, 2005; Schwarz et al., 2009; Ward, 2016; Windschitl, Thompson, & Braaten, 2008). 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, Trygstad, & Banilower, 2016). And since the construction of explanations depends on the development and use of models, the practice of model-based reasoning is of particular importance (Gilbert & Justi, 2016; Lehrer & Schauble, 2006a; National Research Council, 2007; Pasley et al., 2016; Passmore et al., 2009; Texley, 2014; Windschitl et al., 2008). As Passmore et al. (2009) put it, "The development, use, assessment, and revision of models and related explanations play a central role in scientific inquiry and should be a prominent feature of students' science education." Yet modeling practices tend to be underemphasized in school science, particularly in the elementary grades (Forbes, Zangori, et al., 2015; National Research Council, 2007; Schwarz et al., 2009; Windschitl et al., 2008). Forbes, Zangori, et al. (2015) emphasize the need for "consistent, coherent, and integrated opportunities to engage in scientific modeling," and the critical role of instructional and curricular support for early learners.

Since energy is an inherently abstract concept, the study of energy both demands and is an ideal context for modeling-based teaching and learning. At a fundamental level, *all* analysis involving energy is model-based, since energy itself cannot be directly observed. Its presence, changes, transfers, and transformations are inferred from observations and reasoning based on a conceptual model of what energy is, how it is manifested in various phenomena, and how it behaves. In our curriculum, students collectively develop a working model of energy through a carefully structured sequence of classroom activities and group discussions. From this perspective the entire *Focus on Energy* curriculum—and, we would argue, *any* energy curriculum that develops skills in reasoning using energy concepts—revolves around the practice of developing and using models.

On a more specific level, the students must decide, within their general model of energy, how to represent and analyze *the specific scenario* at hand, whether it is two balls colliding, or a cup of hot water cooling, or, as in this study, a solar cell driving a propeller. As the class moves through investigations of increasing complexity, the students use a consistent language and set of energy tracking questions to collectively build a model of energy, and learn to use the model to construct explanations of energy flow in diverse contexts. In each scenario they must choose which physical components to include, what forms of energy are involved, and where in the process energy transfers and transformations are taking place.

In the vision of K-12 science education described in the *Framework* (National Research Council, 2012) and the NGSS (NGSS Lead States, 2013), "developing and using models" appears as but one of eight practices of science in which students should be engaged. But as others have argued (Gilbert & Justi, 2016; Pasley et al., 2016), modeling is in fact a pre-eminent practice and moreover one that of necessity requires almost all of the others. So a secondary focus of this study is to uncover the presence of those other practices within the students' overall activity in model-based reasoning, and to elucidate how those practices contribute to that activity.

The study presented here comes from the first of three years of implementation and evaluation of a curriculum development project. Our development process adopts the approach of design research (Collins, Joseph, & Bielaczyc, 2004), using an iterative process of implementation, evaluation—through reviews of student work, teacher reports, and classroom visits—and revision of activities, assessment probes, teacher guides and professional development to improve classroom feasibility, fidelity of implementation and student comprehension. This study represents a first qualitative look at whether our approach is leading to the kinds of model-based reasoning about energy targeted by the project, and the extent to which the students are engaging in practices of science as they seek to arrive at an explanation of energy flow in a relatively complex system. Subsequent iterations will include systematic assessments of learning gains and comparisons with control classrooms, which will be reported in future publications.

In the present work we take a case-study approach (Yin, 1994) to examine how a small group of fourth-grade students used model-based reasoning, supported by multiple practices of science, as they developed an explanation of the flow of energy when a solar cell was used to drive an electric motor attached to a propeller. We seek to address the research questions:

> RQ1:What aspects of scientific modeling do the students exhibit in analyzing this scenario?
>
> RQ2:What other practices of science did the students use, and how did they contribute to the activity of modeling?
>
> RQ3:When fourth-grade students use model-based reasoning in the context of an energy analysis, how do they interact with each other, with their teacher, and with their representational tools?

Because of the limited scope of the investigation—a single group of students in a particular classroom engaged in a particular task—we do not aim to make causal or generalizable claims. Rather this should be viewed as an exploratory study that suggests possible avenues for future research, and as an illustrative example of what model-based reasoning and the integrated use of multiple practices of science can look like in an elementary-school energy investigation.

3 | THE *FOCUS ON ENERGY* INSTRUCTIONAL PROGRAM

The *Focus on Energy* instructional program incorporates newly developed hands-on investigations, curricular materials, a week-long summer professional development workshop for teachers, teacher support materials, an ongoing professional learning community, and both formative and summative assessment tools. Learners, both teachers and students, are guided through a series of carefully sequenced activities to construct and revise for themselves a partial version of the prevailing scientific model of energy, and to learn to use that model to represent, understand, and explain the flow of energy in a variety of scenarios of increasing complexity.

3.1 | The energy tracking lens

Energy is a powerful scientific concept, and it is unique in the new vision of science education in that it is both a disciplinary core idea in physical science and a crosscutting concept that has relevance in all fields of science and engineering (NGSS Lead States, 2013). But it is unusual, and unusually challenging, in that it does not provide the mechanistic, causal explanations that we often seek in science. Energy arguments can help us understand, for example, that the energy for (most) life on Earth comes from the sun, but they do little to elucidate how photosynthesis works. There is little use in learning facts, definitions, rules, and categories about energy without also learning what kinds of questions energy reasoning can address and how to use energy arguments to analyze and interpret real-world phenomena. In *Focus on Energy*, students learn to use what we call the "Energy Tracking Lens" (ETL) (Crissman, Lacy, Nordine, & Tobin, 2015; Lacy et al., 2014).

Using the ETL means asking the same set of questions about virtually any phenomenon:

> 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.

This set of questions implicitly creates a framework for constructing and using a model of energy, and represents a subtle but critical epistemic shift from a focus on what energy *is* or on simply classifying forms, to a focus on what kinds of *questions* the concept of energy enables us to ask and answer.

By beginning and ending with observations, the ETL emphasizes that even though energy itself is not directly observable, an energy model of any phenomenon must be grounded in observable aspects of the phenomenon. The questions in Part 2 of the ETL suggest that energy is associated with specific components (objects or systems of objects), that it can be manifested in different forms with different observable indicators (e.g. speed, deformation, temperature), that it can be present in different amounts, and that it can move among components and change from one form to another. Finally, the question "Where does the energy come from and where does the energy go?" hints at the principle of conservation. It suggests that, rather than assuming that energy can simply appear or disappear, it always makes

TABLE 1 Motion/elastic energy unit activities

Session/activity	Target model elements	Representation	Related NGSS items
1 Rolling ball	All moving objects have motion energy. Speed is an indicator of amount of motion energy of an object: higher speed ↔ more energy.	Cards with symbols (no motion, some motion, lots of motion).	DCI: 4-PS3.A 4-PS3.B PE: 4-PS3-1 4-PS3-3 4-PS3–4 MS-PS3–5 CCC: Energy and Matter
2 Colliding balls	Motion energy can be transferred between objects through collisions. Stronger interactions (e.g., bigger collisions) transfer more motion energy.	Students' sketches Energy bars	
3a Springboard pom-pom launcher	An elastic object is any object that returns to its original shape after being bent, twisted, stretched, compressed, or otherwise deformed. Elastic objects that are deformed have elastic energy.	Students' sketches Energy bars	
3b Springboard pom-pom launcher	If an elastic object changes its shape more, its elastic energy has increased. The amount that an elastic object's shape is changed is an indicator of how much elastic energy it has.	Energy cubes	
4 Rubber band and propeller	Elastic energy can be transformed into motion energy (and vice versa).	Students' sketches Energy cubes	

sense to look for a source and a recipient for the energy, even when it appears that the phenomenon has ended (e.g., when a rolling ball comes to a stop.)

The ETL framework is provided by the *Focus on Energy* curriculum, and indeed provides its organizing theme, and it is deliberately presented as a set of questions, not as a set of rigid rules. As they conduct their investigations, students wrestle with the questions, creating and revising their own provisional model of what energy is and how it behaves and using that model, in combination with the ETL, to construct explanations of energy flow in a range of diverse contexts.

3.2 | Classroom activities

Teachers and students learn to ask and answer the ETL questions about increasingly complex scenarios involving mechanical, thermal, and electrical phenomena. Each unit comprises three to five 50–60 min lessons. Tables 1–3 list for each lesson the activities, the targeted elements of the energy model, and the representational tools used. Each investigation presents a specific physical scenario and centers on an investigation question that is related to one or more aspects of the energy model. Students first

TABLE 2 Thermal energy unit activities

Session/activity	Target model elements	Representations	Related NGSS items
1 Temperatures of warm, cool and room-temperature water	All objects with a temperature have thermal energy. Temperature is an indicator of amount of thermal energy of an object. Higher temperature ↔ more energy.	Energy bars Arrows to show flow	DCI: 4-PS3.A MS-PS3.B PE: 4-PS3-2 CCC: Energy and Matter Systems and System Models
2 Room temperature rock submerged in warm water.	Thermal energy can be transferred between objects through contact. Thermal energy transfers spontaneously from hotter (higher temperature) objects to cooler (lower temperature) objects.	Energy bars Energy cubes	
3 Warm rock in closed box	Some of the thermal energy of a warm object is transferred to the environment.	Energy bars Energy cubes	

express initial ideas and expectations, and then carry out a hands-on investigation, acquiring evidence to address the question. Finally, they tell the energy story using words, pictures and abstract representations, and discuss their observations both in small groups and in whole-class discussion, drawing on the evidence from the investigation as well as their own intellectual resources. Regardless of the particular phenomenon under investigation, the ETL questions provide the framework for "telling the energy story." In the framing of Gilbert and Justi (2016, p. 58), each investigation, and the curriculum as a whole, establishes a "socio-interactive constructivist teaching [context] in which knowledge building results from student(s)–student(s), student(s)–teacher, and student–resource interactions."

We begin with motion, having found that children readily associate motion with energy. Elastic energy is introduced through its ability to transform into motion energy. (We deliberately avoid the terms "kinetic" and "potential" as unnecessary and possibly misleading.) In these simple scenarios students are already identifying forms of energy and tracking the transfer of energy between objects and transformation from one form to another. For these forms of energy the indicators of amount of energy (speed and deformation) are directly visible and accessible (Nordine et al., 2010).

The next unit involves thermal energy, focusing attention on the idea that energy gains and losses always occur together, and bringing to the foreground the difference between the *indicator* of energy for a given object (in this case temperature) and the actual amount of energy, which can depend on such other factors as the mass and composition of the object (Nordine et al., 2010). The final investigation in the thermal energy unit highlights dissipation into the environment and helps students understand that energy can be transferred into the environment without a perceptible change in temperature. In the third unit we turn to electrical phenomena, which are valuable because our interviews show that children generally accept that batteries "have energy," and because electrical phenomena offer rich possibilities for transfers and transformations. Because there is no directly perceptible indicator of the presence or amount of electrical energy—until it has been transformed into some other form such as motion, light, sound, or heat—reasoning about electrical energy depends heavily on model-based inference.

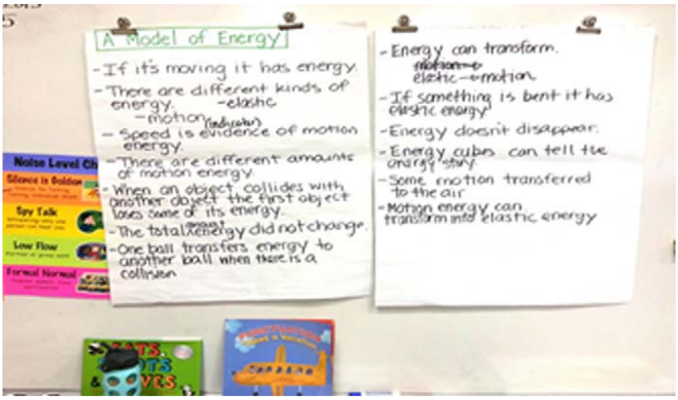
TABLE 3 Electrical energy unit activities

Session/activity	Target model elements	Representations	Related NGSS items
1 Hand-cranked generator and motor with propeller	There is no easily perceptible indicator that an object has electrical energy. The presence of electrical energy can be inferred by its transformation into another kind of energy (such as motion or thermal energy). Electrical energy can be transferred between objects through wires. Electrical energy can be transformed into motion energy by a motor. Motion energy can be transformed into electrical energy by a generator.	Students' sketches Energy cubes	DCI: 4-PS3.A 4-PS3.B PE: 4-PS3-2 4-PS3–4 CCC: Energy and Matter Systems and System Models
2 Using generator to store energy in a capacitor and using it to drive motor/propeller.	Electrical energy can be stored in a capacitor.	Energy cubes	
3a Driving the propeller using a solar cell	Light is a carrier of energy. Light energy can be transformed into electrical energy by a solar cell.	Students' sketches Energy cubes	
3b Driving the propeller using a solar cell		Students' posters	

Through the sequence of *Focus on Energy* activities, the class collectively builds and revises an emerging and increasingly broad and sophisticated model of energy—one that is still incomplete but that can provide a sound basis for future learning. At the conclusion of each unit, the class revisits the model, adding new ideas and solidifying, refining, generalizing, or in some cases deleting previous ideas. Guided by their teacher, the ETL and the structure of the curriculum, the students, individually and collectively, embrace the role of epistemic agents (Stroupe, 2014) defining and applying the principles of energy explanations. Figure 1 shows posters summarizing one class's emerging model near the conclusion of their work on motion and elastic energy.

3.3 | Representations

Telling the energy story for a particular phenomenon, or scenario, requires tracking at least relative amounts of energy associated with different objects and in different forms. In higher grades, mathematical expressions, like the formula $KE = \frac{1}{2} mv^2$ relating kinetic (motion) energy to the mass and speed



A Model of Energy

- If it's moving it has energy.
- There are different kinds of energy. -elastic -motion (indicator)
- Speed is 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 another ball when there is a collision

- 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 1 Posters in one classroom showing the developing model of energy at the conclusion of their work with motion and elastic energy [Color figure can be viewed at wileyonlinelibrary.com]

of an object, allow amounts of energy to be calculated in standard units and compared, at least in some cases. For younger students we introduce representational schemes that allow them to track energy flow in a flexible, context-independent way that emphasizes that the mode of analysis (ETL) remains the same across dissimilar contexts. The representational scheme for each activity is listed in Tables 1–3. As many authors have emphasized (Acher et al., 2007; Forbes, Vo, et al., 2015; Gilbert & Justi, 2016; Greeno & Hall, 1997; Manz, 2012), representational systems that make model-based reasoning visible and public are an essential component of what Windschitl and Thompson (2013) term the “modeling toolkit.”

We have previously reported on students’ use of one representation, 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. This representation focuses on gains and losses by different objects—when one object gains energy another loses energy.

The energy bars representation is accessible to children as young as third grade, but has limitations: It is static, does not lend itself to representing transformations, and is awkward in cases where multiple objects and systems are involved in the scenario. In this article, we focus on students’ use of a more dynamic and flexible representational scheme, Energy Cubes (Scherr, Close, Close, & Vokos, 2012), that engages students kinesthetically as well as analytically. Units of energy are represented by small cubes similar to dice. The amount of energy represented by each cube is arbitrary and context dependent, and is never specified quantitatively. All that matters to the representation is that the amount of energy represented by a cube does not change as the scenario progresses, and that each cube represents the same amount of energy, so that the number of cubes acts as a proxy for the amount of energy. Sides of the cubes are marked with letters or colors to represent different energy forms. Circles drawn on a piece of paper or whiteboard represent different objects. As they proceed through the scenario, students negotiate which objects to represent and how to tell the energy story by moving cubes from one circle to another to represent energy transfer between components of the system, and flipping the cubes to show different labels on the top face to represent energy transformation. Since the number of cubes is fixed, the idea of conservation is implicitly built into the representation.

Both students and teachers found these representations intuitive and engaging, and quickly became fluent in using them both as tools to reason with and as a way to communicate their ideas to one another. One teacher remarked, “They used the energy cubes … and that really helped them explain what they were thinking because the cubes were concrete and tangible.”

3.4 | Professional development

This study focuses on the students, and, as we will show, the teacher's direct interventions in this case study were very limited. Nevertheless, the teacher of course played a crucial role in bringing the class to the point where these students could engage in this activity, so a brief description of the teacher's preparation is a necessary part of the context. As many authors have observed, successful modeling-based teaching and learning places high demands on teachers, demands that conventional teacher training and professional development rarely equip them to meet (Borko, 2016; Gilbert & Justi, 2016; Osborne, 2014; Schwarz et al., 2009; Ward, 2016; Windschitl et al., 2008). Many teachers, moreover, hold ideas about models and modeling that are not consistent with scientific understandings (Justi & Gilbert, 2003; Van Driel & Verloop, 1999). The teachers in the *Focus on Energy* program, including the one involved in this study, engaged in intensive professional development that incorporated the key components of effective PD (Borko, 2016; Gilbert & Justi, 2016): It was content-focused and student-focused, provided opportunities for the teachers themselves to participate as active learners using the same curriculum, was collaborative, and was ongoing through a series of professional learning community (PLC) meetings during the school year. The core was a week-long summer workshop during which the teachers experienced the *Focus on Energy* curriculum together as science learners, building their own understanding of energy as a scientific concept and as an analytical tool for reasoning about diverse phenomena. The teachers experienced the activities through the same kind of modeling- and practices-based pedagogy that they are intended to use in their own classrooms, and experienced both the excitement and apprehension of taking responsibility for constructing (with guidance) their own scientific understanding. They also received guidance in listening to and building on students' energy ideas and 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. The teachers were provided with a detailed curriculum guide, and during the PLC meetings had opportunities to discuss and explore their experiences and questions with each other and with the *Focus on Energy* development team.

4 | THE CASE STUDY

In this case study, we follow four fourth-grade students in a suburban elementary school in the northeastern United States who volunteered, along with their classroom teacher, to participate in a single after-school session designed to capture their investigation of an energy phenomenon on video. The teacher had participated in the summer training workshop, and her class, including the students in this study, had completed the *Focus on Energy* curriculum approximately six months before this activity. As shown in Table 3, the *Focus on Energy* curriculum includes solar-cell activities similar to the one studied here, but these students and their teacher had not revisited the curriculum or the activities in the preceding months. Video and audio recordings were collected throughout the activity, and transcribed.[1]

This case was selected for in-depth analysis not because it is necessarily typical of what is seen in the classroom—although in multiple classrooms using the *Focus on Energy* curriculum we have observed all of the key features we see here: energy reasoning using the ETL, model-based reasoning, use of representations and NGSS practices, and students' epistemic agency—but because it provides a particularly clear, concise, and vivid example of students' engaging in model-based reasoning to learn about energy, and developing skills in model-based reasoning through the topic of energy. It was thus selected both for its analytical value in exploring the research questions and for its narrative power in illustrating and elucidating the interplay between model-based reasoning and reasoning about energy (Derry et al., 2010).

The students first took the solar cells and motor–propeller assemblies outdoors and engaged in an unstructured exploration of their behavior, guided by the overall goal of understanding and explaining the flow of energy through the system in the context of the ETL questions. The students worked in pairs and their teacher asked them to explain what they were observing. One question they wrestled with was the nature of the energy from the sun that is used by the solar cell. The curriculum had not dealt explicitly with light as a form or carrier of energy, but thermal energy was an important topic, so they had to consider whether it was the heat from the sun that provided the energy for the system.

They then returned to the classroom, where all four students worked together to interpret, represent, and explain their observations using the energy cube representation. This required them to decide what components of the system should be included in their representation, what forms of energy were present in each, and where in the system the processes of energy transfer and transformation took place.

4.1 | Methodology

To address the research questions in the context of this case study, the authors reviewed the video recordings and transcripts for evidence of key aspects of modeling-based teaching and learning, taking an inductive approach to the selection of episodes and refinement of the research questions and coding categories guided by overarching theoretical questions of the relation of modeling-based learning and teaching to the learning of energy (Derry et al., 2010). Synthesizing the literature on scientific modeling, Louca and Zacharia (2012) identify four fundamental steps: systematic observation, constructing the model, evaluating the model, and revising the model to apply to new situations. For coding purposes, however, these categories lack specificity about what scientists or science learners *do* in order to accomplish the steps, and about the purposes of modeling. In order to characterize the students' modeling activity in greater detail, we found it more helpful to structure our coding around the six attributes of modeling in science identified by Passmore et al. (2009), which provide a finer-grained description of what scientists do in carrying out model-based inquiry:

M1: Engage in inquiry other than controlled experiments;

M2: Use existing models in their inquiries;

M3: Engage in inquiry to develop and revise models;

M4: Use models to construct explanations;

M5: Use models to unify understanding;

M6: Engage in argumentation.

This list is broadly consistent with characteristics of scientific modeling identified by Louca and Zacharia (2012) and other researchers (Gilbert & Justi, 2016; Lehrer & Schauble, 2006a; National Research Council, 2007; Pasley et al., 2016; Texley, 2014; Windschitl et al., 2008).

In addition, in order to highlight connections to the vision of three-dimensional science learning laid out in the National Research Council Framework (2012) and NGSS Lead States (2013), we also coded for evidence that the students engaged in the eight practices of science identified in those documents:

P1. Asking questions

P2. Developing and using models

P3. Planning and carrying out investigations

P4. Analyzing and interpreting data

P5. Using mathematics and computational thinking

P6. Constructing explanations

P7. Engaging in argument from evidence

P8. Obtaining, evaluating, and communicating information

As Gilbert and Justi point out (2016, p. 77), the practice of authentically developing and using models necessarily includes most of the other practices; they identify P5, using mathematics and computational thinking, as the one practice that is not intrinsically involved in model-based inquiry, and indeed it is the only one for which we do not see evidence in our case, simply because the activity at hand does not call for, or lend itself to, mathematical or computational modes of analysis.

We present selected excerpts and images from five episodes during the activity, and describe in detail where, how and why we identified the attributes of authentic model-based reasoning and the various practices of science. The initial coding was carried out by one of the authors (RGT) who is a research scientist familiar with both the theory and practice of scientific modeling. Other authors and collaborators reviewed that analysis and the coding was refined through several cycles of revision and review. The materials were also reviewed independently by a researcher in physics education who is not otherwise associated with the project.

As Gilbert and Justi (2016, p. 35) emphasize, scientific modeling is a “complex, dynamic, nonlinear, and creative cyclical process.” As a result, the identification of specific aspects of modeling and specific practices is inevitably somewhat subjective, drawing on the reviewers’ expertise as scientists, educators, and education researchers, and requiring attention to various size “chunks.” Some aspects and practices can be clearly associated with specific moments, utterances, or gestures, while others are characteristic of a particular episode, or even of the entire activity taken as a whole. For all of these reasons, the coding of specific modeling attributes and practices of sciences is more suggestive than definitive. Nevertheless, while viewers may differ on exactly where and to what extent each aspect of modeling and practice of science is visible in this case, we selected this case for analysis because we believe that the overall picture it presents is clear: These fourth-graders are productively engaging in authentic scientific modeling and seamlessly combining multiple science practices in service of their goal of arriving at a scientific explanation of energy flow in the phenomenon under investigation.

The five selected episodes from the activity are those that most clearly display the students’ engagement in model-based reasoning. The students often express at least as much through physical manipulation of the cubes as verbally, so we have annotated the transcript with descriptions of their actions and gestures. Nevertheless, it is sometimes difficult to fully appreciate their reasoning from the transcript alone. The names given are pseudonyms. The students were highly animated, with multiple students often speaking at once. When it was not possible to identify which student was speaking, the speaker is listed simply as “Student.”

4.1.1 | Episode 1: Is solar energy light or heat?

Working in pairs on a playground outdoors, two students, Melissa and Sarah, connect the wires from the solar panel to the electric motor and observe that when the panel is placed in sunlight, with its active side facing up, and the wires are connected from the panel to the motor, the propeller spins. The teacher poses a question suggested by the curricular materials:

TEACHER: So is it the light of the sun, or is it the heat of the sun?

SARAH: The light of the sun.

MELISSA: The light, because if we turn it this way—

[*Turns solar panel so that active side faces down, towards the pavement. The propeller slows to a stop.*]

MELISSA: —it slowed down.

TEACHER: How does that prove that it's the light of energy, not the heat?

MELISSA: Because if we turn it over, there's not—

MELISSA: There's still heat there. This is still hot if we go here.

[*Places hand below solar panel, between panel and pavement.*]

SARAH: But it can't see the sun.

MELISSA: The temperature doesn't matter.

TEACHER: OK. So the temperature of the air has not changed, so we think that it's the light energy?

MELISSA: Yes. So then if we turn it over, it'll start again.

In this excerpt, the students are engaged in a semi-structured investigation of the phenomenon. They understand, based on the curriculum and their teacher's description of the activity, that the goal will be to engage in systematic inquiry and interpret the results to construct a model-based explanation of energy flow in the system. In pursuit of that goal the teacher has posed a specific question, prompted by the curriculum, related to the nature of the sun's energy: Is it the light or the heat that provides the energy to make the propeller turn? The students devise and carry out an investigation designed to answer it. (It appears in the video that the students are explaining to the teacher a test that they had already performed, not inventing the test on the spot. We know from separate classroom observations that while the teacher posed the question "is it heat or light?" the students themselves devised the investigation of inverting the solar panel.)

4.1.2 | Episode 2: What are the components?

After experimenting with the equipment, the students returned to the classroom and worked collaboratively in a group of four to explain, represent, and communicate the flow of energy through the system using energy cubes. Their first step is to negotiate which components of the system to represent with circles.

TEACHER: What are the components? Let's start there.

[*Kim is drawing and labeling circles on the shared whiteboard.*]
[…]

STUDENT: The sun, the solar panel, the wires, the motor thing, and the propeller.

[. . .]

SARAH: The solar panel and the wires would be one conjoined—

[*Kim pauses after drawing circles for the sun and the solar panel.*]

STUDENT: I think two, because the solar panel—

JASON: No, they're two different—

MELISSA: The solar panel is like a transfer, and then the wires are all electrical.

SARAH: But wouldn't the wires be part of it, too?

KIM: Well, I think the wires should be a box of their own—

MELISSA: Because for solar panel, it transfers into electric—

JASON: —transfers thermal to electric. That's like a transfer.

MELISSA: So it has to be something else

[*Kim adds and labels a circle for the wires.*]

JASON: Wires are all electrical.

[INTERPOSING VOICES]

MELISSA: One of them to the motor and the propeller, together.

[*Kim adds two circles and labels them "motor" and "propeller".*]

SARAH: And then that's the environment.

JASON: No, because the motor transformates the energy, then the propeller—

SARAH: So then we also need the environment—

[*Kim adds a circle in the middle of the whiteboard and labels it "environment air".*]
[. . .]

MELISSA: We should draw arrows.

ALL STUDENTS TOGETHER: Solar panels, then to the wires. Then to the motor, to the propeller, to the environment.

[*As they speak Kim adds arrows connecting the circles in the order described.*]

Here the students have transitioned fully from investigating and observing the physical system to the activity of creating an abstract model of the system with the goal of constructing an explanation of the energy flow. They are using the framework provided by the ETL questions, beginning by identifying the relevant components of the system.

At first sight this part of the process may not appear to represent model-based reasoning: Aren't they just listing the pieces of the apparatus? We would argue that there is much more going on, and that their discussion and their decisions are grounded both in their observations and in their preexisting model of energy. Their decision to treat the wires as a separate component, rather than combining them with the solar panel—even though as physical objects the wires are integrated with the panel, rather than separate objects that the students must attach—is based on the wires' role in the energy story: The solar panel is the component in which energy is transformed from solar energy into electrical energy, while the energy in the wires is "all electrical," so the two elements play different roles in the flow of energy. Similarly, though it is less explicitly expressed, the motor and propeller are represented as separate components because the energy story of the motor involves a transformation from electrical to motion energy, while the propeller's energy is entirely motion. Thus Melissa wants to combine them, and Jason responds, "No, because the motor transformates the energy, then the propeller . . ." before being interrupted by Sarah.

The students also choose to include the environment as a component. While they do not give an explicit reason, and it is possible they have just internalized the rule that you always include the environment, the model of energy they have previously developed implies that the energy from the system cannot just disappear (as represented by the ETL question, "where does the energy go?") but must be transferred into the environment.

In the context of RQ1, then, in this excerpt the students are already fully engaged in model-based reasoning. In terms of specific aspects of scientific modeling, we can clearly see them engaging in argumentation (M6) that is grounded both in their observations and in their existing model of energy (M2).

4.1.3 | Episode 3: What form of energy does the sun provide?

Next, the students begin to track the flow of energy through the system, using the framework of the ETL questions and the energy cube representation. At the outset, with a prompt from the teacher, they face the question of what form of energy to assign to the initial energy from the sun:

> STUDENT: The sun's where it all begins.
>
> TEACHER: So I think the tricky part is we're not really sure what kind of energy that is, right?
>
> STUDENT: Yeah.

[. . .]

> MELISSA: First the sun shines down.
>
> KIM: All thermal.
>
> MELISSA: Well, I think there's a bit of unknown energy in here.
>
> SARAH: Thermal's the sunlight and the heat.

[*The students place six cubes in the sun. Three of them have the "thermal" label facing up. The other three have blank faces up. Melissa reaches in and flips one of the cubes from thermal to blank.*]

> MELISSA: Actually . . . the air, like the thermal energy, it doesn't really matter with this. It's just the light.
>
> STUDENT: Yeah, it's just the light.
>
> MELISSA: But we don't know so I think it should be just like that.

[*Melissa flips the two thermal cubes to blank, so all six cubes now have blank faces up.*]

JASON: No, I think it should be one thermal.

SARAH: One thermal.

[*Sarah flips one cube back from blank to thermal so now there are five blank and one thermal.*]

KIM: Yeah, one thermal, because the sun does give off heat.

[*Melissa gathers the six cubes together in the middle of the sun, without flipping any of them.*]

Here the students revisit the issue of whether the sun's energy comes from light or heat, but now in the context of how to model the energy flow, rather than as an empirical question. Melissa strongly reaffirms the conclusion that she and Sarah reached from their experiments, that it is the light that matters. While she does not explicitly refer to that evidence, it is plausible to infer that she has that observation in mind when she confidently asserts that "the thermal energy, it does not really matter with this." While Sarah and Kim initially agree, Jason claims (and continues to assert throughout the episode) that thermal energy is at least part of the story, and the group compromises by including "one thermal" cube. Melissa's final gesture of gathering the cubes without flipping them seems to signify that she's willing to go along with that result.

At this point the students are entirely engaged in model-based reasoning. Their discussion is not at all about what happened, but entirely about how to *represent* what happened within their model of energy flow in the system. Even in this brief episode we find evidence for nearly all of the attributes of authentic scientific modeling identified by Passmore et al. (2009). We see them engaging in argumentation (M6) about the nature of the sun's energy as it pertains to the system at hand. Their discussion is framed by their existing model of energy (M2) as they seek to construct an explanation (M4) of the energy flow in this system using the same set of representational rules that they have developed in other contexts. In using the same set of rules and representations in this scenario as they used in quite different contexts, such as ball collisions or thermal transfer, they are using their energy model to unify their understanding (M5) of energy flow across diverse phenomena.

Most striking, however, is the evidence that the students are engaging in inquiry to *revise* their model of energy (M3). Their previous investigations led the class to identify four forms of energy: motion, elastic, thermal and electrical. The labels on the cubes represent these forms. Their inquiry into the behavior of the solar cell, however, has led (most of) them to the conclusion that at least some of the sun's energy does not fit into any of those categories. Whatever it is, it is not part of their existing, agreed-upon model of energy. Later in the episode, they make this quite explicit:

SARAH: So the solar panels are unknown—

MELISSA: Unknown—this is still unknown.

TEACHER: Why is this unknown?

[INTERPOSING VOICES]

KIM: It's sunshine.

TEACHER: Well, what do you think happens inside the solar panel?

JASON: It transforms into electric.

FIGURE 2 Students collaboratively discuss and manipulate the energy cubes to decide how best to represent the energy story [Color figure can be viewed at wileyonlinelibrary.com]

They know the energy from the sun must exist, because the solar panel produces electrical energy when sunlight falls on it, and their existing model of energy (represented by the ETL question "where does the energy come from?") requires that there must be an energy input to produce that energy output (M2). But their uncertainty about the nature of that energy does not prevent them from continuing —they simply turn up a blank cube face, accept the form as unknown, and proceed with the model. Through inquiry they have revised their model by inventing, or discovering, a "new" form of energy (M3).

4.1.4 | Episode 4: What is the energy story of the motor?

The students continue to track the energy (M2), negotiating where it transforms from solar to electric to motion, using verbal arguments, gestures, and direct manipulation of the cubes, as illustrated in Figure 2 (M6). This animated exchange typifies their discussion:

SARAH: The motor, it's electric, and I think we should give it a motion [cube] because it's changing—.

[*Sarah places two cubes in motor, one motion and one electric*.]

MELISSA: Actually, two electric.

[*Melissa moves a cube from wires to propeller and flips it to motion*.]

JASON: No, it's all electric!

[*Sarah flips the motion cube to electric, so now there are two electric cubes in the motor*.]

JASON: It's also motion, because it's transferring from this to this.

[*Jason gestures from motor to propeller*.]
[*Melissa taps her finger in the motor*.]

JASON: This transfers to motion, this transformation.

MELISSA: This has electric and motion, because in the motor, that's when it transfers from electric to motion.

[*Melissa flips one of the electric cubes in motor to motion, but Sarah immediately flips it back to electric*.]

KIM: Yeah, I agree with [Melissa].

[*Kim gestures to motor*.]

SARAH: No, but it starts as electric, then goes to here.

MELISSA: So we should have this here, and then this over here, because it goes in as motion and then transfers.

[*Melissa gestures from wires to motor*.]
[*Eventually the students place one electric cube in the motor at the point where the arrow from the wires touches the motor circle, and a second, motion cube at the point where the arrow to the propeller leaves the motor circle*.]

4.1.5 | Episode 5: How do we model and represent a continuous flow of energy?

As they try to track the flow of energy through the system (M2), they begin to wrestle with a new issue: Unlike most of the previous examples they have modeled, in which there was a fixed amount of energy (such as the elastic energy stored in a twisted rubber band) that flowed through the system once, the sun provides energy continuously. This requires them to revise their previous model (M3) and adapt their representational system to accommodate this new circumstance (M5).

[*Melissa and Sarah move all six cubes from the sun into the solar panel*.]

JASON: Wait. We need to leave some in the sun because the sun doesn't give all of its energy.

FIGURE 3 The whiteboard shows cubes in all of the circles, representing the fact that there is a continuous flow of energy through the system [Color figure can be viewed at wileyonlinelibrary.com]

SARAH: The sun keeps going throughout this whole cycle.

[*Sarah moves one cube back into the sun and makes a large circular gesture with her hand over the whiteboard.*]

STUDENT: The sun doesn't just stop automatically.

JASON: And then the wires . . .

KIM: So the wires have electric

[*Sarah and Kim move four cubes from the solar panel into the wires and, along with Jason, flip them so the "electric" side is facing up.*]

MELISSA: Leave two in here. Leave two in here.

STUDENT: No.

[*Melissa and Kim hold two cubes in the solar panel, but Sarah grabs one and moves it to the wires.*]

SARAH: The solar panel doesn't keep having light, though. It doesn't keep having it, though. It transfers all of its energy.

[INTERPOSING VOICES]

JASON: Yeah, but it still collects energy.

[. . .]

[*After much discussion, the students arrive at a configuration with one blank cube in the sun, one blank cube in the solar panel, one "electric" cube in the wires, one "electric" and one "motion" cube in the motor, and one "motion" cube in the propeller, as shown in Fig.* 3.*]*

MELISSA: Oh, we need one more.

[*Melissa points to the environment circle.*]

JASON: Can we just draw it?

[INTERPOSING VOICES]

JASON: No no no. We don't need to. Draw an arrow to here.

[*Jason gestures from the environment to the sun.*]

JASON: because the environment is the sun, basically. So then it starts all over again.

[*Jason makes a rapid circular gesture over the board.*]

The students have revised their approach to modeling and representing energy flow to incorporate the case of continuous flow (M3), and their effort to use their existing model to represent the energy flow has forced them to think about how to account for the energy flow in such a case (M2, M5). Jason suggests, erroneously, that the energy returns to the sun and cycles through the system indefinitely. The other students do not directly contradict him, but they also do not explicitly agree, or take up his suggestion to add an arrow from the environment to the sun. Jason's proposal, while incorrect, is nevertheless a legitimate modeling move—he is proposing a revision of their representation that would account for the observation that the propeller keeps turning as long as the solar panel is exposed to sunlight, and that is consistent with the rules of their existing general model of energy (M2, M3, M5). Proposing models of phenomena that turn out to be incorrect is a totally normal, legitimate, and productive part of science.

5 | DISCUSSION

In this section, we take our three research questions in turn, and consider what we can learn about them from the five episodes described above. We argue, first, that in these episodes the students exhibited all of the attributes of authentic scientific modeling and second, that in the process they engage in nearly all of the practices of science described in the NGSS. We conclude with some qualitative observations about the nature of the students' engagement, interactions—with each other, with their teacher, and with the representational materials—and their sense of epistemic agency in constructing a scientific explanation of energy flow in this scenario.

5.1 | RQ1: Aspects of scientific modeling exhibited in students' analysis

As we have already emphasized, there is evidence through all the episodes for authentic scientific model-based reasoning at a rather high level of sophistication. In terms of the six characteristics of model-based reasoning in science identified by Passmore et al. (2009) essentially the entire activity consists of *using models to construct explanations* (M4), specifically of how energy flows through the system—what the relevant system components are, what forms the energy takes, where in the system transfers and transformations of energy take place, and the nature of those transfers and transformations. In making the tracking of energy flow the central goal of energy reasoning, *Focus on Energy* differs markedly from other curricula that emphasize definitions, identification of forms, and classification. The ETL questions serve to guide the students toward that overall goal of "telling the energy story" within the context of a model, not just of what energy *is*, but of how it *behaves*.

Throughout this process, the students are *using existing models* (M2), specifically the generic model of energy framed by the ETL questions and collectively constructed by the class through the sequence of curricular activities. These characteristics are mostly clearly seen in Episode 2, where the students are deciding on the components to include, based on the role each one plays in the "energy story" of the system, and in Episode 4, where they are debating how to describe what happens to the energy in the motor. Those two episodes also exemplify the students vigorously *engaging in argumentation* (M6) about how to describe the amounts, forms and behaviors of the energy (represented by the energy cubes) as it moves through the system.

Less salient in this case are M1, *engaging in inquiry other than controlled experiments* and M5, *using models to unify understanding*. We would argue, however, that the students' exploration and experimentation in Episode 1 to determine whether the energy from the sun is light or heat represents *inquiry other than controlled experiments*, as the students explore the system's behavior and find that inverting the solar panel causes the propeller to stop, even though its temperature has not changed. Their experiment is in some sense controlled, in that they are holding the temperature of the panel's environment constant while changing the single variable of its orientation, but in the context of this aspect of inquiry what is most important is that they are not engaged in a linear, structured practice of hypothesis-testing as envisioned in the widely taught caricature of the "scientific method" (Windschitl et al., 2008) but rather in a more open-ended exploratory mode of investigation.

Similarly, their discussions of what to call the energy from the sun in Episode 3 and how to represent continuous flow in Episode 5 represent an effort, through modeling, to *unify their understanding* of energy flow in this system with their previous models of energy flow in other scenarios. Faced with a new physical situation, they are working to use the same set of concepts, questions, rules and representational tools that they have applied in other contexts to arrive at a valid explanation.

Perhaps most striking, however, is that the students *revise* their model of energy through inquiry (M3), particularly in Episode 3, where they "discover" a previously unknown (to them) form of energy through its transformation into previously identified forms, and in Episode 5, where they adapt their model to incorporate a situation of continuous flow. Even Jason's (incorrect) proposal in Episode 5 to connect the components in a big circle, with energy returning to the sun, represents this aspect of model-based reasoning. The revisability of scientific models is a crucial feature that is emphasized by virtually all researchers in this field (Forbes, Zangori, et al., 2015; Gilbert & Justi, 2016; Louca and Zacharia, 2012; Schwarz et al., 2009; Windschitl et al., 2008) but one that is drastically underemphasized in traditional science teaching. Gilbert and Justi (2016), for example, distinguish between "model-based teaching," in which a model is provided by the teacher or text as a fixed entity to be used but not modified by the student, and "modeling-based teaching," in which the student is involved in developing and revising the model. The flexibility and comfort shown by the students in revising their model to incorporate new behaviors and information in Episodes 3 and 5 clearly places this activity in the latter category.

5.2 | RQ2: What other practices of science did the students use, and how did they contribute to the activity of modeling?

As the discussion above emphasizes, the students' goal in this case study, framed by the ETL questions, was to construct an explanation (P6) of the energy flow in the system. Because of the nature of energy as a concept, the explanation is not mechanistic, or causal. They are not explaining *how* the solar cell converts solar into electrical energy, or *how* the motor converts electrical into motion energy. Rather they are explaining how energy must be flowing through the system, in what forms, and where the transfers and transformations must be taking place, in order to account for the observed behavior. Aspects of the explanation are predictive and testable—for example, the motor will not run if the solar cell is in the dark, or upside down, or if the wires are disconnected. Indeed this nonmechanistic aspect of energy is part of what makes energy reasoning so valuable in science—it allows the construction of meaningful explanations and predictions about phenomena even when the mechanisms underlying those phenomena are unknown.

The process of constructing explanations using energy concepts necessarily requires developing and using models (P2), and that practice is highly visible in the episodes described here. Moreover, as Gilbert and Justi (2016) point out, and this study illustrates, the practice of modeling in science is not really a single practice but intrinsically involves almost all of the other practices.

In Episode 1, Sarah and Melissa plan and carry out an investigation (P3) when they invert the solar panel to determine whether the panel uses light or heat to generate electrical energy. They then analyze and interpret the data from that investigation (P4)—the fact that the propeller turns when the panel is facing the sun but stops when it is turned face-down—to conclude that it is the light that matters. Finally they communicate their conclusions to the teacher, using evidence from their investigation to support their claims (P7, P8). In this investigation and at this grade level these practices are informal and qualitative—they are not, for example, systematically varying the amount of light falling on the panel and graphing the rotation rate of the propeller versus light intensity. There are no written experimental protocols, data tables, or graphs. But these students are not just playing. Key elements of systematic scientific inquiry are present. Most importantly, the students show clear understanding of the relationship between the experiment, the results, and their conclusion.

In this activity the major questions, such as whether the sun's energy is light or heat, and the ETL questions about the flow of energy, are either voiced by the teacher or evoked by curricular materials. In the episodes presented we do see students asking questions (P1), such as whether the wires are really part of the story (Episode 2) and how to describe the nature of energy in the motor (Episode 4), but they are largely questions about how to model the phenomenon rather than mechanistic questions about the system itself or predictive questions about possible variations or extensions. Similarly, we certainly see the students actively obtaining, evaluating, and communicating information (P8)—from the physical system, and from and to each other and to their teacher, both verbally and through gestures and manipulations of the cubes—but not collecting information from outside sources or preparing materials to communicate their understanding outside that group, largely because the nature of this particular activity does not require or encourage those practices. For the same reason, we do not find evidence that the students are using mathematics or computational thinking (P5); as Gilbert and Justi observe (2016, p. 77), this is the one practice that is not inherently involved in modeling-based learning and teaching.

The students frequently engage in *argumentation*—about whether the energy from the sun is heat or light in Episode 2, about what form of energy is present in the motor in Episode 4—but they do not explicitly argue *from evidence* (P7). In Episode 3, for example, Melissa argues "the air, like the thermal energy, it does not really matter with this. It is just the light," and it is very likely that she has in mind the experiment that she and Sarah carried out in Episode 1, turning the solar panel upside down, but she does not say that in the moment. At numerous points in Episodes 2 and 4, various students make claims about what kinds of transfers and transformations are taking place in different system components, and other students engage with those claims, but no one volunteers specific evidence for the claim, for example, that the motor transforms energy from electric to motion. Nevertheless, the totality of the conversation strongly suggests that their arguments are based on a shared understanding of what they have all observed, and of how those observations can fit into their model of energy. This may be an example of Shemwell and Furtak's observation (Shemwell & Furtak, 2010) that specific argumentation from evidence is often *not* associated, and may even interfere, with conceptually rich scientific discussion.

5.3 | RQ3: What did model-based reasoning and the other practices of science look like? How did the students interact with each other, with their teacher, and with their representational tools?

If we agree that it is desirable to provide young students with opportunities to engage in model-based learning about science, it is important to have richly documented examples of what such learning looks like in practice, over a range of science topics. Certainly scientific modeling will look different in fourth grade than it does in high school, or in a professional science context. To date there have been a handful of reports on science modeling in the elementary grades, including such topics as the water cycle (Forbes, Zangori, et al., 2015; Schwarz et al., 2009), ecosystems (Manz, 2012) and materials properties (Acher et al., 2007) and this work adds to that literature while contributing a different content area and a fine-grained look at the activity and experience of a small group of students. In this section we offer some qualitative observations.

First, even more than the students' engagement in authentic model-based reasoning to construct an explanation of the energy flow in the system, what we find striking in this study is the students' high level of animation, engagement, and epistemic agency. Their discussion (in Episode 4, for example) is a whirlwind of words, gestures and manipulations of the cubes, in which all four students are eager participants. All of them are eagerly moving and flipping cubes, gesturing, and vigorously presenting ideas and responding to each other's ideas, often interrupting and overlapping. It can appear chaotic, and it is a far cry from an orderly teacher-led discussion in which students raise their hands to be recognized and speak one at a time. But it is a structured, purposeful, highly productive, and student-owned chaos. At no point do the students look to the teacher for guidance, reassurance or for the "right answer." They clearly understand the construction of an energy story to be something that they—individually and collectively—have the tools to do, and that they are invested in doing. While they do not explicitly express ideas about the process of modeling itself—indeed they may not be aware that that's the name of what they are doing—through their actions and words they exhibit the four steps of scientific modeling described by Louca and Zacharia (2012); systematic observation, constructing the model, evaluating the model, and revising the model to apply to new situations.

Although the students are doing most of the heavy lifting, the teacher of course plays a crucial role. At key points she asks important questions: "Is it the light or the heat?" "Why is the sun's energy unknown?" and asks the group to explain their thinking, leading them to step back and both restate and reevaluate their model. Her role is not as the source of the "right answer," but more as a coach, helping the students refine, improve and clarify their own emergent model. Further, in the months preceding this activity she has led them to this level of modeling competence and confidence by establishing classroom norms and leading the class through the curriculum, including the co-construction of an energy model and practice in applying it to a variety of specific scenarios.

Appropriate representational tools are crucial component of the "modeling toolkit" (Gilbert & Justi, 2016; Greeno & Hall, 1997; Lehrer & Schauble, 2006a; Windschitl & Thompson, 2013). In elementary and middle grades, students' representations have often been largely pictorial (Acher et al., 2007; Forbes, Zangori, et al., 2015; Reiser, Berland & Kenyon, 2012; Schwarz et al., 2009), rather than "representations with predictive and explanatory power" (Forbes, Zangori, et al., 2015). The energy cube representation used in this activity, in contrast, is entirely abstract and in no way resembles the actual physical system. The students did not draw pictures of the sun, the solar panel, the propeller, etc.—they are all just represented by circles. The cubes do not represent visible attributes of the system either—students cannot, for example, detect the electrical energy in the wires—but rather represent this invisible entity that we call "energy." What they have created is not a physical replica of the system. Instead it is an abstract representation of a conceptual framework that we can see the students using in these episodes, fluently and enthusiastically, not only for communicating, but as a tool for reasoning about the flow of energy in this system. Its explanatory and generative power can be seen, for example, in the students' "discovery" of the "unknown" form of energy from the sun in Episode 3, and also in Jason's incorrect suggestion that the energy cycles back to the sun in Episode 5. This versatile representation is used throughout the curriculum (see Tables 1–3), in combination with the ETL questions, to model energy flow in a wide range of disparate phenomena, emphasizing the unified and unifying nature of the energy model.

At the same time, however, the abstractness of the representation sometimes makes it difficult to know whether the students fully understand what it is that the cubes actually represent. In Episode 4, for example, when they debate how to represent the energy story of the motor, they often seem to be so focused on the cubes themselves that it is difficult to know whether they are really thinking about the energy.

6 | CONCLUSIONS, CONTRIBUTIONS, AND LIMITATIONS

While a large body of literature emphasizes the importance of modeling-based teaching and learning in science, relatively few studies have examined how modeling can be incorporated in the elementary grades and what it looks like in that context (Acher et al., 2007; Forbes, Zangori, et al., 2015; Forbes, Vo, et al., 2015; Kenyon et al., 2008; Lehrer & Schauble, 2004; Manz, 2012; Schwarz et al., 2009). We are not aware of previous reports of model-based reasoning about energy in these early grades. This study adds to and extends prior work by providing an in-depth look at modeling as practiced by fourth-grade students in the context of energy. Further, this "thick" case-study approach provides a detailed examination of students' rich and complex verbal and nonverbal interactions for key aspects of modeling-based reasoning, and for evidence of the other practices of science that support that reasoning.

We find evidence for all six aspects identified by Passmore et al. (2009) as characterizing model-based reasoning as practiced by scientists: They *engaged in inquiry other than controlled experiments*, when they inverted the solar panel to determine whether the solar energy is heat or light; they *used an existing model* of energy in their inquiry, in order to *construct an explanation* of the energy flow in the specific case under study; their inquiry led to a *revised model* when they identified a previously unknown (to them) form of energy from the sun that must be present to reconcile their observations with their existing model of energy; they used that general model of energy to *unify their understanding* by applying the same model to a wide range of phenomena that on the surface appear highly disparate; and throughout their work they *engaged in argumentation* grounded both on their observations and on their shared model.

In the context of the learning progression for scientific modeling proposed by Schwarz et al. (2009) these students were clearly beyond simply viewing their model as a means of communicating, instead seeing it as a tool to support their thinking. They demonstrated the ability to use and adapt their model to new phenomena and situations, and to consider alternate versions of the model (such as whether to include the wires as a separate component, whether to treat the motor and propeller as separate components, where in the system the energy transformations occur, and how to represent the type of energy coming from the sun) in terms of their affordances for adequately explaining the phenomenon.

In the course of their analysis, moreover, the students in this case study successfully recruited and integrated most of the practices of science identified in the NGSS and the NRC *Framework* to understand and explain the flow of energy. They did not name the practices or show conscious awareness of them, but rather used them un-self-consciously, as scientists do, and combined them fluidly to arrive at an explanation that made sense to them as individuals and as a group, and to their teacher. It thus provides empirical support for Gilbert and Justi's point that authentic modeling-based learning necessarily draws on nearly all the other practices (2016).

Some authors (Louca & Zacharia, 2012; Schwarz & White, 2005) have argued that in order to be effective scientific modelers, students need explicit metacognitive knowledge and instruction about modeling itself as a discrete practice. This study, while certainly limited in scope, raises questions about that claim. While the curriculum does explicitly refer to a "model" of energy constructed collectively by the class, it does not directly address the nature, characteristics, purposes or practices of scientific models and modeling *per se*, and it is not evident that the students in this study were even aware that they were engaging in that practice. Nevertheless, they did so effectively, fluidly and un-self-consciously. The curriculum and the classroom norms built into the activities and reinforced by their teacher led them to understand and expect that making sense of real-world phenomena in the context of energy—"telling the energy story"—requires constructing a model of energy flow, and recruiting an array of scientific practices in support of that task.

The same curriculum and norms also led the students to assume both the authority and the responsibility for sense-making, rather than expecting to turn to their teacher or textbook for the correct answer. The ETL questions and the energy cube representation played a crucial role both in framing the overall goal as one of tracking the flow of energy as it relates to the observed phenomenon and in giving the students a consistent framework for guiding their model-based reasoning. The students demonstrated a commitment to the disciplinary norms of consistency—with current observations, but also with their existing emergent model of energy—and of openness to reasoned argument and disagreement that must be addressed or accommodated, possibly by revising or extending the model itself. In these respects, this study resembles Manz's work on the codevelopment of modeling practice and content knowledge in the context of ecology (2012). Of course, this study cannot tell us whether that understanding, expectation and commitment will extend into other content areas, but we have heard anecdotal reports of students who have completed the *Focus on Energy* units asking their teachers to take a similar approach in other parts of their science curriculum.

This study also has practical implications by pointing to the study of energy as a particularly fruitful topic for model-based teaching and learning, while illuminating a feasible pathway to that goal. As Lehrer and Schauble (2006a) observed: "One cannot engage in the activity of modeling without modeling *something*, and the something (the content and domain) is critical with respect to the questions raised, the inquiry pursued and the conclusions reached. … It is *because* content is so important that perhaps it should be selected with an eye toward its potential for constructing and extending students' model repertoire." (emphasis in original). As we have noted, the study of energy necessarily requires model-based reasoning, and this case study illustrates that it can provide a powerful and accessible context for all the key aspects of authentic scientific modeling, even in relatively early grades.

While this case study is in many respects a best-case scenario, with both teacher and students self-selected for a high level of interest and motivation, it shows that a well-thought-out science curriculum led by a well-prepared teacher can support elementary-school students in engaging in authentic and productive modeling-based reasoning that conforms to all the key characteristics of genuine scientific modeling, albeit at an age-appropriate level. In the process, the students naturally recruited and integrated multiple authentic practices of science in pursuit of their explanatory goal.

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NOTE

[1] The video, Using Energy Cubes to Reason About Energy Forms and Flows, can be found at https://foeworkshop.terc.edu.

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