Telling the Energy Story: Preliminary Results from Grades 4 and 5

Roger G. Tobin,
Department of Physics and Astronomy, Tufts University, Medford Massachusetts 02155

Sara J. Lacy, Sally Crissman, and Nick Haddad
TERC, Cambridge Massachusetts 02140

Abstract

We present preliminary results of an innovative curriculum focused on developing scientific ideas about energy in grades 4 and 5 and based on principles of three-dimensional learning, learning progressions and modeling-based teaching and learning. A diverse set of students in grades 4 and 5 demonstrated substantial growth in their understanding of basic energy forms and processes, and in their ability to integrate that knowledge to track the flow of energy in a relatively complex physical system. One-third spontaneously included dissipation into the environment, a critical step towards future understanding of energy conservation. The curriculum includes a carefully structured sequence of activities and uses a consistent set of questions and representation tools to analyze energy flow in increasing complex phenomena involving motion and elastic energy, thermal energy, and electrical energy. Teachers received a week-long summer training workshop prior to implementing the curriculum, followed by professional development meetings during the school year. Student learning was measured by a pre-post assessment designed to evaluate both knowledge of basic concepts and the ability to construct a coherent account of energy changes and flow in a scenario that was not part of the curriculum. Dramatic improvement was observed.

Background: 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 (NRC 2012, Duit 2014), 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 (Liu & McKeough 2005, Neumann *et al*. 2013, Duit 2014, Herrmann-Abell & DeBoer 2017).

Researchers in energy teaching and learning have identified four key conceptual themes: Forms, Transfers and Transformations, Dissipation and Degradation, and Conservation. These ideas are interdependent and cannot be learned sequentially or in isolation (Neumann *et al.* 2013, Duit 2014, Herrmann-Abell & DeBoer 2017). 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 (Nordine, Krajcik & Fortus 2010, Lee & Liu 2010, Jin & Anderson 2012).

Our curriculum builds on this work, proposed learning progressions for energy learning (Jin & Anderson 2012, Neumann *et al.* 2013) and research on modeling-based teaching and learning (Windshitl, Thompson & Braaten 2008, Gilbert & Justi 2016) to enable elementary students to construct the rich and integrated conceptual background about energy that they will need in later grades. 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.

We present here a preliminary assessment of the effectiveness of this curriculum in supporting students' integrated learning of scientific concepts of energy.

Intervention: A key organizing element of the curriculum is the "Energy Tracking Lens" (ETL – Table 1) – a consistent set of questions that help students track energy flow in any phenomenon. Through a series of structured hands-on activities relating to motion and elastic energy, thermal phenomena, and electricity, students learn not only what energy is, but how to coordinate their understandings to reason about energy flow in increasing complex scenarios. Each learning activity is built around an investigation question. Simple yet interesting materials allow the students to collect evidence that they use to answer the question.

Table 1. The Energy Tracking Lens.

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.

Since energy is an inherently abstract concept that cannot be directly observed, the study of energy both demands and is an ideal context for modeling-based teaching and learning. Through investigations of increasing complexity, the class uses a common language and set of energy tracking questions to collectively build a model of energy and learn to use it to construct explanations of energy flow in diverse contexts.

Representational schemes are an essential component of model-based reasoning (Windshitl, Thompson & Braaten 2008, Gilbert & Justi 2016), and the curriculum introduces representational tools that allow students to track energy flow in a flexible, context-independent way. A key tool is Energy Cubes (Scherr *et al*. 2012). Units of energy are represented by small cubes similar to dice. Cube sides are labeled to indicate different energy forms, such as motion or thermal energy. Students draw circles on a whiteboard to represent the relevant components of the system. The representation provides a context and tool for co-construction of meaning as the students negotiate which components to represent and how to tell the energy story. They move and flip 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. The representation also affords a shared language for communicating that story.

Before teaching the curriculum, teachers participated in a week-long summer workshop, during which they experienced the classroom activities as learners, improving their own understanding of and ability to use energy ideas. The workshop also included attention to model-based teaching, use of representations, interpreting students' ideas, and leading classroom discussions. During the school year the teachers received ongoing support in science and pedagogy through professional development meetings with program staff and other participating teachers.

Assessment Procedure: The project adopts the approach of design research (Collins, Joseph & Bielaczyc 2004), using an iterative process of implementation, evaluation and revision. The data presented here come from the second of three years of implementation and evaluation. In this phase the curriculum was taught in eight classes, across six public schools in the northeastern United States, by six different teachers. One of the classes was Grade 4; the other seven were Grade 5. Five of the Grade 5 classes were in Title 1 schools, with high numbers of students from low-income families. The total number of students was approximately 140.

Fig. 1. Sparklz wind-up toy.

Progress in understanding energy was assessed through an open-ended paper-and-pencil assessment analyzing the energy story of a wind-up toy (Fig. 1). The same assessment was administered before the beginning of energy instruction and again after completion of the curriculum. The probe was designed to assess not only students' knowledge about energy but also their ability to use that knowledge in an integrated way to describe and interpret energy flow in a real situation that did not closely resemble any of the curricular activities. After being wound up and released the toy moves in an erratic manner and generates sparks. Its mechanism is fully visible. Students examined and experimented with the toy, identified key components, described its behavior, and finally described energy flows and changes as the toy operates. Students were free to choose or combine verbal, pictorial or diagrammatic representations, and to decide what aspects of the scenario to include. A checklist of aspects of the energy story, based on the Energy Tracking Lens questions, was provided for reference, but there was no requirement that it be used. As Lee and Liu (2010) note, open-ended questions can be more useful than multiple-choice items for probing higher levels of knowledge integration in complex situations, as opposed to simply identifying energy forms or individual instances of energy transfer or transformation.

We designed and validated a rubric to assign scores in five areas: Forms, Transfer and Transformation, Flow, Dissipation; and Overall Quality and Coherence. The first four were scored on a 0-2 scale, while the last used a 0-3 scale. The categories include relatively advanced aspects of energy reasoning that are frequently not mastered by students even in middle and high school, but that are essential for understanding energy (Lee & Liu 2010, Nordine, Krajcik & Fortus 2010, Jin & Anderson 2012; Neumann *et al.* 2013). Most importantly the rubric assesses not only students' ability to identify discrete energy forms and individual processes of transfer and transformation, but also their ability to integrate those individual elements into a coherent "energy story," including whether they include dissipation into the environment. Conservation of energy was not scored both because it was not an explicit target of the curriculum, and because tests with physics faculty and graduate students showed that this assessment task did not evoke explicit statements about conservation even among subjects with deep content knowledge.

Six members of the project team independently scored six pretests and nine posttests. Interrater agreement measures $r_{WG(J)}$ were greater than 0.93 for all categories. After training and testing for consistency, a student grader scored the remaining tests.

Findings: Both before and after instruction, students found the wind-up toy task interesting and enjoyable, and gave meaningful and often detailed responses. Before instruction, however, their explanations were mechanistic, with little or no energy content, whereas the posttests were generally much richer in accurate energy concepts. Figure 2 compares typical pre- and posttests.

Figure 3 compares average pre- and posttest scores in the five categories. In every category the gain was dramatic and highly statistically significant.

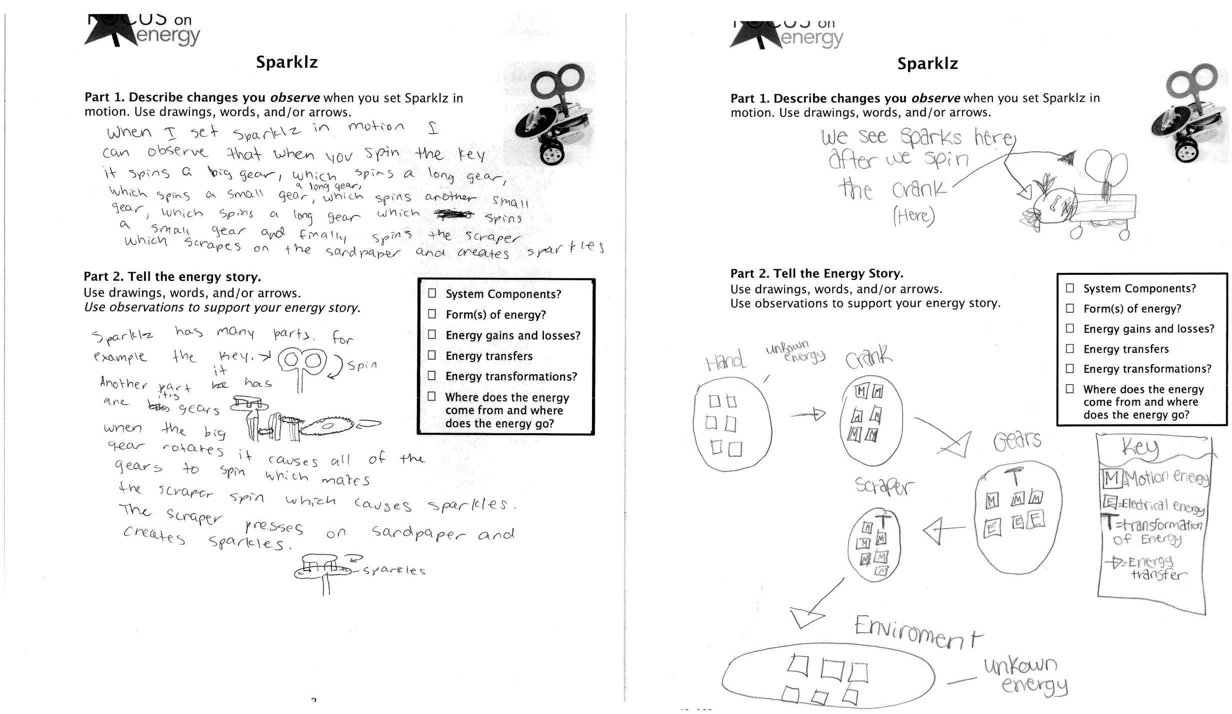

Fig. 2. Typical 5th grade pretest (left) and posttest (right). In this posttest the student used a version of the energy cubes representation to tell the energy story. Most but not all posttests exhibited this approach.

These results show striking growth not only in the students' knowledge about energy, but in their use of energy ideas to construct coherent explanations of energy flow in a relatively complex system.

A few noteworthy observations about the posttests:

- About one third of students (32%) appropriately identified at least 3 forms of energy;
- About 60% appropriately identified examples of both energy transfer and energy transformation;
- About 40% included dissipation of energy into the environment, even though nothing in the prompt specifically called for that idea.
- Though it was not an explicit part of the rubric, overall about a third identified the storage of energy in the coil spring of the toy as part of the energy story, with the percentage varying strongly among the various classes, from less than 10% to more than 50%. Since stored elastic energy was a significant topic in the curriculum, we are surprised that the numbers were not higher. It may be that the unfamiliar form of the coil spring made it difficult to identify its role in storing elastic energy.

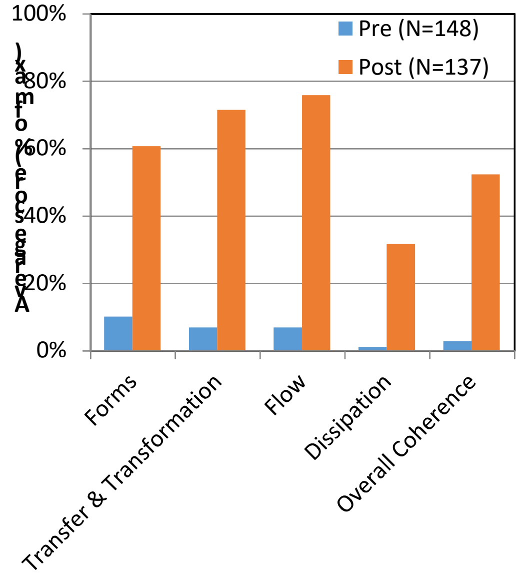

Fig. 3. Comparison of pre- and posttest scores.

Figure 4 compares posttest scores for Title 1 and non-Title 1 classes. Only in the "Forms" category is there a significant difference, providing evidence that the curriculum is accessible and effective for students from a range of socioeconomic backgrounds. Anecdotally, teachers reported that the use of the Energy Cube representation made the content unusually accessible to English language learners.

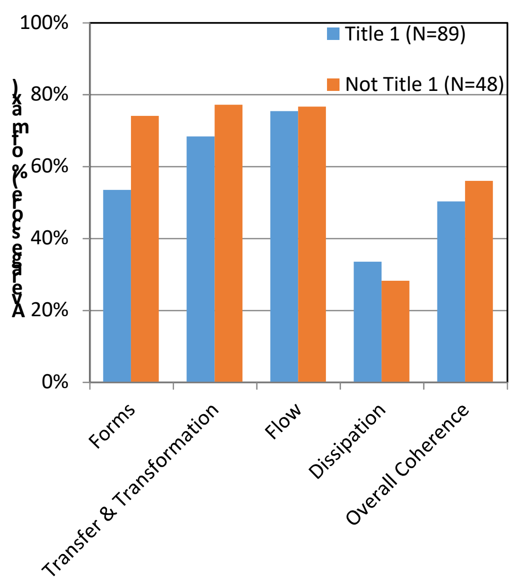

Fig. 4. Comparison of posttest scores for Title 1 and non-Title 1 classes. Only in the "Forms" category is the difference statistically significant ($p < 0.001$).

We also compared posttest results for Grades 4 and 5 (not shown). There was very little difference between the two; the only statistically significance difference was that the younger students scored somewhat *higher* in the "Forms" category. Since the group included only one Grade 4 teacher, we hesitate to attach much significance to this comparison, except as evidence that these energy ideas are accessible to fourth-graders.

Summary and Future Directions:

The preliminary assessment results reported here advance our understanding of energy education in the early grades by showing that this curricular approach has great promise. After completing the curriculum, a diverse set of students in grades 4 and 5 were able to demonstrate not only substantial understanding of basic energy forms and processes, but also an ability to integrate that knowledge to track the flow of energy in a relatively complex physical system. Approximately one-third of them spontaneously included dissipation into the environment as part of their analysis, a critical stepping stone to future understanding of energy conservation.

In the third and final round of implementation, we will conduct a comparison of students who experience our curriculum with a control group of comparable students who receive standard instruction. We will also investigate the ability of students who complete our curriculum to extend the concepts, representations, and analytical approach of the Energy Tracking Lens to phenomena beyond the physical sciences, such as life science contexts.

References

Collins, A., Joseph, D. & Bielaczyc, K. (2004). Design research: Theoretical and methodological issues. *J. Learning Sci.* **13**(1), 15-42.

Duit, R. (2014). Teaching and learning the physics energy concept, in Chen, R.F., Eisenkraft, A., Fortus, F., Krajcik, J., Neumann, K., Nordine, J.C. & Scheff, A., *Teaching and Learning of Energy in K-12 Education*. New York: Springer.

Gilbert, J.K. & Justi, R. (2016). *Modelling-based teaching in science education*. New York: Springer.

Herrmann-Abell, C. & DeBoer, G. (2017). Investigating a learning progression for energy ideas from upper elementary through high school. *J. Res. Sci. Teach.* doi 10.1002/tea.21411.

Jin, H. & Anderson, C.W. (2012). A learning progression for energy in socio-ecological systems. *J. Res. Sci. Teach.* **49**(9), 1149-1180.

Lee, H.-S. & Liu, O.L. (2010). Assessing learning progression of energy concepts across middle school grades: The knowledge integration perspective. *Sci. Educ.* **94**(4), 665-688.

Liu, X. & McKeough, A. (2005). Developmental growth in student' concept of energy: Analysis of selected items from the TIMSS database. *J. Res. Sci. Teach.* **42**(5), 493-517.

National Research Council (NRC). (2012). *A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas.* Committee on a Conceptual Framework for New K-12 Science Education Standards. Board on Science Education, Division of Behavioral and Social Sciences and Education. Washington, DC: The National Academies Press.

Neumann, K., Viering, T., Boone, W.J. & Fischer, H.E. (2013) Towards a learning progression of energy. *J. Res. Sci. Teach.* **50**(2), 162-188.

NGSS Lead States. (2013). Next Generation Science Standards: For states, by states. Washington, DC: National Academies Press.

Nordine, J., Krajcik, J., & Fortus, D. (2010) Transforming energy instruction in middle school to support integrated understanding and future learning. *Science Education* **95**, 670-695.

Scherr, R.E., Close, H.G., Close, E.W. & Vokos, S. (2012) Representing energy. II. Energy tracking representations, *Phys. Rev. ST-PER* **8**, 020115.

Windschitl, M., Thompson, J. & Braaten, M. (2008). Beyond the scientific method: Model-based inquiry as a new paradigm of preference for school science investigations. *Sci. Educ.* **92**(5), 941-967.