Robert F. Chen · Arthur Eisenkraft
David Fortus · Joseph Krajcik
Knut Neumann · Jeffrey Nordine
Allison Scheff *Editors*

Teaching and Learning of Energy in K-12 Education

Springer

Teaching and Learning of Energy in K-12 Education

Robert F. Chen • Arthur Eisenkraft • David Fortus
Joseph Krajcik • Knut Neumann • Jeffrey Nordine
Allison Scheff
Editors

Teaching and Learning of Energy in K-12 Education

Springer

Editors
Robert F. Chen
Environmental, Earth and Ocean Sciences
University of Massachusetts Boston
Boston, MA, USA

Arthur Eisenkraft
Education and Human Development
University of Massachusetts Boston
Boston, MA, USA

David Fortus
Weizmann Institute of Science
Rehovot, Israel

Joseph Krajcik
College of Education
Michigan State University
East Lansing, MI, USA

Knut Neumann
Leibniz-Institute for Science
and Mathematics Education (IPN)
Kiel, Germany

Jeffrey Nordine
San Antonio Children's Museum
San Antonio, TX, USA

Allison Scheff
Massachusetts Department
of Higher Education
Boston, MA, USA

Leibniz-Institute for Science
and Mathematics Education (IPN)
Kiel, Germany

ISBN 978-3-319-05016-4 ISBN 978-3-319-05017-1 (eBook)
DOI 10.1007/978-3-319-05017-1
Springer Cham Heidelberg New York Dordrecht London

Library of Congress Control Number: 2014935241

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

Acknowledgements

This book is a product of an international energy summit held at Michigan State University in December, 2013. The purpose of the conference was to get a better sense of what the research community knows about energy as a crosscutting concept and how to communicate this knowledge in kindergarten through secondary schools. Participants included scientists, science educators, science education researchers and teachers.

This book would not exist without the work of the many authors and the equal contribution of each editor.

We also wish to thank the National Science Foundation. This material is based upon work supported, in part, by the National Science Foundation under Grant NSF DUE-0928666. *Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.*

Contents

Chapter 1
Introduction: Why Focus on Energy Instruction?

Arthur Eisenkraft, Jeffrey Nordine, Robert F. Chen, David Fortus, Joseph Krajcik, Knut Neumann, and Allison Scheff

Energy is one of the most important ideas in all of science and is useful for predicting and explaining phenomena within every scientific discipline. Yet, there are substantive differences in how the energy concept is used across disciplines. While a particle physicist relies heavily on the idea that energy is conserved during interactions between subatomic particles, an ecologist is typically more concerned with the idea energy transfers across system boundaries.

A. Eisenkraft (✉)
Education and Human Development, University of Massachusetts Boston, Boston, MA, USA
e-mail: arthur.eisenkraft@umb.edu

J. Nordine
San Antonio Children's Museum, San Antonio, TX, USA

Leibniz-Institute for Science and Mathematics Education (IPN), Kiel, Germany
e-mail: jeffn@sakids.org; nordine@ipn.uni-kiel.de

R.F. Chen
Environmental, Earth and Ocean Sciences, University of Massachusetts Boston, Boston, MA, USA
e-mail: Bob.Chen@umb.edu

D. Fortus
Weizmann Institute of Science, Rehovot, Israel
e-mail: David.fortus@weizmann.ac.il

J. Krajcik
College of Education, Michigan State University, East Lansing, MI, USA
e-mail: krajcik@msu.edu

K. Neumann
Leibniz-Institute for Science and Mathematics Education (IPN), Kiel, Germany
e-mail: neumann@ipn.uni-kiel.de

A. Scheff
Massachusetts Department of Higher Education, Boston, MA, USA
e-mail: ascheff@bhe.mass.edu

R.F. Chen et al. (eds.), *Teaching and Learning of Energy in K-12 Education*,
DOI 10.1007/978-3-319-05017-1_1,

While the ecologist and the physicist are both aware that the energy of biological systems and of physical systems are fundamentally the same – that the only difference is the analytical methods used to track energy changes – students who are just learning about the energy concept may not be aware of this fundamental similarity. That is, students often do not connect the energy that they learn about in physics class with the energy that they learn about in biology, chemistry, or geoscience. After all, in physics class they talk about energy being "conserved", while in biology 90 % of energy is "lost" in transfers between trophic levels. In chemistry, energy is often described as being "stored" in chemical bonds, and in environmental science, they often discuss energy "flow" from natural resources to end users. In contrast, scientists know that these ways of talking about the role of energy are just a shorthand – a simplified way of speaking about energy that corresponds to the analytical lens we are using.

When a dietician tracks the energy requirements of the human body to help treat a diabetic patient, she needn't be concerned with the thermal energy increase in the surroundings as metabolism occurs. Talking about the body "using" energy from food to carry on life processes is typically sufficient. While she is aware of energy conservation, tracking transfers to the Earth's atmosphere doesn't help her to treat patients, so this portion of energy analysis is typically omitted. In fact, including this portion of energy analysis may ultimately detract from treatment because it can distract her patient from the main idea she is trying to convey.

Teachers face a complicated prospect when teaching students about energy. Like the dietician who is aware that energy is quantitatively conserved but chooses not to discuss this with patients for their own benefit, teachers must choose how to present energy in their discipline-centered classrooms such that the analysis does not unduly confuse students but that is still true to the nature of energy. With the release of the *Framework for K-12 Science Education* (National Research Council 2012) and the *Next Generation Science Standards* (Achieve Inc. 2013), teachers have a new challenge to teach energy as both a core disciplinary idea and a crosscutting concept. That is, teachers are now charged with not only teaching about energy as a disciplinary idea but also teaching explicitly about energy as an analytical framework that cuts across disciplines. While scientists typically do not make these crosscutting connections explicit in their day-to-day work, we are asking teachers to instruct their students in such a way that these connections are made clear. The bet we are placing through these new standards documents is that teaching energy as a crosscutting concept will help to prepare a new generation of scientists and engineers who are well equipped to think about the cross-disciplinary problems that are becoming increasingly important in our world. To respond to the challenge of teaching energy in new ways, teachers need guidance from the science and science education research communities on how to present energy in their classrooms.

In December 2012, 40 scientists, science educators, and teachers gathered for an energy summit to better understand the importance of the energy concept in school science and how to best promote student understanding of the energy concept. While much previous work has been done to understand students' conceptual difficulties with learning the energy concept and the instructional imperatives that emerge from these difficulties, we recognized new imperatives that were not addressed by existing

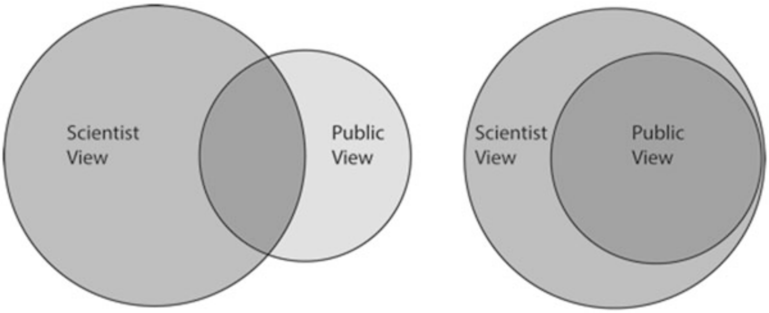

Fig. 1.1 Contrasting possibilities of how scientists' views of energy and the public's view may be related

research. Specifically, no consistent strategies for teaching the concept of energy exist to foster the development of a comprehensive understanding that spans across disciplines, as an empirically validated learning progression of energy that spans K-12 is missing.

As a group, we shared our insights and prior work on a set of three related questions. The first of our questions, "What should people know about the energy concept?" required a careful look at the scientists' view of energy and how this contrasts with the public's view of energy. Imagining a Venn diagram of the scientists' view of energy and the public's view of energy, how much overlap is required? (See Fig. 1.1) In the Venn diagram on the left, the scientists and the public have some overlap. We expect that the scientists will have additional knowledge that is not shared by the public owing to their expertise. The troublesome domain is that of public knowledge that is not shared by the scientists. We might hope that the public's domain of understanding would be completely within the scientists' domain (as in the Venn diagram on the right), but we know that the public (and scientists on many occasions) will adopt a common usage of energy – e.g. vim and vigor – that has little to do with scientific understandings.

The term "energy" has many meanings within everyday contexts. There is no problem with words having multiple meanings if both parties are aware of the different uses and are clear on which meaning is being employed within a conversation. When the common usage makes it difficult for people to understand the scientific view of energy, we need strategies to draw sharp distinctions among the uses of the term "energy" and its meaning.

A fundamental challenge that exists within the energy concept is that a clear, crisp definition of the term seems to be out of our reach. While the principle of conservation of energy is remarkably simple for any isolated system (the total amount of energy never changes), a rigorous and self-consistent definition of that which is being conserved is remarkably difficult to state. Richard Feynman, in his famous Lectures on Physics captured the essence of the energy conservation law:

> There is a fact, or if you wish a law, governing all natural phenomena that are known to date. There is no exception to this law – it is exact so far as is known. The law is called the conservation of energy. It says that there is a certain quantity, which we call energy,

> that does not change in the manifold changes which nature undergoes. That is a most abstract idea, because it is a mathematical principle; it says that there is a numerical quantity, which does not change when something happens. It is not a description of a mechanism, or anything concrete; it is just a strange fact that we can calculate some number and when we finish watching nature go through her tricks and calculate the number again, it is the same (Feynman et al. 2011, pp. 4–3).

Feynman goes on to say, “It is important to realize that in physics today, we have no knowledge what energy is” (Feynman et al. 2011, pp. 4–3). From this abstract notion that “whatever energy is . . . it is conserved” scientists then introduced the related concepts of energy forms/types, transfer, transformations, and degradation/dissipation.

Professional scientists acquire a tacit understanding of energy and it is the job of the teacher to assist students in acquiring a similar understanding. This brings us to our summit’s second question, “What are the challenges we are facing in teaching students about energy?” Why is student learning about energy different from learning about the cell or ionic bonding or buoyancy? What are the unique features of the concept of energy that pose difficulties?

Since energy is both a disciplinary core idea and a crosscutting concept as articulated in the *Frameworks* and NGSS, teachers need students to help understand how energy is a part of the living environment and the physical world. They have to learn about energy in the context of biology, chemistry, physics and the earth and environmental sciences. Simultaneously, they must recognize that the energy of living (e.g., their bodies and various organisms) and nonliving systems (e.g., chemical reactions, roller coasters, tectonic plates) are the same energy.

Students have to learn about energy even though “we have no knowledge of what energy is.” We must provide students with opportunities to explore energy even though they cannot touch it or see it. Though students cannot touch energy, see energy, or even measure it directly, every student has experienced the feeling of “having a lot of energy” or being tired and feeling “low on energy”. Though we cannot define energy, we all feel an intuitive connection to the idea through our everyday lives. In school, students measure temperature and calculate thermal energy or measure speed and calculate kinetic energy, but these activities help very little in helping students gain insight into the energy that they “feel” and “use” in their everyday lives.

Students experience unique challenges in learning about energy because it is a fundamentally abstract idea, yet has precise scientific uses. Further, students use the term energy in their everyday lives well before learning about it in school and come to develop an intuition about it that may or may not map onto a scientific view of energy. The challenges students face when learning about energy are substantial, and much research has been done to try to understand these challenges. Yet, with a strengthened emphasis on helping students to not only understand energy in scientific and everyday context but also across scientific domains, much work remains in understanding the challenges that students face when learning about the energy concept.

As the summit attendees tried to reach consensus on these first two questions ("What should people know about the energy concept?" and "What are the challenges we are facing in teaching students about energy?"), we then confronted the last of our questions, "What can be done to meet the challenges?" How can the topic of energy be approached across the curriculum and across all grades? Compared to the first two questions, the last question is much more difficult. Precious few studies have been done to investigate promising approaches to energy instruction and even less research has been done to explore how K-12 students can be taught to build an integrated understanding of energy (i.e., an understanding that cuts across contexts and is organized around the most broadly applicable principles) over the course of many years. Yet, summit participants were invited precisely because they have been making progress on this front – either through ongoing projects or their own instruction, or both.

Of course, the ultimate goal of the summit and this book is to impact classroom instruction by providing teachers with a clear direction to take in their own energy instruction via consensus recommendations for instruction and identification of promising research directions. As you will see in the subsequent chapters, consensus is difficult to achieve for this complex and indispensible concept that so many disciplines use in different ways. But there is hope. By asking an international and diverse group of scientists, science educators, and teachers to share their own work relative to the three summit questions and to critique each other's ideas in light of their own experience, we were able to make progress toward identifying key energy understandings, naming important challenges faced by students, and sharing promising instructional approaches.

In the remainder of this introductory chapter, we will share how we came to realize a need for the summit and describe the structure of the summit to illuminate how we shared our work and discussed it from a variety of important perspectives. Then, we will introduce the structure of this book and how the chapters within it have been grouped to illustrate some of the common ground – and areas of ongoing debate – that emerged during the energy summit.

1.1 Realizing the Need for a Summit

All attendees have a personal story that brought them to the summit. As one of the organizers of the conference, the University of Massachusetts Boston has been researching energy as a crosscutting concept through our Boston Energy in Science Teaching (BEST) grant funded by the National Science Foundation.

Boston Energy in Science Teaching (BEST) is a partnership between the University of Massachusetts Boston, Boston Public Schools, Northeastern University, and Roxbury Community College. Through this grant, the partnership is looking at how the teaching and learning of energy as a crosscutting concept can impact classroom instruction, student achievement and engagement, teacher content knowledge, and faculty research. This project, which began its investigation prior to the publishing of the NRC Framework and Next Generation Science Standards, has had three full years to investigate where energy is taught in the classroom, what connections can be made between curricula, what type of professional development can help teachers begin to teach with an energy lens, and what it looks like to teach with an energy focus in the classroom. BEST has provided an opportunity for the partnership to contribute to the research summit and lead the teacher summit.

The BEST grant emerged from an interdisciplinary course that we had taught to K-12 teachers for 3 years prior to this grant as part of the NSF sponsored Boston Science Partnership (a Math Science Partnership). The course instructors were professors in biology, physics and environmental chemistry who were present at each class meeting. The experience of teaching this course has enriched their understandings of energy across disciplines and helped them recognize the varied ways in which energy is treated in each discipline.

When the teachers evaluated the course, one comment struck a nerve. A few teachers, not a majority but a few teachers nonetheless, remarked that they wished the professors would have prepared more so that they would not argue in front of us. The teachers making this evaluation had not appreciated the opportunity to see knowledgeable scientists trying to better understand each other, but rather saw the dialog as a problem. These teachers wanted to know the right answer to tell their students and in expressing this desire exposed the impoverished view of science in their classrooms.

What were the professors "arguing" about in the classroom? When discussing the conduction of heat, the physics professor would present a simple equation showing how heat flow across two dissimilar materials was related to the difference between T1 and T2, the contact area, and the thermal conductivity of the materials. The chemical oceanographer saw that the transfer of heat from the warm surface ocean to the colder deepwater as a similar problem but noted that oceanographers model this apparent conduction with the same equation, but use "eddy diffusivity" rather than conductivity. The biology professor claimed that this equation really did not tell the whole story. For an animal with fur, it is difficult to determine T1 and T2, the contact area, and, in fact, the animal could change her metabolism to change T1. All of these perspectives are scientifically correct, but illustrate the diversity of applications for this concept.

The Energy Course was deemed a success by our pre and post test measures and the compilation of student comments, but the concerns of the teachers mentioned above were a catalyst for wanting to further explore energy as a crosscutting concept. We worked with teachers on K-12 vertical articulation of the energy concept and created a second course that focused specifically on how energy is taught in the classroom at each grade level.

Similarly, at UMass-Boston, we began with the premise that there are very few science colloquia where you couldn't raise your hand at the close of the talk and appropriately ask, "What are the energy considerations of your work?" We further realized that almost every science course at the University includes energy and yet we find that our undergraduate students do not realize that ATP in biology, activation energy in chemistry and kinetic energy in physics are all the same energy.

Researchers across the world are having similar experiences as the UMass-Boston group as they pursue the understanding of the energy concept and how it should be taught in the schools. Recognizing the commonalities across our research, the organizers of the conference from the University of Massachusetts Boston, Weizmann Institute of Science (Israel), Michigan State University, Leibniz-Institute for Science and Mathematics Education (IPN), Kiel (Germany) and Trinity University (Texas), began developing a funding proposal and mapping the outcomes of our proposed summit. The proposal was funded by the National Science Foundation as a supplementary grant to the larger and ongoing Boston Energy in Science Teaching (BEST) grant.

1.2 Structure of the Summit

1.2.1 Goals and Participants

Along with addressing the three questions discussed earlier in this chapter, there were three goals for the summit: (1) to synthesize current research on the conceptual understanding of energy, (2) to identify directions for future research on the teaching and learning of energy, and (3) to foster international collaborations among science education researchers.

Key to making progress relative to these three goals was getting the right people to the table. While logistics and funding often prevent assembling an ideal group that includes all relevant players – and this summit was no exception – we attempted to gather a group of scientists, science educators, and teachers who had been conducting their own work in this field and who could represent an important perspective while still keeping the group of participants small enough to have sustained and substantive conversations. In the end, we assembled a group of 40 participants who represented the major branches of science, possessed strong experience in science education, and reflected diversity in their country of origin and career stage. There are, of course, notable exceptions to our participants (for example, we were not able to arrange a scholar from Africa to attend). Still, the assembled participants were representative of many different perspectives and backgrounds. The list of attendees and their affiliations are provided in Appendix A.

1.2.2 Surfacing and Discussing Ideas

The general structure of the summit was interactive. Eighteen of the summit participants were experts who have conducted prior research on the teaching and learning of energy, and these participants wrote a 15–20 page paper prior to the summit. The papers described their research, opinions, and responses to the three guiding questions on the teaching and learning of energy.

At the summit, submitted papers were discussed during small group discussion sessions. Using a "tuning protocol" (Blythe 2008), two sub-groups of participants simultaneously had structured conversations about the ideas presented in three papers (for a total of six papers per tuning protocol session). By engaging in this structured conversation, participants were supported in focusing the discussion around ideas presented in each paper and in providing the author with targeted suggestions for revisions of their papers, which ultimately appear in this book.

Each tuning protocol session was immediately followed by three simultaneous "report-out" sessions that used a "Jigsaw" format (Aronson and Patnoe 1997). These sessions grouped participants such that each tuning protocol sub-group was equally represented; this grouping helped ensure that participants looked for areas of overlap between the tuning protocol conversations.

The summit included three tuning protocol sessions and three report-out sessions (allowing for discussion and synthesis related to all 18 submitted papers). Each report-out session was focused on a different summit guiding question, and participants were tasked with identifying areas of overlap and disparity between the papers presented in the preceding tuning protocol conversations. Thus participants recorded areas of consensus and dispute relating to what students should know about the energy concept, what challenges students face in learning about energy, and promising instructional approaches.

Throughout each tuning protocol session and report-out session, participants were intentionally grouped based on their scientific background and research/teaching experience. This grouping allowed us to explore both disciplinary and cross-disciplinary perspectives as we discussed the three summit questions.

It is also important to note that the summit did not include plenary discussions or keynote speakers. This organizing team made this choice in an effort to keep the attention focused on the collaborations of the researchers presenting their work and to work towards an environment in which no one person's perspective was systematically elevated above another's.

1.2.3 Teacher Voices and a Second Summit for Teachers

At the close of the second day, the K-12 teachers hosted a panel discussion where they shared their reflections of the papers and the discussions of which they had been a part. The summit drew to a close on the third day. In the morning, groups synthesized the commonalities and disagreements from the summit discussions. In addition, each group discussed the structure for this book. This work also paved the way for plans for a teacher summit, which was held in July 2013. To ensure continuity and build upon the work done in the researcher summit, the teacher summit included all teacher participants from the researcher summit and a few scientists and science education researchers. Just as the researcher book has culminated in a book primarily intended for scientists and science education researchers, but that is useful for teachers as well, the teacher summit will culminate in a book for teacher practitioners that will be useful for scientists and science education researchers who are interested in how the recommendations from this book may play out in practice.

1.3 Organization of This Book

While all authors addressed each of the three guiding summit questions, many felt better positioned to comment substantively on a single question and focused their papers accordingly. After the summit, the organizing team grouped the papers (which had been revised based on feedback received during the summit) based on the question to which we felt they made the strongest contribution. In this process, we recognized a need to create a fourth category for papers, since some papers were quite strong in representing what existing research has to say about the teaching and learning of energy. Thus, the parts of this book are organized around four major questions.

- Part I: What should students know about energy?
- Part II: What does the research say about the teaching and learning about energy?
- Part III: What are the challenges about the teaching and learning about energy?
- Part IV: What opportunities/approaches exist for teaching and learning about energy?

Each part begins with a brief introduction and summary of the chapters in that part. Each summary then ends with conclusion statements, recommendations, and a few discussion questions. The part introduction is followed by the research papers that were presented, discussed, and revised by summit participants.

- Part I: What should students know about energy? This part includes two chapters by physicists (Helen Quinn and Ramon Lopez, both of USA) and one by a group of science educators (Jenny Dauer, Hannah Miller, and Charles Anderson, also of USA) who discuss energy in a biochemical context. Since the authors represent multiple disciplinary and instructional backgrounds, it is illuminating to note where their ideas both overlap and diverge.
- Part II: What does the research say about the teaching and learning about energy? This part includes a chapter by Reindeers Duit (Germany) summarizing the prior research on the teaching and learning of energy in grades K-12. This is followed by an analysis of the standards documents from nine countries with hints of a research based model of energy in chemical reactions by Lie Wang and Wang Weizhen (China). Cari Hermann-Abell and George DeBoer (USA) then describe their efforts in creating assessment questions to test for student understanding four key ideas – forms, transfer, transformation and conservation – and the

results of administering this exam to 24,000 students. The part concludes with a chapter by Bob Chen, Allison Scheff, Erica Fields, Pam Pelletier, and Russ Faux (USA) focusing on a concept mapping approach used in Boston Public Schools to identify elements of instruction that can coordinate discussions of energy across different grade levels.

- Part III: What are the challenges about the teaching and learning about energy? The first of five chapters in this part Hui Jin and Xin Wei (USA) explore how common, everyday uses of the term "energy" can become an obstacle to students learning the scientific view of energy. This is followed by their attempt at an energy learning progression that moves from the common language to the scientific uses of the term "energy." In the second chapter, Xiufeng Liu and Mihwa Park (USA) call for a broader exposure to energy in history classes and dealing with the political aspects of energy use. Robin Millar (England) gives his perspective on everyday use of "energy" and how this can be the launching point for learning how science treats energy. Nicos Papadouris and Costas Constatinou (Cyprus) articulate reasons why energy is such a difficult concept and opt for a philosophical approach that emphasizes energy as a crosscutting concept. This chapter concludes with a paper by Margot Vigeant, Michael Prince, Katharyn Nottis, and Ronald Miller (USA) that elaborates on problems associated with teaching energy concepts to engineering students and the inability of many students to understand the concepts even while correctly answering numerical problems.
- Part IV: What opportunities/approaches exist for teaching and learning about energy? The six chapters in this part describe research based curriculum efforts that can provide guidance on how we can effectively teach energy concepts. In the first chapter, Sara Lacy, Roger Tobin, Marianne Wiser, and Sally Crissman (USA) describe their efforts to introduce energy concepts to elementary school children and map out a learning progression for grades 3–5. Kristen Wendell (USA) evaluates an engineering program to see where energy concepts are present and where there may be missed opportunities to introduce additional energy concepts. Angelica Stacey, Karen Chang, Janice Coonrod, and Jennifer Claesgens (USA) explicitly show the dangers of introducing energy simplifications in chemistry and how these can lead to misconceptions that exacerbate other student learning. Melanie Cooper, Michael Klymkowsky, and Nicole Becker (USA) continue describing energy as it relates to chemistry at the college level and how their curriculum addresses the molecular, macroscopic and quantum mechanical approaches to understanding energy. The fifth chapter, written by Rui Wei (China), Lei Wang (China), and William Reed (USA) critique the different metaphors we use for energy and try to determine the benefits and hazards of our reliance on these metaphors in our teaching. The final chapter by Lane Seeley, Stamatis Vokos, and Jim Minstrell (USA) describe some professional development activities in which teachers acquire a more sophisticated view of energy.

These four parts are then followed by a conclusion and future directions that readers can consider as a means to continue this engaging and important work.

As an organizing team, we were thrilled with the outcomes of the summit and are excited to share with readers the contributions from each of the authors in this book. The papers that follow reflect not only the work of the authors, but also the thoughtful comments, insights, and suggestions for revisions from the scientists, science educators, and teachers from around the world who participated in the summit.

References

Achieve Inc. (2013). Next Generation Science Standards. Retrieved October 10, 2013 from, http://www.nextgenscience.org/next-generation-science-standards.

Aronson, E., & Patnoe, S. (1997). *The Jigsaw classroom* (2nd ed.). New York: Longman.

Blythe, T. (2008). *Looking together at student work* (2nd ed.). New York: Teachers College Press.

Feynman, R. P., Leighton, R. B., & Sands, M. (2011). *Feynman lectures on physics 1: Mainly mechanics, radiation, and heat*. New York: Basic Books.

National Research Council [NRC]. (2012). *A framework for K-12 science education*. Washington, DC: National Academies Press.

Part I
What Should Students Know About Energy?

Energy plays a central role in our everyday lives, as well as in all science disciplines. As a disciplinary core idea and a concept that cuts across all science disciplines, it is clear why energy is a critical idea for students to learn school and consequently why this concept receives particular consideration in policy documents, such as in various standards documents across the world. Energy is one of several "big ideas" of science that is also referred to as a "crosscutting concept" or an "enduring understanding" and is found in almost every year of schooling and across disciplines. However, what is it about energy that is critical for students to learn? Is it its importance as an accounting principle that determines what cannot occur? Is its cross-cutting nature what is important, since this allows it to become an integrator and perhaps unifier among the various science disciplines, allowing for a truly inter-disciplinary understanding of science? Is its economic, political, and societal relevance what students really need to understand?

This part contain three chapters, two by physicists and one by a group of science educators, each of which presents a different perspective on energy and what about it is important to understand to make sense of particular types of phenomena.

The first chapter, written by Helen Quinn, presents a particle physicist's musings about energy. Beginning with the lack of a worthy definition of energy at the macroscopic level and the different lingo that scientists in different disciplines have when discussing energy, she makes a case why energy seems so confusing. She argues that a coherent understanding of energy can be attained only when it is considered at the smallest scales and that therefore our aim should be for students to understand energy at these scales and to be able to use these understandings to make sense of energy at macroscopic scales as well. After using this small-scale understanding to describe macroscopic manifestations of energy (thermal, chemical, mechanical, electrical, and nuclear energy), the applicability of the mass-energy relation to all phenomena, and some of the conceptual difficulties associated with each type of energy, she describes four key ideas about energy that she thinks can and should be the basis of K-12 education about energy.

The second chapter, by Ramon Lopez, uses a complex phenomenon from his research field as a probe into student understanding and learning. He provides a brief overview of what happens when the solar wind impinges on a planet with a magnetic field, such as the Earth, focusing in particular on magnetic reconnection and magnetohydrodynamics, and emphasizing the central role energy transformations play in understanding these two topics. He then discusses some of the energy-related conceptual difficulties that many graduate physics students face when learning about these topics, conceptual difficulties that have their root in inadequate K-12 education about energy. From these conceptual difficulties he raises ideas about how energy should be taught at all levels, including K-12.

While not disagreeing with Helen Quinn who focuses on energy as an actual physical entity, Jenny Dauer, Hannah Miller, and Andy Anderson, in the third and final chapter in this part, present energy conservation as an analytical tool, "rules to be followed". Quinn writes of the need to identify matter with energy to reach a coherent understanding of energy; Dauer, Miller, and Anderson write of the necessity to help students distinguish between matter and energy. They describe an instructional scaffold (twist ties) that helps students focus on matter and energy as separately conserved entities.

Quinn, Lopez, and Anderson were all deeply involved in the development of the Framework for K-12 Science Education and the Next Generation Science Standards (NGSS.) The three different perspectives on energy in this part provide insights into how they played out in these policy documents. Is Quinn's perspective appropriate for K-12 students or must K-12 instruction begin by helping students view matter and energy as separate entities (even though they naturally see them as one) and only later combine both perspectives? Do the conceptual issues identified by Lopez really originate in a poor understanding of energy conservation and flow or can complex mathematics mask the physical meaning of equations and thus the problem is not a poor understanding of energy conservation but the under-developed ability to translate between mathematics and the physical entities represented by the mathematics? The lack of uniformity of these three perspectives stimulates further insights.

Chapter 2
A Physicist's Musings on Teaching About Energy

Helen R. Quinn

2.1 Introduction

Energy is at the same time a topic of high relevance for our everyday life and one of the deepest and most subtle ideas of science. When asked about examples of energy, some students list phenomena involving light, heat or electricity (e.g. Trumper 1990). Some may give examples such as energy stored in fuel (e.g. Lijnse 1990), food (e.g. Solomon 1983) or water (behind a dam) (e.g. Duit 1984). Adults may add terms like nuclear energy, solar energy, chemical energy or mechanical energy. Looking at such a list, it is very hard to see what all these diverse phenomena have in common, where they overlap and where they are distinguishable. Adding to this the fact that the way energy is described within different disciplines of science varies greatly – at times so much so that it is difficult to see connections between them – it is not surprising that energy is such a difficult concept for students to understand (e.g. Duit 1981; Driver and Warrington 1985; Liu and McKeough 2005; Neumann et al. 2013; see also Chap. 5 by Duit, this volume).

Students' need to know what energy is often leads to them being acquainted with a simple definition of energy (cf. Papadouris and Constantinou 2011). The teaching of simple definitions to students is based on the misconception that we learn words and concepts by being told their definitions. In fact we learn them by experiencing and applying them in multiple contexts (cf. Bransford et al. 2000). Any definition of energy at the macroscale level that would be general enough to be correct is either vague enough to be worthless, or contains a long list of "forms of energy" that seem so disparate that no concept can be abstracted from such a definition. This may lead to frustration in both teachers and students Perhaps it helps to discuss the fact that

H.R. Quinn (✉)
SLAC National Accelerator Laboratory, Stanford University, Stanford, CA, USA
e-mail: quinn@slac.stanford.edu

R.F. Chen et al. (eds.), *Teaching and Learning of Energy in K-12 Education*,
DOI 10.1007/978-3-319-05017-1_2,

science did not arrive at the concept of energy by defining it, but rather by exploring it (see for example Coopersmith 2010), and that this the path that learners must take too, in order to understand it.

Different forms of energy are measured in different units because they were discovered and categorized at different times. Conservation of energy, first applied only for special and idealized cases (conservative systems), emerged as a more general principle as the relationships and transfers between the different types of energy and the conversion factors between their measures were recognized, and the deeper mathematics behind equations of motion explored. As always in teaching science, we need to untangle the ideas from their history, and decide when recapitulating the historical development of the idea is helpful to students and when it simply immerses them in confusions that they do not need to repeat to get reach a conceptual understanding of the topic being taught as it is understood today. In teaching about energy it is also important to make connections between the concepts related to energy used in different disciplinary contexts, as well as the everyday meanings of the word.

Physicists talk about kinetic and potential energy, using gravitational potential energy for most of the examples of energy transfer they introduce at the high school level, or perhaps elastic potential energy in a spring. Electrical potential differences are introduced in different units and used only to talk about electric circuits. What do they have to do with potential energy? Power is introduced with its own units; the fact that it is a rate of energy flow is not transparent. Energy concepts related to electric and magnetic fields are not discussed till advanced undergraduate courses. Mass-energy equivalence through $E = mc^2$ may be introduced in high school physics in the context of special relativity or nuclear processes, but the true generality of this relationship is seldom stressed. Physicists have adopted a convention that the term heat can only be used for energy transfers between systems, whereas for almost everyone else heat means thermal energy, whether or not it is being transferred. The deep inter-relationship between energy and forces is seldom introduced until advanced undergraduate courses, but the capacity of forces to transfer energy is stressed in introductory physics introducing the added concept of work, which is sometimes presented as a way to define energy (the capacity to do work) which is not particularly enlightening. Chemists talk about bond energy. Nuclear physicists use the term binding energy. Biologists and earth scientists talk about chemical energy, or food and fuel as sources or stores of energy. Engineers talk about electrical and mechanical energy and about energy conversion. Where in all this terminology is a student to develop a coherent concept of energy?

2.2 The Particle Physicist's View of Energy

As I am a particle physicist, the view of energy and matter at the smallest scales informs my thinking. I discuss it here, not because I think we can teach this view as the starting point for understanding energy, but because I think discussing this level of understanding energy allows us to think about what to teach, and when, in order for students to be moving over time towards a deeper and more consistent understanding of energy (i.e. it will prepare the ground for developing learning progression of energy).

At the level of quantum physics, or even advanced classical mechanics, we find that to define energy is to write the laws of nature. If we can define how the energy of a system depends on the relative positions and motions, and on the charges and masses, of the particles within a system, then we can predict (at least probabilistically) how that system will behave. The quantity (technically the Hamiltonian or the related quantity known as the Lagrangian) that describes and defines energy in a system is what determines the laws of physics (i.e. the equations of motion) for that system.

At the atomic or subatomic scale, energy has two basic components, it is either kinetic energy or energy stored in the interaction fields (electromagnetic, gravitational or subnuclear) between the particles. Electromagnetic radiation provides a tricky bridge between the two, because it can be described either as massless particles (photons) which nonetheless carry kinetic energy, or as time-changing and travelling electromagnetic fields carrying energy across space. Both descriptions say it carries energy from place to place, and which is most appropriate to use depends on the situation.

The energy of any system is built up out of these fundamental forms of energy, the motion and interaction energies of the fundamental particles it contains, just as matter is built up from those particles. At different scales it is convenient to describe both the structure of the system and the energy it contains in different ways. However, in the end, I think that, just as we cannot understand many properties of matter without atomic and sub-atomic understanding, we cannot clearly understand many of the commonly used terms for forms of energy until we break them down again and into the underlying particles and their interactions.

The fact that total energy is conserved is a fundamental theorem at this scale, closely linked by the magic of mathematics (Noether's theorem) to the fact physics does not depend on the time, location, or frame of reference. If we write a theory of matter and its interactions for which the function that describes energy has these desirable (and observed) invariance properties, it predicts conservation of energy and momentum among its consequences. However the mathematics that underlies these statements takes us well beyond high school mathematics, so the law of conservation of energy must be presented as a rule which has little empirical support. It is truly difficult to measure all forms and flows of energy, and so any demonstration of the law is at best approximate. While they may be able to see it as a limiting case, that is as true for an idealized system, students have no way to know that it how exact and general a law it is, except by being told it.

Perhaps the most widely recognized and least understood formula in all of science is $E = mc^2$. Most people, including Ph.D. level chemists and biologists, think it is something that only applies in nuclear physics. Instead it is a deep statement that says the quantity we call mass and the quantity we call energy are in fact indistinguishable. (The c^2 in the relationship is just an expression of the fact that we measure them in very different units.) The relationship tells us that, as viewed in the rest frame of the center of mass of any system, what we define and measure as the mass of a system is not just the sum of the masses of the particles that it contains. It includes all forms of energy within it. From outside the system, without probing inside it in some way, there is no measurement that can tell whether the system has a large mass because it contains some high mass objects, or because it contains less-massive but rapidly moving objects.

Indeed as we go to the most fundamental theories we find that most of the mass of protons and neutrons, which means most of the mass of any matter made from atoms, arises from the kinetic energy and interaction energy of the quarks within the protons and neutrons. The sum of the masses of the quarks is only a small fraction of the proton or neutron mass. (Even the quark masses appear as interaction energy. They are due to the interaction of the quarks with the omnipresent Higgs field.) Thus the notion that mass is anything other than an accounting of all energy within a system (when the center of mass of the system is at rest) disappears. Furthermore, for a moving object or system, the division of the energy of a moving particle into two parts, mass-energy (mc^2) and kinetic energy ($1/2\ mv^2$) turns out to be a low speed approximation to the more complete statement of Einstein's formula, which can be written as $E = mc^2/(1 - v^2/c^2)^{1/2}$. In this relationship mass-energy and kinetic energy for a moving system are not separable, but are inextricably intertwined.

While the equivalence of mass and energy is essential to gaining a fundamental understanding of energy, and of conservation of energy, it is irrelevant for most practical purposes, and certainly in the most of school science. In all but nuclear physics situations we do not need to discuss it. We simply leave out mass-energy in all our calculations of energy, because it is a large quantity that, if we are careful about the rest of the accounting, we can treat as a constant. This has an important consequence. Once we have excluded some energy we can never talk about total energy; we can examine only examine changes in energy. However if we are going to discuss conservation of energy as a system changes, we need to be sure we maintain a consistent definition for the energy we have excluded from the accounting.

Kinetic energy for a moving and unchanging object is relatively easy to describe, what is much harder for students to conceptualize is all the various forms of potential energy. In particle theories these all come down to energy stored in fields, relative to that in some reference situation. Theories of fundamental physics are built on a mathematical model in which the interactions between particles are mediated by fields. These fields are essential for modeling the mechanism of forces between distant objects and for modeling interaction energy, and the related concept of potential energy. The key idea is that these fields exist and vary across space, contain energy, and can transfer energy between distant objects. While they are invisible, their presence can be measured by their effect on a test charge or magnet, or in the case of gravitational fields, a test mass, placed in the field. The concept of a force field requires careful qualitative development. It can be introduced well before students are prepared to treat such fields mathematically. Even if students have a vague and science-fiction-based idea of an invisible force field (e.g. Adrian and Fuller 1997) this can be used as a starting point.. The concept can be refined and shaped as students experience phenomena, such as the effect of a magnet on iron filings, or "static electricity," that can be described and explained in terms of fields.

Without the concept of the fields, the interaction energy between the objects is not attached to anything and does not have any location that can be included in the students' mental models of phenomena. In this situation observations that masses speed up as they fall, and that magnets move things without touching them, appear to contradict the notion of conservation of energy. Students tend to conceptualize energy as a thing (e.g. Duit 1987). Physicists conceptualize it as a quantity that can be associated with things, and transferred from one thing to another, but which itself is not a substance[1]. Of course, force fields are not substances either, put they do have a detectable physical reality, that perhaps makes them more readily conceptualized than energy itself. This needs study. How can the concept of interaction energy as energy stored in the space between the interacting objects best be modeled for students? What experiences and activities help students develop this concept? At what stage can potential energy be conceptualized as a difference in interaction energy compared to a reference situation? When does the concept of a force field help, when is it just another meaningless set of words?

2.3 Descriptions of Various Types of Energy

I now examine many of the everyday terms used to describe energy. They overlap and are not generally well defined. It is useful to clarify what they represent and when they are useful. In most cases, as far as I can see, it is not useful to try to define them more precisely – when precision is needed we can achieve it without most of these terms.

2.3.1 Thermal Energy

Many students do not distinguish between heat and (thermal) energy (e.g. Kesidou and Duit 1993 or Maskill and Pedrosa de Jesus 1997). In strict physics definitions this is not acceptable, physics uses the term heat only for energy transfers, and not for energy present in a system. One reason for this is that, as discussed above, total energy present is not a useful concept in most situations, and furthermore it can be difficult to decide what part of that total energy in a given situation should be labeled as thermal energy.

---

[1] "... in physics today we have no notion of what energy is. We do not have a picture that energy comes in little blobs of a definite amount. It is not that way." (Feynman et al. 2011, pp. 4–1).

Indeed until one has a clear particulate understanding of matter, thermal energy cannot even be described. At the particulate level, it is often described as the energy of random translational motion of particles within a system; that is, as kinetic energy. However this description is only true for an ideal (non-interacting) monatomic gas. Whenever we have molecules or solid matter present, thermal motion also includes rotational motions of the molecules and vibrational motion of the atoms in a molecule. If we look more closely we see that the potential energy of interaction of atoms within the material is changing all the time as the atoms vibrate. Energy is constantly being transferred between the atomic motion and the potential energy between the atoms as the molecule stretches and contracts. A little thought makes it clear that if these changes in potential energy were not included in the definition of thermal energy, thermal energy would fluctuate as a molecule vibrates. That would be a most inconvenient definition. So, except in the ideal gas of non-interacting atoms, thermal energy must include some potential or interaction energy as well as kinetic energy.

As soon as we introduce interaction energy we are into the morass of defining energy relative to some fixed condition. Any set of interacting masses and charges has a total energy that depends on the relative positions and motions of the charges and masses, but we seldom need to know or care what that total energy is, in fact we only need to know how it changes when the positions and motions change. In principle we define absolute zero temperature (0 K) to be the temperature at which there is no thermal energy, but since we cannot actually get anything to that temperature that is more a theoretical statement than a practical one. For practical purposes we can relate changes in temperature to changes in thermal energy per unit volume, or per mass of material. With the exception of the ideal gas case, this relationship cannot be easily predicted but rather is extracted from measurements, and it is different for different substances.

The fact that it takes different amounts of heat to achieve the same change of temperature for the same mass of two different substances makes it clear that temperature cannot be measure of energy, or even of energy per unit mass. Students initially conceive of heat and temperature as much the same thing (Kesidou and Duit 1993), after all both have to do with getting hot! Learning to distinguish them and to understand their true relationship is an essential step in reaching a clear view of thermal energy. Many textbooks discuss the relationship only for an ideal gas, which elucidates only a part of the complex relationship.

The concept of heating as an increase in thermal motion clearly breaks down when we consider what happens as matter transitions from solid to liquid, where the energy of interaction between its constituent particles changes significantly. Ice at zero degrees has less energy than the same amount of water at zero degrees, as can be seen by the fact that it takes energy to melt the ice. The water molecules in ice are bound together into a solid. The energy needed to unbind them (that is to break the inter-molecular bonds) is called the latent heat of melting. This is amount of energy we must add to melt a given quantity of ice. This makes it a bit tricky to compare “thermal” energy of ice with that of water. The added energy has broken the bonds that formed the ice crystal. Likewise a change in interaction energy takes place as matter goes from liquid to gas, again energy is added without a change of temperature to achieve the change of state. This energy is called the latent heat of evaporation. So should we call those changes of state changes of thermal energy?

We simply do not need to try to answer to that question. It is a choice, just as defining what part of the energy we remove from the problem by calling it the mass of the system is a choice. Just like total energy as a whole, total thermal energy is not generally a useful concept. (Indeed to completely define the mass of a system you have to define not only its configuration, but also its temperature, because thermal energy too contributes to mass-energy. All of this is generally irrelevant for the problem at hand for K-12 students.) The idea of thermal energy is useful for talking about changes in a system, and where energy goes when it leaves a system, but not for calculating absolute quantities of energy.

2.3.2 Chemical Energy

In any chemical process the set of atoms present does not change, so the mass-energy of the atoms present is constant and thus irrelevant for any energy changes that do occur. Any chemical process takes a set of molecules and converts them to a different set, with different bonds between the atoms. With this in mind we understand why chemists focus on differences in total bond energies to explain energy released or captured in a chemical reaction.

All bond energies are negative because the stable molecule has less energy than the separated atoms. This can also be understood by looking at the electromagnetic fields due to the charged substructure of the atoms, and how the total energy stored in these fields can be reduced by bringing atoms together and "sharing" some of the electrons between them. Actually calculating such changes in energy from first principles is a complex quantum chemistry problem. The language of chemical bonds and bond energies is a useful shorthand to describe the results of such a calculation, or of measurements of energy differences. However it is completely wrong to talk about energy stored in a chemical bond – every chemical bond is a shortage of energy. So what do we mean by chemical energy?

Generally we mean some energy that has been, or could be, released in a chemical process. The energy captured or released in any chemical interaction is the difference between the sum of the bond energies before and after the reaction. Released energy typically manifests itself as increased thermal energy. The energy captured in the inverse process can come from thermal energy or from other forms such a sound energy or radiation. If energy is released, it is because the molecules after the reaction are more tightly bound than those before the reaction – the resulting molecules between them have a greater shortage of energy than the starting ones (compared always to the separated atoms). Thus the term chemical energy is, like thermal energy, not easily defined in any absolute way. All we care about are the changes. It is not meaningful to talk about total amounts of