Learner intuitions about energy degradation

Abigail R. Daane, Stamatis Vokos, and Rachel E. Scherr

Department of Physics, Seattle Pacific University, Seattle, WA 98119

Abstract: A primary learning goal for energy in K-12 science instruction is that energy cannot be created or destroyed. However, learners' everyday ideas about energy often involve energy being "used up" or "wasted." In physics, the concept of energy degradation can connect those everyday ideas to the principle of energy conservation. Learners' spontaneous discussions of aspects of energy degradation and the second law of thermodynamics include ideas concerning the inaccessibility, usefulness and dispersion of energy. These ideas have motivated us to introduce new learning goals into our K-12 teacher professional development courses. We identify alignments between these learning goals and learners' informal ideas and discuss instructional implications created by these alignments. Our aim is to create stronger ties between formal physics knowledge and sociopolitical issues by making these learning goals a priority in our professional development.

TABLE OF CONTENTS

I. INTRODUCTION 2

II. RESEARCH CONTEXT 3

A. Theoretical framework 3

B. Data collection and episode selection 4

C. Instructional context 4

III. ENERGY DEGRADATION IN PHYSICS AND PHYSICS INSTRUCTION 6

A. The physics of energy degradation 6

B. Previous physics education research on energy degradation and the second law of thermodynamics 7

1. Learners' everyday ideas about energy compete with canonical physics concepts. 7

2. Emphasis on energy degradation and the second law of thermodynamics may increase learners' understanding of energy. 8

3. Learners' everyday ideas are productive resources for learning about energy. 9

IV. LEARNERS' IDEAS RELATED TO ENERGY DEGRADATION 9

A. Energy can be present but inaccessible. 9

B. Energy can lose its usefulness as it transforms within a system 10

1. Thermal energy is less useful. 10

2. Sound energy is less useful. 12

C. Energy can lose its usefulness as it disperses 12

D. Energy tends to end as thermal energy. 14

E. Energy's usefulness depends on the objects involved 16

V. LEARNING GOALS FOR ENERGY DEGRADATION 18

A. Learners should be able to distinguish between degraded energy and free energy in specific scenarios. 18

B. LEARNERS SHOULD BE ABLE TO IDENTIFY CHANGES IN DEGRADED ENERGY AS THEY TRACK THE TRANSFERS AND TRANSFORMATIONS OF ENERGY WITHIN AN ISOLATED SYSTEM. 18
C. LEARNERS SHOULD BE ABLE TO EQUATE THE TOTAL ENERGY IN A SYSTEM AT AN INSTANT TO THE SUM OF THE DEGRADED ENERGY AND THE FREE ENERGY. 18
D. LEARNERS SHOULD BE ABLE TO SHOW THAT THE IDENTIFICATION OF ENERGY AS DEGRADED OR FREE DEPENDS ON THE CHOICE OF OBJECTS IN THE SCENARIO. 19
E. LEARNERS SHOULD BE ABLE TO IDENTIFY THE OCCURRENCE OF OVERALL ENERGY DEGRADATION. 19
F. LEARNERS SHOULD BE ABLE TO ASSOCIATE ENERGY DEGRADATION WITH MOVEMENT OF A QUANTITY TOWARDS EQUILIBRIUM....19

VI. CONCLUSION....20

ACKNOWLEDGMENTS....20

REFERENCES....21

I. Introduction

Energy conservation is central both in a sociopolitical sense and in the formal study of physics, but the term has a different meaning in each context. In physics, energy conservation refers to the idea that the same total quantity of energy is always present in any isolated system; energy is neither created nor destroyed. In the public consciousness, however, energy conservation refers to the idea that we have to guard against energy being wasted or used up; the energy available to serve human purposes is both created (in power plants) and destroyed (in processes that render it unavailable to us).

The Energy Project is a five-year NSF-funded project whose goal is to promote elementary and secondary teachers' development of formative assessment practices in the context of energy. K-12 teachers are in a special position in that they introduce both formal science concepts and social responsibility to young members of society. Teachers in our professional development courses have spontaneously considered not only the amount and forms of energy involved in physical processes, but also ideas related to the energy's recoverability and degradation. Some teachers view energy as losing value during certain processes, even as they explicitly recognize the total amount of energy is constant. Others articulate that the quality, usefulness, or availability of the energy may decrease when the energy changes form (for example, from kinetic to thermal) or when the energy disperses in space. We see these ideas as resources from which to build a sophisticated understanding of energy in physics and society, one that is both useful for K-12 teachers and their students and responsible to corresponding topics in formal physics (including energy degradation and the second law of thermodynamics). These ideas might also be the basis for a meaningful model of energy that is in some sense both conserved and used up. Few existing resources support learners in integrating these seemingly contradictory concepts. In this paper, we seek to identify the productive ideas related to energy degradation and the second law of thermodynamics that appear in learners' spontaneous discussions.

We find that learners' spontaneous discussions about the inaccessibility, degradation, dispersion and usefulness of energy are in agreement with aspects of energy degradation and the second law of thermodynamics. These alignments have motivated us to create new learning goals for our K-12 teacher professional development courses that will support future development of teachers' ideas. In what follows, we first describe the context and background for the observations of K-12 teachers-as-learners and explain the methodology used to gather and interpret the data (Section II). We next describe the physics concepts relevant to sociopolitical energy ideas and share prior research on learner ideas about these concepts

(Section III). By analyzing learners' spontaneous discussions about energy usefulness, degradation, dispersion and availability, we identify alignments between physics and learners' intuitive ideas (Section IV). Finally, we introduce learning goals to address the physics concepts that align with learners' ideas (Section V). Our aim is to create stronger ties between formal physics knowledge and sociopolitical issues by making these learning goals a priority in our professional development.

II. Research context

In this section we share our theoretical framework, methods for data collection, and instructional context.

A. Theoretical framework

We take as a premise that learners have rich stores of intuitions about the physical world, informed by personal experience, cultural participation, schooling, and other knowledge-building activities [1-7]. Some of these intuitions are "productive," meaning that they align at least in part with disciplinary norms in the sciences, as judged by disciplinary experts [8-10]. Learners may only apply these intuitions episodically: at some moments of conversation with instructors and peers there may be evidence of productive ideas, whereas at other moments productive ideas may not be visible [11, 12].

We conceptualize learning as a process of growth through which the "seeds" of learners' early ideas mature, through experience, to become more logical, coherent, consistent with observed evidence, and otherwise more fully scientific. Effective instruction, in this view, is instruction that provides favorable conditions for growth. This general conceptualization is common to many specific theories about teaching and learning [7, 13-17]. Some research contrasts this general conceptualization with other conceptualizations that see learners as hindered by ideas that are fundamentally flawed, and instruction as repairing or replacing learners' ideas [10, 18, 19].

Our research is motivated by our experience that attention to learners' productive ideas is among the most powerful tools for facilitating growth. We find that in practice, attending to learners' ideas requires active engagement by both instructors and peers and stimulates learners' own resources for problem solving [20-23]. In courses offered by the Energy Project, instructors place a high priority on attending to learners' productive intuitions. Through the Energy Project, instructors have developed lesson plans and learning targets. They also listen to the disciplinary substance of learners' ideas, adapting and discovering instructional objectives in response to student thinking [24]. As a result, each Energy Project course has a unique trajectory that emerges from the interaction of learners' agency with instructors' judgment of what is worth pursuing [9, 21].

In this paper, we analyze a variety of episodes in which learners show evidence of productive ideas. These episodes do not show instructors responding to the substance of learners' ideas because at the time that these courses took place, we were not intellectually prepared to attend to learners' ideas about energy degradation. However, by studying video records of learners' conversations and developing our own physics understanding, we have come to recognize value in previously overlooked learner ideas. Our new understanding of these ideas has inspired new learning goals, which will shape instructor attention in future courses. Video observations and measurements of effectiveness will feed an iterative cycle of physics model development, improvement of instructional activities, and advancement of learning theory.

For us learners' ideas play the privileged role, consistent with our theoretical stance. Other theoretical perspectives give primacy to canonical understanding and the extent to which learners have or have not achieved it. Regarding the second law of thermodynamics, however, there are two very practical reasons for valuing learners' intuitions as resources for learning, as opposed to evaluating learners' ideas on their alignment (or not) with canonical knowledge. First, if one used an evaluating-student-ideas-for-alignment approach, the list of difficulties would be long and disjointed, partly due to the fact that formal or informal exposure to the second law is often shrouded in mystery and misinformation or unmotivated, inaccessible mathematical formalism. Second, if one were to privilege the typical canonical approach in physics, one would privilege the analysis of reversible processes in idealized situations (e.g., Carnot cycle), whereas everyday experience mainly consists of highly irreversible processes. Thus, rather than thinking of learners' ideas as flawed relative to disciplinary understandings, we value them as productive resources that can grow into rigorous disciplinary knowledge.

B. Data collection and episode selection

Our data includes examples of learners discussing ideas related to energy degradation and the second law of thermodynamics. The examples are from video records of professional development courses for K-12 teachers offered through Seattle Pacific University as part of the Energy Project. In the Energy Project, professional development courses are documented with video, field notes, and artifact collection (including photographs of whiteboards, written assessments, and teacher reflections). In each course, teachers are grouped into 4-8 small groups, and two groups are recorded daily. As researcher-videographers document a particular course, they take real-time field notes in a cloud-based collaborative document, flagging moments of particular interest and noting questions that arise for them in the moment. Later, the researcher-videographers or other members of the Energy Project identify video episodes to share with a research team. We use the term "episode" to refer to a video-recorded stretch of interaction that coheres in some manner that is meaningful to the participants [25]. These episodes are the basis for collaborative analysis, development of research themes, literature searches, and the generation of small or large research projects.

For this analysis, video episodes were identified through (1) initial observations by videographers and (2) a search for key terms in the field notes which could relate to energy degradation (e.g., entropy, spreading, diffusion, thermal energy, wasted). Selected episodes were watched several times to support the creation of detailed narratives and transcripts. On the basis of multiple viewings of the video episodes and analysis of the transcripts and narratives, we identified the productive ideas related to energy degradation and the second law of thermodynamics that appear in learners' spontaneous discussions. Twelve episodes were isolated and captioned to illustrate learner engagement with issues of energy degradation. These episodes are described in Section IV.

C. Instructional context

The Energy Project goals for energy learning are specific to our population of teachers-as-learners and include conceptual understanding, sociopolitical relevance, creative flexibility, and representational competence. Our primary conceptual learning goals are as follows: (1) Learners should be able to conserve energy locally in space and time as they track the transfers and transformations of energy within, into, or out of systems of interest in complex processes and (2) Learners should be able to theorize mechanisms for energy transfers and transformations. Our progress toward some of these goals is reported elsewhere [4, 26-33].

We structure our energy instruction around a substance metaphor for energy, which supports a model of energy as conserved, localized, transferring among objects[1], and transforming among forms [27, 28]. These features constitute a powerful conceptual model of energy that may be used to explain and predict energy

---

[1] The description of energy as being located in objects can be a concern for gravitational and other forms of potential energy, which are properly located in a system of objects or in a field, rather than in individual objects. In our instructional contexts, we allow learners to locate such forms of energy either in isolated objects, in systems of objects, or in fields, as appropriate to the level and learning goals of the course. This approach allows for iterative negotiation and refinement of the meaning of systems, an important learning goal in the study of energy. Alternatively, learners may identify a field as a new kind of (nonmaterial) object that can contain energy.

phenomena [2, 34-38]. Though this substance metaphor has limitations [34, 39, 40], its benefits for our specific instructional goals outweigh its possible disadvantages [27].

In our courses we use Energy Theater, a learning activity that is based on a substance metaphor for energy [28]. In Energy Theater, each participant identifies as a unit of energy that has one and only one form at any given time. Groups of learners work together to represent the energy transfers and transformations in a specific physical scenario (e.g., a refrigerator cooling food or a light bulb burning steadily). Participants choose which forms of energy and which objects in the scenario will be represented. Objects in the scenario correspond to regions on the floor, indicated by circles of rope. As energy moves and changes form in the scenario, participants move to different locations on the floor and change their represented form. The rules of Energy Theater are:

- Each person is a unit of energy in the scenario.
- Regions on the floor correspond to objects in the scenario.
- Each person has one form of energy at a time.
- Each person indicates their form of energy in some way, often with a hand sign.
- People move from one region to another as energy is transferred, and change hand sign as energy changes form.
- The number of people in a region or making a particular hand sign corresponds to the quantity of energy in a certain object or of a particular form, respectively.

For learners who have become comfortable with Energy Theater, we offer a second representational activity called Energy Cubes. This representation is similar to the Energy Theater representation except that units of energy are represented by small cubes that move among object areas marked on a horizontal white board or sheet of paper. Different sides of the cubes are marked to signify different forms of energy. As energy transfers and transforms, learners move and flip the cubes on a whiteboard. The Energy Cubes representation is similar to Feynman's description of energy as a child's set of blocks [41] but with added features: the location of the cube shows the location of the energy and each side of the cube shows a different form of energy.

A snapshot of Energy Theater or Energy Cubes illustrates the energy located in each object at the instant of the snapshot, consistent with understanding energy as a state function. Energy is associated with each object based on perceptible indicators that specify the state of that object. An Energy Theater snapshot may also include energy units in transit between objects. Such energy-in-motion is ontologically different than the energy contained in objects: over a time interval, it reflects *processes* of energy transfer. Heating or performing work are processes that imply a choice of time interval – a choice that defines an initial state, an *a priori* specified final state, and a specific connecting story.

In physics, an arbitrarily defined set of objects can comprise the system of interest. In Energy Theater, learners decide which objects are of relevance to particular energy processes, typically including all objects that play a significant (as judged by them) role in the processes. The *system*, therefore, is made up of all interacting objects and is by construction isolated (no energy comes in or out during the time evolution of the system). In this paper, we use the term *system* to refer to isolated systems, i.e., systems that include all interacting objects.

A *scenario* is a unique story involving the objects comprising the system that has a predetermined time development. That is, the initial and final states of the system are known in advance or assumed in advance. Energy Theater and Energy Cubes represent the scenario; they do not represent causal agents (forces, temperature gradients, pressure differences, electric potential differences). Coordination of the energy story with the story of these causal agents occurs during the negotiation among the participants. Learners who use these representations consistently produce in-depth analyses of energy scenarios and communicate these analyses in detail to instructors, peers, and researchers [28], enabling studies such as this one.

III. Energy degradation in physics and physics instruction

Energy Theater and its associated representations foreground certain aspects of energy, described above. Other aspects of energy are not apparent in these representations, including the idea that energy is not only conserved but also used up. In Section A, we describe the physics of energy degradation. In Section B, we identify literature discussing student understanding of these ideas.

A. The physics of energy degradation

In everyday language, learners may refer to certain quantities of energy as lost or used up, prompting concerns as to whether or not they are committed to the concept of energy conservation. Another possible interpretation is that learners are referring to ideas related to energy degradation. Energy degradation depends on a specific system (which comprises all relevant objects in a specific scenario), a specified time evolution of that system, and a specified or putative final state. *Degraded* energy at time *t*, associated with the system of all relevant objects evolving from some initial state to a specified final state is energy at time *t* that will not be available for the performance of work during the remaining time evolution of the system [42].[2] In order to avoid requiring our learners to integrate models of force and energy prematurely, we define degraded energy equivalently as energy unavailable for the process of mechanical energy transfer (with the provisos of the previous sentence). For example, in a gasoline-powered car, thermal energy that dissipates to the environment as the engine runs is lost in that it cannot be used to propel the car; it is degraded. Energy change associated with the performance of work (or mechanical transfer) is related to *free* energy change in physics ("free" in the sense that it is available for use).[3] The total energy (which remains constant in Energy Theater) is, at every instant, the sum of the degraded energy and the free energy (of the system, within the confines of specific initial and final states bridged by specified time development). Concerns about conserving energy (in the sociopolitical sense of guarding against energy waste) may be interpreted as concerns about preserving free energy.

In physics, energy degradation is associated with movement toward equilibrium in a quantity whose gradient can be harnessed for the performance of work (such as temperature, pressure, or concentration). When a partition is removed between a vacuum and a cube of gas, the gas expands from the area of high concentration into the volume that was a vacuum. This expansion process reduces the pressure difference between the two volumes and degrades the energy that was associated with the filled cube. The expansion also spreads energy more equitably through the system [43]. Energy can also spread through mixing: for example, when a hot gas and a cold gas come into contact with each other, the initial temperature gradient between them is reduced. In this case, the energy spreads in phase space by increasing the range of possible momenta of the particles. In real, irreversible processes, energy spreads within objects, to other objects, through space, by mixing, in phase space, or a combination of these.[4] This spreading is accompanied by an increase in entropy [43]. In other words, energy spreading, energy degradation, reduction of gradients, and entropy production are all features of real, irreversible processes. This co-occurrence prompts a degradation-oriented statement of the second law of thermodynamics: Energy degrades in irreversible processes.

---

[2] Degraded energy as defined here is therefore not a state function.

[3] Free energy as defined here is not a state function but rather the difference between state functions and may correspond with the work-related part of Gibbs or Helmholtz free energy changes depending on specific conditions. Our use of free energy corresponds to exergy [74], a term not widely used in physics instruction.

[4] Not all energy that spreads spatially is associated with irreversibility and energy degradation. For example, compressed springs that are arranged radially as spokes around a fixed center may be released, pushing blocks radially outward on a horizontal frictionless surface: the spatially localized energy in the springs spreads radially outward, but could bounce back from a fixed circular obstacle and re-compress the springs.

Since energy degradation is defined relative to a specific set of objects interacting over a time interval through specified processes and with specified initial and final states, changes in any of those parameters can change the status of the energy (from degraded to free, or vice versa). For example, thermal energy that accumulates in a car as a result of the engine running may be identified as degraded in the system consisting only of the car and the warm surrounding air, because it cannot be used to propel the car. However, that same thermal energy may be identified as free in a different system that would include freezing surrounding air – a different system participating in different possible scenarios, due to a temperature gradient that was not present in the system of only a car and warm air. This gradient could be used, in theory, to power some other process. The addition of new objects into the scenario or reconsideration of the boundaries of the system can introduce new gradients and increase the free energy of the system. Thus, degraded and free are not properties of units of energy; rather, they are qualities of the distribution of energy among interacting objects.

B. Previous physics education research on energy degradation and the second law of thermodynamics

1. Learners' everyday ideas about energy compete with canonical physics concepts.

Students' ideas about energy often include sociopolitical associations with energy sources and consumers that are not consistent with the ideas taught in physics instruction [44-54]. Primary and secondary students categorize fuels, food, and natural phenomena (e.g., the sun) as sources, and humans, animals and cars as users or consumers of energy [51]. Sources are sometimes identified as energy itself, instead of entities from which energy originates. The same source-consumer model was found pre- (ages 10+) and post- (ages 13+) instruction. Among student-identified sources, fuel has a particularly strong association with energy [e.g., 47, 54]. One preliminary study highlights a student's description of energy as "something that can do something for us…say like gas or something" [47]. The "energy as a fuel" framework [54] is seen as problematic in that fuel is a material substance whereas energy is not. Some researchers argue that these ideas must be confronted to improve students' understanding of energy [51, 53]. Some of this same research characterizes students' ideas as not only "obstinately persistent" but also "messy," stating that students' "socially acquired meanings are not consistent or logical" [51]. For example, when asked whether exercise causes a gain or loss of energy, some students argue that exercise both uses up and builds up a person's energy simultaneously [51]. This perspective highlights the context-dependence of students' ideas, a feature also observed in other areas. However, it characterizes students' sociopolitical ideas as difficulties; little mention is made of their potential productive alignment with free energy. We will argue that the idea that energy "can do something for us" is a productive resource for learning about free energy [55].

Students tend to apply their everyday ideas (e.g., energy as fuel) to real world situations in lieu of energy topics from canonical physics (e.g., the principle of energy conservation) [49, 50, 56-62]. Studies involving secondary students in several countries, including Germany, the Philippines, and the United Kingdom, have elicited student responses to questions regarding the principle of energy conservation. Of 171 post-instruction German students, less than 15% mention conservation when asked to explain various phenomena, such as the motion and displacement of a ball rolling without friction along curved paths (down one curve and up another curve) [49]. Students instead use everyday experiences to describe where the ball ends up on the second curve, determining its destination by distance travelled rather than by height [50]. One year later, "most students did not make use of any knowledge stemming from physics instruction. Some students who tried to employ such knowledge failed" [50]. In another study, only 5 of the 75 students (< 7%) "gave satisfactory answers to the questionnaire as a whole," which included both quantitative and qualitative questions about energy post-instruction [58]. Also after instruction, 23 students (> 30%) still referred to conservation as saving energy or recycling, even though the questionnaire asked for scientific answers. The evidence suggests that over 50% of these students have "considerable difficulties with the basic concept of energy and its related ideas, and their application to everyday situations" [58].

Students also rely on their everyday experiences to explain phenomena related to the second law of thermodynamics and the concept of irreversibility [61-63]. One study reports on 34 clinical interviews with 15-16 year old students from a range of physics classrooms regarding their qualitative ideas about the second law of thermodynamics [61]. The majority of these students describe energy as a substance that is used up, after completing four years of traditional physics courses. At the university level, research on student understanding of heat engines identifies difficulties in relating energy efficiency to the overall increase of entropy in the system [64]. University students also view entropy as a conserved quantity post-instruction in introductory physics courses [65] and confuse the concepts of energy and entropy when discussing ideas about the second law of thermodynamics [66]. In advanced undergraduate chemistry courses, students' understandings of entropy are described as "limited, distorted, or wrong" [67]. Students in these courses often define entropy as disorder and consider visual disorder and entropy to be synonymous. K-12 teachers, in professional development and in their own classrooms, use "inappropriate conceptual meanings" [68] of energy degradation including: a) energy transfer or transformation indicates degradation, b) degradation reduces total energy or occurs only when energy is not conserved, c) internal energy is unrelated to degradation, and d) degradation is heat, which teachers seem to define as "a process of losing energy or losing the availability of energy" [68]. These studies highlight the challenge of supporting student learning of the first and second law of thermodynamics, especially if the goal is to build on learners' intuitive ideas.

2. Emphasis on energy degradation and the second law of thermodynamics may increase learners' understanding of energy.

Many researchers tout an increased focus on energy degradation in K-12 classrooms as a way to increase student understanding [49, 51, 59, 61, 62, 69-72]. In one study, lessons that focused on energy degradation significantly increased student learning of the principle of energy conservation [53]. Some researchers offer middle school curricula that include degradation [70, 71]. However, little research into the effectiveness of this approach exists currently.

Some researchers recommend a stronger emphasis on free energy in physics curricula [55, 73-75]. The use of free energy as it relates to gradients in a quantity (e.g., temperature or pressure) is recommended as a central focus in secondary education over the use of energy transfers and transformations because these ideas are more fundamental and offer a reason for the changes that occur [73]. One study promotes the use of the term "fuel energy" for free energy, responding to secondary students' ideas regarding sources and users [55].

Emphasis on the second law of thermodynamics may also improve student understanding of energy in secondary education. Many studies suggest the use of "energy degrades" as a K-12 appropriate conceptual version of the second law of thermodynamics [55, 58, 62, 76]. For example, teachers can increase student understanding of energy conservation by also using the Running Down Principle: "In all energy changes there is a running down towards sameness in which some of the energy becomes useless" [69]. Another study introduces entropy to 10^{th} grade students as a part of an energy curriculum [76]. After instruction that focuses on both entropy and free energy, students demonstrate limited success in correctly answering questions about the second law of thermodynamics in terms of entropy. The results indicate that secondary students can be successful in learning about entropy and the second law of thermodynamics, though the challenges are great.

Some research suggests that attending to the metaphorical representations of the second law of thermodynamics and entropy may improve the effectiveness of instruction [43, 67, 77-83]. Many metaphors for entropy have been analyzed for their usability including entropy as disorder, freedom, energy spreading, and information [83]. Among these, energy dispersal has been argued to be one of the most promising metaphors in helping students to build a qualitative connection between sociopolitical aspects of energy, science energy, and entropy [67]. This conceptual metaphor uses the idea that as energy spreads, gradients are decreased and entropy increases. However, this metaphor has not yet been evaluated for effectiveness in the classroom [83].

3. Learners' everyday ideas are productive resources for learning about energy.

Overall, the literature on student learning of the first and second law of thermodynamics characterizes learner ideas as different from, and in competition with, what they learn in science courses. Some argue that "students are evidently inadequately prepared and/or are unable to use the energy concept and the principle of the conservation of energy in order to explain simple experiments. They prefer to use explanations with which they are familiar from their environment. On the whole, the tenacity of these notions is surprising and instruction is not very successful in changing them" [57]. Even when concepts such as degradation are introduced into the classroom, researchers report that learners lack the ability to connect their ideas to concepts covered in physics instruction, saying, "It is obvious…that students are far from the physicist's conception of energy degradation" [61]. A primary task of education research, in this account, is to identify learner misconceptions or difficulties so that instruction can be designed to address them specifically.

We share these researchers' sense of the importance of learner ideas for instruction. However, we see these ideas not as obstacles to learning but as potentially productive resources for sophisticated understanding [3,82]. Research using a resources theoretical perspective has been conducted for the concept of energy [8, 84], but not energy degradation. We argue that learners' everyday ideas about saving and wasting energy contain the seeds of correct canonical physics concepts: The intuition that energy can be "lost to us" is a productive idea as applied to irreversible processes in the real world. The outcome of our analysis is to propose learning goals that originate from learners' productive ideas and form a coherent concept of energy degradation that is appropriate for K-12 instruction.

IV. Learners' ideas related to energy degradation

Learners in our courses have spontaneously discussed ideas about energy that our instruction was not designed to support. We provide examples of learners considering elements of energy degradation without explicit instruction or encouragement. Their ideas include: (A) energy can be present but inaccessible; (B) energy can lose its usefulness as it transforms within an isolated system; (C) energy becomes less useful as it disperses; (D) energy tends to degrade; and (E) energy's usefulness depends on the choice of objects under consideration. Below we describe these ideas and give examples of their use by learners in our courses.

- Energy can be present but inaccessible.
- Energy can lose its usefulness as it transforms within an isolated system.
- Energy can lose its usefulness as it disperses.
- Energy tends to degrade.
- Energy's usefulness depends on the objects involved in the scenario.

Figure 1. Learners' ideas related to energy degradation.

A. Energy can be present but inaccessible.

Some learners describe energy being used up during a process, even as they explicitly acknowledge that the total amount of energy is constant. In the following episode, learners discuss the energy involved when wind creates waves on water. Four elementary teachers (whose pseudonyms are Joel, Rosie, Hannah, and

Marissa) decide that energy transfers from the wind to the water, and then try to determine what happens to the energy after that. Hannah states that the energy in the water waves is "not absorbed, because it has to continue on to go someplace." Marissa asks what happens to the energy if the wave hits a wall. Joel suggests the wave "goes through this mass and hits every individual particle." He asks, "Does every single thing take a little bit of energy away until it eventually dies off?" Joel's word "it" might refer to either the energy or the wave dying off. In the ensuing exchange, Rosie interprets Joel's question as a suggestion that the energy dies off. Rosie and Hannah then agree that the energy is "gone," but pause to clarify the meaning of that assertion.

Rosie:	But it can't ever die though, right? Isn't that what we decided?
Hannah:	No, but it can though, because look at batteries, a battery is stored energy, and when it's gone, it's gone.
Rosie:	It's *gone!*
Hannah:	It's gone somewhere, but it's gone.
Rosie:	It's not really gone. It's just not there.
Instructor:	It's gone somewhere.
Hannah:	Right, exactly.
Instructor:	It's just not in the battery anymore.
Rosie:	Right, oh, but we just talked about dissipate, so that's the same thing as saying gone away from us.

After Joel's question Rosie counters, "but it can't ever die," possibly referring to conservation of energy. Hannah responds with a reference to batteries, which are sources of energy that are said to "die" when all possible chemical energy has been transformed to electrical energy. Hannah describes the energy in batteries as eventually being "gone." Though Hannah does not initially specify whether she means gone out of existence or gone to another location, she later says, "It's gone somewhere, but it's gone," supporting the location interpretation. Rosie affirms that "it's not really gone; it's just not there." She relates this idea to dissipation, which she seems to understand as a condition in which the energy is inaccessible ("gone away from us").

Rosie, Hannah, Joel, and Marissa retain their commitment to energy conservation when they assert that the energy of the water wave must "go somewhere" when it hits the wall. However, they also attempt to reconcile this commitment with their sense that the energy "goes away from us" as part of that process. In other episodes below, learners recognize that energy may become inaccessible even as its quantity is unchanged (e.g., Dennis in Section IV.B, Vicki in Section I.C, and Jean in Section IV.D).

B. Energy can lose its usefulness as it transforms within a system

Learners describe the usefulness and availability of energy during various energy processes. They distinguish between more or less useful energy and also explain how the usefulness changes during a process (e.g., energy becomes less useful when it transforms from kinetic to thermal energy). These informal descriptions of usefulness seem to correspond to the physics concept of degradation.

1. Thermal energy is less useful.

In our courses, some learners describe a transformation into thermal energy as a loss of useful energy. This idea is also present in the Next Generation Science Standards, in which one standard (PS3.D) pronounces thermal energy as a "less useful form" of energy. However, thermal energy can be useful in a situation where a temperature gradient drives a process (e.g., steam runs a turbine).

In the following episode, Dennis, a secondary teacher, distinguishes between useful energy and energy that has lost its usefulness. He also identifies the change in usefulness during a process. Responding to a question about a block sliding across the floor, Dennis says, "The molecules are heating up in the lower energy state. Somehow the system is going from a higher energy state to a lower energy state." The instructor shares a concern that Dennis's statement might violate the principle of energy conservation.

Instructor:	I'm not sure exactly what you mean by "lower," given that my total energy has not changed.
Dennis:	Oh! The usefulness of the energy is changing. It's going from, oh I can't think of the name, thermodynamic equilibrium?
Tom:	Are you talking about entropy? You can't get the thermal back. It's gone.
Dennis:	Yah, yah, the energy's there, but it's in terms of random motion. So, its quality, its usefulness is getting lost in the exchange.
Joe:	The entropy, wouldn't you have less that can be used?
Dennis:	What's that?
Joe:	You have less that's available.
Tom:	From a higher state to a lower state of entropy
Dennis:	You have less that's available to you.
Joe:	That would be a main condition of entropy
Doug:	Mmhmm. Second law of thermo
Dennis:	The energy stays the same, yet we're losing the usefulness.

Dennis states that a block sliding across the floor causes molecules to heat up and increases random motion. He says that the energy's availability, usefulness, and quality decrease during this process. When the instructor asks about energy conservation, Dennis clarifies that "the energy stays the same, yet we're losing the usefulness." In this statement, he distinguishes between the total amount of energy (constant) and the value of energy (decreasing). Dennis associates a "lower state" of energy with energy being "less available to you" and "less useful." His idea that the energy state is lowered is not aligned with disciplinary norms in physics. However, it conveys his sense that the energy's status is lowered by the transformation from kinetic energy to thermal energy. In this transformation energy disperses in phase space [43], which corresponds to an increase in degraded energy.

The other learners support and extend Dennis's line of thinking. Tom adds, "You can't get the thermal back," and Joe suggests that there is less of something that can be used. The concepts of entropy and the second law of thermodynamics are proposed as potential extensions to the description of energy usefulness. However, the conversation shifts focus after Dennis's last statement and these connections are not discussed further.

In another course, a group of secondary teachers including Jennifer and Marta, discuss an Energy Theater scenario of a hand lowering a ball at constant speed. Jennifer indicates that a transformation into "heat"[5] makes the energy less useful. She says, "You know what? Seriously, the only place it [energy] could be going is heat cause it's obviously not going anywhere useful." Marta also proposes, "Let's just lose one person to heat, or something." Jennifer later suggests, "How about we have some of the people who are going from GPE [gravitational potential energy] to kinetic go away as heat or go into the earth?" The recommendation that some people (who are chunks of energy in Energy Theater) should be lost or should go away as heat does not indicate that the law of conservation is being violated because in Energy Theater, all participants must remain a part of the scenario; they cannot physically disappear. Jennifer and Marta are instead suggesting that the people should go somewhere, possibly into the surroundings or into the loop of rope representing the ground, similar to Hannah and Rosie's suggestion that energy has "gone away." Energy loss implies the energy has moved away from its previous location or energy has become unavailable for its previous use.

[5] Learners in our courses often use "heat" or "heat energy" to refer to a form of energy indicated by temperature (what we call thermal energy), rather than a transfer of energy driven by temperature difference (what we call heat) [25, 85, 86]. Unless otherwise mentioned, we interpret "heat" or "heat energy" as referring to thermal energy for the remainder of the paper.

2. Sound energy is less useful.

To a lesser extent, we also observed that some learners consider sound energy to have limited usefulness. Brice, an elementary teacher, tracks the energy of a ball that rolls to a stop and asks his peers, “If you could measure the sound coming off the ball, would that be a form of energy that's being lost, just like the heat energy?” When Brice asks if he can describe sound energy as lost, just like heat energy, he implies that the transformation into either thermal energy or sound energy renders that energy unavailable.

Similarly, a group of secondary teachers determine that when a falling object hits the ground the kinetic energy transforms into thermal energy and sound energy. The instructor probes further in the following short episode.

Instructor:	Where does the sound go? I mean, so say some of it goes into
Roland:	Well okay**,** air, vibrations, it will spread out into space
Ted:	So less useful form
Leah:	Right.

In this short excerpt, Ted appears to be comparing sound energy to other energy forms, possibly the gravitational potential energy at the beginning of the scenario. It is not clear whether Ted refers to the energy as less useful because it is in the form of sound energy, because it spreads out into space, or for both reasons. Regardless, his sense that energy becomes less useful recalls the concept of energy degradation.

C. Energy can lose its usefulness as it disperses

Several learners describe a loss of energy usefulness being caused by energy dispersal into a larger physical space. These descriptions often come with a gesture indicating spreading. In what follows, an instructor asks a small group of elementary teachers where the energy goes after a falling object hits the ground. Marissa and Vicki share their contrasting ideas about energy conservation and energy dispersal in the subsequent conversation and gestures.

Instructor:	Where does the sound energy and the kinetic energy in the air end up? We only took it to impact, but if we took it all the way, 'til the thing is down.
Vicki:	A little, a little bit of heat [holds and moves the tips of her fingers in contact with each other]
Marissa:	I get stuck because of that whole conversation that it doesn't, it never goes away.
Instructor:	It doesn't go away.
Marissa:	So we could keep following it and following it and following it, until it comes back around. [gesture; see Figure 2]
Vicki:	*Does* it come back around?
Marissa:	Well ultimately,
Vicki:	That's what I'm [shakes her head “no”]
Instructor:	We said it doesn't go away. We didn't say it was necessarily cyclical. I guess that's kind of the question.
Marissa:	Well I wouldn't say it comes back necess- the same energy comes back to the same object, but just thinking that with all of this energy just floating in space, it doesn't come or go. So it's all [gestures like she holds a basketball and shakes it]
Vicki:	It keeps dispersing. I asked this question yesterday. Heat death of the universe. It juuuust keeeps goooing out. [gesture; see Figure 3]
Instructor:	So, how likely is it that I can somehow harness this thermal energy in the ground and do something with it?
Vicki:	[shakes her head “no”]
Marissa:	So you're saying take it to a place where people could use it?
Instructor:	Or *not*.

Vicki: It gets broken up into smaller and smaller pieces, it's not gone, but it's not able to be use[inaudible]. I find it a little depressing. [laughter]

Marissa describes a cyclic model of energy conservation. She says that energy does not come or go, which implies that she is conserving energy. However, she shows a cyclic process of energy through the motion of her hand (Figure 2) as she says, "So we could keep following it and following it and following it [hand makes small bounces to the right] 'til it comes back around [hand makes large arc back to the beginning position]." Marissa's description may not align with degradation because energy is reused for the same process in her model.

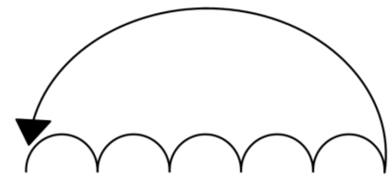

Figure 2. The path of Marissa's hand movement for "So we could keep following it and following it and following it, 'til it comes back around."

Vicki's model of the energy contrasts with Marissa's energy cycle. She describes the energy first as "a little bit of heat" and gestures by holding and moving the tips of her fingers in contact with each other. Then she uses a large gesture (Figure 3) as she says, "It juuuust keeeps goooing out." During this gesture, she slows down each word and moves her hands slowly away from each other sideways, with a slight transverse wave motion up and down with her hands. After the gesture, the instructor asks if it is likely that this energy can be harnessed and Vicki shakes her head no.

Figure 3. Vicki's gesture for "It juuuust keeeps goooing out."

In another elementary professional development course, Owen describes what happens to thermal energy that is produced by a hot plate. He says, "I think essentially it continues to travel [gesture; see Figure 4]. The body of atmosphere that it's affecting becomes greater and greater and greater the more that it travels, so the impact of it becomes more and more negligible." During Owen's explanation, he pauses in silence to gesture outward with his hands (Figure 4). His hands start close to his face with curled fingers and extend outward laterally while his fingers spread apart. He then states that the impact of the energy becomes more negligible as it spreads through a larger volume, similar to the idea that energy becomes less useful as it disperses.

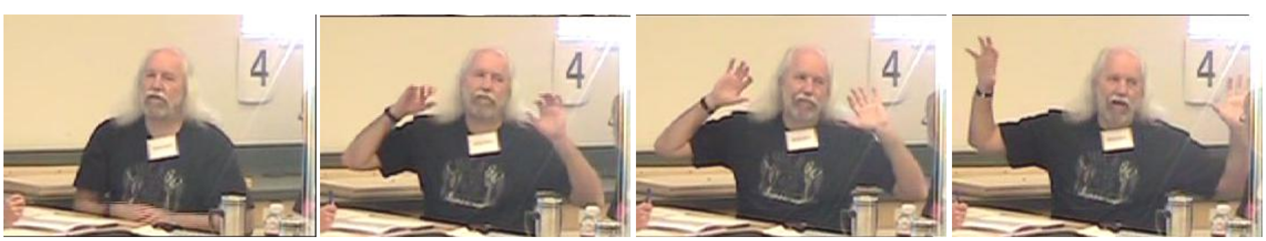

Figure 4. Owen's gesture after he states, "I think it essentially continues to travel."

Rosie, in the episode analyzed in Section IV.A., also discusses dissipation. She suggests that energy in a battery dissipates and equates that to energy going away. She states, "We just talked about dissipate, so that's the same thing as saying gone away from us." Rosie's gesture provides more information about what she means by "dissipate" (Figure 5). Rosie's hands start together and move up and outward away from each other as she talks about the energy going away from us. Similar to Vicki and Owen, her hands spread out during this motion. Rosie's idea and her hand motions about dissipating energy align well with the idea of spreading energy to a less accessible location. This process of losing available energy through dissipation is closely aligned with the dispersal and degradation of energy.

Figure 5. Rosie's gesture for "We just talked about dissipate, so that's the same thing as saying gone away from us." (Rosie is holding a lollipop.)

D. Energy tends to end as thermal energy.

In previous sections, learners describe thermal energy and sound energy as less useful forms of energy. In many scenarios learners award thermal energy the lowest possible status of any energy form. Some learners view a transformation into thermal energy as a terminal process, describing thermal energy as a "dead end" or the final form of energy. This idea aligns well with the second law of thermodynamics in that the energy in a given scenario experiences overall degradation. However, thermal energy does not have to be permanently degraded energy. In the following dialogue, a small group of elementary teachers considers where thermal energy goes when boiling water on a hot plate. Owen reminds the group of a conclusion the class made previously that all energy ends in the form of thermal energy. A conversation in response to this idea about the terminal nature of thermal energy ensues.

Owen: Well, the idea that came up yesterday was that ultimately it all goes
Jean: to thermal!
Owen: [inaudible] to thermal.
Karen: All the energy ends there.
Brianna: It's just sitting there.
Jean: It's just sitting there! Yah, so how long does it sit there?
[Short digression until Jean reiterates her description of the hot plate scenario upon the arrival of the instructor.]
Jean: I was saying that when I have done units on energy, so I have taken a hot plate, turned it on, and boiled water. And so we're talking about the energy transfers and transformations going on, but we always stop at heat energy and then we stop, like it's over.
Owen: When everything's warm.
Jean: Like the energy has, it's complete,
Instructor: [inaudible]
Jean: Yah, like it's done.
[15 second discussion about how this idea has not come up in Jean's class]
Karen: Then you're sitting there wondering where
Jean: It's not really done because it's always there.
Karen: But weren't you asking at what point is it not, thermal energy anymore? At what point is it not there?
Jean: My question was: how long can energy stay the same thing in the thermal stage? Is it *days* or is that unrealistic? Or, I mean does it, because as soon as it changes, like with the wind, some of it is going to become sound energy and I don't know. It just made me wonder, what the life, the shelf-life is of thermal?
Owen: Yah, is it the shelf-life of Twinkies? Or

Jean: Yah! [Laughter]
Instructor: Forever.
Owen: And with yesterday's proposition that all energy ultimately is converted or transferred into thermal. So then, how long does thermal energy last?
Jean: Or if you were going to categorize energy would um, the largest percentage be thermal, and this percentage is sound, and this percentage is kinetic and this
Instructor: And that's energy in the entire universe?
Jean: Yah, yah, if you categorize it. It seems like it would mostly be thermal then, cause that's where everybody, everything ends.

In describing the result of a transformation into thermal energy, these learners state that thermal energy "is just sitting there," and that once thermal energy is produced, this energy process is "complete," "over," or "done." They further generalize that "ultimately" all energy transforms into thermal energy and thermal energy is where "everything ends." Their idea that overall degradation occurred during the process is valid. These learners also correctly view thermal energy in the air as unable to transfer or transform further in this isolated system (consisting of the hot plate, boiling water and the air in the classroom). In physics, many common energy scenarios used when teaching the principle of energy conservation end in thermal energy (e.g., a sled sliding to a stop, a damped oscillator, a car braking). However, the idea that thermal energy is a permanently degraded form of energy could only be true if the entire universe were in thermal equilibrium. If the system consisting of only a hot plate in a classroom also included the cold surroundings of the outdoors (i.e., if a new gradient were introduced to the system), thermal energy in the air could transform and be used to perform work again.

In another elementary course, Brianna asks Brice and Bart about energy conservation and they conclude that all energy ends in the form of thermal energy.

Brianna: Somewhere in the back of my mind energy is never lost. Is that true? Energy is never, it just changes from one form to another and it never goes away. Is that true?
Brice: That is true.
Bart: I think that's true. [Laughter] It always changes into heat I think.
Brianna: Eventually?
Bart: It always degrades into heat. Yeah.

Bart first confirms that energy is conserved and then states that the energy "always changes" and "degrades" into heat. Bart's term heat might refer to thermal energy or radiation. Regardless, the use of the words "eventually" and "always" implies an overall degradation of the energy.

In a course for secondary teachers, Nancy, Ron, and Lucy track the energy of a hand pushing a ball vertically downwards under water. They conclude that energy cannot transform once it becomes thermal energy.

Instructor: Under what circumstances can I go from this form to that form? What must be going on in order for me to be doing that, and is that relevant?
Nancy: It's so interesting to me that intuitively I think in terms of things going from gravitational to thermal, or kinetic to thermal and not the other way around and that thermal is not going to be becoming something else.
Lucy: Kind of a dead end? That means things stays as thermal or?
Nancy: Yah? Maybe?

Nancy articulates that energy has a unidirectional tendency. She states that thermal energy "is not going to be becoming something else." Lucy suggests that thermal energy might be a dead end. Later in the conversation, Ron reiterates Nancy's idea, stating, "Because these T's (units of thermal energy) can't go back into G's (units of gravitational potential energy) can they?" Nancy agrees and suggests that the amount of thermal energy always increases stating, "And of course there's my little idea that T's always get more." Although it is not the case that thermal energy cannot transform, nor is it true that thermal energy always increases, energy does degrade in spontaneous processes (the second law of thermodynamics), consistent with Nancy's intuition. Other learners make similar statements. Toni, a secondary teacher discussing the Energy Theater for a light bulb asks, "Isn't heat our dead end?" [26]. Tom (Section IV.B) states, "You can't get the thermal back. It's gone."

Elementary and secondary teachers, both those who are new to our courses and those returning for subsequent professional development, suggest that transformation into thermal energy is a terminal process. This idea surfaces in a variety of energy scenarios: Owen and Jean discuss water boiling on a hot plate, Lucy and Nancy consider a hand pushing a ball into water, Brianna and Bart search for energy examples outside the classroom, Toni describes the energy in a light bulb, and Tom considers the energy scenario of a hand that pushes a block along the floor. The prevalence of this idea may be due to disciplinary emphasis on scenarios in which thermal energy is the endpoint of a process (e.g., friction). However, thermal energy is not always a dead end. The use of counterexamples in physics instruction might help highlight the fact that thermal energy can be used to perform work.

E. Energy's usefulness depends on the objects involved

Above, Jean describes that many experiments and example scenarios, such as water boiling on a hot plate or a ball slowing to a stop, end in thermal energy. She asks, "How long does [the thermal energy] sit there?" Her question implies that the thermal energy in the scenario does change eventually. Later, she brings up wind as a possible mechanism for transforming the thermal energy into sound energy. In questioning the finality of the situation, Jean touches on a subtle idea that energy degradation is not a property of each unit of energy but depends on the objects and processes in a particular scenario. For a given Energy Theater scenario, learners tend to choose objects that constitute an isolated system (where all energy involved stays in that group of objects). Although many learners in our courses distinguish between useful and less useful energy in the isolated system, few discuss how this designation depends on the choice of objects involved in the scenario.

In the following conversation, Jennifer, a secondary teacher, first reflects that Energy Theater and Energy Cubes neglect to take into account energy usefulness and Irene, Kate, and Abdul respond to her ideas. The learners then discuss the conditions under which thermal energy is useful and begin to compare scenarios involving different objects.

Jennifer: I was thinking about how in both Energy Theater and in the Energy Cubes, that they had us use a different symbol or a different letter depending on what type of energy is represented. But the concept that you can't go backward, that once you have some of the energy transferred to the floor or the air as heat, that kids might think that you can, that that's equally reclaimable, or equally can be converted back to a more useful form of energy.

Abdul: Be reversible.

Jennifer: Reversible. So I wondered, what if you introduce the idea, or maybe kids could come up with the idea that in Energy Theater, the more useful the form of energy is, the taller you stand or something and every time the energy becomes less useful, like if it's sound or heat or something like that, that they shrink.

Irene: Especially as heat because it's wasted, part of entropy, that's why it's [Gestures with hand brushing away]

Jennifer: Yeah.

Kate: Although heat can be useful, because if you burn coal then heat is useful, and that's what you're getting, right?

Jennifer: Right, but, what's useful, is, burning coal heats water, the steam turns the turbine, so what's really useful is the mechanical energy of the turbine moving.
Abdul: Amount of control could be useful, amount of control, when you can control this amount of heat could be useful. But in our case, you cannot control the heat energy.
Irene: Exactly.

Jennifer recognizes that Energy Theater and Energy Cubes do not address the “concept that you can’t go backward.” She states that “once you have some of the energy transferred to the floor or the air as heat that kids might think … that's equally reclaimable, or equally can be converted back to a more useful form of energy.” To remedy this situation, she suggests that “in Energy Theater, the more useful the form of energy is, the taller you stand or something and every time the energy becomes less useful, like if it's sound or heat or something like that, that [the students] shrink.” Although this addition of growing and shrinking could distinguish between free and degraded energy, we have not adopted this idea of shrinking into Energy Theater due to concerns about appearing not to conserve energy.

Jennifer’s initial insights have motivated many of our new learning goals and are the original reason for a more detailed analysis of our representations. First, her description of the inability of energy to go backward, or convert back to a more useful form of energy, aligns well with the unidirectionality of irreversible processes and overall degradation of the energy in the system. Jennifer also distinguishes between more and less useful forms of energy, giving heat and sound as examples of less useful energy. These ideas parallel the formal physics distinction between free and degraded energy. Finally, Jennifer specifies that a change occurs in the usefulness of the energy when “the energy transferred to the floor or the air as heat.” This loss of useful energy through the process of energy transfer describes energy degradation.

The discussion that follows Jennifer’s observations suggests that learners do not agree on whether or not thermal energy can be useful energy. First, Irene agrees with Jennifer that heat is not useful, saying heat is “wasted, part of entropy.” Kate does not agree that thermal energy is always a less useful form. She counters, “Although heat can be useful, because if you burn coal then heat is useful, and that's what you're getting, right?” Jennifer’s response to Kate indicates that she defines useful energy differently: she explains that coal produces useful “mechanical energy” in a turbine, aligning well with the formal physics definition of free energy. However, canonical physics would also identify the thermal energy from coal burning as useful because it transforms into mechanical energy. Finally, Abdul introduces yet another definition of useful, stating that thermal energy is useful “when you can control this amount of heat.” Abdul implies that since, in this case, “you cannot control the thermal energy,” it is not useful.

In this episode, learners do not reach consensus about what useful energy is and what defines less useful or wasted energy. The lack of agreement highlights that whether energy is free or degraded depends on the scenario. If the scenario includes the coal, steam, and turbine, then thermal energy can be useful. However, if there is no turbine, then the thermal energy in the steam cannot be used to perform work. In other words, whether or not you can control or use the thermal energy depends on the chosen set of objects in a system. The disagreement between teachers about the status of thermal energy may have been because each had a different scenario in mind. Kate noted that it is possible to change the status by changing the scenario, and Abdul noted that the “amount of control” over the thermal energy determines its usefulness.

To summarize, Jennifer identifies the usefulness of energy, or the sociopolitical aspect of energy, as a concept that is missing in the representations. Learners begin to address the idea that the usefulness of energy depends on the objects that are included in a given scenario. However, even for a small group of learners, controversy exists regarding the definition of useful energy and in what (if any) situations thermal energy is considered useful. They touch on the idea that the status of energy as degraded or free is not a property of thermal energy, rather, status of energy depends on the scenario, or the choice of objects involved in an isolated system, and the corresponding gradients present because of the differences among objects.

V. Learning goals for energy degradation

Among the reasons teachers join the Energy Project is that they view science instruction as a way to support their students in becoming conscientious members of society, and they judge energy instruction to be particularly well-suited to this purpose. We share the teachers' sense of purpose in creating energy instruction that will support long-term innovation to meet socially relevant needs. Based on previous literature and ideas from learners in our courses, we have developed learning goals for our professional development that explicitly address energy degradation and the second law of thermodynamics. These learning goals (summarized below in Figure 6) aim to help K-12 teachers make connections between physics instruction and urgent sociopolitical issues.

A. *Learners should be able to distinguish between degraded energy and free energy in specific scenarios.*

Free energy is energy that is available for the performance of work (or available for energy transfer). Free energy should be distinguished from degraded energy that cannot be used to perform work in a specific set of objects. In a K-12 context, we do not expect learners to distinguish among subtypes of free energy (e.g., Gibbs and Helmholtz). Though learners in our courses rarely use *degraded* or *free* to describe energy, they often describe energy as losing usefulness or accessibility. For example, Dennis (Section IV.B) describes thermal energy in his scenario as having less quality, usefulness and availability than the initial kinetic energy and he distinguishes between degraded and free energy; Ted (Section IV.B) states that sound energy is a less useful form of energy; and Jennifer (Section IV.E) suggests that students should indicate degradation by shrinking down in height. The distinction of energy as having more or less value is also made by Rosie, Vicki, Jean, and Owen (Sections IV.A, C, and D, respectively).

B. *Learners should be able to identify changes in degraded energy as they track the transfers and transformations of energy within an isolated system.*

Learners should not only distinguish between degraded energy and free energy, but also describe the circumstances associated with conversions from free to degraded energy and identify the mechanisms by which the changes take place. Energy degradation is often associated with movement towards equilibrium in some quantity, and can occur by means of dissipative processes such as friction. In many (though not all) physical processes, energy degrades. Several learners in our courses identify this degradation: Dennis (Section IV.B) describes bulk movement transforming into random motion as a process by which energy becomes less useful (i.e., degraded). In Section IV.C, learners describe the transfer of energy to a larger volume as the mechanism for a decrease in the accessibility or availability of energy. Many of the learners in Section IV.D (e.g., Jean) describe transformation as a process that decreases the usefulness of energy. Finally, Jennifer identifies a decrease in usefulness as energy transforms into sound or thermal energy in Section IV.E.

C. *Learners should be able to equate the total energy in a system at an instant to the sum of the degraded energy and the free energy.*

This learning goal adds a key corollary to the principle of energy conservation: While the total energy of any isolated system does not change, the relative amounts of degraded and free energy may change. This statement has the potential to reconcile the everyday meaning of conservation with the physics meaning, in that a decrease in free energy corresponds to sociopolitical energy being used up. Learners in our episodes often explicitly state that energy is conserved, even as they are describing a loss of useful (i.e., free) energy. Rosie in Section IV.A points out that the total energy does not change in an isolated system, even as the energy becomes inaccessible (or has "gone away from us"). In Section IV.B, Dennis states that the energy is still there, even as its usefulness is getting lost. Vicki (Section IV.C) states that energy is not gone (indicating energy conservation) even as she laments that it becomes more spread out and less able to be harnessed. Finally, Jean (Section IV.D) argues that the thermal energy is "not really done, because it's always there," implying that although the energy seems to be no longer able to transfer or transform, it is still conserved.

D. Learners should be able to show that the identification of energy as degraded or free depends on the choice of objects in the scenario.

In Energy Project instruction, learners identify the objects that interact in a given energy scenario and track the energy as it transfers among those objects. The introduction of a new object into the scenario can change the status of energy from degraded to free if the new object is not in equilibrium with the other objects. Thus, degraded and free are not properties of units of energy; rather, they are qualities of the distribution of energy among interacting objects. Learners in Section IV.E highlight the relative nature of degradation when they discuss the meaning of useful energy and compare thermal energy in different scenarios. Jennifer and Kate describe how thermal energy may be useful in some situations and not in others. Implicit in these descriptions is the change of objects in the system (thereby changing the scenario).

E. Learners should be able to identify the occurrence of overall energy degradation.

Though the total amount of energy in an isolated system is unchanged regardless of what physical processes may take place, the amount of free energy decreases during many physical processes. In other words, during many physical processes, energy degrades. This is a statement of the second law of thermodynamics that we see as particularly appropriate for K-12 teachers and students. Learners in our courses recognize that energy becomes less useful as it goes through processes. In Section IV.D, Jean identifies the tendency for energy scenarios to end in thermal energy, which, in equilibrium, is degraded. The idea of energy reaching equilibrium is seen in statements describing thermal energy as a "dead end" or where energy "ends up." A similar idea is suggested in Section IV.C in Vicki's statement about the "heat death of the universe."

Inherent in the previously identified statements of the second law of thermodynamics are the seeds of understanding entropy concepts. While explicitly teaching about entropy using the abstract mathematics that normally characterizes learning about entropy is not our goal at the secondary level, we are alert to opportunities to help teachers make valuable connections from energy to other concepts that can be constructed from everyday experience, including concepts associated with entropy. The discipline of physics stands to benefit from teachers' insightful conceptualizations of these concepts in terms that will be of use to them and their students.

F. Learners should be able to associate energy degradation with movement of a quantity towards equilibrium.

Free energy is associated with a difference (gradient) in some quantity potentially associated with work, and degraded energy with a lack of gradient in that quantity. Learners should be able to identify the quantity whose gradient decreases and describe the corresponding energy degradation as that quantity moves towards equilibrium. Echoes of this learning goal can be heard in Sections IV.C in the descriptions of energy dispersal. For example, Vicki says that as energy spreads and disperses, it is not likely to be harnessed, aligning with the idea that degraded energy cannot be used for work. Dennis (Section IV.B) refers to thermal equilibrium and Rosie (Section IV.A) mentions dissipation as the reason for a loss of accessible energy. The gestures that Vicki, Owen, and Rosie use during their explanations also illustrate dispersal.

- Learners should be able to distinguish between degraded energy and free energy in specific scenarios.
- Learners should be able to identify changes in degraded energy as they track the transfers and transformations of energy within an isolated system.
- Learners should be able to equate the total energy in a system to the sum of the degraded energy and the free energy.
- Learners should be able to show that the identification of energy as “degraded” or “free” depends on the choice of the objects involved.
- Learners should be able to identify overall energy degradation.
- Learners should be able to associate energy degradation with movement of a quantity towards equilibrium.

Figure 6. Learning goals for energy degradation and second law of thermodynamics

VI. Conclusion

Teachers have the responsibility to help students become conscientious citizens by connecting their everyday use of energy in society to formal physics concepts. Observations of K-12 professional development show that many teachers spontaneously focus on sociopolitical aspects of energy. By viewing these ideas as resources from which to build a sophisticated understanding of energy, we find that learners’ discussions about energy’s inaccessibility, degradation, dispersal and usefulness are in agreement with aspects of energy degradation and the second law of thermodynamics. These alignments have motivated us to create learning goals for our K-12 teacher professional development courses that are intended to support further development of learners’ ideas.

Future work will investigate the development of learners’ ideas through the use of energy scenarios that involve energy spreading and degradation. We hope that explicitly supporting learners in discussions about energy degradation will lead to improvement of learners’ understanding of the concept of energy in both sociopolitical and physics contexts. We expect that a connection between these concepts can increase the relevance of energy instruction in teacher professional development, K-12 classrooms, and university contexts.

Acknowledgments

We gratefully acknowledge all the elementary and secondary teachers who have participated in Energy Project courses for their generosity in making their own and their students’ reasoning accessible to the Energy Project team. We are grateful to Seattle Pacific University’s Physics Education Research Group, including Amy D. Robertson, Sarah B. McKagan, Lezlie DeWater, Lane Seeley, and Kara Gray and the University of Maryland Physics Education Research Group, especially Edward F. Redish, Benjamin D. Geller and Vashti Sawtelle, for substantive discussions of this work. We also appreciate Benedikt Harrer and Virginia Flood for their help with gesture analysis and Jesper Haglund and Steve Kanim for their assistance with the manuscript. This material is based upon work supported by the National Science Foundation under Grants No. 0822342 and 1222732.

References

1. Hammer, D., *Epistemological considerations in teaching introductory physics.* Science Education, 1995. **79**(4): p. 393-413.
2. diSessa, A.A., *Toward an Epistemology of Physics.* Cognition and instruction, 1993. **10**(2-3): p. 105-225.
3. Duckworth, E., *"The Having of Wonderful Ideas" and other essays on teaching and learning.* 1996, New York, NY: Teachers College Press.
4. Daane, A.R., S. Vokos, and R.E. Scherr, *Conserving energy in physics and society: Creating an integrated model of energy and the second law of thermodynamics.* AIP Conference Proceedings, 2013. **1513**: p. 114.
5. Elby, A., *Helping physics students learn how to learn.* American Journal of Physics Physics Education Research Supplement, 2001. **69**(7): p. S54-S64.
6. Hammer, D., *Student resources for learning introductory physics.* American Journal of Physics, 2000. **68**(S1): p. S52-S59.
7. Dewey, J., *Experience and education*1938: Simon & Schuster.
8. Harrer, B.W., V.J. Flood, and M.C. Wittmann, *Productive resources in students' ideas about energy: An alternative analysis of Watts' original interview transcripts.* Physical Review Special Topics-Physics Education Research, 2013. **9**(2): p. 023101.
9. Hammer, D., F. Goldberg, and S. Fargason, *Responsive teaching and the beginnings of energy in a third grade classroom.* Review of Science, Mathematics and ICT Education, 2012. **6**(1): p. 51-72.
10. Hammer, D., *More than misconceptions: Multiple perspectives on student knowledge and reasoning, and an appropriate role for education research.* American Journal of Physics, 1996. **64**(10): p. 1316-1325.
11. Amin, T.G., *A cognitive linguistics approach to the layperson's understanding of thermal phenomena.* Conceptual and discourse factors in linguistic structure, 2001: p. 27-44.
12. Gupta, A., D. Hammer, and E.F. Redish, *The case for dynamic models of learners' ontologies in physics.* Journal of the Learning Sciences, 2010. **19**(3): p. 285-321.
13. Rousseau, J.J. and B. Foxley, *Emile: Or, On Education*2009: Floating Press.
14. Bruner, J.S., *The process of education*, 1960, Harvard University Press (Cambridge).
15. Montessori, M., *The discovery of the child*1978: Ballantine Books.
16. Piaget, J. and B. Inhelder, *The psychology of the child*1969, New York: Basic Books.
17. Vygotsky, L.S., *Thought and Language*1986, Cambridge, MA: MIT Press.
18. Smith, J.P., A.A. diSessa, and J. Roschelle, *Misconceptions reconceived: A constructivist analysis of knowledge in transition.* Journal of the Learning Sciences, 1994. **3**(2): p. 115-163.
19. Hammer, D., *Misconceptions or p-prims: How may alternative perspectives of cognitive structure influence instructional perceptions and intentions.* The Journal of the Learning Sciences, 1996. **5**(2): p. 97-127.
20. Ball, D.L., *With an eye on the mathematical horizon: Dilemmas of teaching elementary school mathematics.* The Elementary School Journal, 1993. **93**(4): p. 373-397.
21. Hammer, D., *Discovery learning and discovery teaching.* Cognition and instruction, 1997. **15**(4): p. 485-529.
22. Rogers, C.R., *On Becoming a Person-A Psychotherapists View of Psychotherapy*, 1961, London: Constable.
23. Empson, S.B. and V.J. Jacobs, *Learning to listen to children's mathematics*, in *International handbook of mathematics teacher education*, P. Sullivan, Editor 2008, Sense Publishers: Rotterdam, the Netherlands. p. 257-281.
24. Coffey, J., D. Hammer, and D. Levin, *The Missing Disciplinary Substance of Formative Assessment.* Journal of Research in Science Teaching, 2011.
25. Jordan, B. and A. Henderson, *Interaction Analysis: Foundations and Practice.* Journal of the Learning Sciences, 1995. **4**(1): p. 39-103.

26. Scherr, R.E., et al., *Negotiating energy dynamics through embodied action in a materially structured environment.* Physical Review Special Topics - Physics Education Research, 2013. **9**(2): p. 020105.
27. Scherr, R.E., et al., *Representing energy. I. Representing a substance ontology for energy* Physical Review - Special Topics: Physics Education Research, 2012. **8**(2).
28. Scherr, R.E., et al., *Representing energy. II. Energy tracking representations.* Physical Review - Special Topics: Physics Education Research, 2012. **8**(2).
29. Close, E.W., et al. *Development of proximal formative assessment skills in video-based teacher professional development*. in *2011 Physics Education Research Conference*. 2011. Omaha, NE: American Institute of Physics.
30. McKagan, S.B., et al. *Criteria for creating and categorizing forms of energy*. in *2011 Physics Education Research Conference*. 2011.
31. Close, H.G., et al. *Using the Algebra Project method to regiment discourse in an energy course for teachers* in *AIP Conf. Proc. (2010 Physics Education Research Conference)*. 2010.
32. Harrer, B.W., et al. *Elements of proximal formative assessment in learners' discourse about energy*. in *AIP Conference Proceedings*. 2012.
33. Daane, A.R., S. Vokos, and R.E. Scherr, *Learner understanding of energy degradation.* Accepted for publication in AIP Conference Proceedings 2013.
34. Duit, R., *Should energy be illustrated as something quasi-material?* International Journal of Science Education, 1987. **9**(2): p. 139-145.
35. Swackhamer, G., *Cognitive resources for understanding energy*. . [unpublished draft]. 2005.
36. Brewe, E., *Energy as a substancelike quantity that flows: Theoretical considerations and pedagogical consequences.* Physical Review Special Topics - Physics Education Research, 2011. **7**(020106): p. 1-14.
37. Herrmann, F., *The Karlsruhe Physics Course.* European Journal of Physics, 2000. **21**(1): p. 49.
38. Millar, R., *Teaching about energy*, 2005, York University: Department of Educational Studies Research Paper.
39. Amin, T.G., *Conceptual metaphor meets conceptual change.* Human Development 2009. **52**: p. 165-197.
40. Dreyfus, B.W., et al., *Negative energy: Why interdisciplinary physics requires multiple ontologies.* Accepted for publication in 2013 AIP Conference Proceedings.
41. Feynman, R.P., R.B. Leighton, and M. Sands, *The Feynman lectures on physics*1969, Reading, MA: Addison-Wesley.
42. Knight, R.D., *Physics for Scientists and Engineers: A Strategic Approach : with Modern Physics*2008: Pearson Addison Wesley.
43. Leff, H.S., *Thermodynamic entropy: The spreading and sharing of energy.* American Journal of Physics, 1996. **64**(10): p. 1261-1271.
44. Bliss, J. and J. Ogborn, *Children's choices of uses of energy.* European Journal of Science Education, 1985. **7**(2): p. 195-203.
45. Solomon, J., *Learning about energy: How pupils think in two domains.* European Journal of Science Education, 1983. **5**(1): p. 49-59.
46. Trumper, R., *Being constructive: An alternative approach to the teaching of the energy concept--part one.* International Journal of Science Education, 1990. **12**(4): p. 343-354.
47. Watts, D.M., *Some alternative views of energy.* Physics Education, 1983. **18**(5): p. 213.
48. Brook, A. and R. Driver, *Aspects of secondary students' understanding of energy - full report.* , 1984, University of Leeds: Centre for Studies in Science and Mathematics Education: Leeds.
49. Duit, R., *Learning the energy concept in school - empirical results from The Philippines and West Germany.* Physics Education, 1984. **19**: p. 59-66.

50. Duit, R., *Energy conceptions held by students and consequences for science teaching.*, in *Proceedings of the International Seminar "Misconceptions in Science and Mathematics"*, H. Helm and J.D. Novak, Editors. 1983: Ithaca, N. Y.: Cornell University. p. 316-321.
51. Solomon, J., *Messy, contradictory and obstinately persistent: A study of children's out-of-school ideas about energy.* School Science Review, 1983. **65**: p. 225-229.
52. Nicholls, G. and J. Ogborn, *Dimensions of children's conceptions of energy*. International Journal of Science Education, 1993. **15**(1): p. 73-81.
53. Solomon, J., *Teaching the conservation of energy.* Physics Education, 1985. **20**(4): p. 165.
54. Driver, R., et al., *Making sense of secondary science : Research into children's ideas*1994, New York, NY: Routledge.
55. Ross, K.A., *Matter scatter and energy anarchy; The second law of thermodynamics is simply common experience.* The School Science Review, 1988. **69**(248): p. 438-445.
56. Driver, R. and L. Warrington, *Students' use of the principle of energy conservation in problem situations.* Physics Education, 1985. **20**(4): p. 171.
57. Duit, R., *Understanding energy as a conserved quantity - Remarks on the article by R. U. Sexl.* European Journal of Science Education, 1981. **3**(3): p. 291-301.
58. Goldring, H. and J. Osborne, *Students' difficulties with energy and related concepts.* Physics Education, 1994. **29**(1): p. 26-31.
59. Lijnse, P., *Energy between the life-world of pupils and the world of physics.* Science Education, 1990. **74**(5): p. 571-583.
60. Loverude, M.E., C.H. Kautz, and P.R.L. Heron, *Student understanding of the first law of thermodynamics: Relating work to the adiabatic compression of an ideal gas.* American Journal of Physics, 2002. **70**(2): p. 137-148.
61. Kesidou, S. and R. Duit, *Students' conceptions of the second law of thermodynamics—an interpretive study*. Journal of Research in Science Teaching, 1993. **30**(1): p. 85-106.
62. Solomon, J., *How children learn about energy or does the first law come first?* School Science Review, 1982. **63**(224): p. 415-422.
63. Duit, R. and S. Kesidou, *Students' understanding of basic ideas of the second law of thermodynamics.* Research in Science Education, 1988. **18**: p. 186-195.
64. Cochran, M.J. and P.R.L. Heron, *Development and assessment of research-based tutorials on heat engines and the second law of thermodynamics.* American Journal of Physics, 2006. **74**(8): p. 734-741.
65. Christensen, W.M., D.E. Meltzer, and C.A. Ogilvie, *Student ideas regarding entropy and the second law of thermodynamics in an introductory physics course.* American Journal of Physics, 2009. **77**(10): p. 907-917.
66. Loverude, M.E. *They still remember what I never taught them: Student understanding of entropy*. in *AIP Conference Proceedings*. 2013.
67. Bennett, J.M. and M. Sözbilir, *A Study of Turkish Chemistry Undergraduates' Understanding of Entropy.* Journal of Chemical Education, 2007. **84**(7): p. 1204.
68. Pinto, R., D. Couso, and R. Gutierrez, *Using research on teachers' transformations of innovations to inform teacher education: The case of energy degradation.* Wiley Periodicals, Inc., 2004: p. 38-55.
69. Solomon, J., *Getting to know about energy: In school and society*1992, Bristol, PA: The Falmer Press.
70. Papadouris, N. and C.P. Constantinou, *A philosophically informed teaching proposal on the topic of energy for students aged 11-14.* Science and Education, 2010. **20**(10): p. 961-979.
71. Papadouris, N., C.P. Constantinou, and T. Kyratsi, *Students' use of the energy model to account for changes in physical systems.* Journal of Research in Science Teaching, 2008. **45**(4): p. 444-469.
72. Solomon, J., *Learning and evaluation: A study of school children's views on the social uses of energy.* Social Studies of Science, 1985. **15**(2): p. 343-371.

73. Ogborn, J., *Energy, change, difference, and danger.* School Science Review, 1990. **72**(259): p. 81-85.
74. Ogborn, J., *Energy and fuel: The meaning of 'the go of things'.* School Science Review, 1986. **68**(242): p. 30-35.
75. Odum, H.T., *Environment, power, and society for the 21st century: The hierarchy of energy*2007, New York, NY: Columbia University Press. 418.
76. Ben-Zvi, R., *Non-science oriented students and the second law of thermodynamics.* International Journal of Science Education, 1999. **21**(12): p. 1251- 1267.
77. Falk, G., *Entropy, a resurrection of caloric - a look at the history of thermodynamics.* . European Journal of Physics, 1985. **6**: p. 108-115.
78. Lambert, F.L., *The conceptual meaning of thermodynamic entropy in the 21st century.* International Research Journal of Pure & Applied Chemistry, 2011. **1**(3): p. 65-68.
79. Leff, H., *Removing the mystery of entropy and thermodynamics - Part 1.* The Physics Teacher, 2012. **50**(1).
80. Amin, T.G., et al., *Arrow of time: Metaphorical construals of entropy and the second law of thermodynamics.* Science Education, 2012. **96**(5): p. 818-848.
81. Styer, D.F., *Insight into entropy.* American Journal of Physics, 2000. **68**(12): p. 1090-1096.
82. Jeppsson, F., et al., *Exploring the use of conceptual metaphors in solving problems on entropy.* Journal of the Learning Sciences, 2012. **22**(1): p. 70-120.
83. Jeppsson, F., J. Haglund, and H. Stromdahl, *Exploiting Languages in Teaching of Entropy.* Journal of Baltic Science Education, 2011. **10**(1): p. 27-35.
84. Hammer, D. and E. van Zee, *Seeing the science in children's thinking : case studies of student inquiry in physical science*2006, Portsmouth, NH: Heinemann.
85. Kraus, P. and S. Vokos, *The role of language in the teaching of energy: The case of 'heat energy,'.* Washington State Teachers' Association Journal, 2011.
86. Warren, J., *The teaching of the concept of heat.* Physics Education, 1972. **7**(1): p. 41.