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How Crosscutting Is the Energy Concept within Physics Teaching and Learning

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Abstract: Much of the attention on the crosscutting concepts within the Next-Generation Science Standards (NGSSs) have gone to their coherence across different STEM disciplines. In this paper, we raise the question of the coherence of the energy concept within the teaching and learning of physics itself. Our investigations of teachers' and students' approach to solving problems, where both mechanical and thermal energy play equally important roles, indicate that the separation of energy studies in different units (mechanics, thermodynamics, etc.) leads to a cognitive disconnect of the understanding of different energy types and the inability to explain processes that involve both mechanical and internal energy, especially when the internal energy of the living organisms that are associated with a process is involved. We also find that when students gain experience analyzing scenarios where thermal energy plays a subtle yet critical role in addition to mechanical energy, they are able to apply this understanding to novel scenarios.

Keywords: crosscutting concepts; energy; internal; thermal; mechanical; living organisms; NGSS

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1. Introduction: Energy As a Crosscutting Concept

The US Framework for K-12 Science Education recommends building science education around three major dimensions: science and engineering practices, disciplinary core ideas, and crosscutting concepts [1]. Crosscutting concepts unify the study of science and engineering through their common application across fields and disciplinary core ideas in the major disciplines of natural science. One of the crosscutting concepts in the Framework and in the NGSS, Appendix G is *Energy and matter: flows, cycles and conservation* [2]. According to the NGSS, Appendix G: tracking fluxes of energy and matter into, out of, and within systems helps one understand the systems' possibilities and limitations. Specifically, in middle school, students are expected to learn that "...within a natural or designed system, the transfer of energy drives the motion and/or cycling of matter. Energy may take different forms (e.g., energy in fields, thermal energy, energy of motion). The transfer of energy can be tracked as energy flows through a designed or natural system". In high school, the concept becomes more sophisticated: "...students learn that the total amount of energy in closed systems is conserved. They can describe changes of energy in a system in terms of energy and matter flows into, out of, and within that system. They also learn that energy cannot be created or destroyed. It only moves between one place and another place, between objects and/or fields, or between systems. Energy drives the cycling of matter within and between systems".

We agree that the focus on energy as a crosscutting concept is vital for preparing students to engage with the complex role that energy plays in their everyday lives from the energy of their bodies to the energy resources they depend on every day. A flexible and crosscutting understanding of energy is also critical for navigating significant societal issues such as climate change and equitable access to energy resources.

While much of the attention on the crosscutting concepts in the NGSS have gone to their coherence across student learning in different STEM disciplines, in this paper, we raise the question of the coherence of student learning of the energy concept within physics itself. Our investigations of teachers' and students' approach to solving problems, where both mechanical and thermal energy play equally important roles, suggest that the separation of energy studies in different units (mechanics, thermodynamics, etc.) might lead to students' cognitive disconnect of the understanding of different energy types and their inability to explain processes that involve both mechanical and internal or thermal energy. The challenge of recognizing the critical role of thermal energy is particularly significant in scenarios involving living organisms. While the Framework and the NGSS expect the energy to cut across multiple science disciplines, we, in this paper, ask a much narrower question: to what extent do students and teachers conceptualize energy as a crosscutting concept within the discipline of physics? Specifically, our research question is as follows: How do learners approach situations where mechanical processes occur simultaneously with thermal and chemical processes, including the cases when a living organism is a part of the system?

2. Energy As a Crosscutting Concept in Physics Instruction

In this section, we discuss how energy is approached in physics curricula and papers and books for teachers. Before we delve into this issue, we should spend some time defining key ideas in energy without which the rest of the conversation will not be clear. Specifically, we need to define the terms "system", "conservation", "conserved", "work", and "heat".

2.1. Definitions of Important Terms

The language that is used in physics to describe energy and energy conservation is not consistent or coherent across physics textbooks and educational resources [3,4]. Therefore, it will be helpful to precisely define key terms here:

System—A single object or any grouping of objects in a particular process that one is free to choose; the remaining objects, if any, form the environment, which may or may not interact with the system. Choosing a set of objects to constitute a system does not necessarily mean that the objects outside it do not interact with it. If the objects that are within the system do not exchange significant amounts of energy with the environment, the system is an isolated system for energy analysis purposes.

Constant quantity—A physical quantity that remains unchanged in time.

Conserved quantity—A physical quantity that remains constant in an isolated system but can change when the system is not isolated. However, if a quantity is conserved, we can always find a larger system in which this quantity remains constant. We can track the movement of a conserved quantity between the system and environment; *because* it is conserved, it does not disappear or appear within the boundaries of a system. If it changes during a time interval, any difference must have transferred to/from the system from/to the environment. For a more in-depth description of the difference between a conserved quantity and a quantity that is merely constant, see the recent article in the American Journal of Physics [5].

Energy—A quantity of a system that depends on the motion, as well as the interactions of matter within that system. That there is a single quantity called energy is due to the fact that a system's *total* energy is a conserved quantity, even as, within the system, energy is continually transferred from one object to another and converted among its various possible forms [5,6]. The conservation of energy means that the total change in energy in any system is always equal to the total energy transferred into or out of the system (see the means of transfer below). Individual forms of energy, on the other hand, are never conserved, even though they may remain constant in specific processes.

Work—A physical quantity that characterizes *the process* of transferring energy to a system through macroscopic force interactions. For work to be done on a system, an object in the environment should be exerting a force on an object in the system, and the displacement of the point of application of that force must have a component along the direction of the force (in the same or in the opposite direction). Work can be positive or negative. Positive work is associated with a transfer of energy into a system, whereas negative work is associated with a transfer of energy out of a system. Work does not reside in a system; it is not a property of the system.

Heat—A physical quantity that characterizes *the process* of transferring energy to a system as a result of a temperature difference between the environment and the system. The energy is transferred to a system through heat when at least some portions of the system and the environment are at different temperatures. Positive heat is associated with the transfer of energy to the system and negative heat is a transfer of energy from the system. Heat refers to a transfer of energy and, therefore, is not a quantity that resides in a system. It is important to differentiate heat from thermal energy, which does reside in a system and is associated with the temperature of the system.

2.2. Traditional Approaches to Energy Instruction in High School and College Physics

Traditionally, in high school and college, physics courses begin with mechanics, where students learn about mechanical energy, potential energies, and work. Mechanical energy typically refers to the combination of kinetic energy and various forms of potential energy. Typically, when energy is taught in a mechanics unit, emphasis is given to gravitational and elastic potential energies. This approach to energy instruction focuses on idealized scenarios in which energy transfers between objects and converts from macroscopic kinetic energy to gravitational and/or elastic energy and vice versa. Dissipative processes involving kinetic friction and air resistance are often treated as negligible. A reason for this approach is that physicists believe that it is important to shield learners from complications when they first formally encounter the concept of energy. However, students bring vast resources about energy to the physics classroom. The net effect is that this approach to energy inhibits learners from developing a deep understanding of energy conservation for both theoretical and practical reasons. Theoretically, only energy as a holistic physical quantity is conserved. The sum of macroscopic kinetic, gravitational, and elastic energy may be constant for certain systems and scenarios but it cannot be conserved, because only energy as a whole is a conserved quantity. Practically, most of our everyday experiences cannot be reasonably approximated by idealized conversions between gravitational, elastic, and macroscopic kinetic energies. Our lives are dominated by friction, air resistance, and thermal and chemical energies often in subtle or imperceptible ways. This is particularly true when living beings are involved. When learners are encouraged to prioritize idealized energy scenarios, they are likely to construct an understanding of energy conservation that seems irrelevant to their lives outside the physics classroom.

Many physics textbooks describe mechanical energy as a conditionally conserved quantity. In order to do this, they often distinguish between "conservative" and "nonconservative" forces. We have argued previously that mechanical energy is fundamentally not a conserved quantity and describing it as conditionally conserved can lead to confusion about the fundamental conservation principle for energy that is applicable to all situations for all types of forces [5]. Additionally, as introductory mechanics mostly deals with the particle models of objects without internal structure [7], the textbooks introduce the kinetic energy theorem, where a particle-like object changes its kinetic energy due to the work being done on it. This introduces another confusion—fake conservation of kinetic energy. In addition, most textbooks introduce students to mechanical work without differentiating between real work and pseudo-work (see more about this issue in Sherwood, 1986), which makes the discussion of the processes including friction difficult or plain impossible [8–10]. Finally, most textbooks and even the NGSS confuse the concept of conservation with the concept of constancy starting from the first encounter of the students with the concept of energy [11]. Finally, many curriculum materials discuss energy without using the concept of a system, which makes tracking energy extremely difficult. But these are just the issues in mechanics.

Students often first learn about energy in a unit that prioritizes idealized mechanical processes and may introduce mechanical energy as a conserved or conditionally conserved quantity. Later, they revisit energy in a unit that prioritizes thermal processes and introduces the first law of thermodynamics. They may not realize that the first law of thermodynamics is simply a special case of energy conservation for situations where only internal energy is changing and energy transfers only occur through mechanical work and/or heat. The way energy is traditionally taught here may introduce more confusion. Students may think that heat is an entity, a thing belonging to the system [12]. They may also find it difficult to relate internal energy to mechanical energy, as the first law of thermodynamics (TD) is limited to internal energy and the examples that the students analyze primarily involve ideal gases and the change in their internal energy proxied by the change in temperature [13,14].

Finally, in most textbooks and studies about energy in both units, living organisms are rarely present. There are few examples where people or other living organisms are a part of the system in which students need to track energy, in the textbooks or literature researching students' understanding of energy [15–17].

2.3. Student Learning of Energy

The research literature on students' understanding of the concept of energy and effective methods of teaching this subject matter spans over 60 decades. An overview of the field is beautifully given by Neumann and Nordine (2023) in their chapter "Energy" in the recently published *Handbook of Research in Physics Education* [18]. There, the authors discuss energy as a core concept in physics, student conceptions of energy and their development, existing learning progressions for energy, student difficulties, and different instructional approaches to teaching energy. The chapter contains 130 references and shows that educators have given a great deal of attention to the learning and teaching of energy. In this paper, we focus on the studies directly related to the research question—students' and teachers' approaches to the processes involving mechanical and internal energy conversions including the cases when a living organism is a part of the system. Studies of students' understanding of energy [19] showed that while younger students give a lot of attention to the energy within living systems, older students reverse this understanding and start excluding living organisms as important systems when thinking about energy.

In addition to many studies of students' understanding of energy and the difficulties involved in the development of such an understanding, there has been a significant effort in clarifying the concepts of work, and especially work involving friction [8,9,20], systems [9,10], conserved and non-conserved forces [4,5], the language about heat, and the issue of energy being a conserved quantity that is not necessarily constant [11,12]. Most of the research on scenarios that involve both mechanical and thermal energy focus on dissipative processes in mechanics (friction and air resistance). For excellent examples, see [4]. Few papers examine energy situations when living organisms are involved [21]. Even fewer researchers include in their investigations students' understanding of such processes [17,22]. In the former paper [17], the authors investigated how students understand energy, and they have situations for the students to explain when a person is in the system: "As the child is running, what forms of energy would be involved in this transfer/transformation of energy?" They found that all students (older and younger) had trouble tracking the energy when it was changing forms and when people were involved. All students had trouble understanding energy conservation in biological systems. The students had trouble connecting chemical energy to mechanical energy in the processes where humans were involved. In the latter paper [22], the authors leading a professional development program investigated teachers' explanations of what occurs to the energy of the person–Earth system when a person lowers an object at constant speed. They found teachers' reluctance to acknowledge that the mechanical energy of the system is converted into the thermal energy of the person as the change in temperature is imperceptible.

The studies of the textbooks and research literature indicate that due to our teaching of energy, there might be a disconnect in students' and teachers' understanding of energy processes in the systems where mechanical and thermal/internal energies play equally important roles. If this is true, then both the students and the teachers would have difficulties analyzing processes involving mechanical and thermal energy together, or mechanical energy and internal energy when a living organism is involved.

3. A Study of Students' Understanding of Energy As a Crosscutting Concept in Physics: Materials and Methods

In order to better understand students' ability to navigate energy as a crosscutting concept within the discipline of physics, we collected survey data from various participant groups. Our surveys were composed of short-answer questions that probed participants' understanding of energy processes in two challenging scenarios. In order to study the learner's ability to apply energy conservation to living organisms, we used a scenario (henceforth called the *lowering scenario*) that involves a person lowering a bowling ball at a constant speed [22]. In order to study the learner's ability to navigate scenarios that are both mechanical and thermal, we used a water jet scenario in which a compressed gas is used to launch a column of water upward. The participants had to solve the problems either on paper or using a Google form. We did not time them and we did not ask them to do it alone. After we collected the responses, we developed a content coding scheme for the responses and analyzed the patterns in the responses. A description of our participant groups, the survey problems, and our analysis of the responses is presented below.

3.1. Study Participants

Five different groups of participants responded to the problems. We chose several groups to investigate how students with different levels of preparation and teachers respond to the problems above. Specifically, we wanted to investigate (see Table 1):

1. High-school students (these were the students who had 4 years of physics instruction in a European country with a rigorous physics curriculum and who were getting ready to take an optional final physics exam);
2. Introductory physics students (for these students, the lowering scenario served as a pretest at the beginning of their energy unit. Some of these students will have had up to a year of high-school physics and some of them had not yet taken any physics course);
3. Sophomore- or junior-level physics majors who were just completing an upper division course in thermal physics.
4. Pre-service physics teachers in the master's-level physics teacher preparation program, all with a complete undergraduate degree in physics (these were students who had instruction on energy through the systems approach with the inclusion of internal energy changes and *with* experience in solving problems involving living organisms);
5. In-service physics teachers (these were teachers who went through a rigorous program of physics teacher preparation (at different times) that also focused on the systems approach and inclusion of internal energy into mechanical processes but had *no* experience in solving problems involving living organisms).

Table 1. Participants who responded to our questions.

Participant Group	Number	Problem Solved
High-school students	20	1
Introductory college physics students	71	1
Physics majors at the end of a sophomore/junior-level thermal physics course	7	1 and 2
Pre-service teachers with systems energy instruction (PS teachers)	9	1 and 2
In-service teachers with systems energy instruction (IS teachers)	13	1 and 2

Not all participants responded to both problems (see Table 1).

3.2. Survey Problem 1: Lowering a Ball at a Constant Speed

This problem has been described elsewhere and was designed to study students' ideas about the energy associated with a person involved in a simple mechanical process [22,23]. The survey prompt for this question was as follows:

3.2.1. Survey Prompt

A person carefully lowers a bowling ball from eye level to waist level. During this motion the bowling ball moves downward at a slow, constant speed. Describe what you think is happening with energy during this process in as much detail as possible. Please include all relevant objects (bowling ball, person, Earth, surrounding air, etc...) in your system for energy analysis and make sure to describe where the energy goes.

3.2.2. Solution

In this process, the ball, person, and Earth are all relevant for the energy analysis. Air resistance plays a negligible role but we will include the air in our system for completeness. With all four of these objects in our system, we can track all energies involved: gravitational potential energy, kinetic energy, internal energy of the person (includes chemical energy and thermal energy), and thermal energy of air. The initial state is the ball already moving down at some initial height H_i above Earth's surface and the final state is the same moving ball but closer to the surface of Earth, at some final height H_f above Earth's surface.

We choose the gravitational potential energy to be zero in the final state (U_gf = 0). Because the ball moves with constant speed, the kinetic energy is constant through the whole process. Since air, Earth, the person, and the bowling ball are all in the system, there are no other objects in the surroundings that interact with the system and, therefore, the work done on the system and the energy exchanged by heating are both zero. The decrease in gravitational potential energy must therefore be equal to the increase in internal energy of the system. Which part of the system gains the internal energy? Since the speed of the ball is small, we can assume that air drag is negligible, meaning that the increase in the thermal energy of air and the ball due to air drag is also negligible. This leaves us with the increase in the internal energy of the person (Figure 1a).

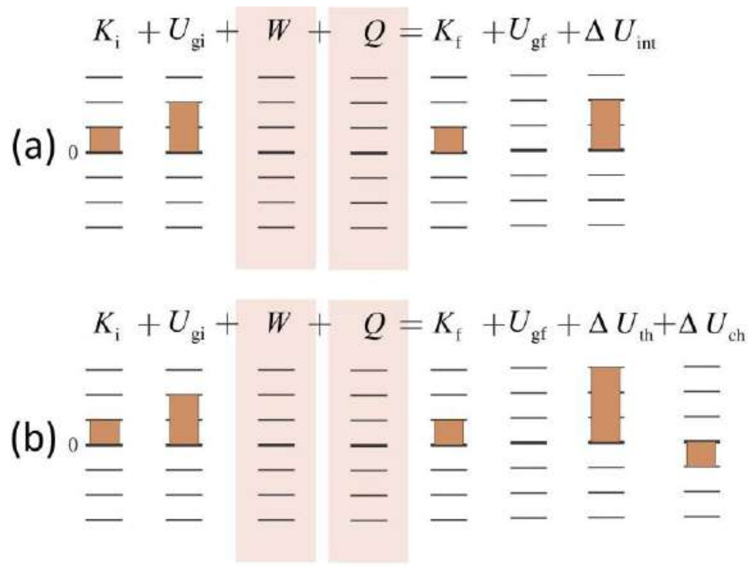

Figure 1. Energy bar charts for the analysis of the process described in problem 1. (**a**) with the changes in the internal energy of the person; (**b**) with the changes in the internal energy separated into the changes in the thermal energy and the chemical energy of the person.

While the energy analysis shown in Figure 1a is correct, it fails to showcase a very important aspect of this scenario, namely that it takes physiological or metabolic effort to lower a bowling ball at constant speed. In order to foreground this idea, we can further separate the internal energy change of the person into a thermal energy change (change in the body temperature) and a chemical energy change (chemical changes in the body due to metabolism) (Figure 1b). As for every living organism, the person reduces their chemical energy ($\Delta U_{ch} < 0$) in order to perform this physical task (strictly speaking, the chemical energy of person plus oxygen in the air decreases). In our case, the increase in thermal energy of a person comes partly from the chemical energy change but also from the change in the gravitational potential energy of the ball. We can see the process in the following way: the person prevents the ball from speeding up by continuously transforming any increase in the kinetic energy of the ball into the thermal energy of the muscles and joints.

3.2.3. Coding Scheme

The choice of codes is based on the research question that we are trying to answer and our review of the literature. Specifically, we wanted to see if the participants included the person into their analysis (living organisms in the systems), if they noticed that some form of energy should increase when the gravitational potential energy decreased, if they noticed that the increased energy was thermal, and if the energy was treated as a conserved quantity independently of what system the participant chose. These aspects of participant reasoning were identified in the literature as important for understanding energy as a crosscutting concept and we wanted to see if the participants attended to these ideas.

To develop the coding scheme and establish reliability, we read 4 arbitrary chosen responses and looked for the above indications. Analyzing the responses, we came up with the 4 code indications scheme that addressed each of the above issues. All 4 authors then independently scored all responses from the last group of participants (we started with this group as we assumed that those responses would be the most complete) and achieved an 85% agreement among those scored. We then had a discussion of every score and modified the wording to achieve 100% after the discussion. Then, authors 1 and 3 scored the responses of groups 1 and 4 and authors 2 and 4 scored the responses from groups 2 and 3. Both teams achieved a 100% agreement after the discussion.

Table 2 shows the coding scheme for participant responses to problem 1 and examples of responses for each code. Each code indication was assigned 3 scores: 0—not present or completely unclear or incorrect; 1—present but not articulated or slightly incorrect; 2—clearly articulated and correct. In Table 2, we only show examples for scores 2 for each code indication.

Table 2. Coding scheme for problem 1.

Code Indications	Description	Example
Includes the person in the system	As excluding the person from the system removes the issue of internal energy change, we specifically asked in the problem to include all relevant objects in the system to perform a complete energy analysis. Some participants pushed against it and used the person as an external object who does work. We assigned the highest scores to those who explicitly included the person in the system. Participants who received 0 s chose not to include the person in the system and used negative work.	If everything is in the system, the best way to explain the observations is that the decrease in GPE leads to an increase in internal energy of the body, surrounding air, etc. (warming up, chemical reactions within body/muscles).
Some energy is increasing	The participant understands that some energy is increasing in the process but does not say explicitly what this energy is.	Because there is a decrease in gravitational potential energy, the other objects in the system must have an increase in energy.
Thermal energy of the person is increasing	The participant says that the lost gravitational potential energy of the system was transferred to the person but does not articulate clearly what energies decreased.	If everything is in the system, the best way to explain the observations is that the decrease in GPE leads to an increase in internal energy of the body, surrounding air, etc. (warming up, chemical reactions within body/muscles).
The balance of energy is complete and correct.	The participant says that the thermal energy of the person must be increasing enough to balance the decrease in gravitational energy and chemical/metabolic energy.	The potential energy of the system decreases because the elevation of the ball lowers. Because of muscle twitching, the person's chemical internal energy also decreases. In turn, the person's inner thermal energy increases, so the net energy change of the system is 0 as no work was done on the system.

3.3. Survey Problem 2: Compressed Air Water Jet

3.3.1. Survey Prompt

Watch this video https://youtu.be/lN5datUGEMU in which Finn uses a bicycle pump to add air and increase the pressure inside a plastic container which is half filled with water. Finn then opens a valve at the bottom of the container and a jet of water shoots several meters upward.

a. *Focus on the portion of this experiment during which the valve is opened and the water shoots upward. Explain what you think is happening with energy during this process in as much detail as possible. Specify what you included in your system for energy analysis. If you think that the energy of the gas inside the container changes during this experiment, please describe what physical property of the gas changes to account for the change in energy. Feel free to speculate when you are uncertain.*

b. *As you go, write below any questions that you ask yourself and need to answer in order to provide a reasonably complete description of the energy processes involved.*

After submitting the answers to steps a and b, students continued to the next section:

We repeated the experiment that you have seen before only this time we mounted a sensitive thermometer into the container. Watch the video of the experiment https://youtu.be/Rw3mcK6PPho. Note that the thermometer is mounted above the water level in the container.

c. *If you would like to revise your explanation that you gave in the previous section, write your revision below. Please, do not change anything in the previous section. All your ideas are very valuable to us.*

3.3.2. Solution

Let the system be the water and air that are initially in the plastic container, and Earth. Let the initial state be just before Finn opens the valve and the final state be after some water has shot from the container and has not yet reached the maximum height of several meters. We make the following assumptions. We assume that the kinetic energy K describes the motion of bulk water only and that the process is fast enough, so we can neglect any heat exchange between the system and the surrounding environment ($Q = 0$). We treat the air in the container as an ideal gas whose internal (thermal) energy is proportional to its absolute temperature. We choose the gravitational potential energy in the initial state to be zero ($U_{gi} = 0$).

Initially, the kinetic energy and the gravitational potential energy are zero. When Finn opens the valve, the air in the container starts expanding, pushing water out from the container. As a result, water starts moving out from the container ($K_f > 0$) and rises up in the air ($U_{gf} > 0$). At the same time, the center of mass of water in the container moves down a little bit, but the corresponding decrease in U_{gf} is much smaller than the increase due to the water jet rising up. As the water is emerging from the container, the ambient pressure (about 1 bar) is exerting a force on water that is directed opposite to the displacement of water, therefore doing negative work on the system (note that if the ambient pressure was lower, the water would rush out from the nozzle at higher speed). As air molecules in the container are hitting the downward-moving water surface, their average speed after the collision with water decreases (adiabatic expansion). As a result, the internal energy (and the temperature) of the gas decreases. The balanced energy bar chart is shown in Figure 2.

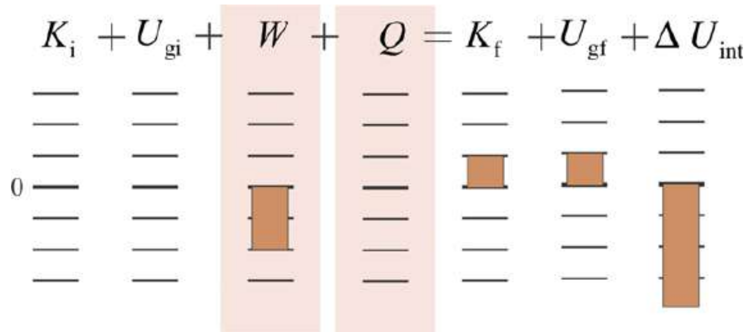

Figure 2. Energy bar chart for the analysis of the situation in problem 2.

3.3.3. Coding Scheme

To develop the coding scheme, we followed the same approach as in problem 1. Here, our focus was on whether the participants explicitly or implicitly mentioned that gas particles have kinetic energy, whether this kinetic energy means that gas has energy as a whole, and that the increase in mechanical energy of water is the result of the decrease in the thermal energy of the air. We also wanted to find out whether the participants connected the energy of the gas to its temperature and whether they understood that the changes in the energy of the gas would lead to the changes in the temperature as the observable variable. Finally, in this question, we also wanted to see whether the participants could modify their reasoning based on the additional evidence presented to them. The codes are shown in Table 3.

Table 3. Coding scheme for problem 2.

Code Indication	Description	Example
Gas particles have kinetic energy	The person attributes the energy of the gas inside to the kinetic energy of the particles.	The internal energy from the faster-moving air particles and the thermal energy from the increased temperature from the increased pressure are converted to kinetic energy in the water particles.
Energy analysis and choice of system	The person analyzes the process correctly from the point of view of energy even if considering inside air doing work on the water (considering air outside the system)	System: Water, air inside the tank. When the valve is opened, the water shoots up, meaning it gains both KE and GPE. The energy must be coming from the expansion of the compressed air inside the tank, because as it expands, it loses internal energy and thus temperature.
Gas has energy	The person explicitly mentions the energy of the inside air.	The way to explain it is that the compressed air does work on the water, exerting a force on it once the valve is opened. Positive work in this case as it increases the energy of the system. In order for the gas to do positive work, this means that if you take the gas as your system, its energy decreases.
Energy of gas decreased	The person says that the energy of the inside air decreased.	See the answer for the above code
Temperature of the gas decreased	The person says that the temperature of the inside air decreased.	When the valve is opened, the water shoots up, meaning it gains both KE and GPE. The energy must be coming from the expansion of the compressed air inside the tank, because as it expands, it loses internal energy and thus temperature.
Is able to reconcile the observation of temperature drop	After watching the second video, the person revises their reasoning if needed to correct the accounting of the energy of the inside air.	Would I like to change anything? Sure. The reduction in temperature would mean that there's a change in thermal energy that is not insignificant, meaning that I would also have to incorporate that into my analysis. Basically, I treated the previous process as being isothermal, but I think the broad conclusion (an overall reduction in internal energy leads to increase in kinetic + gravitational potential energy) is still correct.

We proceeded with the same approach to establishing the reliability of the coding scheme. All 4 authors scored 4 responses from the last group of participants (in-service teachers) and, prior to discussion, achieved 80% agreement. After the discussion and minor adjustment to the wording of the codes, we achieved a consensus of 100%. Then, the authors proceeded to score the remaining responses of the rest of the participants from the last group (in-service teachers) and achieved complete agreement after discussing the scores. Then, authors 2 and 4 scored the responses of group 3 and authors 1 and 3 scored the responses of group 4. The teams reconciled minor disagreements on the scores. The data presented in the Results section reflect our agreed-upon scores.

4. Results

In this section, we present the results of the scoring of participant responses for both problems.

4.1. Survey Problem 1: Lowering a Ball at a Constant Speed

Participant data for problem 1 are shown for all participants (N = 113) in Figure 3. Only in one group of participants (pre-service teachers with systems energy instruction who had experience with including living organisms in problem scenarios) did 100% indicate that some energy in the process of lowering the ball must be increasing. Among the rest of the participants, including the in-service teachers, the average percent of those who recognized that some energy should be increasing was about 50%. The only group that attributed the increase in energy to the increase in the energy of the person was again the group of pre-service teachers. Almost 90% of them either explained this connection clearly or partially. A smaller portion of those participants (50%) could clearly articulate that the thermal energy of the person must be increasing enough to balance the decrease in gravitational energy and chemical/metabolic energy.

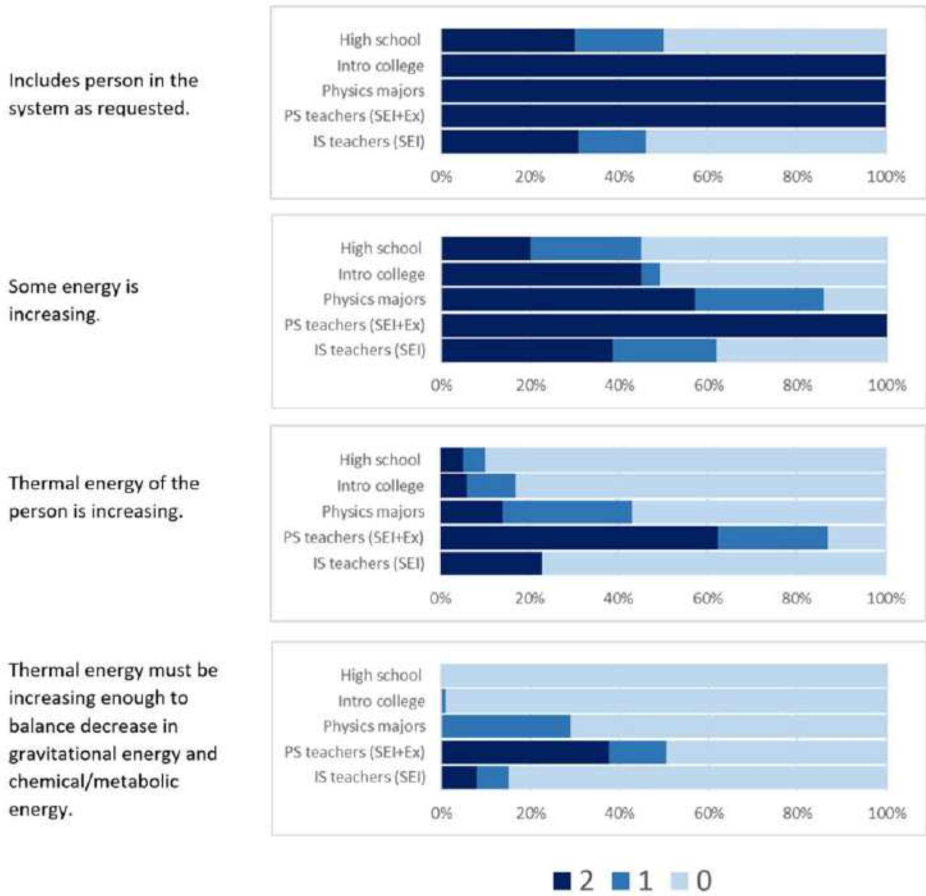

Figure 3. Analysis of the response to the first problem (lowering ball scenario). Descriptions of group names: high-school students with a lot of physics instruction, intro college physics students with minimal energy instruction, physics majors with experience in thermodynamics, pre-service teachers with systems energy instruction and experience in solving a problem that includes living organisms, and in-service teachers with systems energy instruction.

While responses to this scenario were similar among the other study groups, there was one striking difference. Among in-service teachers with extensive prior energy instruction focusing on the system's analysis (ISs) and those who studied energy in high school through traditional instruction, we measured a widespread resistance to including the person in the system for energy analysis. The prompt requested that they "please include all relevant objects in your system for energy analysis" and explicitly mentioned the person. In both of our study groups with extensive prior energy instruction, a significant fraction of participants explicitly pushed back against this request. Many of the participants in this group ignored the request and specified a system including only the ball and Earth. Many of those participants in the IS group were able to correctly describe how the person does negative work on this system and, therefore, avoided describing where this energy actually goes once it is transferred via work to the person. These participants were comfortable describing the energy story for this scenario without including the person in the system and, therefore, elected not to follow the directions given in the question. Among the study group with relatively little prior energy instruction (intro college), we found no evidence of excluding the person from the system for energy analysis.

4.2. Survey Problem 2: Compressed Air Water Jet

The data for the participants who solved problem 2 (N = 29) are shown in Figure 4.

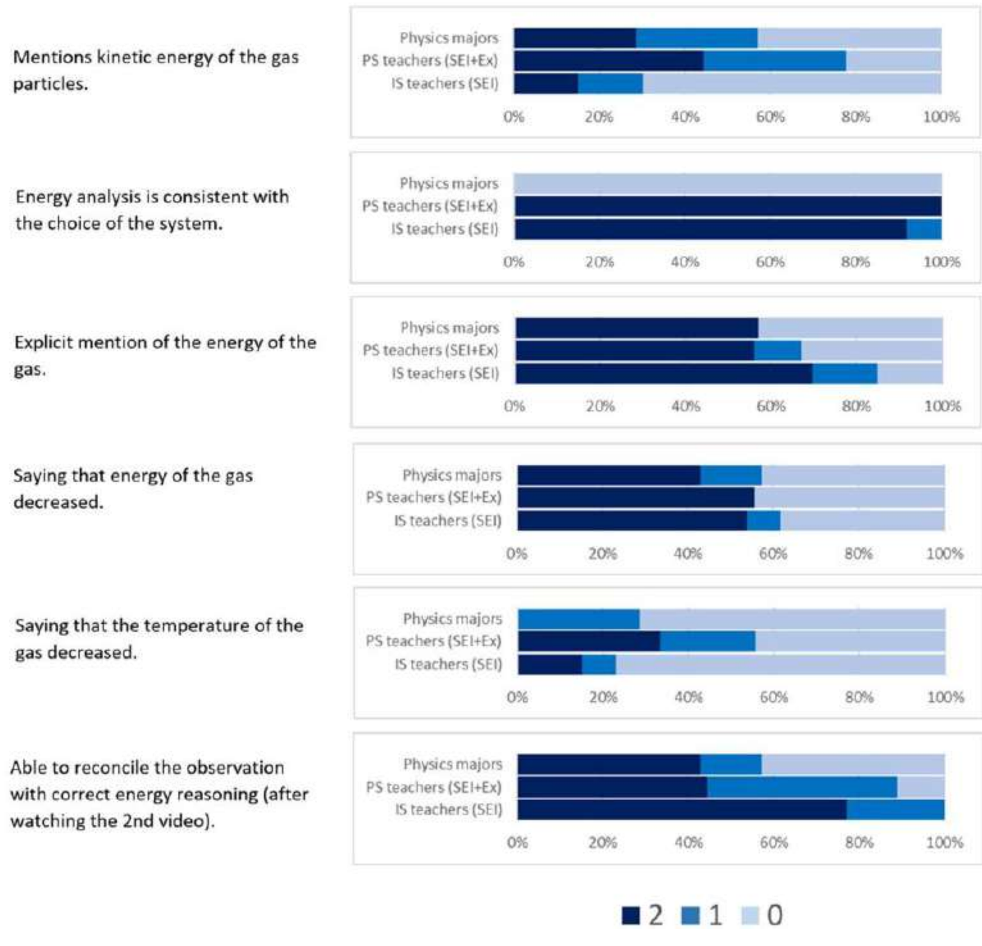

Figure 4. Analysis of the response to the second problem (compressed air water jet). Descriptions of group names: physics majors with experience in thermodynamics, pre-service teachers with systems energy instruction and experience in solving a problem that includes living organisms, and in-service teachers with systems energy instruction.

Those participants had much more experience with energy, especially physics majors, who just finished the thermodynamics course where they explored kinetic molecular theory and the first law of thermodynamics. The majority of the participants mentioned the energy of the gas (about 70%) with the lowest percentage (55%) by physics majors, compared to almost 90% of the in-service teachers. The same percentage of the participants in each group (about 60%) said that the energy of the gas decreased. However, more of the physics majors mentioned the kinetic energy of motion of the gas particles than the in-service teachers (60% vs. 30%). Interestingly, although fewer in-service teachers mentioned the kinetic energy of the gas molecules, almost all of those who did were able to predict the decrease in the temperature of the gas with the correct explanation, in contrast to physics majors out of whom no one had a score of 2 for the prediction of the lowered temperature. The same discrepancy existed for the prediction of the decrease in the temperature of the gas due its energy being transferred to the shooting water.

Another interesting finding is that while almost 100% of pre- and in-service teacher participants had their energy analysis consistent with the choice of the system, none of the physics majors mentioned what system they used for the analysis, despite the question asking to specify it.

Finally, we note that after watching the second video with the outcome of the experiment that they had to predict, all of the in-service teachers were able to reconcile the outcome with the correct energy reasoning, while a smaller portion of the pre-service teachers did and very few physics majors did.

5. Discussion

5.1. Survey Problem 1: Lowering a Ball at a Constant Speed

On some level, the qualitative energy story for this scenario is simple. A decrease in gravitational energy is clearly indicated by the lowering of the bowling ball. A decrease in chemical energy can be readily inferred based on the effort required to slowly lower a bowling ball. These energy decreases must be compensated by a significant increase in some other energy, and the thermal energy of the person is the only reasonable destination for this lost energy. So, why was a correct and complete energy analysis so elusive for these study participants? We think that many participants struggled to identify the critical role of thermal energy in this scenario largely because they were unfamiliar with including people in their system when analyzing energy transfers and conversions. This hypothesis is supported by the striking difference in the performance of the group of participants who had experience with humans and other live organisms (PSs). The majority of this group were successful in identifying the increase in energy in the person and a significant portion of them performed a complete analysis including the decrease in chemical energy and increase in thermal energy that compensated for the decrease in gravitational and chemical energies in the system. This is also supported by the finding that in-service teachers with systems energy instruction pushed back on including the person in the system. Similarly, in the study reported in reference [22], teachers in a professional development program questioned whether mechanical energy can be converted into the thermal energy of a person. This finding suggests that including a person as a part of a system that participates in energy conversions is a learned skill through energy instruction. As the data show, when students are experienced in analyzing energy conversions in living organisms (in one semester course, they worked on two problems of this type), and are instructed to include a person in their system and consider the thermal energy of the person, they are able to perform relatively sophisticated energy analysis.

5.2. Survey Problem 2: Compressed Air Water Jet

We can see that the performance of the participants is better on this problem than on problem 1. We can explain this difference by the fact that the problem did not contain living organisms and involved the objects that are commonly used in thermodynamics problems (excluding the water having a kinetic energy of motion as a whole). Two things are important to mention here. First, the undergraduate physics majors did not specify their choice of system. This omission of the system choice in the responses is consistent with research reported in [24]. Second, the in-service teachers initially did not associate the internal energy of the gas with the motion of its particles. What can be the reasons for this deficiency? There are several possible answers: (1) In their physics teacher preparation program, they had no instruction on the first law of thermodynamics; all the instruction they had was in their major and not of all of them had a physics major. Some had a minor and thus did not remember that gas molecules do not have a potential energy of interaction. (2) In their regular teaching duties, they do not have thermodynamics or kinetic molecular theory, as those are not part of the traditional physics curriculum in their country, but are taught in chemistry. Therefore, they do not encounter any problems involving gases in their teaching. The fact that physics majors did not define the system in their energy analysis immediately after they had a course on thermodynamics can be explained by the fact that the systems approach was not part of their course material.

Finally, how do we explain the finding that all of the in-service teachers were able to go back and revise their explanations in light of new experimental data with almost 80% performing it perfectly (score of 2) compared to 40% of the pre-service teachers and physics majors (more of them had an attempt scored as 1). One possibility is that the teachers forgot about the fact that ideal gas molecules only have kinetic energy in their original explanation, and when they saw the outcome of the second experiment, they remembered it and were able to revise their reasoning. Another explanation is that this group of teachers are skilled in the Investigative Science Learning Environment (ISLE) approach to learning physics that specifically teaches how to revise one's reasoning based on new data [25]. Having used this approach in their teaching for many years, they had no problem applying it to themselves.

6. Conclusions

In the introduction, we posed the following research question as the goal of our study:

How do learners approach situations where mechanical processes occur simultaneously with thermal and chemical processes, including the cases when a living organism is a part of the system?

We found that, while in our sample of participants, the majority were relatively successful in analyzing situations involving mechanical and thermal processes in inanimate systems common to physics learning contexts, most participants had a lot of difficulty analyzing energy processes in the situations that involve living organisms. This finding is in agreement with studies that point to the lack of connections between energy learning in inanimate systems and living organisms [17,22]. We also found that when students have experience with such situations, they have no trouble including living organisms in the energy analysis. This finding is consistent with everything that we know about how people learn—they learn what we teach them. Another important finding is that having data disconfirming participants' original responses to the second problem led only one group of participants to systematically revise their answers. This finding is consistent with research by Chinn and Malhotra [26] who found that learners have difficulties adjusting their explanations based on anomalous data. However, we found that those who have longitudinal experience with the Investigative Science Learning Environment approach internalize such processes and are successful in applying it when solving problems. This finding is consistent with the previous findings of ISLE students [27]. While our study is small in size and limited to only two problems, we can say that it suggests that both teachers and students have difficulties including living organisms in energy analysis. We also found that even undergraduate physics majors often conduct energy analysis without clearly identifying a system, and that students have difficulties revising their explanations when new data are provided to them.

7. Limitations

As we mentioned above, the study has several limitations. First, we only used two problems to probe participants' responses to specific situations and only one of them included a living organism. Therefore, our results provide a case study of prevalent student ideas rather than a comprehensive assessment of student understanding in this domain. Second, our sample of participants was relatively small, and we did not interview them after they submitted the survey, due to the anonymous nature of the study. Finally, while we did include physics teachers among our study groups, we did not interview teacher participants by asking them about their teaching practices in the units containing energy; therefore, we cannot connect their responses to the survey questions to how they teach this material. Despite these limitations, we hope that our study will promote further research in this area. While we continue to study the teaching and learning of energy as a crosscutting concept among scientific disciplines, we should not neglect the need to study gaps in students' understanding of energy as a crosscutting concept within scientific disciplines. Understanding these gaps will allow us to adapt instructional approaches to foster a more coherent and flexible understanding of energy among our students.

8. Implications for Instruction and Further Research

The findings reported here suggest a need for a greater focus on energy as a crosscutting concept even within the discipline of physics. Traditional energy instruction in physics has often separated mechanical scenarios from thermal scenarios and inanimate contexts from animate. As a result, many students may be unprepared to recognize the critical role of thermal energy in mechanical scenarios. This is particularly apparent when the role of thermal energy is not simply accounting for energy "lost to" friction or air resistance (as in our first problem).

The good news is that when students have opportunities to actively engage with mechanical scenarios in which living organisms and their thermal energy play a significant role, they are able to expand and adapt their understanding of energy as a crosscutting concept within physics. In our study, the group (PS Teachers) had only solved two problems in which living organisms were involved, but they did so in a way where all were actively engaged, worked in small groups, reflected at the end of the class, etc. It is also important to note that these students (PS) participated in the survey 2 years after the experience with those kinds of problems.

Therefore, we argue that for students to apply energy as a crosscutting concept, we should prioritize their engagement with multiple scenarios that are both explicitly mechanical and where thermal energy plays a significant and non-trivial role. We specifically recommend engagement with scenarios involving people, or other living organisms, and to include the energy changes of the people in their analysis.

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Data Availability Statement: Data are not publicly available because we believe that it could be possible to identify the institutions and even the courses which participated in this study based on the authorship and identifying details present in specific student responses.

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