

Article

Conceptualization of Energy by Practicing Scientists: Do Researchers from Different Disciplines Grasp Energy as a Crosscutting Concept?

Shahar Abramovitch * and David Fortus Department of Science Teaching, Weizmann Institute of Science, Rehovot 7610001, Israel;
david.fortus@weizmann.ac.il

* Correspondence: abramovitch@gmail.com

Abstract: Energy is one of the fundamental concepts of science in all disciplines. For this reason, it can serve as a concept that crosses disciplinary lines and serves as a bridge for students trying to describe a scientific phenomenon using different lenses. Underlying this vision, which is highlighted by the Framework for K-12 Science Education is the implicit assumption that the different disciplinary perspectives of energy have something in common, which should be the focus of instruction and supports the way scientists in the different disciplines use energy. However, does a “unified conception” of energy actually underlie the ways diverse scientists use energy in their fields? To answer this question, we conducted a small-scale interview study in which we interviewed 30 top-level interdisciplinary researchers and asked them to explain several phenomena from different disciplines; all phenomena could be explained in various ways, one of which was an energetic explanation. Our results suggest that researchers from different disciplines do not think of energy in the same way and do not think of energy as an interdisciplinary concept. We argue whether teaching energy in an interdisciplinary way may support the development of future scientists and lay citizens or an expectation that may add more difficulty to an already difficult task.



Citation: Abramovitch, S.; Fortus, D. Conceptualization of Energy by Practicing Scientists: Do Researchers from Different Disciplines Grasp Energy as a Crosscutting Concept?. *Educ. Sci.* **2023**, *13*, 1179. <https://doi.org/10.3390/educsci13121179>

Academic Editor: Federico Corni

Received: 8 May 2023

Revised: 7 August 2023

Accepted: 6 November 2023

Published: 23 November 2023



Copyright: © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

Keywords: energy; curriculum; future scientists; crosscutting concepts

1. Background

1.1. Teaching Cross-Disciplinary Unifying Concepts

There are concepts and practices that cross disciplinary borders and can potentially support both students and scientists in understanding and investigating a phenomenon from different angles. As students construct meaning by connecting new experiences to prior knowledge, providing a broad framework that builds on unifying concepts that cross disciplinary boundaries can allow for the development of a deeper understanding of science [1]. The use of unifying concepts across disciplines is similar to how some scientists use different disciplinary approaches as different lenses can reveal different aspects of a phenomenon [2].

The United States took this vision of building on concepts that can bridge the disciplines and called them crosscutting concepts (CCCs). The American national K-12 science standards have included an emphasis on broad cross-disciplinary themes in science as a way to unify seemingly disparate science content [3]. The National Research Council outlined a three-dimensional pedagogical approach that integrates disciplinary core ideas (DCIs) and crosscutting concepts (CCCs) with scientific and engineering practices (SEPs). Krajcik, Codere, Dahsah, Bayer, and Mun [4] explained that like strands in a rope, the three dimensions work together to “build an integrated understanding of a rich network of connected ideas. The more connections developed, the greater the ability of students to solve problems, make decisions, explain phenomena, and make sense of new information” (p. 157). The intention behind the CCCs was to explicitly address the different concepts

that cross disciplinary borders and can be used as links to analyze and understand concepts across science disciplines [1,2].

1.2. Energy

Energy is one of the fundamental concepts of science in all disciplines. It is central to understanding a broad range of phenomena and the solution to many science-related problems in our daily lives. Energy is defined as a central concept across disciplines. Due to its centrality across the disciplines, the transfer of energy in and between systems was identified by the Framework ([3], p. 84) as part of a crosscutting concept that bridges the different disciplines, allows for common thinking across the disciplines, and should be learned by all middle school students in every discipline: “Tracking transfers of energy and matter into, out of, and within systems helps one understand the systems’ possibilities and limitations”.

Given that one of the challenges in learning about energy is the difficulty in understanding that energy in physics is the same as the energy in chemistry and biology [5,6], it makes sense that it be recommended that energy be taught and learned as a unifying concept that crosses disciplinary borders. Park and Liu [7] found that while students had difficulty understanding how energy is related to different phenomena, there was no disciplinary dependence regarding this difficulty. We interpret this as indicating one of the unifying characteristics of energy: it is very difficult for students to understand it across disciplines. Students’ difficulties may be partially explained by looking at how energy is typically presented in science curricula. Looking at the curricula from Israel, the UK, and the USA indicates different uses of the energy concept in various disciplines; this may lead students to conclude that energy is not the same concept in the different disciplines. In chemistry, energy has traditionally been presented as something stored in chemical bonds and released when the bonds are broken in a chemical reaction (actually, it takes energy to break bonds; energy is released when new bonds are formed) [8]. In physics, energy is traditionally used to compare two states of an isolated system by requiring that the total energy in both states be identical. In biology, many issues are concerned with the availability of free energy (though it is usually not called this) rather than energy conservation. Given these different perspectives on energy, it is not surprising that students learn to perceive energy as something different in the different disciplines [6]. Thus, when the concept of energy appears to be treated differently in the different disciplines, addressing energy as a unifying concept is likely to be challenging and may not serve the different disciplines equally well.

Underlying the expectation that energy should be taught as a crosscutting concept is the implicit assumption that these different perspectives on energy have something in common, which should be focused on during instruction. We should support students in learning to think about energy similarly to how scientists in different disciplines use it. What is common to these different disciplinary perspectives of energy? Does this crosscutting conception of energy serve the needs of all students? Does this crosscutting conception of energy align with the ways different scientists use energy in their different fields?

1.3. Energy in Instruction

Traditionally, energy has been introduced to students in physics contexts [9]. Research on the teaching and learning of energy as part of the physics curriculum has identified five key ideas about energy that underlie an understanding of the concept: (1) forms—energy is manifested in different forms; (2) transformation—energy can be transformed from one form into another; (3) transfer—energy can be transferred from one place to another; (4) degradation/dissipation—whenever energy is transformed or transferred, some energy is converted into its thermal form and spreads out; and (5) conservation—the overall amount of energy in an isolated system is conserved [10,11]. Many students fall short of

developing a full understanding of energy, failing to reach an understanding of energy conservation [12,13].

Many chemistry textbooks and instructors falsely assume that students have a good understanding of energy from their physics class [14,15]. Studies show that by the end of their thermodynamics studies, many students fail to understand the difference between heat, energy changes, and temperature changes [14,16]. Research on the teaching and learning of energy in chemistry indicates that while traditional physics instruction mostly deals with energy considerations in macroscopic systems, in chemistry, energy must be understood at the atomic and molecular levels [9].

Students develop an understanding of energy in the context of biology very early in school since it is intuitive that we need to eat in order to have the energy for the body's functions [17]. The concept that we digest food by breaking it down to make the energy in the food available for the body's functions contradicts the scientific interpretation of energy. This can lead to different errors like the well-documented misconception that energy is released when breaking a molecular bond [9,18,19]. This misconception is very difficult to modify, even after instruction [18], and leads to various misconceptions, both in biology and chemistry [9] (Cooper & Klymkowsky, 2013). Later, students are introduced to the "high-energy bonds" in ATP. In return, students construct and retain a mental model in which chemical bonds contain energy (like batteries) that is released when the bonds break [9].

1.4. Conceptual Profile Theory

Conceptual profile theory [20,21] states that many major concepts in science can be thought of in heterogeneous ways that may have pragmatic value in different contexts. Conceptual profile theory proposes framing the problem of generating new meanings in science by considering different modes of thinking. It also implies that different sub-cultures in science may think differently about the same concepts and constitute relatively stable zones of meaning that, in turn, compose a common language used by individuals of this sub-culture when using this concept in a diversity of situations [20]. This means that different communities may use this concept differently for energy, giving it a spectrum of meanings ascribed to the concept in each community. Therefore, different energy attributes may be found in daily life, school science, or specific scientific disciplines [20,22].

Many curriculum designers consult leading scientists to integrate contemporary research into the curriculum. For example, Yonai and Blonder [23] consulted with scientists to build connections between a middle school nanoscale science and technology (NST) curriculum and their contemporary research-driven insights.

Present-day scientists were likely taught about energy more traditionally than is suggested by the NGSS and the Framework. However, we believe that as scientists specialized, they may have developed "diverse" conceptions of energy that best fit the needs of their fields. They may have developed a "hybrid" conception at some stage in their career, starting from one perspective and then blending in another, especially if their research is interdisciplinary. Since many curricula worldwide are based on the perceptions that leading scientists have of their field and their declaration of what is most important for students to know while studying this field [24], we assume that the way to conceptualize energy is critical. Understanding how scientists resolved the conception of energy to fit the different concepts of their research may be vital to creating a unified method of instruction for this concept. It is to be expected that different conceptions of energy influence scientists' abilities to use the concept of energy to make sense of phenomena.

The purpose of this study was to conduct a small-scale interview study designed to find out how scientists from different disciplines use energy to explain a range of phenomena. Our goal was to investigate which conception(s) of energy works best for present-day scientists from different disciplines and understand whether this conception is disciplinary in nature, like they were taught at school, or evolved to an interdisciplinary conception as an outcome of their scientific practice.

2. Methods

2.1. Sample

The 30 participants were a non-random convenience sample of senior professors from three different science disciplines—physics, chemistry, and biology—10 from each discipline, from different research universities across Israel. Many of the participants work on interdisciplinary issues or have been trained in one discipline but work in another. According to the Institutional Review Board (IRB), those who agreed were first explained their rights before being interviewed in person. Table 1 presents the fields in which the participants completed their Ph.D. and their present field of research. In Table 1 and all other references from now on, we refer to the biology professors as B1, B2, etc.; the chemistry professors as C1, C2, and so on; and the physics professors as P1, P2, etc.

Table 1. Scientists' particular specialization according to their Ph.D. discipline and field of study.

Discipline	Alias	Specialization
Biology professor	B1	Structural biology
	B2	Structural biology
	B3	Ecology
	B4	Microbiology
	B5	Computational immunology
	B6	Biochemistry and cell biology
	B7	Neurobiology
	B8	Developmental biology
	B9	Immunology
	B10	Biochemistry and proteomics
Physics professor	P1	Physics of soft matter
	P2	Particle physics and astrophysics
	P3	Theoretical physics
	P4	Quantum and matter physics
	P5	Biophysics
	P6	String theory
	P7	Particle physics and astrophysics
	P8	Physical chemistry
	P9	Theoretical physics
	P10	Particle physics and astrophysics
Chemistry professor	C1	Materials and interfaces
	C2	Inorganic chemistry
	C3	Organic chemistry
	C4	Synthetic chemistry
	C5	Materials and interfaces
	C6	Organic chemistry
	C7	Green chemistry and renewable energy
	C8	Organic chemistry
	C9	Nanomaterials
	C10	Materials and interfaces

2.2. Instruments

Semi-structured audio-recorded interviews were conducted, transcribed, and analyzed following Shkedi [25] and Chi [26]. In the interviews, each participant was presented with the same seven (at the start we had only one question from each discipline and added additional questions later; this is the reason why some of the cells in Table 2 are blackened: some of the participants were not presented with all seven questions) questions (elaborated in Supplement S1), with each one based on a different phenomenon: two were from physics, two from chemistry, and three from biology. The phenomena were chosen after a search and

trial on colleagues to find ones that anyone with a broad scientific background might be able to explain (you need not be a content expert to answer them). Also, another consideration was that the energetic perspective could be one way of making sense of the phenomena, but not the only one. See Supplement S1 for the questions used in the interview.

Table 2. Scientists' answers are coded according to whether they used the energy concept spontaneously to make sense of a phenomenon.

Discipline	Alias	Biology Q1	Biology Q2	Biology Q3	Chemistry Q1	Chemistry Q2	Physics Q1	Physics Q2
Biology Professor	B1	EO			E		E	
	B2	E			E		EO	
	B3	EO	E	EO	O	E	O	E
	B4	O	E	E	E	E	EO	EO
	B5	EO	E	EO	E	EO	E	O
	B6	EO	E	E	EO	E	O	O
	B7	EO	E	O	E	EO	O	O
	B8	EO	E	E	EO	E	O	O
	B9	EO	E	EO	E	E	O	EO
	B10	EO	O	E	EO	E	O	O
Physics Professor	P1	O			EO		EO	
	P2	O			E		E	
	P3	O	E	EO	O	O	E	E
	P4	EO	E	E	E	O	E	E
	P5	EO	E	EO	E	EO	EO	E
	P6	O	EO	EO	E	EO	E	EO
	P7	O	EO	E	E	E	E	EO
	P8	O	EO	O	E	O	EO	E
	P9	EO	EO	E	EO	EO	EO	EO
	P10	EO	EO	E	EO	O	E	E
Chemistry Professor	C1	EO			E		E	
	C2	O			E		EO	
	C3	EO			E		EO	
	C4	EO	E	E	E	E	O	O
	C5	O	E	E	E	EO	EO	O
	C6	O	E	E	E	E	E	E
	C7	E	E	E	E	E	O	EO
	C8	O	EO	EO	EO	E	O	O
	C9	O	E	E	E	E	EO	EO
	C10	E	EO	EO	E	E	EO	EO
E		Used energy spontaneously						
EO		Used energy among other explanations						
O		Did not use energy even after being asked to						

The participants were told that we were not looking for correct answers, just for how they thought about the questions, and they were encouraged to think aloud [27]. We always began the interviews with a question that lay in the participant's field of expertise, which they would likely feel successful at answering. At no point during this stage was the word "energy" mentioned.

After responding to all the questions, the participants were asked to revisit the questions and construct an energy-based explanation if they did not do so spontaneously.

Lastly, participants were asked to describe how they conceptualized energy and whether they grasped it as being used similarly across the disciplines.

2.3. Analysis

All the interviews were transcribed and analyzed according to Shkedi's verbal analysis [25] and then quantified using Chi's approach [26]. The answers provided by the interviewees were divided into three categories: (A) used energy spontaneously; (B) used energy along with other concepts; and (C) did not use energy, even after being prompted to do so (see Supplement S2 for examples).

When being asked to make sense of a phenomenon, we typically first choose the simplest explanation we can find. For this reason, we inferred that the spontaneous answer was the one that the scientists thought was the easiest one.

After this coding, the responses that drew on energy were categorized according to their use of the five key elements of the energy concept—forms, transformation, transfer, degradation/dissipation, and conservation [6] (see Table 3). While categorizing the answers according to these five categories, the need for a 6th category arose, namely, “energy as a resource”, which aligned quite well with the non-scientific conception of energy that was formerly referred to as activity/work. All answers that suggested that energy is needed to make something happen were placed in this category. An answer could be placed in more than one category. See Supplement S2 for examples.

A quarter of the transcripts were read and analyzed independently by both authors to ensure inter-rater reliability. The initial percentage of agreement was 90%. All disagreements were discussed and resolved to reach a 100% agreement. The remaining transcripts were then analyzed only by the first author. Lastly, we looked at the anecdotes, which were as interesting as the other results, showing the different states of mind that the different scientists had.

Table 3. Characterizing professors’ phenomena explanations according to energy’s key elements.

Field	Alias	Biology Q1					Biology Q2					Biology Q3					Chemistry Q1					Chemistry Q2					Physics Q1					Physics Q2						
		forms	transformation	transfer	dissipation	conservation	resource	forms	transformation	transfer	dissipation	conservation	resource	forms	transformation	transfer	dissipation	conservation	resource	forms	transformation	Transfer	dissipation	conservation	resource	forms	transformation	Transfer	dissipation	conservation	resource	forms	transformation	transfer	dissipation	conservation	resource	
Biology	B1	v				v								v						v							v	v		v								
	B2	v				v								v						v							v	v										
	B3	v				v							v											v	v								v	v			v	
	B4												v	v						v				v	v								v	v			v	
	B5					v							v	v										v	v	v			v									
	B6	v				v							v																									
	B7					v								v						v				v														
	B8					v							v	v						v				v														
	B9					v							v							v				v													v	
	B10					v							v	v						v				v														
Chemistry	C1					v								v						v						v	v			v								
	C2																									v	v		v	v								
	C3	v																												v								
	C4	v				v							v	v						v				v	v													
	C5												v											v	v	v							v				v	
	C6												v											v	v	v							v	v				
	C7	v				v							v	v										v													v	
	C8																							v														
	C9							v		v			v							v				v	v								v	v				
	C10	v	v			v		v					v							v				v									v	v				
Physics	P1													v												v	v	v	v	v								
	P2													v												v	v		v	v								
	P3																									v	v							v	v			v
	P4																									v	v	v	v									
	P5					v																				v	v	v						v	v			
	P6																									v	v	v				v			v	v		
	P7																									v	v							v	v			
	P8																																					
	P9	v				v																				v	v		v	v				v	v			
	P10	v				v																																

3. Results

3.1. Did the Scientists Use the Energy Concept Spontaneously to Make Sense of Phenomena?

Table 2 presents the participants' responses to the different questions according to used/did-not-use energy codes.

The results show that 6 of the 10 biologists spontaneously answered most of the biology and chemistry questions using energy; on the other hand, they had much more difficulty using energy with the physics questions. Some biologists mentioned that it had been a long time (ever since high school) since they had engaged in physics-like thinking. For instance, B2's response to PQ1 was as follows: "In order to answer the physics question I need to return to my high school knowledge. It feels wrong that I have to go back there to answer a basic question, but I have not learned anything about it since". B2 was a very distinguished scientist involved in an interdisciplinary field of research. We received similar reactions from other biologists. Another example was B8, whose first reaction to PQ1 was as follows: "I haven't thought about something like this for 30 years. It reminds me that I'm really bad at physics".

Almost all the physicists spontaneously answered the physics questions using energy. On the other hand, none used energy spontaneously to answer BQ1 (ecosystem) and most were unable to use energy in this question even after being prompted to do so. Most had difficulty using energy to answer CQ2 (catalysts) but were able to use energy to answer BQ2 (fatigue), BQ3 (body temperature), and CQ1 (starting combustion).

It is also worth mentioning that P1 explicitly refused to use energy to answer the biology questions, stating that "I do not want to go for an energetic explanation in this case because biological systems are not in equilibrium". P7 was another physicist who refused to use energy to explain biological phenomena, saying "It's annoying. If someone would offer me an energetic explanation for this question, it would really annoy me".

It fascinated us that several of the physicists said that biologists do not really understand energy and use it as a currency (ATP). For example, "Biologists use the term energy in a much less accurate way than it is. . . it is something that can be measured and has a certain value. . ." (P9 about how energy is conceived in the different disciplines). However, earlier, when they tried to use energy to answer the biology questions, the physicists also used energy as a currency. For example, the same P9 said the following while answering BQ3: ". . . there is a limited amount of energy in the body and it cannot run forever (giggles) because running requires ah. . . requires a lot of energy in order to activate the muscles".

The chemists used energy spontaneously to answer BQ2 and BQ3 for both chemistry questions, and only seldom for the physics questions. As C9 put it, "Biologists do not understand physics and physicists do not understand biology. We as chemists know both and chemistry, so we are in the middle and function as the real science of the three. . .".

3.2. Coding According to the Five Key Elements

Table 3 shows the coding results according to the six categories (energy as a resource, forms, transformation, transfer, degradation/dissipation, and conservation).

The results show that the biologists almost always used energy as a resource. For example, "This energy is now available to fuel the rest of the creatures in the biotic system" (B2 answering BQ1) and "The reason for heating is to overcome an energetic barrier. You need the energy to pass it and once it is passed the reaction starts spontaneously" (B1 answering CQ1). It was surprising to see that some of the biologists used energy as a resource even when referring to PQ2. For example, B3 said, "...the roller coaster needs to have enough energy to complete the loop". The biologists rarely referred to forms of energy in the biology questions, except when they referred to sunlight in BQ2 and heat in BQ3, which we coded as a reference to an energy form.

The physicists primarily used forms and transformation to answer the physics questions (one cannot use transformation without referring to forms) but seldom used transfer and conservation for the physics questions. As for the chemistry questions, the physicists talked about the need to pass an energy barrier.

As written earlier, the physicists could not craft an energy-based answer for the macro-biology question (BQ1), even when they were explicitly asked to do so. When they answered the micro-biology questions (BQ2 and BQ3), they used energy as a resource.

The chemists mostly answered the chemistry questions using energy as a resource. In CQ1, most of them added that energy must be transferred to the system in order to overcome the energy barrier. For example, “You have to add enough energy into the system to overcome some high energy barrier to make the reactions happen” (C6). They managed much better than the physicists in answering the biology questions, using sunlight as a form of energy in BQ1 and referring to energy as a resource in all the biology questions. For example, “You need to invest energy to create a living organism.” (C4). They also used energy to answer the physics questions. In contrast with the physicists, the chemists did not use transfer while answering the physics questions but frequently used forms and transformations. For example, “A bullet has kinetic and potential energy. When it is in the highest altitude, it has its most kinetic energy and while falling it gains its potential energy again” (C6).

A remarkable result was the scarcity with which degradation, dissipation, and conservation were used in answering almost all the questions. It seemed very hard for all participants to use these terms without apologizing for dealing with a non-ideal, realistic world. These concepts apply only to idealized situations. In the same breath, some also remarked that it is incorrect to apply the concept of energy conservation to biological phenomena since biological systems are not in equilibrium. For example, “Clearly, the answer cannot refer to energy conservation in biological questions. Such an answer would be bull----” (P7 explaining her view about the use of energy in biological phenomena).

3.3. Did the Practicing Scientists Grasp Energy as a Concept Similarly across the Disciplines?

Our last question was whether the scientists conceived energy as an interdisciplinary concept. Most researchers from the different disciplines did not believe that energy was treated the same in the different disciplines and was not a crosscutting concept. A few examples representing the scientists’ opinions about the attempt to characterize energy as a crosscutting concept are as follows:

- “There are clear definitions of what energy is. Naturally, physicists are very accurate about what energy is. We’re talking about the same term we’re talking about energy and there’s a point in being precise so we can explain our ideas to physicists in a coherent way clearly.” (B4).
- “No. I don’t think that biologists recognize the physical concept of energy but use it as a currency ATP.” (B6).
- “I do not doubt that energy is a universal interdisciplinary concept. Will people in different research fields answer in the same manner? Of course not. Physicists are more mathematical and therefore, will give you the formulas. Biologists will use less math and will explain in their words the same phenomenon.” (B7).
- “Biology is complex systems, energy describes only a small part of the story ... energy may be a crosscutting concept, but it tells a lot less about what happened....” (P1).
- “There is no doubt that the term energy is used in the same way in all disciplines ... but it is not grasped in the same way.” (P6).
- “It is very dangerous to teach energy as a crosscutting concept. If so, soon everyone will start treating energy as “Reiki” and transfer energy from rocks to the spirit. ... There is only one energy that is in the physical concept of energy.” (P10).
- “Biologists perhaps because of their education and what they have learned all these years are less likely to use energy as an explanation in general.” (C4).

4. Discussion

The results indicate that the conception of energy by scientists is context and discipline dependent. While scientists acknowledge that energy is the same in all phenomena [28,29], it was easier for them to address energy differently according to the disciplinary context

and according to their disciplinary expertise. This outcome fits the idea of conceptual profiles that was proposed by Mortimer [20]. Aguiar et al. [22] suggested a conceptual profile model for energy built with six zones. Each zone involves different ways of thinking and talking about energy, which can overlap in individuals' utterances, depending on the specific communication context. Their study concluded that the most obvious of the zones found in the classroom was the one they referred to as the "substantialist zone". According to this zone, energy is treated as a quasi-material substance, which is easily recognizable in the metaphors used that addressed energy as something that could be located in objects and used to do something [22]. This finding fits our findings on using energy as a resource by scientists, especially when discussing a biological phenomenon. Since energy is an abstract concept, conceptual metaphors allow one to conceptualize it in terms of other concepts [30]. Scientists frequently use such metaphors, and these metaphors help scientists to communicate their models and interpretations of the physical world. Our concern is that while practicing scientists find the need to use metaphors to explain phenomena, it is expected that students use scientific language and make connections that some experts find complicated to do.

While it appears that the biology questions were the most difficult for the non-biologists to provide an energy-based response to, the physics questions were the most likely to be answered in an energy-based way, regardless of the researcher's discipline. Altogether, it was easier for researchers to express themselves in an "energetic" manner when the question was closer to their discipline. Kohn et al. [29] interviewed college students taking introductory courses in biology and chemistry to explore their perceptions of energy integration in these courses. They found that many students were confused or even unaware of how to make connections between the use of energy between the disciplines. For example, it was common to use the term "kinetic energy" and "potential energy" in chemistry, but students could not use these terms while explaining a biological phenomenon.

The concepts of energy dissipation and conservation were used solely in the physics questions. The transfer concept was used a bit more often and by all the scientists. Cooper and Klymkowsky [9] and Kohn et al. [29] argued that the frequent use of forms and the lack of use of transformation outside the physics world is because of the abundance of forms that students encounter while studying and, on the other hand, the complexity of navigating various definitions of energy encountered in multiple science contexts and physics. In this case, the new approach suggested by the NGSS [31] highlights that the transfer of energy from one system to another without burdening the students with a wide array of energy forms is in place. Indeed, all the various forms of energy can be grouped into only two forms of energy: kinetic and potential energy [30,32–34].

Our finding leads us to ask whether it makes sense to expect junior high school students to perform and think in ways that contrast with those used by the practicing scientists we interviewed. We acknowledge that current scientists were taught traditionally and, together with their research's needs, have developed diverse conceptions of energy that fit their needs. In this case, if we consider the next generation of scientists and wish that their research will be interdisciplinary, the unified vision of teaching energy is in place.

On the other hand, as noted by Osborne, Rafanelli, and Kind [35], one should consider whether energy is, in fact, a good unifying concept. It may be that the unified conception of energy is proper from the perspective of some science disciplines but not others.

Since the authors believe that the next generation of scientists should have a more interdisciplinary approach to science, we think that the unifying approach to energy should be further investigated. The value of energy is that it is the same concept across disciplines and can be used to bridge them. We suggest that at the very least, the energy curriculum should note the differences between the way disciplines address energy and not hide them. Perhaps by stressing the differences between how energy is used, we will be helping students to become thoughtful consumers of scientific knowledge that involves the concept

of energy and help future scientists to have more scientific and interdisciplinary lenses to help them look at their data.

5. Conclusions

A decade has passed since the notion of crosscutting concepts (CCCs) was raised by the National Research Council [3]; there is still a dearth of empirical investigations on scientists' different (or common) perceptions of CCCs, the use of them as unifying concepts in classes, and students' perceptions of them in different phenomena. This study showed that even leading scientists struggle to use energy in a unified manner across disciplinary lines. We wonder what the situation is like concerning other potential unifying concepts. This study's results suggest that we should not take it for granted that just because different disciplines use the same terms, they are used similarly in the different disciplines.

6. Future Research and Implications

Future research should investigate whether the use of the physical concept of energy (which is the way it is usually taught in schools) is appropriate and valuable in describing biological and chemical phenomena in schools. For example, one could examine the value of connecting biological diversity with energy forms and transformations or connecting between the degradation of energy and cell respiration and the warming of an organism. One could also investigate whether the transfer-only approach promoted by the NGSS [31] better supports understanding biological phenomena than the traditional forms-based approach to energy. Authors [36] compared a transfer-only approach to energy with a traditional forms-based approach to energy and found it superior in supporting middle school students' thinking about physical science phenomena. It will be interesting to see whether this approach is also beneficial in explaining phenomena in other disciplines.

7. Limitations of the Study

There are some limitations to this study. The first is that although an effort was made to interview a wide variety of scientists engaged in many different fields, the sample we used is possibly not representative of all scientists in the different disciplines. De facto, we were limited to interviewing only scientists who agreed to participate. A second limitation was that we considered the use of energy by physicists, chemists, and biologists, but not by earth scientists or engineers. Also, we interviewed only scientists who were at the top of their fields in academia and not scientists who worked in industry. The third limitation was that the questions we posed to the scientists could not reflect each discipline's entire richness, and thus, clearly, some ways of using energy in each discipline were not investigated. Fourth, the physics questions were similar to traditional high school physics questions and may have evoked a "high school" manner of thinking. Fifth, since the phenomena presented to the scientists were discipline-based rather than interdisciplinary ones, we cannot say anything about how the scientists would have addressed truly interdisciplinary phenomena.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/educsci13121179/s1>, S1: Questions and phenomena used in interviews; S2: Examples of coded statements. References are cited as [37–41].

Author Contributions: Conceptualization, S.A. and D.F.; methodology, S.A. and D.F.; validation, D.F.; formal analysis, S.A.; investigation, S.A.; data curation, S.A.; writing—original draft preparation, S.A. and D.F.; writing—review and editing, S.A. and D.F.; visualization, S.A.; supervision, D.F.; project administration, S.A.; funding acquisition, D.F. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki, and approved by the Institutional Review Board of the Weizmann Institute of Science, 20 February 2016.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to privacy concerns.

Conflicts of Interest: The authors declare no conflict of interest.

References

- Chesnutt, K.; Gail Jones, M.; Corin, E.N.; Hite, R.; Childers, G.; Perez, M.P.; Ennes, M. Crosscutting concepts and achievement: Is a sense of size and scale related to achievement in science and mathematics? *J. Res. Sci. Teach.* **2019**, *56*, 302–321. [\[CrossRef\]](#)
- Fick, S.J. What does three-dimensional teaching and learning look like?: Examining the potential for crosscutting concepts to support the development of science knowledge. *Sci. Educ.* **2018**, *102*, 5–35. [\[CrossRef\]](#)
- National Research Council. *A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas*; National Academies Press: Washington, DC, USA, 2012.
- Krajcik, J.; Codere, S.; Dabsah, C.; Bayer, R.; Mun, K. Planning instruction to meet the intent of the Next Generation Science Standards. *J. Sci. Teach. Educ.* **2014**, *25*, 157–175. [\[CrossRef\]](#)
- Driver, R.; Millar, R. (Eds.) *Energy Matters: Proceedings of an Invited Conference: Teaching about Energy Within the Secondary Science Curriculum*; University of Leeds, Centre for Studies in Science and Mathematics Education: Leeds, UK, 1986.
- Nordine, J.C.; Krajcik, J.S.; Fortus, D. Transforming energy instruction in middle school to support integrated understanding and future learning. *Sci. Educ.* **2011**, *95*, 670–699. [\[CrossRef\]](#)
- Park, M.; Liu, X. Assessing understanding of the energy concept in different science disciplines. *Sci. Educ.* **2016**, *100*, 483–516. [\[CrossRef\]](#)
- Sanderson, R. *Chemical Bonds and Bonds Energy*; Elsevier: Cambridge, MA, USA, 2012; Volume 21.
- Cooper, M.M.; Klymkowsky, M.W. The trouble with chemical energy: Why understanding bond energies requires an interdisciplinary systems approach. *CBE—Life Sci. Educ.* **2013**, *12*, 306–312. [\[CrossRef\]](#)
- Chen, R.F.; Eisenkraft, A.; Fortus, D.; Krajcik, J.S.; Neumann, K.; Nordine, J.C.; Scheff, A. (Eds.) *Teaching and Learning of Energy in K-12 Education*; Springer: Berlin/Heidelberg, Germany, 2014.
- Duit, R. Learning the energy concept in schools—Empirical results from The Philippines and West Germany. *Phys. Educ.* **1984**, *19*, 59–66. [\[CrossRef\]](#)
- Liu, X.; McKeough, A. Developmental growth in students' concept of energy: Analysis of selected items from the TIMSS database. *J. Res. Sci. Teach.* **2005**, *42*, 493–517. [\[CrossRef\]](#)
- Neumann, K.; Viering, T.; Boone, W.J.; Fischer, H.E. Towards a learning progression of energy. *J. Res. Sci. Teach.* **2013**, *50*, 162–188. [\[CrossRef\]](#)
- Ben-Zvi, R.; Silberstein, J.; Mamlok, R. A model of thermal equilibrium: A tool for the introduction of thermodynamics. *J. Chem. Educ.* **1993**, *70*, 31. [\[CrossRef\]](#)
- Levy Nahum, T.; Mamlok-Naaman, R.; Hofstein, A.; Taber, K.S. Teaching and learning the concept of chemical bonding. *Stud. Sci. Educ.* **2010**, *46*, 179–207. [\[CrossRef\]](#)
- Granville, M.F. Student misconceptions in thermodynamics. *J. Chem. Educ.* **1985**, *62*, 847. [\[CrossRef\]](#)
- Opitz, S.T.; Harms, U.; Neumann, K.; Kowalzik, K.; Frank, A. Students' energy concepts at the transition between primary and secondary school. *Res. Sci. Educ.* **2014**, *45*, 691–715. [\[CrossRef\]](#)
- Barker, V.; Millar, R. Students' reasoning about basic chemical thermodynamics and chemical bonding: What changes occur during a context-based post-16 chemistry course? *Int. J. Sci. Educ.* **2000**, *22*, 1171–1200. [\[CrossRef\]](#)
- Storey, R.D. Textbook errors & misconceptions in biology: Cell energetics. *Am. Biol. Teach.* **1992**, *54*, 161–166.
- Mortimer, E.F. Conceptual change or conceptual profile change? *Sci. Educ.* **1995**, *4*, 267–285. [\[CrossRef\]](#)
- Mortimer, E.F.; El-Hani, C.N. (Eds.) *Conceptual Profiles: A Theory of Teaching and Learning Scientific Concepts*; Springer Science & Business Media: Berlin/Heidelberg, Germany, 2014; Volume 42.
- Aguiar, O.; Sevan, H.; El-Hani, C. Teaching about energy. *Sci. Educ.* **2018**, *27*, 863–893. [\[CrossRef\]](#)
- Yonai, E.; Blonder, R. Scientists suggest insertion of nanoscience and technology into middle school physics. *Phys. Rev. Phys. Educ. Res.* **2020**, *16*, 010110. [\[CrossRef\]](#)
- Ornstein, A.C.; Hunkins, F.P. *Curriculum: Foundations, Principles, and Issues*; Pearson Education: Essex, UK, 1988.
- Shkedi, A. *Words of Meaning: Qualitative Research—Theory and Practice*; Ramot Publishers: Tel Aviv, Israel, 2003. (In Hebrew)
- Chi, M.T. Quantifying qualitative analyses of verbal data: A practical guide. *J. Learn. Sci.* **1997**, *6*, 271–315. [\[CrossRef\]](#)
- Ericsson, K.; Simon, H. *Protocol Analysis*; MIT Press: Cambridge, MA, USA, 1993.
- Cooper, M.M.; Klymkowsky, M.W.; Becker, N.M. Energy in chemical systems: An integrated approach. In *Teaching and Learning of Energy in K-12 Education*; Springer: Berlin/Heidelberg, Germany, 2014; pp. 301–316.
- Kohn, K.P.; Underwood, S.M.; Cooper, M.M. Energy connections and misconceptions across chemistry and biology. *CBE—Life Sci. Educ.* **2018**, *17*. [\[CrossRef\]](#)
- Harrer, B.W. On the origin of energy: Metaphors and manifestations as resources for conceptualizing and measuring the invisible, imponderable. *Am. J. Phys.* **2017**, *85*, 454–460. [\[CrossRef\]](#)

31. NGSS Lead States. *Next Generation Science Standards: For States, by States*; National Academies Press: Washington, DC, USA, 2013.
32. Mezey, P.G. *Potential Energy Hypersurfaces*; Elsevier: Amsterdam, The Netherlands, 1987.
33. Quinn, H.R. A physicist's musings on teaching about energy. In *Teaching and Learning of Energy in K-12 Education*; Springer: Berlin/Heidelberg, Germany, 2014; pp. 15–36.
34. Von Mayer, J.R. *Die Mechanik der Wärme: In gesammelten Schriften*; JG Cotta: Stuttgart, Germany, 1874.
35. Osborne, J.; Rafanelli, S.; Kind, P. Toward a more coherent model for science education than the crosscutting concepts of the next generation science standards: The affordances of styles of reasoning. *J. Res. Sci. Teach.* **2018**, *55*, 962–981. [\[CrossRef\]](#)
36. Fortus, D.; Kubsch, M.; Bielik, T.; Krajcik, J.S.; Lehari, Y.; Neumann, K.; Nordine, J.C.; Opitz, S.T.; Touitou, I. Systems, transfer, and fields: Evaluating a new approach to energy instruction. *J. Res. Sci. Teach.* **2019**, *56*, 1341–1361. [\[CrossRef\]](#)
37. Sahney, S.; Benton, M.J. Recovery from the most profound mass extinction of all time. *Proc. R. Soc. B Biol. Sci.* **2008**, *275*, 759–765. [\[CrossRef\]](#)
38. Lamanna, C.; Blonder, B.; Violle, C.; Kraft, N.J.B.; Sandel, B.; Šímová, I.; Donoghue, J.C., II.; Svenning, J.-C.; McGill, B.J.; Boyle, B.; et al. Functional trait space and the latitudinal diversity gradient. *Proc. Natl. Acad. Sci. USA* **2014**, *111*, 13745–13750. [\[CrossRef\]](#)
39. Rosenzweig, M. How to reject the area hypothesis of latitudinal gradients. In *Macroecology: Concepts and Consequences*; Blackburn, T.M., Gaston, K.J., Eds.; Blackwell Publishing: Oxford, UK, 2003; pp. 87–106.
40. London, A. Why Do We Get Tired While Running? 2013. Available online: https://davidson.weizmann.ac.il/online/askexpert/life_sci/%D7%9E%D7%93%D7%95%D7%A2%20%D7%94%D7%92%D7%95%D7%A3%20%D7%9E%D7%AA%D7%A2%D7%99%D7%99%D7%A3%20%D7%9B%D7%A9%D7%A8%D7%A6%D7%99%D7%9D%3F (accessed on 7 May 2023).
41. Brown, T.E.; LeMay, H.E.H.; Bursten, B.E.; Murphy, C. *Chemistry: The Central Science*, 12th ed.; Prentice Hall: Upper Saddle River, NJ, USA, 2012.

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.