

STUDENTS' PROGRESSING  
UNDERSTANDING OF THE ENERGY  
CONCEPT

AN ANALYSIS OF LEARNING IN BIOLOGICAL AND  
CROSS-DISCIPLINARY CONTEXTS

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# Summary

Science curricula and standards have been criticized for covering too many details and putting insufficient focus on the connections between individual contents. As, for example, studies have found that experts organize their knowledge efficiently around central ideas, curricular innovations have introduced disciplinary core ideas that organize and connect different topics of a school subject (e.g., biology). At a higher level, crosscutting concepts fulfill the function of linking contents across different disciplinary contexts. The *energy concept* stands out, as it is both a core idea in biology, chemistry, and physics, as well as a crosscutting concept that spans these disciplines. While students learn about energy in all science classes, the majority of prior studies on students' energy understanding have targeted physics contexts. Instead, few empirical insights describe (i) how students understand energy in biological contexts and (ii) how students' energy understanding is interconnected between the different disciplinary contexts.

To address these open fields, four studies have been conducted as part of this dissertation project (Chapters 2-5). An additional teaching practice article provides an exemplary approach that focuses on relevant aspects of the energy concept in a typical middle school biology topic (Chapter 6). All five chapters focus on students' understanding of four central energy aspects: energy forms/sources, energy transfer/transformation, energy degradation/dissipation, and energy conservation. Study 1 uses a quantitative, cross-sectional design and explores how primary students' (grades 3-6) energy understanding progresses along early, mostly implicit learning opportunities that students encounter prior to the concept's explicit introduction. The findings suggest that students develop the initial stages of their energy understanding along biological contexts, thus highlighting that these learning gains should be taken into account in later, explicit energy instruction. Study 2 extends the scope of study 1 by focusing on progressing energy understanding in middle school and by including a cross-disciplinary perspective on energy learning. The respective research article presents the development and validation of an instrument that assesses energy understanding across contexts from biology, chemistry, and physics. The new instrument is applied in a cross-sectional study (grades 6, 8, and 10) in order to compare progression trends in energy understanding across the three disciplinary contexts. The results identify similarities and differences in students' energy understanding in the three disciplinary contexts. However, the question of how energy understanding is specifically connected across disciplinary boundaries, and how this connection changes as the students learn more about energy throughout middle school, is left open. This question is picked up by study 3, which re-analyzes data from study 2. The results indicate a parallel progression of energy understanding in the three disciplinary contexts with—at all grade levels—highly correlated energy understanding between biology, chemistry, and physics contexts. These findings are in line with recent studies, but are also critically discussed, as they oppose prior assumptions about students' cross-disciplinary energy understanding. Lastly, study 4 is the qualitative part of a mixed-method approach pursued by this dissertation. The findings from the earlier quantitative studies were extended through qualitative content analysis of interviews that were conducted with students at the beginning of grades 5, 7, 9, and 11. The findings provide an in-detail analysis of conceptions that students employ about the four energy aspects (see above) in typical biological contexts.

A conclusion of the conducted studies suggests that progressing energy understanding in biological contexts closely resembles progression trends described in earlier studies on energy understanding in physics contexts. The

## Summary

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studies provide novel insights, for example, by indicating that students' difficulties with energy in a given disciplinary context (e.g., biology) are likely overridden by more general problems related to everyday connotations of the term energy. The results highlight the need to coordinate energy instruction across biology, chemistry, and physics contexts in order to help students combine different disciplinary perspectives on energy. Notwithstanding the new insights to students' progressing energy understanding, future experimental studies have to tackle the important task of identifying effective instructional methods for energy teaching.

## Zusammenfassung

Lehrpläne und Bildungsstandards sind mehrfach dafür kritisiert worden, viele detaillierte Lerninhalte zu fordern, jedoch zu wenig Fokus auf die Verbindungen zwischen Fachinhalten zu legen. Da etwa Forschung mit Experten gezeigt hat, dass diese ihr Wissen um zentrale Ideen ihres Fachgebietes organisieren, setzt heutige naturwissenschaftliche Bildung vermehrt auf die Strukturierung von Lerninhalten durch Basiskonzepte. Diese verbinden zum Beispiel Inhalte des Biologieunterrichts dadurch, dass sie in verschiedenen Unterrichtsthemen immer wieder auftauchen und dabei ein wichtiges Mittel zur Analyse und Erklärung von beobachteten Sachverhalten darstellen. Innerhalb der Basiskonzepte sticht besonders das Energiekonzept heraus, da es in den naturwissenschaftlichen Fächern Biologie, Chemie und Physik eine entscheidende Rolle spielt und somit auch Inhalte zwischen diesen Fächern miteinander verbindet (*'energy as a crosscutting concept'*). Obwohl Schüler/-innen in allen drei naturwissenschaftlichen Fächern mit Kontexten konfrontiert werden, in denen Energie eine wichtige Rolle spielt, haben die meisten bisherigen Studien das Energieverständnis von Schüler/-innen in Kontexten der Physik untersucht. Im Gegensatz dazu gibt es bisher kaum Forschung, die das Energieverständnis in biologischen Kontexten beschreibt. Darüber hinaus ist es weitestgehend unbekannt, wie das Energieverständnis von Schüler/-innen über Fachgrenzen hinweg miteinander verbunden ist.

Diese zwei offenen Forschungsfelder liegen im Fokus der vorliegenden Dissertation, in deren Rahmen vier Studien durchgeführt wurden (Kapitel 2-5). In einem zusätzlichen Artikel für die Schulpraxis (Kapitel 6) wird ein Beispiel dafür vorgestellt, wie wichtige Aspekte des Energiekonzepts in ein typisches Unter- bzw. Mittelstufenthema des Biologieunterrichts (Winterschlaf) eingebunden werden können. Alle fünf Artikel legen den Fokus auf vier zentrale Aspekte des Energiekonzepts: Energieformen/-speicher, Energietransfer/-transformation, Energieentwertung/-dissipation und Energieerhaltung. Studie 1 nutzt einen quantitativen Zugang und untersucht in einem querschnittlichen Design (Klassenstufen 3-6), wie sich das Energieverständnis von Schüler/-innen entlang biologischer Kontexte entwickelt, die die Schüler/-innen noch vor der späteren, expliziten Einführung des Energiekonzepts antreffen. Die Ergebnisse legen dabei nahe, dass Schüler/-innen frühe Lernmöglichkeiten in biologischen Kontexten nutzen, um erste Grundzüge des wissenschaftlichen Energiekonzepts zu erlernen. Diese Wissensbasis sollte vom späteren, expliziten Unterricht zum Energiekonzept aufgegriffen werden. Studie 2 setzt die Forschung aus Studie 1 für den Sekundarbereich fort, wobei nicht nur Lernzuwächse in biologischen Kontexten untersucht werden, sondern auch die Verbindung des Energieverständnisses zwischen Kontexten der Fächer Biologie, Chemie und Physik. Im Zentrum des entsprechenden Forschungsartikels steht dabei die Entwicklung und Validierung eines Instrumentes zur Erfassung des Energieverständnisses in biologischen, chemischen und physikalischen Kontexten. Die Anwendung des Instruments in einer quantitativen, querschnittlichen Studie (Klassen 6, 8 und 10) wird genutzt, um Lernzuwächse für die drei disziplin-spezifischen Kontexte zu beschreiben und diese zu vergleichen. In Studie 3 wird eine erneute Analyse des Datensatzes aus Studie 2 vorgestellt. Hierbei geht es darum, zu untersuchen, wie das Energieverständnis der Schüler/-innen in biologischen, chemischen und physikalischen Kontexten miteinander in Verbindung steht und wie sich diese Verbindung im Laufe der Sekundarstufe (Klasse 6, 8 und 10) verändert. Der Vergleich verschiedener Modelle des Energieverständnisses legt eine parallele Verständnisenwicklung in den drei Fachkontexten und über die Klassenstufen hinweg nahe. Da die Testleistungen für die drei Kontexte jeweils stark miteinander korrelieren, ist davon auszugehen, dass Schüler/-innen – über die Klassenstufen hinweg – ein Energieverständnis für alle Fachkontexte nutzen. Diese Ergebnisse bestätigen zwar aktuelle Forschung zu fächerübergreifendem Energieverständnis, werden jedoch auch kritisch diskutiert, da sie einer weit verbreiteten

Meinung widersprechen. Zuletzt wird Studie 4 vorgestellt, die den qualitativen Teil eines *mixed-method* Ansatzes zur Beantwortung der übergreifenden Forschungsfragen dieser Dissertation darstellt. Dabei werden die oben genannten quantitativen Analysen durch einen qualitativen Zugang gestützt und spezifiziert. Hierzu wurden mittels qualitativer Inhaltsanalyse Interviews ausgewertet, die mit Schüler/-innen zu Beginn der Klassenstufen 5, 7, 9 und 11 geführt wurden. Im Rahmen der Ergebnisse wird ein detailliertes Kategoriensystem von Schüler/-innen-Vorstellungen zu Energie in typisch biologischen Kontexten vorgestellt. Beispiele beschreiben, wie sich zentrale Vorstellungen zu den vier genannten Energieaspekten über die Jahrgangsstufen verändern.

Die Zusammenfassung der durchgeführten Studien zeigt, dass Entwicklungstrends des Energieverständnisses in biologischen Kontexten denen in physikalischen Kontexten deutlich ähneln. Die Studien erbringen dabei neue Einblicke in die Entwicklung des Energieverständnisses, indem sie zum Beispiel darstellen, dass Schwierigkeiten im Energieverständnis in einem bestimmten disziplinären Kontext von allgemeineren Verständnisproblemen überlagert werden können. Die Ergebnisse unterstreichen dabei die Wichtigkeit, Unterricht zum Energiekonzept über die Fachgrenzen von Biologie, Chemie und Physik hinweg zu koordinieren um Schüler/-innen dabei zu helfen, verschiedene disziplinäre Perspektiven zum Energiekonzept miteinander zu kombinieren. Trotz der neuen Erkenntnisse dieser Doktorarbeit zur Verständniserwicklung des Energiekonzepts ist es eine wichtige Aufgabe zukünftiger Studien, effektive Ansätze des Lehrens und Lernens für das Energiekonzept zu identifizieren.





# CHAPTER 1

## Introduction

The central goal of science instruction is to help learners develop robust scientific literacy, i.e. the ability to “explain phenomena scientifically, evaluate and design scientific enquiry, and interpret data and evidence scientifically” (OECD, 2013, p. 5). This goal encompasses not only all of school science education (Kindergarten to high school, ‘K-12’), but also learning opportunities after school. As scientific knowledge is rapidly evolving in the natural sciences, scientific literacy has to enable learners to independently access new knowledge (MNU, 2001). This process is likely facilitated if students are able to recognize patterns and derive assumptions about how to analyze encountered phenomena (Anderson, 2009, p. 205; Bransford, Brown, and Cocking, 2000, p. 32; Linn, Eylon, and Davis, 2004, p. 43, 69). Research in cognitive psychology furthermore suggests that a highly interconnected understanding of different science contents is efficient for accessing knowledge and solving new problems (e.g., Bransford et al., 2000, p. 38; Anderson, 2009). Accordingly, curricular reforms in different countries have organized science education along core ideas and crosscutting concepts to address two main goals (e.g., KMK, 2005 a, b, c; NRC, 2012):

- (1) Provide learners with central concepts that work as analytical tools and help students to access different science phenomena.
- (2) Use these central, recurring concepts to help students form connections between science contents from different topics, grade levels, and disciplinary backgrounds.

Energy is an important core idea that occurs numerous times both across all grade bands and across school topics in biology, chemistry, and physics education (Chen et al., 2014).

However, the energy concept has been identified as particularly difficult for students to understand (e.g., Duit, 1984; Goldring and Osborne, 1994; Nordine, Krajcik, and Fortus, 2011). Several recent studies have analyzed how students' energy understanding progresses across grade levels. The goal is hereby to derive an empirical basis of students' learning and, accordingly, structure energy teaching in a way that is more meaningful for students (Chen et al., 2014). Until now, most of these studies have analyzed physics contexts (e.g., Liu & McKeough, 2005) while few empirical results describe how students' energy understanding progresses in biological contexts or how energy understanding is interrelated between disciplinary contexts. These two open research fields have been addressed by this dissertation project.

The following sections provide the theoretical and empirical backgrounds for the research conducted in this project. In regard to the two main goals for using energy as a core idea in science education (see above), energy is first introduced as an analytical concept of the natural sciences (section 1.1). The following section 1.2 describes the rationale for using core ideas in science education and introduces energy as an exemplary core idea. On the basis of these backgrounds, previous studies on students' progressing energy understanding are reviewed (section 1.3), thus deriving the overarching research questions addressed by this dissertation project (section 1.4). This last section furthermore introduces the four conducted studies, as well as a connected teaching practice article. Summaries of each study are provided and connections between the studies are highlighted. A tabular overview includes the individual studies' research questions, study designs, and the analyzed variables.

### **1.1 Energy as a Concept in Science**

Similar to Einstein's theory of General Relativity, the energy concept was introduced and successively further developed due to the concept's explanatory power, deriving from the simplicity of the thermodynamic laws and the wide range of phenomena that the energy concept can be applied to (Coopersmith, 2010, p. 352). Across sciences, energy is used as an analytical framework that allows assumptions about the behavior of objects in changing systems (Lerner and Trigg, 2005, p. 720). The application of the energy concept has deepened scientific understanding both in individual disciplinary, as well as in interdisciplinary settings. The tracking of energy and the assumptions formulated according to the law of energy conservation have played an important role in scientific breakthroughs. These encompass, for example, the discovery of neutrinos (see Nordine, 2016, p. 17) or the first indirect evidence for gravitational waves (observation of decreasing energy levels in binary pulsars – Ju, Blair, and Zhao, 2000, p. 1320).

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In biology, the relevance of energy derives from the fact that all life processes are accompanied by energetic changes. Energy is therefore a concept relevant for numerous topics in biology that range from molecular-level to ecosystem-level perspectives (Harms, 2016). The survival of cells (and organisms) depends on their ability to transform energy (Reece et al., 2011, p. 143). Just as in physics or chemistry, these energy transformations underlie the thermodynamic laws. While all energy transfers and transformations must increase the entropy of the universe (second law of thermodynamics), living organisms have to function in a way that increases entropy only in their surroundings, while the organisms have to build up and maintain ordered structures within themselves.

To illustrate the above, the following example demonstrates how the analysis of energy can be used in biology to deepen scientific insights and thus provide an overview of observable processes in the object of study. The common starfish, *Asterias rubens*, is a keystone species in the Baltic Sea. Simple, calcifying organisms, such as *A. rubens*, lack effective pH regulation of their extracellular fluid and are hence liable to ocean acidification caused by rising aquatic CO<sub>2</sub> levels. Increasingly more acidified conditions make it harder for growing calcifying organisms to build up and maintain calcium skeletons. In a multiple-week experiment, juvenile *A. rubens* were exposed to three different simulated levels of ocean acidification. Growth, activity, feeding, calcification, as well as several physiological parameters were measured regularly (Appelhans, Thomsen, **Opitz**, Pansch, Melzner, and Wahl, 2014). It was observed that starfish growth was strongly limited by realistic future levels of ocean acidification. To try to approach reasons for the limited growth, Scope for Growth (*SfG*) was computed. This measure describes the energy available for growth that remains after the energy requirements for respiration and excretion are subtracted from the energy uptake through feeding. The results showed that, under acidified conditions, the energy balance between the decreased food uptake and the still high energy demands for excretion and respiration shifted negatively. The starfish had thus not enough energy to sustain regular growth rates.

Through the use of the energy concept in this experiment, different separate parameters were connected to determine limitations to the occurrence of certain processes (in this case growth). The energy concept thus helped to analyze a complex interplay of factors, thus identifying relevant (growth) and less relevant (e.g., excretion, calcification) variables that can be further analyzed by continuing studies. The provided example focuses on the analysis of energy flow through an organism. Here, body processes degrade energy, which is then transferred into the environment via heat. In biology, dissipated thermal energy is hence an important focal point of the analysis, as it determines how well an organism can employ limited resources of energy. The efficiency

of an organism's energy transformations can hereby be an important factor for evolutionary success (e.g., when mutations result in new enzymes for energy-extensive reactions). In contrast to a biological perspective that focuses on open systems (Harms, 2016; Reece et al., 2011, p. 144), a physics perspective would, for example, shift the focus more towards energy conservation, while the energy given off into the environment may be disregarded in an idealized isolated system (NRC 2012, p. 120). Accordingly, it has been concluded that different science disciplines employ varying foci on energy, as well as different ways of speaking about the concept (Eisenkraft et al., 2014). These differences pose a major challenge for science teachers and students who have to meaningfully combine different disciplinary perspectives on energy and differentiate between contradictory sets of thinking about the concept.

### 1.2 Theoretical Background

The previous section introduced energy as an analytical concept in the natural sciences. In extension, the following provides the theoretical and empirical backgrounds on conceptual learning, thus introducing the second rationale for the prominent position of the energy concept in modern science education (see p. 1).

#### 1.2.1 Science Literacy Depends on Efficient Knowledge Organization

Science instruction confronts students with an extensive amount of content. In biology, for example, students have to organize this knowledge both vertically (across levels of perspective: e.g., ecosystem—organism—organ) and horizontally (across knowledge domains: e.g., genetics—evolution—cell biology). Biology classes (as well as other science classes) therefore run an intrinsic risk of presenting students 'additively' with a chain of contents that the students may experience as rather unrelated (MNU, 2001; NRC, 2012). *Assimilation* of new knowledge (i.e., using existing knowledge to reason about new information) is hereby distinguished from *knowledge accommodation* (i.e., the replacement or reorganization of prior knowledge in relation to new information—Inhelder and Piaget, 1972; Posner, Strike, Hewson, and Gertzog, 1982). The theory of conceptual change (e.g., Vosniadou, 2008) suggests that learners experience a conceptual conflict at some point of assimilating more and more knowledge. This conflict has been considered to radically change students' prior understanding if there is reason for dissatisfaction with the prior conceptualization, and if an alternative understanding is intelligible, plausible, and likely more fruitful (Posner et al., 1982). However, empirical findings suggest that conceptual change occurs not rapidly, but gradually over longer periods of time (Vosniadou, 2008).

Importantly, learners appear to frequently add new information that can be incongruent with prior knowledge. Learners thereby don't necessarily reconcile conflicts between competing sets of understanding and students thus maintain robust alternative conceptions in addition to scientifically more accurate views (Duit and Treagust, 2003; Smith et al., 1994—in regard to the energy concept, see Solomon, 1982; Vosniadou, 2008). Varying conceptualizations relate to the learners' different experiences and have been attributed to competing cognitive schemata. More stable cognitive structures develop as one schema dominates over others by fitting the learners' experiences more often and more accurately (Schnotz, 1999, p. 61, 88). The extent to which a schema, for example regarding conceptualizations of energy, is connected or transferred across different contexts, depends on how closely related these contexts are (Barnett and Ceci, 2002; Bransford, Brown, and Cocking, 2000, p. 53; Schnotz, 1999, p. 79). Learning about scientific concepts like energy thus requires students to challenge and reflect their everyday conceptions about energy (e.g., 'I have worked so hard. All my energy is gone.'). As students are likely to maintain potentially adverse conceptions across their school careers, their understanding of this content may become less cohesive as students mature and experience an increasing number of learning opportunities (Linn et al., 2004, p. 36).

### **1.2.2 Experts Organize Knowledge around Core Ideas**

A thorough understanding of a given content area is characterized by structural and functional relations between the elements of this content area. An interconnected science understanding has been considered an important aspect of enabling students to critically analyze, evaluate, and tackle future challenges (Nordine, 2007; Sakschewski, Eggert, Schneider, and Bögeholz, 2014). Cohesiveness of understanding has hence been identified as a key factor for more advanced understanding. For example, experts organize knowledge around key principles of their expertise area and recognize underlying principles in the analysis of problems (Anderson, 2009, p. 183, 204; Bransford et al., 2000, p. 36; Linn et al. 2004, p. 36). Similarly, multiple years of professional experience lead science teachers to restructure their knowledge and increasingly organize contents around core ideas of their discipline (Arzi and White, 2007). Likewise, students use extensive learning opportunities to progress from sets of disconnected facts towards a more robust and interconnected understanding (Clark, 2000). However, students also frequently contextualize their knowledge (i.e., connect certain conceptions only to specific contexts—e.g., Lancor, 2015; Neuman, Viering, Boone, and Fischer, 2013) and can hence experience difficulties in transferring knowledge between related

contexts or problems (Anderson, 2009, p. 168; Bransford et al., 2000, p. 51; Gick and Holyoak, 1980; Pugh & Bergin, 2006).

### **1.2.3. Knowledge Integration Organizes Science Understanding**

*Knowledge integration* is an important aspect of helping students to overcome the aforementioned problems in organizing newly learnt contents in relation to prior knowledge (Fortus and Krajcik, 2012; NRC, 2012, p. 31). Knowledge integration describes the “process of adding, distinguishing, organizing, and evaluating of accounts of phenomena, situations, and abstractions” (Linn et al., 2004, p. 30). Three cognitive processes are encompassed by knowledge integration: The recognition and addition of new conceptions, the generation of connections between different contents, and the reflection and evaluation of the employed knowledge (Linn et al., 2004, p. 46). Knowledge integration can be promoted, for example, through learning autonomy (Linn et al., 2004, p. 49) or the coherence between instructional units (Fortus and Krajcik, 2012). Linn et al.’s (2004) concept of knowledge integration encompasses processes of knowledge differentiation. However, knowledge integration and differentiation can also be seen as complimentary processes. Hereby, integration describes the synthesis of different elements of knowledge, while knowledge differentiation depicts the analysis of a previous conception respective its components and their interrelations (Harms and Bänder, 1999).

### **1.2.4 Coherent Curricula Implement Goals of Knowledge Integration**

Curricular coherence addresses learning goals connected to knowledge integration. It reflects principles for the development of cognitive structures by enabling the continuous construction of a coherent mental model of a content area (Schnotz, 1999, p. 254). Curricular coherence describes “the alignment of the specified ideas, the depth at which the ideas are studied, and the sequencing of the topics within each grade and across the grades” (Fortus and Krajcik 2012, p. 783). Schmidt, Wang, and McKnight (2005) identified curricular coherence as a central predictor of students’ science and mathematics performance. Hence, recent endeavors have been made to design internally coherent science curricula that focus on the internal alignment and connection of contents standards and learning goals, as well as on the coherence of contents within and across instructional units (Fortus and Krajcik, 2012; Fortus, Sutherland Adams, Krajcik, and Reiser, 2015; Shwartz et al., 2012). The development of coherent curricula and learning materials are empirically informed by *learning progressions of core science ideas*. The following section reviews the backgrounds to these concepts with regard to the energy concept.

### 1.2.5 Core Ideas Foster Interconnected Science Understanding

Ideally, school science instruction engages students in learning environments that systematically foster the construction of meaningful webs of understanding (e.g., Harms and Bänder, 1999). Similar to experts (see above), learners hereby profit from understanding basic, underlying principles that organize a given content area (Schnotz, 1999, p. 71). However, science standards have been criticized for covering a broad range of details with insufficient connection between individual contents (e.g., Bransford et al., 2000, p. 24; Schaefer, 2002; Schmidt et al., 2005). To take these issues into account and address learning goals connected to knowledge integration and curricular coherence, *core ideas* (German ‘*Basiskonzepte*’) have been introduced as frameworks that weave across science learning contexts.

Experts from different disciplinary backgrounds have identified the energy concept as an exemplary core idea. The concept hereby stands out from other important disciplinary ideas or topics (e.g., recombination in biology or relativity in physics), as the energy concept connects numerous learning opportunities across biology, chemistry, and physics contexts (e.g., Schaefer, 2002). Accordingly, core ideas are considered to foster knowledge integration that causes qualitative changes in the structure of students’ understanding, thus leading to a more interconnected conceptualization of science (KMK, 2005a, b, c; NRC, 2012). Core ideas also function as a pivot to help students develop sustainable ways of thinking about science, i.e. by “providing students with sufficient core knowledge so that they can later acquire additional information on their own” (NRC, 2012, p. 31). Thus, in applying core ideas, students learn what they *could* discover in observed phenomena and, subsequently, to derive appropriate questions and hypotheses for further analyses (Beyer, 2006, p. 18; Lichtner, 2003). While suggestions differ between authors, the following criteria have been proposed for identifying a concept as a core idea (Beyer, 2006, p. 6; NRC, 2012, p. 29; Schaefer, 2002, p. 36):

- (1) A core idea is an organizing principle in science or engineering that connects multiple phenomena.
- (2) A core idea is applicable to enhance the understanding of complex ideas and it informs problem solving.
- (3) A core idea relates to students’ life experiences and social concerns.
- (4) Understanding of the core idea contributes to general education and facilitates the teaching of competencies that are relevant for the respective discipline.
- (5) A core idea is accessible to students across grade levels and in increasingly more sophisticated ways of thinking about it.



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- (6) A core idea is interwoven with other core ideas in a way that helps students build up an interconnected web of knowledge.
- (7) A core idea is a concept or principle that allows students to connect knowledge from different disciplinary contexts.

In Germany, energy is a core idea in the chemistry and physics standards for middle school (KMK 2005b, c). In the equivalent standards in biology (KMK, 2005a), energy flow and matter cycles are mentioned as central elements for understanding two of three core ideas, i.e. 'systems' and 'structure and function'. The standards for high-school graduation in biology (KMK, 2004a) list energy as the separate core idea 'matter and energy transformations'. Educational standards in other countries similarly consider energy as a major organizing principle (e.g., Switzerland: EDK, 2011; UK: DfE, 2013; USA: NRC, 2012, NGSS, 2013). In addition to being a disciplinary core idea in the different science subjects, energy is also considered as a crosscutting concept. Such concepts with interdisciplinary relevance address—in analogy to the role of core ideas within disciplines—the connection and integration of knowledge across disciplinary contexts (NRC, 2012). Besides structuring science instruction and learning, core ideas and crosscutting concepts also provide a framework for different types of assessments and they can be used to develop science learning standards for specific grade levels (Gotwals and Alonzo, 2012; NRC, 2012; NGSS, 2013). As an example for their range, Table 1.1 provides an overview of core ideas and crosscutting concepts employed in German and US science standards.

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**Table 1.1.** Core ideas and crosscutting concepts in the German science standards for middle school (KMK, 2005a, 2005b, 2005c), high school graduation (KMK, 2004a, 2004b, 2004c), and in the US Next Generation Science Standards (NGSS, 2014; NRC, 2012).

<b>German standards for middle school</b>			
<b>Biology</b>	<b>Chemistry</b>	<b>Physics</b>	
(1) Systems (2) Structure and function (3) Development	(1) Relations between matter and particles (2) Relations between structure and properties (3) Chemical reactions <b>(4) Energetic analyses of matter transformations</b>	(1) Matter (2) Interactions (3) Systems <b>(4) Energy</b>	
<b>German standards for high school graduation</b>			
(1) Structure and function (2) Reproduction (3) Compartmentation (4) Steering and regulation <b>(5) Matter and energy transformations</b> (6) Information and communication (7) Variability and adaptation (8) History and relatedness	(1) Matter-particle concept (2) Structure-property concept (3) Donator-acceptor concept <b>(4) Energy</b> (5) Equilibrium states	(1) Fields (2) Waves (3) Quanta (4) Matter  <i>(Furthermore mentioned as underlying principles: causality, systems, conservation laws)</i>	
<b>US Next Generation Science Standards—Disciplinary core ideas</b>			
<b>Life sciences</b>	<b>Physical sciences</b>	<b>Earth/space sciences</b>	<b>Engineering/technology</b>
(1) From molecules to organisms: Structures and processes <b>(2) Ecosystems: Interactions, energy, and dynamics</b> (3) Heredity: Inheritance and variation of traits (4) Biological evolution: Unity and diversity	(1) Matter and its interactions (2) Motion and stability: Forces and Interactions <b>(3) Energy</b> (4) Waves and their applications	(1) Earth’s place in the universe (2) Earth’s systems (3) Earth and human activities	(1) Engineering design (2) Links between engineering, technology, science, and society
<b>US Next Generation Science Standards—Crosscutting concepts</b>			
(1) Patterns (2) Cause and Effect: Mechanisms and explanations (3) Scale, proportion, quantity (4) Systems and system models <b>(5) Energy and matter: Flow, cycles, and conservation</b> (6) Structure and function (7) Stability and change			

### 1.2.6 Learning Progressions Depict Increasing Levels of Understanding

As core ideas and crosscutting concepts address goals of knowledge integration, they cannot be taught as distinct topics, but have to be developed across topics, subjects, and grade levels (Beyer, 2006, p. 18; KMK, 2005 a, b, c; NRC, 2012). In order to help students organize science contents cumulatively, research has to investigate learning

trajectories that describe how students revise and re-organize their understanding (Linn et al., 2004, p. 38). A valuable branch of this research tracks how students' understanding of core ideas progresses across grade levels (Krajcik, Sutherland, Drago, and Merritt, 2012). Recent science education research has addressed this field by describing empirically derived *learning progressions*<sup>1</sup>. These progressions depict a sequence of increasingly more sophisticated ways of understanding core ideas (Gotwals and Alonzo, 2012; Krajcik et al., 2012; NRC, 2012, p. 26; Jin and Anderson, 2012). Learning progressions thereby provide (i) a roadmap that describes how students can develop an understanding of the most central ideas in science (NRC, 2012), and thus (ii) identify ways to increase the coherence between different contents in science instruction in a way that is meaningful for the students (Gotwals and Alonzo, 2012). The effectiveness of learning progressions towards these ends has been analyzed, for example, by Furtak and Heredia (2014), who evaluated the development and implementation of a learning progression on natural selection.

Descriptions of learning progressions are empirically derived and depend on valid assessments of students' understanding (Krajcik, 2012). These assessments are usually based on models (frameworks) that encompass different dimensions for describing levels of sophistication in understanding. Such dimensions have been derived both empirically and from learning theories (e.g., proficiency levels in the PISA or TIMS-studies). Different approaches to describing levels of progressing understanding have been presented (Neumann et al., 2007; Parchmann, 2010; Schecker and Parchmann, 2006). Kauertz et al. (2010) suggested assessing levels of understanding along three dimensions: (i) competence (or content) areas, (ii) levels of occurring cognitive processes, and (iii) levels of cognitive complexities. Here, the dimension (ii) (cognitive processes) describes a hierarchical sequence of activities that a student has to go through to fully understand a given content. These activities encompass simple reproductions, the selection of information, their organization, and the integration of facts into the existing understanding. The levels of dimension (iii) (cognitive complexity) reflect the increasing amount of information and the respective interconnections that the students' understanding is composed of. However, the operationalization of dimensions (ii) and (iii) have only had a comparatively small effect on item difficulties (Kauertz et al., 2010; Neumann et al., 2013). The identification of students' levels of understanding along these dimensions can hence be difficult. Thus, descriptions of progressing understanding strongly rely on increasingly more sophisticated content understanding (dimension i). For example,

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<sup>1</sup> 'Kompetenzentwicklungsmodelle' represent a comparable idea employed in the German research community, see Schecker and Parchmann, 2006 or Viering, Fischer, and Neumann, 2010.

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researchers have described energy understanding to progress from insights based on concrete experiences to abstract concepts (e.g., Trumper, 1998). The other dimensions can, however, be used as a framework to systematically vary item difficulties in assessments.

Specific (approaches to) learning progressions for the energy concept have mostly focused on contexts from physics education (e.g., Hermann-Abell and DeBoer, 2011; Lee and Liu, 2009; Liu & McKeough, 2005; Liu and Tang, 2004; Neumann et al., 2013; Jin and Anderson, 2012). The respective studies are reviewed as part of section 1.3.3 below.

*Summary of section 1.2:* The previous sections introduced the theoretical background for using core ideas like energy in biology and, more generally, science instruction: In order to develop robust scientific literacy, students need to organize and connect science contents that they learn in different school years and different science subjects (sections 1.2.1 and 1.2.2). To help students integrate knowledge from this wide variety of science contexts (section 1.2.3), core ideas like energy have been introduced into modern curricula (section 1.2.5). Empirically derived learning progressions of these core ideas hereby describe how students develop increasingly more sophisticated ways of thinking about the respective core idea (section 1.2.6). These learning progressions can be used to design curricula and learning standards in a way that is meaningful for students (section 1.2.4). While energy is typically associated with physics, it is also a highly relevant concept in biology instruction. If students are to use the energy concept to connect knowledge from these and other disciplinary contexts, energy instruction has to be coordinated across school science subjects. To support this process, researchers have to provide learning progressions for the energy concept that take into account energy learning opportunities from different disciplinary contexts.

To extend insights from previous research, this dissertation focuses specifically on how students' understanding of energy progresses in biological contexts. As a basis for deriving the overarching research questions for this dissertation, the following section 1.3 introduces relevant contents for energy teaching, reviews studies on students' alternative energy conceptions, and then focuses on studies that explore students' progressing energy understanding.

## 1.3 Literature Review: Research on Students' Energy Understanding

The literature review of this section relates to the dissertation project as a whole and its overarching research questions. More specific reviews in regard to each study's specific research questions are provided in chapters 2–5.

### 1.3.1 Relevant Contents for Energy Teaching and Learning

Previous articles have discussed relevant contents for the teaching and learning of the energy concept (e.g., Doménech et al., 2012). To promote knowledge integration (see above), recent energy learning expectations have focused on the description of increasingly more sophisticated ways of thinking about energy, thus exemplifying how energy understanding should develop from Kindergarten to high school. Table 1.2 provides central energy learning goals that were summarized by Nordine (2016, p. 21) with reference to the US *Next Generation Science Standards* (NGSS, 2013; NRC, 2012). The city of Hamburg/Germany, where the studies of this dissertation were conducted, provides learning standards that reflect a similarly increasing depth of students' energy understanding (see 'Attachment B—Online material for Chapter 3').

**Table 1.2.** Central learning expectations for energy as a disciplinary core idea and a crosscutting concept (NRC, 2012; NGSS, 2013). Summary from Nordine (2016).

Component ideas	Elementary school	Middle school	High school
<b>Energy as a disciplinary core idea</b>			
<b>Definitions</b>	<ul style="list-style-type: none"> <li>- Associate energy with motion, sound, light, heat, or electricity</li> </ul>	<ul style="list-style-type: none"> <li>- Formalize connections between energy forms (potential vs. kinetic) and observed phenomena</li> <li>- Recognize how energy forms depend on variables, e.g., kinetic energy on the mass of an object</li> <li>- Link matter and energy, e.g., recognize an increase in thermal energy as an increase in particle speed</li> </ul>	<ul style="list-style-type: none"> <li>- Use quantitative models that allow the tracking of energy through systems</li> <li>- Describe all energy forms as manifestations of the same energy</li> <li>- Connect energy across living and non-living entities</li> <li>- Connect energy analysis to atomic theory</li> <li>- Link macroscopic manifestations of energy to (sub)atomic particles and their interactions</li> </ul>

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Component ideas	Elementary school	Middle school	High school
<b>Energy transfer and conservation</b>	<ul style="list-style-type: none"> <li>- Explore a variety of phenomena with types of energy transfer (e.g., sound, heat)</li> <li>- Develop first stages of understanding that an increase of energy in one object is related to a decrease in another object</li> </ul>	<ul style="list-style-type: none"> <li>- Track magnitudes of energy transfers/transformations within and across systems</li> <li>- Extend knowledge about the dependencies of energy increase in one system to a decrease in a different system</li> <li>- Use evidence to realize that energy cannot appear or vanish</li> </ul>	<ul style="list-style-type: none"> <li>- Approach the quantitative energy conservation principle as a numerical quantity that limits changes in a system</li> <li>- Use energy conservation in quantitative calculations to determine limits of processes</li> </ul>
<b>Energy and forces</b>	<ul style="list-style-type: none"> <li>- Recognize that objects can push/pull each other, thus transferring energy</li> <li>- Realize that force can be applied without direct contact between objects</li> <li>- Connect energy transfer to the interaction of different objects</li> </ul>	<ul style="list-style-type: none"> <li>- Connect forces to the notion of potential energy</li> <li>- Connect potential energy of a system to the interaction of objects through electric, magnetic or gravitational forces</li> <li>- Realize that energy transfer between systems can occur over longer distances through different forces</li> <li>- Identify energy transfers through electromagnetic radiation</li> </ul>	<ul style="list-style-type: none"> <li>- Use the notion of fields to connect energy and forces</li> <li>- Recognize that propagating field oscillations can transfer energy across distances/systems</li> <li>- Use models to explain how fields store/transfer potential energy</li> </ul>
<b>Energy in chemical processes and everyday life</b>	<ul style="list-style-type: none"> <li>- Focus on energy input and output of living/non-living systems</li> <li>- Realize that systems emit energy to the environment in the form of heat</li> </ul>	<ul style="list-style-type: none"> <li>- Learn about processes by which energy is transformed in systems (e.g., photosynthesis)</li> <li>- Describe how stored energy can be built up by plants and released through combustion/digestion</li> <li>- Describe how organisms and artificial systems emit energy as heat</li> </ul>	<ul style="list-style-type: none"> <li>- Explore occurring processes of energy transformation in living /non-living systems in greater depth</li> <li>- Evaluate the efficiency of reactions and energy transformations</li> <li>- Compare the efficiency, availability, waste products, as well as benefits and drawbacks of different energy resources</li> </ul>

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Component ideas	Elementary school	Middle school	High school
<b>Energy as a crosscutting concept</b>			
<p><b>Application of five ‘big ideas’ across disciplinary contexts:</b></p> <p><b>(1)Energy forms/ manifestations,</b></p> <p><b>(2)Energy transformation,</b></p> <p><b>(3)Energy transfer,</b></p> <p><b>(4)Energy conservation,</b></p> <p><b>(5)Energy dissipation</b></p>	<p><i>Prepare big ideas 1, 2 and 3:</i></p> <ul style="list-style-type: none"> <li>- Focus on matter</li> <li>- Recognize different energy manifestations</li> <li>- Connect the observed manifestations to one underlying concept</li> <li>- Observe evidence for energy transfer (e.g., heating/acceleration)</li> <li>- Track energy in processes like collisions</li> </ul>	<p><i>Formalize big ideas 1, 2 and 3 - prepare 4 and 5:</i></p> <ul style="list-style-type: none"> <li>- Explicitly connect energy manifestations like light or movement to kinetic energy</li> <li>- Provide evidence for the decrease/increase of energy manifestations</li> <li>- Realize that increases in energy are connected to decreases in energy or energy transfers within a system</li> <li>- Describe that living and designed systems will cease to work without constant energy input</li> <li>- Realize that processes stop because energy is transferred from the system to the environment</li> </ul>	<p><i>Apply big ideas 1-5:</i></p> <ul style="list-style-type: none"> <li>- Recognize energy forms across various phenomena and calculate their values</li> <li>- Track energy changes quantitatively</li> <li>- Model conservation quantitatively</li> <li>- Quantitatively test idealized model assumptions versus real-world experiments</li> <li>- Assign difference between these two settings to energy dissipation and calculate the amount of dissipated energy</li> <li>- Use energy consistently as an analytical model to explain various phenomena from different disciplinary contexts</li> </ul>

The overview in Table 1.2 shows that—both within and across disciplines—students are expected to learn about four central aspects of the energy concept. These aspects were initially highlighted by Duit (1984, 1986) and later confirmed by several other authors (Doménech et al., 2012; Lancor, 2015; Liu and McKeough, 2005; Jin and Anderson, 2012; Neumann et al., 2013; Wang, Wang, and Wei, 2014):

- (1) While energy is a unified, abstract quantity, it can be observed or measured in different forms of manifestations. These are frequently referred to as ‘*energy forms*’. When stored as part of, e.g., chemically stable compounds, students speak of different ‘*energy sources*’ that can be used to cause changes within a system.
- (2) Manifestations (forms) of energy can be *transferred* within and across systems. Likewise, different forms of energy can, to a certain degree, be *transformed* into each other. While Nordine (2016, see Table 1.2) considers transfer and transformation as separate aspects, this dissertation presents them together, as transfer and transformation are often analyzed in combination (e.g., in energy flow charts).

- (3) In energy transformations (e.g., in a combustion engine), energy is not only transformed into the target energy form (here: kinetic energy), but also into less useful energy forms (here: thermal energy). This share of the initially supplied energy is *degraded*. The degraded energy spreads within the system or across its boundaries through the transfer of kinetic energy at particle level. This energy is distributed more evenly—it is *dissipated*. The entropy of the system increases through this process (see second law of thermodynamics).
- (4) Within the boundaries of a system, energy may be transformed or transferred through occurring processes, but the system's total energy is the same before and after the processes—the energy is *conserved* (see first law of thermodynamics).

In addition to these central aspects of understanding the energy concept, Domenéch et al. (2007) highlight that a deeper understanding of energy is also connected to further aspects of core scientific knowledge. These include, for example, the nature of science (see also Constantinou and Papadouris, 2012; Papdouris and Constantinou, 2011), the history of the energy concept, or the concept's potential to unify separate science approaches (see also Rizaki and Kokkotas, 2013).

### 1.3.2 Research on Students' Alternative Ideas about Energy

Science contents in everyday lives (e.g., nutrient contents, power ratings) and popular culture (e.g., action scenes in movies like Star Wars, Harry Potter etc.) feature countless references to energy. These often depict energy as an entity that drives process or as a physical, usually powerful substance (compare Lancor, 2014, 2015). In addition, numerous alternative connotations of energy denote strength, vitality or the power of a person. Students have been found to use these everyday experiences as a basis for understanding energy in scientific contexts (e.g., Boyes and Stanisstreet, 1990; Duit, 1984; Solomon, 1985). Besides the distinction between everyday/scientific connotations of the term energy, students also need to learn to distinguish between energy and related concepts (Hirça, Calikund, and Akdeniz, 2008). For example, prior studies found that students typically conflate conceptions of energy with force (Kattmann, 2015, p. 93; Kruger, 1990; Megalakaki and Thibaut, 2015; Nordine, 2016, p. 26; Papadouris, Constantinou, and Kryatsi, 2008; Trumper, 1997), work, power (Kurnaz & Sağlam-Arslan, 2011) or matter (Kattmann, 2015, p. 93; Lin and Hu, 2003—see above).

Watts (1983) presented one of the first analyses of students' energy understanding. The author confronted students with simple representations of energy in



different processes (e.g., chemical reactions, eating, pushing a box up a hill) and identified seven dominant frameworks of students' energy understanding (for later applications and refinements of the frameworks, see Boyes and Statistreet, 1990; Forde, 2003; Gilbert and Pope, 1986; Trumper, 1997, 1990). Among these frameworks, anthropocentric views of energy (e.g., 'Energy is connected to human actions only. '), the view of energy as an ingredient (e.g., 'Food provides energy only when it's eaten'), and the view of energy as a product (e.g., 'Chemical reactants release some of their energy and produce heat') are relevant conceptions that describe students' understanding of energy in biological contexts. Watts' (1983) findings furthermore indicate that students sometimes employ several alternative energy conceptions at the same time and that they maintain some of these conceptions until secondary level (e.g., the anthropocentric framework).

Later studies provided more specific analyses that identify alternative student conceptions about energy in different disciplinary settings. Boo (1998) analyzed high school students' understanding of energy in chemical reactions. The author found, for example, that students typically conceptualize chemical bonds as physical entities or that bonds require energy to be formed and release energy when they are broken. Students' understanding of energy at this micro-level perspective forms a basis to understanding energy at macro-level. The latter perspective on energy is prominently employed in biology contexts (Dreyfuß, Redish, and Watkins, 2012; Liu et al., 2002; Jin and Anderson, 2012). However, students confuse micro and macro-level properties of processes (Boo, 1998; Liu et al., 2002) and even advanced students rarely combine perspectives from these different levels (Dreyfuß et al., 2012; Jin and Anderson, 2012). In order to help students address increasingly interdisciplinary challenges (NRC, 2012; Sakschewski, Eggert, Schneider, and Bögeholz, 2014; Viglietta, 1990), energy instruction should hence meaningfully link learning opportunities with different energy perspectives.

Burger (2001) provided one of the few detailed analyses of primary and secondary students' energy conceptions in biological processes (e.g., cellular respiration, bacterial decomposition, thermal regulation, nutrition and food webs). By summarizing students' answers to open-ended questions, the author found the following underlying student conceptions to prevail across grade levels:

- (1) Living beings take up energy through heat.
- (2) The sun provides living beings with energy in the form of heat.
- (3) Energy transformations produce heat.
- (4) Energy transformations can be influenced through heat, a universal energy 'currency'. The source of heat energy is the sun.

- (5) Energy is like a substance. Components of nutrition (e.g., vitamins) are directly considered to be energy. Similarly, energy is also conceptualized as a particle-like, additional component of matter. These particles are sometimes considered flammable.
- (6) Energy can be exchanged both between life forms and their environment.
- (7) Energy is produced in life forms. These consume the energy for life processes. To survive, they have to take up energy.
- (8) Biomass stores energy in specific places, for example, in cells. Movable parts of a body are associated with energy more often than non-movable parts.
- (9) Similar to matter, energy is conceptualized to cycle. Life forms take up energy and give it off when they die. Plants take up energy from the soil and this energy passes along the food chain to get back into the ground through decomposition.

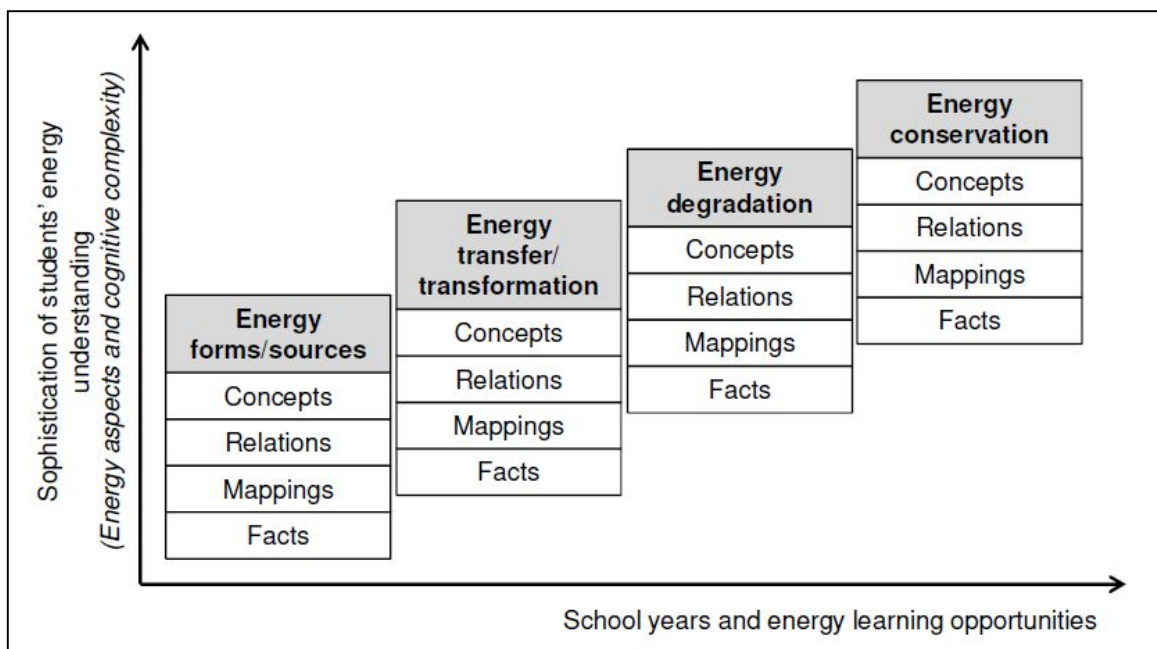
Burger's (2001) detailed results provide excellent information for designing specific teaching materials and, for example, assessment item distracters/attractors. Similar studies (e.g., Boyes and Stanisstreet, 1990, 1991) described student ideas in relation to energy sources employed by plants and animals (e.g., the idea that plants get energy also from vitamins in the soil). However, these studies allow only few insights into students' progressing understanding of the four central energy aspects (section 1.3.1).

A recent approach to describing students' energy understanding highlights that students often have to use metaphors to describe the abstract notion of energy: Lancor (2014, 2015) found that the majority of undergraduate college students employed substance-based metaphors for energy. Different metaphors were thereby used for specific contexts (e.g., the metaphor 'energy as a flowing substance' in the contexts ecosystems and electrical circuits). However, the full range of metaphors was also observed in different disciplinary contexts, thus suggesting that variances in energy understanding between disciplinary contexts were rather small. The findings by Lancor can be connected to an analysis by Scherr, Close, Kagan, Vokos (2012), who found that energy representations in teaching materials often support a substance-based conception of energy. Despite the technically incorrect nature of this conception, the authors stress that the substance ontology can also be helpful, as it supports, for example, the ideas of localization of energy, energy transfer/transformation, and energy conservation.

## 1.3.3 Research on Progressing Energy Understanding

The findings presented in the previous section highlight that energy instruction has to build on students' alternative energy conceptions and connect these to the scientific understanding of energy (Nordine, 2016, p. 18). To facilitate this process, the teaching of energy can be aligned with empirically validated learning progressions that describe the sequence in which students typically learn about energy (Gotwals and Alonzo, 2012; Krajcik et al., 2012—see also section 1.2.6). Accordingly, this section concludes research that focus on the analysis of students' progressing energy understanding.

**A framework for the analysis of progressing energy understanding.** To analyze the sequence of progressing energy understanding, Neumann et al. (2013) described a model (see Figure 1.1) that combines the four energy aspects (see section 1.3.1) with four levels of cognitive complexity (see section 1.2.6).



**Figure 1.1.** Model of students' progressing energy understanding. The model suggests a progression along four content aspects of the energy concept (dark grey) and four levels of cognitive complexity (light). Adapted from Neumann et al. (2013).

The studies in this dissertation employ the model above as an underlying framework for the development of the enclosed instruments (see studies 1 and 2). However, Neumann et al. (2013) found students' understanding to progress along the four energy aspects, but not clearly along the four levels of cognitive complexity (see also Kauertz et al., 2010)<sup>2</sup>. Thus, the dimension of cognitive complexity serves primarily as a means to systematically

<sup>2</sup> Later results (unpublished—please refer to Knut Neumann/IPN Kiel) suggest that cognitive complexity can in fact depict a dimension of more sophisticated energy understanding if specific operationalizations of this dimension are met.

vary items for each energy aspect and thus receive a broad range of item difficulties. Importantly, the rationale for transferring this model from physics to biology (studies 1 and 4) and cross-disciplinary contexts (studies 2 and 3) was that the four energy aspects have been identified as essential contents for energy teaching in different disciplines (Jin and Anderson, 2012; Lancor, 2015; Liu and McKeough, 2005; Liu and Park, 2016; Neumann et al., 2013; Nordine et al., 2016; Wang, Wang, and Wei, 2014).

So far, few studies have provided an explicit distinction between the assessment of energy understanding (i) as a disciplinary core idea and (ii) as a crosscutting concept (compare Table 1.2 above). Following recent suggestions (Nordine, 2016, p. 21), the studies in this dissertation assess and compare students' energy understanding across disciplinary contexts by focusing on the central energy aspects described above. However, it should be noted that the assessment of a strictly 'crosscutting' energy concept may require more specific assessment approaches. For example, respective assessments may be structured around specifically interdisciplinary contexts (e.g., energy resources, Neumann et al., 2016, p.162) or they may focus strongly on a cumulatively growing knowledge basis across grade bands. In the latter case, constructed-response or performance task may be useful to register in how far students realize the respective performance expectations (Duschl, 2012).

**Early energy learning.** Earlier studies on energy instruction stressed that energy as an abstract concept should not be taught before middle school (e.g., Burger, 2001; Warren, 1982, 1985). Several recent works, however, conclude that energy teaching should build on early, often implicit, energy learning opportunities at primary or even kindergarten level (e.g., Lacy, Tobin, Wiser, and Crissman, 2014; Lin and Hu, 2003; Nordine, 2016, p. 18; van Hook and Huziak-Clark, 2008). The purpose of early energy instruction is hereby to connect teaching contents to students' intuitive or alternative ideas about energy (Constantinou and Papdouris, 2012; Kattmann, 2015, p. 96; Lancor, 2014; Liu and Tang, 2004; Nordine, 2016, p. 35; Novak and Musonda, 1991; Novak, 2005; NRC, 2012; van Hook and Huziak-Clark, 2008). In contrast to prior arguments against early energy teaching, research showed that primary students are able to conceptualize first stages of an understanding of energy conservation and entropy (Shultz and Coddington, 1981). Additionally, early energy instruction can have long-lasting positive effects on students' understanding until high school (Novak, 2005).

On the basis of the energy aspects described above, Lacy et al. (2014) presented a learning progressing for energy in the elementary grades 3-6, showing that basic ideas of the energy concept can be meaningfully taught to young learners. To achieve this, the authors started with descriptions of simple appliances (e.g., a battery-run propeller) and

only later progressed to more complex contexts (e.g., notions of gravitational energy or energy in foods/fuels). Across the teaching units, the authors highlighted the value of a set of recurring questions (e.g., 'Where does the energy come from/go?'). These were employed to serve students as a stepping stone from which to later build an understanding of energy degradation/dissipation and energy conservation.

**Progressing energy understanding at secondary level.** Driver, Squires, Rushworth, and Wood-Robinson (1994) used a review of previous studies to suggest one of the first sequences of progression energy understanding. The authors assumed students to commence with an understanding of energy in psychological/physiological states (e.g., 'I have a lot of energy today!') and then associate energy first with animate and then inanimate objects. The authors suggested that students would only later progress to an understanding of stored energy and, lastly, energy degradation and conservation.

Several studies (Hermann-Abell and DeBoer, 2011; Lee and Liu, 2009; Liu and McKeough, 2005; Liu and Ruiz, 2008; Liu and Tang, 2004; Neumann et al., 2013) found that—across different educational systems—middle and high school students' energy understanding progresses along a remarkably similar learning sequence that follows the energy aspects described above. As a precursory step to understanding the mentioned energy aspects, Liu and McKeough (2005) described young learners' energy understanding to represent an activity/work-conceptualization, in which the students connect energy with food/fuel-run activities of animate/inanimate objects and may begin to define energy more broadly as the ability to conduct work. Afterwards, students commence with an understanding of different energy forms and sources and then approach an understanding of energy transfer/transformation. At the end of middle school, only the most capable students' understanding encompasses energy degradation/dissipation and conservation (see Figure 1.1 above; Neumann et al., 2013). These findings on progressing energy understanding suggest that regular classroom practice does not sufficiently enable students to develop a fully functional understanding of energy until high school (Liu and McKeough, 2005; Liu and Ruiz, 2008). Despite these convergent results on students' understanding of the four energy aspects, it should be noted that students' performance on energy tests is not primarily influenced by the items' background respective these aspects. Instead, Liu and Ruiz (2008) found that the items' cognitive demand, their context (everyday vs. non-everyday) and the students' age were more prominent predictors of students' test scores.

Jin and Anderson (2012) suggested that deriving an interdisciplinary energy learning progression may be too broad to account for requirements in specific disciplinary

contexts. Thus, the authors suggested a more specific learning progression for energy understanding in carbon transforming processes. This progression was structured around four hierarchical levels of understanding: The lowest level (i) typically characterized elementary students' understanding. These knew the term energy, regarded energy as a force-dynamic property of agents (e.g., humans), and assigned constraints to processes on the basis of an actor's properties, but not on the basis of energy. Progression level (ii) was most prominently employed at middle school. Here, students saw energy as a necessity for processes and confounded energy and matter, thus often considering energy to cycle along with nutrients. The authors characterized the third level (iii) as one in which students discovered foods/fuels as energy resources and start to perceive energy as an enduring quantity that can be distinguished from matter. The highest progression level (iv) was only achieved by few high school students. Students at this level began to consider the role of energy dissipation, tracked energy and matter separately, regarded energy at macro/micro levels, and began to use energy as constraint to occurring processes.

**Energy and knowledge integration.** Studies on progressing energy understanding have recently focused on knowledge integration (and differentiation) to account for the role of the energy concept in connecting and structuring students' science knowledge (see section 1.3.3). Lee and Liu's (2009) findings suggest that students' knowledge integration of energy understanding increases throughout middle school, while the level of knowledge integration remains generally low. Furthermore, the findings indicate that the students' knowledge integration differs substantially with the specific science class that a student receives energy instruction in (e.g., participation in life science versus physics classes). In order to use the energy concept meaningfully, students need to integrate their understanding of the four energy aspects (Nordine, 2016, p. 21). This requirement is reflected in findings by Neumann and Nagy (2013), which suggest that students, as they learn more about energy throughout middle school, use a more and more interconnected understanding of the four energy aspects.

**Cross-disciplinary energy learning.** Students are required to employ the energy concept as an analytical tool across disciplinary boundaries (e.g., NRC, 2012). Hence, it is relevant to determine in how far energy instruction succeeds in helping students to connect and transfer energy knowledge across different disciplinary contexts (e.g., Eisenkraft et al., 2014; Hirça et al., 2008; Lancor, 2015; Nordine, 2016, p. 37). However, few studies have yet systematically assessed cross-disciplinary energy learning (cf. Lancor, 2014, 2015; Liu et al., 2015; Park and Liu, 2016).

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The available research basis suggests that even advanced students are challenged by transferring energy knowledge across disciplinary boundaries or levels of analysis (e.g., Chabalengula et al., 2011; Dreyfuß et al., 2012—see also Barnett and Ceci, 2002). Likewise, Arzi and White (2007) found that even science teachers with extensive professional experience find it difficult to integrate energy teaching across disciplinary contexts. Furthermore, different disciplines employ varying approaches to the energy concept, for example, in terms of terminology or foci on specific aspects of the energy concept. Thus, it has been commonly assumed that students likely miss the fact that the same energy principles apply across disciplinary contexts (see also Barak, Gorodetsky, and Chipman, 1997). Eisenkraft et al. (2014) describe the connected challenges in energy teaching:

*That is, students often do not connect the energy that they learn about in physics class with the energy that they learn about in biology, chemistry, or geoscience. [...] teachers must choose how to present energy in their discipline-centered classrooms such that the analysis does not unduly confuse students but that is still true to the nature of energy. [...] teachers are now charged with not only teaching about energy as a disciplinary idea but also teaching explicitly about energy as an analytical framework that cuts across disciplines.* (Eisenkraft et al., 2014, p. 2)

In contrast to this prevalent assumption, recent studies have found that students' energy understanding in different disciplinary contexts is substantially interrelated. For example, Lancor's (2014, 2015) results suggest that students employ similar metaphors for energy across disciplinary contexts. The author concluded that these metaphors are strongly connected to everyday connotations of energy and hence transcend disciplinary boundaries. Park and Liu (2016) provided one of the first approaches to assessing energy understanding across disciplinary boundaries, i.e. in physics, chemistry, biology, and environmental science contexts. Even though students' performance on items for different disciplinary contexts was strongly related ( $r_{(latent)} = 0.77-0.91$ ), their understanding of the four energy aspects differed with disciplinary contexts (Park, 2013, p. 88): For example, items that covered energy forms/sources in biological contexts were comparatively easy for students, while energy degradation and conservation items were similarly difficult across the disciplinary contexts.

Lastly, Fortus et al. (2015) developed a curriculum with a strong focus on inter-unit coherence (see also section 1.2.4). The teaching units encompassed energy contexts from different disciplines, which were presented in a highly interconnected manner so that one unit informed or prepared energy learning in a following unit. The findings show that coherent energy teaching approaches are able to foster knowledge integration in students' energy understanding both across disciplinary contexts and across grade

levels. Thus, the findings underline that the promotion of a cross-disciplinary energy understanding is feasible through adequate instructional formats.

*Summary of section 1.3:* Students have been found to experience difficulties in transferring energy understanding across disciplinary context (e.g., Barak et al., 1997; Chabalengula et al., 2011; Eisenkraft et al., 2014). Likewise, it has been assumed that students may employ different ways of thinking about energy in different disciplinary contexts. It has hereby been suggested that it is a key element of efficient energy instruction to help students integrate their understanding of central energy aspects across disciplinary boundaries (e.g., Liu and Tang, 2004; Nordine, 2016). While the relevance of cross-disciplinary energy learning has been underlined, the available research basis on students' energy understanding has to a large part focused on physics contexts (e.g., Liu and McKeough, 2005; Neumann et al., 2013). In contrast, very few studies have described how students' energy understanding progresses in biological contexts (cf. Burger, 2001; Jin and Anderson, 2012) or how students understand energy across disciplinary boundaries (cf. Park and Liu, 2016).

### 1.4 Research Questions and Overview of Conducted Studies

In order to provide a research basis for connecting energy teaching more meaningfully (i) across different biology topics and (ii) across different disciplines, the following overarching research questions have been formulated to guide the studies in this dissertation. These more global questions have been addressed through the specific research questions of the individual studies (Chapters 2-5).

**RQ1:** How does students' understanding of energy progress in biologically contexts with regard to central aspects of the energy concept (i.e., forms/sources, transfer/transformation, degradation/dissipation, and energy conservation)?

**RQ2:** How is students' energy understanding in biological contexts connected to their energy understanding in other disciplinary contexts?

The following paragraphs introduce the studies (research articles) presented in Chapters 2-5, as well as a connected teaching practice article (Chapter 6). The purpose of these sections is to highlight the rationale for each study and to identify connections and differences between them. These introductions are complemented by Table 1.3 (see



below), which provides an overview of the studies' individual research questions, their designs, samples, and the included variables.

### **Study 1 (Chapter 2): Students' Energy Concepts at the Transition between Primary and Secondary School**

This quantitative, explorative study addresses the yet widely disregarded field of energy learning at primary level. The study resulted from two findings: First, research has shown that students' energy understanding benefits sustainably from early energy instruction (Novak, 2005). Second, observations indicated that students encounter multiple, mostly implicit energy learning opportunities before the students receive formal energy instruction (Liu and Tang, 2004; Nordine, 2016, p. 18). These learning opportunities are often situated in biological contexts. Thus, study 1 assessed to what extent students learn about energy in biological contexts before the onset of later, explicit energy instruction. This study presents the development of a MC-item assessment instrument for primary students' energy understanding in biological contexts. The instrument is applied in a cross-sectional study (grades 3-6) to provide insights to primary students' progressing energy understanding.

### **Study 2 (Chapter 3): How Do Students Understand Energy in Biology, Chemistry, and Physics? Development and Validation of an Assessment Instrument**

Study 2 continued and widened the analyses conducted in study 1, as data was collected from secondary students, and as the study covered a cross-disciplinary perspective by assessing energy understanding in biology, chemistry, and physics contexts. This study was conducted because previous research had provided few insights into the connection of students' energy understanding across disciplinary boundaries. As no respective test instrument was yet available, this particular study focused on the development and validation of a MC-test instrument that assesses energy understanding in biology, chemistry, and physics contexts. The newly developed instrument was deployed in an explorative, cross-sectional study with  $N = 752$  students from grades 6, 8, and 10. This study provides first insights and detailed examples for students' progressing energy understanding progresses in the three disciplinary contexts.

### **Study 3 (Chapter 4): Students' Energy Understanding across Biology, Chemistry, and Physics Contexts**

Study 3 is an in-detail analysis of the data set generated by study 2. Here, the goal was to assess how students' energy understanding is related across disciplinary boundaries and, more specifically, in how far this relation undergoes changes as students progress

through middle school. In this regard, confirmatory factor analysis was employed to compare three idealized progression scenarios that could characterize cross-disciplinary energy understanding: (i) a parallel progression, in which students' understanding progresses in similar ways in biology, chemistry, and physics contexts, (ii) a process of knowledge differentiation, in which a general energy understanding is differentiated into discipline-specific sets of energy understanding, and (iii) a process of knowledge integration, in which discipline-specific sets of energy understanding are merged into a cross-disciplinary understanding.

### **Study 4 (Chapter 5): Characteristics of Students' Energy Understanding in Biological Contexts**

As an extension to the quantitative studies 1 and 2, study 4 uses a qualitative approach. In this cross-sectional study ( $N = 30$  students from grade 5, 7, 9 and 11), interviews were analyzed by using qualitative content analysis. The study was conducted as part of a mixed method approach, as the design of the study allows a comparison between students' understanding as assessed by the energy questionnaire (studies 2 and 3) and the student conceptions expressed in the interviews (study 4). The rationale was hereby to deepen and verify the earlier, quantitative findings on progressing energy understanding. Using qualitative content analysis (Mayring, 2000), the interviews were used to develop a detailed category system of students' conceptions. The goal was hereby to identify central conceptions that characterize students' understanding of the four energy aspects in typical biological contexts (i.e., human growth, plant growth, human activity).

### **Teaching practice article (Chapter 6): *Winterschlaf: Energiesparen als Überlebensstrategie* [Hibernation: Energy Saving as a Survival Strategy]**

The teaching practice article in Chapter 6 builds on findings from studies 1-4 and provides a teaching unit in which the four energy aspects are used to guide instruction and help students explain biological phenomena. The unit focuses on changes in energy requirements during hibernation, a classical biology topic at lower middle school. The students learn about the extreme physiological adaptations of the edible dormouse (*Glis glis*) during hibernation and they analyze related changes in the animals' energy uptake, energy storage, and in the release of energy. The enclosed working materials for students encompass, for example, a multi-group student experiment to help them understand changing energy requirements during winter. In other materials, students combine the analysis of energy and matter, reflect everyday ideas about energy, and explore diagrams to describe major physiological changes during hibernation.

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**Table 1.3.** Overview of the conducted studies and the additional teaching practice article. Grey font (study 4) denotes a research question that was part of the rationale for designing the study, but that was not addressed in this dissertation as the respective analyses are still pending.

<b>Study 1 (Chapter 2)</b> (Primary level; biology contexts)	<b>Title</b> Students' Energy Concepts at the Transition Between Primary and Secondary School
	<b>Publication</b> Opitz, S., Harms, U., Neumann, K., Kowalzik, K., Frank, A. (2015). Students' Energy Concepts at the Transition between Primary and Secondary School. <i>Research in Science Education</i> , 49(5), 691-715. doi 10.1007/s11165-014-9444-8
	<b>Research questions</b> (1) Do primary students' scores on an energy test for biological contexts increase significantly from grade 3–6, i.e., prior to the concept's formal instruction in physics? (2) Can specific contents and time points be identified at which primary students' energy understanding progresses towards a more scientific understanding of energy?
	<b>Design and sample</b> - Quantitative, explorative questionnaire study - Cross-sectional study at the end of grades 3, 4, 5, and 6 ( $N = 540$ )
	<b>Variables</b> <i>Dependent:</i> Energy understanding in biological contexts <i>Independent:</i> Grade level <i>Control:</i> Fluid intelligence, reading speed and accuracy, motivation/interest, person data (e.g., age, SES)
<b>Study 2 (Chapter 3)</b> (Secondary level, biology, chemistry, and physics contexts)	<b>Title</b> How Do Students Understand Energy in Biology, Chemistry, and Physics? Development and validation of an assessment instrument
	<b>Manuscript</b> Opitz, S., Neumann, K., Bernholt, S. (Resubmitted after major revisions, 02/2016). How Do Students Understand Energy in Biology, Chemistry, and Physics? Development and validation of an assessment instrument. <i>International Journal of Science Education</i> .
	<b>Research questions</b> (1) What progression trends of energy understanding can be identified in biology, chemistry, and physics contexts? (2) How is students' energy understanding related across these contexts?
	<b>Design and sample</b> - Quantitative, explorative questionnaire study - Cross-sectional design with assessment at the end of grades 6, 8, and 10 ( $N = 752$ )
	<b>Variables</b> <i>Dependent:</i> Energy understanding in biology, chemistry, and physics contexts <i>Independent:</i> Grade level <i>Control:</i> Crystallized intelligence, person data (e.g., age, gender)

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<b>Study 3 (Chapter 4)</b> Secondary level; biology, chemistry, and physics contexts	<b>Title</b> Students' Progressing Energy Understanding across Biology, Chemistry, and Physics Contexts
	<b>Manuscript</b> Opitz, S., Harms, U., Neumann, K, Bernholt, S. (submitted 01/2016). Students' progressing energy understanding across biology, chemistry, and physics contexts. <i>Research in Science Education</i>
	<b>Research question</b> How is students' energy understanding related across contexts from biology, chemistry, and physics as the students mature and learn more about energy throughout middle school (grades 6, 8, and 10)?
	<b>Design and sample</b> See study 2
	<b>Variables</b> See study 2
<b>Study 4 (Chapter 5)</b> (Primary and secondary level; biology contexts)	<b>Title</b> Characteristics of Students' Energy Understanding in Biological Contexts
	<b>Manuscript</b> Opitz, S., Blankenstein, A., Harms, U. (in preparation). Characteristics of Students' Progressing Energy Understanding in Biological Contexts. <i>Journal of Biological Education</i> .
	<b>Research questions</b> (1) What conceptions do students' employ in biological contexts respective four central aspects of the energy concept? (2) How does students' understanding of these aspects differ between grade levels? (3) Perspective: How does the description of students' energy understanding differ between the MC-questionnaires (study 2) and the interview data (study 4)?
	<b>Design and sample</b> - Explorative, cross-sectional study at the beginning of grade 5, 7, 9, and 11 - Qualitative interview analysis (Mayring, 2000) - Interviews with questions based on representative items from the earlier quantitative studies 1 and 2 - Grades 7, 9, and 11 students had earlier participated in study 2 (questionnaire study), thus allowing a comparison of the two research approaches.
	<b>Variables</b> Dependent: Energy understanding in biological contexts Independent: Grade level Control: /
<b>Teaching practice article</b> (Chapter 6)	<b>Title</b> Winterschlaf als Überlebensstrategie
	<b>Publication</b> Opitz, S., & Opitz, M.-T. (2016). Winterschlaf: Energiesparen als Überlebensstrategie [ <i>Hibernation: Energy Saving as a Survival Strategy</i> ]. <i>Unterricht Biologie</i> , 40(411), 18-23.
	Please see summary above

### 1.5 Associated Bachelor and Master Thesis Projects

The studies of this dissertation have been supported by one bachelor and three master thesis projects. The purpose of the four qualification works was to assess validity evidence for the conducted studies. Table 1.4 provides an overview of the four projects, including the addressed validity aspects, as well as the study/chapter that the respective qualification project is referenced in. The validity aspects refer to Messick's (1995) unified construct validity. The validity aspects not addressed by these qualification works were assessed as part of studies 1 and 2 (please see the respective discussion sections).

**Table 1.4.** Overview of associated bachelor and master thesis projects.

<b>Author and qualification degree</b>	<b>Submission</b>	<b>Project title</b>	<b>Validity aspect</b>	<b>Reference in:</b>
<b>Kowalzik, Kristin.</b> <i>Master thesis</i>	09/ 2012	Der Energiebegriff im Biologieunterricht – Sachanalyse und Analyse von Lehrplänen und Lehrwerken <i>[The Energy Concept in Biology Classrooms—Content Analysis and Analysis of Curricula and Textbooks]</i>	Content aspect	Study 1 (Chapter 2)
<b>Frank, Arne</b> <i>Bachelor thesis</i>	10/ 2012	Die Anwendung des Energiekonzepts im Biologieunterricht der Sekundarstufe 1 (Gymnasium) in Schleswig-Holstein – Eine Lehrerbefragung <i>[The Application of the Energy Concept in Biology Classrooms at Lower Secondary Level (Gymnasium) in Schleswig-Holstein)—A Teacher Survey]</i>	Content aspect	Study 1 (Chapter 2)
<b>Wernecke, Ulrike</b> <i>Master thesis</i>	08/ 2013	Erfassung des Schülerverständnisses von Energie – Validierung eines Quantitativen Erhebungsinstruments durch die Methode des Lauten Denkens <i>[Assessing Students' Energy Understanding—Validation of a Quantitative Assessment Instrument via Think Aloud Protocols]</i>	Substantive aspect	Studies 2 and 3 (Chapters 3 and 4)
<b>Blankenstein, Andreas</b> <i>Master thesis</i>	08/ 2014	Entwicklung eines Kategoriensystems zur Analyse von Schülervorstellungen von Energie im biologischen Kontext <i>[Development of a Category System for the Analysis of Students' Energy Understanding in Biological Contexts]</i>	Structural aspect and aspect of generalizability	Study 4 (Chapter 5)

### 1.6 References

Please see references at the end of the dissertation (Chapter 7).



## CHAPTER 2

# Students' Energy Concepts at the Transition between Primary and Secondary School

(Study 1)

### Abstract

Energy is considered both a core idea and a crosscutting concept in science education. A thorough understanding of the energy concept is thought to help students learn about other (related) concepts within and across science subjects, thereby fostering scientific literacy. This study investigates students' progression in understanding the energy concept in biological contexts at the transition from primary to lower secondary school by employing a quantitative, cross-sectional study in grades 3–6 ( $N = 540$ ) using complex multiple-choice items. Based on a model developed in a previous study, energy concepts were assessed along four aspects of energy: (1) forms and sources of energy, (2) transfer and transformation, (3) degradation and dissipation, and (4) energy conservation. Two parallel test forms (A and B) indicated energy concept scores to increase significantly by a factor of 2.3 (A)/1.7 (B) from grade 3 to grade 6. Students were observed to progress in their understanding of all four aspects of the concept and scored highest on items for energy forms. The lowest scores and the smallest gain across grades were found for energy conservation. Based on our results, we argue that despite numerous learning opportunities, students lack a more integrated understanding of energy at this stage, underlining the requirement of a more explicit approach to teaching energy to young learners. Likewise, more interdisciplinary links for energy learning between relevant contexts in each science discipline may enable older students to more efficiently use energy as a tool and crosscutting concept with which to analyze complex content.

### Keywords

Energy, Biology, Core idea, Crosscutting concept, Learning progression, Interdisciplinary learning

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### 2.1 Introduction

International large-scale assessments such as the Trends in Mathematics and Science Study (TIMSS) found that students are challenged by meaningful learning, as they form few connections between single facts of knowledge, thus hampering the development of an interconnected knowledge basis (Duschl et al. 2007, p.213; Walter et al. 2006, p.91). However, meaningful learning (i.e., learning that systematically builds on students' prior knowledge) has been identified as an important means to improve students' scientific literacy (Ausubel 1963; Doménech et al. 2007). Several official documents (NRC National Research Council and Committee on Conceptual Framework for the New K-12 Science Education Standards 2012) and studies (Krajcik et al. 2012) have considered core ideas and crosscutting concepts to promote meaningful learning. Even though empirical evidence for a beneficial effect of core ideas on students' knowledge integration learning has not yet been published, Bransford et al. (1999) conducted a literature review and concluded that expert knowledge is closely constructed around core ideas. It may therefore be assumed that core ideas can support the integration of new knowledge into existing understanding and that students also can benefit from using core ideas to structure learning. While core ideas aim at the organization and revision of contents within one subject, crosscutting concepts are of general scientific importance and therefore enable students to organize learning across disciplinary boundaries more coherently (NRC National Research Council and Committee on Conceptual Framework for the New K-12 Science Education Standards 2012). Energy is a core idea in all science disciplines, but is also considered a crosscutting concept (Constantinou and Papadouris 2012; Liu and McKeough 2005; Nordine et al. 2010). As such, it is thought to enable a deeper understanding through a unified analysis of various contexts (Krajcik et al. 2012; Solbes et al. 2009). In order to be able to develop meaningful learning materials and curricular standards with respect to core ideas like energy, research on students' progression in learning these concepts is required.

Most studies have so far focused on students' understanding of energy in physics contexts. In order to be able to integrate energy more effectively with respect to the concept's interdisciplinary character, research is also required for the evolvment of students' understanding of energy in the other science disciplines. This study originated from the observation that students are likely to encounter energy implicitly (informally) in biological contexts prior to formal teaching of energy in lower secondary physics, thus potentially creating dependence of energy learning across subjects. By implicit (informal) learning opportunities, we refer to the term energy being used with reference to its



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scientific meaning, while the concepts' meaning is not explained or introduced. At primary level, examples for such learning opportunities on energy include contexts like nutrition, health, growth, movement, plant growth, and energy sources. In addition to the available research on energy learning in biology (e.g., Jin and Anderson 2012), we focus specifically on young learners' (grade 3–6) understanding of energy and how the students' later understanding of central energy aspects (e.g., in physics) may be influenced by the learning about energy in the mentioned relevant contexts from early science and biology classes.

### 2.2 Theoretical Background

Apart from its scientific understanding, energy is associated with various everyday connotations and gets extensive media attention due to socio-economically or environmentally relevant topics such as climate change, (renewable) energy sources, health issues (ozone hole, malnutrition, nuclear energy), or globalization. As a result, students' understanding of energy is influenced by both everyday and scientific contexts (Boyes and Stanisstreet 1990; Jin and Anderson 2012; Solomon 1983).

The concept's overarching importance in science lead to a strengthened position of the energy concept in science standards and curricula of different countries in the last years (e.g., Australia: ACARA 2013; Germany: KMK 2005a, 2005b Switzerland: EDK 2011; UK: DfE 2013; USA: NRC 2012). As an example, the US *Next Generation Science Standards* (NGSS Lead States [NGSS], 2013) introduces energy as both a core idea in all science subjects and as a crosscutting concept, thereby underlining its unique role for science education: As a core idea, energy is introduced as a continuous basis for learning and revision of different content and to stimulate the coherence and depth of learning between the various topics within each discipline (NRC 2012, p.2, 11). Through its recurring position in science and engineering, energy as a crosscutting concept is to help students organize knowledge and core ideas from different subjects into a more coherent and scientific understanding of the world (NRC 2012, p.2, 83). Table 2.1 summarizes the NGSS' learning expectations for different disciplinary contexts for students from kindergarten to high school.

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**Table 2.1.** Successively more complex content of understanding energy as proposed by the Next Generation Science Standards (NGSS Lead States 2013)

Discipline	Content area	Grade	Contents
Life science	Organization for matter and energy flow in organisms	3–5	“Food provides animals with the materials and energy they need for body repair, growth, warmth, and motion. Plants [...] obtain energy from sunlight.”
		6–8	“Plants use the energy from light to make sugars through photosynthesis. Within individual organisms, food is broken down through a series of chemical reactions that rearrange molecules and release energy.”
		9–12	“Through cellular respiration, matter and energy flow through different organizational levels of an organism as elements are recombined to form different products and transfer energy.”
	Cycles of matter and energy transfer in ecosystems	6–8	“Food webs model how matter and energy are transferred among producers, consumers, and decomposers as the three groups interact within an ecosystem.”
		9–12	“Photosynthesis and cellular respiration provide most of the energy for life processes. [...] At each link in an ecosystem elements are combined in different ways and matter and energy are conserved.”
Crosscutting concept	Energy [and matter] as a crosscutting concept	3–5	“Students learn matter is made of particles and energy can be transferred in various ways and between objects.”
		6–8	“[...] [Students] also learn 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”
		9–12	“Students learn that the total amount of energy and matter in closed systems is conserved. They can describe changes of energy and matter 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.”

Shown content are examples limited (a) to the field of life science and (b) to energy as a crosscutting concept (cf. NGSS' appendix E for examples concerning earth/space- and the physical sciences)

Apart from national standards, more general expectations for an understanding of energy have been proposed (e.g., Duit 1984) and used for researching students' progression towards understanding energy (Liu and McKeough 2005; Liu and Ruiz 2008). These studies have usually identified the following four energy aspects (referred to as such in the following). These are required for a working understanding of the concept: (1) manifestations of energy in different forms and sources, as well as the nature of energy, (2) energy transfers and transformations, (3) energy degradation and dissipation, and (4) energy conservation (Chen et al. 2014).

### 2.1.1 Research on Students' Energy Concepts

**Earlier qualitative approaches.** Most studies on students' energy concepts focused on physics contexts. Here, learners of all age groups were found to have limited understanding of energy (kindergarten: Van Hook and Huziak-Clark 2008; primary: Liu and Ruiz 2008; lower secondary: Trumper 1993; upper secondary: Duit and Kesidou 1988; Finegold and Trumper 1989). Studies showed that students especially lack insight to energy degradation and conservation (Driver and Warrington 1985; Duit 1984; Duit and Kesidou 1988; Forde 2003; Gayford 1986; Goldring and Osborne 1994; Liu and McKeough 2005). For example, student's difficulties to recognize energy export as heat from open systems into the environment (Burger 2001) or student's failure to adapt energy conservation in idealized closed systems (Duit 1984) have been reported. Similarly, elementary teachers (Trumper 1997a, 1997b; Trumper et al. 2000), pre-service biology students, and biology teachers (Chabalengula et al. 2011) had limited understanding of energy. Several publications (Trumper 1990, 1993; Wandersee et al. 1994) conclude that, despite explicit instruction on energy, earlier everyday notions on energy are retained in favor of alternative energy conceptions that differ from the scientific energy concept. Students have been furthermore shown not to recognize energy as abstract and immaterial, but rather as a concrete substance (Hirca and Akdeniz 2008; Warren 1982). Further research findings about qualitative facets of understanding energy can be found in review articles by Kurnaz and Sağlam Arslan (2011), Millar (2005), and Nordine et al (2010) or Tatar and Oktay (2007).

**Energy in biological contexts.** Specifically for biology, the empirical results for learning about energy are similar to those for physics contexts, but only a few studies were conducted in this field. On a general level, the available studies emphasize the problematic link between everyday connotations of energy and the often strongly contextualized scientific nature of biological contexts (Jin and Anderson 2012). Boyes and Stanisstreet (1990) described students' (age 11–17) understanding of energy sources for animals and plants. Most students thought that energy for plants is received from the sun, but they also named water, soil, or air as sources of energy. Energy sources for animals were often seen in wind, keeping warm, water, and sleeping. A detailed analysis of students' (grades 5–12) alternative conceptions to energy in biology is available in a study by Burger (2001). Chabalengula et al. (2011) tested 1<sup>st</sup> year biology university students and found that energy conservation may be reproduced as a definition, but that the law was not applied in biological contexts. Furthermore, the authors asked students to explain energy using a biological context. Students, however,

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did not refer to the biological context, but rather explained energy using a physical context instead. More than half the sample was found to think of energy in biological systems as a different type of energy than the energy in physical systems, which the authors linked to vitalistic conceptions such as the idea that living beings are constituted from different materials than inanimate objects. Lin and Hu (2003) addressed energy flow and matter cycling in 7<sup>th</sup> grade students. The authors concluded that even though energy is explicitly introduced 2 years later, energy already has an important role for contexts relevant to students in 7<sup>th</sup> grade. An emphasis on recalling definitions in textbooks, insufficient teacher knowledge, and students' difficulties with transferring principles from the non-living world to living beings have been reported as potential reasons for limitations in integrated conceptual learning. Jin and Anderson (2012) proposed a learning progression for energy concepts in carbon transforming processes. Of four possible achievement levels, only students at the highest level were able to use the energy concept as an analytical tool. In contrast, level 1 students were found to employ force-dynamic accounts and see energy as a cause of life and actions, while constraints in processes were seen in agents or life itself and not in conservation laws. Only 10 % of high school students reached level 4, while the majority were categorized as level two. These results suggest that energy understanding in biological contexts is progressing little from elementary school onwards, if no specific learning approaches or cross-disciplinary links for learning about energy are provided.

**Energy learning for young students.** Despite the reported shortcomings in students' energy understanding, young learners have been shown to be able to learn about energy sources, transfers, and storage possibilities through inquiry-based, hands-on activities (Van Hook and Huziak-Clark 2008). Shultz and Coddington (1981) showed that even primary students can conceptually grasp the more difficult energy aspects concerning thermodynamics through practical mechanical experiments. Furthermore, the benefits from an early start of energy concept learning have been addressed by Novak (2005), who showed in a long-term longitudinal study that early energy learning (grade 1 and 2) has positive effects on students' energy concepts in science classes of their later school life. The above mentioned studies show that students—in relation to the concept's relevance in science and education—know relatively little about energy, even though they could conceptually handle the concept and would also benefit from an early learning start. Dawson-Tunik (2006) showed that energy learning is characterized by both transitional (moving from one level of understanding to the next) and obligatory consolidation stages, at which the understanding is elaborated at the same conceptual level before students can progress to the next level. These findings are especially relevant for early learning

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opportunities or learning about energy in different disciplinary contexts, where teachers (or school books) may consider energy on a much higher level (e.g., including thermodynamic aspects) than the students, who may only use the concept as a term without conceptual reference. The previous sections presented studies on students' energy understanding, which has often been found to be limited for various age groups, encompassing restricted knowledge transfer to other subjects (e.g., biology) and insufficient inclusion of young learners' potential. The following section addresses energy learning across disciplinary contexts and is followed by a summary of the literature review.

**Towards a learning progression for energy.** Lee and Liu (2009) presented one of the few studies to focus on the interdisciplinary nature of energy learning. The authors focused on knowledge integration and found middle school students' (grade 7–9) energy concepts to depend much on the classes taken. The highest levels of knowledge integration were found for students with a physics-class profile. Life and earth science students were considered to require further instructional support for knowledge integration in energy concept learning. Lancor (2012) published an interdisciplinary (ecology, chemistry, mechanics, electronics) study with university students using student-generated analogies. The results showed that conceptual metaphors used by students differed much more according to the specific context than with the discipline the students originated from. These findings underline the requirement of an interdisciplinary teaching approach for energy based more prominently on a learning progression across disciplines. With respect to potential context- or discipline-specific differences in energy understanding, a broad empirical basis concerning students' energy understanding could be helpful for future restructuring of energy education.

Krajcik et al. (2012) argue that the key to support meaningful learning is to study how learners develop core concepts over time and to use these learning progressions as a basis for helping students to make necessary connections between individual pieces of knowledge. Learning progressions are “descriptions of the successively more sophisticated ways of thinking about a topic that can follow one another as children learn about and investigate a topic over a broad span of time” (Duschl et al. 2007, p.214). Several learning progressions have been published and will be briefly recapitulated. These more recent approaches to students' energy concepts were often taken via quantitative assessment and usually large samples or re-analyses of large data sets (e.g., Liu and Ruiz 2008). Liu and Tang (2004) showed significant progression in understanding forms of energy among Chinese and Canadian students in grades 4, 8, and 12. In contrast, students showed little knowledge gain for energy transformation in grades 4–8.

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Even among grade 12 students (Canada), less than 30 % made reference to energy conservation, when they were asked to make a list of energy-related terms and clarify these. Liu and McKeough (2005) described a staircase- like progression of students' understanding from grade 3–12 across the above mentioned energy aspects. Students developed high proficiency in the basic stage of activity and work until grade 8. Middle school students achieved only intermediate results until grade 8 for energy forms and sources as well as energy transfer. Degradation and conservation were ideas understood insufficiently even by grade 12 students specializing in physics and math. Similarly, Neumann et al. (2013) focused on middle school students' energy learning. Their data suggest that students simultaneously develop an understanding of energy transfer and energy dissipation. By grade 10, most students mastered an understanding of forms of energy. Energy dissipations and transfer were mastered by above-average students and energy conservation was only understood by the most able/oldest students. Concerning energy learning at primary level, Lacy et al. (2014) proposed a hypothetical energy learning progression for grades 3–5 based on mostly mechanical problems. In exploratory interviews, the authors found indications that grade 3 and grade 5 students progressed after a 2-week tutorial towards quantitatively assessing the amount of energy in a system, recognising different energy forms, recognising the idea of energy transfer between objects, and associating energy gains by one object with energy losses by another object in the same system.

**Summary.** Similarities in alternative student conceptions have been shown for the different disciplinary backgrounds. Concerning the learning progressions mentioned earlier, greater insight is required into students' progression in contexts other than physics. Here, a common frame or model (e.g., energy aspects) can be useful to project energy learning across disciplinary backgrounds in order to approach a more coherent, crosscutting learning approach to energy. The previous section showed that despite the often reported constraints in energy understanding, young learners are able to learn about energy and can later benefit from doing so. Even though several (mostly biological) contexts with relevance for energy are part of early science instruction, little information is available on when and how young students' energy understanding progresses along these contexts. This study addresses this concern in order to provide further insight for a crosscutting energy learning progression.

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### 2.1.2 Research Questions and Hypotheses

#### Research questions.

- (1) Do primary students' scores on an energy test for biological contexts increase significantly from grade 3–6, i.e., prior to the concept's formal instruction in physics?
- (2) Can specific contents and time points be identified at which primary students' energy understanding progresses towards a more scientific understanding of energy?

**Hypotheses.** Primary students are confronted with numerous biological contexts that are relevant to the energy concept before the concept's scientific understanding is formally (explicitly) introduced in school. These contexts have the potential to trigger the progression towards a basic level of energy concept understanding. This progression in understanding should be statistically testable through the application of test items in the grade band of interest (3–6) and changes will be observable on (a) a quantitative scale (progression of student scores on complex multiple-choice items) and (b) on a qualitative scale, representing different patterns of understanding that relate to the learning opportunities in school. The pattern changes can point at progression points, where students turn towards a more scientific understanding of energy. With respect to the work of Lacy et al. (2014), we hypothesise that, for instance, more advanced students more often recognise heat loss of living organisms as an energy transfer to the environment, or, that older students less frequently uphold a conception of used energy as being 'just gone/lost'.

### 2.2 Methods

The research questions were addressed through an explorative, cross-sectional quantitative study in grades 3–6 using multiple-choice questionnaires. A quantitative explorative design was chosen, as research using qualitative data had already been conducted for biological contexts (e.g., Burger 2001; Chabalengula et al. 2011). On the other hand, no comparable data were available for quantitative learning trends in biology like those presented for physics contexts (e.g., Liu and McKeough 2005). However, insight to learning trends is required from all disciplinary backgrounds for the formulation of an interdisciplinary learning progression for energy as a crosscutting concept. With respect to research question two and the hypothesis concerning changing patterns in understanding, a more qualitative analysis through distractor and attractor analysis was conducted (section Results - Distractor-Based Analysis). Three smaller studies (a school book analysis, a teacher survey and an inter-rater agreement on item-model fit) were conducted as part of the instrument development and in order to address

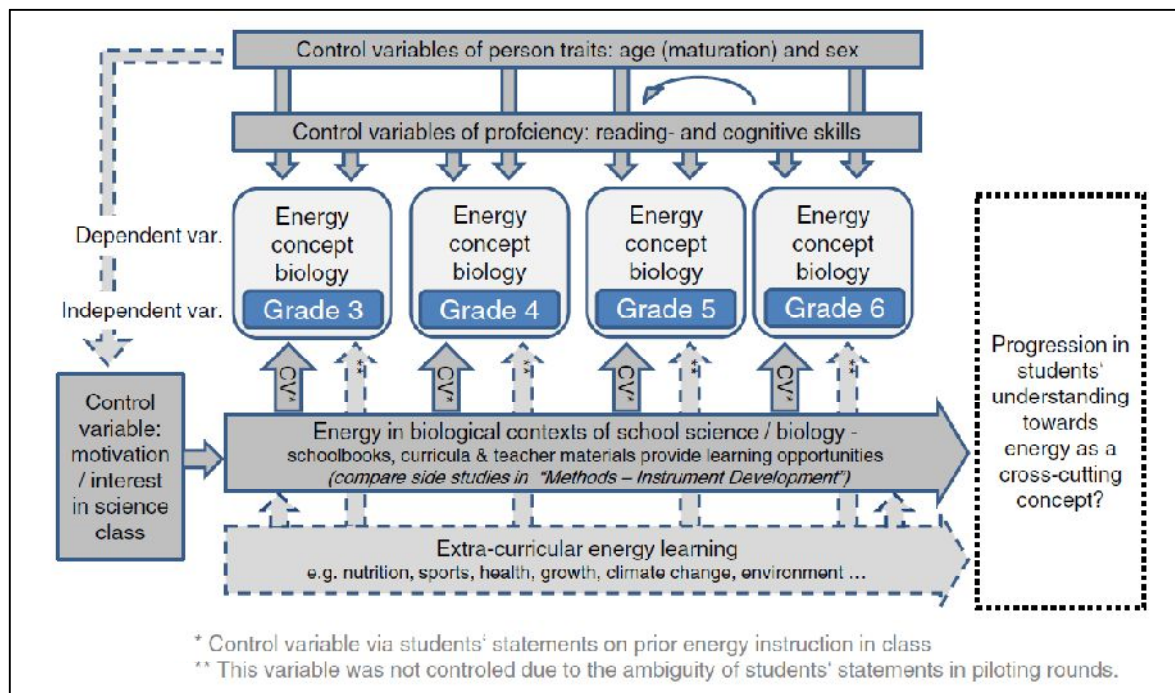
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aspects of validity. Accordingly, findings from these studies are detailed within the following section and will again be discussed at the end of this paper in the light of validity and implications. Figure 2.1 provides the reader with an overview for the following section concerning the employed variables and their relations.

### 2.2.1 Instrument Development

Since measuring an abstract construct such as energy may strongly depend on the employed instrument, the following section lays open the steps taken in the development process.

Complex multiple-choice items were employed as a medium of assessment to enable the analysis of a larger group of students. Items were developed on the basis of a two-dimensional model of energy concept understanding, suggested by Neumann et al. (2013). The first dimension focuses on the four central aspects of energy understanding, which were also identified in previous studies: (1) forms and sources of energy, (2) energy transfer and transformation, (3) energy degradation and dissipation, as well as (4) energy conservation.



**Figure 2.1.** Variables and their proposed relation as employed in this study. *Solid-lined connecting arrows* mark relations between variables analysed in this data set, *dash-lined connection arrows and variables* mark hypothetical relations or contents not covered in this study

Empirical data (Neumann et al. 2013; Liu and McKeough 2005) suggest an overlapping progression in students' learning of these energy aspects. The second dimension



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consists of four levels of cognitive complexity ranging from factual knowledge (a single fact, e.g., the energy source for humans) via mappings (combination of two facts) and relations (combination of three facts) to conceptual understanding (complex insight into an energy aspect). Since Neumann et al. (2013) found no clear progression along the levels of cognitive complexity, these levels were used only as a structured guideline for items construction. The instrument for the data sampling was constructed in four steps:

1. To identify relevant contexts for energy learning in early science/biological class, an analysis of science/biology school books was conducted along with a survey on teachers' use of energy in biology class. In the discussion section, findings from these accompanying studies are compared with the progression of students' energy understanding with respect to the relatedness of the respective findings. For primary level, two up-to-date school books (-series) were used for each of the grades 3/4 (Kraft 2009; Meier 2007a, 2007b) and 5/6 (Gottlieb et al. 2010; Jütte and Kähler 2008). The analysis revealed a substantial, explicit (direct) presence of energy in early science learning. Here, the occurrences of the energy concept increase from an average 14 occurrences per book in grades 3 and 4 to 84 occurrences per book in grades 5 and 6. However, only 10 % of the total number of occurrences of energy concern energy degradation and conservation. Even though these aspects still only make out 16 % of the occurrences of energy in high school books, the aspects of degradation and conservation were further considered for the instrument development, as they represent crucial components of an understanding of energy.

In the general science school books for elementary school selected for this study (see above), 15 out of 28 total occurrences were concerned with biological contexts. A different distribution was found for implicit energy mentioning. This we defined as the occurrence of a context, which was linked to the energy concept in a reference biology high school textbook (Bayhuber et al. 2010). Implicit occurrences were found to be much more diverse (grades 5/6, 210 contexts per book), thereby underlining the number of opportunities for teachers to come across energy in early science/biology class.

A second accompanying study was carried out, surveying teachers ( $N = 16$ , average teaching experience 14.7 years) with respect to their teaching of energy in primary school science/biology classes. The results indicated that one of the aspects being used in this research, forms of energy, is referred to by all teachers in lower secondary biology class, while the focus was on heat (12/16) and kinetic energy (9/16) or energy in chemical bonds (7/16). Energy transfers were treated by 4/16 teachers, while thermodynamic aspects were considered by only a minority (5/16), showing a similar trend as in the school books. Teachers varied greatly between addressing (only

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mentioning) and explaining energy in biology class: For “body movement” (10/14), “nutrition/digestion” (13/14), and “respiratory/circulatory system” (12/14), the majority of teachers only mentioned the term energy when teaching these contexts. At the same time, energy was widely applied with at least some teachers mentioning energy in each of the contexts required by the curricula for teaching in grades 5/6 (except “human sexuality”).

In summary, all energy aspects from the model (see above) were also identified in the school book analysis and in the biology teacher survey. Additionally, neither of these two smaller studies identified biology-specific energy aspects. We concluded that, until grade 6, all aspects from the model play a role in biology education and can therefore be used for instrument development.

2. First, context-independent expectations for students' response behaviour were formulated for all combinations of energy aspects and levels of cognitive complexity in order to allow a parallel construction of items for different contexts. To achieve different levels of cognitive complexity, Neumann et al. (2013) limited the amount of additional information in the stem of items of higher complexity. However, the authors found no clear trend in generating different levels of difficulty through this design feature and concluded that the additional information may have increased cognitive load as students have to process this information. Consequently, we did not pursue this design criterion for items in this study, but achieved varying difficulty by increasing the amount and complexity of information expected in students' replies to higher-complexity items. The generalised expectations for each combination of energy aspects and levels of cognitive complexity were then specified for the contexts found in the school book analysis (step 1). In the following, these specified expectations were used as authoring guidelines for the items. Only multiple-choice items were constructed, to exclude writing difficulties among the younger students. Distractors were formulated according to common alternative energy conceptions in biology (e.g., Barak et al. 1997; Boyes and Stanisstreet 1990; Burger 2001). Due to the young age of the students, only few items were feasible for the development of the instrument. Consequently, the guessing probability and the reading effort were limited by distributing the correct response on two options. The students could therefore score half credit ( $\geq 50\%$  correct) and full credit (100% correct) on each item, while items left blank were awarded 0 points (compare discussion of structural validity). Classically, sums of item scores were formed for each energy aspect and across all items (“mean energy score”, compare Figure 2.2) and then divided by the number of items. Mean scores across all students of the different grade bands were used for the cross-grade comparison.

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3. Qualitative student feedback was collected for each item from one grade 4 and one grade 5 student using a questionnaire for assessing item quality (AAAS 2007). Items, which students had difficulties with (e.g., with respect to wording) were adapted accordingly. Most students struggled with items representing the higher cognitive levels (“relations” and “concepts”—compare model in the theoretical background), possibly due to the amount of required content knowledge and reading requirements. Consequently, items from these two levels were disregarded for further quantitative field testing.

4. The remaining 48 items from the two lower levels of complexity (“facts” and “mappings”, see model) were subjected to quantitative field testing with  $N = 168$  students from grades 3–6. Three criteria were used to select items for the main data sampling: (a) Since the required instrument aimed at investigating progression in understanding from elementary to secondary school, item difficulty in grades 5 and 6 was used as a reference (minimum 10 %; best fit to normal distribution of difficulties; range 11–47 %). Since items were still difficult for students in the field testing, we provided a help-box on each item of the main data sampling, telling the students how many options were correct in each item. Through this measure, mean item difficulty in grade 6 was lowered to 40 % (range 5–80 %) for full credit and to 71 % (range 49–100 %) for half credit. (b) As a second criterion, items that showed a distinctly negative correlation with grade level ( $r < -0.15$ ) were excluded from the analysis, as they were considered likely to represent content specific to a single grade or learning group and could therefore introduce construct-irrelevant variance to the results. (c) As a third criterion, the goodness of fit of items and model was assessed: Researchers ( $N = 18$ ) in the field of biology education without any prior knowledge about this study were asked to sort items into the model. These raters were provided with information about expected content in student responses only, while no clues were given for specific item design or formulation features. Item selection for data sampling only considered items that had been sorted into the model completely correct in terms of energy aspects by at least 2 of the 3 raters (average correct across all items 75 %). Fleiss' Kappa (Fleiss et al. 1969) furthermore showed substantial inter-rater agreement ( $\kappa = 0.61 \pm 0.08SE$ ) for energy aspects. All items and item parameters are provided in the online resources 1 and 2.

### 2.2.2 Data Sampling

As students in grades 3 to 6 can be expected to have a short attention span, test time was limited to one lesson (45 min), in which each student received 8 items (elementary school 6 items). Besides these, reading ability (Retelsdorf and Becker 2012—short test

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for reading speed and correctness), cognitive abilities (KFT-N2—graphic analogies: Heller and Perleth 2000), and intrinsic motivation/interest in science/biology class (Deci and Ryan 2012) were tested as control variables (compare Figure 2.1). All tests were administered by the first author and three university students while classroom teachers were present. Testing did not stop until all students had finished.

In order to partially make up for the limited feasible number of items per student, two parallel test forms (A and B) were deployed, thereby allowing for a replication and comparison of trends found among students. Each test form contained a separate set of eight items representing the four energy aspects mentioned in the theoretical background section. T tests were conducted to compare mean item difficulty in the two test forms for grades 3/4 (6 items) and grades 5/6 (8 items). The test forms were not significantly different in item difficulty at both levels (grades 3/4:  $t(5) = 0.37, p = 0.72$ ; grades 5/6:  $t(7) = 1.27, p = 0.25$ ), therefore allowing comparability of the two forms.

Since the items were constructed analogously to those used by Neumann et al. (2013), we assumed a one-dimensional construct of energy. Cronbach's  $\alpha$  was therefore calculated as an approximate across all six items used in grades 3–6. Due to the small number of items and potentially undetected subscales (e.g., for energy aspects) among the items, internal consistency was low ( $\alpha = 0.55/0.52$ ) in the two test forms, respectively. However, the Spearman-Brown formula (Remmers et al. 1927) predicted  $\alpha = 0.70/0.82$  for an increase in test length from 6 to 12/24 items, which can easily be put into practice in studies with older students.

Participants were sampled from schools in a large metropolitan area in northern Germany. Altogether, 25 classes from 8 schools with  $N = 540$  students (grade 3  $N = 110$ ; grade 4  $N = 120$ ; grade 5  $N = 188$ ; grade 6  $N = 122$ ) participated. Sample sizes were equally distributed across gender (49 % female). To control for variation in social variability, only schools with an intermediate social background index ("KESS" = 3–4 on a scale of 1–6) were chosen. In elementary schools, students of all abilities were present. In grades 5 and 6, students from both main secondary school types—"Stadtteilschulen" (mixed abilities) and "Gymnasien" (higher abilities)—were represented in the sample. Data were collected at the end of the school year 2012 within 2 weeks to ensure comparability across classes and schools, respectively. Data and Statistical Analysis

Tests on differences in energy understanding were conducted through one-way ANOVA in SPSS. Each of the procedures were tested (Shapiro-Wilk's) and inspected visually for normal distribution. Hartley's  $F_{\text{Max}}$  variance ratio (Pearson and Hartley 1954) was computed due to the larger sample size and showed homogeneity of variances to be

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given ( $F_{\text{Max}} = 1.61 < 1.96$  for  $N > 60$ ). Post-hoc analysis was conducted using Games-Howell's test, which is reported to perform well in unequal sample sizes (Field 2009, p.374f). Correlation coefficients were calculated using Pearson's  $r$  in parametric and Kendall's  $\tau$  in non-parametric data settings. Since several groups were compared, effect sizes were calculated using  $\omega$  (Field 2009) and the rating of their strength followed benchmarks by Kirk (1996). Analysis of age effects on energy scores were analysed by regression discontinuity analysis via Chow's test (Chow 1960), following procedures recommended by Lee (2008). Due to significant variation of the covariates reading ability and motivation across levels of the independent variable (grade level), ANCOVA was not a valid procedure in this dataset (Field 2009, p.397). Instead, multiple regression analysis was conducted with forced entry of variables and following limitation to only variables that significantly improved the model.

### 2.3 Results

#### 2.3.1 Progression of Energy Concepts in Biological Contexts in Grades 3-6

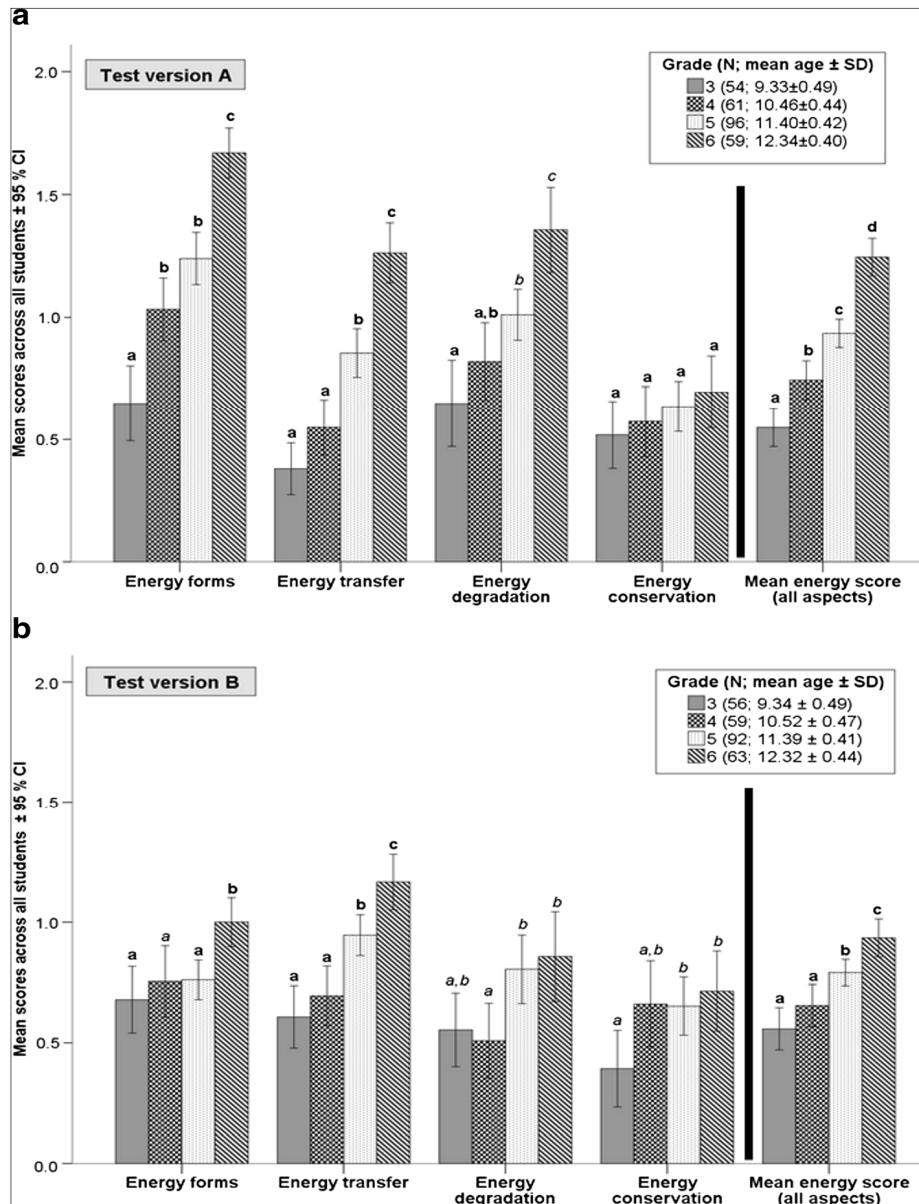
The main results to address research question one are presented in Figure 2.2a (test form A) and Figure 2.2b (test form B). The mean energy scores across all students of grades 3–6 are presented in separate column stacks for each of the four energy aspects (left) and as a mean energy score across these aspects (right). The two test forms showed similar trends in energy understanding with a significant increase in energy scores in grades 3–6 for both test forms,  $F(3, 266) = 59.50, p < 0.001$  (A) and  $F(3, 266) = 17.44, p < 0.001$  (B). The columns labeled “Mean energy aspects (all aspects)” suggest a gain from grade 3–6 by a factor of 2.3/1.7 with a large (Kirk 1996; threshold = 0.14) effect size of  $\omega = 0.39/0.15$  for the grade level.

Student scores were generally low with considerable, but proportionally decreasing variation from grade 3–6. Significant progression of mean energy scores was prominently observed from grade 4 onwards. The scores received by students even in the higher grades do not far progress beyond a score of one (out of two), indicating that most students are only able to partially solve energy items in biological contexts.

**Table 2.2.** Mean scores ( $\pm$ SD) across grades 3–6 for the four energy aspects

	Energy forms	Energy transfer	Energy degradation	Energy conservation
Test A	1.16 ( $\pm$ 0.60)	0.78 ( $\pm$ 0.55)	0.97 ( $\pm$ 0.65)	0.61 ( $\pm$ 0.53)
Test B	0.79 ( $\pm$ 0.48)	0.87 ( $\pm$ 0.50)	0.70 ( $\pm$ 0.67)	0.62 ( $\pm$ 0.63)
Mean	0.98	0.83	0.83	0.62

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**Figures 2.2 a/b.** Mean scores across all students in grades 3–6 (see key) for four energy aspects (*left*) and as a mean score across all aspects (*right*). a: Test form A. b: Test form B. A score of 1 refers to a performance with  $\geq 50\%$  of the respective items or choices within the items being solved correctly; a score of 2 refers to all items being solved correctly. *Error bars* denote 95 % confidence intervals (CI). *Different lower case bold letters* indicate significant difference of  $p < 0.001$ , *italic lower case letters* show a difference at the level of  $p < 0.05$ . Numbers in brackets behind the key indicate sample size and mean age ( $\pm$  standard deviation, SD)

The differences between students' scores for the aspects of energy were compared across grades 3–6 for each test form. With the exception of the difference between energy forms and energy degradation in test form B, T-tests showed significant differences between each combination of energy aspects ( $p < 0.001$  in 9/12 combinations), indicating a different progression of students' energy concepts with respect to the energy aspects. Table 2.2 sums up Figure 2.2a, b and shows mean scores

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( $\pm$  standard deviations, *SD*) for the energy aspects across grade 3–6 in both test forms, as well as means across the two. On average, students in both tests scored lowest for energy conservation, while students scored highest in the two aspects not linked to an understanding of thermodynamics, namely energy forms and transfer. The average across the two test forms showed that scores for energy forms were highest, while energy transfer and degradation received medium scores and energy conservation received only 2/3 of the scores of energy forms.

### 2.3.2 Distractor-Based Analysis of Energy Concepts in Biological Contexts

To obtain a more detailed insight into the quantitative findings presented above and to address the second research question, the qualitative patterns of students' selection of attractors (i.e., the correct answering options) and distractors (i.e., the incorrect answering options) were analysed. Figure 2.3a–f show progressions in students' understanding of plant and animal/human energy sources (Figure 2.3a, b), energy transfer in plants and animals/humans (Figure 2.3c, d), as well as transfer with focus on degradation and conservation (Figure 2.3e, f, respectively).

Students demonstrate limited understanding across all grade levels for energy storage in plants (Figure 2.3a). The data indicate that older students increasingly selected the distractor "light stores" and least of all the correct ideas of sugars, fats, and proteins. When students were asked to rediscover light energy transformed in a tree (Figure 2.3e), their understanding that energy is stored in tree material clearly increases from 1/4 of the 3<sup>rd</sup>/4<sup>th</sup> graders to 73 % in grade 6. Concerning a beginning understanding of energy degradation, a substantial share of students in all grades (> 44 %) acknowledges heat loss from a tree into the environment. Few students of all groups traced energy into tree movement or electrical currents in nerves (< 20 %). The incorrect understanding of energy leaving the tree via water decreased only among 6th graders (19 %), while roughly half of students in grades 3–5 still held this idea.

For energy in human nutrition (Figure 2.3b–d), 6<sup>th</sup> graders generally understand that humans obtain energy through foods from sugar, fat, and protein (> 78 %, compare Figure 2.3c) with less than 17 % selecting the distractors heat, vitamins, and nutrients. Third and 4th graders show no such trend and select all options to similar degrees. Fifth graders selected similar options as older students, but still widely disregard fat (< 40 %) as an energy source in food and more often select vitamins (43 %) instead, thereby potentially demonstrating a more vitalistic conception of energy (Barak et al. 1997). Figure 2.3c also focuses on the often neglected role of oxygen with respect to nutrients as energy sources (Warren 1983). Here, the progress between elementary and secondary students' appreciation of the role of oxygen for nutrient degradation (here: fat)

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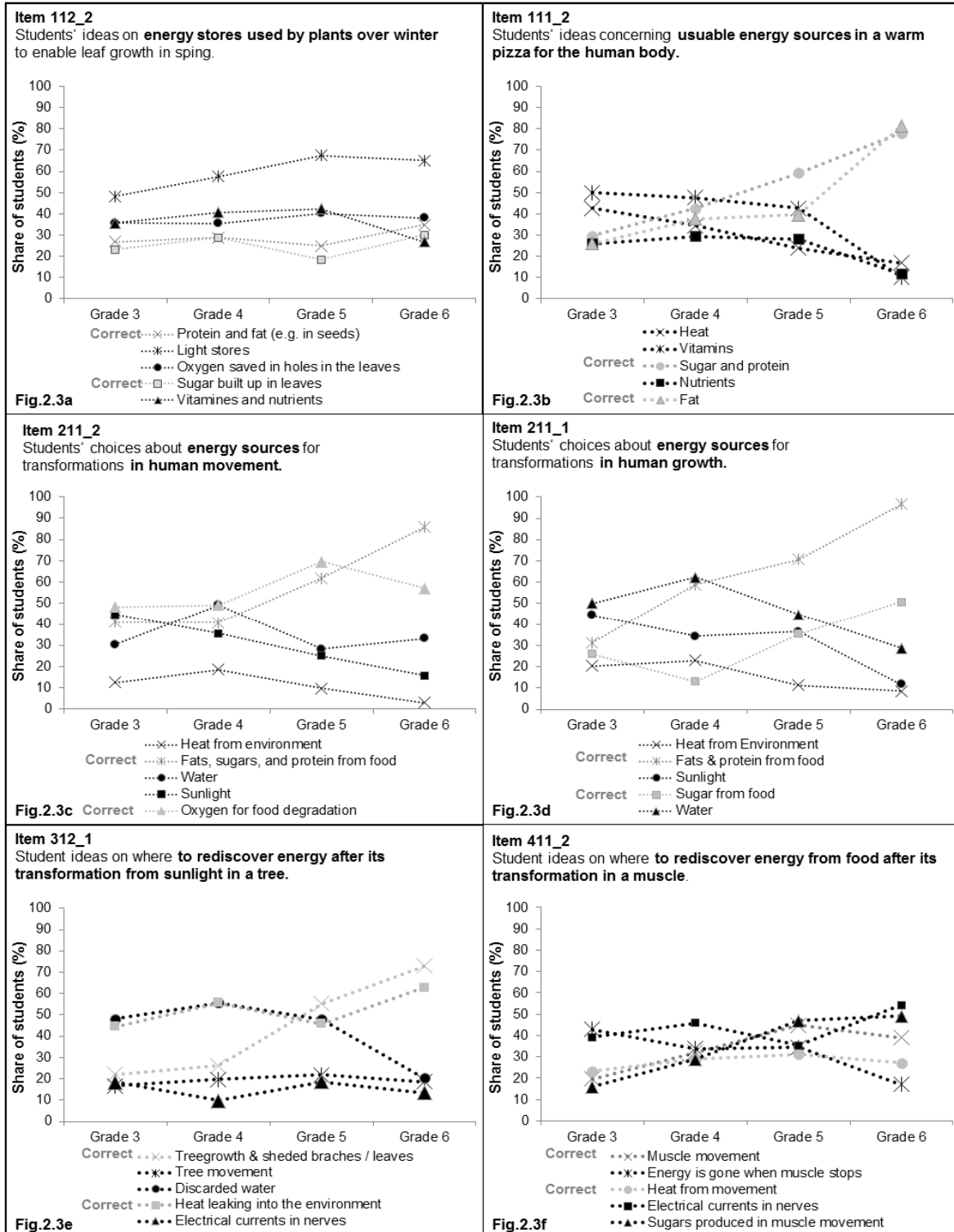
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is comparatively small, with 2/3 of secondary students seeing this relation. In both Figure 2.3c, d, a third of the elementary students selected water and sunlight as energy sources for human movement, while these distractors are less selected by older students. Heat from the environment as an energy source was in both items disregarded by more than 80 % of all students. At the same time, distinctly more students (43 and 34 %, respectively) incorrectly saw the heat in foods (here: a warm pizza) as an energy source (Figure 2.3b).

When students were asked to rediscover energy after its transformation in a muscle (Figure 2.3f), the results were more consistent in progression than for the parallel item concerning trees (Figure 2.3e): More students recognised heat energy leaking into the environment in the botanical item than in the corresponding zoological item. Few students actively rejected energy conservation: In Figure 2.3f, less than 20 % of 4<sup>th</sup>–6<sup>th</sup> graders and roughly 30 % of the 3rd graders selected the incorrect option that energy is lost after the muscle movement stops. In contrast, older students more often agreed that sugars are produced in a muscle during movement and that the sugars then store the energy of the movement.



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**Figure 2.3 (a-f).** Distractor analysis on energy items concerning energy sources, transfer, degradation, and conservation in plants and humans/animals. Progression of the share (%) of 3<sup>rd</sup>-6<sup>th</sup> grade students selecting distractors or the correct options (see key). Dotted lines indicate assumed, but not measured progressions, since the study design was cross-sectional. Percentages refer to between  $N = 54-96$  students per grade level

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### 2.3.3 Influence of Control Variables on Energy Scores

All results in this section were achieved by contrasting mean energy scores with the control variable (compare Figure 2.1) scores for all students simultaneously through multiple regression analysis. Variables that significantly contributed to the improvement of the regression model are presented in Table 2.3. Regression coefficients ( $B$ ), their standard errors ( $SE B$ ), and the standardised regression coefficients ( $\beta$ ) are shown for the variables in each model step. The note below Table 2.3 shows the corresponding model fit values: The model accounted for 34.5 % of variance ( $R^2$ ) in the energy scores. Generalisation is possible to a far extent with only 0.4 % shrinkage when transferring the results from the sample to the population ( $adj. R^2$ ). Standardised regression coefficients (in brackets) allow a comparison of relevance between the following factors, which contributed to the best fitting model: Grade level (0.37), reading ability (0.27), and cognitive abilities (0.16), with  $p < 0.001$  for all three.

The following variables were excluded from multiple regression analysis due to a non-significant contribution to model improvement and low or non-significant ( $n.s.$ ) correlations/differences with/in students' energy scores: student statements on the extent of prior energy instruction ( $r = 0.27$ ), interest/motivation in science/biology class ( $r = 0.27$ ), sex ( $n.s.$ ), and grade received in biology/science class ( $n.s.$ ). In addition to multiple regression analysis, the influence of age was assessed through two procedures. First, the correlation of age and energy scores in each of the 24 participating classes identified only one class with a significant correlation of  $r = -0.58$  ( $p < 0.01$ ), indicating little effect of age besides the effect of grade level ( $r = 0.53$ ,  $p < 0.001$  across all students). Second, the effect of age was contrasted with the effect of grade through regression discontinuity analysis (Lee 2008; Luyten 2006). The Chow test showed that the interaction effect between age and grade level was described by significant differences between both slopes and intercepts between grade levels,  $F(3, 539) = 17.34$ ,  $p < 0.001$ , indicating that energy scores were primarily related to grade level and only to a minor extent to age.

To control for a possible school effect (higher representation of high-ability students in grades 5 and 6 in comparison to grades 3 and 4), the progression of student scores was calculated again with only students from mixed ability schools ("Stadtteilschulen") in grades 5 and 6. In this case, the differences between grade levels were slightly levelling, yet still significant, thereby indicating a school effect to be negligible.

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**Table 2.3.** Multiple regression model. Steps show forced entry inclusion of significantly contributing variables to predicting energy scores (see below)

	<i>B</i>	<i>SE B</i>	$\beta$
Step 1			
Constant	0.06	0.06	–
Grade	0.18	0.01	0.53**
Step 2			
Constant	0.06	0.06	–
Grade	0.12	0.02	0.38**
Reading ability	0.01	0.00	0.25**
Step 3			
Constant	–0.03	0.06	–
Grade	0.12	0.02	0.37**
Reading ability	0.00	0.00	0.22**
Cognitive abilities	0.01	0.00	0.16**

Model summary:  $R^2 = 0.282$  (Step 1),  $R^2 = 0.32$  (Step 2),  $R^2 = 0.345$  (Step 3),  $p < 0.001$ , *adj. R*<sup>2</sup> = 0.341

*B* regression coefficients, *SE B* standard error of regression coefficient,  $\beta$  standardised regression coefficients

\*\* $p < 0.001$

### 2.4 Discussion

The following section addresses aspects of validity and reliability. Afterwards, findings from this study are discussed and possible implications are pointed out.

#### 2.4.1 Discussion of Reliability and Validity

In the section Methods - Data Sampling, we introduced limitations of the questionnaire approach in relation to the learners' age in this study. Accordingly, the maximum length of the instrument was limited, causing low reliability levels in both test forms ( $\alpha = 0.55/0.52$ ). Measurement accuracy is therefore limited. Even though we could only compare average student performance in different energy aspects on the basis of few items, it needs to be reiterated that our research focus lay in discovering broad learning trends, which we found in both test forms. With respect to the predicted results for the reliability of longer tests (Spearman-Brown), we therefore deem reliability sufficient for our needs. In the following, we use Messick's (1995) unified concept of construct validity to discuss our findings.

**Content aspect.** The findings from the school book analysis supported our hypothesis, suggesting that students are early (and often implicitly) confronted with energy in biological contexts before explicit instruction on energy in physics. We found

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that the model by Neumann et al. (2013) was well applicable for school book and curricular analysis, as all occurrences could be assigned to energy aspects. A curricular analysis supported the findings from school book analysis. The results from the teacher questionnaires indicated that teachers implement at least parts of the suggested teaching of energy found in school books.

**Substantive aspect.** The theoretical basis of this study was generally addressed through the foundation on core concept-based meaningful learning. For the processes required by students for solving the energy tasks in the items, we refer to the studies by Shultz and Coddington (1981), as well as Novak (2005), showing that early learning about an abstract concept such as energy is possible and sustainable. For empirical proof of the occurring processes in the developed items, think-aloud protocols ( $N = 4-5$  per grade level) are currently evaluated. Results indicate that by grade 6, students are able to apply the intended processes for solving the employed items.

**Structural aspect.** In many publications the energy concept has been identified to consist of the four energy aspects mentioned above. These aspects were used as a basis for assessing students' understanding in this study. Additional aspects specific to biological contexts were not identified in the analysis of school books or the teacher survey. The assessment of fit of the model to items through researcher-ratings showed substantial agreement of Fleiss  $\kappa = 0.61 \pm .08$  SE for the four energy aspects. Distractor analysis revealed that some alternative conceptions are readily decreasing while others persist, indicating that a categorical scoring rubric (0–1–2) was content-wise helpful to achieve more representative results especially among younger learners. This trend was confirmed, as both the number of items that were only partially worked on (grade 3: 12 %, grade 6: 4 %) and the number of items left blank (grade 3: 7 %, grade 6: 4 %) decreased, indicating that learners early ideas about energy were included in this scoring system. Less than 2 % (grade 3) and  $< 1$  % (grade 6) of students misunderstood the instructions and ticked more than the correct amount of options, thereby showing that this factor in influencing energy scores over the grade band was negligible. Even though mean student scores for the different energy aspects vary only on an interval scale due to the limited number of items, we see this problem manifested as a reliability issue which was discussed above.

**Generalizability.** This study contained two test forms, which showed similar trends. These may also reflect the specificity of the assessed construct. Concerning the latter, it is important to note that the findings are intended as insight for formulating a

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more general learning progression on energy. The results from multiple regression analysis have furthermore shown that the findings are well generalizable to the population level (shrinkage: 0.4 %).

**External aspect.** The data showed a significant correlation of energy scores and students' reading skills ( $r = 0.48$ ), underlining the limitations at elementary school for written assessment concerning more abstract/difficult topics like energy. The correlation with cognitive skills (written language independent, fluid intelligence;  $r = 0.28$ ) was low, indicating—in combination with the limited correlations with further control variables—that the energy scores in this study were not bound to other common learning variables. Taking a closer look, the limited empirical connection between motivation/interest in science and our measured energy scores ( $r = 0.27$ ) may reflect that the energy concept—as we tested it—is not among the regular science topics primary students want to find out about. If students are interested in energy, content they would face are possibly more likely to include e.g., the energy transition or global change and less often energy in the sense of an abstract concept to be used as a tool. The low correlation between test scores and students' statements on prior coverage of energy in school may relate to the trend of teachers and school books mentioning energy without explaining it (compare results from school book analysis and teacher interviews in the section Methods - Instrument Development). This, as well, may be reflected by the non-significant correlation with students' science grades. Our finding that energy scores were more related to grade level than to age would suggest that curricular-dependent factors are more relevant for energy scores than extra-curricular ones.

**Consequential aspect.** The section Discussion - Weaknesses and Perspective below points out limitations of the presented data. In light of this, it is important to note that this study aims only at the identification of learning trends to provide further insight for the formulation of a wider learning progression. The instrument was neither developed for diagnosis at the level of single students nor for giving quantitative statements concerning students' achievement in relation to e.g., science standards.

### 2.4.2 Main Findings, Relevance, and Implications

Following the theory of meaningful learning (Ausubel 1963) and results from international student assessment studies, this study was motivated by the long-term goal to pursue more cumulative, meaningful learning in science through the core idea and crosscutting concept energy. We focused on providing further insight for the formulation of a more coherent learning progression for energy. For this, we targeted young students' learning

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of energy in biological contexts before explicit introduction of energy in physical contexts (here, typically in grade 8 or 9). Novak (2005, p.36) points out that the commonly “grossly underestimate[d]” capability of young students for conceptual learning was markedly opposed by their findings, showing beneficial effects for later learning through an early introduction of core concepts like energy.

Our analysis of primary school books and teachers' statements on the inclusion of energy in primary school showed substantial presence of energy in biological contexts at primary level. In combining these findings with Novak's (2005), a detailed empirical analysis of early energy learning can provide valuable information for the formulation of an energy learning progression that builds on young learners' potential and includes the respective learning opportunities for energy.

Concerning our research questions, the results showed (1) a significant increase in energy concept understanding in biological contexts prior to the concept's explicit instruction in physics. (2) Until grade 6, the average student scored half the possible points. Still, several students at this level scored almost full credit on our energy test forms. The analysis of distractors and attractors (Figure 2.3a–f) showed for specific contents that students' average understanding of energy progressed at specific grades, thereby approaching—at a basic level—the scientific energy concept. Student proficiency differed significantly between items for different energy aspects. Across test forms, understanding of energy conservation showed least progression and the lowest scores. On average, the score for energy degradation was similar to that of understanding energy transfers and transformation (mean across all grades and across both test forms = 0.83 for both aspects, Table 2.2).

We also related the observed student energy understanding to findings from the adjoining sub-studies (school book analysis and teacher interviews, see section Methods - Instrument Development) in order to account for the role of the (intended and enacted) curriculum on students progression in understanding the energy concept. A focus on the concepts' aspects forms and transfer in both school-books and teacher interviews was analogous to students' understanding, which progressed distinctly within the same two energy aspects (compare Figure 2.2a, b, Table 2.2). We therefore argue that the similar scores for energy degradation and energy transfer may have been effected by limited measurement accuracy, as the students' understanding per energy aspect and per test form was based on so few items. In relation to the findings from the school book analysis, understanding of energy degradation may have therefore been overestimated in our measurement. As the analysis of regression discontinuity showed an effect of grade level over maturation (age), we argue that the differences in students' understanding of the respective energy aspects may be a reflection of the focus on forms

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and transfer of energy in biology school books and the science biology classes (compare teacher survey). These learning opportunities concerning e.g., energy forms may enable 6th grade students to solve items for this aspect more often than younger students. In contrast, the older students may have to make sense of e.g., energy conservation items on our test in the same way as younger students do, since they had a similar amount of learning opportunities for this aspect. Since students performed well on items for energy forms, we agree with Jin and Anderson (2012) in suggesting that despite its limitations, the forms of energy approach should be continued, as students may use it as a scaffold for further learning opportunities with energy.

The focus in biology on energy forms/sources and energy transfer/transformation limits the potential of energy as a crosscutting concept and analytical tool, as students cannot apply e.g., the essential idea of energy conservation, for which this analytical concept was developed (Lacy et al. 2014). Our qualitative analysis (Figure 2.3e, f) may present an example, in which relatively few students indicated by grade 6 that energy was “just gone” after an energy transformation—at the same time, relatively few students were able to explain where the energy went, indicating a constraint on their ability to apply energy conservation to a specific context (Chabalengula et al. 2011; Constantinou and Papadouris 2012). For biological contexts, this would require an increased emphasis on energy degradation and conservation in curricula, school books, and the teachers' awareness when addressing energy in biology. It has already been shown that learning of difficult concepts such as energy conservation is possible in lower secondary school and before (Novak 2005; Shultz and Coddington 1981; Van Hook and Huziak-Clark 2008) if adequate learning arrangements are provided. Our data suggest, that to a certain degree, students learn about energy from implicit learning opportunities. On the basis of the above and our findings, that in early biology contexts, energy is much more implicitly introduced than explicitly addressed, we argue that an early beginning of a more explicit teaching of energy in biology may have a positive effect on older students' understanding of energy.

Concerning the interdisciplinary character of energy, our findings suggest that students—apart from an everyday energy understanding—enter explicit energy instruction in physics with early stages of the scientific understanding of energy, which the students already start to construct in early learning opportunities in biological contexts. The overlap between disciplinary contexts that students encounter when learning about energy are unlikely to decrease among older students. In the light of meaningful (Ausubel 1963) and interdisciplinary learning, appropriate links between the disciplinary contexts are required as a scaffold for students. With these, an improved application of energy as a tool for analysis of complex contexts at different levels

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(subatomic/molecular, macro, global—compare theoretical background) and across disciplines could be supported.

For overarching learning goals in biology (such as to understand socio-environmentally relevant topics like climate change or health issues), Holden and Barrow (1984) showed that traditional energy instruction has only a minor effect on the understanding of these topics. For their understanding and evaluation, an appreciation of energy conservation is crucial (Jin and Anderson 2012). If future students are expected to use energy as an analytical tool for deeper analysis of these topics, students' understanding of energy degradation and conservation in biological contexts is crucial and—in light of the above findings—can still be strengthened.

### 2.4.3 Reflection of Findings in the Light of Other Studies

The broad trends concerning learning of different energy aspects in biology are similar to those found for physics by Lee and Liu (2009), Liu and McKeough (2005), Liu and Tang (2004), and Neumann et al. (2013) in that our data also demonstrate students' difficulties in understanding the thermodynamic aspects of energy. Neumann et al. (2013) found that the understanding of energy degradation was not much more difficult than understanding energy transfer, while conservation was understood only by the most able students. Across the two test forms, our results were similar. However, we argue in biological contexts, difficulties in both energy conservation and degradation may be a reflection of the focus on forms and transfer in biology school books, curricula, and teachers' employment of energy in biology class (see section Methods - Instrument Development).

The findings from distractor analysis suggest a differentiated progression for alternative conceptions: While some (e.g., Figure 2.3c “sunlight”—idea that humans use energy from sunlight for movement) decline steadily with higher grade levels, others seem not to change until grade 6 (e.g., Figure 2.3a “oxygen”—plants store energy in the form of oxygen inside leaves), while a third set of alternative conceptions decline markedly at a specific age group (e.g., Figure 2.3e “discarded water”—idea that energy transformed by a tree can be rediscovered in discarded water). Concerning the hypothesised pattern change of qualitative understanding, the data indicate that students' energy understanding can progress in a specific context along several ways: for some ideas, students' understanding is aligning with the scientific understanding, e.g., the decreasing understanding that energy is simply lost after it was used. Other ideas in the students' energy understanding represent persistent alternative conceptions that limit the students' ability to use energy effectively in this context. With respect to the



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progression of an alternative energy understanding, Burger (2001) demonstrated that 99.8 % of the combinations of students' correct and incorrect conceptions about energy are logically sound, meaning that students may obtain certain alternative conceptions in order to make them logically fit other conceptions. For the formulation of a learning progression of energy, we therefore think it is important to consider stagnating progression in understanding of energy in a specific context as a possible effect of students' energy understanding in other disciplinary contexts or other topics.

Boyes and Stanisstreet (1990) and Burger (2001) also analysed grade 5 students with respect to their understanding of energy sources. Similarities across the two studies and our findings with respect to the share of students holding specific conceptions can be identified, e.g., students' belief that animals take up energy through food was similar in all data sets (Boyes and Stanisstreet 90% / Burger 67 % / this study 86 %). Based on our data, we agree with Boyes and Stanisstreet (1990) that students may have difficulties with distinguishing between energy requirements and other requirements for plants and animals.

### **2.4.4 Weaknesses and Perspective**

The findings from school book/curriculum analysis and teacher questionnaires have to be analysed with reservations as they focus on results from only one region and are not representative. These analyses were conducted only in relation to requirements for this study. Even though the language was revised in qualitative piloting and strictly kept short and simple, the effect of reading ability on energy scores would suggest, in further research, to conduct a triangulation of the results from this study with interview data. Due to students' young age and their consequently limited attention span, this study was restricted in testing time, thereby causing further constraints for additional instruments, e.g., for crystallised intelligence. Further studies currently assess the effect of this possible confounding variable. More importantly, the short testing time markedly limited the number of available items for testing, which thereby decreased reliability, the predictive force of the multiple regression model, and the accuracy of scores for the energy aspects. In this study, we have tried to overcome parts of this problem by replicating our research in two test forms.

We see the benefits of this study in addressing significant contexts for energy learning at an important age, where first ideas concerning energy are constructed and possible connections to everyday conceptions of energy may form. With the design of this study oriented along an understanding of energy as used in physics education research, we try to work towards an interdisciplinary approach to research on the crosscutting facet of the energy concept, which is still too little recognised. In addition to

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further results for all grade levels and disciplinary contexts, longitudinal research will have to serve as confirmation, once an initial interdisciplinary learning progression has been formulated. Implementations of these findings for classrooms will require prior addressing in experimental design studies in order to develop and evaluate useful learning materials.

### 2.5 Conclusion

Young learners have been shown to be able to learn about energy through specially designed instruction (Van Hook and Huziak-Clark 2008). Our results show, that students also progress towards basic stages of the scientific understanding of energy in informal, often implicit learning opportunities in regular science/biology classes. Performance on the energy items was linked to students' reading and cognitive skills. Yet, no or little connection was found with students' interest in science and their grades in this subject. This led us—in combination with findings from school book analysis and teacher interviews—to conclude that energy as a concept itself is not likely a part of the regularly taught topics in science class, but that students instead formulate their own ideas about the energy concept on the basis of energy-relevant contexts they encounter in implicit energy learning opportunities at school. At primary level, understanding of energy conservation (and potentially degradation) is restricted in the contexts that we analysed, thereby confirming common concerns about early teaching of energy (Warren 1982). Since a basic understanding of conservation has been found conceptually possible at primary level (Shultz and Coddington 1981), we conclude from our findings that energy instruction has to focus more on interdisciplinary learning in order to make up for e.g., a bottleneck of young learners' energy understanding forming in biological contexts. The progression in understanding the concept in our data is not only likely to influence later energy learning in physics or chemistry through persistent alternative conceptions, but also through valid ideas developed in biological contexts. With respect to possible benefits of an early start of energy instruction (Novak 2005) and the often described difficulties in students' later understanding of energy (Herrmann-Abell and DeBoer 2011), we conclude that the numerous implicit opportunities for early energy learning in biological contexts could form the basis for a deeper understanding of the concept in students' later school life. This may enable learners to use energy more effectively as an interdisciplinary core idea and analytical tool for complex sets of facts.

### 2.6 Acknowledgments

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### 2.7 Online Materials

Material 1: Energy items

Material 2: Items parameters

### 2.8 References

- AAAS (American Association for the Advancement of Science). (2007). Getting assessment right. *2061 Today*, 17(1), 1–7.
- Ausubel, D. P. (1963). *The psychology of meaningful verbal learning*. New York: Grune & Stratton.
- Barak, J., Gorodetsky, M., & Chipman, D. (1997). Understanding of energy in biology and vitalistic conceptions. *International Journal of Science Education*, 19(1), 21–30.
- Bayrhuber C v, Hauber, W., & Kull, U. (2010). *Linder Biologie*. Gesamtband. (23 ed.). Braunschweig: Schroedel. [Linder biology school book for upper high school]
- Boyes, E., & Stanisstreet, M. (1990). Pupils' ideas concerning energy sources. *International Journal of Science Education*, 12(5), 513–529.
- Bransford, J. D., Brown, A. L., & Cocking, R. R. (1999). *How people learn: brain, mind, experience and school*. Washington: National Academy Press.
- Burger, J. (2001). *Schülervorstellungen zu “Energie im biologischen Kontext”-Ermittlungen, Analysen und Schlussfolgerungen*. Bielefeld: Bielefeld university, dissertation. [Student conceptions concerning energy in biological contexts-research, analysis and conclusions]
- [http://www.ipn.uni-kiel.de/de/das-ipn/personal#c4=H&b\\_start=0](http://www.ipn.uni-kiel.de/de/das-ipn/personal#c4=H&b_start=0). Accessed 16 January 2012.

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- Chabalengula, V., Sanders, M., & Mumba, F. (2011). Diagnosing students' understanding of energy and its related concepts in biological contexts. *International Journal of Science and Mathematics Education*, 10(2), 241–266.
- Chen, B., Eisenkraft, A., Fortus, D., Krajcik, J., Neumann, K., Nordine, J., & Scheff, A. (Eds.). (2014). *Teaching and learning of energy in K–12 education*. New York: Springer.
- Chow, G. C. (1960). Tests of equality between sets of coefficients in two linear regressions. *Econometrica*, 26(3), 591–605.
- Constantinou, C. P., & Papadouris, N. (2012). Teaching and learning about energy in middle school: an argument for an epistemic approach. *Studies in Science Education*, 48(2), 161–186.
- ACARA (Australian Curriculum, Assessment and Reporting Authority) (2013). *The Australian Curriculum – Science*. <http://www.australiancurriculum.edu.au/Download/F10>. Accessed 31 October 2013.
- Dawson-Tunik, T. L. (2006). Stage-like patterns in the development of conceptions of energy. In X. F. Liu & W. Boone (Eds.), *Applications of Rasch measurement in science education* (pp. 111–136). Maple Grove, Minnesota: JAM Press.
- Deci, E. L., & Ryan, R. M. (2012). *Intrinsic Motivation Inventory (IMI)*. <http://www.selfdeterminationtheory.org/questionnaires.%20%20%20%20Accessed%2027%20June%202012>. Accessed 27 June 2012.
- DfE (Department for Education) (2013). *Science programs of study: key stage 3-National curriculum in England*. [https://www.gov.uk/government/uploads/system/uploads/attachment\\_data/file/335174/SECONDARY\\_national\\_curriculum\\_-\\_Science\\_220714.pdf](https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/335174/SECONDARY_national_curriculum_-_Science_220714.pdf). Accessed 31 October 2013.
- Doménech, J., Gil-Pérez, D., Gras-Martí, A., Guisasola, J., Martínez-Torregrosa, J., Salinas, J., et al. (2007). Teaching of energy issues: a debate proposal for a global reorientation. *Science & Education*, 16(1), 43–64
- Driver, R., & Warrington, L. (1985). Students' use of the principle of energy conservation in problem situations. *Physics Education*, 20(4), 171.
- Duit, R. (1984). Learning the energy concept in school—empirical results from the Philippines and West Germany. *Physics Education*, 19(2), 59–66.
- Duit, R., & Kesidou, S. (1988). Students' understanding of basic ideas of the second law of thermodynamics. *Research in Science Education*, 18(1), 186–195.

## Chapter 2 (Study 1): Students' Energy Concepts at the Transition between Primary and Secondary School

---

- Duschl, R. A., Schweingruber, H. A., & Shouse, A. W. (2007). *Taking science to school: learning and teaching science in grades K-8*. Washington: The National Academies Press.
- EDK (Schweizerische Konferenz der kantonalen Erziehungsdirektoren) (2011). *Grundkompetenzen für die Naturwissenschaften-Nationale Bildungsstandards-Freigegeben von der EDK-Plenarversammlung am 16.Juni 2011*.  
[http://edudoc.ch/record/96787/files/grundkomp\\_nawi\\_d.pdf.%20Accessed%2031%20October%202013](http://edudoc.ch/record/96787/files/grundkomp_nawi_d.pdf.%20Accessed%2031%20October%202013). Accessed 31 October 2013.
- Field, A. (2009). *Discovering statistics using SPSS* (3rd ed.). London: Sage Publications.
- Finegold, M., & Trumper, R. (1989). Categorizing pupils' explanatory frameworks in energy as a means to the development of a teaching approach. *Research in Science Education*, 19(1), 97–110.
- Fleiss, J. L., Cohen, J., & Everitt, B. S. (1969). Large sample standard errors of kappa and weighted kappa. *Psychological Bulletin*, 72(5), 323–327.
- Forde, T. (2003). "When I am watching television I am not using any energy"—an empirical study of junior science students' intuitive concepts of energy. *Irish Educational Studies*, 22(3), 71–89.
- Gayford, C. G. (1986). Some aspects of the problems of teaching about energy in school biology. *European Journal of Science Education*, 8(4), 443–450.
- Goldring, H., & Osborne, J. (1994). Students' difficulties with energy and related concepts. *Physics Education*, 29(1), 26.
- Gottlieb, M., G. Haala, et al. (2010). *Natura 1. Biologie für Gymnasien-Nordrhein-Westfalen G8*. Stuttgart/ Leipzig: Klett. [Biology textbook for grammar schools in North Rhine-Westphalia, 8 year-curriculum]
- Heller, K. A., & Perleth, C. (2000). *KFT 4-12+R-Kognitive Fähigkeiten Test für 4.-12. Klassen, Revision*. Göttingen: Hogrefe. [Test of cognitive abilities in grades 4–12, revised]
- Herrmann-Abell, C. F., & DeBoer, G. E. (2011). Investigating Students' Understanding of Energy Transformation, Energy Transfer, and Conservation of Energy Using Standards-Based Assessment Items. *Paper presented at the 2011 National Association for Research in Science Teaching (NARST)*, Orlando, Florida, 3–6 April 2011.  
[http://www.project2061.org/publications/2061connections/2011/media/herrmann-%20abell\\_narst\\_2011.pdf](http://www.project2061.org/publications/2061connections/2011/media/herrmann-%20abell_narst_2011.pdf). Accessed 19 June 2014.
- Hirca, N. C., & Akdeniz, F. (2008). Investigating grade 8 students' conceptions of 'energy' and related concepts. *Journal of Turkish Science Education*, 5(1), 75–87.

## Chapter 2 (Study 1): Students' Energy Concepts at the Transition between Primary and Secondary School

---

- Holden, C. C., & Barrow, L. H. (1984). Validation of the test of energy concepts and values for high school. *Journal of Research in Science Teaching*, 21(2), 187–196.
- KMK (Sekretariat der ständigen Konferenz der Kultusminister der Länder in der Bundesrepublik Deutschland) (2005a). *Bildungsstandards im Fach Physik für den Mittleren Schulabschluss Beschluss vom 16.12. 2004*. München: Luchterhand. [German national education standards concerning physics for middle school graduation. Decision of December 16th 2004]
- KMK (Sekretariat der ständigen Konferenz der Kultusminister der Länder in der Bundesrepublik Deutschland) (2005b). *Bildungsstandards im Fach Biologie für den Mittleren Schulabschluss-Beschluss vom 16.12.2004*. München: Luchterhand. [German national education standards concerning biology for middle school graduation. Decision of December 16th 2004]
- Jin, H., & Anderson, C. W. (2012). A learning progression for energy in socio-ecological systems. *Journal of Research in Science Teaching*, 49(9), 1149–1180.
- Jütte, M., & Kähler, H. (2008). *Biologie heute entdecken 1. Ein Lehr- und Arbeitsbuch. Schleswig-Holstein*. Schroedel, Braunschweig. [Biology discovered today 1: A text- and workbook; for lower secondary school]
- Kirk, R. E. (1996). Practical significance: a concept whose time has come. *Educational and Psychological Measurement*, 56(5), 746–759. doi:10.1177/0013164496056005002.
- Kraft, D. (2009). *Pusteblume. Das Arbeitsbuch 3 und 4*. Braunschweig: Schroedel. [‘Dandelion’. Workbook for lower science education in grades 3 and 4]
- Krajcik, J. S., Sutherland, L. A., Drago, K., & Merritt, J. (2012). The promise and value of learning progression research. In S. Bernholt, K. Neumann, & P. Nentwig (Eds.), *Making it tangible: learning outcomes in science education* (pp. 261–283). Münster: Waxmann.
- Kurnaz, M. A., & Sağlam Arslan, A. (2011). A thematic review of some studies investigating students' alternative conceptions about energy. *Eurasian Journal of Chemistry and Physics Education*, 3(1), 51–74.
- Lacy, S., Tobin, R., Wisner, M., & Crissman, S. (2014). Looking through the energy lens: a proposed learning progression for energy in grades 3–5. In B. Chen, A. Eisenkraft, D. Fortus, J. Krajcik, K. Neumann, J. Nordine, & A. Scheff (Eds.), *Teaching and learning of energy in K-12 education*. New York: Springer.
- Lancor, R. A. (2012). Using student-generated analogies to investigate conceptions of energy: a multidisciplinary study. *International Journal of Science Education*, doi: 10.1080/09500693.2012.714512
- Lead States, N. G. S. S. (2013). *Next generation science standards: for states, by states*. Washington: The National Academies Press.

## Chapter 2 (Study 1): Students' Energy Concepts at the Transition between Primary and Secondary School

---

- Lee, H. B. (2008). Using the chow test to analyze regression discontinuities. *Tutorials in Quantitative Methods for Psychology*, 4(2), 46–50.
- Lee, H.-S., & Liu, O. L. (2009). Assessing learning progression of energy concepts across middle school grades: the knowledge integration perspective. *Science Education*, 94(4), 665–688.
- Lin, C.-Y., & Hu, R. (2003). Students' understanding of energy flow and matter cycling in the context of the food chain, photosynthesis, and respiration. *International Journal of Science Education*, 25(12), 1529–1544.
- Liu, X., & McKeough, A. (2005). Developmental growth in students' concept of energy: analysis of selected items from the TIMSS database. *Journal of Research in Science Teaching*, 42(5), 493–517.
- Liu, X., & Ruiz, M. E. (2008). Using data mining to predict K–12 students' performance on large-scale assessment items related to energy. *Journal of Research in Science Teaching*, 45(5), 554–573.
- Liu, X., & Tang, L. (2004). The progression of students' conceptions of energy: a cross-grade, cross-cultural study. *Canadian Journal of Science, Mathematics, and Technology Education*, 4(1), 43–57.
- Luyten, H. (2006). An empirical assessment of the absolute effect of schooling: regression-discontinuity applied to TIMSS-95. *Oxford Review of Education*, 32(3), 397–429.
- Meier, R. (2007a). *Mobile 3. Sachunterricht Nord*. Braunschweig: Westermann [Work- and textbook for grade 3 science education].
- Meier, R. (2007b). *Mobile 4. Sachunterricht Nord*. Braunschweig: Westermann [Work- and textbook for grade 4 science education].
- Messick, S. (1995). Validity of psychological assessment: validation of inferences from persons' responses and performances as scientific inquiry into score meaning. *American Psychologist*, 50(9), 741–749.
- Millar, R. (2005). *Teaching about Energy*. University of York: Department of Educational Studies. ISBN: 1-85342- 626-1.  
<http://www.york.ac.uk/media/educationalstudies/documents/research/Paper11Teachingaboutenergy.pdf>. Accessed 19 June 2014.
- Neumann, K., Viering, T., Boone, W. J., & Fischer, H. E. (2013). Towards a learning progression of energy. *Journal of Research in Science Teaching*, 50(2), 162–188.
- Nordine, J., Krajcik, J., & Fortus, D. (2010). Transforming energy instruction in middle school to support integrated understanding and future learning. *Science Education*, 95(4), 670–699.

## Chapter 2 (Study 1): Students' Energy Concepts at the Transition between Primary and Secondary School

---

- Novak, J. D. (2005). Results and implications of a 12-year longitudinal study of science concept learning. *Research in Science Education*, 35(1), 23–40.
- NRC (National Research Council and Committee on Conceptual Framework for the New K-12 Science Education Standards). (2012). *A framework for K-12 science education: practices, crosscutting concepts, and core ideas*. Washington: The National Academies Press.
- Pearson, E. S., & Hartley, H. O. (1954). The distribution of the ratio, in a single normal sample, of range to standard deviation. *Biometrika*, 41, 491.
- Remmers, H. H., Shock, N. W., & Kelly, E. L. (1927). An empirical study of the validity of the spearman-brown formula as applied to the Purdue rating scale. *Journal of Educational Psychology*, 18(3), 187–195.
- Retelsdorf, J., & Becker, M. (2012). "Reading development in a tracked school system: a longitudinal study over 3 years using propensity score matching". *British Journal of Educational Psychology*, 82(4), 647–671.
- Shultz, T. R., & Coddington, M. (1981). Development of the concepts of energy conservation and entropy. *Journal of Experimental Child Psychology*, 31(1), 131–153.
- Solbes, J., Guisasola, J., & Tarín, F. (2009). Teaching energy conservation as a unifying principle in physics. *Journal of Science Education and Technology*, 18(3), 265–274.
- Solomon, J. (1983). Learning about energy: how pupils think in two domains. *European Journal of Science Education*, 5(1), 49–59.
- Tatar, E., & Oktay, M. (2007). Students' misunderstanding about the energy conservation principle: a general view to studies in literature. *International Journal of Environmental & Science Education*, 2(3), 79–81.
- Trumper, R. (1990). Being constructive: an alternative approach to the teaching of the energy concept—part one. *International Journal of Science Education*, 12(4), 343–354.
- Trumper, R. (1993). Children's energy concepts: a cross-age study. *International Journal of Science Education*, 15(2), 139–148.
- Trumper, R. (1997a). The need for change in elementary school teacher training: the case of the energy concept as an example. *Educational Research*, 39(2), 157–174.
- Trumper, R. (1997b). A survey of conceptions of energy of Israeli pre-service high school biology teachers. *International Journal of Science Education*, 19(1), 31–46.



## Chapter 2 (Study 1): Students' Energy Concepts at the Transition between Primary and Secondary School

---

- Trumper, R., Raviolo, A., & Shnersch, A. (2000). A cross-cultural survey of conceptions of energy among elementary school teachers in training: empirical results from Israel and Argentina. *Teaching and Teacher Education*, 16(7), 697.
- Van Hook, S., & Huziak-Clark, T. (2008). Lift, squeeze, stretch, and twist: research-based inquiry physics experiences (RIPE) of energy for kindergartners. *Journal of Elementary Science Education*, 20(3), 1–16.
- Walter, O., Senkbeil, M., Rost, J., Carstensen, C. H., & Prenzel, M. (2006). Die entwicklung der naturwissenschaftlichen kompetenz von der neunten bis zur zehnten klassenstufe: Deskriptive befunde. In M. Prenzel, J. Baumert, W. Blum, R. Lehmann, D. Leutner, M. Neubrand, R. Pekrun, J. Rost, & U. Schiefele (Eds.), *PISA 2003: Untersuchungen zur Kompetenzentwicklung im Verlauf eines Schuljahres* (pp. 87–118). Münster: Waxmann [The development of scientific competence from grade 9 to grade 10: descriptive findings].
- Wandersee, J., Mintzes, J., & Novak, J. (1994). Research on alternative conceptions in science. In D. Gabel (Ed.), *Handbook of research on science teaching and learning*. New York: Macmillan.
- Warren, J. W. (1982). The nature of energy. *European Journal of Science Education*, 4(3), 295–297.
- Warren, J. W. (1983). Energy and its carriers: a critical analysis. *Physics Education*, 18(5), 209–212.



## CHAPTER 3

# How Do Students Understand Energy in Biology, Chemistry, and Physics? Development and Validation of an Assessment Instrument (Study 2)

### Abstract

One major aim of science education is to help students develop an integrated understanding of science. Educational standards identify core disciplinary ideas and cross-cutting concepts as a means to achieve this goal. *Energy* is a concept that is both a disciplinary core idea in biology, chemistry, and physics, as well as a concept cutting across these three contexts. In extension of previous, mostly discipline-specific studies on energy learning, this study targets the development of a cross-disciplinary energy understanding. As no instrument to assess such an understanding in middle and high school was yet available, we developed and validated an instrument for a systematic comparison of students' energy understanding across contexts from biology, chemistry, and physics. In a cross-sectional study, we administered this new instrument to  $N = 752$  students at the end of grades 6, 8 and 10. The results suggest that the test instrument can reliably and validly assess students' energy understanding in the three disciplinary contexts. The findings reveal similar progression trends in students' energy understanding across biology, chemistry, and physics. Discipline-specific differences in understanding were observed with respect to the four energy aspects forms, transfer, degradation, and conservation. This article concludes with a discussion of the connection and integration of energy understanding across disciplines. The developed instrument and additional information on progression patterns in specific contexts are provided in the online materials.

### Keywords

Energy; Crosscutting Concept; Core Idea; Biology; Chemistry; Physics; Knowledge integration; Curricular coherence

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### 3.1 Introduction

Large-scale assessments have identified limited connections between content elements in both students' knowledge and curricula (Bransford, Brown, & Cocking, 2000; Michaelis, Shouse, & Schweingruber, 2008). Experts, on the contrary, possess a well-connected knowledge base that is built around the core ideas of their domain (Bransford et al., 2000). These findings underline the need to particularly support low-achieving students who struggle to connect the wide-range of contents that they learn in science (Linn, Eylon, & Davis, 2004; Michaelis et al., 2008). Accordingly, multiple countries have revised their science standards to include disciplinary core ideas and interdisciplinary crosscutting concepts as a means to organise and connect science contents (e.g. Next Generation Science Standards [NGSS], 2013). The overarching goal is to foster cumulative learning and thereby enable students to develop a more connected science understanding. *Energy* is the only concept that is considered both a core idea in biology, chemistry, and physics, as well as a concept cutting across these disciplines.

With regard to energy as a core idea, learning progressions (Alonzo & Gotwals, 2012) have been proposed as a basis for designing teaching materials and assessment tools in order to help students develop a deeper understanding of core ideas and crosscutting concepts (Fortus, Sutherland, Reiser, & Krajcik, 2015). Descriptions of how students progress in understanding the energy concept have mostly focussed on individual disciplines (Jin & Anderson, 2013; Lacy, Tobin, Wiser, & Crissman, 2014; Neumann, Viering, Boone, & Fisher, 2013). To our knowledge, a systematic assessment and comparison of middle school students' progressing energy understanding *across* different disciplinary contexts has not yet been presented. Due to the discipline-specific scope of most prior studies, a test instrument for a respective study is not yet available (Jin & Anderson, 2012; Liu and McKeough, 2005; Neumann et al., 2013).

To address this gap in the current research base, our article first presents the development of a 43-item test instrument on energy understanding across biology, chemistry, and physics contexts. Secondly, findings are presented from administering this instrument to a cross-sectional study with  $N = 752$  students from grades 6, 8, and 10, thereby providing first insights to students' progressing energy understanding across disciplinary contexts.

## 3.2 Theoretical Background

### 3.2.1 Energy as a Core Idea and a Crosscutting Concept in Science Education

The energy concept is a fundamental idea in science (e.g. Bevilacqua, 2014; Bodzin, 2012; Chen et al., 2014; Duit, 1984) and has accordingly been identified as a central concept for science education.

*From a content perspective, learning about energy can facilitate the analysis of science contexts.* Experts were found to be able to quickly recognise and address the key ideas relevant for solving a given problem (Bransford et al., 2000). As one such key idea, the energy concept is helpful for addressing problems in various science contexts. Students can use the energy concept as a tool with which they analyse energy changes within the boundaries of a system. For example, analysing the conversion between different energy forms can enable students to make predictions about the extent to which processes can occur in a defined system (Lerner & Trigg, 2005).

*As a core idea, the energy concept can support learning by organising knowledge.* Students learn about energy in a wide variety of contexts which require them to transfer energy-related knowledge along a spatial, temporal, and domain-specific continuum (Pugh & Bergin, 2006). Effective cognitive structures for knowledge transfer have been described as interconnected. Experts' knowledge structures are organised around core ideas, which were found to support knowledge transfer (Bransford et al., 2000; Pugh & Bergin, 2006). If science instruction provides adequate opportunities for knowledge transfer, for example, via instruction along core ideas, students are considered to organise newly learnt contents more cumulatively and thereby build an integrated science understanding. By 'integration of understanding', we refer to the construct of *knowledge integration*, i.e. the extent to which knowledge about encountered phenomena, situations, and abstractions is added, differentiated, and evaluated in relation to prior conceptions (Linn et al., 2004, p. 30). As students have been shown to rather spontaneously add knowledge instead of differentiating it, fostering students' levels of knowledge integration is a goal of ongoing research (Linn et al., 2004). As such, an integrated science understanding is considered beneficial for the critical analysis, evaluation, and decision making in future challenges (Sakschewski, Eggert, Schneider, & Bögeholz, 2014).

To support knowledge integration in science education, core ideas and crosscutting concepts have been introduced into the science standards and curricula of several countries (e.g. NGSS, 2013). At the level of individual disciplinary contexts, *core ideas* aim to organise and revise contents, while *crosscutting concepts* are intended to enable students to organise contents more coherently across disciplinary boundaries

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(NGSS, 2013). Energy incorporates a unique position, as it is both a core idea in different science disciplines, as well as a crosscutting concept spanning across them. In order to be able to use energy as a crosscutting concept, aspects of understanding energy in different disciplines have to be integrated by students across disciplinary boundaries.

In conclusion, core ideas such as energy can function as a pivot to underline links between contents and highlight similarities in the complexity of science contents. Thereby, core ideas are thought to facilitate knowledge integration of students' science understanding. However, the extent to which this goal is achieved depends on the coherence (Fortus & Krajcik, 2012) with which concepts like energy are taught across different (disciplinary) contexts (Fortus et al., 2015).

### 3.2.2 Research on Students' Energy Understanding

Four aspects have been identified to play a major role in understanding the energy concept: (1) Energy forms and sources, (2) energy transfer and transformation, (3) energy degradation and dissipation, and (4) energy conservation (e.g. Duit, 1984; Lancor, 2015; Neumann et al., 2013). While these four aspects are part of instruction in all disciplinary fields, the focus on them can vary substantially across different disciplinary backgrounds (Eisenkraft et al., 2014). A biology approach typically analyses energy transfer and transformation in open systems, for example, animals. The extent to which an organism transforms limited available energy into desirable energy forms (e.g. kinetic energy) instead of degrading it into thermal energy is an important factor in natural selection. Therefore, the efficiency of energy transformations and the emission of heat are often focussed on in biological approaches (e.g. in energy flow diagrams). In contrast, a physics perspective may address the question to what extent work can be conducted through an energy transformation. Here, the focus lies on work, while emitted heat is frequently seen as a by-product or even disregarded when the analysis focuses on idealised, closed systems (Stacy, Chang, Coonrod, & Claesgens, 2014). The four energy aspects have been used to analyse energy understanding (e.g. Herrmann-Abell & DeBoer, 2011; Liu & McKeough, 2005) and to structure energy teaching (e.g. Nordine et al., 2010). Further characteristics of energy understanding, for example, the relevance of systems boundaries, have been discussed by Doménech et al. (2007).

Generally, students' energy understanding has been found to be limited (e.g. Chen et al., 2014; Watts, 1983). A wider body of studies focused on (persistent) alternative conceptions and categorised these into frameworks (Boyes & Stanisstreet, 1990; Burger, 2001; Nordine et al., 2010; Trumper, 1993; Watts, 1983). Learning difficulties with respect to the energy concept are imposed, for example, by the concept's abstract nature, its wide and varied applications, connotations in everyday language (e.g.

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Liu & Ruiz, 2008; Trumper, 1993), as well as confusions with related concepts such as force, work, power (Kurnaz & Sağlam-Arslan, 2011) or matter (Lin & Hu, 2003).

The following paragraphs provide an overview of research on students' energy understanding. These studies span from early, less discipline-specific energy learning via discipline-specific aspects of energy understanding, towards differentiation and integration processes in students' progressing energy understanding.

**Early energy learning.** Few studies have addressed the energy understanding of young learners (e.g. Lacy et al., 2014). In an energy learning sequence initially suggested by Driver, Squired, Rushworth, and Wood-Robinson (1994), students are expected to enter formal education with alternative conceptions from everyday experiences, such as a feeling of being 'energetic'. Next, the students progress by relating energy first to living and then to non-living entities before apprehending stored energy and, finally, energy degradation and conservation. Research suggests that early energy learning is possible (Shultz & Coddington, 1981), and can be sustainably effective until high school (Novak, 2005). If alternative conceptions are explicitly addressed (Trumper, 1993), alternative ideas such as the application of energy forms or energy as a quasi-material substance, can be helpful scaffolds for later understanding (Jin & Anderson, 2012; Lancor, 2015).

**Energy learning in different disciplinary contexts.** Since studies on energy understanding in physics have been summarized in several publications (e.g. Kurnaz & Sağlam-Arslan, 2011; Millar, 2005; Nordine et al., 2010; Tatar & Oktay, 2007), this section focuses on biology and chemistry contexts. In these two disciplines, students' alternative conceptions have been found to exhibit similar learning constraints as in physics, for example, the difficulty in identifying reference systems. Further discipline-specific ideas (e.g. concerning endo-/exothermic reactions) have been described by Tastan et al. (2008). Chemical engineering students' energy understanding in bond breaking/bond forming has been shown to rely strongly on textbook definitions. Similar to physics, students only incompletely applied normative conceptions of energy conservation and degradation and only rarely reasoned at concrete and abstract levels simultaneously (Liu, Ebenezer, & Frazer, 2002).

Energy understanding in chemical reactions forms the basis for detailed analyses of energy changes in biology (Quinn, 2014). However, the connection in energy understanding between the two contexts is not clearly understood (Hirça et al., 2008). Energy understanding in biology is frequently linked to concrete manifestations (e.g. energy sources) instead of abstract notions such as work or conservation (Forde, 2003). Learning opportunities are often more contextualised than in physics, thereby promoting

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confusion between the scientific energy concept and energy connotations in everyday language (Jin & Anderson, 2012; Lin & Hu, 2003). Categories of students' energy understanding in life processes have been abstracted from a larger questionnaire study (Burger, 2001). Specific alternative student ideas on energy sources for living beings have been identified, for example, in the ideas that plants get energy from soil, air or water (Boyes & Stanisstreet, 1990). While the analysis of energy flow through ecosystems is a highly relevant aspect of understanding energy in biological contexts (Eisenkraft et al., 2014), students frequently confuse system boundaries or cycle versus flow conceptualisations (Doménech et al., 2007; Jin & Anderson, 2012; Lin & Hu, 2003). The application of energy flow charts builds on an understanding of energy conservation. In contrast, the threshold-concept character of energy in biology is mostly limited to transfer and transformation (Ross et al., 2010). A focus on the latter energy aspect also becomes apparent in learning materials and curricula, while energy degradation/dissipation and energy conservation are less understood by students and only sparsely represented in biology instruction (e.g. Forde, 2003; Opitz, Harms, Neumann, Kowalzik, & Frank, 2015). Chabalengula et al. (2011) found that even university students exhibit difficulties in transferring energy contents from physics to biological contexts, thereby raising the question how energy understanding is related between disciplinary contexts (Lancor, 2015).

### 3.2.3 Promoting Integrated Energy Understanding

Learning progressions are models that describe how core ideas are understood in successively more complex ways (Krajcik, Sutherland, Drago, & Merritt, 2012; Michaelis et al., 2008). If curricula are organised along learning progressions, students are thought to connect knowledge more meaningfully around the respective core idea and thereby achieve a more integrated science understanding (Alonzo & Gotwals, 2012; Linn et al., 2004). Learning progressions are derived and validated through empirical research findings. Principles for assessing these data have been described by Krajcik et al. (2012) and, more specifically, with regard to an energy learning progression by Neumann et al. (2013).

In the past years, several studies have presented energy learning progressions or provided data to inform their development. Predictors for energy test scores have been found—in this order of impact—in the cognitive levels of tasks, the context (everyday vs. scientific), students' age, and in the specific content (Liu & Ruiz, 2008). These results underline the impact that assessment designs can have on the interpretation of study findings and the development of learning progressions (Alonzo & Gotwals, 2012). Most approaches to an energy learning progression have so far focussed on physics contexts.



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In these studies, students were found to reach an understanding of energy forms at elementary level, while understanding of energy transfer was marginally achieved in lower secondary school. Energy degradation and conservation were not even fully understood in high school (Liu & McKeough, 2005). Similar results have reported, for example, by Neumann et al. (2013) or Herrmann-Abell and DeBoer (2011). Dawson-Tunik (2008) found that students' progressing energy understanding is characterised by both consolidation and transitory stages during which students achieve higher levels of abstraction. Other learning progressions have been proposed for specific contexts, for example, in relation to energy understanding in carbon-transforming processes (Jin & Anderson, 2012). These approaches can provide valuable insights for an interdisciplinary energy learning progression.

Progressing energy understanding should also be characterised by the ability to apply the energy concept across an increasing number of different contexts and disciplines (Jin & Anderson, 2012; Novak, 2005). Accordingly, recent studies have focused on integration processes (Linn et al, 2004) that occur as students learn about energy. Nordine et al. (2010) designed a teaching sequence that successfully fostered a more integrated energy understanding. While levels of energy knowledge integration have been shown to increase across middle school, they are generally low, especially among life science students (Lee & Liu, 2009). At an interdisciplinary level, purpose-built curricula with high levels of coherence between individual units have been able to promote integrated energy understanding across disciplines and school years (Fortus et al., 2015).

These findings show that the aforementioned learning goal of a crosscutting energy concept is practically feasible. In a qualitative analysis, Lancor (2015) found that most university students employed a substance-based analogy for energy. Furthermore, students in discipline-specific courses referenced the energy aspects more prominently than students in a general science course. Hence, knowledge integration in students' energy understanding likely varies with the structure of the educational system. With respect to energy understanding in different disciplines, Park (2013) showed that college students' discipline-specific subsets of energy understanding are highly related, especially between physics and chemistry (biology–chemistry:  $r = .79$ ; biology–physics:  $r = .77$ ; chemistry–physics:  $r = .91$ ). These findings indicate that energy understanding across disciplines is either built on one energy conceptualisation that is consistently applied to varying contexts, or, that students' energy understanding is generally vague, possibly based on alternative conceptions from everyday language, and therefore highly related between disciplines.

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### 3.2.4 Research Objectives and Questions

A summary of previous research on students' energy understanding shows that (i) the majority of studies have focused on physics contexts (e.g. Liu & McKeough, 2005), whereas energy learning in other disciplinary contexts has received little attention (cf. Jin & Anderson, 2012). (ii) In addition, it has been concluded that learners are likely challenged by connecting energy knowledge across topics from different disciplines, thus potentially making it difficult for learners to use energy in the sense of a crosscutting concept (Eisenkraft et al., 2014). However, few empirical insights describe how students' progressing energy understanding in different disciplinary contexts is interconnected (Hirça et al., 2008; Lancor, 2015; Park, 2013). Specifically, research has widely overlooked cross-disciplinary energy learning in middle school and high school. A more robust empirical basis in this field is important for the development of energy learning progressions and the strengthening of coherence in energy instruction across topics and school science subjects (Fortus et al., 2015). (iii) To our knowledge, a test instrument for the systematic comparison of middle/high school students' progressing energy understanding across different disciplinary contexts has not yet been presented. Prior instruments focus on single disciplinary contexts (e.g. Jin & Anderson, 2012; Neumann et al., 2013) or employ items from varied disciplinary backgrounds (e.g. Lee & Liu, 2010; Liu & McKeough, 2005), thus hampering a systematic comparison of students' energy understanding across disciplines. To address these issues in our study, we pursued two objectives:

Firstly, we aimed to develop and validate an instrument to assess progressing energy understanding across middle and high school biology, chemistry, and physics contexts. Secondly, this instrument was deployed in a cross-sectional study to obtain insights into cross-disciplinary energy understanding. Our study was guided by two research questions (RQs):

(RQ 1) What progression trends of energy understanding can be identified in biology, chemistry, and physics contexts?

(RQ 2) How is students' energy understanding related across these contexts?

## 3.3 Methods

### 3.3.1 Procedure

With respect to the first objective, an instrument for energy understanding in biology, chemistry, and physics contexts was developed around a shared framework for energy understanding (Neumann et al., 2013). This approach was taken to ensure a parallel test

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design with similar items in the three disciplinary contexts, hence allowing comparisons across these. For the second objective, a cross-sectional study was employed in which students' energy understanding was assessed via the new instrument at the end of grades 6, 8, and 10. The study also assessed students' crystallised intelligence (CI—LPS subtests 1 and 2, Horn, 1983) as a control variable. The assessment of crystallised intelligence served two purposes: The variable (i) provided an additional measure to assess the comparability between students at different grade levels, and (ii) it was used—in extension to previously analysed covariates (Opitz et al., 2015)—as an important external variable with which to address discriminant validity. To facilitate readability, the rationale for specifically including this variable is provided in the validity discussion.

### 3.3.2 Instrument Development (Objective 1)

**Item construction.** For this study, physics and biology items were employed from previous studies (Neumann et al., 2013; Opitz et al., 2015). These items, as well as newly developed chemistry items, were constructed around the same framework and used similar guidelines for item development. The underlying two-dimensional framework of energy understanding was operationalised for the development of all items. In this framework, the first dimension concerns the aforementioned four energy aspects, while the second dimension consists of four levels of increasing cognitive complexity (facts, mappings, relations, and concepts). The dimension of energy aspects was used to generate the respective contents for the items, while the dimension of cognitive complexity was used as a means to vary item difficulties (for details on the theoretical justification of the framework see Neumann et al., 2013). The operationalisation of items showed that the number of factors that needed consideration varied substantially across contexts and disciplines. To take this variance into account, three types of multiple choice items were employed (1-attractor, 2-attractor, and complex MC-items). The differences in item type had only a small effect on student performance (see online material 2 for details).

All items were controlled for adequate and comprehensive language, i.e., by using feedback from teachers for chemistry items and qualitative student feedback for the physics and biology items (American Association for the Advancement of Science, 2007).

**Item selection.** The instrument was designed for students from lower middle to high school. In this regard, a total of 128 items (biology: 48; physics: 48; chemistry: 32) were field tested with  $N = 336$  grade 6, 8, 10, and 12 students. In field testing, each item was answered by an average of 78 students. A total of 48 items were selected for the instrument (16 items per disciplinary context, four items per energy aspect in each

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discipline). As the instrument was designed as a developmental test, grade 10 and 12 students served as a reference group with respect to the instruments' distribution of item difficulties. Item selection was conducted iteratively along the following sequence of criteria and included new parameter computation after each step: (1) Exclusion of items with negative correlation between solution probability and grade level ( $r < -.1$ )<sup>3</sup>, (2) exclusion of items with a discrimination  $< .15$ , (3) selection of discipline-specific item sets with regard to best fitting normal distribution of item difficulties in grade 10/12, (4) selection of items with the largest possible item discrimination, and (5) selection of items in accordance to the distribution of levels of cognitive complexity. All items, item parameters and attractor/distractor selection frequencies for each grade level are provided in online material 1.

**Item discipline-specificity.** In addition to the items' construction by researchers from the respective disciplines, an expert rating was conducted to ensure the items' discipline-specificity.  $N = 12$  high school teachers and scientists from biology, chemistry and physics rated—without further instruction—all 48 items with respect to the items' disciplinary background. The findings from the rating relate to the first research objective and will be presented in the results section.

### 3.3.3 Data Collection and Sample for the Study (Objective 2)

Students in grades 6, 8 and 10 received the same 48 items. Data sampling was conducted during school lessons in the last four weeks of the school year. All students were able to finish the test within the 90-minute testing sessions. 47 classes from 10 metropolitan secondary schools in northern Germany (Hamburg) participated in this study, including all socio-economic strata (Hamburg Social Index, range 1–6,  $m = 4.00$ ) and both prevalent school-types—*Gymnasium* (high-performance students) and *Stadtteilschule* (mixed-performance students). Participating students received science classes with content from mixed disciplinary backgrounds until grade 6 and separate biology, chemistry, and physics classes from grade 7 onwards. The relevant curricula and science standards for Hamburg (e.g. KMK 2005a, 2005b, 2005c) include energy as a core idea and a concept to bridge the science subjects. The curricula list numerous energy learning opportunities from grade 2 to 12/13 (see online material 3).

The sample analysed below consisted of  $N = 752$  students from grade 6 ( $m_{\text{age}} = 12.3$ ;  $n = 255$ ), 8 ( $m_{\text{age}} = 14.3$ ;  $n = 268$ ) and 10 ( $m_{\text{age}} = 16.4$ ;  $n = 229$ ). Table 3.1 shows

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<sup>3</sup> Negative correlations between item solution probability and grade level were considered likely to represent contents specific to individual grade levels only. However, the interest of this study lay—with respect to cumulative learning—on contents addressed across grade levels.

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characteristics of the subgroups (grade levels). The data indicate comparability between the groups, with significant differences only between the percentage of students from high-performance schools and the socio-economic index, the latter indicating only negligible differences. To account for these small differences, the results below were weighted with regard to the school types.

**Table 3.1.** Characteristics of subsamples (grade levels). Different lower case letters denote significant differences,  $p < .05$ , *n.s.* = not significant

Grade level	Average crystallised intelligence, <i>T</i> -standardised	Percentage of male students	Percentage of students from high-performance schools	Average socio-economic index
6	46.07 – <i>n.s.</i>	51.8 – <i>n.s.</i>	56.9 – <i>a</i>	3.97 – <i>a</i>
8	45.03 – <i>n.s.</i>	57.4 – <i>n.s.</i>	84.0 – <i>b</i>	4.43 – <i>b</i>
10	45.97 – <i>n.s.</i>	50.2 – <i>n.s.</i>	64.6 – <i>b</i>	4.49 – <i>c</i>
<b>6–10</b>	45.69	53.13	67.6	4.30

### 3.3.4 Statistical Procedures

For the first objective, the discipline-specificity of the items was assessed through the expert rating described above. Fleiss Kappa ( $\kappa$ ) was used as an index to describe the agreement between the raters. The discussion of validity also concerned the question how much variance the assessment could explain and to what extent the findings were generalizable from the sample to the population level. These issues were addressed by using  $r^2$  and shrinkage indices derived from (forced entry) multiple regression models (Field, 2009, p. 221). As this was an auxiliary analysis, its findings are presented in online material 4).

For the second objective, mean energy scores for the test and the respective subtests were employed as the measure for comparison. Outliers were assessed via standard SPSS box plots and then excluded from the data presented below. Data weighting with regard to the school-type was conducted according to recommendations by Maletta (2007). Neither the exclusion of outliers nor the data weighting had substantial effects on the results. Comparisons of energy scores across grades were conducted via ANOVA, using conservative Games-Howell post-hoc tests (Field, 2009, p. 374). Effect sizes were calculated via  $\omega^2$  (Field, 2009, p. 391; Kirk, 1996).

In addition to these classical statistics procedures, the objectives of this study have also been addressed by Rasch analysis (Wu, Adams, and Wilson, 2007). The advantage of this method is, for example, that the adequacy of item difficulties can be

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easily assessed with regard to the ability spectrum of a given sample. However, some of the in-detail analyses for this article were not computable through Rasch estimation. The results from Rasch analysis, however, produced results similar to those from the classical statistics procedures mentioned above. Thus, in order to avoid confusion between the different statistical procedures, this paper presents findings solely from classical statistic. Interested readers can access the methods and results from Rasch analysis in online material 4. These results incorporate a Wright map of student abilities/item difficulties, WLE person separation reliabilities, and an analysis of differential item functioning (DIF) regarding gender.

### 3.4 Results

#### 3.4.1 Instrument Development (Objective 1)

**Item discipline-specificity.** The 12 raters agreed on a 'near-perfect' basis ( $\kappa = .81$ , Kirk, 1996) on the discipline-specificity of the items. Similar values were obtained for the items of each disciplinary item set ( $\kappa = .78-.85$ ). The rating was used to sort items into four categories: (1) High discipline-specificity (> 80 % agreement, 34/48 items), (2) substantial specificity (66–80% agreement, 6/48 items), (3) lesser specificity (50–66% agreement, 3/48 items), and, (4) specificity for another than the intended discipline (> 50% agreement on another discipline, 5/48 items). While the three items from category (3) were kept to represent more interdisciplinary contexts, the five items from group (4) were excluded from further data analyses. Therefore, the final instrument consisted of 43 items (biology: 15, chemistry: 13, physics: 15).

**Reliability.** Reliabilities across grades were high for the complete test ( $\alpha = .85$ ) and satisfactory for the three subtests ( $\alpha = .61-.71$ ). Similar values were obtained from the Rasch analysis (compare online material 4): Across grades 6–10, WLE person separation reliability was high (.82) for the full test (grade 6: .57, grade 8: .76, grade 10: .83) and sufficient to satisfactory for the three disciplinary subtests (.58–.62).

**Item difficulties and discrimination.** Item parameters for each item and grade level are provided in online material 1. In the reference group grade 10, the distribution of item difficulties was widespread and could thereby address students of all abilities (range of item difficulties,  $p = .03-.96$ ). Due to the study's original intent to also include grade 12 students, mean item difficulties slightly exceeded student abilities (grade 10:  $m_{\text{difficulty}} = .42$ , biology: .36, chemistry: .35, physics: .53). Item discrimination increased with grade

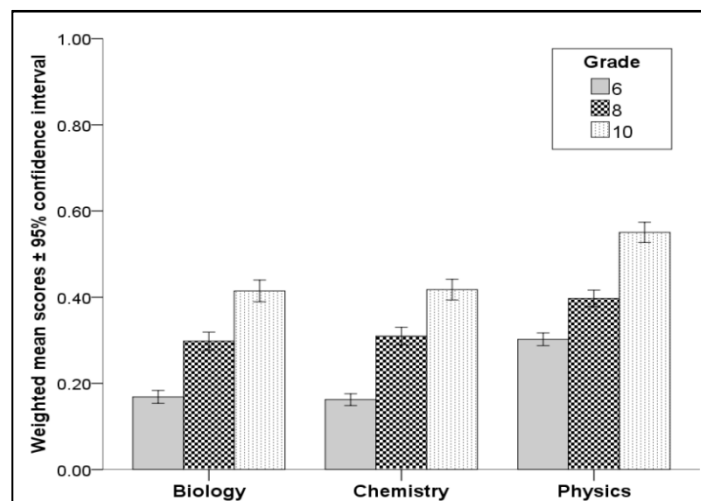
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level and showed good values across grades 6 to 10 ( $m_{\text{biology}} = .32$ ,  $m_{\text{chemistry}} = .29$ ,  $m_{\text{physics}} = .34$ ).

**Control variable.** The connection between energy scores and age-standardised crystallised intelligence showed low correlations with energy understanding both across ( $r = .14$ ,  $p < .01$ ), and within grades (grade 6:  $r = .25$ ; grade 8:  $r = .17$ ; grade 10:  $r = .22$ ,  $p < .01$ ).

### 3.4.2 Energy Understanding across the Three Disciplines (Objective 2)

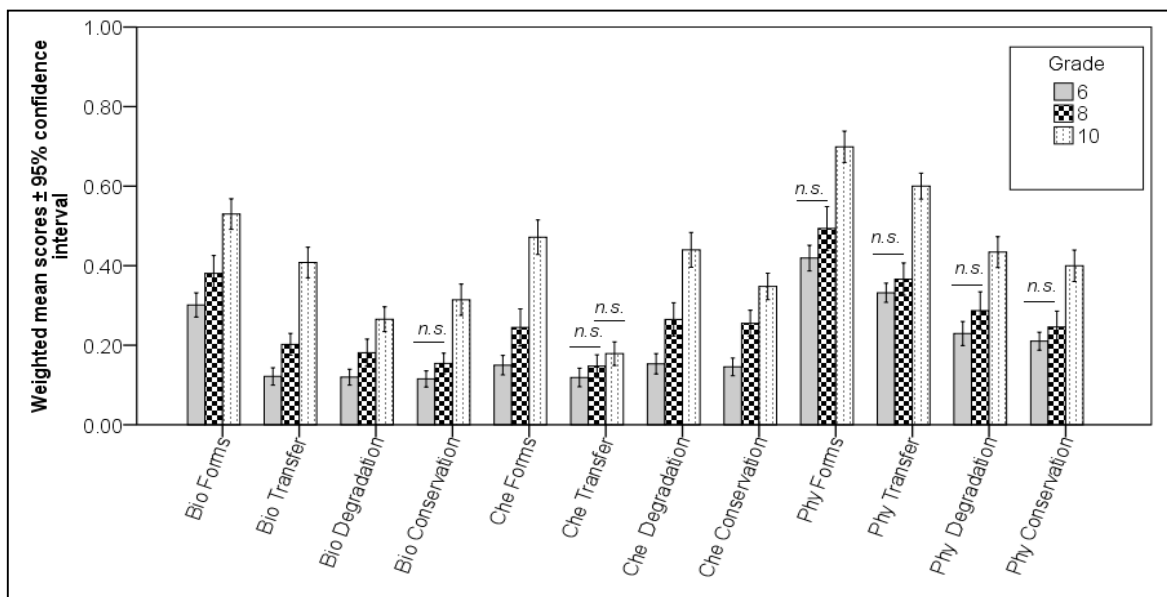
**Progressing understanding across grades 6–10 (RQ 1).** With respect to the first research question, Figure 3.1 shows progression trends in energy understanding in biology, chemistry, and physics contexts for grades 6 to 10. Student scores increased significantly and to a similar extent in all contexts (biology:  $F = 121.37$ ,  $df = 2$ ,  $p < .001$ ; chemistry:  $F = 132.83$ ,  $df = 2$ ,  $p < .001$ ; physics:  $F = 156.89$ ,  $df = 2$ ,  $p < .001$ ). These progressions relate to ‘large’ (Kirk, 1996) effects in biology ( $\omega^2 = .24$ ), chemistry ( $\omega^2 = .26$ ) and physics ( $\omega^2 = .29$ ).



**Figure 3.1.** Progressing energy understanding in biology, chemistry, and physics contexts from grades 6 to 10. All differences between grade levels are significant,  $p < .001$

**Discipline-specific foci in energy understanding.** In the three disciplinary contexts, students showed similar patterns in their progressing understanding along the four energy aspects, especially in biology and physics (Figure 3.2). Here, only 3–4 items were available per energy aspect in each of the three subtests. Consequently, the results address broad comparisons of mean item difficulties, but not the comparison of individual student performances.

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**Figure 3.2.** Grade 6–10 students’ mean scores on items for four energy aspects in biology (‘Bio’), chemistry (‘Che’), and physics (‘Phy’) contexts. Mean scores correspond to mean item difficulties ( $p$ ). Differences between columns are significant ( $p < .01$ ), if not marked as *n.s.* ( $p > .05$ )

Items on energy forms were the easiest in all disciplines and across the grade levels, while conservation items were generally more difficult. In biology and physics, mean item difficulties increased along the following order of energy aspects: forms, transfer, degradation, and/or conservation. While in biology, degradation and conservation items were similarly difficult, physics items on energy conservation were more difficult and only answered correctly by older students than the items on degradation. In chemistry, the progression pattern differed from biology and physics, as items for energy transfer were comparatively difficult, while the share of students that answered these items correctly did not increase significantly across grades. When related to the distribution of item difficulties across aspects in biology and physics, students scored comparatively higher on chemistry degradation items.

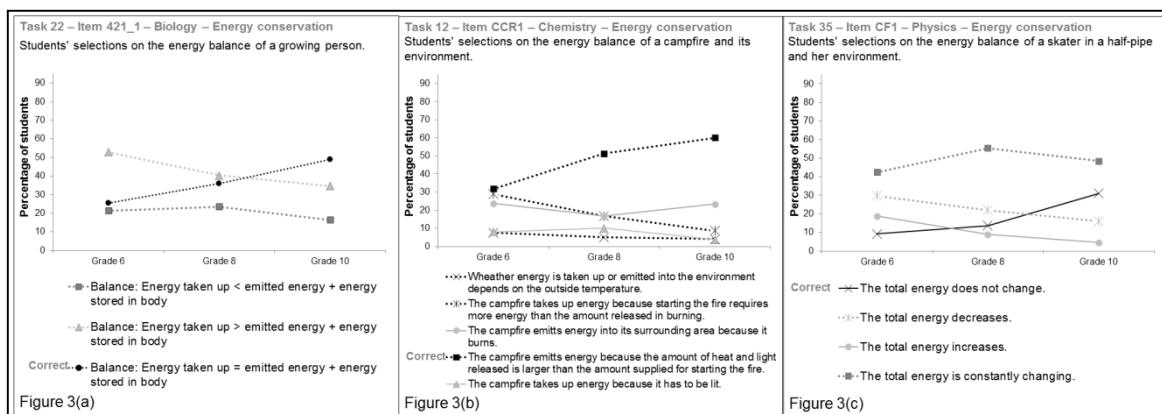
**Relation of energy understanding between disciplines (RQ 2).** With respect to the second research question, student scores on the three discipline-specific subtests were strongly correlated with each other (across grades 6 to 10: biology–chemistry,  $r = .63$ ,  $p < .001$ ; biology–physics:  $r = .62$ ,  $p < .001$ ; chemistry–physics,  $r = .60$ ,  $p < .001$ ). Only slightly higher correlations were obtained in a random assignment of the instrument’s 43 items to three subscales ( $r = .64$ – $.69$ ,  $p < .001$ ).

**Examples of progressing understanding.** To illustrate the relation of energy understanding across disciplines, Figures 3.3(a)–(c) present selection frequencies of



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attractors and distractors in items that concern energy conservation in one exemplary biology, chemistry and physics context, each.



**Figure 3.3 (a–c).** Progression trends in distractor/attractor selection frequencies for one biology, chemistry, and physics item on energy conservation. As data are cross-sectional, trend lines between data points are only auxiliary

All three items focus on identifying energy balances. In the biological item (Figure 3.3a), the percentage of students who correctly identified energy uptake to be equal to energy storage and release increased by the factor two from grade 6 to 10 (grade 6: 26%, grade 10: 49%). Here, a relatively large percentage of students retained (53% → 35%) the notion that energy uptake was larger than energy storage and release, thereby relating to the idea of energy 'loss'. The chemistry item on the energy balance of a campfire (Figure 3.3b) shows a similarly large increase in students' ability to identify the correct energy balance (32% in grade 6, 60% in grade 10). The physics item (Figure 3.3c) showed a comparable developmental pattern, even though generally fewer students (grade 6: 9%, grade 10: 31%) harboured the correct idea that the total energy of the skater and his/her environment are constant.

Tendencies of students to select similar answering options across disciplines can also be found in other items. For example, students adhered similarly to the alternative idea that energy is used up in a process. In a physics context, 45% of the 6<sup>th</sup> to 10<sup>th</sup> graders selected the distractor describing that a pendulum uses up its kinetic energy when swinging back and forth (item DF1, Task 32, see online material 1). Similarly invariant across grade levels, roughly 30% of 6<sup>th</sup> to 10<sup>th</sup> graders selected the answering choice that energy from gasoline is used up, if a combustion engine uses fuel to propel a car (chemistry item CDC1, Task 9). Similar examples of progressing energy understanding can be found for all 43 items in online material 1.

### 3.5 Discussion

#### 3.5.1 Instrument Development (Objective 1)

**Reliability.** Similar reliability values in terms of Cronbach's  $\alpha$  and WLE person separation reliability (see online material 4) indices support the findings presented in this study. The observed reliability is satisfactory for the purpose of identifying broad learning trends across disciplines. The lower values in grade 6 indicate that the subtests for the three disciplinary contexts should not be employed as stand-alone tests for students below grade 8.

**Validity.** Evidence and arguments in relation to six aspects of validity are discussed according to suggestions and standards by the Joint Committee (2014).

**Test content.** Energy is clearly a core idea in curricula and science standards relevant for the sample tested in this study (KMK 2005a, 2005b, 2005c; see online material 3). Unlike in the NGSS (2014), however, the respective expectations for energy learning were, in most cases, too broadly formulated for a systematic development of test items. Thus, the developed instrument does not assess specific standards with respect to energy learning. Instead, the fit between item contents and expectations expressed in science standards was approximated by ensuring that the four energy aspects (see framework, Neumann et al., 2013) were adequately representing the learning expectations. This criterion was assessed through analyses of school textbooks and curricula, as well as through a teacher survey (Opitz et al., 2015). In other educational systems, the four energy aspects have likewise been described as central elements of energy education in different disciplinary contexts (e.g. Lancor, 2015; Liu & McKeough, 2005; Wang, Wang, & Wei, 2014).

**Cognitive processes.** Think-aloud protocols (Ericsson & Simon, 1993) were conducted to assess if students ( $N = 9$  from grades 6, 8, 10) used the intended cognitive processes for solving items of the new instrument. The results are detailed in Wernecke (2013). Students' think-aloud protocols were analysed by differentiating content-related strategies of item solving (i.e. arguments based on energy understanding) from non-content-related strategies (i.e. guessing, deciding according to item format). Across items, students obtained the clear majority of solutions by using content-related strategies, while non-content-related strategies comprised just a small share of the observed solutions (grade 6: 13%, grade 10: 3%). This analysis suggests that grade 6–10 students can solve the items of the new instrument validly with regard to the intended cognitive processes.

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**Internal structure.** This aspect of validity was addressed through two approaches. First, two expert ratings were used to structure the development of the instrument in relation to (i) the three disciplinary contexts and (ii) the four aspects of energy understanding from the employed framework. The first rating regarding item discipline-specificity (see above) resulted in the exclusion of five items, thereby decreasing the correlations between the three subtests and ensuring their discipline-specificity (before exclusion:  $r \sim .85$ ,  $N_{\text{items}} = 48$ ; after exclusion:  $r \sim .62$ ,  $N_{\text{items}} = 43$ ). A second, previously conducted rating indicated substantial agreement on the items' specificity for the four energy aspects of the framework ( $\kappa = .61$ , Opitz et al., 2015).

The second approach used confirmatory factor analysis (CFA) to study the internal structure of students' energy understanding in the three disciplinary contexts. This study is described in a separate article (Opitz, Neumann, Bernholt, and Harms, submitted). The analysis suggests that students' energy understanding is likely one-dimensional across disciplinary contexts. This result does not affect the goal of our study, i.e. to develop an instrument that can assess energy understanding in biology, chemistry, and physics contexts. Instead, it suggests that students likely employ a single understanding of energy that can be assessed with items from different disciplinary contexts.

As additional evidence for the validity of the instrument's internal structure, online material 4 includes results from an analysis of differential item functioning (see Joint Committee, 2014, p. 16).

**Relation to other variables.** Different external variables (e.g. reading skills, fluid intelligence, motivation/interest) have been assessed in previous research (Opitz et al., 2015), but only had minor effects on energy test performance. To extend these findings, crystallised intelligence (CI) was included as a potential covariate of progressing energy understanding (see methods section). CI is a measure of a person's ability to apply general knowledge (Horn, 1983). In contrast to measures considered as more developmentally stable (e.g. working memory capacity/efficiency), levels of CI increase as students mature and learn more. This sub-aspect of intelligence has been found to be strongly connected to different measures of academic achievement (Marzano, 2003, p. 134). As the energy test scores assessed by our instrument concern the understanding of a wide range of everyday contexts, we assumed test performance to depend on a general knowledge measure like CI. However, students' results on the CI-test were just weakly correlated with energy scores ( $r \sim .20$ ). This finding—coupled with the previous ones

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described above—indicates that the employed items assess a different construct than a general performance measure.

**Relation with criteria.** This aspect of validity is concerned with the accuracy of the test scores' prediction of a criterion—in this case 'energy understanding'. Firstly, to ensure that differences in energy understanding between groups (grade levels) were not affected by construct-irrelevant sources of variance (Joint Committee, 2014, p. 18), we compared students from different grades along several variables (see Table 3.1).

Secondly, the relation between the scores assessed by the new instrument and the intended criterion (energy understanding) can be approximated by correlations between the derived test scores and those from similar instruments. As the items for physics contexts in the new instrument stemmed from the one presented in Neumann et al. (2013), the strong correlation between the test scores on the physics subtest and the biology/chemistry subtests indicates that these two instruments assess a highly similar construct. In extension, Park (2013, p. 98) found that energy scores on her instrument were to a large extent predictable ( $r^2 = .86$ ) through scores from the test presented by Neumann et al. (2013). We therefore conclude that the instrument presented here is substantially related to the intended criterion.

Lastly, multiple regression was used to determine how well findings from the sample employed in this study can be generalised to the population level (Field, 2009, p. 221; Joint Committee, 2014, p. 19). The regression model included grade level and crystallised intelligence as predictors of students' energy understanding. The model results showed negligible shrinkage of .1% ( $r^2 = .43$ ), thus indicating good generalisability of the findings (see online material 4 for detailed results).

**Consequences of testing.** The developed instrument is intended for research and is not to be used for assessments with diagnostic or student-placement impact. In this study, teachers and their classes participated voluntarily; the research team conducted the testing, and testing results were evaluated anonymously. Thus, besides potential effects on interest in the energy concept itself, the application of the instrument had no consequences for participating students, teachers, or schools. Potentially resulting changes to an educational system fall outside the realm of this validity discussion (Joint Committee, 2014, p. 20).

**Limitations of the instrument.** The instrument presented in this study was designed to assess discipline-specific sets of energy understanding and their relation to each other. Even though items with more interdisciplinary scope were retained in the

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instrument, specifically interdisciplinary dimensions of energy understanding are not sufficiently assessable through the presented items. A further limitation lies in the few items per energy aspect within each discipline. Consequently, the subtests should be extended for more fine-grained analyses with regard to these aspects, for example, when knowledge integration patterns within disciplines are of interest.

In accordance with the field testing reported in 'Instrument Development', additional data had originally been collected from a 12<sup>th</sup> grade sample, as well. However, this subsample had to be excluded in the analysis due to an unresolvable school-type effect that would have biased the comparability between grade levels. However, the developed instrument was designed to assess energy understanding up to high school and can be applied accordingly in future studies.

**Conclusion.** The developed instrument fitted students' abilities well, while reliabilities were satisfactory and the relevant validity aspects could be addressed. In relation to the positive outcome of the rating, it can be assumed that the instrument is able to analyse middle school students' energy understanding across biology, chemistry, and physics contexts.

### 3.5.2. Energy Understanding across the Three Disciplines (Objective 2)

**Progression in energy understanding.** For research question 1, the results indicate similarities in progression trends in biology, chemistry, and physics contexts (see Figures 3.1 and 3.2), as well as in the selection of similar ideas across different disciplines (see Figure 3.3). The reason for the comparatively high performance in physics may be attributed to the fact that these contexts are typical examples of students' first formal energy instruction. Additionally, physics contexts are comparatively less complex than the ones in biology or chemistry (e.g. pendulums, Duit, 1984). While previous findings identified energy knowledge transfer between disciplines as a major learning hurdle (Chabalengula et al., 2011), learning transfer from the less complex physics contexts may also provide a starting point from which to access more complex contexts in other disciplines. However, transfers in the opposite direction must also be considered for coherent energy instruction, as early, often implicit learning opportunities in biological contexts can form a basis for later, more explicit energy instruction (Opitz et al., 2015).

In biology and physics, the sequential, yet overlapping progression of energy understanding along energy forms, transfer, degradation, and conservation was similar to findings in other studies (e.g. DeBoer & Herrmann-Abell, 2011; Liu & McKeough, 2005; Neumann et al., 2013). An understanding of energy forms was well established in all

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disciplines and can therefore function as a scaffold to more advanced energy aspects (Jin & Anderson, 2012). In contrast, energy conservation was little understood in all disciplinary contexts, suggesting that students at this stage are not yet able to use an integrated energy concept in the sense of a conceptual tool (Lacy et al., 2014). In chemistry, students' understanding of energy transfer was low and didn't progress, while understanding of degradation was surprisingly well established. However, these strengths and weaknesses in students' energy understanding in chemistry can only partly be explained by energy contents proposed in the respective learning standards (KMK, 2005b; see online material 3).

**Relatedness in energy understanding across disciplines.** With respect to research question 2, the findings showed clear similarities and relations between progressing energy understanding in different disciplinary contexts. These similarities are stronger than one might expect, as (i) discipline-specific foci regarding the energy aspects are generally accepted (Eisenkraft et al., 2014), (ii) empirical results of learners' performances have been found to reflect these foci (Park, 2014), and (iii) some energy aspects are rarely addressed in the instruction of individual disciplines, for example, conservation in biology (Opitz et al., 2015).

A critical argument would be that the similarities in progressing energy understanding across disciplines and the strong correlations ( $r \sim .62$ ) between the three subtest scores may be caused by dependencies in the instrument. However, the subtests were clearly identified as discipline-specific. Furthermore, correlations computed before the exclusion of items in the rating ( $r > .80$ ) are comparable to those found by Park (2013), who used a similar instrument without a rating on item discipline-specificity. Additionally, the correlations between the three scales of randomly assigned items were found to be only slightly higher ( $r \sim .67$ ) than those between the three discipline-specific subtests. These results suggest that students' energy understanding is less discipline-dependent as indicated by the aforementioned arguments.

A possible reason for the similarities in energy understanding across disciplines lies in the conceptual dependence between energy aspects, which may strengthen an inherently similar progression pattern across disciplinary contexts, for example, the dependence on energy forms when describing energy transfer. The strong relation between disciplines may be furthermore promoted by general answering characteristics, for example, by students' widespread application of problematic ideas like 'energy loss' or their inconsistent distinction between abstract conceptualisations and concrete observations (Liu et al., 2002; compare also physics item 'Task 35' or biology item 'Task 22' in online material 1).

**Limitations of the study.** Further discipline-specific foci on energy understanding (e.g. energy flow in biology or macro/micro-level analyses in chemistry) were not addressed in detail by the new instrument. Similarly, students' distinction between energy in states and energy in processes was not a primary focus of this study (Papadouris & Constantinou, 2014). While these important facets of understanding can be derived from specific answering options in some items (see online material 1), future studies should address these characteristics of energy understanding in more detail.

This study presented findings from students who were taught in separate science classes throughout middle school. While an educational system with separate science classes may not be common in all countries, this organization is widely employed, for example, throughout the European Union (European Commission, 2011, p. 60). As the items of this instrument were not developed in regard to specific educational standards, the instrument can be applied in other educational systems, as well. For example, studies may analyse learning processes that take place as students progress from integrated science instruction in middle school to separated science classes in high school.

### 3.6 Implications and Perspective

To our knowledge, this study proposes one of the first approaches for the analysis of students' energy understanding across disciplinary contexts. The attached items and additional information offer interested science education researchers the opportunity to further elaborate discipline-specific as well as interdisciplinary aspects of students' progressing energy understanding.

Coherent curricula that are structured around core ideas and crosscutting concepts like energy can promote an integrated science understanding (Fortus et al., 2015). Students depend on an integrated energy understanding if they are to use energy as a concept across topics and disciplinary contexts. With this in mind, the importance of a stronger focus on energy conservation and degradation can be derived as a goal for teaching in all science subjects. In contrast, students' widespread understanding of energy forms (Jin & Anderson, 2012), as well as their comparatively high performance in physics contexts could be further developed as the stepping stones to more complex energy contexts in biology and chemistry.

It is not yet well understood in what ways students draw on different disciplinary contexts when learning about energy and what hurdles they encounter in transferring knowledge across these contexts (Chabalengula et al., 2011; Hirça et al., 2008). The findings in this study suggest strong correlations in energy understanding across

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disciplines. However, in-detail analyses still have to determine how the relation between energy understanding in different disciplinary contexts changes as students progress in school and learn more about energy (Fortus et al., 2015; Opitz et al., submitted). Future experimental studies have to identify effective educational settings that can enable students to use energy both as a disciplinary core idea and as a crosscutting concept (NGSS, 2013).

### 3.7 Acknowledgements

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### 3.8 Supplemental Online Material

*Material 1* Items, Item Parameters and Distractor/Attractor Analyses

*Material 2* Analysis of Differences in Item Types

*Material 3* Energy Learning Opportunities at Schools in Hamburg/Germany

*Material 4* Additional Statistical Procedures: Multiple Regression and Rasch Analysis

### 3.9 References

- American Association for the Advancement in Science (2007). Getting Assessment Right. *2061 Today*, 17(1), 1-7.
- Alonzo, A. C., & Gotwals, A. W. (2012). *Learning Progressions in Science - Current Challenges and Future Directions*. Rotterdam: Sense Publishers.
- Bevilacqua, F. (2014). Energy: Learning from the Past. *Science & Education*, 23(6), 1231-1243. doi: 10.1007/s11191-014-9690-1
- Bodzin, A. (2012). Investigating Urban Eighth-Grade Students' Knowledge of Energy Resources. *International Journal of Science Education*, 34(8), 1255-1275.
- Boyes, E., & Stanisstreet, M. (1990). Pupils' Ideas Concerning Energy Sources. *International Journal of Science Education*, 12(5), 513-529.



### Chapter 3 (Study 2): Assessing Energy Understanding across Biology, Chemistry, and Physics Contexts

---

- Bransford, J. D., Brown, A. L., & Cocking, R. R. (2000). *How People Learn: Brain, Mind, Experience and School*. Washington, D.C.: National Academy Press.
- Burger, J. (2001). *Schülervorstellungen zu "Energie im biologischen Kontext" - Ermittlungen, Analysen und Schlussfolgerungen*. [Student conceptions concerning energy in biological contexts: Research, analysis and conclusions]. (Unpublished doctoral dissertation). University of Bielefeld, Bielefeld/Germany.
- Chabalengula, V., Sanders, M., & Mumba, F. (2011). Diagnosing Students' Understanding of Energy and Its Related Concepts in Biological Contexts. *International Journal of Science and Mathematics Education, 10*(2), 241-266.
- Chen, B., Eisenkraft, A., Fortus, D., Krajcik, J. S., Neumann, K., Nordine, J., & Scheff, A. (2014). *Teaching and Learning of Energy in K-12 Education*. New York: Springer.
- Dawson-Tunik, T. L. (2006). Stage-Like Patterns in the Development of Conceptions of Energy. In X. F. Liu & W. Boone (Eds.), *Applications of Rasch Measurement in Science Education* (pp. 111-136). Maple Grove, MN: JAM Press.
- Doménech, J., Gil-Pérez, D., Gras-Martí, A., Guisasaola, J., Martínez-Torregrosa, J., Salinas, J., . . . Vilches, A. (2007). Teaching of Energy Issues: A Debate Proposal for a Global Reorientation. *Science & Education, 16*(1), 43-64.
- Driver, R., Squires, A., Rushworth, P., & Wood-Robinson, V. (1994). *Making Sense of Secondary Science: Supporting Material for Secondary Teachers*. London: Routledge.
- Duit, R. (1984). Learning the Energy Concept in School - Empirical Results from the Philippines and West Germany. *Physics Education, 19*(2), 59-66.
- Ericsson, K. A. & Simon, H. A. (1993). *Protocol Analysis: Verbal Reports as Data*. Cambridge: MIT Press.
- Field, A. (2009). *Discovering Statistics Using SPSS* (Third Ed. ed.). London: Sage Publications.
- Forde, T. (2003). "When I Am Watching Television I Am Not Using Any Energy" - An Empirical Study of Junior Science Students' Intuitive Concepts of Energy. *Irish Educational Studies, 22*(3), 71-89.
- Fortus, D., & Krajcik, J. (2012). Curriculum Coherence and Learning Progressions. In B. J. Fraser, K. Tobin & C. J. McRobbie (Eds.), *Second International Handbook of Science Education* (Vol. 24, pp. 783-798): Springer Netherlands.
- Fortus, D., Sutherland, L., Reiser, B. J., & Krajcik, J. S. (2015). Assessing the Role of Curriculum Coherence in Student Learning About Energy *Journal of Research in Science Teaching, 52*(10), 1408-1425.
- Herrmann-Abell, C. F., & DeBoer, G. E. (2011). *Investigating Students' Understanding of Energy Transformation, Energy Transfer, and Conservation of Energy Using*

### Chapter 3 (Study 2): Assessing Energy Understanding across Biology, Chemistry, and Physics Contexts

---

- Standards-Based Assessment Items*. Paper presented at the NARST Annual International Conference Orlando.
- Hirça, N., Çalik, M., & Akdeniz, F. (2008). Investigating Grade 8 Students' Conceptions of 'Energy' and Related Concepts. *Journal of Turkish Science Education*, 5(1), 75-87.
- Horn, W. (1983). *Leistungsprüfsystem - LPS* (Vol. 2). [Intelligence test LPS] Rosdort/Göttingen: Hogrefe.
- Jin, H., & Anderson, C. W. (2012). A learning progression for energy in socio-ecological systems. *Journal of Research in Science Teaching*, 49(9), 1149-1180.
- Joint Committee (2014). *Standards for Educational and Psychological Testing*. Washington, D.C.: American Education Research Association (AERA).
- Kirk, R. E. (1996). Practical Significance: A Concept Whose Time Has Come. *Educational and Psychological Measurement*, 56(5), 746-759. doi: 10.1177/0013164496056005002
- KMK - Ständige Konferenz der Kultusminister der Länder in der Bundesrepublik Deutschland. (2005a). *Bildungsstandards im Fach Biologie für den Mittleren Schulabschluss - Beschluss vom 16.12.2004*. [German middle school learning standards for biology]. München: Luchterhand.
- KMK - Ständige Konferenz der Kultusminister der Länder in der Bundesrepublik Deutschland. (2005b). *Bildungsstandards im Fach Chemie für den Mittleren Schulabschluss: Beschluss vom 16.12.2004*. [German middle school learning standards for chemistry]. München: Luchterhand.
- KMK - Ständige Konferenz der Kultusminister der Länder in der Bundesrepublik Deutschland. (2005c). *Bildungsstandards im Fach Physik für den Mittleren Schulabschluss Beschluss vom 16.12. 2004*. [German middle school learning standards for physics]. München: Luchterhand.
- Krajcik, J. S., Sutherland, L. A., Drago, K., & Merritt, J. (2012). The Promise and Value of Learning Progression Research. In S. Bernholt, K. Neumann & P. Nentwig (Eds.), *Making it tangible: Learning outcomes in science education* (pp. 261-283). Münster: Waxmann.
- Kurnaz, M. A., & Sağlam-Arslan, A. (2011). A Thematic Review of Some Studies Investigating Students' Alternative Conceptions About Energy. *Eurasian Journal of Chemistry and Physics Education*, 3(1), 51-74.
- Lacy, S., Tobin, R., Wisner, M., & Crissman, S. (2014). Looking Through the Energy Lens: A Proposed Learning Progression for Energy in Grades 3-5. In B. Chen, A. Eisenkraft, D. Fortus, J. S. Krajcik, K. Neumann, J. Nordine & A. Scheff (Eds.),

### Chapter 3 (Study 2): Assessing Energy Understanding across Biology, Chemistry, and Physics Contexts

---

- Teaching and Learning of Energy in K-12 Education*. Cham Heidelberg New York Dordrecht London: Springer.
- Lancor, R. A. (2015). An Analysis of Metaphors Used by Students to Describe Energy in an Interdisciplinary General Science Course. *International Journal of Science Education*, 1-27. doi: 10.1080/09500693.2015.1025309
- Lee, H.-S., & Liu, O. L. (2009). Assessing learning progression of energy concepts across middle school grades: The knowledge integration perspective. *Science Education*, 94(4), 665-688.
- Lerner, R. G., & Trigg, G. L. (2005). *Encyclopedia of Physics Volume 1 (A-L)*. Weinheim: Wiley-VCH.
- Lin, C.-Y., & Hu, R. (2003). Students' understanding of energy flow and matter cycling in the context of the food chain, photosynthesis, and respiration. *International Journal of Science Education*, 25(12), 1529-1544.
- Linn, M. C., Eylon, B.-S., & Davis, E. A. (2004). The Knowledge Integration Perspective on Learning and Instruction. In M. C. Linn, E. A. Davids & P. Bell (Eds.), *Internet Environments for Science Education* (pp. 29-46). Mahwah, NJ: Lawrence Erlbaum.
- Liu, X., Ebenezer, J., & Fraser, D. M. (2002). Structural characteristics of university engineering students' conceptions of energy. *Journal of Research in Science Teaching*, 39(5), 423-441.
- Liu, X., & McKeough, A. (2005). Developmental growth in students' concept of energy: Analysis of selected items from the TIMSS database. *Journal of Research in Science Teaching*, 42(5), 493-517.
- Liu, X., & Ruiz, M. E. (2008). Using data mining to predict K–12 students' performance on large-scale assessment items related to energy. *Journal of Research in Science Teaching*, 45(5), 554-573.
- Maletta, H. (2007). *Weighting*. Retrieved March 25th, 2015, from <http://www.spsstools.net/Tutorials/WEIGHTING.pdf>
- Marzano, R. J. (2003). *What Works in Schools: Translating Research into Action*. Alexandria, VA, USA: Association for Supervision and Curriculum Development.
- Messick, S. (1995). Validity of Psychological Assessment: Validation of Inferences From Persons' Responses and Performances as Scientific Inquiry Into Score Meaning. *American Psychologist*, 50(9), 741-749.
- Michaelis, S., Shouse, A. W., & Schweingruber, H. A. (2008). *Ready, Set, Science! Putting Research to Work in K-8 Science Classrooms*. Washington, D.C.: The National Academic Press.

### Chapter 3 (Study 2): Assessing Energy Understanding across Biology, Chemistry, and Physics Contexts

---

- Millar, R. (2005). Teaching about Energy: Research Paper 2005/11. York, University of York, Department of Educational Studies.
- Neumann, K., Viering, T., Boone, W. J., & Fischer, H. E. (2013). *Towards a Learning Progression of Energy*. *Journal of Research in Science Teaching*, 50(2), 162-188.
- Nordine, J., Krajcik, J., & Fortus, D. (2010). Transforming energy instruction in middle school to support integrated understanding and future learning. *Science Education*, 95(4), 670-699.
- NGSS (Lead States) (2013). *Next Generation Science Standards: For States, By States*. Washington, DC: The National Academies Press.
- Novak, J. D. (2005). Results and Implications of a 12-Year Longitudinal Study of Science Concept Learning. *Research in Science Education*, 35(1), 23-40.
- Opitz, S., Harms, U., & Neumann, K., Kowalzik, K., & Frank, A. (2015). Students' Energy Concepts at the Transition between Primary and Secondary School. *Research in Science Education*, 45(5). 691-715. doi 10.1007/s11165-014-9444-8
- Opitz, S., Neumann, K., Bernholt, S., & Harms, U. (submitted). *Students' Energy Understanding across Biology, Chemistry, and Physics Contexts*. Submitted to *Research in Science Education*.
- Papadouris, N. K., T & Constantinou, C.P. (2014). An Exploratory Investigation of 12-Year-Old Students' Ability to Appreciate Certain Aspects of the Nature of Science through a Specially Designed Approach in the Context of Energy. *International Journal of Science Education*, 36(5), 755-782.
- Park, M. (2013). *Developing an Instrument for Assessing Students' Understanding of the Energy Concept Across Science Disciplines*. (Unpublished doctoral dissertation). University of Buffalo, Buffalo, New York/USA. Retrieved from <http://search.proquest.com/pao/docview/1511026690>
- Pugh, K. J., & Bergin, D. A. (2006). Motivational Influences on Transfer. *Educational Psychologist*, 41(3), 147-160. doi: 10.1207/s15326985ep4103\_2
- Quinn, H. (2014). A Physicist's Musings on Teaching Energy. In B. Chen, A. Eisenkraft, D. Fortus, J. S. Krajcik, K. Neumann, J. Nordine & A. Scheff (Eds.), *Teaching and Learning of Energy in K-12*. New York: Springer.
- Ross, P. M. T., Charlotte E. ; Hughes, Chris ; Whitaker, Noel ; Lutze-Mann, Louise ; Kofod, Michelle ;Tzioumis, Vicky. (2010). Threshold Concepts in Learning Biology and Evolution. *Biology International*, 47, 47-52.
- Sakschewski, M., Eggert, S., Schneider, S., & Bögeholz, S. (2014). Students' Socioscientific Reasoning and Decision-making on Energy-related Issues—Development of a measurement instrument. *International Journal of Science Education*, 36(14), 2291-2313. doi: 10.1080/09500693.2014.920550

### Chapter 3 (Study 2): Assessing Energy Understanding across Biology, Chemistry, and Physics Contexts

---

- Shultz, T. R., & Coddington, M. (1981). Development of the concepts of energy conservation and entropy. *Journal of Experimental Child Psychology*, 31(1), 131-153.
- Stacy, A. M., Chang, K., Coonrod, J., & Claesgens, J. (2014). Launching the Space Shuttle by Making Water: The Chemist's View of Energy. In J. S. Krajcik, B. Chen, A. Eisenkraft, D. Fortus, K. Neumann, J. Nordine & A. Scheff (Eds.), *Teaching and Learning Energy in K-12 Energy Education*. New York: Springer.
- Tastan, Ö. Y., Eylem, & Boz, Y. (2008). Effectiveness of Conceptual Change Text-oriented Instruction on Students' Understanding of Energy in Chemical Reactions. *Journal of Science Education and Technology*, 17(5), 444-453.
- Tatar, E., & Oktay, M. (2007). The effectiveness of problem-based learning on teaching the first law of thermodynamics. *Research in Science & Technological Education*, 29(3), 315-332.
- Trumper, R. (1993). Children's energy concepts: a cross-age study. *International Journal of Science Education*, 15(2), 139-148.
- Wang, L., Wang, W., & Wei, R. (2014). What Knowledge and Ability Should High School Students Have for Understanding Energy in Chemical Reactions? An Analysis of Chemistry Curriculum Standards in Seven Countries and Regions In R. Chen, A. Eisenkraft, D. Fortus, J. S. Krajcik, K. Neumann, J. Nordine & A. Scheff (Eds.), *Teaching and Learning of Energy in K-12 Education*. New York: Springer.
- Watts, D. M. (1983). Some alternative views of energy. *Physics Education*, 18(5), 213.
- Wernecke, U. (2013). *Erfassung des Schülerverständnisses von Energie - Validierung eines quantitativen Erhebungsinstruments durch die Methode des Lauten Denkens*. [Assessing students' energy understanding. Validating a quantitative assessment tool via think-aloud protocols]. (Unpublished master 's thesis). Kiel University, Kiel/Germany.
- Wu, M. L., Adams, R. J., & Wilson, M. R. (2007). ACER ConQuest version 2.0: generalized item response modelling software. Camberwell, VIC: Acer Press.



## CHAPTER 4

# Students' Energy Understanding across Biology, Chemistry, and Physics Contexts

(Study 3)

### Abstract

Energy is considered both as a disciplinary core idea and as a concept cutting across science disciplines. Most previous approaches studied progressing energy understanding in specific disciplinary contexts, while disregarding the relation of understanding across them. Hence, this study provides a systematic analysis of cross-disciplinary energy learning. On the basis of a cross-sectional study with  $N = 742$  students from grades 6, 8 and 10, we analyze students' progression in understanding energy across biology, chemistry, and physics contexts. The study is guided by three hypothetical scenarios that describe how the connection between energy understanding in the three disciplinary contexts changes across grade levels. These scenarios are compared using confirmatory factor analysis (CFA). The results suggest that, from grade 6 to grade 10, energy understanding in the three disciplinary contexts is highly interrelated, thus indicating a parallel progression of energy understanding in the three disciplinary contexts. In our study, students from grade 6 onwards appeared to have few problems to apply one energy understanding across the three disciplinary contexts. These findings were unexpected, as previous research concluded that students likely face difficulties in connecting energy learning across disciplinary boundaries. Potential reasons for these results and the characteristics of the observed cross-disciplinary energy understanding are discussed in the light of earlier findings and implications for future research and the teaching of energy as a core idea and a crosscutting concept are addressed.

### Keywords

crosscutting concept; disciplinary core idea; energy; knowledge integration

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Opitz, S., Neumann, K., Bernholt, S. (Submitted, 01/2016). Students' Energy Understanding across Biology, Chemistry, and physics Contexts. *Research in Science Education*.

### 4.1 Introduction

The energy concept is a fundamental concept in all natural sciences, in engineering, and in the geosciences. For example, energy balances of reactions can be used to determine in how far a process can occur within a defined system (Lerner and Trigg 2005, p. 720). Learners who apply the energy concept can thereby attain an overview of contexts without first having to acquire extensive content knowledge. Contexts for which such an overview can be especially helpful are often complex and require multi-disciplinary approaches. For example, the application of the energy concept in a teaching sequence on climate change can be examined from a wide range of perspectives, such as physics (e.g., climate models), chemistry (e.g., atmosphere constitution), biology (e.g., changes at ecosystem level), the geosciences (e.g., paleoclimate records), engineering (e.g., carbon sequestration and storage), politics (e.g. carbon emission regulations) and economics (e.g., Intergovernmental Panel on Climate Change 2013). As can be seen in the climate change example, complex science contexts often require the organization of a great amount of information. To help students with this challenge, the focus of science instruction has been shifted to promote connections between different science contexts in order to foster the development of an interconnected science understanding (Bransford, Brown, and Cocking 2000; Clark and Linn 2003). Such a knowledge basis can, for example, be promoted through coherent curricula that are based on disciplinary core ideas and interdisciplinary crosscutting concepts (Fortus, Sutherland Adams, Krajcik, and Reiser 2015).

The energy concept stands out by being simultaneously considered as a core idea in different disciplinary contexts *and* as a concept cutting across them (e.g., Chen et al. 2014; Next Generation Science Standards [NGSS] 2013). However, most studies on students' energy understanding have so far focused on particular disciplinary contexts (e.g., Jin and Anderson 2012; Liu and McKeough 2005; Tastan, Yalcinkaya, and Boz 2008; Trumper 1997; Watts 1983). In contrast, only a few studies have addressed cross-disciplinary energy learning (Fortus et al. 2015; Lancor 2015; Liu, Ryoo, Linn, Sato, and Svihla 2015). Specifically, it has rarely been analyzed how students' progressing energy understanding is related between disciplinary contexts (Park 2013).

In this study, we analyze data from grade 6, 8 and 10 students who learned about energy in separate biology, chemistry and physics classes. The goal was to systematically analyze how the connection of students' progressing energy understanding is related across disciplinary contexts and how this relation changes as the students learn more about energy throughout middle school. In this regard, three hypothetical scenarios



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for changes in understanding across disciplinary contexts were derived from previous research. These were compared by applying confirmatory factor analysis (CFA). The study is conducted to provide an empirical basis for future research on how to develop and assess instruction that fosters students' understanding of energy as both a disciplinary core idea and a crosscutting concept.

### 4.2 Theoretical Background

A well-organized knowledge basis is regarded as an important factor for developing a robust science understanding. The energy concept is attributed a central role in helping students organize their understanding of different science contents. Thus, research on efficient knowledge organization as well as the respective adaptations of science standards form a basis to understanding the role of energy in science instruction. The following sections address this background before presenting research on students' energy understanding that informed this study's research question and hypotheses.

#### 4.2.1 Organizing Science Knowledge

In science education, students are expected to apprehend connections in the extensive body of scientific knowledge (NGSS 2013). However, students may struggle with the vast amount of information they are presented with and may hence fail to notice relevant connections or underlying concepts that weave across science topics. As a result, contents across different science lessons or classes can appear ambiguous or disconnected (Tenenbaum, Kemp, Griffiths, and Goodman 2011) and students may not succeed in developing an interconnected science understanding. To address this difficulty, studies have focused on ways to promote students to integrate newly learned content into existing knowledge. Here, the concept of knowledge integration describes the "process of linking, connecting, distinguishing, organizing and structuring ideas" (Clark and Linn 2003, p. 452). The effectiveness of knowledge integration depends, amongst other factors, on the learner's knowledge structure, which has been described as efficient if structured around core ideas (e.g., Bransford et al. 2000; Pugh and Bergin 2006). In large-scale assessments, knowledge integration has been identified as a major predictor of student performance (Schmidt, Wang, and McKnight 2005). Similarly, curricula have been criticized for covering an often extensive range of details (Fortus and Krajcik 2012; Schönborn and Bögeholz 2007), while studies have indicated that limiting the number of topics per year in favor of a greater depth of content coverage can have positive effects

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on students' learning outcomes (Bransford et al. 2000; Linn, Lewis, Tsuchida, and Songer 2000).

The aforementioned findings have been reflected in the incorporation of core ideas and crosscutting concepts into science standards. These ideas underline the most central concepts that students need to understand in science (NGSS 2013; National Research Council [NRC] 2012).

### 4.2.2 Energy as a Core Idea

Energy represents a core idea because it is considered to foster students' ability to learn about a variety of scientific topics in increasing depth over multiple grades (NRC 2012). More specifically, students can benefit from using energy in two ways. Firstly, by learning about energy in science, students can receive a deeper insight by using energy as a conceptual tool, e.g., when they analyze energy balances that provide an overview of occurring physiological processes (Lacy et al. 2014; Lerner and Trigg 2005). Secondly, students can learn about science with energy as a link between numerous science contexts, thereby facilitating cumulative learning and helping students to develop an interconnected science understanding (see above).

### 4.2.3 Energy as a Crosscutting Concept

Energy has also been considered as a crosscutting concept to promote the connection of science understanding across disciplinary boundaries, thereby strengthening students to apply multi-perspective approaches (Chen et al. 2014; Nordine et al. 2010; NRC 2012). While the same aspects of the scientific energy concept (Neumann, Vierung, Boone, and Fischer 2013) apply across different disciplinary contexts (e.g. Lacy, Tobin, Wisner, and Crissman 2014; Lancor 2015), varying foci and different language for the energy concept are used in different disciplinary contexts (Eisenkraft et al. 2014). These varying foci may lead students to assume that different energy concepts exist across disciplinary contexts. Hence, it may be assumed that, as students mature and use the energy concept in more sophisticated ways, they not only accumulate knowledge about energy within each disciplinary context, but likely also develop connections between knowledge from different disciplinary contexts as the students revisit, re-connect and prioritize energy-related ideas (Clark and Linn 2003).

Learning progressions for core ideas and crosscutting concepts can serve as an empirical basis for the development of coherent curricula by providing a framework of unfolding knowledge that describes how students add and differentiate between new ideas and previous ones (Alonzo and Gotwals 2012; Fortus and Krajcik 2012; Fortus et

al. 2015). In this regard, the studies reviewed below have provided valuable empirical insights into progressing energy understanding in specific disciplinary contexts. Additionally, the yet rare insights into energy learning in cross-disciplinary settings are presented as a basis for the research presented in this article, which focuses on the relation of energy understanding across disciplinary contexts.

### 4.2.4 Research on Students' Energy Understanding

**Learning about energy in disciplinary contexts.** Progressing energy understanding has been described in relation to (i) the purpose of the energy concept and energy tracking (Jin and Anderson 2012; Lacy et al. 2014), (ii) central energy aspects (Liu and McKeough 2005), and (iii) the energy concept's relation to other core ideas (Cooper et al. 2014). While the following approaches with focus on specific disciplinary contexts can provide valuable information to suit the needs of the respective discipline, such approaches alone cannot sufficiently describe how students can learn to link energy understanding across disciplinary contexts (Stacy et al. 2014).

**Physics contexts.** Most studies have analyzed students' energy understanding in physics contexts (see summaries/reviews by Chen et al. 2014; Doménech et al. 2007; Kurnaz and Saglam-Arslan 2011; Nordine et al. 2010; Tatar, Erdal, Oktay, and Münir 2007). This research has identified alternative ideas about energy that students apply prior to (e.g., Boylan 2008; Lacy et al. 2014; Trumper 1993; van Hook and Huziak-Clark 2008), as well as during formal education (e.g., Barak, Gorodetsky, and Chipman 1997; Kurnaz and Saglam-Arslan 2011; Lancor 2015; Watts 1983). While energy descriptions across all disciplinary contexts rely heavily on the consideration of system boundaries (Cooper, Klymkowsky, and Becker 2014), physics contexts usually regard idealized, closed systems, while biology and chemistry contexts employ open systems (NRC 2012, p. 120).

In physics contexts, energy understanding was found to progress through a sequence of four energy aspects (e.g., Driver, Squires, Rushworth, and Wood-Robinson 1994; Liu and McKeough 2005), which were subsequently used as a basis for describing energy learning progressions (e.g., Lacy et al. 2014; Neumann et al. 2013). According to this sequence, students initially develop an understanding of energy forms/sources (i) as a conceptual framework, which they employ from an early age onwards (Jin and Anderson 2012; Opitz, Harms, Neumann, Kowalzik, and Frank 2015; Kaper and Godehart 2002a, 2002b; Lacy et al. 2014). They only later progress to an understanding of transfer and transformation (ii) (Liu and McKeough 2005). Degradation and dissipation

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(iii) and especially energy conservation (iv) have been identified as highly difficult aspects, as they are only understood by more able students (Lee and Liu 2009; Liu and McKeogh 2005; Liu and Ruiz 2008; Liu and Tang 2004; Neumann et al. 2013; Park 2013). Energy conservation, in particular, is rarely applied to new contexts (Chabalengula et al. 2011; Driver and Warrington 1985; Krajcik et al. 2014) and may be counter-intuitive for students due to everyday connotations, e.g., ideas connected to 'energy loss' (Lancor 2015; Tatar et al. 2007). As, for example, energy conservation is important for a purposeful understanding and application of the energy concept, fostering knowledge integration across the four energy aspects is a goal of ongoing research (Lacy et al. 2014; Nordine et al. 2010).

**Biology contexts.** So far, few studies have addressed energy learning in biology (Chabalengula et al. 2011; Dauer et al. 2014; Jin and Anderson 2012). Specific alternative ideas about energy have been presented for biological contexts (e.g., Boyes and Stanisstreet 1991; Burger 2001; Trumper 1997). Generally, similarities in progressing understanding have been observed between biology and physics contexts (Opitz, Neumann, Bernholt, and Harms submitted). However, a focus in biology on energy transfer/transformation has been identified (Opitz et al. 2015; Park 2013, p.88). Difficulties in understanding energy in biology arise as even university students have been found challenged by transferring energy knowledge between disciplinary contexts, e.g., when they are asked to apply the law of energy conservation to biological contexts (Chabalengula et al. 2011). Additionally, the substantial contextualization of biological topics has been described as a learning hurdle that may lead to a confusion between scientific and everyday-based energy connotations (Jin and Anderson 2012).

**Chemistry contexts.** Physics and biology often use energy to describe work, while heat is regarded as a byproduct and as an indicator of inefficiency. Adversely, chemistry regularly focuses on heat (and light) to describe energy transfer, while work is 'only' the effect (cf. Stacy, Chang, Coonrod, and Claesgens 2014). In chemical contexts, students often disregard a system-based approach to energy, and instead employ single objects to describe energy (Lindsey et al. 2012). Furthermore, learners rarely make a connection between macro, atomic-molecular and quantum-mechanical perspectives on energy (Cooper et al. 2014; Nagel and Lindsey 2014). In biological contexts, explanations about states of energy are frequently described as energy being 'stored' in bonds (e.g., '1 ATP = -30kJ/mol'). From a chemical perspective, this simplification is incorrect, as

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reactions only emit energy when the products are chemically more stable and have less potential energy than the educts (Cooper et al. 2014; Stacy et al. 2014).

**Learning about energy across disciplinary contexts.** Instruction about energy is expected to foster the development of energy understanding both within and across specific disciplinary contexts (e.g. NGSS 2013). However, the development of teaching materials, curricula, and science standards mostly has to rely on assumptions regarding the connection of energy understanding across disciplinary contexts, as few studies provided insights into cross-disciplinary energy learning (Krajcik et al. 2014; Liu et al. 2015; Park 2013).

Lancor (2015) found that university students from different disciplinary backgrounds usually only adhere to one metaphor for energy, which is mostly connected to a substance-based conception. The author concluded that specific contexts more prominently influence students' energy understanding than disciplinary backgrounds. More specifically, findings by Park (2013) suggest that energy understanding is highly correlated between university-level biology, chemistry, physics, and environmental science contexts ( $r > .80$ ). Further results (Opitz et al. submitted) indicate that the difficulty pattern of items across energy aspects is similar in biology, chemistry, and physics contexts. Here, energy degradation and conservation appear to be especially difficult aspects across disciplinary contexts.

Processes of knowledge integration are an important factor for strengthening the connections between different aspects of energy understanding (cf. Nordine et al. 2010). However, students' levels of knowledge integration have been found to increase only to mediocre levels in middle school. Furthermore, the extent to which students succeed in energy knowledge integration differs across science courses, while contexts from physics were found to contribute more to knowledge integration than those from earth or life sciences (Lee and Liu 2009). With regard to strengthening a cross-disciplinary energy understanding, research has shown that specifically designed curricula with a coherent presentation of energy across disciplinary contexts can promote knowledge integration in students both between subjects and between school years (Fortus et al. 2015). Similarly, longitudinal data indicate that students with early energy instruction sustain a sophisticated energy understanding for many years after the instruction, while their peers without such early energy learning opportunities do not achieve this level of understanding (Novak 2005).

### 4.2.5 Research Questions and Hypotheses

The literature review suggests: (i) Four energy aspects, i.e. forms/sources, transfer/transformation, degradation/dissipation, and conservation, are considered as a useful organizational structure for energy learning across school grades (e.g., Lacy et al. 2013; Lancor 2014). Across middle school, students' understanding of these four aspects has been found to increase quantitatively in different disciplinary contexts (Opitz et al. submitted). (ii) A parallel development and integration of these energy aspects has been described as a desideratum for energy learning (Lacy et al. 2014; Neumann and Nagy, 2013). The research on cross-disciplinary energy understanding is, especially for middle school students, rare and provides a mixed picture: On the one hand, varying foci on energy in different disciplinary contexts have been identified (e.g. Eisenkraft et al. 2014; Park 2013) and even older or more advanced students are likely challenged by transferring and connecting energy understanding across disciplinary boundaries (Chabalengula et al. 2011; Dreyfuß, Redish, and Watkins 2012; Eisenkraft et al. 2014). On the other hand, students were found to employ similar metaphors across disciplinary contexts (Lancor 2014) and energy understanding has been found to be strongly connected between contexts from environmental science, biology, chemistry, and physics (Park 2013).

So far, however, it has not been systematically analyzed how the connection between energy understanding in different disciplinary contexts changes across middle school grades. We address this open field by focusing on the research question below and by comparing three possible progressing scenarios for cross-disciplinary energy understanding (cf. hypotheses).

**Research question.** How is students' energy understanding related across contexts from biology, chemistry, and physics as the students mature and learn more about energy throughout middle school (grades 6, 8, and 10)?

**Hypotheses.** We hypothesize and compare three different scenarios that could characterize students' progressing energy understanding across disciplinary contexts: The first scenario (i) describes a parallel progression of energy understanding in biology, chemistry, and physics contexts with similar connections between the three contexts at all grade levels. This scenario could be realized in two ways: First, students could independently develop three separate and thus less strongly connected sets of energy understanding in the three disciplinary contexts. Second, all three disciplinary contexts could contribute to similar extents to the development of students' energy understanding.

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In this case, energy understanding would at all grade levels be highly connected between the three contexts.

The second scenario (ii) entails a process of differentiation, in which a general, unspecific energy understanding is differentiated into discipline-specific sets of energy understanding, as students, throughout middle school, learn about energy with different foci in different disciplinary contexts. In the third scenario (iii), learning about energy in different disciplinary contexts would contribute to a process of integration, in which discipline-specific sets of energy understanding are combined into a cross-disciplinary, integrated understanding of energy (cf. Nordine et al. 2010).

As we analyze students that are taught about energy in separate biology, chemistry, and physics classes, we assume that the second scenario is most likely for our sample, as this teaching setting may cause students to differentiate their energy understanding according to the three disciplinary contexts (cf. Eisenkraft et al. 2014).

### 4.3 Method

#### 4.3.1 Research Design and Justification

This study employed a cross-sectional design to assess students' energy understanding throughout middle school (grades 6, 8, and 10) by using a multiple-choice (MC) instrument. Data from this study were used to derive models of students' energy understanding, which allowed a comparison of the three scenarios outlined in the hypotheses. This research method was selected as it is widely applied and a convenient way to interpret the underlying structure of data and thus specify relations between variables (Kline 2012, p.1)—in this case energy understanding across disciplinary contexts. Alternative approaches to modelling and assessing cross-disciplinary energy understanding are addressed in the discussion.

Similar to previous research (e.g., Liu and Tang 2004), this study relied on a cross-sectional instead of a longitudinal design as it is more time and cost efficient. As earlier studies identified alternative conceptions about energy, these provided a robust basis for the construction of the employed MC instrument, thus allowing the application of a quantitative study with a larger sample than an approach with open-ended questions.

#### 4.3.2 Instrument

The MC instrument was designed to assess secondary students' progressing energy understanding in contexts from biology, chemistry, and physics. Items for the three contexts were constructed by using a shared framework of the energy concept (Neumann

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et al. 2013), thus ensuring the comparability of student performance across disciplinary contexts. This framework focuses on assessing the qualitative understanding of the four energy aspects mentioned above: forms/sources, transfer/transformation, degradation/dissipation, and energy conservation. Items were built around commonly encountered contexts such as digestion, combustion, or a swinging pendulum. After item development, qualitative feedback from students and teachers was used to improve the items. Representative items were cognitively pretested via think-aloud protocols. 128 items were administered in a field testing ( $N = 336$ ), in which 16 items per disciplinary context (four per energy aspect and context) were selected according to item discrimination ( $> .15$ ), the normal distribution of item difficulties in grades 10/12, and the correlation between item difficulty and grade level ( $> -.1$ ). In a next step, a rating with  $N = 12$  teachers and researchers from biology, chemistry, and physics was conducted to ensure the specificity of the employed items for each disciplinary context. This rating led to the exclusion of five items. The raters agreed on a 'near perfect' basis ( $\kappa = .81$ , Kirk 1996) on the disciplinary context that the items in the final instrument represented. This instrument encompassed 15 biology, 13 chemistry, and 15 physics items. Item examples for the three disciplinary contexts are presented in Figure 4.1. Details of the instrument development are provided in Opitz et al. (submitted). All items and item parameters of the instrument are provided in online resource 1, including the five items rejected through the rating on item discipline-specificity (see items in grey font).



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### **Biology Item (Task 31 – Energy aspect: degradation/dissipation)**

A growing person transforms energy from food or body fat to run various life processes.

*Select, where you can rediscover the energy after the transformation.*

- (1) In new grown body structures, in the person's movement and in undigested parts of the food [correct]
- (2) The energy is almost completely stored in new grown body mass (body weight). The left over energy remains as heat in the body.
- (3) In heat of the body and heat in the environment [correct]
- (4) In electric currents of nerves which control the body functions
- (5) In heat stores, which the body uses to generate movement

### **Chemistry Item (Task 9 – Energy aspect: degradation/dissipation)**

When gasoline is burnt in an engine, the gasoline's energy can no longer be used after the combustion reaction.

*What is the correct explanation?*

- (1) Energy was stored in the gasoline. This energy no longer exists after combustion.
- (2) The energy is destroyed in the combustion. Therefore, it can no longer be used.
- (3) The engine has to ignite again. Otherwise the energy cannot be used.
- (4) The energy has propelled the car. In this process, the energy is lost.
- (5) Energy is released into the environment through the propulsion and through combustion products. Therefore, it can no longer be used. [correct]

### **Physics Item (Task 35 – energy aspect: conservation)**

A child skateboards in a halfpipe.

*What can be said about the total energy of the child and his/her environment?*

- (1) The total energy remains the same. [correct]
- (2) The total energy decreases.
- (3) The total energy increases.
- (4) The total energy changes constantly.

**Figure 4.1.** Examples of energy items for biology, chemistry and physics contexts. Task numbers refer to items in online resource 1

The reliability of the instrument was high ( $\alpha = .85$ ), while the subtests for the three disciplinary contexts provided satisfactory reliabilities ( $\alpha = .61-.71$ ). The validity of the instrument was discussed according to Messick's (1995) aspects of construct validity, including findings from, e.g., school book and curricula analyses (Opitz et al. 2015). In addition to the energy items, a test on crystallized intelligence (Horn 1983) was included in this study to serve as a covariate of progressing energy understanding. However, this variable, as well as previously assessed covariates (e.g., fluid intelligence, reading ability, motivation/interest, gender), had only a minor influence on progressing energy scores (Opitz et al. 2015, submitted; see also Liu et al. 2015).

### 4.3.3 Testing and Sample

The sample consisted of  $N = 742$  students from grades 6, 8 and 10 ( $n = 255 / 268 / 229$ ;  $M_{\text{age}} = 12.3 / 14.3 / 16.4$  years). Testing sessions were conducted in the four weeks before the end of the school year and provided sufficient time for all students to finish the test.

Students stemmed from 33 classes in six secondary schools in a larger metropolitan area in northern Germany. As the data were cross-sectional, the subsamples (grade levels) were assessed for comparability in relation to intelligence, gender, socio-economic status, and the proportion of students from each of two secondary school types. The respective data and further details of the sample are provided in Opitz et al. (submitted). Participating students were taught according to science standards that included energy as a core idea in the different disciplinary contexts, and as a concept to span across them. Students in our sample had received integrated science classes from grade 1-6 and separate science classes (biology, chemistry, physics) from grade 7 onwards. For each science subject, the science standards encompass numerous energy learning opportunities from grades 2 to 12/13, as listed in online resource 2.

### 4.3.4 Analysis and Statistical Procedures

To analyze the connection and changes in students' energy understanding across different disciplinary contexts, the questionnaire data were used to compare different models of students' energy understanding across disciplinary contexts. These models were specified using Confirmatory Factor Analysis (CFA) with *Mplus* software (Muthén and Muthén 2007). The analysis was conducted in a two-step procedure:

(i) First, measurement invariance tests (van de Schoot et al. 2012) were conducted across grade levels. The purpose of this step was to determine whether the connection of energy understanding between the three disciplinary contexts changed across grades and, consequently, whether models of energy understanding should be compared separately at each grade level or across grades. Generally, a low level of invariance would suggest that the connection of energy understanding in the three contexts changes across grades. The models used for the measurement invariance tests were compared via AIC/BIC values and overall model fit criteria (see following paragraph). Four hierarchical levels of invariance were tested in addition to an underlying level of configural invariance ('Level 0'), i.e., the unconstrained model at all grade levels:

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Level 1: 'Metric invariance', i.e., equal factor loadings across groups

Level 2: Invariance of intercepts with varying factor loadings

Level 3: 'Scalar invariance', i.e., invariance of factor loadings and intercepts

Level 4: 'Full uniqueness measurement invariance', i.e., invariance of factor loadings, intercepts, and residuals

(ii) The second step was conducted according to the results from the measurement invariance tests. In this step, a 1-dimensional (1d) and a 3-dimensional (3d) model were compared in relation to the three scenarios outlined in the hypotheses. The 1d model included a single latent variable, representing cross-disciplinary energy understanding. This single variable was represented by all items from the three disciplinary contexts. The 1d model assumed that students apply the same understanding of energy across the three disciplinary contexts. In contrast, the 3d model included three latent variables, representing separate sets of energy understanding respective the three disciplinary contexts. Each variable was represented by the items from one disciplinary context only (e.g., the biology variable was represented by all biology items). The two models were compared by using standardized cutoff criteria suggested by Hu and Bentler (1999) for the  $\chi^2$  test ( $p > .05$ ), the comparative fit indices CFI and TLI ( $> .95$ ) and the absolute fit indices RMSEA ( $< .06$ ) and WRMR ( $< 1.0$ ; Yu 2002).

With respect to the three hypothesized scenarios of change (see hypotheses), we assumed that a parallel progression in understanding of the three contexts would result in the same model (either 1d or 3d) at all grade levels (scenario i). A process of differentiation into discipline-specific sets of energy understanding was assumed to be characterized by a superior fit of the 1d model in lower grades and a 3d model at higher grade levels (scenario ii). Regarding scenario (iii), a process of knowledge integration was assumed to lead from discipline-specific sets of energy understanding (3d) in the lower grades to cross-disciplinary understanding (1d) among more advanced students.

The success of latent modeling depends on the ratio between the number of model parameters and the sample size, which is described by the  $N:q$  rule (Kline 2011, p.12). This rule suggests a minimum of five times as many cases as parameters. As only half of the sample size suggested by the  $N:q$  rule was available for this study, item parcels were used as a means to limit the number of model parameters, thereby ensuring that the models were not negatively affected by the limited sample size. The parcels were constructed using sum scores across the three to four items for each energy aspect and disciplinary context (Kline 2011, p.179). To validate the parceling approach, each parcel was modeled as a (1  $PI$ -) Rasch model in CONQUEST. The resulting infit and outfit

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estimates were evaluated in relation to conservative cutoff criteria for high-stakes tests and larger samples ( $0.8 < \text{infit/outfit} < 1.1$ ; Bond and Fox 2001, p.243). The analysis showed good infit and outfit values for all items in their respective twelve item parcels, thereby indicating that the parcels measured a single construct ( $m_{\text{MNSQ outfit}} = 1.00 \pm .03$  SD;  $m_{\text{MNSQ infit}} = 0.99 \pm .08$  SD). The results for each parcel are provided in online resource 3. As additional validation steps, other parceling strategies (e.g., random assignment of items to parcels) were applied and all models were also computed without parcels. These models provided similar results as those from the more adequate and stable parceling approach.

Two different sets of estimation procedures had to be employed to compare the 1d- and 3d-models: First, the overall model fit was compared using WLSMV estimation for categorical data (mean- and variance-adjusted weighted least squares). Due to each parcel's sum scores across the dichotomously scored items, this first estimation procedure was most appropriate and provided the reference models for model comparisons (Kline 2011, p. 176; Muthén and Muthén 2012). However, only nested models can be compared in absolute terms via WLSMV estimation (Muthén and Muthén 2012, p. 451f.). As the 1d and 3d models were non-nested, the second estimation procedure assumed data to be continuous, thus allowing the use of ML estimation (maximum likelihood) to derive approximant models (Kline 2011, p.154). In addition to the consideration of the general fit indices mentioned above (including SRMR,  $< 0.08$ , Hu and Bentler 1999), this second procedure allowed the comparison of the 1d and 3d models in absolute terms by using the indices AIC and BIC.

### 4.4 Results

This section first presents the results from the measurement invariance tests, which assess in how far students' energy understanding in the three disciplinary contexts changes across grade levels. These results provide the empirical basis for the comparisons of the cross-disciplinary (1d) and context-specific (3d) models in the second section. Lastly, the models' results are interpreted with regard to the research question.

#### 4.4.1 Tests for Measurement Invariance across Grade Levels

Table 4.1 reports the results from the measurement invariance tests for both the 1d and 3d models. Models for invariance tests are conducted in a hierarchical order until a more constrained/higher-level invariance model shows a worse fit than the hierarchically lower one (cf. van de Schoot et al. 2012). While all invariance levels were tested, models for

higher-order levels are not reported here if hierarchically lower levels already showed worse model fits.

The data in Table 4.1 show that measurement invariance had to be rejected for both the 1d and the 3d model. In detail, the data indicate that students at different grade levels applied different meanings (i) to the latent constructs of the two models and (ii) to specific item parcels. Additionally, (iii) error variances of item parcels differed across grade levels (cf. van de Schoot et al. 2012). It is therefore assumed that students' energy understanding across disciplinary contexts *generally* changed from grade 6 to grade 10. Consequently, the model comparisons conducted in relation to the research question had to be compared at individual grade levels and not across them. These findings are presented in the following section.

### **4.4.2 Comparison of the Cross-Disciplinary (1d) and the Discipline-Specific (3d) Model of Energy Understanding**

According to the test procedure described in the method section, the comparison of models for the research question was conducted via two estimation procedures. First, the reference models are presented which were derived from WLMSV estimation. Second, models from ML estimation are presented as approximants. The models from this second estimation procedure extend the results from WLMSV estimation by allowing an absolute comparison of the respectively superior model via AIC/BIC fit values.

**Estimation procedure 1.** Table 4.2 shows WLSMV estimator based fit criteria for grades 6, 8 and 10 respective the 1d model (cross-disciplinary energy understanding) and the 3d model (different sets of energy understanding in the three disciplinary contexts).

Both the 1d and 3d reference models from WLSMV estimation showed generally good fit values at the different grade levels. In grade 6, minor misfits were observed for both models ( $\chi^2$ -tests, CFI, TLI). While in grade 8, the models generally fitted well, the 1d model was preferable to the 3d model as the latter produced a non-resolvable error warning due to a non-positive definite covariance matrix. This was caused by a high correlation between the latent variables for energy understanding in physics and chemistry. In grade 10, both models showed equally good fit criteria.

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**Estimation procedure 2.** Table 4.3 presents the results for the approximate models derived from maximum likelihood (ML) estimation that include AIC/BIC fit indices for the comparison of the 1d and 3d models in absolute terms.

The model fits derived from ML estimation were comparable to those from the reference WLSMV estimation (Table 4.2). In grade 6, both the 1d and 3d models showed similar (minor) problems with model fit. Due to an error warning for the 3d model, the 1d model should be preferred. In grade 8, AIC/BIC scores suggested a preference for the 3d model, but the 3d model produced error warnings due to latent correlation estimates  $> 1.0$ . Consequently, the 1d model was preferred for grade 8, as well. In grade 10, the 3d model showed superior fit to the 1d model due to lower AIC/BIC values. However, the 3d model's three latent variables for energy understanding in each disciplinary context were very strongly correlated ( $r \sim .9$ ). Thus, with respect to the principle of model parsimony (Kline 2011), the 3d model also had to be rejected for grade 10 and the 1d model has to be assumed, instead.

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**Table 4.1.** Results for statistically relevant levels of *measurement invariance tests* across grades 6, 8 and 10 respective the 1d and 3d models of energy understanding

Invariance Level	<i>N</i>	Parameters	$\chi^2 M$	<i>Df</i>	<i>p</i> $\chi^2 > .05$	CFI > 0.95	TLI > 0.95	RMSEA < 0.06	SRMR < 0.08	AIC	BIC
1d model											
<b>Level 0*</b>	742					Cf. Tables 2 and 3*					
Level 1	742	84	372.29	186	0	0.81	0.80	0.06	0.06	20899.86	21285.56
Level 2	742	84	624.82	186	0	0.56	0.53	0.10	0.27	21152.39	21538.09
3d model											
<b>Level 0*</b>	742					Cf. Tables 2 and 3*					
Level 1	742	93	401.00	177	0	0.78	0.75	0.07	0.11	20920.60	21347.62
Level 2	742	93	645.64	177	0	0.53	0.47	0.10	0.10	21165.24	21592.26

*Note:* Values in column titles denote cutoff criteria suggested by Hu and Bentler (1999) and Yu (2002). *Italic and grey* values are critical with respect to these criteria. **Bold** print indicates highest assumable level of invariance.

\* Construct-level invariance ('Level 0') tests, if a model fits at each grade level. These findings are reported in Tables 2 and 3.

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**Table 4.2.** Fit indices from *WLSMV estimation* for the 1d and 3d models of energy understanding

Grade	Model	<i>N</i>	Parameters	$\chi^2 M$	<i>Df</i>	$p \chi^2 > .05$	CFI > 0.95	TLI > 0.95	RMSEA < 0.06	WRMR < 1.0
6	1d	255	54	57.30	40	<i>.04</i>	<i>0.90</i>	<i>0.89</i>	0.04	0.78
	3d	255	51	52.30	38	.05	<i>0.89</i>	<i>0.88</i>	0.04	0.76
8	1d	268	54	46.80	41	.25	0.99	0.99	0.02	0.62
	<i>3d *</i>	268	56	42.58	39	.32	0.99	0.99	0.02	0.60
10	1d	229	54	51.69	40	.10	0.99	0.99	0.04	0.63
	3d	229	57	46.99	38	.15	0.99	0.99	0.03	0.61

*Note: Italic and grey values are critical with respect to cutoff criteria suggested by Hu and Bentler (1999) and Yu (2002).*

\* Estimation error due to a non-positive definite covariance matrix caused by a correlation estimate between the latent constructs for physics and chemistry > 1.0.



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**Table 4.3. Fit indices from *ML estimation* for the 1d and 3d models of energy understanding**

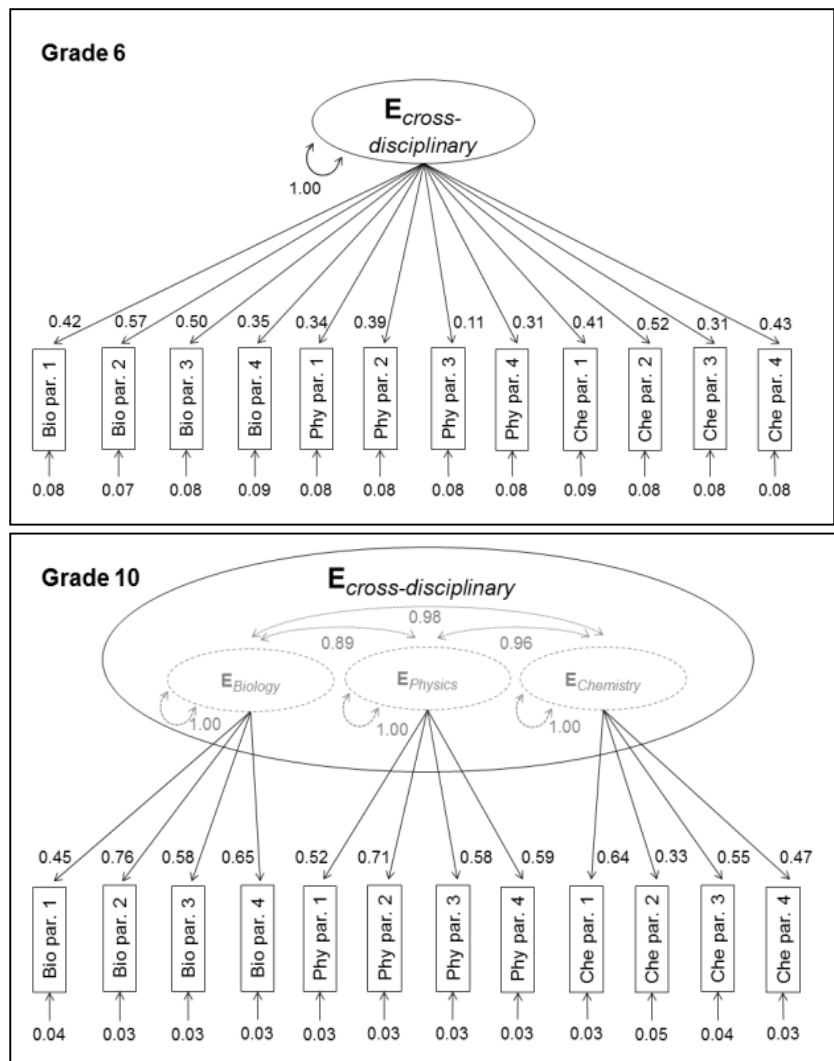
Grade	Model	<i>N</i>	Parameters	$\chi^2 M$	<i>Df</i>	$p X^2 > .05$	CFI > 0.95	TLI > 0.95	RMSEA < 0.06	SRMR < 0.08	AIC	BIC
6	<b>1d</b>	255	36	72.65	54	.05	<i>0.89</i>	<i>0.86</i>	0.04	0.05	<b>6479.07</b>	<b>6606.55</b>
	<i>3d*</i>	255	39	66.09	51	.08	<i>0.89</i>	<i>0.86</i>	0.03	0.49	6504.57	6642.62
8	<i>1d</i>	268	36	61.98	54	.21	0.98	0.98	0.02	0.04	8088.26	8217.54
	<b>3d*</b>	268	39	53.78	51	.37	0.99	0.99	0.01	0.04	<b>8050.83</b>	<b>8190.88</b>
10	1d	229	36	83.78	54	.01	0.95	<i>0.94</i>	0.05	0.04	7088.00	7211.61
	<b>3d</b>	229	39	75.99	51	.01	0.96	<i>0.94</i>	0.05	0.04	<b>7075.99</b>	<b>7209.94</b>

*Note: Italic and grey* values are critical with respect to cutoff criteria suggested by Hu and Bentler (1999) and Yu (2002). **Bold** print indicates better-fitting models respectively AIC and BIC.

\* Estimation error due to a non-positive definite covariance matrix caused by a correlation estimate between the latent constructs for physics and chemistry > 1.0.

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In summary and with respect to the research question, the findings indicate that energy understanding is best represented by a 1-dimensional, cross-disciplinary model of energy understanding across grades 6, 8 and 10. Thus, a clear change respective the hypothesized scenarios was not observable, as neither a change in the form of a differentiation (ii) nor integration (iii) were observable in students' energy understanding across disciplinary contexts. To illustrate these findings as endpoints of progressing energy understanding, Figure 4.2a/b present CFA model diagrams for grades 6 and 10.



**Figure 4.2a (top)/4.2b (bottom).** Best-fitting models at progression endpoints. *Figure 4.2a:* Grade 6. 1-dimensional, cross-disciplinary energy understanding (1d,  $E_{cross-disciplinary}$ ). *Figure 4.2b:* Grade 10. 1-dimensional model with three highly correlated subsets of energy understanding in the three disciplinary contexts (dashed/grey). Rectangular boxes denote item parcels, each representing 3-4 items. All values are standardized (STDXY) results. Correlations between disciplinary contexts are latent estimates (Pearson's  $r$  values for grade 10: bio-phy:  $r = .62$ , bio-che:  $r = .58$ , phy-che:  $r = .51$ )

## 4.5 Discussion

The findings are unexpected with regard to our hypotheses. In the first section of the discussion, possible methodological and conceptualization-related causes for the results are addressed. Based on these considerations, the second section discusses in how far the observed cross-disciplinary energy understanding can be understood as a parallel progression of students' conception of energy in different disciplinary contexts (scenario i), thereby also referring back to the results from the measurement invariance tests.

### 4.5.1 Discussion of the Procedure

The extent to which conclusions can be drawn about our research depends on the sample size, the specific testing procedure, and the employed models.

**Limitations in design and sample.** In this study, the ratio between the sample size and the number of estimated parameters of the employed models required the application of item parcels (see method section). As this procedure has been criticized for making the often inaccurate assumption that clustered items measure the same construct (Kline 2011, p.181), different parceling strategies were compared and the final parcels were assessed for uni-dimensionality in order to back the employed parcels. The parceling approach also made it necessary to use a combination of the reference WLSMV and the approximate ML estimation procedures for model comparison. However, the similarity between both estimation procedures suggests that the approximate ML estimation was acceptable for this data set.

The analysis of more complex models would require much larger samples than the one available in this study. For example, the application of more fine-grained models, e.g., with the scope of comparing cross-disciplinary knowledge integration between the four energy aspects, was not feasible with this data set (cf. Neumann and Nagy 2013). Furthermore, an approach with a more representative item set for the numerous energy learning opportunities across grades would allow it to, e.g., differentiate between students' understanding of energy in states versus energy in processes, which was only inconsistently addressed in the employed instrument.

**Alternative models of energy understanding.** In addition to the 1d and 3d models addressed above, several alternative models were compared via their criteria to ensure that the 1d and 3d models were good representatives of students' knowledge. For example, energy understanding was modeled according to the four energy aspects

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described above and different modeling approaches were devised on the basis of specific contexts (e.g., plant growth, movement, combustion; cf. Lancor 2015). All models were additionally combined with test results for crystallized intelligence as a covariate of energy understanding (Opitz et al. submitted; cf. method section). With respect to the research question, testing a 4-dimensional alternative model was especially relevant. This model encompassed the three disciplinary contexts, as well as a fourth dimension of interdisciplinary energy understanding, represented by the items rated as being less specific for a disciplinary contexts (see method section). In conclusion, none of these alternative models showed better fit indices than those presented in the results.

**Validity of the testing procedure.** It could be questioned if the absence of observable changes in the relation of sets of energy understandings between disciplinary boundaries was caused by unwanted properties of the employed instrument. A 1-dimensional energy understanding would be supported by an instrument that employs unspecific items with regard to the disciplinary contexts. However, the rating of the items' specificity for the three contexts showed high levels of agreement (Fleiss'  $k = .81$ , cf. Opitz et al. submitted) and lowered correlations between the three subtests substantially.

We operationalized energy understanding in the three contexts through the same set of four energy aspects that served as the framework for item construction. While any underlying framework will influence the development of instruments, we chose this approach because we perceived the framework to represent energy understanding in the three disciplinary contexts well and because it allowed a systematic comparison across them (cf. Lancor 2014). Nevertheless, to exclude effects of the framework on the results, we encourage future studies on cross-disciplinary energy understanding to also employ approaches with independently constructed items for each disciplinary context. However, such alternative approaches, e.g., with energy tasks from regular school books also face limitations. Energy tasks in school books can have a broad scope with an undifferentiated perspective on energy that, e.g., rarely addresses energy degradation and conservation in biological contexts (cf. Wernecke 2015). Hence, it would be difficult to use regular school book tasks to systematically compare energy understanding across disciplinary contexts.

Despite these possible constraints, further evidence for the validity of our findings can be found in the results of Park's (2013) study on cross-disciplinary energy understanding. Here, the correlations between energy understanding in different disciplinary contexts were similar to those found in our study, even though Park (2013) applied another instrument and assessed much more advanced students. As our and

earlier studies (Lancor 2014; Park 2013) obtained similar findings despite differences in students' educational background/-setting, their age, and the research method, the results indicate that a high dependence between energy understanding in different disciplinary contexts may be a general characteristic of students' understanding of this concept.

**Specificity of research method and findings.** The energy concept's degree of abstraction (Constantinou and Papadouris 2012), its numerous everyday connotations (Lacy et al. 2014), and the varying degree of contextualization in different disciplinary contexts (Dauer et al. 2014) are specific to the energy concept. These characteristics may cause students' progressing energy understanding to substantially differ from their understanding of other crosscutting concepts. Furthermore, energy is considered both as a disciplinary core idea *and* as a crosscutting concept in different subjects. This study approached the interdisciplinary perspective of energy learning by analyzing changes in the connection between sets of energy understanding in different disciplinary contexts. Hence, the testing procedure is specific to the energy concept and our findings and research method are not simply transferable to the study of other crosscutting concepts (compare, e.g., approaches for the matter concept, Shwartz, Weizman, Fortus, Krajcik, and Riser 2008). A study that specifically assesses energy understanding in the sense of a crosscutting concept (cf. NGSS 2013) would likely have to employ a different testing methodology with, e.g., constructed response formats, practice tasks, and the inclusion of social dimensions of understanding energy (cf. Duschl 2012).

### 4.5.2 Energy as a Disciplinary Core Idea and a Crosscutting Concept

Students' energy understanding appears to progress along two dimensions: First, energy test scores increase quantitatively over time (Opitz et al. submitted). Second, students' understanding undergoes a structural change: Even though our results did not indicate a clear progression with regard to the hypothesized scenarios, a change was—more generally—observable through the measurement invariance tests (cf. Lee and Liu 2009). These changes can be expected, as learning opportunities regarding the four energy aspects change across grade levels (Neumann et al. 2013), thus causing factor loadings of items to vary at different grade levels. The observed variance in measurements across grades may furthermore be caused by more fine-grained changes in energy understanding across disciplinary boundaries, e.g., regarding students' energy understanding in specific contexts (cf. Lancor 2015; Neumann et al. 2013).

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In revisiting the three hypothesized scenarios for changes in energy understanding across grades, we conclude that our data best resembles a parallel progression of understanding in the three disciplinary contexts (scenario i, cf. hypotheses). This parallel progression is realized by high correlations between the three sets of energy understanding, which should hence be regarded as one (cf. hypotheses).

The findings suggest that, as the students mature and proceed from grade 6 to 10, they neither exhibit a discipline-specific differentiation of their energy understanding (scenario ii), nor a process of integration that combines discipline-specific sets of energy understanding into a cross-disciplinary energy concept (scenario iii). While more subtle processes of differentiation or integration may have remained unregistered by our testing procedure and study design, it is important to note that the observed highly correlated energy understanding across disciplinary contexts is not necessarily an integrated one, as suggested by scenario (iii). These results are unexpected with regard to previous research and our hypotheses, as students at all grade levels applied one energy understanding across disciplinary contexts and as the teaching of energy in separate biology, chemistry, and physics classes did not seem to promote the development of discipline-specific sets of energy understanding. The following sections discuss these findings in detail.

**Interpretation of the observed 1-dimensional energy understanding.** Varying foci on the energy concept in different disciplinary contexts have been discussed as a hurdle for progressing energy understanding and even advanced students have been found challenged by transferring energy knowledge across disciplinary boundaries (cf. Chabalengula et al. 2011; Chen et al. 2014; Dreyfuß et al. 2012; Jin and Anderson 2012; Lancor 2015). In this regard, an unexpected result of our study was that students from grade 6 onwards seem to employ a cross-disciplinary energy understanding, while, instead, particularly younger students' energy understanding has frequently been found limited (cf. Lacy et al. 2014; Neumann et al. 2013; Opitz et al. 2015). If students, despite being taught in a way that likely promotes discipline-specific characteristics of energy understanding, don't exhibit such characteristics, their conceptualization of energy is possibly less connected to the scientific energy concept, but more to everyday-based energy connotations (e.g., Lacy et al. 2014). In this regard, prior analyses indicated that students solve equivalent tasks from different disciplinary contexts by using similar explanations, e.g., the consistent application of alternative conceptions such as 'energy loss' (Opitz et al. submitted). Additionally, earlier studies (e.g., Lancor 2014; Neumann et al. 2013) concluded that students' energy understanding varies between specific

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contexts. Both these variances within disciplinary contexts as well as the described difficulties across disciplinary boundaries may overwrite traits of energy understanding that are specific for individual disciplinary contexts and thus favor the 1-dimensional model in the results.

As neither processes of differentiation nor integration were observable (scenarios ii and iii), the 1d structure of energy understanding may therefore primarily indicate that students' conceptions of energy are unspecific with regard to disciplinary contexts. Prototypically, such a 1-dimensional, 'unspecific' energy understanding would likely be characterized by the application of similar everyday connotations and metaphors across disciplinary contexts and would thus substantially differ from a conceptualization respective the three disciplinary contexts (3d): Here, students would apply different perspectives depending on the disciplinary background, e.g., a macro-level analyses in biology versus a molecular-level perspective in chemistry (cf. Dreyfuß et al. 2012). Furthermore these different perspectives would take into account different reference systems, e.g., idealized closed scenarios versus open ecosystems. Also, the focus on the four energy aspects would likely differ with the disciplinary contexts, as, e.g., older students may focus on enthalpy and entropy in chemical reaction systems, while analyzing energy flow in a biological system with regard to the available energy for life processes (cf. theoretical background). An important part of progressing towards energy understanding in the sense of a crosscutting concept (NRC 2012) likely includes that students learn to combine these different disciplinary perspectives.

**Relation between intra- and interdisciplinary energy learning.** *Within* disciplinary contexts, students' energy understanding was found to exhibit—at least partly—processes of knowledge integration (Lee and Liu 2009; Neumann and Nagy 2013). In contrast, an integration of discipline-specific sets of energy understanding *across* disciplinary contexts was not observed in our study until the end of middle school. Similarly, even students with an elaborate energy understanding were found to experience difficulties in combining different disciplinary perspectives on energy (Dreyfuß et al. 2012). Hence, knowledge integration of energy understanding within disciplinary contexts possibly antecedes or forms a basis for a later combination of discipline-specific characteristics of energy understanding. Analogously, findings from curriculum development research suggest that intra-unit coherence forms the basis for inter-unit coherence (Fortus et al. 2015; Shwartz et al. 2008). Research therefore has to identify adequate instructional formats that can support the coherence of energy instruction within disciplinary contexts (cf. Lee and Liu 2009).

### 4.5.3 Conclusions and Implications

This study provides some of the first insights into the relation of progressing energy understanding across disciplinary contexts. A methodology is exemplified on how progressing energy understanding can be studied across disciplinary boundaries and how processes of knowledge integration and differentiation across different contexts can be included into the analysis. The results can, e.g., be used to determine from what grade level onwards students employ a cross-disciplinary energy understanding with which the students can address interdisciplinary tasks in science education.

The results suggest a difference between purpose-designed, coherent instruction that succeeds in fostering cross-disciplinary knowledge integration (Fortus et al. 2015) and day-to-day instruction that appears to neither lead towards discipline-specific sets of understanding, nor towards an integration of energy knowledge from different disciplinary contexts. These first insights into cross-disciplinary energy learning from our and previous studies (Lancor 2014; Park 2013) need to be verified and further examined through experimental and longitudinal studies.

We conclude that teaching about energy should commence by acknowledging that students likely employ one energy understanding across disciplinary boundaries. Once energy teaching is well connected across different science subjects and in between different teaching units, discipline-specific foci on energy (e.g., transfer in biology, conservation in physics) can be highlighted to help students better understand the different aspects of the energy concept. Furthermore, the development of energy teaching and learning across disciplinary boundaries could likely benefit from teacher trainings that demonstrate how energy learning opportunities can be effectively connected across disciplinary boundaries. In conclusion of previous research, several approaches may be employed to implement this goal: (i) Connecting similar energy-related topics across disciplinary contexts (e.g., cellular respiration in biology and chemistry), (ii) connecting specific aspects of energy instruction across disciplinary contexts (e.g., energy conservation in mechanics and exothermic reactions), (iii) connecting levels of analysis across disciplinary contexts (e.g., macro-micro thinking), and (iv) using coherent energy terminology across disciplinary contexts (Eisenkraft et al. 2014; Fortus et al. 2015). Additionally, fostering students to combine different disciplinary perspectives likely depends on an effective demonstration of the fruitfulness of a multi-perspective energy analysis (Dreyfuß et al. 2012).

Students in our study applied a cross-disciplinary energy understanding from an early age onwards and we discussed that this result can be caused by, e.g., alternative ideas about energy. As a consequence, we suggest that the scientific community should



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re-evaluate performance expectations connected to cross-disciplinary energy understanding.

Several perspectives can be derived for continuing research. With regard to our findings, deeper insight into progressing energy understanding could be attained by controlling for energy instruction within disciplinary contexts to determine the contribution of different school subjects to students' learning of the energy concept (cf. Dreyfuß et al. 2012). Future studies should expand our findings to include progressing energy understanding in high-school/university. Large-scale assessments could provide insights into more detailed models of energy understanding to shed light on the related processes of knowledge integration and differentiation. These explorative studies, however, only provide the empirical basis for much needed experimental research that identifies effective instructional methods to promote energy learning both as a core idea in different disciplinary contexts and as a crosscutting concept.

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### 4.7 Online Resources

Online resource 1: Items and item parameters

Online resource 2: Energy learning opportunities at Hamburg schools/Germany

Online resource 3: Item fits within parcels

#### 4.8 References

- Alonzo, A. C., & Gotwals, A. W. (2012). *Learning Progressions in Science - Current Challenges and Future Directions*. Rotterdam: Sense Publishers.
- Bond, T. G., & Fox, C. M. (2001). *Applying the Rasch Model: Fundamental Measurement in the Human Sciences*. Mahwah, NJ: Lawrence Erlbaum Associates, Inc.
- Boyes, E., & Stanisstreet, M. (1991). Misconceptions in First-Year Undergraduate Science Students about Energy Sources for Living Organisms. *Journal of Biological Education*, 25(3), 209-213.
- Boylan, C. (2008). Exploring Elementary Students' Understanding of Energy and Climate Change. *International Electronic Journal of Elementary Education*, 1(1), 1-15.
- Bransford, J. D., Brown, A. L., & Cocking, R. R. (2000). *How People Learn: Brain, Mind, Experience and School*. Washington, D.C.: National Academy Press.
- Burger, J. (2001). *Schülervorstellungen zu "Energie im biologischen Kontext" - Ermittlungen, Analysen und Schlussfolgerungen* [Student conceptions on energy in biological contexts - Assessment, Analyses and Conclusions]. Doctoral dissertation, University of Bielefeld, Germany.
- Chabalengula, V., Sanders, M., & Mumba, F. (2011). Diagnosing Students' Understanding of Energy and Its Related Concepts in Biological Contexts. *International Journal of Science and Mathematics Education*, 10(2), 241-266.
- Chen, B., Eisenkraft, A., Fortus, D., Krajcik, J. S., Neumann, K., Nordine, J., & Scheff, A. (2014). *Teaching and Learning of Energy in K-12 Education*. New York: Springer.
- Clark, D., & Linn, M. C. (2003). Designing for Knowledge Integration: The Impact of Instructional Time. *Journal of the Learning Sciences*, 12(4), 451-493. doi: 10.1207/s15327809jls1204\_1
- Constantinou, C. P., & Papadouris, N. (2012). Teaching and Learning about Energy in Middle School: An Argument for an Epistemic Approach. *Studies in Science Education*, 48(2), 161-186.
- Cooper, M. M., Klymkowsky, M. W., & Becker, M. (2014). Energy in Chemical Systems. An integrated Approach. In R.F. Chen, A. Eisenkraft, D. Fortus, J.S. Krajcik, K. Neumann, J. Nordine & A. Scheff (Eds.), *Teaching and Learning of Energy in K-12 Education*. New York: Springer.
- Dauer, J. M., Miller, H. K., & Anderson, C. W. (2014). Conservation of Energy: An Analytical Tool for Student Accounts of Carbon-Transforming Processes. In R.F. Chen, A. Eisenkraft, D. Fortus, J.S. Krajcik, K. Neumann, J. Nordine & A. Scheff (Eds.), *Teaching and Learning of Energy in K-12 Education*. New York: Springer.

## Chapter 4 (Study 3): Energy Understanding across Biology, Chemistry, and Physics Contexts

---

- Doménech, J., Gil-Pérez, D., Gras-Martí, A., Guisasola, J., Martínez-Torregrosa, J., Salinas, J., . . . Vilches, A. (2007). Teaching of Energy Issues: A Debate Proposal for a Global Reorientation. *Science & Education*, 16(1), 43-64.
- Dreyfuß, B. W., Redish, E. F., & Watkins, J. (2012). *Students' Views of Macroscopic and Microscopic Energy in Physics and Biology*. Paper presented at the AIP Conference, Proceedings, 1413.
- Driver, R., Squires, A., Rushworth, P., & Wood-Robinson, V. (1994). *Making Sense of Secondary Science: Supporting Material for Secondary Teachers*. London: Routledge.
- Driver, R., & Warrington, L. (1985). Students' Use of the Principle of Energy Conservation in Problem Situations. *Physics Education*, 20(4), 171.
- Duschl, R. A. (2012). The Second Dimension—Crosscutting Concepts Understanding A Framework for K–12 Science Education. *Science Teacher*, 79(2), 34-38
- Eisenkraft, A., Nordine, J., Chen, R. F., Fortus, D., Krajcik, J. S., Neumann, K., & Scheff, A. (2014). Introduction: Why focus on Energy Instruction? In R.F. Chen, A. Eisenkraft, D. Fortus, J.S. Krajcik, K. Neumann, J. Nordine & A. Scheff (Eds.), *Teaching and Learning of Energy in K-12 Education*. New York: Springer.
- Fortus, D., & Krajcik, J. (2012). Curriculum Coherence and Learning Progressions. In B. J. Fraser, K. Tobin & C. J. McRobbie (Eds.), *Second International Handbook of Science Education* (Vol. 24, pp. 783-798): Springer Netherlands.
- Fortus, D., Sutherland Adams, L. M., Krajcik, J. S., & Reiser, B. J. (2015). Assessing the Role of Curriculum Coherence in Student Learning About Energy. *Journal of Research in Science Teaching*, 52(10), 1408-1425.
- Horn, W. (1983). *Leistungsprüfsystem - LPS* (Vol. 2). [Intelligence test LPS] Rosdort/Göttingen: Hogrefe.
- Hu, L., & Bentler, P. M. (1999). Cutoff criteria for fit indexes in covariance structure analysis: Conventional criteria versus new alternatives. *Structural Equation Modeling: A Multidisciplinary Journal*, 6(1), 1-55. doi: 10.1080/10705519909540118
- Intergovernmental Panel on Climate Change (2013). *Climate Change 2013. The Physical Science Basis - Working Group I. Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. New York: Cambridge University Press.
- Jin, H., & Anderson, C. W. (2012). A learning progression for energy in socio-ecological systems. *Journal of Research in Science Teaching*, 49(9), 1149-1180.

## Chapter 4 (Study 3): Energy Understanding across Biology, Chemistry, and Physics Contexts

---

- Kaper, W. H., & Goedhart, M. J. (2002a). 'Forms of Energy', an intermediary language on the road to thermodynamics? Part I. *International Journal of Science Education*, 24(1), 81-95.
- Kaper, W. H., & Goedhart, M. J. (2002b). 'Forms of energy', an intermediary language on the road to thermodynamics? Part II. *International Journal of Science Education*, 24(2), 119-137.
- Kirk, R. E. (1996). Practical Significance: A Concept Whose Time Has Come. *Educational and Psychological Measurement*, 56(5), 746-759. doi: 10.1177/0013164496056005002
- KMK [Ständige Konferenz der Kultusminister der Länder in der Bundesrepublik Deutschland] (2005a). *Bildungsstandards im Fach Biologie für den Mittleren Schulabschluss - Beschluss vom 16.12.2004* [Science Standards for Middle School Biology, Germany]. München, Germany: Luchterhand.
- KMK [Ständige Konferenz der Kultusminister der Länder in der Bundesrepublik Deutschland] (2005b). *Bildungsstandards im Fach Chemie für den Mittleren Schulabschluss: Beschluss vom 16.12.2004* [Science Standards for Middle School Chemistry, Germany]. München, Germany: Luchterhand.
- KMK [Ständige Konferenz der Kultusminister der Länder in der Bundesrepublik Deutschland] (2005c). *Bildungsstandards im Fach Physik für den Mittleren Schulabschluss Beschluss vom 16.12. 2004*. [Science Standards for Middle School Physics, Germany] München, Germany: Luchterhand.
- Krajcik, J. S., Chen, B., Eisenkraft, A., Fortus, D., Neumann, K., Nordine, J., & Scheff, A. (2014). Conclusion and Summary Comments: Teaching Energy and Associated Research Effort. In R.F. Chen, A. Eisenkraft, D. Fortus, J.S. Krajcik, K. Neumann, J. Nordine & A. Scheff (Eds.), *Teaching and Learning of Energy in K-12 Education*. New York: Springer.
- Kurnaz, M. A., & Sağlam-Arslan, A. (2011). A Thematic Review of Some Studies Investigating Students' Alternative Conceptions About Energy. *Eurasian Journal of Chemistry and Physics Education*, 3(1), 51-74.
- Lacy, S., Tobin, R., Wisner, M., & Crissman, S. (2014). Looking Through the Energy Lens: A Proposed Learning Progression for Energy in Grades 3-5. In R.F. Chen, A. Eisenkraft, D. Fortus, J.S. Krajcik, K. Neumann, J. Nordine & A. Scheff (Eds.), *Teaching and Learning of Energy in K-12 Education*. New York: Springer.
- Lancor, R. A. (2014). Using Student-Generated Analogies to Investigate Conceptions of Energy: A multidisciplinary study. *International Journal of Science Education*, 36(1), 1-23. doi: 10.1080/09500693.2012.714512

## Chapter 4 (Study 3): Energy Understanding across Biology, Chemistry, and Physics Contexts

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- Lancor, R. A. (2015). An Analysis of Metaphors Used by Students to Describe Energy in an Interdisciplinary General Science Course. *International Journal of Science Education*. doi: 10.1080/09500693.2015.1025309
- Lee, H.-S., & Liu, O. L. (2009). Assessing learning progression of energy concepts across middle school grades: The knowledge integration perspective. *Science Education*, 94(4), 665-688.
- Lindsey, B. A., Heron, P. R. L., & Shaffler, P. S. (2012). Student understanding of energy: difficulties related to systems. *American Journal of Physics*, 80(2), 154-163.
- Linn, M. C., Lewis, C., Tsuchida, I., & Songer, N. B. (2000). Beyond fourth grade science: Why do U.S. and Japanese students diverge? *Educational Researcher*, 29(3), 4-14.
- Liu, X., & McKeough, A. (2005). Developmental growth in students' concept of energy: Analysis of selected items from the TIMSS database. *Journal of Research in Science Teaching*, 42(5), 493-517.
- Liu, X., & Ruiz, M. E. (2008). Using data mining to predict K–12 students' performance on large-scale assessment items related to energy. *Journal of Research in Science Teaching*, 45(5), 554-573.
- Liu, X., & Tang, L. (2004). The progression of students' conceptions of energy: A cross-grade, cross-cultural study. *Canadian Journal of Science, Mathematics and Technology Education*, 4(1), 43-57.
- Liu, O. L., Ryoo, K., Linn, M., Sato, E. & Svihla, V. (2015). Measuring Knowledge Integration Learning of Energy Topics: A two-year longitudinal study. *International Journal of Science Education*. doi:10.1080/09500693.2015.1016470
- Messick, S. (1995). Validity of psychological Assessment: Validation of Inferences From Persons' Responses and Performances as Scientific Inquiry Into Score Meaning. *American Psychologist*, 50(9), 741-749.
- Nagel, M. L., & Lindsey, B. A. (2014). Student use of energy concepts from physics in chemistry courses. [10.1039/C4RP00184B]. *Chemistry Education Research and Practice*. doi: 10.1039/c4rp00184b
- National Research Council [NRC] (2012). *A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas*: The National Academies Press.
- National Research Council [NRC] (2014). *Developing Assessments for the Next Generation Science Standards*. Washington, D.C.: The National Academies Press.

## Chapter 4 (Study 3): Energy Understanding across Biology, Chemistry, and Physics Contexts

---

- Neumann, K., Viering, T., Boone, W. J., & Fischer, H. E. (2013). *Towards a Learning Progression of Energy*. *Journal of Research in Science Teaching*, 50(2), 162-188.
- Neumann, K. & Nagy, G. (2013). *Students' Progression in Understanding Energy*. Paper presented at the NARST Annual International Conference, Puerto Rico, Rio Grande.
- Next Generation Science Standards [NGSS] (2013). *Next Generation Science Standards - For States, By States*. National Academic Press, Washington.
- Nordine, J., Krajcik, J., & Fortus, D. (2010). Transforming energy instruction in middle school to support integrated understanding and future learning. *Science Education*, 95(4), 670-699.
- Novak, J. D. (2005). Results and Implications of a 12-Year Longitudinal Study of Science Concept Learning. *Research in Science Education*, 35(1), 23-40.
- Opitz, S., Harms, U., & Neumann, K., Kowalzik, K., & Frank, A. (2015). Students' Energy Concepts at the Transition between Primary and Secondary School. *Research in Science Education*, 45(5). 691-715. doi 10.1007/s11165-014-9444-8
- Opitz, S., Neumann, K., Bernholt, S. (submitted). How Do Students Understand Energy in Biology, Chemistry, and Physics? Development and validation of an assessment instrument. Submitted to the International Journal of Science Education.
- Park, M. (2013). *Developing an Instrument for Assessing Students' Understanding of the Energy Concept Across Science Disciplines*. Doctoral dissertation, University of Buffalo, Buffalo, New York. Retrieved from <http://search.proquest.com/pao/docview/1511026690>
- Pugh, K. J., & Bergin, D. A. (2006). Motivational Influences on Transfer. *Educational Psychologist*, 41(3), 147-160. doi: 10.1207/s15326985ep4103\_2
- Schmidt, W. H., Wang, H. C., & McKnight, C. C. (2005). Curriculum coherence: An examination of US mathematics and science content standards from an international perspective. *Journal of Curriculum Studies*, 37(5), 525-559.
- Schönborn, K., & Bögeholz, S. (2009). Knowledge Transfer in Biology and Translation across External Representations: Experts' Views and Challenges for Learning. *International Journal of Science and Mathematics Education*, 7(5), 931-955. doi: 10.1007/s10763-009-9153-3
- Shultz, T. R., & Coddington, M. (1981). Development of the concepts of energy conservation and entropy. *Journal of Experimental Child Psychology*, 31(1), 131-153.

## Chapter 4 (Study 3): Energy Understanding across Biology, Chemistry, and Physics Contexts

---

- Shwartz Y., Weizman, A., Fortus, D., Krajcik, J., & Reiser, B. (2008). The IQWST experience: Using coherence as a design principle for a middle school science curriculum. *Elementary School Journal*, 109, 199-219.
- Stacy, A. M., Chang, K., Coonrod, J., & Claesgens, J. (2014). Launching the Space Shuttle by Making Water: The Chemist's View of Energy. In R.F. Chen, A. Eisenkraft, D. Fortus, J.S. Krajcik, K. Neumann, J. Nordine & A. Scheff (Eds.), *Teaching and Learning of Energy in K-12 Education*. New York: Springer.
- Tastan, Ö., Yalcinkaya, E., & Boz, Y. (2008). Effectiveness of Conceptual Change Text-oriented Instruction on Students' Understanding of Energy in Chemical Reactions. *Journal of Science Education and Technology*, 17(5), 444-453.
- Tatar, E., & Oktay, M. (2007). The effectiveness of problem-based learning on teaching the first law of thermodynamics. *Research in Science & Technological Education*, 29(3), 315-332.
- Tenenbaum, J. B., Kemp, C., Griffiths, T. L., & Goodman, N. D. (2011). How to Grow a Mind: Statistics, Structure, and Abstraction. *Science*, 331(6022), 1279-1285.
- Trumper, R. (1993). Children's energy concepts: a cross-age study. *International Journal of Science Education*, 15(2), 139-148.
- Trumper, R. (1997). Applying Conceptual Conflict Strategies in the Learning of the Energy Concept. *Research in Science & Technological Education*, 15(1), 5-18.
- van de Schoot, R., Lugtig, P., & Hox, J. (2012). Developmetrics: A checklist for testing measurement invariance. *European Journal of Developmental Psychology*, *iFirst article*, 1-7. doi: 10.1080/17405629.2012.686740
- van Hook, S., & Huziak-Clark, T. (2008). Lift, squeeze, stretch, and twist: Research-based Inquiry Physics Experiences (RIPE) of energy for kindergartners. *Journal of Elementary Science Education*, 20(3), 1-16.
- Watts, D. M. (1983). Some alternative views of energy. *Physics Education*, 18(5), 213.
- Wernecke, U. (2015). *Students' understanding of energy and future learning about energy*. Paper presented at the NARST Annual International Conference, Chicago, USA.
- Yu, C.-Y. (2002). *Evaluating Cutoff Criteria of Model Fit Indices for Latent Variable Models with Binary and Continuous Outcomes*. Doctoral Dissertation, Los Angeles, CA.





## CHAPTER 5

# Characteristics of Students' Energy Understanding in Biological Contexts

*(Study 4)*

### **Abstract**

The energy concept serves biologists as a powerful analytical model to describe the extent to which processes can occur in the natural world. Due to the concept's relevance, educational standards of different countries identify energy as a core idea for the teaching and learning of biology and other science subjects. However, previous studies on students' energy understanding have mostly focussed on physics contexts, while providing only scarce insights into students understanding of energy in biological contexts. To fill this gap, this cross-sectional study analysed interviews from  $N = 30$  students (grades 5, 7, 9, 11) to provide a systematic analysis of students' conceptions about the central energy aspects in biological contexts, i.e. (1) energy forms/sources, (2) transfer/transformation, (3) degradation/dissipation, and (4) energy conservation. The findings identify substantial changes in students' conceptions about energy between the different grade levels. The results additionally reveal conceptions that students employed across age groups. The identified conceptions are discussed in the light of previous research on energy understanding and the article provides possible implications for the further development of energy teaching in biological contexts.

### 5.1 Introduction

Biology describes processes in the living world that, without exception, rely on the transformation of energy. Energy flows through organisms, thus allowing them to build up and maintain ordered structures that support their lives. As energy sources are often limited, the survival and evolutionary success of organisms depends on the efficiency of their energy transformations and the rate with which the organisms degrade energy (Reece et al., 2011). Accordingly, energy is a major concept for the analysis of all biological processes (Harms, 2016), for example, when biologists use the energy concept to determine the extent to which specific changes can occur in a given system.

Due to the concept's relevance in science, energy is also considered as a core (or big) idea for the teaching and learning of biology (e.g., DfE, 2013; NGSS, 2014). As such, energy is to serve students as a powerful analytical model to describe, for example, changes of a system in terms of movement, temperature, or chemical composition (DfE 2013, 10). Furthermore, the frequent occurrences of the energy concept connects biological topics across different grade levels, thus helping students to construct of a more interconnected understanding of biology (see also organization of expert knowledge: e.g., Bransford, Brown, and Cocking 2000, 9). The energy concept is also a core idea for the other science and engineering subjects (e.g., DfE 2013, 3) and is, accordingly, a means to foster students to connect science contents across disciplinary boundaries (e.g., Nordine 2016, 35; Opitz, Neumann, Bernholt, and Harms submitted; Park and Liu 2016). Besides its significance in school science instruction, the energy concept also concerns students' everyday lives, for example, when they speak about nutrition, sports, 'energy consumption and saving', or topics like climate change (Harms, 2016).

Despite the importance of the energy concept for biology instruction, previous research has mostly focussed on students' energy understanding in physics contexts. To extend this research and to provide an empirical basis for the further development of energy instruction in biology, this study provides a systematic analysis of students' conceptions about energy in biological contexts.

### 5.2 Literature Review

Detailed summaries of research on students' energy understanding have been provided in previous publications (e.g., Chen et al. 2014; Neumann et al., 2013; Nordine, Krajcik,

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and Fortus 2011). According to the focus of this study, this section reviews research that specifically focuses on energy learning in biological contexts.

Even though energy is an abstract concept, students are likely to encounter several implicit references to energy before the concept's explicit introduction in school (Lin and Hu 2003). An early start of energy instruction was hereby found to have sustainable learning effects until high school (Novak, 2005). More so, early energy learning opportunities concern numerous biological contexts and students use these learning opportunities to develop first stages of their energy understanding (Opitz, Harms, Neumann, Kowalzik, and Frank 2015).

Burger (2001) identified central student conceptions of energy in life processes, for example, that energy is created by animals; that the animals take up heat as a source of energy; or that energy cycles in systems. While the author found specific student conceptions to change across grade levels, the students' conceptual understanding of energy underwent only minor changes from lower middle to high school. Similarly, persistent alternative conceptions, for example, with respect to energy sources for animals and plants, have been presented by Boyes and Stanisstreet (1990). In learning about energy in biology, learners have been found to apply hybrid (instead of single) frameworks of understanding (Nordine et al. 2011) and students' comprehension of energy was found to depend on specific learning contexts (Lancor, 2015; Neumann et al. 2013; Park and Liu 2016).

Jin and Anderson (2012) presented an energy learning progression for biological processes by describing four hierarchical levels of complexity: (1) Commonly at elementary-level, students used everyday conceptions of energy, in which they trace cause-and-effect chains in force-dynamic accounts and see energy as an enabler. (2) Across middle and high school, students prominently applied force-dynamic accounts in which students blended the analysis of energy and matter and described energy as a cause for occurring processes. (3) At the third level, students identified organic materials as energy sources, while still disregarding thermal energy and energy dissipation. (4) Only few of the participating high-school students achieved the highest progression level, at which students employed a scientific energy concept to constrain processes, trace energy separately from matter, apply energy conservation, and recognize heat dissipation.

Across disciplinary contexts, four aspects of the energy concept have been identified as relevant contents for energy teaching and students' energy understanding has been found to progress along the following sequence of these aspects: (1) energy forms/sources, (2) energy transfer/transformation, (3) energy degradation/dissipation, and

(4) energy conservation (e.g., Neumann et al. 2013; Nordine 2016, 32; Opitz et al. 2015; Park and Liu 2016). Different science disciplines and school science subjects emphasise these energy aspects to varying degrees (Chen et al. 2014, 2; Harms 2016). Biology classes, for example, may address energy conservation less explicitly, while emphasising energy transfer and transformation (Opitz et al. 2015, submitted). Even advanced students have hereby been found to disconnect energy understanding in biological processes from an understanding of energy in the inanimate world. For example, students may be able to recite the law of energy conservation, while failing to apply this law to biological contexts (Chabalengula et al. 2011). A related problem for students' energy understanding in biology has been attributed to the distinction between energy flow and matter cycles (Lin and Hu 2003).

### Research Questions

Energy instruction has to build on students' prior understanding and help them connect different disciplinary perspectives on the energy concept. In order to archive this, research has to identify conceptions that students employ in different disciplinary contexts. However, few studies describe students' energy understanding in biological contexts. Our study addresses this research field and analyses students understanding in regard to the four central energy aspects described above (e.g., Chen et al., 2014; Nordine 2016, 33). Through this approach, we also connect our analysis to previous studies on energy understanding and thus hope to provide insights for a stronger coordination of energy education across disciplinary contexts.

The following research questions guided our analysis.

- (1) What conceptions do students employ in biological contexts respective four central aspects of the energy concept, i.e. energy forms/sources, transfer/transformation, degradation/dissipation, and energy conservation?
- (2) How does students' understanding of these aspects differ between middle school grade levels?

## 5.3 Method

### 5.3.1 Procedure

This study is part of a mixed methods approach to describe students' energy understanding in biological contexts. A central goal of this study was to deepen findings from prior quantitative studies (Opitz et al. 2015, submitted). In this article, we present the

analysis of German primary and middle school student conceptions about energy in biological contexts. The results were obtained from a cross-sectional study that analysed structured one-on-one interviews using qualitative content analysis (Mayring, 2014).

### 5.3.2 Development of an Interview Guideline

A structured interview guideline was developed by providing a larger number of questions that students could address through comparatively short answers. This approach was conducted to (a) facilitate the comparability of students' understanding across primary and middle school grade levels and (b) to allow for an overlap between the interview questions and the previous questionnaire tasks. The purpose of this qualitative study was hereby to differentiate the earlier quantitative findings and to analyse students' conceptions about energy against the backdrop of their understanding of the respective biological contexts (e.g., Berg 2001, 7).

The interview guideline confronted students with a similar set of questions in each of three simple contexts: a running child, a growing tree, and a growing child. These particular contexts stemmed from an earlier study on students' energy understanding (Jin and Anderson 2012) and were selected as students regularly encounter these contexts both in schools and in their everyday lives, and from primary school until high school.

In each of the three contexts, the interviews focussed on energy in two sections. The first section included more general questions about energy (e.g., about energy sources for a growing tree) and originated from the interview guideline by Jin and Anderson (2012). The second interview section contained more detailed questions concerning the four central energy aspects mentioned above (see exemplary questions in Figure 5.1). With regard to the planned method comparison, these questions were open-ended adaptations from representative items of a previous quantitative questionnaire study (Opitz et al. submitted). While all students were interviewed with the same interview guideline, both interview sections contained also some more advanced questions (e.g., on energy in chemical bonds) that were skipped if students had difficulty answering them. The developed interview guideline was iteratively tested and refined in three trial interviews with 9<sup>th</sup> grade students. The full interview guideline is provided in online supplemental material 1.

Question level	Example question
<b><i>Energy forms/sources</i></b>	
Entry level	Where does the energy stem from that a child uses for running?
Advanced	Chemical energy is stored in parts of the human body. What needs to happen to make this energy available for the human body?
<b><i>Energy transfer/transformation</i></b>	
Entry level	As the child is running, energy is being 'transferred' and 'transformed'. What is happening in these two processes?
Advanced	In spring, the tree has not yet grown leaves. How does energy from sunlight get into the growing leaf buds?
<b><i>Energy degradation/dissipation</i></b>	
Entry level	The tree takes up energy and uses it for its growth. Where can you rediscover the energy after the tree has used it?
Advanced	In the tree's different life processes, energy is also 'degraded'. What does 'energy degradation' mean?
<b><i>Energy conservation</i></b>	
Entry level	Is energy being lost during the child's growth? <i>If 'yes'</i> : What do you imagine happens when energy is lost? <i>If 'no'</i> : Why is energy not getting lost in this process?
Advanced	Energy transfer is happening within a system. Where are the boundaries of the system for the energy transferred during the child's growth?

Figure 5.1. Example questions from the interview guideline

### 5.3.3 Sample and Data Collection

Interviews were conducted with students at the beginning of grades 5, 7, 9, and 11, thus allowing us to qualitatively characterize changes between students' energy understanding at different grade levels. With respect to the planned comparison between questionnaire and interview data, all but the grade 5 interviewees had taken part in the earlier questionnaire study (Opitz et al. submitted) three months before the interviews. The duration of the interviews was approximately 60 minutes.

Table 5.1 comprises characteristics of the sub-samples in the respective grade levels. As the goal was to compare students across grades, we tried to limit school effects by selecting students from only one primary and one secondary metropolitan school, both from similar socio-economic background. Students from different classes were interviewed to provide variance in students' conceptions (Berg 2011, 31). The sample for

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grade 5 was twice as large as in the upper grades to take into account the bandwidth of young students' conceptions, as well as their tendency to be shy in talking about a difficult topic like energy. The range of the interviewed students' test scores in the previous questionnaire study indicates (Table 5.1) that the participating students represent a wide range of student abilities, thus supporting the detection of an equally wide range of student conceptions.

**Table 5.1.** Overview of the subsamples at each grade level

	Grade 5	Grade 7	Grade 9	Grade 11
<i>n</i>	12	6	6	6
<i>m</i> <sub>age (years)</sub>	10.54	12.41	14.44	16.68
School/-s	A, B	B	B	B
School socio-economic index (range: 1–6*)	4, 5	5	5	5
Females	8	3	3	4
<i>n</i> <sub>classes</sub>	2	2	3	3
<i>m</i> <sub>scores</sub> ± range <sub>scores</sub> on previous energy assessment [0-1**]	—	0.25 ± 0.15/0.42	0.45 ± 0.15/0.69	0.59 ± 0.44/0.73

\* '1' denotes students with a strongly constrained socio-economic background, '6' denotes students from a preferred socio-economic background.

\*\* '0' denotes no correct answers, '1' denotes only correct answers.

The federal state where the interviews were conducted (Hamburg, northern Germany) employs learning standards that feature energy as a core idea for science/biology learning. Due to the extensive presence of the energy concept in school curricula, we can assume that the interviewed students had numerous energy learning opportunities from primary to middle school (see Opitz et al. submitted for details).

### 5.3.4 Analysis

**Development of the category scheme.** Data analysis was conducted using Mayring's (2014) method of qualitative content analysis. The formulation and revision of a category system of students' energy understanding in biological contexts was conducted using verbatim transcriptions in MAXQDA 11 software. Categories of student conceptions were inductively constructed under deductively formed, superordinate categories (Berg, 2001, 246) that consisted of the four energy aspects mentioned above (Neumann et al., 2013).

As a first step of analysing students' understanding, a total of 2293 units of analysis ('coding units') were identified, each representing a single conception expressed by a student (Mayring 2014, 51). Second, categories of student conceptions were

formulated, revised, and ordered hierarchically using category definitions, positive ('Apply if...') and negative ('Do not apply if...') coding rules, as well as anchor examples of student utterances (Mayring 2014, 37). While the derived category system was largely saturated after the analysis of roughly a third of the interviews, all further material was coded, as well, to strengthen the category system and the comparability of student conceptions across grade levels.

**Iterative inter-ratings.** To ensure the quality and operability of the category system, three expert-ratings assessed inter-coder agreement in iterative steps (Mayring, 2014, p. 114). All raters received coding instructions and exemplary student utterances for each category. The first two inter-ratings served as pilot-ratings and helped to improve the functionality of the category system. The third and final inter-rating was conducted with the second author and two external raters, who were unfamiliar with the research project. This final rating included a randomly selected 32% of all coding units. Due to the content-related overlap of the four energy aspects, the rating was conducted for each energy aspect separately. The results indicate a high internal reliability of the four sections of the category system and a substantial to near-perfect (Kirk 1996) agreement on the category membership of the coding units: Fleiss'  $k_{\text{forms/sources}} = 0.89$ ,  $k_{\text{transfer/transformation}} = 0.76$ ,  $k_{\text{degradation/dissipation}} = 0.76$ ,  $k_{\text{conservation}} = 0.89$ .

**Selection of categories.** The developed category system contains—at the most detailed level—a total of 291 categories. For the presentation in this article, the degree of specificity was reduced, while the original bandwidth of student conceptions was maintained. First, we only selected categories for presentation if they were meaningful in relation to the research questions. We thereby left out a substantial share of the observed categories that related only to the planned comparison of research methods. As a second criterion, categories were only selected, if multiple student utterances allowed a robust foundation of the category.

### 5.4 Results

The results exemplify the observed range of students' understanding by presenting prominent student conceptions for each of the four energy aspects, as well as differences in students' understanding between the grade levels. As a resource to future studies and interested readers, the full category system of student conceptions, as well as the selection frequencies of each category are provided in online material 2.

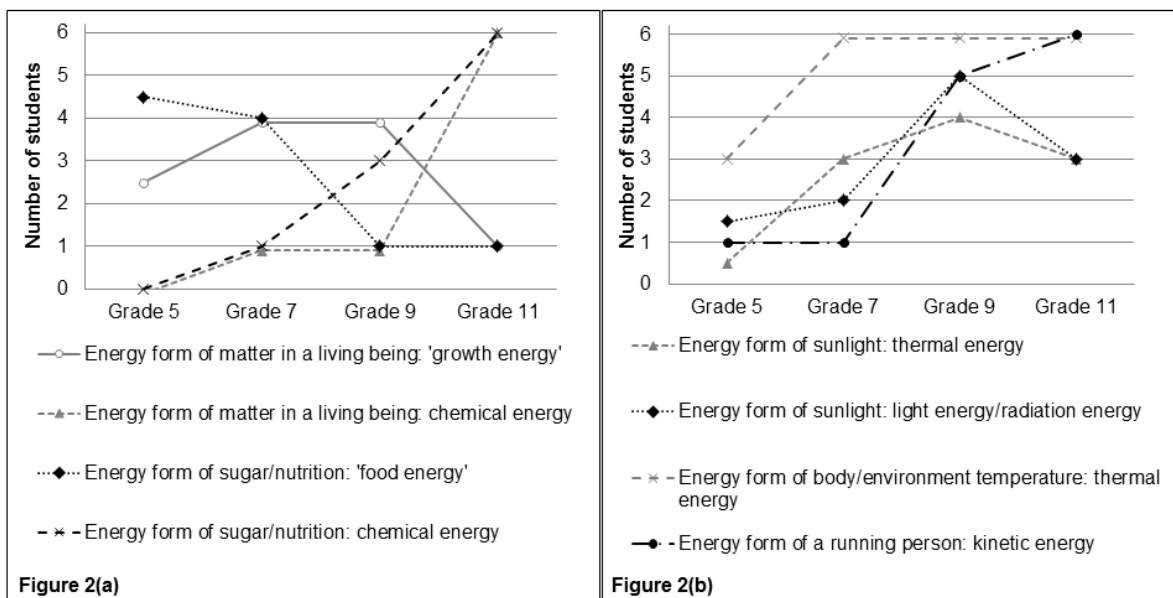


### 5.4.1 Energy Forms

Previous studies already presented students' conceptions about energy sources (e.g., Boyes and Stanisstreet, 1990). As the respective findings from our study are similar to the earlier findings, this section targets students' conceptions about energy forms. However, readers can access the respective conceptions about energy sources in online material 2.

Figure 5.2(a) presents student conceptions regarding manifestations of potential energy. Alternative names for chemical energy, such as 'growth energy' or 'food energy' were widely used across the grade levels and their appearance only decreased among 11<sup>th</sup> graders. The term 'chemical energy' was not yet employed by 5<sup>th</sup> graders, but its application increased across grades (grade 11: 6/6 students). Few middle school students, but half of the 11<sup>th</sup> graders associated air/oxygen with 'chemical energy'.

Even young students were able to identify manifestations of kinetic energy (e.g., thermal energy) correctly (Figure 5.2b). Between grades 7 and 9, a substantial change in understanding was observable in the identification of kinetic energy and light/radiation energy. Roughly half the students from grades 7, 9, and 11 mentioned (also) thermal energy as the form of energy behind sunlight. Across grades, alternative names for energy forms, for example, 'running energy', 'friction energy', or energy forms ascribed to sleep were rarely employed. Similarly, few students employed anthropocentric views and directly equated energy with power or attributed the energy behind human movement directly to concepts like 'sportsmanship'.



**Figures 5.2(a/b).** Student conceptions concerning manifestations of potential energy (Figure 5.2a) and kinetic energy (Figure 5.2b).

### 5.4.2 Energy Transfer and Transformation

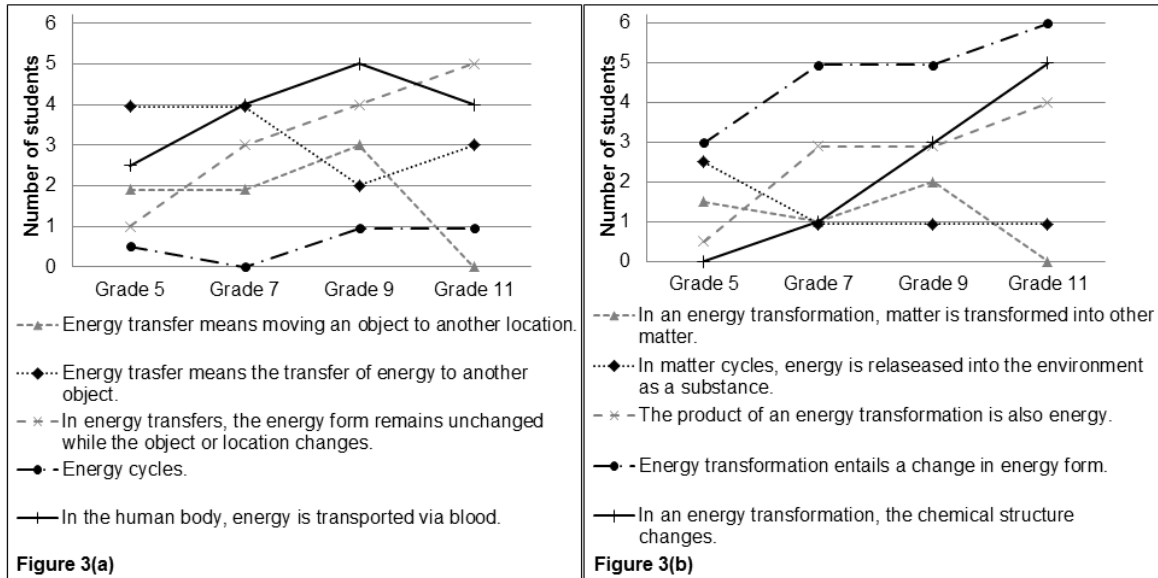
When speaking about energy transfer (Figure 5.3a), students often referred to the transport of energy in the blood of a human being. The findings indicate a substantial change in understanding towards an acceptable view that describes energy transfer as a dislocation of the same energy form (grade 5: 1/6 students, grade 11: 5/6 students). However, alternative or abbreviated conceptions on energy transfer were—sometimes additionally—employed by roughly half the students (e.g., ‘energy transfer means moving an object to another location’). The previously described (e.g., Burger, 2001) inaccurate conception of energy as a cycling or recycled substance was only rarely found.

Figure 5.3(b) presents conceptions regarding energy transformations. From grade 7 onwards, the majority of students described correctly that energy transformations entail a change in energy form. Across grades, few students confused energy transfer and energy transformation. However, roughly a third of the 5<sup>th</sup> grade students still considered an energy transformation to be a change of matter or as a release of matter into the environment. Furthermore, younger students’ descriptions of energy transformations widely disregarded that the product of energy transformations is still energy. Across grades, students increasingly combined their descriptions of energy transformations with changes in chemical bonds. However, these explanations were frequently built on an abbreviated conception, for example, by considering only the ‘breaking’ of bonds to be responsible for the release of energy. CP (grade 9), for example, already uses this common shorthand view on energy in chemical bonds in his analysis of a digestion process. However, CP does not (yet) include a conceptualization of bond energy, in which energy is released when reaction products are chemically more tightly bound and hence possess less bond energy than the reaction educts.

I: [CP had earlier referred to energy in chemical bonds of nutrients.] Can you imagine what has to happen to these bonds to make the energy accessible?

CP: In this sense, they [the bonds] have to be broken down. So...you can always brake up things and I think that they are broken down in the body...in the intestines, because acid is added there. The acid brakes down the bonds and they [the constituents] are then taken up.

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**Figures 5.3(a/b).** Student conceptions concerning energy transfer (Figure 5.3a) and energy transformation (Figure 5.3b).

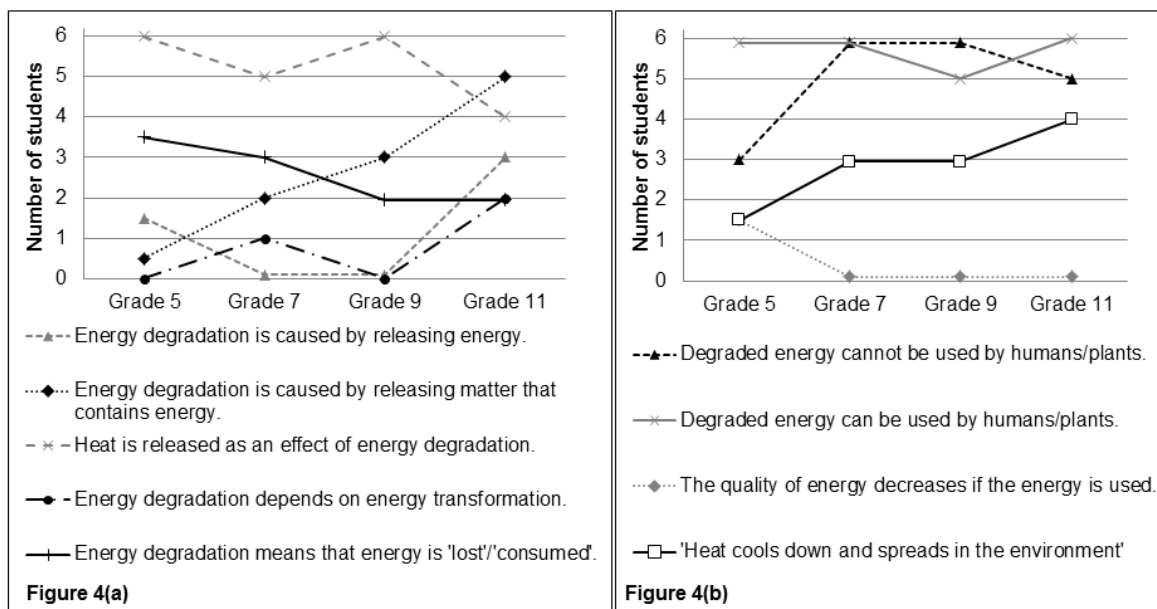
### 5.4.3 Energy Degradation and Dissipation

Figure 5.4(a) describes student conceptions connected to energy degradation. At all grade levels, roughly half the participating students equated energy degradation with energy loss or consumption. A conceptualization of degradation on the basis of energy transformations or the release of energy into the environment was only more prominently described by grade 11 students. However, more mature students *also* increasingly used limited alternative views, for example, the conception that energy degradation is caused by releasing energy-containing matter into the environment. Despite students' difficulties with energy degradation, students at all grade levels described the 'release of heat' as an effect of degradation. Here, younger students were often unsure about the causes for the release of heat, or they provided unspecific explanations (e.g., 'activity'). Instead, most of the older students correctly referred to energy transformation processes as the cause (see online material 2). Regarding the release of thermal energy, only one student explicitly stated that thermal energy represents the lowest value of energy, while an increasing number of students (grade 11: 4/6) was able to address dissipation by explaining that released thermal energy spreads out in the environment, while the temperature next to the organism decreases (Figure 5.4b).

Across grades, few changes were observable in students understanding of irreversibility as a central principle of energy degradation (Figure 5.4b). The students hereby expressed at least partly opposing conceptions: On the one hand, almost all students described that degraded energy can still be used for life processes. Hereby, only a single student mentioned that energy degradation increases the temperature and

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thereby allows chemical reactions to occur faster (see online material 2). A decrease in the quality/value of energy through energy degradation was hardly addressed. On the other hand, the vast majority of the interviewed students *also* used the adverse (accepted) conception in one of the other contexts, i.e. that degraded energy can no longer be used by humans/plants.



**Figures 5.4(a/b).** Student conceptions connected to the conceptualization of energy degradation (Figure 5.4a) and the irreversibility of energy degradation (Figure 5.4b).

### 5.4.4 Energy Conservation

Similar to students' understanding of energy degradation, the conceptions concerning energy conservation (Figure 5.5a) were partly also opposing each other: Almost all students mentioned in at least one of the three contexts that energy cannot be consumed or created. However, when they described energy in one of the other contexts, all of the younger students and 2/3 of the older students *also* stated the opposite, i.e. that energy can be created, consumed, or 'lost' (see online material 2). Within these descriptions, the anthropocentrically-oriented view that energy consumption is related to energy usage was employed decreasingly among older students. Alternative conceptions of energy consumption/loss (e.g., that energy consumption refers to the transformation of energy into another entity), were only used by few students. When asked to elaborate their statements on energy consumption/loss, only two students referred to energy degradation (see online material 2). In 5<sup>th</sup> grade, half the students explicitly stated that energy loss causes the energy to stop existing. An example for this understanding is provided by KG (grade 5):

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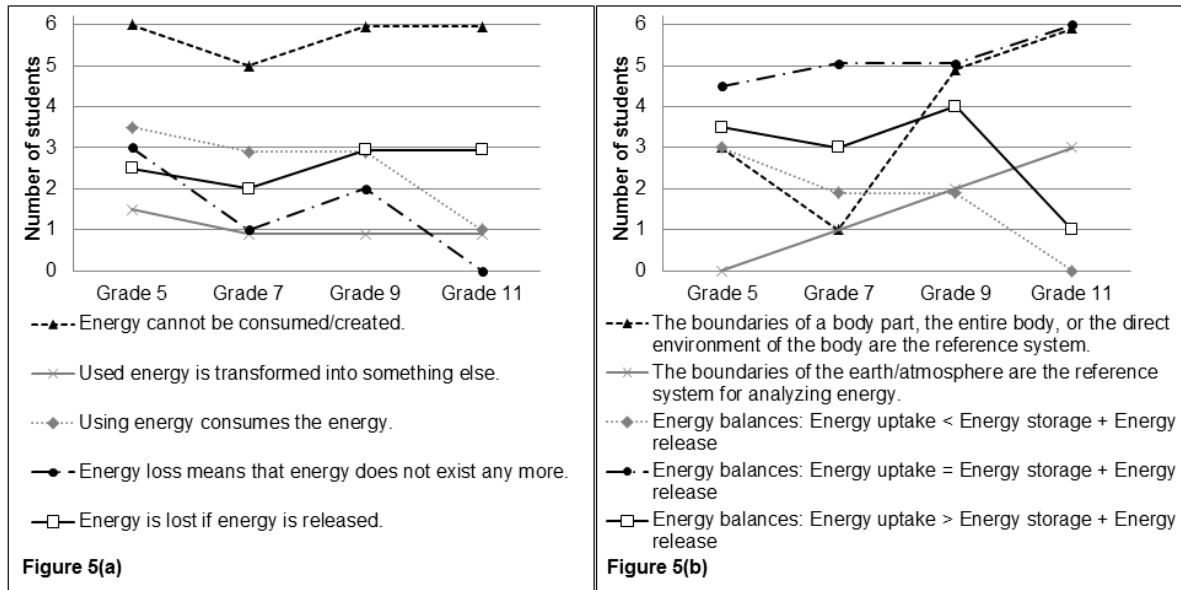
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- I: [The student had earlier mentioned that energy is 'lost' when a child grows. The interviewer enquired accordingly.] What do you imagine happens when energy is getting lost?
- KG: For example, let's look at teeth: We grow milk teeth and afterwards, we grow the real, adult teeth. And if one of the milk teeth is falling out, energy would get lost there.
- I: Because the energy in the tooth is no longer useful to the body?
- KG: Yes.
- I: Ok, but is this energy—after the tooth fell out—still in the tooth or is it somehow gone?
- KG: I don't think it is there anymore.

Considerations of energy conservation within non-idealized biological contexts rely on the definition of system boundaries. Our findings on the respective students' conceptions did not indicate a full change towards a scientifically more accurate view (Figure 5.5b). While older students seemed to generally consider system boundaries more often, the respective explanations focussed only on organism parts, the entire organism, or the organism's direct environment as the reference system. However, older students also broadened their perspective by regarding also the atmosphere as part of the system, while they did not mention energy transfers between the global system and the universe.

In each of the three employed contexts, the majority of students from each grade level were able to correctly describe at least one energy balance. As, however roughly half the students in grade 5, 7, and 9 also suggested an inaccurate energy balance, it appears that only the grade 11 students were able to describe energy balances with more certainty.

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**Figure 5.5 (a/b).** Student conceptions regarding energy conservation (Figure 5.5a) and the analysis of energy within system boundaries (Figure 5.5b).

### 5.5 Discussion

#### 5.5.1 Research Question 1 (What conceptions do students employ in biological contexts respective four central aspects of the energy concept?)

Similar to several earlier studies (e.g., Lancor, 2015; Neumann et al., 2013; Park and Liu, 2016), students from all grade levels had more difficulties with the aspects energy degradation/dissipation and energy conservation, while an understanding of energy forms/sources and transfer/transformation appeared as more accessible for the students (see also Jin and Anderson 2012). Students' furthermore seemed to make only few connections between their understanding of individual energy aspects. For example, when students traced energy through the human body, they rarely used conceptions of energy flow in the sense of a combination of the analysis of energy transfer, degradation, or conservation.

Many of the identified student conceptions cannot be clearly identified as either correct or wrong, but were characterized by imprecise language use or by an abbreviated view that focussed only on sub-aspects of a full scientific understanding (e.g., conceptions about energy degradation, see Figures 5.4a/b). However, our results provide several examples of varying, sometimes incoherent (Lakoff and Johnson 1980, 44) conceptions that characterise students' understanding of individual energy aspects. Obvious examples can be found in conceptions connected to the irreversibility of energy degradation (see section 3.3) or conceptions connected to the 'consumption/loss' of

energy (see section 3.4). Earlier studies indicated that students' energy understanding differs substantially with specific contexts (e.g., Lancor 2015; Neumann et al. 2013; Park and Liu 2016). The three different contexts employed by this study may hence be a potential explanation for the observed incoherence in students' conceptions.

We interviewed students about their energy understanding in typical biological contexts. However, among students' prominently employed conceptions, relatively few appeared to be clearly connected to a biology-specific understanding. Instead, most of the student explanations appeared to be based on a discipline-general understanding of energy. As this observation is hardly quantifiable with the available data, it should be verified by future interview studies that compare students' conceptions across different disciplinary contexts. However, previous research would support the observation of a less discipline-oriented energy understanding, as students' performance on energy tests was highly related between disciplinary contexts (Opitz et al. submitted; Park and Liu 2016), and as students were reported to employ similar metaphors for energy across disciplinary contexts (Lancor 2015).

### **5.5.2 Research Question 2 (How does students' understanding of these aspects differ between middle school grade levels?)**

The findings of this qualitative study should not be understood as reliable progression trends in understanding across grade levels, as these would require the verification through additional quantitative studies (cf. Jin and Anderson 2012; Neumann et al., 2013). Instead, the findings are used to reveal increasingly employed acceptable conceptions and decreasingly used inaccurate alternative student conceptions. Positive changes in understanding can especially be observed for the energy aspects forms/sources and transfer/transformations (see Figures 5.2a/b and 5.3a/b). In contrast, students' understanding regarding the aspects degradation/dissipation and conservation changed less distinctly. Increasingly employed conceptions often related 'only' to sub-aspects of the accepted scientific view (see Figures 5.4a/b and 5.5a/b). Rather distinct changes in conceptions at specific grade levels have similarly been identified in the analysis of distractor/attractor frequencies of prior quantitative studies (Opitz et al. 2015, submitted). The interviews provided several examples where students' conceptions about energy depended on their understanding of related concepts (see also Megalakaki and Thibaut 2015), for example, in regard to thermal energy or heat (see Figures 5.4a/b, compare online material 2, section energy degradation/dissipation). Apart from these changes in students' energy understanding, our study also identified alternative conceptions that students employed to similar extents across grade levels. Such alternative conceptions

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are likely connected to an everyday understanding of energy (Lancor 2015) and encompass, for example, the conception that energy degradation refers to energy loss (Figure 4a) or that energy is consumed when used (Figure 5.5a).

Students' difficulties with the energy concept have frequently been connected to students' imprecise application of everyday versus scientific connotations of the energy concept (e.g., Lancor, 2015; Jin and Anderson, 2012). While this differentiation is certainly difficult for learners, our findings show relatively few examples where progressing understanding was mediated only by more elaborate or precise wording (e.g., students' explanations of 'energy loss', see online material 2). Thus, our results indicate that the progression trends observed by prior quantitative studies (e.g., Jin and Anderson, 2012; Opitz et al. 2015) do not only reflect an increasingly more sophisticated use of language among older students, but also that the students' understanding changes across grades as students develop new conceptions and abandon prior ones.

### 5.5.3 Study Limitations

The comparatively high level of structure in the employed interview guideline limited the freedom of student replies. Yet, this interview form was a necessary compromise with regard to the students' broad age span and the perspective comparison between qualitative and quantitative findings (Opitz et al. submitted).

A further limitation to consider refers to the study's focus on conceptions that students employed. This leads, especially among younger learners, to an underrepresentation of the absence of conceptions. Thus, the derived category system shows some examples where younger students appear to employ a more elaborate understanding, as these students rather kept alternative conceptions to themselves. Instead, older and more confident students also expressed alternative conceptions they were not entirely sure about (e.g., conceptions about systems boundaries, Figure 5.5(b) and online material 2). To address these issues, we used a larger sample in grade level 5 and analysed additional interview material after the saturation of the category system had been reached (see methods).

### 5.5.4 Implications for Research and Instruction

This study provides one of the first systematic descriptions of conceptions that students use to describe energy in biological contexts. Students' understanding was analysed in regard to four relevant energy aspects, thus making the findings also more meaningful for researchers and educators from different science backgrounds (e.g., Lancor 2015; Neumann et al. 2013; Nordine 2016, 33; Opitz et al. submitted). Accordingly, we derive



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the following possible implications for the further development of energy instruction in biology:

(1) As the majority of students were able to correctly attribute energy forms from grade 9 onwards, students' understanding of this aspect may function as a scaffold for later energy learning (Jin and Anderson 2012). However, the students could likely still profit from more explicit teaching on the meaning of 'chemical energy', the release of energy from chemical bonds, as well as the role of oxygen in life processes (see sections 3.1 and 3.2 ).

(2) Even students in the lower grade levels often gave correct scientific explanations about the meaning of energy transfer/transformation, thus underlining the focus of biological contexts on this aspect (Authors 2015a). As students hardly focussed on energy flow, energy instruction in biology could likely profit from a stronger focus on this perspective on energy, thus also combining the understanding of transfer/transformation with conceptions of energy degradation/dissipation and conservation.

(3) The findings suggest that students employ potentially opposing views on the irreversibility and value of degraded energy (see section 3.4). Biology instruction could hence support students' by a stronger consideration of energy degradation. For example, teachers could hereby focus on body heating as a means to increase the speed of chemical reactions (and thus activity) or the perspective could be put on the regulation of energy dissipation as a means to prevent damages through overheating.

(4) Students' understanding of energy conservation was characterised by both scientifically acceptable and everyday-based explanations. Hence, students may especially benefit from reflecting adequate language registers for analysing energy. The results furthermore highlight the importance to explicitly address system boundaries and foster students' ability to distinguish between (idealized) isolated, closed, and open systems.

Perspective studies could extend our research by analysing how instruction can foster students to form connections between the different energy aspects and integrate their energy understanding accordingly (Nordine et al. 2011). Analogously, future studies should identify ways to strengthen the coherence of energy teaching across disciplines (Lin and Hu 2003) in order to help students combine, for example, macro and micro level perspectives from biology and chemistry.

### 5.6 Acknowledgement

We would like to thank the city of Hamburg for funding the *komdif* research project and allowing easy access to the field. The support from all teachers and students made this research project a very enjoyable one. We are especially thankful to Silke Gatermann for her help in organising the study. For his extended support in data entry and interview analysis, we want to acknowledge Marc Rodemer.

### 5.7 Online Supplemental Material

Material 1: Interview guideline

Material 2: Categories of student conceptions about energy in biological contexts

### 5.8 References

- Anderson, J. R. (2015). *Cognitive Psychology and Its Implications* (8th ed.). New York: Worth Publishers.
- Berg, B. L. (2001). *Qualitative Research Methods for the Social Sciences* (4th ed.). Needham Heights, MA: Pearson Education Company.
- Boyes, E., & Stanisstreet, M. (1990). Pupils' Ideas Concerning Energy Sources. *International Journal of Science Education*, 12(5), 513-529.
- Bransford, J. D., Brown, A. L., & Cocking, R. R. (2000). *How People Learn: Brain, Mind, Experience and School*. Washington, D.C.: National Academy Press.
- Burger, J. (2001). Schülervorstellungen zu "Energie im biologischen Kontext" - Ermittlungen, Analysen und Schlussfolgerungen. [Student conceptions concerning energy in biological contexts-research, analysis and conclusions]": *University of Bielefeld, Dissertation*.
- Chabalengula, V., Sanders, M., & Mumba, F. (2011). Diagnosing Students' Understanding of Energy and Its Related Concepts in Biological Contexts. *International Journal of Science and Mathematics Education*, 10(2), 241-266.
- Chen, B., Eisenkraft, A., Fortus, D., Krajcik, J. S., Neumann, K., Nordine, J., & Scheff, A. (2014). *Teaching and Learning of Energy in K-12 Education*. New York: Springer.
- Department for Education [DfE] (2013). Science programmes of study: key stage 3 - National curriculum in England.
- Gayford, C. G. (1986). Some Aspects of the Problems of Teaching about Energy in School Biology. *European Journal of Science Education*, 8(4), 443-450.

## Chapter 5 (Study 4): Characteristics of Energy Understanding in Biological Contexts

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- Harms, U. (2016). Ohne Energie geht nichts! [Nothing works without energy!] *Unterricht Biologie*, 411(40), 2-11.
- Jin, H., & Anderson, C. W. (2012). A learning progression for energy in socio-ecological systems. *Journal of Research in Science Teaching*, 49(9), 1149-1180.
- Kirk, R. E. (1996). Practical Significance: A Concept Whose Time Has Come. *Educational and Psychological Measurement*, 56(5), 746-759. doi: 10.1177/0013164496056005002
- Lakoff, G., & Johnson, M. (1980). *Metaphors We Live By*. Chicago: The University of Chicago.
- Lancor, R. (2015). An Analysis of Metaphors Used by Students to Describe Energy in an Interdisciplinary General Science Course. *International Journal of Science Education*, 1-27. doi: 10.1080/09500693.2015.1025309
- Lin, C.-Y., & Hu, R. (2003). Students' understanding of energy flow and matter cycling in the context of the food chain, photosynthesis, and respiration. *International Journal of Science Education*, 25(12), 1529-1544.
- Mayring, P. (2014). *Qualitative Content Analysis Theoretical Foundation, Basic Procedures and Software Solution*. Klagenfurt: SSOAR.
- Megalakaki, O., & Thibaut, J. (2015). Development and differentiation of force and energy concepts for animate and inanimate objects in children and adolescents. *Research in Science Education*, 1-24. doi: 10.1007/s11165-015-9467-9
- Neumann, K., Viering, T., Boone, W. J., & Fischer, H. E. (2013). Towards a Learning Progression of Energy. *Journal of Research in Science Teaching*, 50(2), 162-188.
- Next Generation Science Standards [NGSS] (2013). *Next Generation Science Standards: For States, By States*. Washington, DC: The National Academies Press.
- Nordine, J. (2016). What should students know about energy? In J. Nordine (Ed.), *Teaching Energy Across the Sciences, K-12*. Arlington, VA: National Science Teachers Association [NSTA].
- Nordine, J., Krajcik, J., & Fortus, D. (2011). Transforming energy instruction in middle school to support integrated understanding and future learning. *Science Education*, 95(4), 670-699.
- Novak, J. D. (2005). Results and Implications of a 12-Year Longitudinal Study of Science Concept Learning. *Research in Science Education*, 35(1), 23-40.
- Opitz, S., Harms, U., Neumann, K., Kowalzik, K., & Frank, A. (2015). Students' Energy Concepts at the Transition between Primary and Secondary School. *Research in Science Education*, 45(5). 691-715. doi 10.1007/s11165-014-9444-8

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Opitz, S., Neumann, K., Bernholt, S. (submitted). How Do Students Understand Energy in Biology, Chemistry, and Physics? Development and validation of an assessment instrument. Submitted to the International Journal of Science Education.

Park, M., & Liu, X. (2016). Assessing Understanding of the Energy Concept in Different Science Disciplines. *Science Education*. doi: 10.1002/sce.21211



## CHAPTER 6

# Winterschlaf: Energiesparen als Überlebensstrategie [Hibernation: Energy Saving as a Strategy for Survival] (Teaching Practice Article)

### Abstract

This article presents an approach to teach middle school students the application of the energy concept as a means to explain biological phenomena. Students analyze energy uptake, storage and release during hibernation of the edible dormouse (*Glis glis*).

The first part of this article provides teachers with a content basis by summarizing aspects of hibernation and the respective adaptations. Dormice are used as an exemplary hibernator as their duration of inactivity is unusually long (up to 10 months) and as the animals exhibit extreme adaptations of physiological parameters during this state. The second section of the article provides an overview of a suggested teaching sequence, the related materials and possible solutions to the included tasks: Materials 1a and 1b include a multi-group student experiment and a small card game as a simple model of food distribution and food search in winter. These activities provide students with a basis to understand differences in energetic requirements (e.g., transfer of heat, search for food) between summer and winter. Materials 2-4 focus on dormice and can be applied in variable order. In material 2, students have to combine the analysis of energy and matter by working out how the decrease of body mass during winter relates to the animals' energy turnover. In material 3, students reflect everyday ideas about energy and explore diagrams to describe major physiological changes during hibernation and the effects of these changes on the animals' energy requirements. In material 4, students compare diagrams of a dormouse's activities in two consecutive years. This material is intended to help students broaden their perspective on the energy concept by deriving that an animal's life strategy (i.e., activity phases versus hibernation) not only depends on energetic preconditions, but also on factors such as reproduction and maintenance of body functions.

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<http://www.friedrich-verlag.de/shop/sekundarstufe/naturwissenschaften/biologie/unterricht-biologie/energie-in-der-biologie?SID=U>

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**Opitz, S.** und Opitz, M.-T. (2016). Winterschlaf: Energiesparen als Überlebensstrategie. *Unterricht Biologie*, 411, 18-23.

**Siebenschläfer reagieren auf die veränderten energetischen Bedingungen des Winters. Sie halten Winterschlaf. Die Reduzierung ihres Energieumsatzes bis an die Schwelle der Überlebensfähigkeit stellt dabei mehr als eine reine Energiesparmaßnahme dar.**

**Lerngruppe:** 8.-9. Klasse

### **6.1 Ziele**

Unterschiede in der Energiebilanz von Tieren zwischen Sommer und Winter beschreiben; Veränderung von Stoffwechsel (z. B. Kreislauf, Körpertemperatur) und Verhalten als Anpassungen an energetische Voraussetzungen der Umwelt herausarbeiten.

### **6.2 Winterschlaf als Anpassung**

Kleine Tiere haben im Verhältnis zum Körpervolumen eine überproportional größere Körperoberfläche und geben dadurch viel Wärme an die Umwelt ab. Endotherme Tiere mit gleichbleibender Körpertemperatur setzen 5-10 mal mehr Energie um als gleichgroße ektotherme Tiere. Entsprechend besitzen speziell kleine Säuger eine sehr hohe Stoffwechselrate. Da ihre Körper weiterhin eine hohe Wärmedurchgangszahl besitzen, können kleine Säuger nur für verhältnismäßig kurze Aktivitätsphasen ohne Nahrungsaufnahme ausreichend energetisch nutzbare Stoffe (hauptsächlich Körperfett) anlegen (Eckert, 2002). Im Winter würde die Stoffwechselrate von kleinen Tieren bei gleichbleibender Aktivität fast doppelt so hoch liegen wie im Sommer (Campbell, Reece, & Markl, 2006). Da gleichzeitig die Nahrung im Winter knapper ist und eine längere, energieaufwändige Suche nötig wird, verschiebt sich die Energiebilanz besonders für kleinere Tiere zum Negativen. Kleine und mittelgroße Säuger (z.B. Siebenschläfer, Ziesel, Igel) nutzen daher häufig die Strategie, den Energieumsatz durch Winterschlaf oder ähnliche Ruhezustände massiv einzugrenzen – und zwar teils um mehr als den Faktor 100 (Eckert, 2002). Dass gleichzeitig ähnliche Tiere keinen (z.B. Mäuse) oder einen weniger ausgeprägten Winterschlaf halten, kann – neben dem entwicklungsgeschichtlichen Hintergrund der Art – daran liegen, dass spezielle Anpassungen gerade noch Aktivität im Winter erlaubt, während dies bei ähnlichen Arten nicht der Fall ist. Größere Tiere besitzen in Bezug auf ihre Reserven energetisch nutzbarer Stoffe einen deutlich geringeren Basalstoffwechsel und nutzen in gemäßigten Zonen die kalten Jahreszeiten für die häufig im Verhältnis zu kleineren Tieren deutlich längeren Tragzeiten, was es wiederum ermöglicht, dass die Nachkommen zu Beginn des nächsten Winters größer und resistenter sind.

Während bei normalem Schlaf die Körpertemperatur nur geringfügig absinkt, wird diese im Zustand des Winterschlafes durch spezielle Anpassung teils bis knapp unter den Gefrierpunkt abgesenkt (Bachmann & Arndt, 2013). Da der Unterschied zur Außentemperatur dann deutlich geringer ist, wird pro Zeit entscheidend weniger Wärme in die Umwelt abgegeben. Der Hypometabolismus, also die Absenkung physiologischer Parameter, ist die eigentliche Leistung des Winterschlafes – die energetische wichtige Verringerung der Wärmeabgabe ist deren Effekt.

### 6.3 Siebenschläfer sind extreme Winterschläfer

Der Siebenschläfer (*Glis glis*, Familie der Bilche), ein mit Schwanz ca. 30 cm langes und 120 g schweres Nagetier, überdauert den Winter in einem meist sieben Monate dauernden Winterschlaf. Die Tiere verdoppeln vor dem Winterschlaf ihr Gewicht, da sie während des Winters keine Nahrung zu sich nehmen und komplett auf angefressene Fettvorräte angewiesen sind (Krystufek, 2010).

Nach einer längeren Einschlafphase verringern Siebenschläfer ihren Herzschlag von 200-300 auf ca. 8 Schläge pro Minute (Bachmann & Arndt, 2013; Krystufek, 2010). Der Stoffwechsel wird von Zucker auf Fett umgestellt, die Atmung verlangsamt sich und weist Pausen von bis zu 60 Minuten auf. Die Umstellung des Stoffwechsels auf Fett ist für die Tiere während des Winterschlafes vorteilhaft, da Körperfett im Gegensatz zu den eher kurzfristig genutzten Glykogenspeichern der Leber langfristig gut speicherbar ist. Zusätzlich stellt Fett pro Gramm ca. doppelt so viel Energie bereit wie Kohlenhydrate oder Proteine.

Im Winterschlaf kann die Körpertemperatur auf bis zu 0,7° C sinken, womit wahrscheinlich die untere Grenze der Überlebensfähigkeit erreicht ist (Bachmann & Arndt, 2013). Wie bei anderen Winterschläfern unterbricht auch der Siebenschläfer den Winterschlaf für Phasen ‚normalen‘ Schlafes – und dies teilweise mehrmals pro Woche. Obwohl diese normalen Schlafphasen 70 % des gesamten Energieumsatzes während des Winters ausmachen, ist die offensichtlich wichtige Funktion dieser Phasen noch nicht letztendlich geklärt. Hierbei werden unter anderem Regenerationsphasen für Immun- und Nervensystem als mögliche Ursachen angeführt.

Reicht in einem Jahr die verfügbare Energie im Nahrungsangebot nicht für den zusätzlichen Energiebedarf einer Fortpflanzung, können die Tiere auch im Sommer in eine Ruhephase fallen (Sommerschlaf). Insgesamt verbringen die Siebenschläfer dann bis zu zehn Monate des Jahres inaktiv – mehr als irgendeine andere bekannte Tierart. Die Forschung geht davon aus, dass eventuelle Nachteile durch den langen Winterschlaf,



wie beispielsweise die Verschlechterung des Immunsystems, von Vorteilen der Feindvermeidung stark überwogen werden könnten, sodass selbst bei ausreichender Nahrung der Sommerschlaf in bestimmten Jahren eine erfolgreiche Strategie darstellt (Bieber & Ruf, 2009).

### 6.4 Überlegungen zum Unterricht

Da das Wissen zu Energie gerade in der Sekundarstufe 1 oft undifferenziert ist und auf Alltagsvorstellungen aufbaut (Opitz, Harms, Neumann, Frank, & Kowalzik, 2015), ist für diese Einheit eine Einführung bzw. Wiederholung des Energiekonzepts eine wichtige Voraussetzung. Bei dem Begriff ‚Energiekonzept‘ bezieht sich dieser Artikel auf das Verständnis der vier Energieaspekte, die im Basisartikel dieses Hefts beschrieben werden. So sollten die SuS in den unten dargestellten Inhalten zum Beispiel Prozesse von Energieübertragung, -umwandlung und -entwertung identifizieren können und in ihre Überlegungen mit einbeziehen, dass die gesamte von einem Organismus aufgenommene Energie nicht ‚verloren‘ geht, sondern erhalten wird. Mit Blick auf Energie als Basiskonzept der Naturwissenschaften sollten die Inhalte dieser Einheit mit vorhergehendem Wissen verknüpft werden. Hierzu können z.B. Inhalte zur energetischen Nutzbarkeit der Nahrung, zu Überwinterungsstrategien, sowie Inhalte aus Physik und Chemie (z.B. Pendel, Federn) zählen.

Die hier gezeigten Stationen zum Lernen mit Energie können im Rahmen der genutzten Unterrichtssequenz durch für die SuS interessante *hands-on* Aktivitäten angereichert werden (z.B. den Bau eines Modells einer Winterschlafhöhle).

Die Einheit ist in einen gemeinsamen ersten Unterrichtsabschnitt (Material 1a/b) und drei anschließende Stationen (Material 2-4) unterteilt. Eine Sicherungsphase muss entsprechend der Schülerfähigkeiten angeboten werden.

**1. Gemeinsamer Unterrichtsabschnitt:** In der Einstiegsphase wird ein Bild von einem Tier gezeigt, das im Schnee nach Futter sucht. Die SuS sammeln (a) Vorwissen und (b) offene Fragen zu Angepasstheiten von Tieren an die Bedingungen im Winter. Das vorhandene Wissen und die Fragen werden von der Lehrkraft in einer Mind map an der Tafel sortiert. Die Mind Map kann fotografiert und für eine Sicherungsphase wieder aufgegriffen werden.

In Anschluss schafft →Material 1 für die SuS die inhaltliche Grundlage für die drei folgenden Stationen. Hier werden Unterschiede in der Energiebilanz von Tieren zwischen Sommer und Winter erarbeitet. An diesem Material können die SuS die Bedeutung des

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Winterschlafes als Angepasstheit an veränderte energetische Bedingungen im Winter nachvollziehen. Wichtig: Es muss vor der Durchführung des hier eingebundenen Versuches geprüft werden, ob genügend Versuchsmaterial vorhanden ist (evtl. Gruppengröße anpassen!). Hierzu muss auch ein Warmwasservorrat (38 °C, ca. 1,5 l) vorbereitet werden – dies ist, z.B., leicht durch ein Wasserbad aus dem Labor möglich.

**2. Unterrichtsabschnitt:** In → Material 2 beschreiben die SuS anhand der Gewichtsentwicklung des Siebenschläfers während des Winterschlafes den Zusammenhang zwischen der Abgabe von Energie durch Wärme, dem Abbau von energiespeicherndem Fettgewebe und der Gewichtsabnahme der Tiere.

**3. Unterrichtsabschnitt:** In → Material 3 werden zentrale Veränderungen von Körperfunktionen (z.B. Atmung, Kreislauf) während des Winterschlafes erarbeitet. Die SuS beschreiben den Nutzen dieser Angepasstheiten mit Blick auf die begrenzte Verfügbarkeit von gespeicherter Energie und die Einschränkung der Wärmeabgabe im Winter.

**4. Unterrichtsabschnitt:** In → Material 4 gehen SuS über die rein energetische Betrachtung des Winterschlafes hinaus. Die SuS beschreiben im Hinblick auf Fortpflanzung Schlafphasen als erfolgreiche Lebensstrategie. Anhand von ‚Schlafprofilen‘ entwickeln die SuS Vermutungen, warum Phasen ‚normalen‘, energieaufwändigen Schlafes während des Winterschlafes dennoch für die Tiere lohnenswert und wichtig sind.

### 6.5 Literatur

- Bachmann, K., & Arndt, I. (2013). Schlaf, Igelchen, Schlaf. *GEO*, 1, 68-78.
- Bieber, C., & Ruf, T. (2009). Summer dormancy in edible dormice (*Glis glis*) without energetic constraints. *Naturwissenschaften*, 96, 165-171. doi: DOI 10.1007/s00114-008-0471-z
- Campbell, N. A., Reece, J. B., & Markl, J. (2006). *Biologie* (6. Auflage ed.). München: Pearson's Education.
- Eckert, R. (2002). *Tierphysiologie* (3. Auflage ed.). Stuttgart: Thieme.
- Krystufek, B. (2010). *Glis glis* (Rodentia: Gliridae). *Mammalian Species*, 42, 195-206. doi: 10.1644/865.1
- Opitz, S., Harms, U., & Neumann, K. (2015). Students' Energy Concepts at the Transition between Primary and Secondary School. *Research in Science Education*. 49(5),691-715. doi: 10.1007/s11165-014-9444-8

## Chapter 6 (Teaching practice article): Winterschlaf: Energiesparen als Überlebensstrategie

### Material 1: Warum halten Tiere Winterschlaf?

In Material 1 analysiert ihr die Energieaufnahme, -abgabe und -speicherung im Winter als eine Erklärung für bestimmte Anpassungen von Tieren an den Winter.

#### Teil 1a - Wärmeabgabe

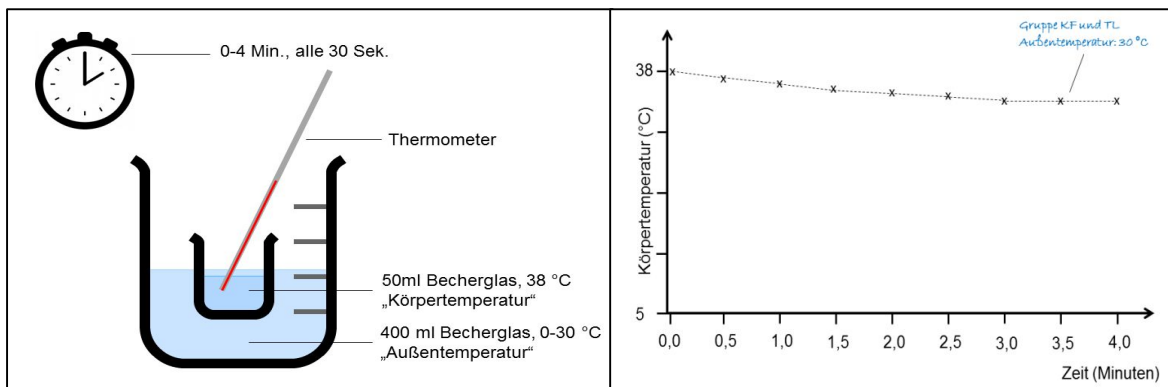
Mit Hilfe eines Versuchs könnt ihr herausfinden, wie sich die Wärmeabgabe an die Umwelt – und damit der Energiebedarf – bei kälteren Außentemperaturen verändert.

#### Anleitung zum Versuch

##### Material

Becherglas 400 ml (mit „Außentemperatur“ beschriftet), Becherglas 100 ml (mit „Körpertemperatur, 38° C“ beschriftet), Gefäß mit 38° C warmem Wasser, Gefäß mit Eiswürfel-Wasser, Thermometer ca. 0-50° C, Uhr, Flipchart/Tafel mit Diagramm (siehe unten), Karten mit den „Außentemperaturen“ 0-30° C.

1. *Arbeitet in 3-er Gruppen:* Zieht eine der bereitliegenden Karten, die euch die „Außentemperatur“ vorgeben. Füllt das 400 ml Becherglas mit 200 ml Wasser der auf der Karte angegebenen Temperatur. Die richtige Temperatur ermittelt ihr per Thermometer durch das Vermischen von warmem Leitungswasser mit dem Eiswürfel-Wasser.
2. Füllt das kleine Becherglas (100 ml) mit 50 ml von dem bereitstehenden, 38° C warmem Wasser und stellt es vorsichtig (!!!) in das große Becherglas.
3. Messt vier Minuten lang alle 30 Sekunden die Wassertemperatur im kleinen Becherglas. Tragt die Ergebnisse in das Diagramm an der Tafel/Flipchart ein und verbindet eure Datenpunkte. Beschriftet eure Datenlinie mit „eurer Außentemperatur“ und euren Namen.



Die folgenden Aufgaben könnt ihr erst bearbeiten, wenn die meisten Gruppen Ihre Ergebnisse eingetragen haben. Bearbeitet so lange den Teil 1b dieses Arbeitsmaterials.

#### Aufgaben

1. Beschreibt die Unterschiede zwischen den einzelnen Temperaturverläufen.
2. Nehmt an, dass ein Tier im Winter genauso aktiv ist wie im Sommer. Beschreibt auf Grund der gesammelten Daten, wie sich die Energieentwertung durch Wärmeabgabe zwischen Sommer und Winter unterscheidet.
3. Erklärt auf Grundlage eurer Beobachtung, welche Auswirkung eine gleichbleibende Aktivität für die Energiebilanz des Tieres im Winter hätte.

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### Teil 1b - Nahrungssuche

Mit dem Lege-Set im Onlinematerial könnt ihr darstellen, wie sich die Nahrungssuche und die Verfügbarkeit von Energie durch Nahrung im Winter verändert. Ihr benötigt zwei A4 Blätter, die ihr jeweils mit „Sommer“ bzw. „Winter“ beschriftet, sowie die ausgeschnittenen Fotos der Nahrung unten.

### Anleitung und Aufgaben

1. Die A4-Blätter stellen den Lebensraum eines kleinen Säugers dar (z.B. eines Siebenschläfers). Verteilt die Bilder gemäß der Tabelle gleichmäßig auf dem jeweiligen Blatt. Notiert, wie sich die Verfügbarkeit von Energie durch Nahrung im Winter verändert!

	Sommer	Winter
<b>Bucheckern, Haselnüsse, Eicheln, Kastanien</b> Energetische Nutzbarkeit der Nahrung: ca. 400 kcal / 100 g	4	1
<b>Früchte</b> Energetische Nutzbarkeit der Nahrung: ca. 100 kcal / 100 g	4	1
<b>Knospen</b> Energetische Nutzbarkeit der Nahrung: ca. 480 kcal / 100 g	2	1
<b>Insekten</b> Energetische Nutzbarkeit der Nahrung: ca. 140 kcal / 100 g	4	1

2. Zeichnet auf jedem Blatt eine möglichst kurze Strecke ein, die das Tier laufen müsste, um alle Nahrung zu finden. Berechnet, wie weit das Tier im Winter laufen müsste, um gleich viel Energie über die Nahrung aufzunehmen wie im Sommer. Notiert, wie sich durch die veränderte Nahrungssuche die Wärmeabgabe der Tiere im Winter verändert.
3. **Energiebilanz:** Fasst in einer Tabelle zusammen, wie sich die Energieaufnahme, -abgabe, und -speicherung im Winter ändern würde, wenn das Tier ähnlich aktiv ist wie im Sommer. Bezieht euch dabei auch auf eure Ergebnisse, die ihr im Aufgabenteil 1 auf dem Flipchart/an der Tafel gesammelt habt. Beschreibt in einer weiteren Spalte, wie das Tier auf diese veränderten Bedingungen reagieren könnte.

### Material 2

#### Vorbereitung auf den Winterschlaf

Siebenschläfer werden Ende Juli geboren und haben nach ihrer Geburt nur etwa 2 Monate Zeit, sich auf den Winterschlaf vorzubereiten, der bei keinem anderen Tier so lange dauert wie bei ihnen. Siebenschläfer müssen sich schnell entwickeln und ausreichend körpereigene Energievorräte anlegen, um die lange Periode des Winterschlafs zu überstehen.

Muttermilch und Nahrung mit hoher energetischer Nutzbarkeit, wie z.B. Samen, Knospen, Früchte und Nüsse, ermöglichen das Anlegen von Fettdepots.

**Tabelle 6.1.** Gewichtszunahme neugeborener Siebenschläfer

Alter (Tage)	1	6	9	12	16	22	28	35	46	58	67	90
Gewicht (g)	1	5	7	9	13	19	24	31	52	78	110	140

#### Aufgaben

1. Überträgt die Werte aus Tabelle 5.1 in ein Diagramm.
2. Stellt Vermutungen über die Gründe des Verlaufs des Graphen an.
3. **Zusatz:** Berechnet, um wie viel % das Körpergewicht in dieser Zeit gestiegen ist.

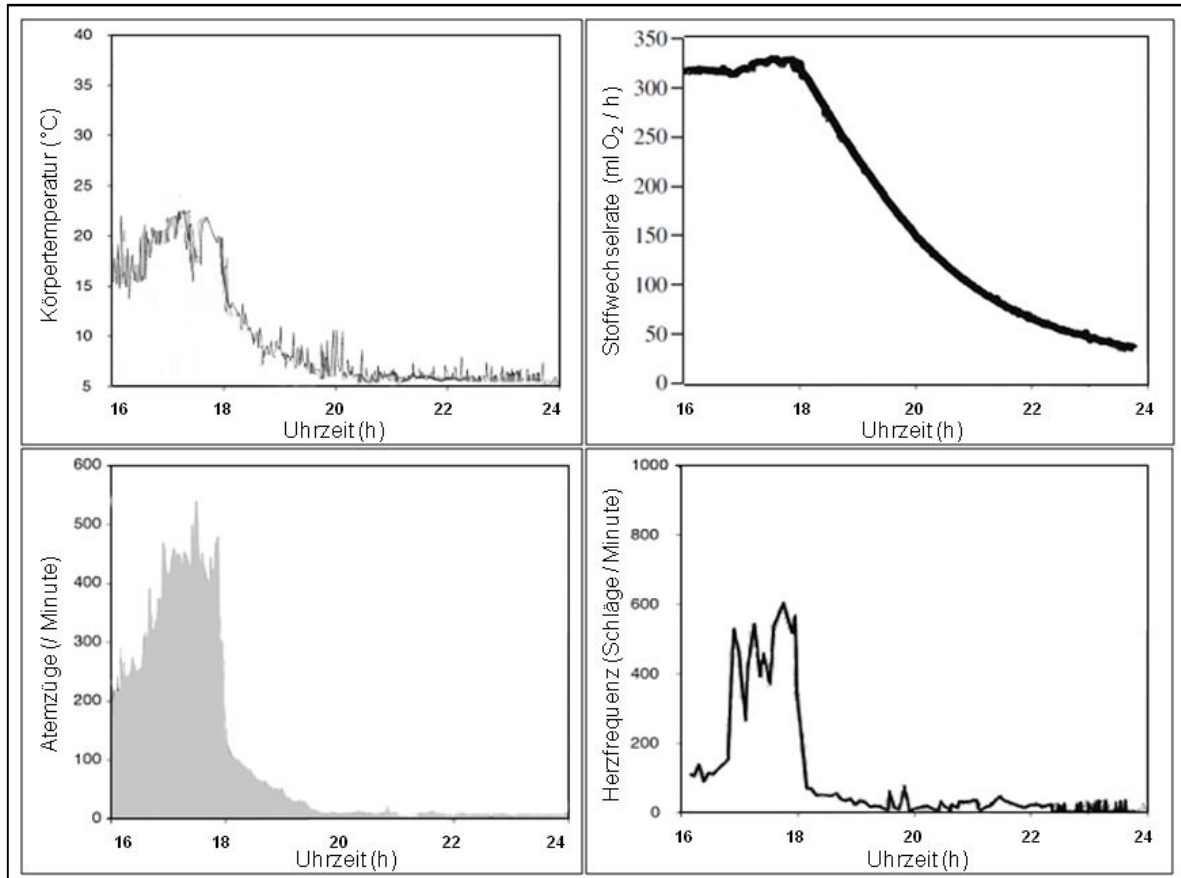
Der Winterschlaf der Siebenschläfer dauert meist sieben Monate. Dabei wird der Winterschlaf teilweise mehrmals pro Woche durch Phasen normalen Schlafes unterbrochen (siehe Material 4!). Ein Jungtier wiegt nach seinem ersten Winterschlaf noch etwa 80 g.

4. Ergänzt dieses Aufwachgewicht in Tabelle 6.1 und in eurem Diagramm.
5. Beschreibt, wie das Fett energetisch genutzt wird und wie die Nutzung des Fettgewebes mit der Gewichtsabnahme zusammen hängt.

### Material 3

#### Körperfunktionen während des Winterschlafes

Ende September beginnt der Winterschlaf der Siebenschläfer. Die Zeit des Winterschlafes verbringen Siebenschläfer in geschützten Erdhöhlen. Während des gesamten Winterschlafes nehmen die Tiere keine Nahrung und kein Wasser zu sich. Die Abbildungen 6.1a-d geben Auskunft über die Änderungen der Körperfunktionen in den Stunden des Übergangs von der aktiven Phase zum Winterschlaf.



**Abbildung 6.1a-d.** Körperfunktionen des Siebenschläfers beim Eintritt in den Winterschlaf

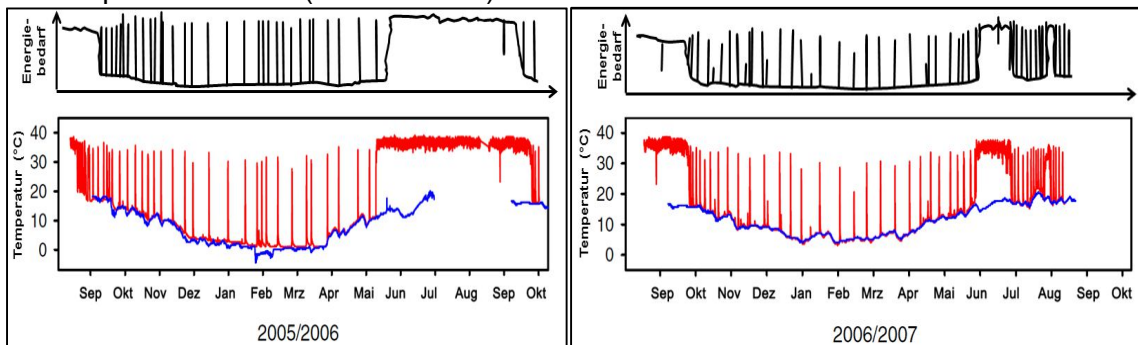
#### Aufgaben:

1. Beschreibt und erklärt die Veränderungen in den Körperfunktionen zu Beginn des Winterschlafes. Listet Organe auf, die von dieser Umstellung betroffen sind.
2. Beschreibt, welchen Vorteil die Veränderung der Körperfunktionen für Siebenschläfer und speziell deren Energiebilanz hat. Bezieht euch dabei darauf, in welcher Form Energie für die Tiere nutzbar beziehungsweise nicht mehr nutzbar ist.
3. **Zusatz:** Man liest häufig von „Energiesparen“, auch im Zusammenhang mit dem Winterschlaf. Beschreibt, was darunter zu verstehen ist, dass Siebenschläfer ‚Energie sparen‘.

### Material 4

#### Winterschlaf ist nicht gleich Winterschlaf

Siebenschläfer verbringen einen Großteil ihres Lebens im Winterschlaf. Forscher haben in den Jahren 2005/6 und 2006/7 die Körperfunktionen eines Siebenschläfer-Weibchen beobachtet. Die Daten von den zwei Jahren zeigen (Abb. 5.2a/b), wie sich der Energiebedarf (schwarze Linien) im Verhältnis zur Körpertemperatur (rote Kurven) und der Temperatur im Bau (blaue Kurven) über das Jahr ändert.



**Abbildung 6.2 a/b.** Körpertemperatur (rote Linien), Umgebungstemperatur im Bau (blaue Linien) und Energiebedarf (schwarze Linien) eines Siebenschläfer-Weibchens

#### Aufgaben

1. Beschreibt die Veränderungen des Energiebedarfs im Verhältnis zur Körpertemperatur und zur Temperatur im Bau. Benennt die Unterschiede zwischen den Jahren.
2. 2005/2006 bringt das Weibchen im Sommer Nachwuchs zur Welt, 2006/2007 nicht. Diskutiert, wie sich die Energiebilanz (Energieaufnahme, -abgabe, -speicherung) des Tieres in den zwei Jahren unterscheidet.
3. Formuliert Vermutungen, wodurch die Unterschiede zwischen den beiden Grafiken zu Stande kommen können. Bezieht eure Argumente auch auf die Energiebilanz des Tieres.
4. Die roten Spitzen der Körpertemperatur im Winter (Abb. 5.2a/b) kennzeichnen Phasen, in denen sich der Körper des Siebenschläfers kurzzeitig aufheizt. Diese Phasen sind Unterbrechungen des Winterschlafes, in denen die Tiere ‚normal‘ schlafen – dieses Phänomen ist auch bei anderen Winterschläfern weit verbreitet. Für das Aufheizen während der Schlafphasen wird jedoch ein Großteil der für den Winter im Fett gespeicherten energetisch nutzbarer Stoffe benötigt.

Diskutiert, welche Funktionen und welchen Vorteil der ‚Energieaufwand‘ für die normalen Schlafphasen für die Tiere haben könnte.

### Lösungsvorschläge

#### Material 1 – Teil 1a

**Aufgabe 1.** Die Abgabe von Wärme aus dem kleinen Becherglas findet bei geringeren Außentemperaturen deutlich schneller statt als bei höheren. Der Versuch zeigt, dass Tiere mit sinkender Außentemperatur schneller Wärme in die Umwelt abgeben.

**Aufgabe 2.** Bei gleicher Aktivität würde ein Tier im Winter pro Zeit mehr Energie über Wärme in die Umwelt abgeben (entwerten) und müsste entsprechend mehr Energie für die Aufrechterhaltung seiner Körpertemperatur einsetzen.

**Aufgabe 3.** Die Tiere besitzen im Winter einen erhöhten Energiebedarf und müssen mehr Energie über die Nahrung aufnehmen. Sollte dies nicht ausreichend möglich sein, wird zusätzliche, im Körperfett chemisch gespeicherte Energie umgewandelt, wodurch die Gesamtenergie des Tierkörpers abnimmt.

#### Material 1 – Teil 1b

**Aufgabe 1.** Im Winter sind in diesem vereinfachten Beispiel  $< 1/3$  der Fundstellen für Futter verfügbar. Die Summe der verschiedenen Nahrungsanteile entspricht ca.  $1/3$  der energetisch nutzbaren Nahrung die im Sommer verfügbar wäre.

**Aufgabe 2.** Um im Winter die gleiche Energiemenge über die Nahrung aufnehmen zu können, müssen die Tiere im Winter eine mehrfach längere Strecke laufen. Durch den gesteigerten Energiebedarf für die längere Nahrungssuche steigt im gleichen Maße die Wärmeabgabe in die Umwelt. Im Winter ist die Aufnahme der gleichen Energiemenge über die Nahrung mit einem mehrfach höheren Energieaufwand verbunden als im Sommer.



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### Aufgabe 3

Veränderung im Winter	Energieaufnahme	Energieabgabe	Energiespeicherung	Mögliche Reaktion auf die Veränderung
<b>Außentemperatur sinkt</b>	Im Gegensatz zum Sommer findet keine Wärmeaufnahme in den Tierkörper statt.	Je größer die Differenz zwischen Körper- und Außentemperatur, desto mehr Wärme wird pro Zeit in die Umwelt abgegeben.	Beim Abbau von energiespeicherndem Fettgewebe nimmt die Gesamtenergie des Körpers ab.	Ein dickeres Fellkleid oder Isolation im Bau führen zur Verringerung der Wärmeabgabe in die Umwelt.
<b>Nahrungsverfügbarkeit nimmt ab</b>	Pro Zeit wird weniger energetisch nutzbare Nahrung gefunden, sodass weniger Energie mit der Nahrung aufgenommen wird.	Eine längere Nahrungssuche und z.B. Hindernisse wie Schnee vergrößern den Energiebedarf für die Nahrungssuche. Durch die zusätzliche Bewegung wird auch zusätzliche Wärme in die Umwelt abgegeben.		Im Herbst wird mehr Energie über die Nahrung aufgenommen als das Tier für seine Körperfunktionen benötigt. Dadurch können im Körperfett Speicher chemischer Energie für den Winter angelegt werden.

### Material 2

**Aufgaben 1 und 4.** X-Achse: Zeit, y-Achse: Gewicht. Bitte Platz für die zu ergänzenden Werte aus Aufgabe 4 lassen.

**Aufgabe 2.** Die Gewichtszunahme steigt zunächst im Verhältnis zur Lebensspanne immer schneller an, flacht jedoch im dritten Lebensmonat ab. Der Grund hierfür liegt einerseits an der zunehmenden Nahrungsaufnahme, andererseits nimmt auch die energetische Nutzbarkeit der Nahrung durch die Umstellung von Muttermilch auf feste Nahrung zu. Das Abflachen der Wachstumskurve geht mit dem Übergang in den ersten Winterschlaf einher (vgl. Abbildung 6.1, Material 4).

**Aufgabe 3.** Das Gewicht nimmt in den ersten drei Monaten um den Faktor 140 zu – das entspricht einem Zuwachs von 13900%.

**Aufgabe 5.** Fette werden im Rahmen der Zellatmung (genauer: Beta-Oxidation und Citratzyklus) abgebaut und in CO<sub>2</sub> zerlegt, welches in die Umwelt abgeatmet wird. Durch die Verbindung mit Sauerstoff wird chemisch gespeicherte Energie entweder (über ATP) weiteren Körperprozessen zur Verfügung gestellt oder sie wird z.B. im brauen

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Fettgewebe direkt in Wärme umgewandelt. Sämtliche im Körper umgewandelte Energie gelangt langfristig als Wärme in die Umwelt.

### Material 3

**Aufgabe 1.** Die Körpertemperatur des Siebenschläfers sinkt am Anfang des Winterschlafes auf  $< 10^{\circ}\text{C}$  (Hinweis: Der reguläre Wert ist  $38^{\circ}\text{C}$ . In der Abbildung ist die Temperatur bereits gesunken). Die Stoffwechselrate verringert sich auf  $< 15\%$  des Ausgangswertes, die Atemzüge verdoppeln sich zunächst und fallen dann auf ca.  $1\%$  des Ausgangswertes ab. Ähnlich verfünffacht sich die Herzfrequenz zunächst, um dann auf ca.  $10\%$  des Ausgangswertes zu sinken. Die Änderungen finden am Herzen und in der Lunge statt, betreffen aber durch den Kreislauf alle Organe im Körper.

**Aufgabe 2.** Die deutliche Verringerung des Stoffwechsels im Winterschlaf geht mit einer massiven Verringerung des Energiebedarfs einher, sodass die Tiere pro Zeit deutlich weniger der begrenzten, nutzbaren, chemisch gespeicherten Energie (Nahrung und Körperfett) benötigen. Die Abgabe von Energie an die Umwelt durch nicht weiter nutzbare Wärme wird auf ein Minimum eingeschränkt. Durch den Winterschlaf wird vermieden, dass sich die Energiebilanz durch die energetisch aufwändige Nahrungssuche und das geringe Nahrungsangebot zu stark ins Negative verschiebt. Zusätzlich stellt der Winterschlaf eine Feindvermeidungsstrategie dar, wodurch die Überlebenschancen gesteigert werden.

**Aufgabe 3.** Der Begriff ‚Energie sparen‘ ist inhaltlich unsauber, da Energie aufgrund des Energieerhaltungssatzes nicht verloren gehen kann. ‚Energie sparen‘ bezieht sich hier darauf, dass durch die Einschränkung von Stoffwechselprozessen während des Winterschlafes die verfügbare bzw. nutzbare Energie für einen längeren Zeitraum ausreicht.

### Material 4

**Aufgabe 1.** Das Siebenschläfer-Weibchen senkt seine Körpertemperatur auf knapp über die Temperatur des Baus ab ( $< 10^{\circ}\text{C}$ ). Der Energiebedarf des Tiers verläuft in Abhängigkeit zur Körpertemperatur. Auffällig ist, dass die Körpertemperatur während des Winterschlafes in beiden Jahren durch viele kurze Phasen eines rapiden Körpertemperaturanstieges ( $> 30^{\circ}\text{C}$ ) unterbrochen wird. Im Jahr 2005/06 besitzt das

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Weibchen für ca. 4,5 Monate eine durchgängig hohe Körpertemperatur (Mai bis September) – im Jahr 2006/2007 ist diese Phase nur ca. 1 Monat lang (Juni bis Juli).

**Aufgaben 2 und 3.** Da sich das Weibchen 2005/2006 fortpflanzt, ist das Tier im Sommer aktiv um den Nachwuchs aufzuziehen. Für die Aufzucht, die Nahrungssuche und die hohe Körpertemperatur muss das Tier in diesem Jahr entsprechend viel energetisch nutzbare Stoffe mit der Nahrung aufnehmen. Im folgenden Jahr findet keine Fortpflanzung statt und das Tier verbringt einen Großteil des Spätsommers in Winterschlaf-ähnlichem Zustand. Dadurch sinkt der Energiebedarf und die Abgabe von Energie über Wärme an die Umwelt wird stark verringert. Ohne Fortpflanzung können Siebenschläfer den wie hier stark verlängerten Winterschlaf als Feindvermeidungsstrategie nutzen.

**Aufgabe 4.** Die Aufwärmphasen stellen einen Kompromiss zwischen energetischer Einsparung und dem Schutz von Organen dar. Hierbei werden die energetisch ungünstigen Aufwachphasen wahrscheinlich dazu genutzt, Schädigungen des Nerven- und Immunsystems durch die lange, extrem niedrige Körpertemperatur vorzubeugen.



# CHAPTER 7

## Discussion and Perspective

This chapter summarizes the results from studies 1-4 (section 7.1), discusses their combined outcome and meaning (section 7.2), and recapitulates the findings with regard to their limitations and generalizability (section 7.3). The relevance of the conducted research as well as implication for future studies and teaching practice are discussed in the final section 7.4.

### 7.1 Summary of the Results from Studies 1-4

**Study 1.** This study focused on energy learning at primary school level. As many of the early and often implicit learning opportunities for energy concern biological contexts, study 1 assessed to what extent primary students' (grades 3-6) energy understanding progresses along biological contexts before the energy concept's explicit introduction. The findings suggest that students at primary level develop first stages of their energy understanding along biological contexts. This progression was only to a smaller extent influenced by the development of general abilities (e.g., fluid intelligence, reading skills). The primary students' energy understanding was still limited, as it relied strongly on an understanding of energy forms/sources and transfer/transformation, while the students experienced substantial difficulties with energy dissipation/degradation and conservation. Despite these limitations in understanding, the results highlight that students not only enter formal energy education with problematic alternative conceptions (as indicated by earlier studies), but that they also possess first stages of a scientific energy understanding that formal energy education should build on. As students often receive formal energy instruction in physics or chemistry, the study points at the need to link energy instruction across boundaries of school subjects and, in this case, take into

account energy learning in biological contexts. Similarly, the study highlights the importance of coordinating energy instruction between school levels (i.e., primary, secondary), as the teachers' educational backgrounds and the instructional approaches to energy likely vary greatly between the school levels.

**Study 2.** Study 2 extended the scope of study 1 by focusing on secondary level students and by including a cross-disciplinary perspective on energy learning. In preparation for study 3, this piece of research focused on two goals: (i) develop and validate a test instrument for assessing middle/high school students' energy understanding across biology, chemistry, and physics contexts, and (ii) describe and compare progression trends in energy understanding across the disciplinary contexts. The results indicate that the developed instrument provides three reliable and clearly discipline-specific sub-scales for assessing energy understanding in the three contexts. The detailed validity discussion provides, for example, evidence regarding cognitive processes, external variables, and the relation with the intended criterion, i.e. energy understanding. Findings from the included cross-sectional study (grades 6, 8, and 10) suggest several similarities in students' progressing energy understanding in different disciplinary contexts. These relate both to students' understanding of the four energy aspects and to the selection frequencies of similar item attractors and distracters in the different disciplinary contexts.

**Study 3.** This study presented a re-analysis of the data from study 2. The research focused more specifically on how students' energy understanding is related across biology, chemistry, and physics contexts and how this relation changes as the students mature and learn more about energy throughout middle school. A comparison of three hypothesized progression scenarios (see also introduction of the studies, section 1.4) suggests that students' energy understanding progresses in parallel in the three disciplinary contexts. In contrast, the results did not identify knowledge integration/differentiation processes with respect to the three disciplinary contexts. Hence, students from all grade levels (6, 8, and 10) employed three highly interrelated sets of energy understanding. In the conducted model comparisons, the data was thus at all grade levels best represented by a 1-dimensional model that depicts a single, cross-disciplinary energy understanding. This result was unexpected, as earlier studies pointed at students' difficulties with the transfer of energy knowledge across disciplinary boundaries. Accordingly, the article critically discussed reasons for the cross-disciplinary appearance of students' energy understanding and suggests that this conceptualization is

likely connected to students' application of similar everyday connotations of energy in the different disciplinary contexts.

**Study 4.** Studies 1-3 are quantitative studies that base the assessment of energy understanding on multiple-choice questions. However, the respective instruments can register broad learning trends, but not specific conceptions that students employ in a given context. As the focal point of this dissertation was to assess and describe progressing energy understanding in biological contexts, study 4 used a qualitative approach and analyzed student interviews to identify specific conceptions that characterize students understanding of the four central energy aspects (see section 1.3.1) in biological contexts. The scope of study 4 was hereby to verify and deepen the findings of the quantitative studies 1-3. The results provide a detailed category system that presents prominent student conceptions at specific grade levels. Progressing energy understanding is depicted by students' development, maintenance, and abandonment of specific conceptions. These changes in understanding share several similarities with the progression trends observed in the quantitative studies 1 and 2. While study 4 does not allow for a direct comparison of students' energy conceptions in different disciplinary contexts, remarkably few of the observed energy conceptions appeared as clearly biology-specific. Instead, students often used rather general explanations to reason about the four energy aspects in biological contexts. The article hence also discussed these findings in relation to the studies on cross-disciplinary energy understanding.

### 7.2 Progressing Energy Understanding

This section reflects the studies' findings in regard to the two global research questions that guided the four studies of this dissertation, i.e. regarding (i) the progression of energy understanding in biological contexts and (ii) the connection of energy understanding across different disciplinary contexts.

#### 7.2.1 Progressing Energy Understanding in Biological Contexts

The observed progression trends in biological contexts are in several ways similar to previous studies that described sequences of progression energy understanding in physics contexts (Lacy et al., 2014; Liu and McKeough, 2005; Liu and Ruiz, 2008; Liu and Tang, 2004; Neumann et al., 2013; see also: Park and Liu, 2016). Early energy learning opportunities in biology may hereby be especially relevant for the first stages of students' progressing energy understanding (see study 1).

Students' conceptualization of energy in biology was limited by several alternative views, for instance, regarding energy as a concrete substance (see also Lancor, 2014, 2015), energy loss (see also Hirça et al., 2008), the switching between colloquial and scientific connotations of energy, overlaps between the understanding of energy and related concepts (see also Megalakaki and Thibaut, 2015; Solomon, 1983), as well as the confusion between energy requirements and other necessities for living organisms (e.g., nutrients, vitamins—see also Boyes and Stanisstreet, 1991). More generally, the conducted studies suggest that biology instruction's often limited regard for energy degradation and conservation is at least partly reflected in students' limited understanding of these energy aspects. A related issue hereby concerns tasks in biology textbooks. These frequently require students to rather unspecifically 'apply the energy concept' to a given problem (Wernecke, 2015). Such tasks likely aim at a higher understanding than that of the students, who may not be aware that such a general task may, for example, also require them to focus on energy degradation (see also Dawson-Tunik, 2006). Hence, energy instruction in biology could be strengthened by applying a more explicit focus on energy degradation and conservation. In contrast, students' relatively well-founded understanding of energy forms/sources can be a valuable framework for their later, more elaborate conceptualization of energy (Jin and Anderson, 2012). Continuing studies could hereby identify relevant learning opportunities and settings that support students in including energy degradation/dissipation and conservation into their analyses of energy.

In accordance with findings by Lancor (2014) and Neumann et al. (2013), the results from the conducted studies also suggest that energy understanding differs substantially between specific learning contexts (e.g., energy in photosynthesis versus energy in human nutrition). Similarly, Liu and Ruiz (2008) show that energy items become more difficult for students if they enclose a scientific instead of an everyday context. Thus, students' energy understanding could likely benefit if teachers help them to transfer energy knowledge from more familiar contexts (e.g., nutrition and health) to less well-known contexts (e.g., photosynthesis).

The conducted studies analyze progressing energy understanding across multiple grade levels. Accordingly, the studies presented relatively broad learning trends that may resemble linear gains in understanding (see studies 1 and 2). However, findings by Dawson-Tunik (2006) indicate that students' progressing understanding is not linear, but characterized by progression discontinuities. These encompass consolidation phases, where students learn about energy at the same level of conceptual insight, and transitional phases, where students progress to the next higher level of conceptual understanding. These discontinuities may also be reflected in the progressing



understanding of specific conceptions, which were characterized by rather abrupt changes at specific grade levels (studies 1, 2, and 4; see Burger, 2001 for similar findings). However, these studies used cross-sectional designs and the distinct changes in students' understanding could also correspond to sample effects between the grade levels. These analyses should thus be verified through additional longitudinal studies.

### **7.2.2 Connection of Students' Energy Understanding across Disciplinary Contexts**

An important finding in this dissertation is that students seem to apply a highly similar understanding of energy across disciplinary contexts (see study 3). Park and Liu (2016) conducted a similar study on cross-disciplinary energy learning. Even though the authors used a different instrument and analyzed college-level students, correlations between energy test scores for different disciplinary contexts were similarly high as those found in study 3. This result is furthermore reflected in research by Lancor (2014, 2015), which suggests that learners employ similar energy metaphors across disciplinary contexts. The scarcity of clearly discipline-specific ideas about energy in the qualitative study 4 additionally supports the finding that students employ a similar understanding of energy across disciplinary contexts.

Even though these results are consistent with each other, they oppose a widespread opinion in the current discussion about energy teaching (Eisenkraft et al., 2014): Based on, for example, the observation that students face difficulties in transferring energy understanding across disciplinary boundaries (e.g., Chabalengula et al., 2011; Dreyfuß et al., 2012), it has been concluded that students may assume different sets of energy understanding for different disciplinary contexts. However, due to the absence of observable knowledge integration processes, the students in study 3 did seemingly not learn to better combine different disciplinary perspectives when they applied the energy concept throughout middle school (see study 3). This finding corresponds to results by Dreyfuß et al. (2012), indicating that even advanced students do not make such connections unless they are explicitly shown the benefits of doing so. Accordingly, it is important to note that the apparently opposing views/findings (cross-disciplinary energy understanding versus transfer difficulties between disciplinary contexts) are not necessarily contradictory. In contrast, it seems likely that students employ an unspecific, everyday-based understanding of energy across disciplines (thus causing results as in study 3), while it may, at the same time, be hard for them to combine different foci and perspectives on energy from different disciplines. This possibly binary nature of students' cross-disciplinary energy understanding highlights the need to clarify learning expectations related to a *crosscutting* energy understanding. For example,

Nordine's (2016, p. 35) approach seems fruitful, in which students' crosscutting energy understanding is based on the consistent application of central energy aspects across disciplinary contexts. Respectively, the results suggest that the development of future instructional approaches for energy teaching should aim to strengthen students' ability to combine different disciplinary perspectives on energy. Suggestions to achieve this goal have, for example, been provided by Dreyfuß et al. (2012), who underlined the merits of multi-perspective approaches to energy, or by Fortus et al. (2015), who designed curricula with strong coherence between teaching units from different disciplinary backgrounds.

Study 3 found that students' energy understanding across disciplinary contexts was best represented by a 1-dimensional model. Alternative models, for example, based on the four energy aspects, were not able to explain the data more accurately (see discussion of Chapter 4). Likewise, findings by Liu and Ruiz (2008) suggest that the energy aspects are only responsible for a relatively small proportion of the explained variance in students' energy test scores. From a psychometric perspective, it may thus be questioned if future research on energy learning still needs to focus on a pre-defined set of energy aspects. However, these aspects represent widely agreed-upon contents that students are required to comprehend if they are to develop a useful understanding of the energy concept (e.g., Doménech et al., 2012; Lancor, 2015; Liu and McKeough, 2005; Jin and Anderson, 2012; Neumann et al., 2013; Nordine, 2016; Wang, Wang, and Wei, 2014). While other concepts may be empirically separable into sub-dimensions of understanding (e.g., matter, see Hadenfeldt, 2014, p. 129), a close connection in students' understanding between the different energy aspects is to be expected as they are mutually dependent. It is, for example, difficult to describe energy degradation without mentioning energy transfer and transformation.

A potential issue with the four energy aspects may relate to their function as an underlying framework for item development (see study 2). Here, the observed cross-disciplinary energy understanding (study 3) may have been influenced by the framework which represented each disciplinary context through an equivalent number of items for each energy aspect. The application of the framework thereby did not consider that the combined representation of the energy aspects may differ between disciplines (Schecker and Theyßen, 2007). The energy aspects worked well as a structural guideline to analyze, describe, and compare energy understanding the three disciplinary contexts. However, in order to verify the findings from studies 2 and 3, future research should also employ an approach in which discipline-specific energy items are developed independently.

### 7.3 Limitations and Perspectives

The research articles in chapters 2-5 discuss the validity and limitations of the individual studies. In addition, this section reflects on more global issues that relate to all four conducted studies in terms of their limitations and the resulting perspectives for continuing research.

**Reliability and validity.** The developed instruments (see studies 1 and 2) are sufficiently reliable to assess broad learning trends in energy understanding. However, the reliability of the sub-scales (e.g., for specific energy aspects) are too low to serve as stand-alone tests and would thus have to be extended if used separately. The discussion sections of studies 1 and 2 address the instruments' validity in regard to test content, students' cognitive processes in items solving, the structure of the students' energy understanding, different measures for discriminant and convergent validity, as well as the fit between the developed items and the underlying framework for item development (Joint Committee, 2014; Messick, 1995—see also overview of associated sub-studies, section 1.6). The collected data provide evidence that supports the validity of the developed instruments and hence suggests that they assess the intended construct (i.e., energy understanding) reasonably well. Authors who apply the developed instruments may additionally need to assess the validity of the instruments in relation to the science standards of their respective educational system.

**Study design.** This dissertation used—partly—a mixed-method approach by combining three quantitative studies and one qualitative study. The inclusion of the qualitative study provided a more detailed picture of conceptions about energy. The quantitative studies were used to allow the assessment of a larger and hence more representative group of students. However, the number of items was limited and, consequently, also constrained the possible level of detail in the provided analyses (e.g., in regard to the comparison of processes of cross-disciplinary knowledge integration for individual energy aspects).

Due to the limited duration of this dissertation project, the presented studies used cross-sectional designs. However, longitudinal studies usually generate a better foundation of data and should hence be applied to verify the presented findings. For example, the design does not allow the analysis of students' progressing energy understanding along topics of a specific biology class (e.g., nutrition/digestion, sensory perception/excitement of nerves, movement/transport in a body). Future studies could

deepen current research by analyzing what specific learning opportunities support or impede relevant aspects of energy understanding and how these learning opportunities can be meaningfully connected.

**Energy learning expectations.** The conducted studies assess energy understanding by operationalizing a model of progressing energy understanding (Neumann et al., 2013). This approach was conducted as science learning standards were often too broad in scope to provide a robust basis for a systematic construction of test items. The developed instruments (studies 1 and 2) hence don't claim to assess performance with regard to specific educational standards. On the one hand, this approach facilitates the application of the instruments across different educational systems. On the other hand, however, it is difficult to determine whether the assessed performance is sufficient with respect to educational standards. Thus, the findings of this dissertation should be used to identify content areas in which students require specific support, thus providing information for the development of effective instructional methods for energy teaching. In turn, the prospective German science standards for high school could benefit from using more specific goals for energy learning to provide a basis for future assessments. Such specific learning goals would also foreground the need to help students further expand their energy understanding also after middle school (see findings on middle school energy learning outcomes: Jin and Anderson, 2012; Liu and Ruiz, 2008; Neumann et al., 2013).

**Transfer of the results.** The presented data have solely been collected at one German federal state (Hamburg) and therefore only represent one curricular approach to energy teaching (considering, of course, that the implementation of this approach also differs between schools and teachers). While assessments have found a remarkably similar progression in energy understanding across students from different educational backgrounds, there are also distinctive differences between them (Liu and Tang, 2004). For example, study 3 (see Chapter 4) did not find indices for knowledge integration across disciplinary contexts, while Fortus et al. (2015) found such processes in students taught according to a specifically designed curriculum. Hence, future studies should determine in what ways specific approaches to energy teaching (i.e., curricula) influence students' progressing energy understanding.

The presented results cannot be easily compared to students' understanding of other core ideas or crosscutting concepts. Reasons for this specificity, can, for example, be seen in the energy concept's abstract nature and its widespread everyday

connotations. While the assessment of different crosscutting concepts (see section 1.2.5) would likely differ due to their specific nature, the requirement to coordinate connotations, contents, and language across school years and disciplinary boundaries does not only apply to the energy concept, but also to other crosscutting concepts. Furthermore, it is still to be discussed how to operationalize and differentiate between an understanding of energy as a disciplinary core idea versus energy as a crosscutting concept (see Duschl, 2012; Nordine, 2016; p. 35). This dissertation, by design, cannot distinguish between the two conceptualizations and hence has to leave this distinction open for future studies.

**Continuing research.** The paragraphs above have already identified several gaps in current scientific knowledge that could be addressed by future research. A major task for prospective studies on energy understanding is hereby to develop effective instructional formats to teach energy as a disciplinary core idea and a crosscutting concept (see Fortus et al., 2015; Nordine, 2016). These approaches need to take into account students' understanding of related concepts (e.g., fields, the nature of science) and employ topics that relate to students' lives and social concerns (NRC, 2012). To inform these developments, studies need to identify contexts in which students' understanding can especially benefit from the application of the energy concept. For example, energy understanding has been considered as an important factor for apprehending and decision making in socio-scientific issues (e.g., the choice between different energy resources—Sakschewski et al., 2014; see also European Parliament and Council, 2006, p. 15). Ongoing studies hereby need to determine what contents, concepts, and teaching methods can effectively support students to critically analyze problems related to these socio-scientific issues and derive actions accordingly.

### 7.4 Implications for Energy Teaching

This dissertation encompasses explorative studies to provide some of the first insights into students' progressing energy understanding in biological and cross-disciplinary contexts (compare Burger, 2001; Chabalengula et al., 2011). The findings can be used to inform the development of future, possibly interdisciplinary energy learning progressions and they form the empirical basis for continuing experimental studies. The design of the conducted studies does not allow it to derive in-detail implications for energy teaching. However, the following general recommendations can be concluded from the conducted research, as well as from earlier works:

(1) In accordance to previous research, studies 1–4 found that a thorough, qualitative understanding of energy is difficult even for more advanced secondary students (e.g., Dreyfuß et al., 2012; Nordine, 2007, 2016, p. 21). A focus of instruction on the nature of the energy concept and the four energy aspects can hereby provide students with a more valuable knowledge basis than the disputed attempt to provide students with a definition of energy (e.g., Doménech et al., 2007). A goal of energy instruction is hence to help students acquire *a sound qualitative understanding of energy before asking them to conduct extensive quantitative analyses* of energy.

(2) Students had considerable difficulties to *distinguish colloquial and scientific ways of speaking about energy* (study 4; see also Solomon, 1986). Teaching students to apply the two connotations of energy appropriately and helping them to apprehend the respective uses/merits is a challenge for future science teaching. Problematic formulations encompass, for example, the ‘burning’ of energy sources or descriptions of ‘energy loss’ (Burger, 2001, p. 249). Such language-related issues are especially relevant for topics in biology, which are often strongly contextualized and can thus lead students to apply everyday energy connotations also to scientific contexts (Jin and Anderson, 2012).

(3) Based on their experiences, students develop and maintain multiple *alternative conceptions about energy* (compare studies 2 and 4). Instruction should pick up these conceptions by addressing and challenging them openly to cause cognitive conflicts and thus trigger changes in students’ conceptualization of energy (Trumper, 1997, see also Posner, 1982).

(4) The findings of the dissertation are in line with prior studies that underlined the *relevance and feasibility of early energy instruction* (e.g., Lacy et al., 2014; Novak, 2005; Shultz and Coddington, 1981; van Hook and Huziak-Clark, 2008—for opposing views see: Burger, 2001; Warren, 1983). Instructional approaches for young learners can, for example, focus on tracing energy in occurring processes, thus preparing a later and more sophisticated understanding of energy (Lacy et al., 2014). Early, implicit energy learning opportunities are not only the source of alternative energy conceptions, but likely form the basis for students’ later energy understanding (see study 1). Formal energy instruction needs to take this knowledge into account and energy instruction thus also has to bridge students’ transition between primary and secondary school levels.

(5) Studies 2 and 3 show that students’ energy understanding in biological contexts is very similar to their understanding of energy in, for example, physics (see also Lancor, 2014; Park and Liu, 2016). Across disciplinary contexts, and especially in biology, students’ energy understanding can likely profit from instruction that *focuses more*

*strongly on energy degradation/dissipation and energy conservation.* Despite students' strong connection of energy understanding in different disciplinary contexts, the students likely experience difficulties in combining different disciplinary perspectives on energy (e.g., macro/micro-level analyses, Dreyfuß et al., 2012). With regard to energy as a crosscutting concept, *energy instruction hence still has to be better coordinated across disciplinary boundaries.*

(6) Students' understanding of energy likely differs substantially between specific contexts (see studies 1, 2, and 4—compare Lancor, 2014; Neumann et al., 2013). If students successfully apply the energy concept, for example, in a context on dietary requirements, they will not necessarily be able to do so in a context on energy turnover in ATP synthesis. *Learning about energy in well-known (everyday) contexts with concrete observations of energy manifestations may thus be a useful basis for understanding energy in more complex, more scientific, and more abstract contexts later on* (Lin and Ruiz, 2008). Accordingly, teaching units on energy can be connected to earlier, more accessible energy contexts, for example when biology teachers remind students of previously encountered, less complex contexts from physics.

In extension to these broad recommendations, future experimental studies should explore effective conditions for energy teaching under standardized conditions, thus providing an empirical basis for the much needed development of energy teaching strategies and materials (cf. Fortus et al., 2015; Nordine, 2007). These approaches can, in turn, be used to analyze in greater detail how using energy as a core idea and a crosscutting concept can support students in developing robust scientific literacy (OECD, 2013).

### 7.5 References

- Anderson, J. R. (2013). *Kognitive Psychologie* (7. Deutsche Auflage) [Cognitive Psychology]. Heidelberg: Springer.
- Appelhans, Y. S., THomsen, J., Opitz, S., Pansch, C., Melzner, F., & Wahl, M. (2014). Juvenile sea stars exposed to acidification decrease feeding and growth with no acclimation potential. *Marine Ecology Progress Series*, 509(227-239).
- Arzi, H. J., & White, R. T. (2007). Change in Teachers' Knowledge of Subject Matter: A 17-year Longitudinal Study. *Science Education*, 92(2), 221-251.
- Barak, J., Gorodetsky, M., & Chipman, D. (1997). Understanding of Energy in Biology and Vitalistic Conceptions. *International Journal of Science Education*, 19(1), 21-30.
- Barnett, M. S., & Ceci, S. J. (2002). When and where do we apply what we learn? A taxonomy for far transfer. *Psychological Bulletin*, 128, 612-637.
- Beyer, I. (2006). *Natura - Biologie für Gymnasien. Basiskonzepte (Sekundarstufe I und II)*. [Natura – Biology for Academic-Track Schools: Core Ideas] Stuttgart: Ernst Klett Verlag GmbH.
- Boyes, E., & Stanisstreet, M. (1990). Pupils' Ideas Concerning Energy Sources. *International Journal of Science Education*, 12(5), 513-529.
- Boyes, E., & Stanisstreet, M. (1991). Misconceptions in First-Year Undergraduate Science Students about Energy Sources for Living Organisms. *Journal of Biological Education*, 25(3), 209-213.
- Bransford, J. D., Brown, A. L., & Cocking, R. R. (2000). *How People Learn: Brain, Mind, Experience and School*. Washington, D.C.: National Academy Press.
- Burger, J. (2001). *Schülervorstellungen zu "Energie im biologischen Kontext" - Ermittlungen, Analysen und Schlussfolgerungen*. [Student conceptions concerning energy in biological contexts-research, analysis and conclusions]. University of Bielefeld, Dissertation.
- Chabalengula, V., Sanders, M., & Mumba, F. (2011). Diagnosing Students' Understanding of Energy and Its Related Concepts in Biological Contexts. *International Journal of Science and Mathematics Education*, 10(2), 241-266.
- Chen, B., Eisenkraft, A., Fortus, D., Krajcik, J. S., Neumann, K., Nordine, J., & Scheff, A. (2014). *Teaching and Learning of Energy in K-12 Education*. New York: Springer.
- Clark, D. B. (2000). *Scaffolding knowledge integration through curricular depth*. Doctoral Dissertation, University of California, Berkely.



- Constantinou, C. P., & Papadouris, N. (2012). Teaching and Learning about Energy in Middle School: An Argument for an Epistemic Approach. *Studies in Science Education*, 48(2), 161-186.
- Coopersmith, J. (2010). *Energy - The Subtle Concept*. New York: Oxford University Press.
- Davis, E. A., & Linn, M. L. (2000). Scaffolding students' knowledge integration: prompts for reflection in KIE. *International Journal of Science Education*, 22(8), 819-837.
- Dawson-Tunik, T. L. (2006). Stage-Like Patterns in the Development of Conceptions of Energy. In X. F. Liu & W. Boone (Eds.), *Applications of Rasch Measurement in Science Education* (pp. 111-136). Maple Grove, MN: JAM Press.
- [DfE] Department for Education (2013). Science programmes of study: key stage 3 - National curriculum in England.
- Doménech, J., Gil-Pérez, D., Gras-Martí, A., Guisasola, J., Martínez-Torregrosa, J., Salinas, J., . . . Vilches, A. (2007). Teaching of Energy Issues: A Debate Proposal for a Global Reorientation. *Science & Education*, 16(1), 43-64.
- Dreyfus, B. W., Redish, E. F., & Watkins, J. (2012). *Students' Views of Macroscopic and Microscopic Energy in Physics and Biology*. Paper presented at the AIP Conference Proceedings 1413.
- Driver, R., Squires, A., Rushworth, P., & Wood-Robinson, V. (1994). *Making Sense of Secondary Science: Supporting Material for Secondary Teachers*. London: Routledge.
- Duit, R. (1984). Learning the Energy Concept in School - Empirical Results from the Philippines and West Germany. *Physics Education*, 19(2), 59-66.
- Duit, R. (1986). In Search of an Energy Concept. In R. Millar & R. Driver (Eds.), *Energy Matters* (pp. 67-101). Leeds: University of Leeds.
- Duit, R., & Treagust, D. F. (2003). Conceptual change: A powerful framework for improving science teaching and learning. *International Journal of Science Education*, 25(6), 671-688. doi: 10.1080/09500690305016
- Duschl, R. A. (2012). The Second Dimension—Crosscutting Concepts Understanding A Framework for K–12 Science Education. *Science Teacher*, 79(2), 34-38.
- [EDK] Schweizerische Konferenz der Kantonalen Erziehungsdirektoren (2011). Grundkompetenzen für die Naturwissenschaften - Nationale Bildungsstandards - Freigegeben von der EDK-Plenarversammlung am 16.Juni 2011. [Science Learning Standards Switzerland]
- Eisenkraft, A., Nordine, J., Chen, R. F., Fortus, D., Krajcik, J. S., Neumann, K., & Scheff, A. (2014). Introduction: Why focus on Energy Instruction? In R. Chen, A.

- Eisenkraft, D. Fortus, J. S. Krajcik, K. Neumann, J. Nordine & A. Scheff (Eds.), *Teaching and Learning of Energy in K-12 Education*. New York: Springer.
- European Parliament and European Council. (2006). *Recommendation of the European Parliament and of the Council of 18 December 2006 on Key Competences for Lifelong Learning (2006/962/EC)*.
- Forde, T. (2003). "When I Am Watching Television I Am Not Using Any Energy" - An Empirical Study of Junior Science Students' Intuitive Concepts of Energy. *Irish Educational Studies*, 22(3), 71-89.
- Fortus, D., & Krajcik, J. (2012). Curriculum Coherence and Learning Progressions. In B. J. Fraser, K. Tobin & C. J. McRobbie (Eds.), *Second International Handbook of Science Education* (Vol. 24, pp. 783-798): Springer Netherlands.
- Fortus, D., Sutherland Adams, L. M., Krajcik, J. S., & Reiser, B. J. (2015). Assessing the Role of Curriculum Coherence in Student Learning About Energy. *Journal of Research in Science Teaching*, 52(10), 1408-1425.
- Furtak, E. M., & Heredia, S. C. (2014). Exploring the influence of learning progressions in two teacher communities. *Journal of Research in Science Teaching*, 51(8), 982-1020. doi: 10.1002/tea.21156
- Gayford, C. (1986). ATP: A Coherent View for School Advanced Level Studies in Biology. *Journal of Biological Education*, 20(1), 27-32.
- Gick, M. L., & Hoyoak, K. J. (1980). Analogical Problem Solving. *Cognitive Psychology*, 12(306-355).
- Gilbert, J. K., & Pope, M. L. (1986). Small Group Discussions About Conceptions in Science: A Case Study. *Research in Science & Technological Education*, 4(1), 61-76.
- Goldring, H., & Osborne, J. (1994). Students' Difficulties with Energy and Related Concepts. *Physics Education*, 29(1), 26.
- Gotwals, A. W., & Alonzo, A. C. (2012). Introduction: Leaping into Learning Progression in Science. In A. C. Alonzo & A. W. Gotwals (Eds.), *Learning Progressions in Science: Current Challenges and Future Directions* (Vol. Rotterdam). 2012: Sense Publishers.
- Hadenfeldt, J.-C. (2014). *Die Entwicklung der Kompetenz im Umgang mit dem Materiekonzept* [The Development Competence in Dealing with the Matter Concept]. Doctoral, Kiel University.
- Harms, U., & Bündler, W. (1999). *Fächergrenzen erfahrbar machen: Fachübergreifendes und fächerverbindendes Arbeiten*. [Making subject boundaries perceivable: Working in Interdisciplinary and Subject-Combining Settings] Kiel: IPN.

- Harms, U. (2016). Ohne Energie geht nichts! [Nothing works without energy!] *Unterricht Biologie*, 411(40), 2-11.
- Herrmann-Abell, C. F., & DeBoer, G. E. (2011). *Investigating Students' Understanding of Energy Transformation, Energy Transfer, and Conservation of Energy Using Standards-Based Assessment Items*. Paper presented at the NARST 2011 Orlando.
- Hirca, N., Calik, M., & Akdeniz, F. (2008). Investigating Grade 8 Students' Conceptions of 'Energy' and Related Concepts. *Journal of Turkish Science Education*, 5(1), 75-87.
- Inhelder, B., & Piaget, J. (1972). *The growth of logical thinking from childhood to adolescence*. New York: Baic Books.
- Jin, H., & Anderson, C. W. (2012). A learning progression for energy in socio-ecological systems. *Journal of Research in Science Teaching*, 49(9), 1149-1180.
- Joint Committee (AERA, A., NCME). (2014). *Standards for Educational and Psychological Testing*. Washington, D.C.: American Education Research Association (AERA).
- Ju, L., Blair, D. G., & Zhao, C. (2000). Detection of gravitational waves. *Reports on Progress in Physics*, 63, 1317-1427.
- Kattmann, U. (2015). *Schüler besser verstehen: Alltagsvorstellungen im Biologieunterricht*. [Understanding Students Better: Everyday Conceptions in Biology Classrooms] Hallbergmoos: Aulis Verlag.
- Kauertz, A. F., H.E.; Mayer, J.; Sumfleth, E. & Walpuski, M. (2010). Standardbezogene Kompetenzmodellierung in den Naturwissenschaften der Sekundarstufe I. [Standard-Based Competence Modelling for Middle School Science]. *Zeitschrift für Didaktik der Naturwissenschaften*, 16, 135-153.
- [KMK] Ständige Konferenz der Kultusminister der Länder in der Bundesrepublik Deutschland (2004a). *Einheitliche Prüfungsanforderungen in der Abiturprüfung Biologie*. [Requirements for German High School Graduation – Biology]
- [KMK] Ständige Konferenz der Kultusminister der Länder in der Bundesrepublik Deutschland (2004b). *Einheitliche Prüfungsanforderungen in der Abiturprüfung Chemie*. [Requirements for German High School Graduation – Chemistry]
- [KMK] Ständige Konferenz der Kultusminister der Länder in der Bundesrepublik Deutschland (2004c). *Einheitliche Prüfungsanforderungen in der Abiturprüfung Physik*. [Requirements for German High School Graduation – Physics]
- [KMK] Ständige Konferenz der Kultusminister der Länder in der Bundesrepublik Deutschland (2005a). *Bildungsstandards im Fach Biologie für den Mittleren*

- Schulabschluss - Beschluss vom 16.12.2004*. [German Learning Standards for Middle School Biology] München / Germany: Luchterhand.
- [KMK] Ständige Konferenz der Kultusminister der Länder in der Bundesrepublik Deutschland (2005b). *Bildungsstandards im Fach Chemie für den Mittleren Schulabschluss: Beschluss vom 16.12.2004*. [German Learning Standards for Middle School Chemistry]. München / Germany: Luchterhand.
- [KMK] Ständige Konferenz der Kultusminister der Länder in der Bundesrepublik Deutschland (2005c). *Bildungsstandards im Fach Physik für den Mittleren Schulabschluss Beschluss vom 16.12. 2004*. [German Learning Standards for Middle School Physics]. München / Germany: Luchterhand.
- Krajcik, J. S., Sutherland, L. A., Drago, K., & Merritt, J. (2012). The Promise and Value of Learning Progression Research. In S. Bernholt, K. Neumann & P. Nentwig (Eds.), *Making it tangible: Learning outcomes in science education* (pp. 261-283). Münster: Waxmann.
- Kruger, C. (1990). Some primary teachers' ideas about energy. *Physics Education*, 25(2), 86.
- Kurnaz, M. A., & Sağlam-Arslan, A. (2011). A Thematic Review of Some Studies Investigating Students' Alternative Conceptions About Energy. *Eurasian Journal of Chemistry and Physics Education*, 3(1), 51-74.
- Lacy, S., Tobin, R., Wiser, M., & Crissman, S. (2014). Looking Through the Energy Lens: A Proposed Learning Progression for Energy in Grades 3-5. In B. Chen, A. Eisenkraft, D. Fortus, J. S. Krajcik, K. Neumann, J. Nordine & A. Scheff (Eds.), *Teaching and Learning of Energy in K-12 Education*. Cham Heidelberg New York Dordrecht London: Springer.
- Lancor, R. (2015). An Analysis of Metaphors Used by Students to Describe Energy in an Interdisciplinary General Science Course. *International Journal of Science Education*, 1-27. doi: 10.1080/09500693.2015.1025309
- Lancor, R. A. (2014). Using Student-Generated Analogies to Investigate Conceptions of Energy: A multidisciplinary study. *International Journal of Science Education*, 36(1), 1-23. doi: 10.1080/09500693.2012.714512
- Lee, H.-S., & Liu, O. L. (2009). Assessing learning progression of energy concepts across middle school grades: The knowledge integration perspective. *Science Education*, 94(4), 665-688.
- Lerner, R. G., & Trigg, G. L. (2005). *Encyclopedia of Physics Volume 1(A-L)*. Weinheim: Wiley-VCH.

- Lichtner, H.-D. (2004). Strukturierendes Lernen in der Biologie mit Basiskonzepten. (Überarbeitete Version des Artikels: Konzepte und Erschließungsstrategien als Instrumente des kumulativen Lernens) [Structuring Learning in Biology with Core Ideas]. In Ballmann, Dieckmann, Freiman, Langlet, Ohly, Saathoff, Sandmann, Vogt, Woldd, Zabel & Lichtner (Eds.), *Handreichung für den Biologieunterricht in den Jahrgängen 5 – 10*: Verband Deutscher Biologen und biowissenschaftlicher Fachgesellschaft e.V.
- Lin, C.-Y., & Hu, R. (2003). Students' understanding of energy flow and matter cycling in the context of the food chain, photosynthesis, and respiration. *International Journal of Science Education*, 25(12), 1529-1544.
- Linn, M. C., Eylon, B.-S., & Davis, E. A. (2004). *Internet Environments for Science Education*. Mahwah, NJ: Lawrence Erlbaum.
- Liu, X., & McKeough, A. (2005). Developmental growth in students' concept of energy: Analysis of selected items from the TIMSS database. *Journal of Research in Science Teaching*, 42(5), 493-517.
- Liu, X., & Ruiz, M. E. (2008). Using data mining to predict K–12 students' performance on large-scale assessment items related to energy. *Journal of Research in Science Teaching*, 45(5), 554-573.
- Liu, X., & Tang, L. (2004). The progression of students' conceptions of energy: A cross-grade, cross-cultural study. *Canadian Journal of Science, Mathematics and Technology Education*, 4(1), 43-57.
- Mayring, P. (2000). Qualitative Content Analysis. *Forum: Qualitative Social Research (Sozialforschung)*, 1(2).
- Megalakaki, O., & Thibaut, J. (2015). Development and differentiation of force and energy concepts for animate and inanimate objects in children and adolescents. *Research in Science Education*, 1-24. doi: 10.1007/s11165-015-9467-9
- Messick, S. (1995). Validity of Psychological Assessment: Validation of Inferences From Persons' Responses and Performances as Scientific Inquiry Into Score Meaning. *American Psychologist*, 50(9), 741-749.
- [MNU] Deutscher Verein zur Förderung des Mathematischen und Naturwissenschaftlichen Unterrichts (2001). *Biologieunterricht und Bildung: die besondere Bedeutung des Faches Biologie zur Kompetenzentwicklung bei Schülerinnen und Schülern: Empfehlungen zur Gestaltung von Lehrplänen und Richtlinien für den Biologieunterricht*. [Biology Teaching and Education: The Special Meaning of the Subject Biology for Students' Competence Development:

- Recommendations for Design of Curricula and Guidelines for Biology Teaching]. Neuss: Seeberger.
- Neumann, K., & Nagy, G. (2013). *Students' progression in Understanding Energy*. Paper presented at the NARST Annual International Conference, Puerto Rico, Rio Grande.
- Neumann, K., Viering, T., Boone, W. J., & Fischer, H. E. (2013). Towards a Learning Progression of Energy. *Journal of Research in Science Teaching*, 50(2), 162-188.
- Neumann, K. K., A. ; Lau, A. ; Notarp, H. & Fischer, H.E. (2007). Die Modellierung physikalischer Kompetenz und ihrer Entwicklung [Modelling Competence in Physics and Its Development]. *Zeitschrift für Didaktik der Naturwissenschaften*, 13, 101-121.
- [NGSS] Next Generation Science Standards Lead States. (2013). *Next Generation Science Standards: For States, By States*. Washington, DC: The National Academies Press.
- Nordine. (2007). Supporting Middle School Students' Development of an Accurate and Applicable Energy Concept. *Dissertation*.
- Nordine, J. (2016). *Teaching Energy Across the Sciences, K-12*. Arlington, VA: National Science Teachers Association [NSTA].
- Nordine, J., Krajcik, J., & Fortus, D. (2011). Transforming energy instruction in middle school to support integrated understanding and future learning. *Science Education*, 95(4), 670-699.
- Novak, J. D. (2005). Results and Implications of a 12-Year Longitudinal Study of Science Concept Learning. *Research in Science Education*, 35(1), 23-40.
- [NRC] National Research Council. (2012). *A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas*: The National Academies Press.
- [OECD] Organization for Economic Cooperation and Development (2013). PISA 2015 - Draft Science Framework.
- Papadouris, N., & Constantinou, C. (2011). A Philosophically Informed Teaching Proposal on the Topic of Energy for Students Aged 11-14. *Science & Education*, 20(10), 961-979.
- Papadouris, N., Constantinou, C. P., & Kyratsi, T. (2008). Students' use of the energy model to account for changes in physical systems. *Journal of Research in Science Teaching*, 45(4), 444-469.
- Parchmann, I. (2010). Kompetenzmodellierung in den Naturwissenschaften. Vielfalt ist wertvoll, aber nicht ohne ein gemeinsames Fundament. Review. In E. Klieme (Ed.),

- Kompetenzmodellierung. Eine aktuelle Zwischenbilanz des DFG-Schwerpunktprogramms [Competence Modelling: A Preliminary Conclusion of the DFG Core Program]*. Weinheim, Basel: BELTZ, 135-142.
- Park, M. (2013). *Developing an Instrument for Assessing Students' Understanding of the Energy Concept Across Science Disciplines*. Doctoral, University of Buffalo, Buffalo, New York. Retrieved from <http://search.proquest.com/pao/docview/1511026690>
- Park, M., & Liu, X. (2016). Assessing Understanding of the Energy Concept in Different Science Disciplines. *Science Education*, n/a-n/a. doi: 10.1002/sce.21211
- Posner, G. J., Strike, K. A., Hewson, P. W., & Gertzog, W. A. (1982). Accommodation of a scientific conception: Toward a theory of conceptual change. *Science Education*, 66(2), 211-227.
- Pugh, K. J., & Bergin, D. A. (2006). Motivational Influences on Transfer. *Educational Psychologist*, 41(3), 147-160. doi: 10.1207/s15326985ep4103\_2
- Reece, J. B., Urry, L. A., Cain, M. L., Wasserman, S. A., Minorsky, P., Jackson, R. B., & Campbell, N. A. (2011). *Campbell Biology*. Boston: Benjamin Cummings/Pearson.
- Rizaki, A., & Kokkotas, P. (2013). The Use of History and Philosophy of Science as a Core for a Socioconstructivist Teaching Approach of the Concept of Energy in Primary Education. *Science & Education*, 22(5), 1141-1165.
- Saglam-Arslan, A. (2010). Cross-Grade Comparison of Students' Understanding of Energy Concepts. *Journal of Science Education and Technology*, 19(3), 303-313.
- Sakschewski, M., Eggert, S., Schneider, S., & Bögeholz, S. (2014). Students' Socioscientific Reasoning and Decision-making on Energy-related Issues—Development of a measurement instrument. *International Journal of Science Education*, 36(14), 2291-2313. doi: 10.1080/09500693.2014.920550
- Schaefer, G. (Editor) (2002). *Wittenberger Initiative: Vorschläge zur Allgemeinbildung durch Naturwissenschaften*. Gesellschaft Deutscher Naturforscher und Ärzte e.V. Hamburg. Retrieved from: <http://madipedia.de/images/5/51/Witt.pdf>
- Schecker, H. P., I. (2006). Modellierung naturwissenschaftlicher Kompetenz [Modelling Science Competence]. *Zeitschrift für Didaktik der Naturwissenschaften*, 12, 45-66.
- Schecker, H., & Theyßen, H. (2007). Energie – Ein Konzept in allen Naturwissenschaften. [Energy – A Concept for all Science Subjects]. *Naturwissenschaften im Unterricht – Chemie*, 17(100/101), 82-87.
- Scherr, R. E., Close, H. G., McKagan, S. B., & Vokos, S. (2012). Representing energy. I. Representing a substance ontology for energy. *Physical Review Special Topics - Physics Education Research*, 8(2), 020114.

- Schmidt, W. H., Wang, H. C., & McKnight, C. C. (2005). Curriculum coherence: An examination of US mathematics and science content standards from an international perspective. *Journal of Curriculum Studies*, 37(5), 525-559.
- Schnotz, W. (1994). *Aufbau von Wissensstrukturen: Untersuchungen zur Kohärenzbildung beim Wissenserwerb mit Texten* (Vol. 20) [Acquiring Knowledge Structures: Analyses of Coherence Building in Text-Based Knowledge Acquisition]. Weinheim: Beltz.
- Shultz, T. R., & Coddington, M. (1981). Development of the concepts of energy conservation and entropy. *Journal of Experimental Child Psychology*, 31(1), 131-153.
- Shwartz, Y., Weizman, A., Fortus, D., Krajcik, J., & Reiser, B. (2008). The IQWST experience: Using coherence as a design principle for a middle school science curriculum. *The Elementary School Journal*, 109(2), 199-219.
- Smith, J. P., diSessa, A. A., & Roschelle, J. (1994). Misconceptions Reconceived: A Constructivist Analysis of Knowledge in Transition. *Journal of the Learning Sciences*, 3(2), 115-163. doi: 10.1207/s15327809jls0302\_1
- Solomon, J. (1983). Learning about energy: how pupils think in two domains. *European Journal of Science Education*, 5(1), 49-59.
- Solomon, J. (1985). Teaching the conservation of energy. *Physics Education*, 20(4), 165.
- Trumper, R. (1990). Energy and a constructivist way of teaching. *Physics Education*, 25(4), 208.
- Trumper, R. (1997). Applying Conceptual Conflict Strategies in the Learning of the Energy Concept. *Research in Science & Technological Education*, 15(1), 5-18.
- van Hook, S., & Huziak-Clark, T. (2008). Lift, squeeze, stretch, and twist: Research-based Inquiry Physics Experiences (RIPE) of energy for kindergartners. *Journal of Elementary Science Education*, 20(3), 1-16.
- Viglietta, L. (1990). A more efficient approach to energy teaching. *International Journal of Science Education*, 12(5), 491-500.
- Vosniadou, S. (2008). Conceptual Change Research: An Introduction. In S. Vosniadou (Ed.), *International Handbook of Research on Conceptual Change* (pp. xiii-xxvii). New York: Routledge.
- Wang, L., Wang, W., & Wei, R. (2014). Chapter 6: What Knowledge and Ability Should High School Students Have for Understanding Energy in Chemical Reactions? An Analysis of Chemistry Curriculum Standards in Seven Countries and Regions In R. Chen, A. Eisenkraft, D. Fortus, J. S. Krajcik, K. Neumann, J. Nordine & A.



Scheff (Eds.), *Teaching and Learning of Energy in K-12 Education*. New York: Springer.

Warren, J. W. (1991). The teaching of energy. *Physics Education*, 26(1), 8-9.

Watts, D. M. (1983). Some alternative views of energy. *Physics Education*, 18(5), 213.

Wernecke, U. (2013). *Erfassung des Schülerverständnisses von Energie - Validierung eines quantitativen Erhebungsinstruments durch die Methode des Lauten Denkens [Assessing Students' Energy Understanding: Validating a Quantitative Assessment Instrument Using Think-Aloud Protocols]*. Master thesis, Kiel / Germany.



## Attachments

This section encloses the online supplemental materials for the four research articles and the teaching practice article that are part of this dissertation:

**Attachment A:** Online Materials 1 and 2 for Chapter 2 / Research article 1

Material 1: Items

Material 2: Item parameters

**Attachment B:** Online Materials 1-4 for Chapter 3 / Research article 2

Material 1: Items, items parameters, and distractor/attractor frequencies

Material 2: Analysis of Differences in Item Types

Material 3: Energy Learning Opportunities at Schools in Hamburg/Germany

Material 4: Additional Statistical Procedures: Multiple Regression and Rasch Analysis

**Attachment C:** Online Materials 1-3 for Chapter 4 / Research article 3

Material 1: Items, items parameters, and distractor/attractor frequencies

→See 'Attachment B, Material 1'

Material 2: Energy Learning Opportunities at Schools in Hamburg/Germany

→See 'Attachment B, Material 3'

Material 3: Item fits within parcels

**Attachment D:** Online Materials 1-2 for Chapter 5 / Research article 4

Material 1: Interview protocol

Material 2: Category system

**Attachment E:** Online Material for Chapter 6 / Article 5 (Teaching practice)

Material 1: Game cards

**ATTACHMENT A: ONLINE MATERIALS FOR CHAPTER 2**

**Online Material 1: Items for Testing the Energy Concept in Biological Contexts**

111\_2 (Aspect: energy forms / sources – Level of cognitive complexity: facts)



Imagine you are eating a slice of warm pizza.

**Task**

Select those parts of the pizza, which you think store energy that your body can use (for example, for movement)!

2 answers are correct!

- The heat from the pizza
- Vitamins
- Sugar and protein
- Nutrients
- Fats

Correct choices:

211\_1 (Aspect: energy transfer / transformation – Level of cognitive complexity: facts)



Everybody needs energy so they can grow. When growing up, energy is transferred from the environment into the growing body. During this process, the body also transforms energy.

**Task**

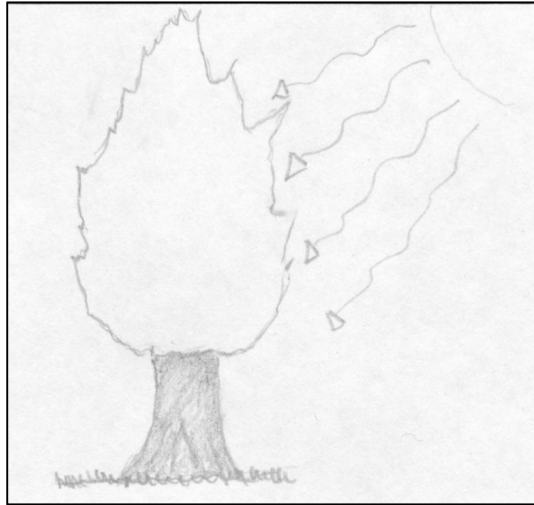
Select from the following, where the energy needed for growth comes from.

2 answers are correct!

- From heat in the environment
- From fat and proteins in foods
- From the energy of the sunlight
- From the energy of sugar in foods
- From water

Correct choices:

312\_1 (Aspect: energy degradation / dissipation – Level of cognitive complexity: facts)



A tree absorbs energy from the sun in the form of light. The tree then transforms this energy.

### Task

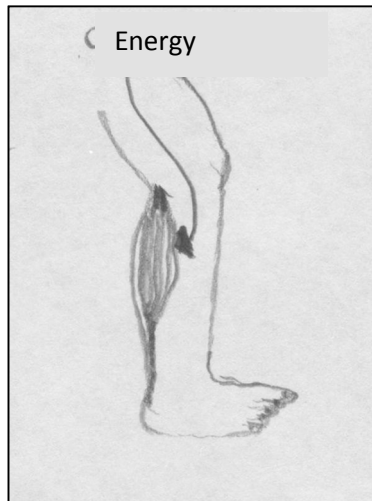
Select from the following points, where you can rediscover the light's energy after the transformation.

2 answers are correct!

- In growing parts of the tree, shed leaves and branches
- In the tree's movement (for example, movement of leaves)
- In the energy from water that the tree releases into the environment after using it
- In heat released by different processes in the tree (e.g. during the transformation of sunlight in leaves). This heat is then released into the environment.
- In electrical currents in nerves, which control the tree's functions

Correct choices: X  
O  
O  
X  
O

411\_2 (Aspect: energy conservation – Level of cognitive complexity: facts)



A muscle absorbs energy and transforms it.

**Task**

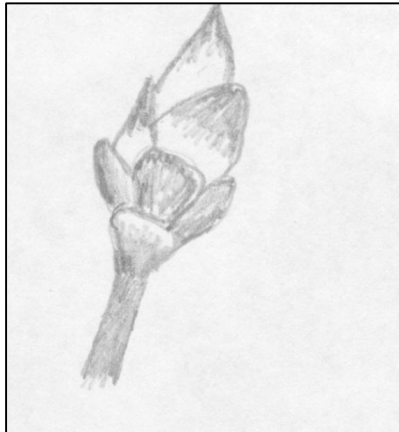
Select, where you can rediscover the energy after the transformation.

2 answers are correct!

- In the muscle's movement (as long as the muscle is moving)
- When the muscle stops moving, energy can no longer be found anywhere
- In heat released in the movement of the muscle
- In electrical currents of nerves that control the muscles of the body
- In sugar that is produced during the energy transformation in the muscle

Correct choices: X  
O  
X  
O  
O

112\_2 (Aspect: energy forms / sources – Level of cognitive complexity: facts)



Plants grow new leaves in spring. The energy for growing the leaves has to be stored in autumn, for example, in seeds or flowering bulbs.

**Tasks**

Tick the options, where you think the plant stores this energy

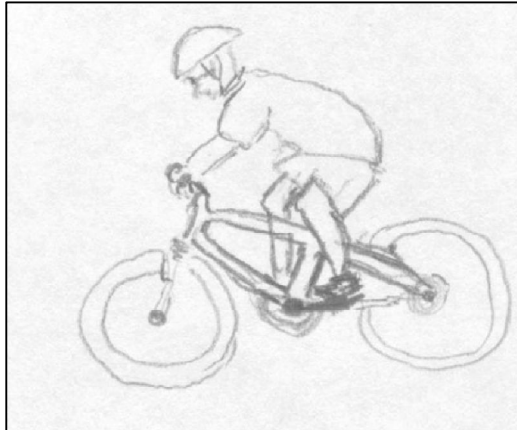
2 answers are  
correct!

- In protein and fat (e.g. in seeds)
- In light stores: in summer, leaves absorb energy and store it.
- In oxygen from the air that is stored in small holes
- In sugar that is collected as an energy store in the leaves in summer
- In vitamins and nutrients which the tree absorbs

Correct choices:    X  
                              O  
                              O  
                              X  
                              O



211\_2 (Aspect: energy transfer / transformation – Level of cognitive complexity: facts)



When people move, they transform energy.

**Task**

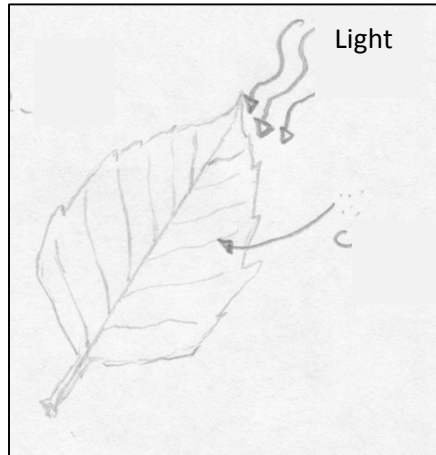
Select from the list, where the energy for these transformations comes from.

2 answers are correct!

- From heat energy in the environment.
- From food, specifically from fat, sugar and protein.
- From water
- From sunlight. It warms the body and thereby causes the muscles to move.
- From energy of the oxygen in the air. It is needed to degrade food.

Correct choices:

312\_2 (Aspect: energy degradation / dissipation – Level of cognitive complexity: facts)



A leaf absorbs energy from sunlight. This energy is transformed in the leaf.

**Task**

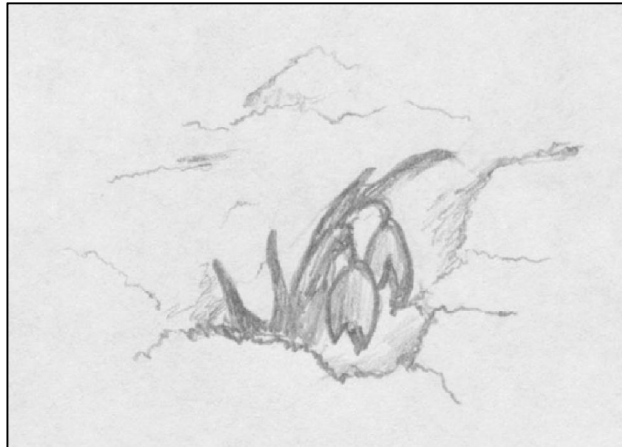
Select where you can rediscover the energy after the transformation.

2 answers are correct!

- In water that the tree emits into the environment after using it
- In the movement of the leaf
- In heat released by different processes in the leaf, which is then released into the environment
- In sugar which the tree builds up as a form of storage by using sunlight. The leaf can grow with the support of sugar as building material.
- In light that is stored in the leaf. It can be found in light stores, which slowly release light to the leaf.

Correct choices:

412\_2 (Aspect: energy conservation – Level of cognitive complexity: facts)



Snowdrops grow in February. As the plants grow, the snow melts around the plant. For its growth, the plant transforms energy from the energy store in its flower bulb.

**Task**

Select from the list where you can rediscover the energy from the flower bulb after its transformation.

2 answers are correct!

- In growing parts of the plant
- In heat released into the environment
- In the movement of the plant
- In the energy of released air
- In electrical currents of nerves that control functions of the plant

Correct choices: X  
X  
O  
O  
O

**121\_1 (Aspect: energy forms / sources – Level of cognitive complexity: mappings)**



A person climbs a mountain. The energy the person needs for climbing can be described with the points below.

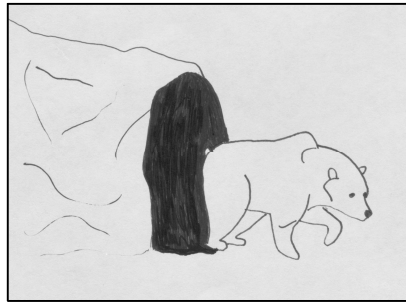
**Task**

Match each of the four points to the correct energy form.

<div style="border: 1px solid black; padding: 5px; width: fit-content; margin: auto;">                     In each line, <b>one</b> energy form is correct.                 </div>	Energy forms			
	Thermal energy	Kinetic energy	Potential energy	Chemical energy
1) The speed of the person				
2) The person's body and the food that's in the body				
3) The height of the person on the mountain				
4) The person's body heat				

<b>Correct responses:</b>	O	X	O	O
	O	O	O	X
	O	O	X	O
	X	O	O	O

**223\_2 (Aspect: energy transfer/transformation – Level of cogn. complexity: mappings)**



If a bear wakes up in winter and leaves its cave, it's protected from the cold by its layer of fat. It limits the release of heat to the outside world *and* produces body heat.

**Task**

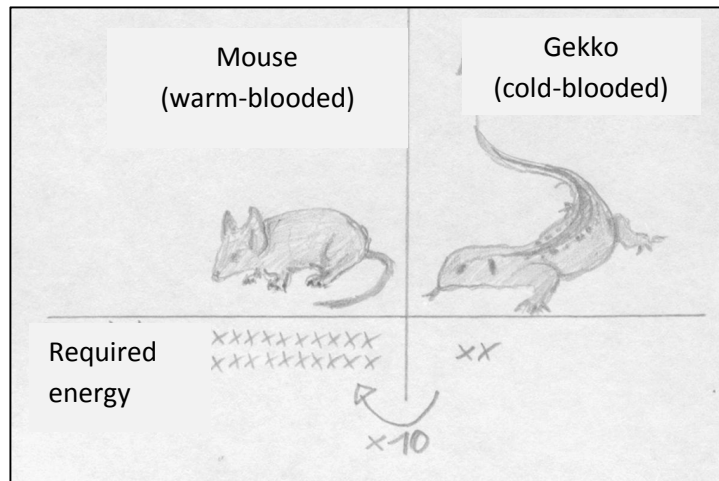
For the following three steps, select ...

- (A) which pair of energy forms is involved and ...
- (B) how the energy is passed on!

<div style="border: 1px solid black; padding: 5px; width: fit-content; margin: auto;">                     For each of the three steps, tick <b>one box for (A)</b> AND <b>one box for (B)</b>.                 </div>	(A) Pair of energy forms			(B) How energy is passed on	
	Chemical energy → Kinetic energy	Chemical energy → Thermal energy	Thermal energy → Thermal energy	Transfer, because the energy form stays the same	Transformation, because the energy form changes.
(1) WITHOUT its layer of fat, the body heat of the bear would be emitted given off to the surrounding air very quickly.					
(2) The chemical energy of the layer of fat is “burned up”. In this process, the body of the bear heats up.					
(3) If the bear wakes up in winter, its body will use energy from the layer of fat so that he can move.					

<b>Correct choices:</b>	(A)    O    O    X    (B)    X    O (A)    O    X    O    (B)    O    X (A)    X    O    O    (B)    O    X
-------------------------	---

323\_1 (Aspect: energy degradation/dissipation – Level of cogn. complexity: mappings)



Warm-blooded animals (body temperature remains constant as outside temperature changes) need 10 times more energy than similar cold-blooded animals (body temperature changes with outside temperature). Warm-blooded animals “degrade” much more energy.

**Task**

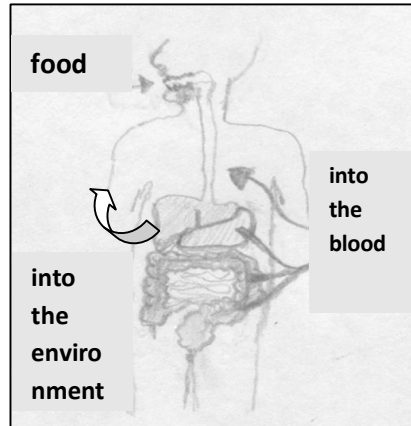
Select the options that correctly explain the meaning of energy “degradation” in this process!

**Several options can be correct!**

- Warm-blooded animals use much more energy to keep their body temperature constant. Heat energy, which is released into the environment, can no longer be used by the animal.
- Energy leaking as heat into the environment, can only be transformed by warm-blooded animals into “less valuable” energy forms (e.g. movement).
- Once energy leaked as heat into the environment, warm-blooded animals cannot transform it back into chemical energy as a food source.
- The degraded energy can be “re-charged”. But warm-blooded animals have to take up additional energy with food to run this process.

**Correct choices:** X  
O  
X  
O

**421\_1 (Aspect: energy conservation – Level of cognitive complexity: mappings)**



A person absorbs energy from the environment and transforms it in its body. A part of the energy is released back into the environment, whereas another part remains in the body.

**Task**

For **(A)**, select **1 option** in each line. For **(B)**, select **1**.

**(A)** In the following three steps, select if the energy is absorbed by the body / stored in it, OR, if it's released back into the environment.

	Energy absorbed by / stored in the body	Energy released by the body into the environment
1) Chemical energy from food	<input type="radio"/>	<input type="radio"/>
2) Chemical energy in growing body parts	<input type="radio"/>	<input type="radio"/>
3) Energy transformed into heat in the body	<input type="radio"/>	<input type="radio"/>

**(B)** Select the correct relation of the given amounts of energy.

The amount of energy absorbed from the environment ...

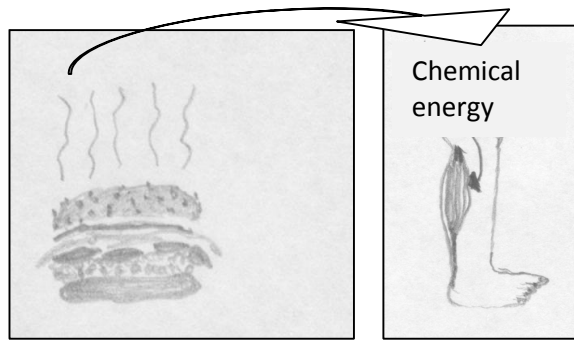
- ... is smaller than ...
- ... is larger than...
- ... is equal to ...

...the amount of energy **released** into the environment AND the amount of energy **stored** in the body.

**Correct choices:**

(A)	X	O	(B)	O
(A)	O	X	(B)	O
(A)	O	X	(B)	X

**221\_2 (Aspect: energy transfer/transformation – Level of cogn. complexity: mappings)**



In order to be able to walk, muscles pass on chemical energy from food.

For the following three steps, select ...

**(A)** which pair of energy forms is involved and ...

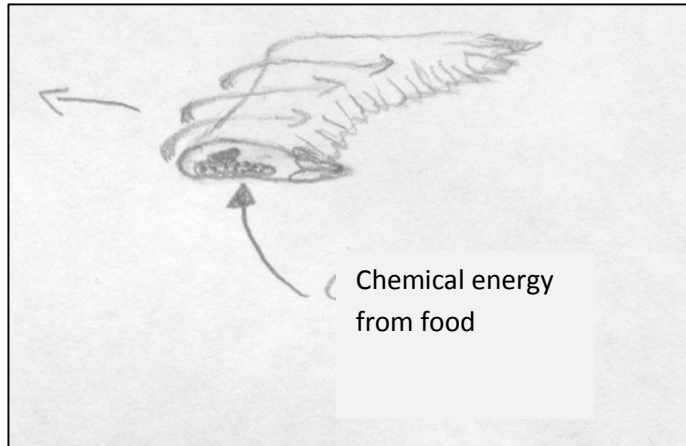
**(B)** how the energy is passed on!

	<b>(A) Energy forms</b>			<b>(B) How energy is passed on</b>	
	Kinetic energy → Kinetic energy	Chemical energy → Kinetic energy	Chemical energy → Thermal energy	<b>Transfer</b> , because the energy form remains the same	<b>Transformation</b> , because the energy form changes
For each of the three steps, tick <b>one box for (A)</b> AND <b>one box for (B)</b> .					
(1) Chemical energy from food is passed on to the muscle. As a result, the muscle contracts.					
(2) As the muscle produces movement, heat is also released.					
(3) The movement of the muscle is conveyed to the leg and then to the body. The whole person can then move.					

<b>Correct choices:</b>	(A)	<input type="radio"/>	<input checked="" type="radio"/>	<input type="radio"/>	(B)	<input type="radio"/>	<input checked="" type="radio"/>
	(A)	<input type="radio"/>	<input type="radio"/>	<input checked="" type="radio"/>	(B)	<input checked="" type="radio"/>	<input checked="" type="radio"/>
	(A)	<input checked="" type="radio"/>	<input type="radio"/>	<input type="radio"/>	(B)	<input checked="" type="radio"/>	<input type="radio"/>



323\_2 (Aspect: energy degradation/dissipation – Level of cogn. complexity: mappings)



A bird is flying. While flying, the chemical energy derived from food is not only transformed into kinetic energy of the bird's wing, but energy is also "degraded" during this process.

**Task**

Select the options that correctly explain the meaning of energy "degradation" in this process!

Several options can be correct!

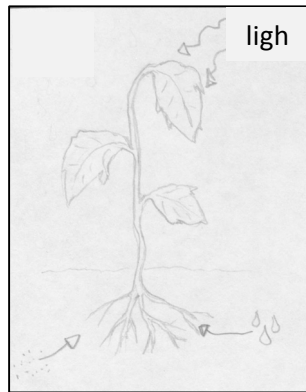
- Chemical energy is transformed into kinetic energy and is thereby degraded. The degraded energy has to be "recharged" with further chemical energy.
- Chemical energy is transformed into kinetic energy. In the process, energy is also transformed into thermal energy, which can no longer be used by the bird.
- In the process of transforming chemical energy, energy is also degraded as heat. This energy can no longer be transformed into other forms of energy.
- In the process of transforming chemical energy, energy is also degraded as heat. It's difficult for the bird to transform this energy into more kinetic energy.

Correct choices :

Attachments  
Attachment A: Online Materials for Chapter 2/Study 1

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**122\_1 (Aspect: Energy forms / sources – Level of cognitive complexity: mappings)**



Plants produce sugar for their growth from carbon dioxide (“CO<sub>2</sub>”) with the help of sunlight. The amount of sugar that is produced depends on several aspects.

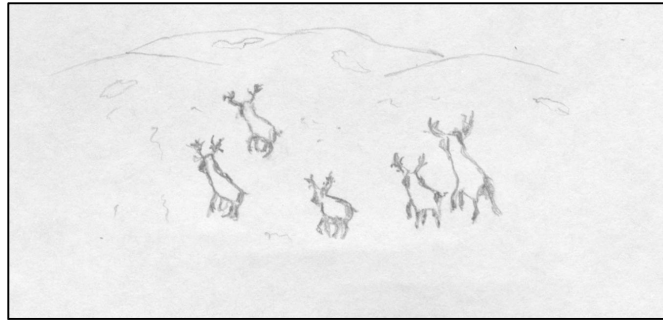
**Task**

Match each of the four points to the correct energy form.

	Energy forms			
	Thermal energy	Light energy	Kinetic energy	Chemical energy
<div style="border: 1px solid black; padding: 5px; width: fit-content; margin: auto;">                     In each line, <b>one</b> energy form is correct.                 </div>				
1) Sunlight				
2) Temperature of the environment				
3) Wind speed (in a storm, leaves rarely directly face the sun)				
4) <u>Sugar</u> produced for plant growth with the help of sunlight				

<b>Correct choices :</b>	O	X	O	O
	X	O	O	O
	O	O	X	O
	O	O	O	X

423\_2 (Aspect: energy conservation – Level of cognitive complexity: mappings)



Reindeers find lots of food in northern Canada in summer. As it gets colder in autumn, the animals move south. On the way, they can absorb energy, emit energy or store energy in their body.

**Tasks**

For **(A)**, select **1 option in each line**. For **(B)**, select **1**.

**(A)** For each of the following three cases, select whether the energy in each step is absorbed by the reindeer, OR, stored in its body / released into the environment.

	Energy emitted by the reindeer	Energy <b>stored in the reindeer's</b> body / released into the environment
1) Kinetic energy (which eventually becomes heat)	<input type="radio"/>	<input type="radio"/>
2) Energy transformed into heat in various processes inside the reindeer's body	<input type="radio"/>	<input type="radio"/>
3) Chemical energy of food (which the reindeer eats before or during its move south)	<input type="radio"/>	<input type="radio"/>

**(B)** Select the correct ratio of the given amounts of energy.

The amount of energy absorbed by the reindeer is ...	<input type="radio"/> ... equal to ... <input type="radio"/> ... smaller than ... <input type="radio"/> ... larger than ...	...the amount of energy stored in the reindeer AND the energy released the environment.
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Correct choices : (A)	OX	(B)	X
	OX		O
	XO		O

Attachments  
Attachment A: Online Materials for Chapter 2/Study 1

**Online Material 2: Item Parameters**

Energy Aspect	Forms & Sources of Energy				Transfer & Transformation of Energy				Degradation & Dissipation of Energy				Energy Conservation			
	Facts		Mappings		Facts		Mappings		Facts		Mappings		Facts		Mappings	
<b>Cognitive complexity</b>																
Item Code	111_2	112_2	121_1	122_1	211_1	211_2	221_2	223_2	312_1	312_2	323_1	323_2	411_2	412_2	423_2	421_1
Guessing probability	0.05	0.05	0.004	0.004	0.05	0.05	0.005	0.005	0.05	0.05	0.067	0.067	0.05	0.05	0.012	0.012
Guessing prob. - 50% correct	0.45	0.45	0.375	0.375	0.45	0.45	0.11	0.11	0.45	0.45	0.134	0.134	0.45	0.45	0.333	0.333
<b>Grade 3</b>																
Item difficulty	.019	.037	.275	.354	.098	.204	.029	.022	.109	X	X	.049	.093	X	.000	X
Item difficulty (50% correct)	.548	.518	.628	.583	.471	.760	.315	.326	.652	X	X	.708	.259	X	.667	X
Mean Scores (0-2 possible)	0.566	0.555	0.902	0.938	0.569	0.963	0.343	0.348	0.761	X	X	0.756	.444	X	0.668	X
Item variance	.289	.327	.650	.783	.450	.451	.291	.276	.408	X	X	.289	.440	X	.228	X
<b>Grade 4</b>																
Item difficulty	.115	.086	.281	.525	.100	.121	.021	.059	.132	X	X	.063	.115	X	.039	X
Item difficulty (50% correct)	.705	.500	.685	.230	.633	.672	.468	.510	.679	X	X	.563	.385	X	.648	X
Mean Scores (0-2 possible)	0.787	0.586	0.965	1.279	0.733	0.914	0.489	0.569	0.943	X	X	.625	.675	X	0.686	X
Item variance	.404	.422	.606	.704	.402	.326	.299	.370	.324	X	X	.367	.477	X	.300	X
<b>Grade 5</b>																
Item difficulty	.221	.043	.315	.667	.250	.391	.089	.036	.138	.099	.157	.165	.056	.056	.010	.122
Item difficulty (50% correct)	.758	.336	.826	.844	.792	.924	.622	.596	.893	.681	.674	.649	.562	.562	.625	.633
Mean Scores (0-2 possible)	0.979	0.380	1.141	1.510	1.042	1.315	0.711	0.631	1.032	0.780	0.831	0.813	.652	0.674	0.635	0.756
Item variance	.468	.326	.474	.568	.461	.327	.388	.308	.246	.373	.460	.487	.346	.336	.255	.434

Attachments  
Attachment A: Online Materials for Chapter 2/Study 1

Energy Aspect	Forms & Sources of Energy			Transfer & Transformation of Energy			Degradation & Dissipation of Energy			Energy Conservation						
	Facts	Mappings	Item Code	Facts	Mappings	Item Code	Facts	Mappings	Item Code	Facts	Mappings	Item Code				
<b>Grade 6</b>																
Item difficulty	.617	.065	.484	.797	.508	.452	.298	.222	.474	.159	.210	.211	.051	.111	.053	.161
Item difficulty (50% correct)	.967	.597	.847	.950	.964	1.000	.789	.682	.830	.698	.662	.702	.542	.492	.667	.709
Mean Scores (0-2 possible)	1.583	0.661	1.371	1.746	1.475	1.452	1.088	0.905	1.012	1.404	0.871	0.912	.742	.714	0.719	0.871
Item variance	.315	.359	.467	.296	.323	.252	.510	.539	.306	.388	.540	.510	.337	.433	.313	.442
<b>Average across grades 3-6</b>																
Item difficulty	.245	.056	.340	.606	.244	.308	.118	.086	.208	.123	.179	.135	.081	.079	.024	.137
Item difficulty (50% correct)	.743	.470	.771	.790	.733	.880	.585	.549	.840	.753	.669	.654	.469	.847	.646	.660
Mean Scores (0-2 possible)	0.989	0.526	1.111	1.405	0.977	1.188	0.703	.635	1.048	0.877	0.848	0.635	.632	.691	0.671	0.797
Item variance	.504	.363	.559	.645	.513	.395	.447	.406	.367	.357	.490	.406	.397	.374	.271	.439
Item discrimination	.383	.044	.334	.255	.379	.413	.420	.379	.294	0.073*	-.073*	.205	.051	.114*	.021	.079*

X = Item not used at this grade level  
 \* Item discrimination for these cases could only be calculated on the basis of the respective test booklet and only for students in grades 5&6, so that reliability was consequently low ( $\alpha=0.159$ ) and these results are therefore to be regarded only as an approximant.

**ATTACHMENT B: ONLINE MATERIALS FOR CHAPTER 3**

**Online material 1: Items, Item Parameters and Distractor/Attractor Analyses**

**Energy Assessment in Biology, Chemistry, and Physics Contexts**

This document contains: (a) An overview table for the distribution of the 43-item instrument, (b) all items in English translation, (c) item parameters respective grades 6, 8 and 10, and (d) specific attractors/distractors selection frequencies for each item

**Table 1 (AttB).** Overview of items by discipline, aspect and specific contents

		<b>Biology</b>	<b>Chemistry</b>	<b>Physics</b>
<b>Forms/ sources</b>	$N_{\text{items}}^*$	3* (4)	3* (4)	4 (4)
	Contents	Plant growth Bird migration Hunting wolves	Barbeque Batteries Energy drink	Running car Stretched springs Rolling balls Bow & arrow
<b>Transfer/ transformation</b>	$N_{\text{items}}^*$	4 (4)	3* (4)	4 (4)
	Contents	Plant growth: tree Plant growth: flower Bird migration Human growth	Cool/heat package Fire place Temp. at particle level	Ring on finger Bouncing rubber ball Falling ball Rubber band
<b>Degradation/ dissipation</b>	$N_{\text{items}}^*$	4 (4)	3* (4)	3* (4)
	Contents	Plant growth: gener. Food chain Growth/nutrition Sweating/exercise	Combustion engine Turnover in che. react. Candle	Bicycles Pendulum Cooling tea
<b>Conservation</b>	$N_{\text{items}}^*$	4 (4)	4 (4)	4 (4)
	Contents	Animal growth Reindeer migration Nutrition Biogas plant	Catalyst Balance in che. react. Camp fire Endoth./ exoth. react.	Slingshot Half pipe Falling ball Heat exchange (drink)
<b>Total number of items*</b>		<b>15 (16)</b>	<b>13 (16)</b>	<b>15 (16)</b>
<i>m</i> item difficulty grade 10		0.36	0.35	0.53
<i>m</i> item discrimination grade 10		0.32	0.29	0.34

## Attachments

### Attachment B: Online Materials for Chapter 3/Study 2

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\* Number of employed items for data analysis. Numbers in brackets indicate number of items before the inter-rating on item-specificity. The inter-rating excluded tasks 6, 15, 20, 37, and 45. These items are provided in this material as additional information. These items stand out by grey font and red comments above them.

#### **Cautionary note**

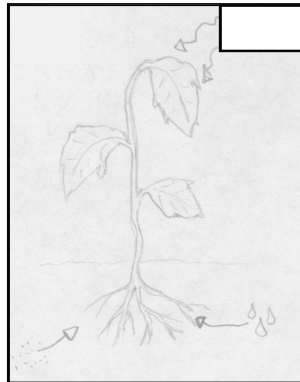
The here presented instrument was purposefully designed as a progression test for grade 6–10/12 students' energy understanding in biology, chemistry and physics. Readers are invited to use the presented items for other studies. The given item parameters were assessed in a sample of German metropolitan–background students. Test performance strongly differs with students' background and should be assessed in field testing before the application of the items in newly developed instruments.

**Discipline:** biology – **Energy aspect:** forms/sources – **Cognitive complexity:** facts

**Correct solutions:** 2 – 1 – 3 – 4

**Task 1**

Item 122\_1



With the help of sunlight, plants produce sugar from carbon dioxide (CO<sub>2</sub>) for their growth. The amount of produced sugar depends on several factors.

Match each of the four factors to the correct energy form.

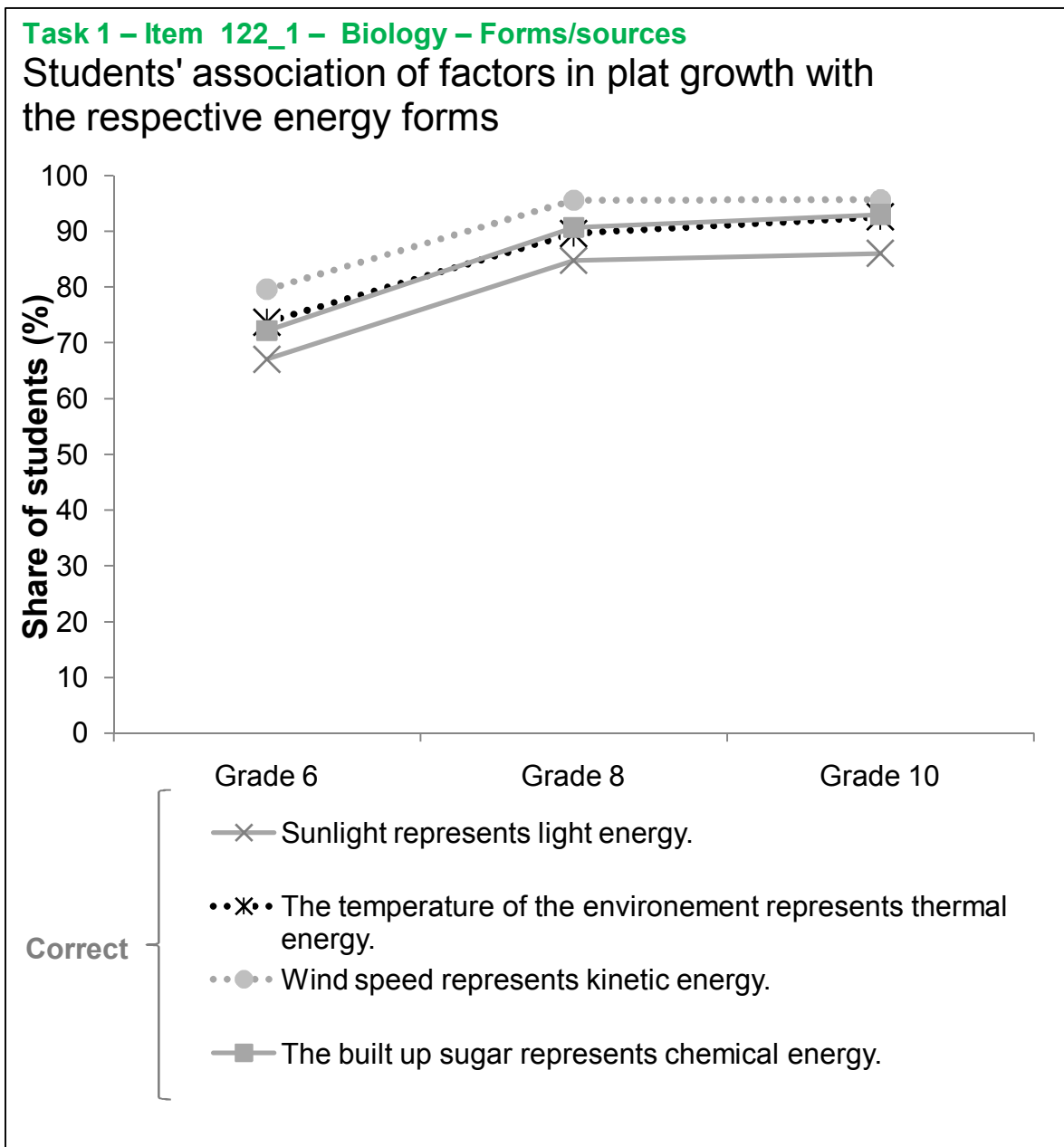
<div style="border: 1px solid black; padding: 5px; width: fit-content; margin: 0 auto;">                     In each line, <b>one form of energy</b> is correct!                 </div>	<b>Energy form</b>			
	Thermal energy	Light energy	Kinetic energy	Chemical energy
<b>Factor</b>				
Sunlight	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Temperature of the environment	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Wind speed (in a storm, leaves rarely face the sun)	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
<u>Sugar</u> produced for plant growth with the help of sunlight	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>



**Item parameters for item 122\_1**

	Grade 6	Grade 8	Grade 10
<b>Item difficulty (solution <math>p</math>)</b>	0.57	0.81	0.83
<b>Item discrimination</b>	0.27	0.33	0.21

**Distractor/attractor analysis** (For readability, only correct answers are shown)



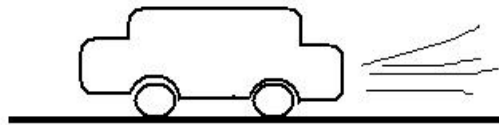
**Discipline:** physics – **Energy aspect:** forms/sources – **Cognitive complexity:** facts

**Correct solution:** 1

## Task 2

Item FF1

A car runs on a flat road.



Regarding the car's energy, which statement is correct?

1 answer is  
correct!

- The car has kinetic energy.
- The car only has gravitational potential energy.
- The car only has stored elastic potential energy.
- No statement can be made without further information.

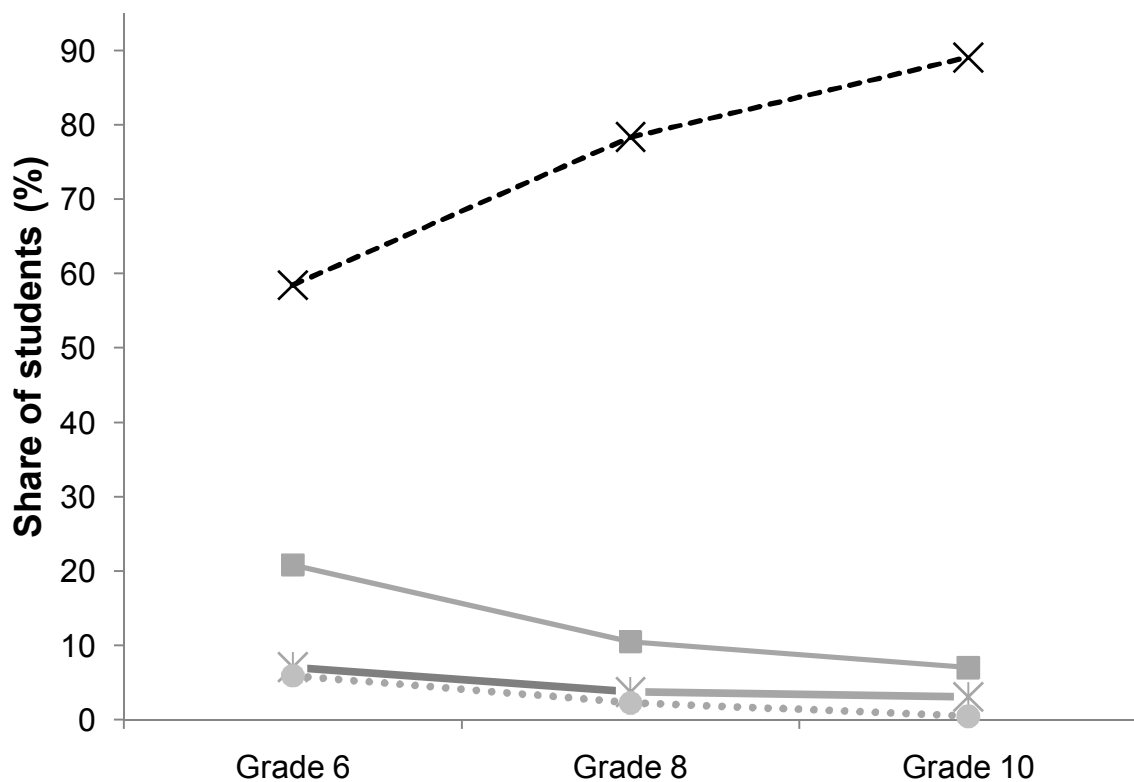
**Item parameters for item FF1**

	Grade 6	Grade 8	Grade 10
<b>Item difficulty (solution <math>p</math>)</b>	0.58	0.78	0.89
<b>Item discrimination</b>	0.15	0.16	0.26

**Distractor/attractor analysis**

**Task 2 – Item FF1 – Physics – Forms/sources**

Students' selections about the energy form of a car running on a flat surface



- Correct** -x- The car has kinetic energy.  
 -x- The car has gravitational potential energy.  
 ••• The car has elastic potential energy.  
 -■- No statement is possible without further information.

**Discipline:** chemistry – **Energy aspect:** forms/sources – **Cognitive complexity:** mappings

**Correct solution:** 4

### Task 3

Item CFM4



When the weather is good in summer, you can often see people having barbecues.

Which forms of energy occur when coal is burnt?

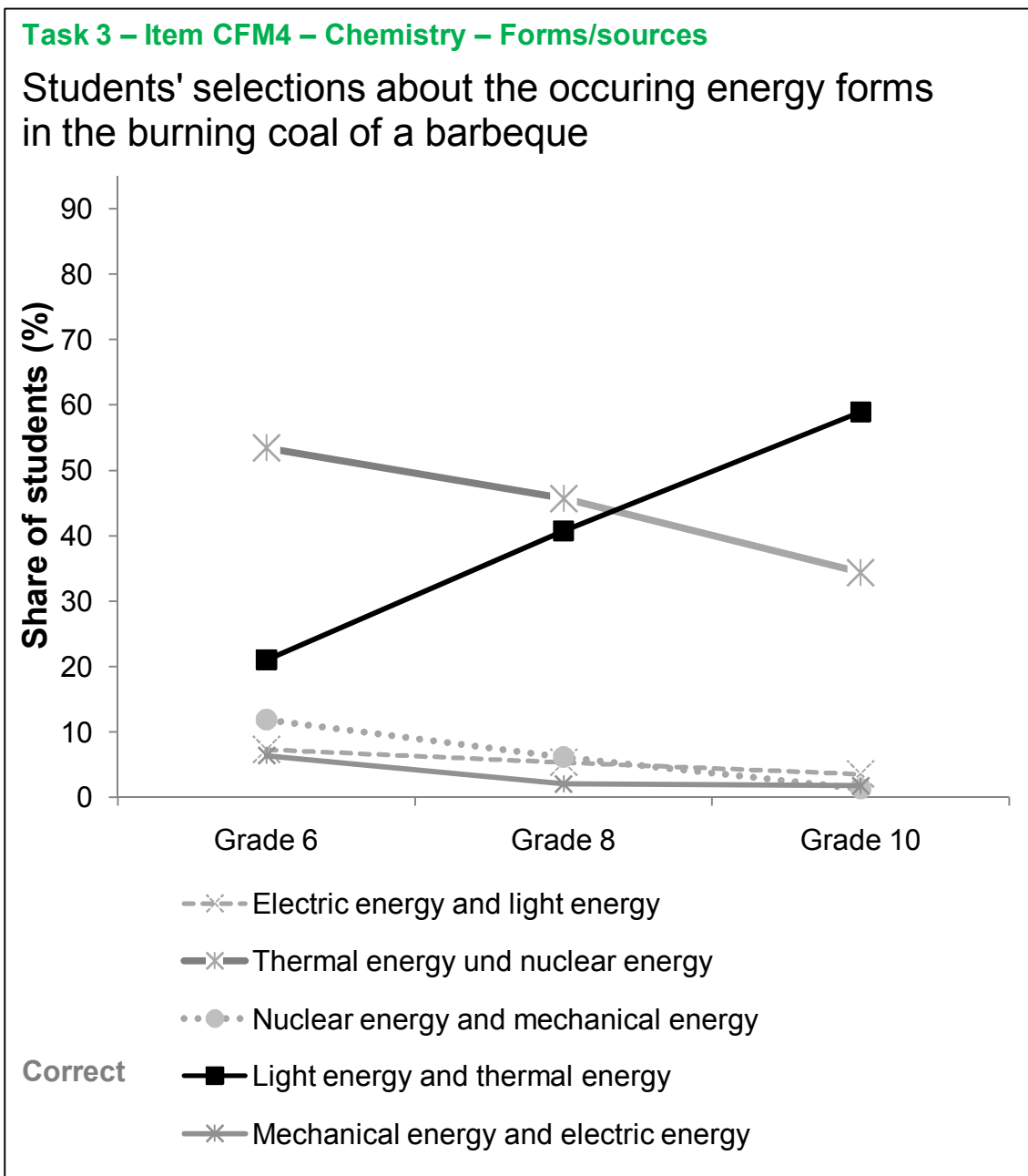
**1 answer** is correct!

- Electric energy and light energy
- Thermal energy und nuclear energy
- Nuclear energy and mechanical energy
- Light energy and thermal energy
- Mechanical energy and electric energy

**Item parameters for item CFM4**

	Grade 6	Grade 8	Grade 10
<b>Item difficulty (solution <math>p</math>)</b>	0.18	0.37	0.58
<b>Item discrimination</b>	0.01	0.43	0.45

**Distractor/attractor analysis**



**Discipline:** biology – **Energy aspect:** transfer/transformation – **Cognitive complexity:** facts

**Correct solutions:** 2 & 5

Task 4

Item 211\_1



Humans need energy to grow. They transfer energy onto their growing bodies and transform energy into heat.

Select the sources that the build-up chemical energy and the energy converted into heat stem from.

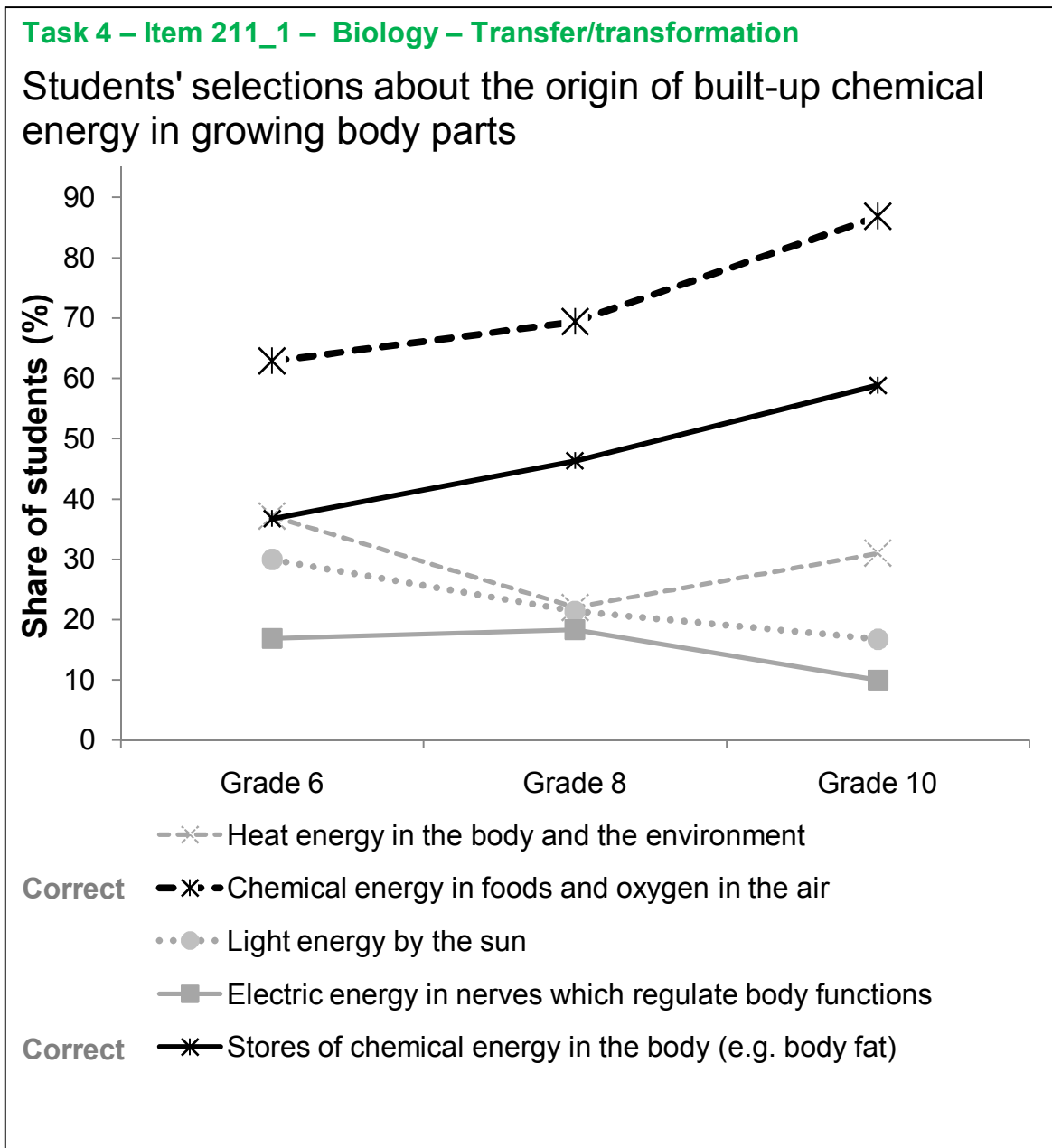
**2 answers  
are correct!**

- From thermal energy in the body and the environment
- From chemical energy in foods and from oxygen in the air
- From light energy originating from the sun
- From electric energy in nerves which regulate body functions
- From stores of chemical energy in the body (e.g. body fat)

**Item parameters for item 211\_1**

	Grade 6	Grade 8	Grade 10	Grade 6
<b>Item difficulty (solution <math>p</math>)</b>		0.23	0.31	0.49
<b>Item discrimination</b>		0.24	0.36	0.38

**Distractor/attractor analysis**



**Discipline:** physics – **Energy aspect:** transfer/transformation –  
**Cognitive complexity:** mappings

**Correct solution:** 2

## Task 5

Item TM3

Every morning, Luisa puts a ring on her finger. The ring feels cold.

Will the ring become warmer when she wears it?

**1 answer is  
correct!**

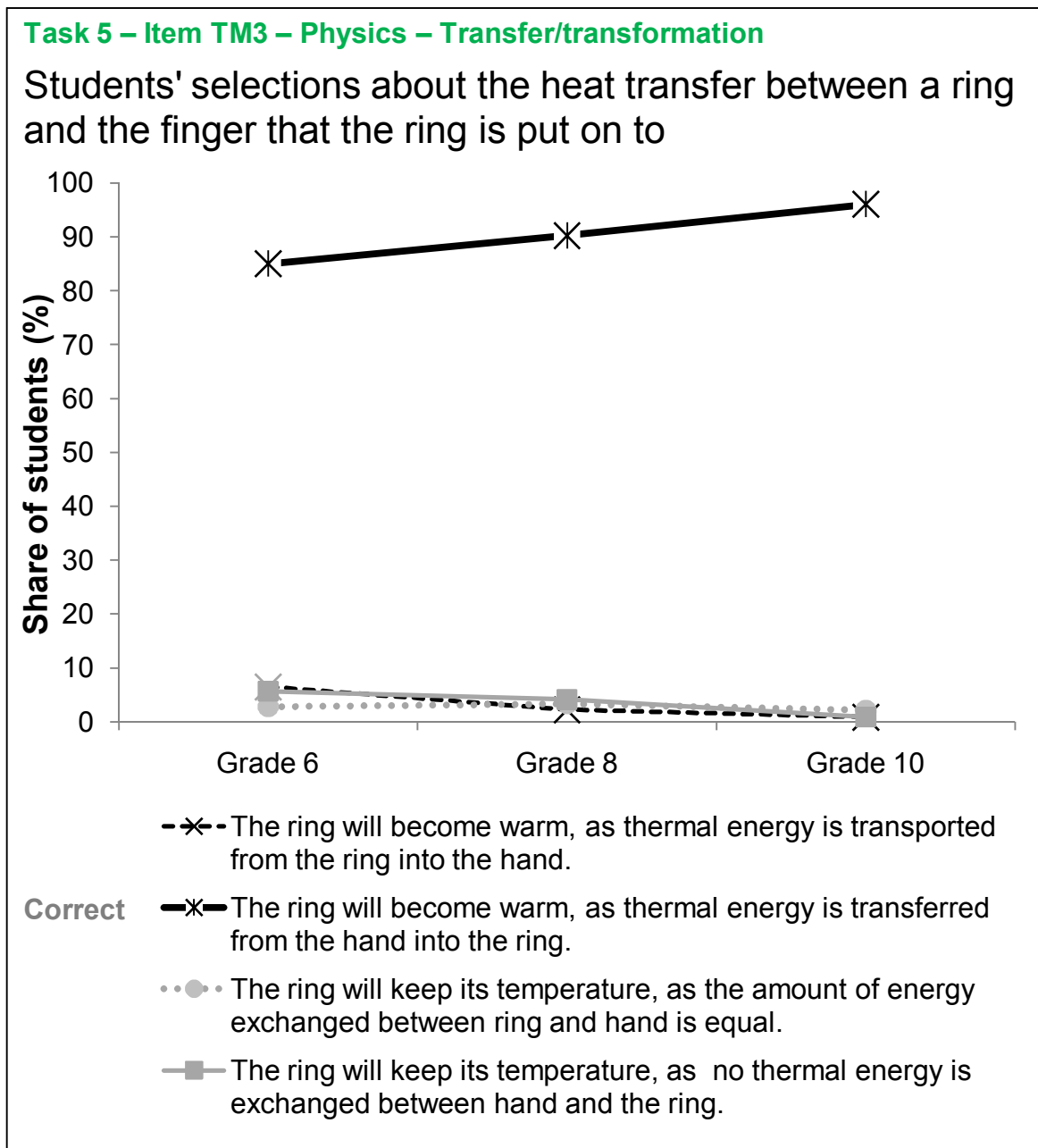
- Yes, the ring will become warm, because thermal energy is transported from the ring into Luisa's hand.
- Yes, the ring will become warm, because thermal energy will be transferred from Luisa's hand into the ring.
- No, the ring will keep its temperature, as the amount of energy exchanged between the ring and Luisa's hand is the same.
- No, the ring will keep its temperature, as there is no thermal energy exchanged between Luisa's hand and the ring.



**Item parameters for item TM3**

	Grade 6	Grade 8	Grade 10
<b>Item difficulty (solution <math>p</math>)</b>	0.82	0.90	0.96
<b>Item discrimination</b>	0.14	0.15	0.22

**Distractor/attractor analysis**



Attachments  
Attachment B: Online Materials for Chapter 3/Study 2

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THIS IS ONE OF FIVE ITEMS EXCLUDED THROUGH AN INTERRATING FOR BEING DISCIPLINE-UNSPECIFIC ( $k = .81$  for the remaining 43 items – This item: 8% agreement on the intended discipline [chemistry])

**Discipline:** chemistry – **Energy aspect:** transfer / transformation –

**Cognitive complexity:** mappings

**Correct solution:** 3

Task 6

Item CTM2



The sun enables plants to perform photosynthesis. In this process, plants produce substances which we can use as food. People therefore say that the sun's energy is stored in these substances.

Which processes take place in photosynthesis from an energy perspective?

**1 answer is correct!**

- Thermal energy is taken up and then stored.
- Thermal energy is transformed into chemical energy, which is then stored.
- Light energy is transformed into chemical energy and is then stored.
- Thermal energy is taken up and emitted again.
- Light energy is transformed into thermal energy and is then stored.

**Discipline:** biology – **Energy aspect:** degradation/dissipation –  
**Cognitive complexity:** relations

**Correct solutions:** 1 & 4

Task 7

Item 331\_2



People sweat when they move a lot. Sweating helps to keep the body temperature constant.

Select the statements that correctly describe the relation between increasing movement and the degradation of energy into heat!

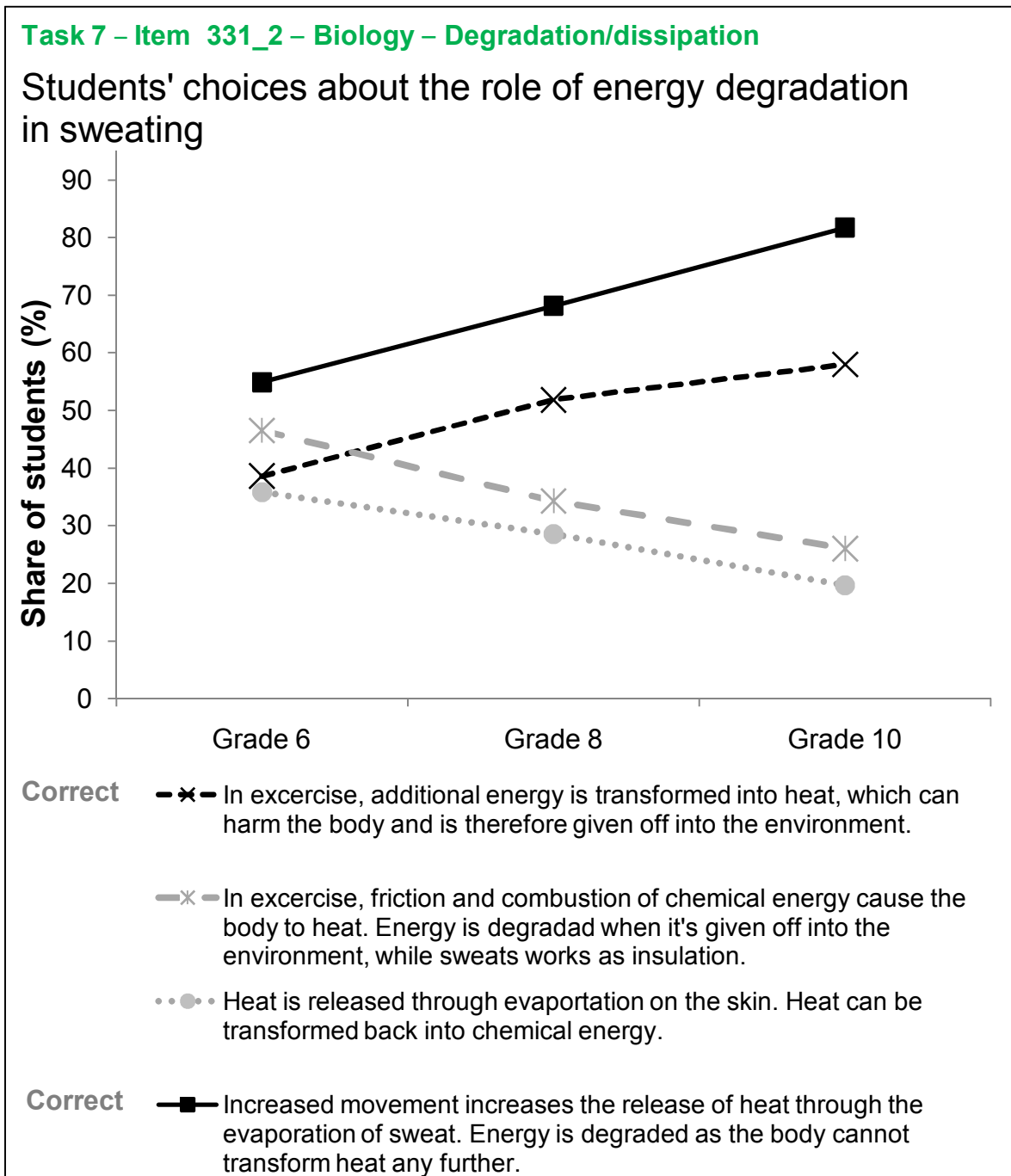
**2 answers**  
are correct!

- Through increased movement, additional chemical energy is converted into heat. This additional energy has to be released into the environment because a build-up of heat would harm the body.
- During exercise, friction in the body increases. Through combustion of chemical energy in the body, additional heat is released. As the environment is cooler than the body, heat is released to the environment, where it is degraded. As a form of 'insulation', sweat works as a counter measure.
- Through evaporation of sweat, the skin is cooled. This way, excessive heat is released. However, the skin can transform heat back into chemical energy. Thereby, degraded energy is 're-valued'.
- The skin is cooled down by the evaporation of sweat. In this process, excessive heat is released into the environment. Thereby, the body is protected from overheating. However, the energy is 'degraded', because the body cannot transform heat any further.

**Item parameters for item 331\_2**

	Grade 6	Grade 8	Grade 10
<b>Item difficulty (solution <math>p</math>)</b>	0.12	0.33	0.47
<b>Item discrimination</b>	0.20	0.37	0.40

**Distractor/attractor analysis**



**Discipline:** physics – **Energy aspect:** degradation/dissipation – **Cognitive complexity:** relations

**Correct solution:** 2

## Task 8

Item DR1

There are many types of bikes, for example racing bikes, mountain bikes and city bikes.

Which type of bike has the greatest loss of energy when it's driven?

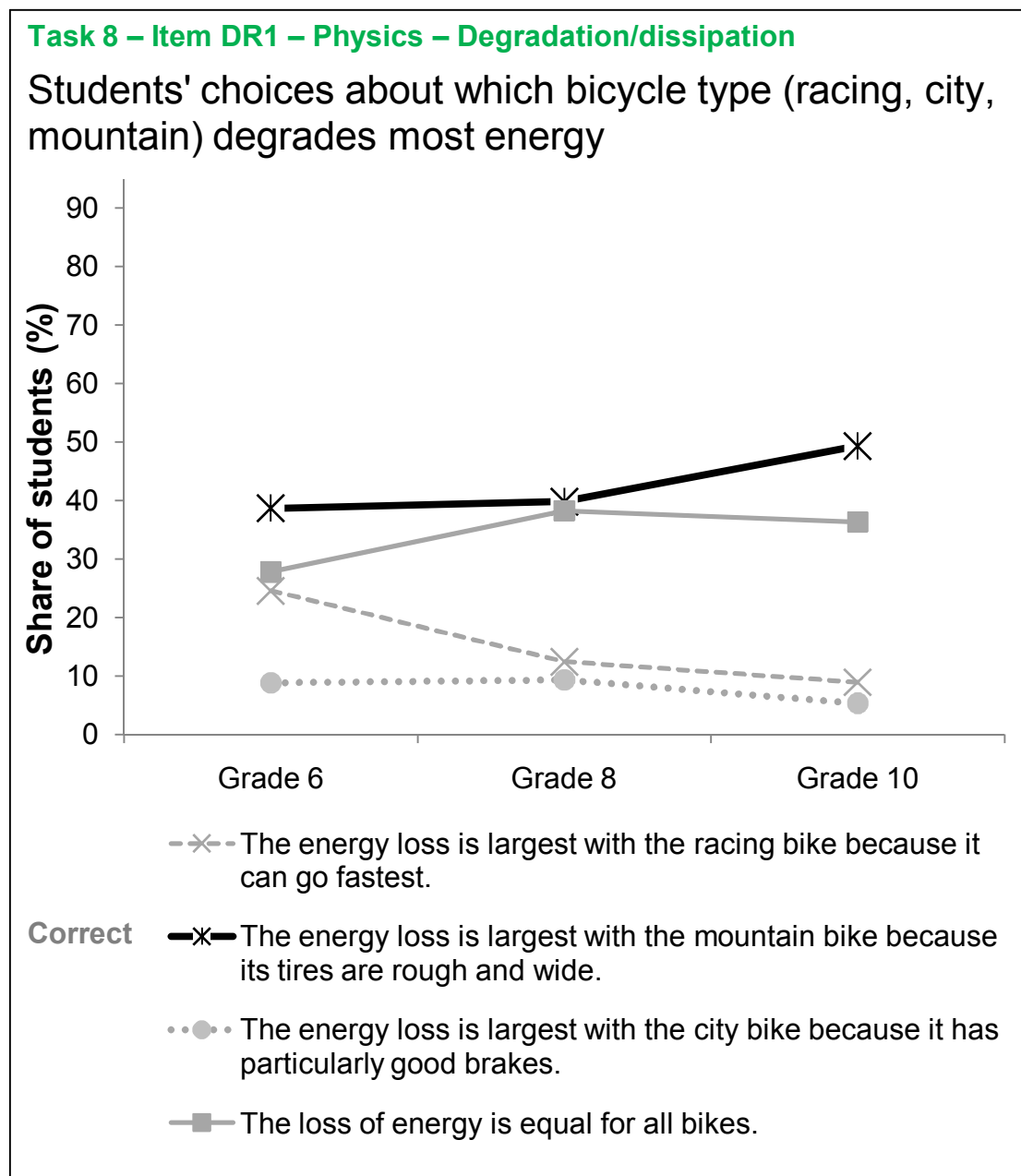
**1 answer is correct!**

- The racing bike because it can go fastest.
- The mountain bike because the tire profile is very rough and the tires are very wide.
- The city bike because it has especially good brakes.
- The loss of energy is the same in all bikes.

**Item parameters for item DR1**

	Grade 6	Grade 8	Grade 10
<b>Item difficulty (solution <math>p</math>)</b>	0.38	0.38	0.48
<b>Item discrimination</b>	0.06	0.21	0.10

**Distractor/attractor analysis**

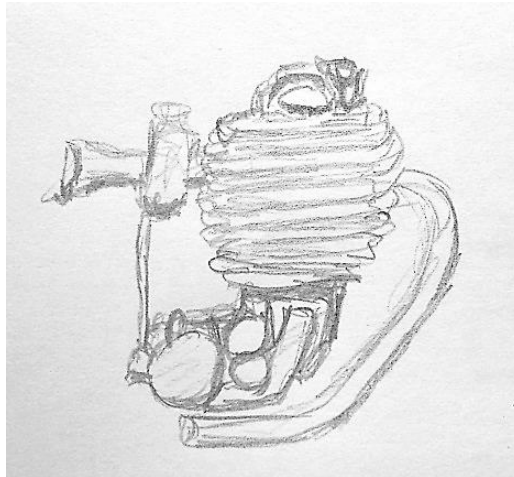


**Discipline:** chemistry – **Energy aspect:** degradation/dissipation –  
**Cognitive complexity:** concepts

**Correct solution:** 5

Task 9

Item CDC1



When gasoline is burnt in an engine, the gasoline's energy can no longer be used after the combustion reaction.

What is the correct explanation?

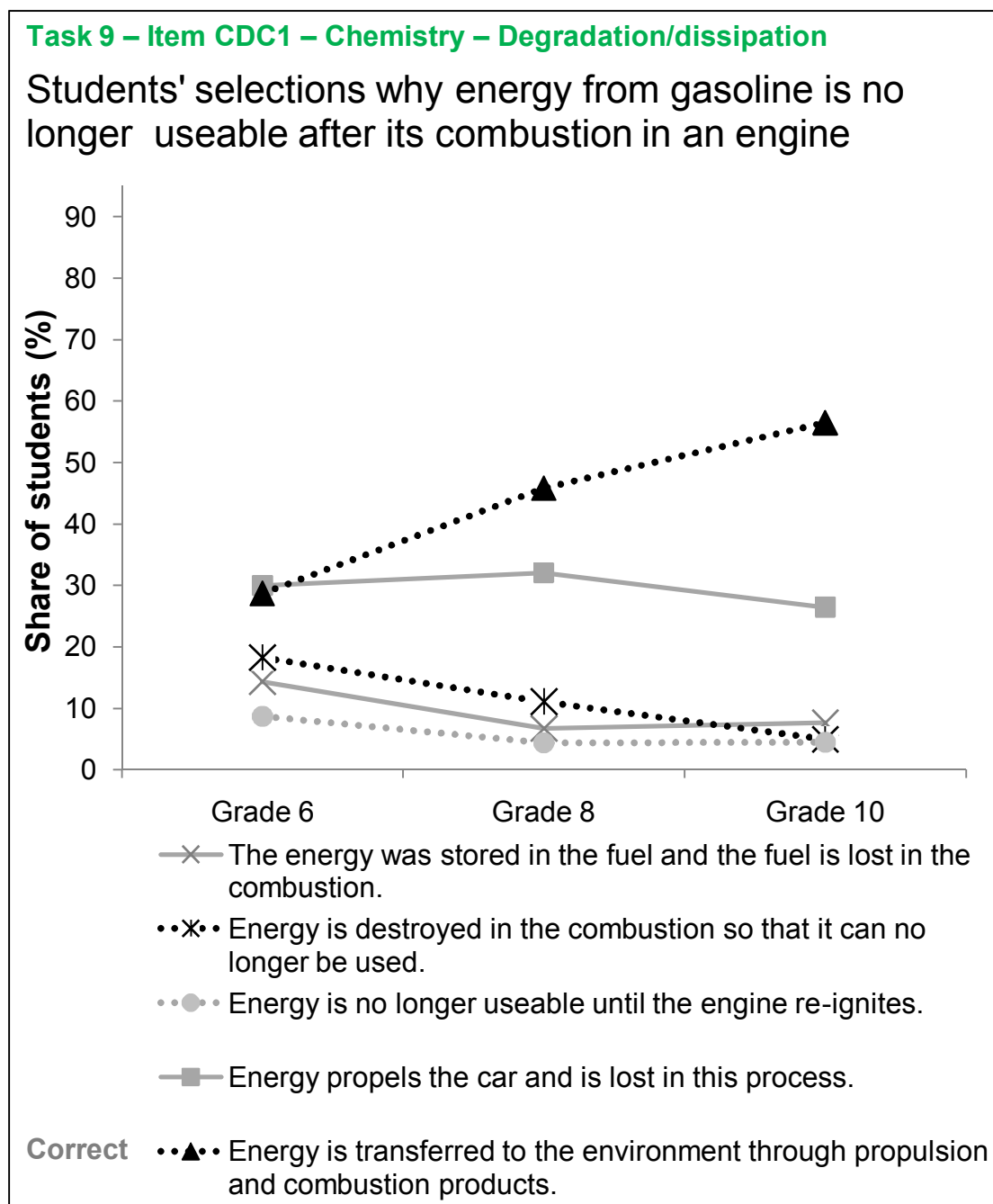
**1 answer is correct!**

- Energy was stored in the gasoline which no longer exists after combustion.
- The energy is destroyed in the combustion. Therefore, it cannot be used any longer.
- The engine has to ignite again. Otherwise the energy cannot be used.
- The energy has propelled the car and was lost in the process.
- Energy is released into the environment through the propulsion and through combustion products. Therefore, it can no longer be used.

**Item parameters for item CDC1**

	Grade 6	Grade 8	Grade 10
<b>Item difficulty (solution <math>p</math>)</b>	0.26	0.43	0.55
<b>Item discrimination</b>	0.07	0.24	0.31

**Distractor/attractor analysis**





**Discipline:** biology – **Energy aspect:** conservation – **Cognitive complexity:** facts

**Correct solution:** 1 & 4

Task 10

Item 413\_1



A young wolf takes up energy with its food. He transforms this energy in his body.

Select the energy forms in which you can rediscover the energy after the transformation!

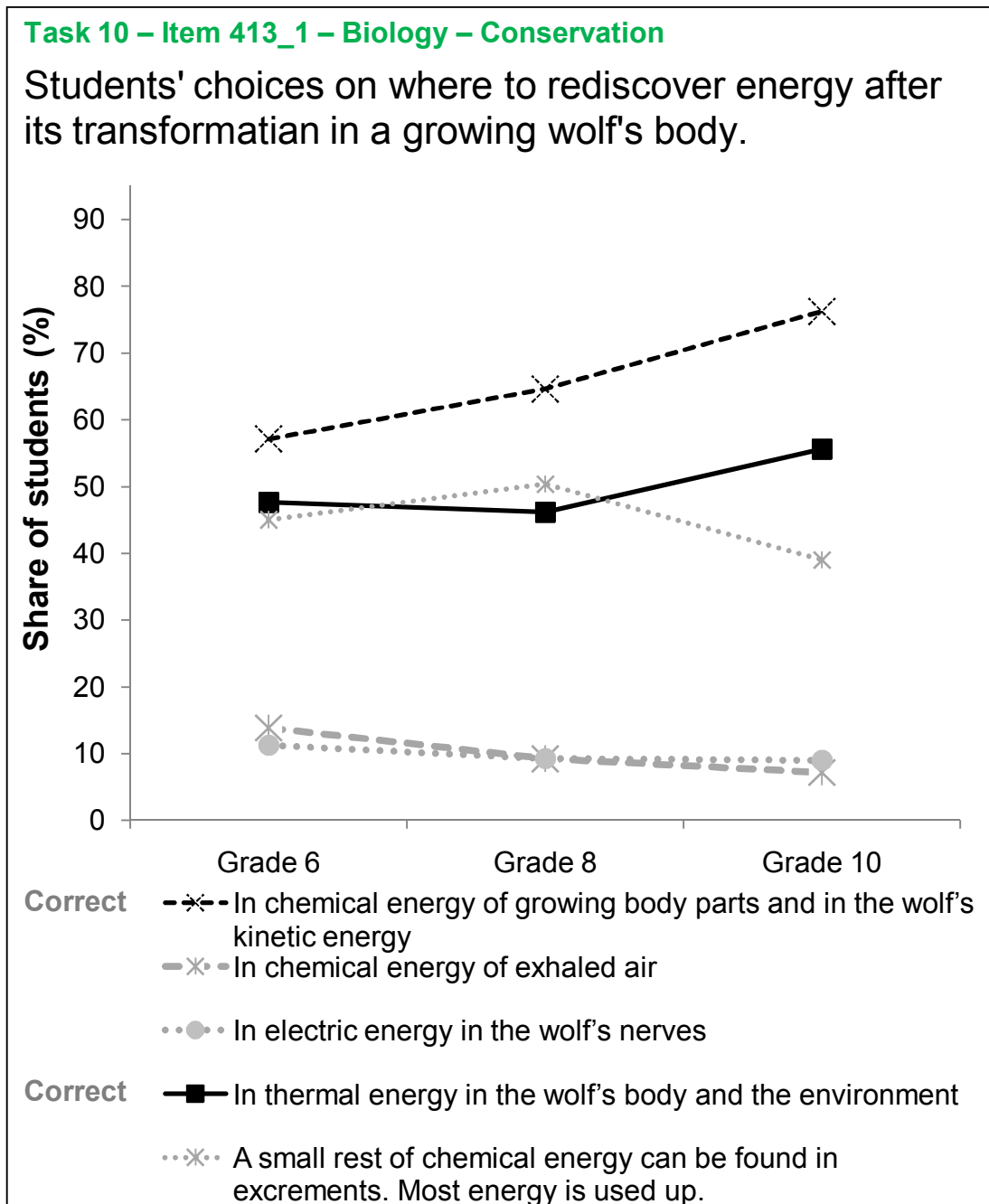
**2 answers**  
are correct!

- In chemical energy of growing body parts and in the wolf's kinetic energy
- In chemical energy of exhaled air
- In electric energy in the wolf's nerves
- In thermal energy of the wolf's body and the environment
- Only a small residue of chemical energy can be found in the wolf's excrements. Most of the energy is used up by the wolf.

**Item parameters for item 413\_1**

	Grade 6	Grade 8	Grade 10
<b>Item difficulty (solution <math>p</math>)</b>	0.20	0.25	0.43
<b>Item discrimination</b>	0.08	0.31	0.22

**Distractor/attractor analysis**



**Discipline:** physics – **Energy aspect:** conservation – **Cognitive complexity:** facts

**Correct solution:** 1

## Task 11

Item CF2

A tennis ball is dropped from a specific height. It falls down, hits the ground, is compressed, relaxes and gains height again. However, this height is lower than the original height that it had been released from.

Does energy conservation apply in this process?

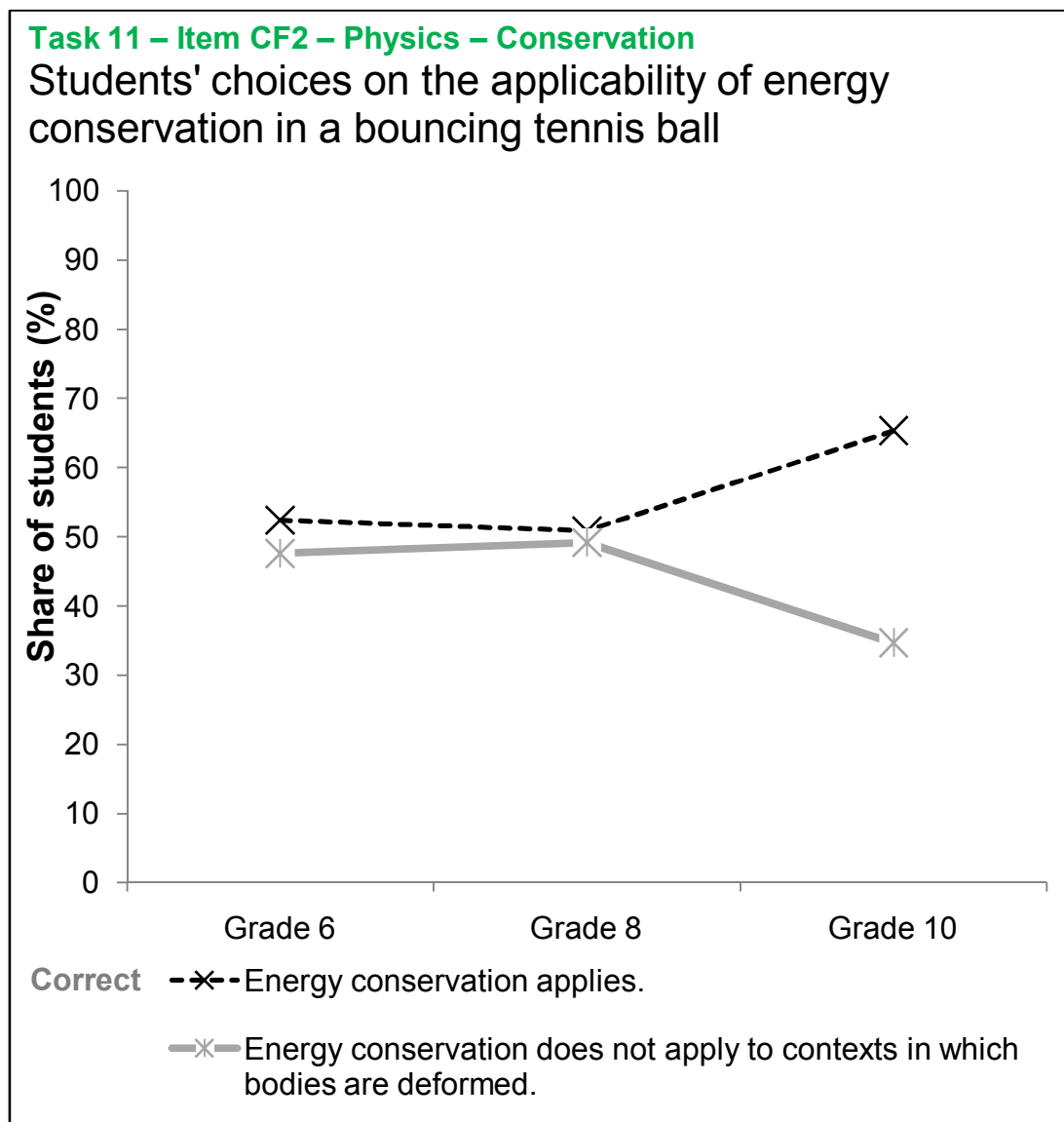
**1 answer is correct!**

- Yes, the law of energy conservation applies.
- No, the law of energy conservation does not apply to processes in which bodies are deformed.

**Item parameters for item CF2**

	Grade 6	Grade 8	Grade 10
<b>Item difficulty (solution <math>p</math>)</b>	0.47	0.45	0.57
<b>Item discrimination</b>	0.05	0.08	0.11

**Distractor/attractor analysis**



**Discipline:** chemistry – **Energy aspect:** conservation – **Cognitive complexity:** relations

**Correct solution:** 4

Task 12

Item CCR1

A campfire needs to be lit in order to burn.

What is the energy balance of the campfire and its environment?

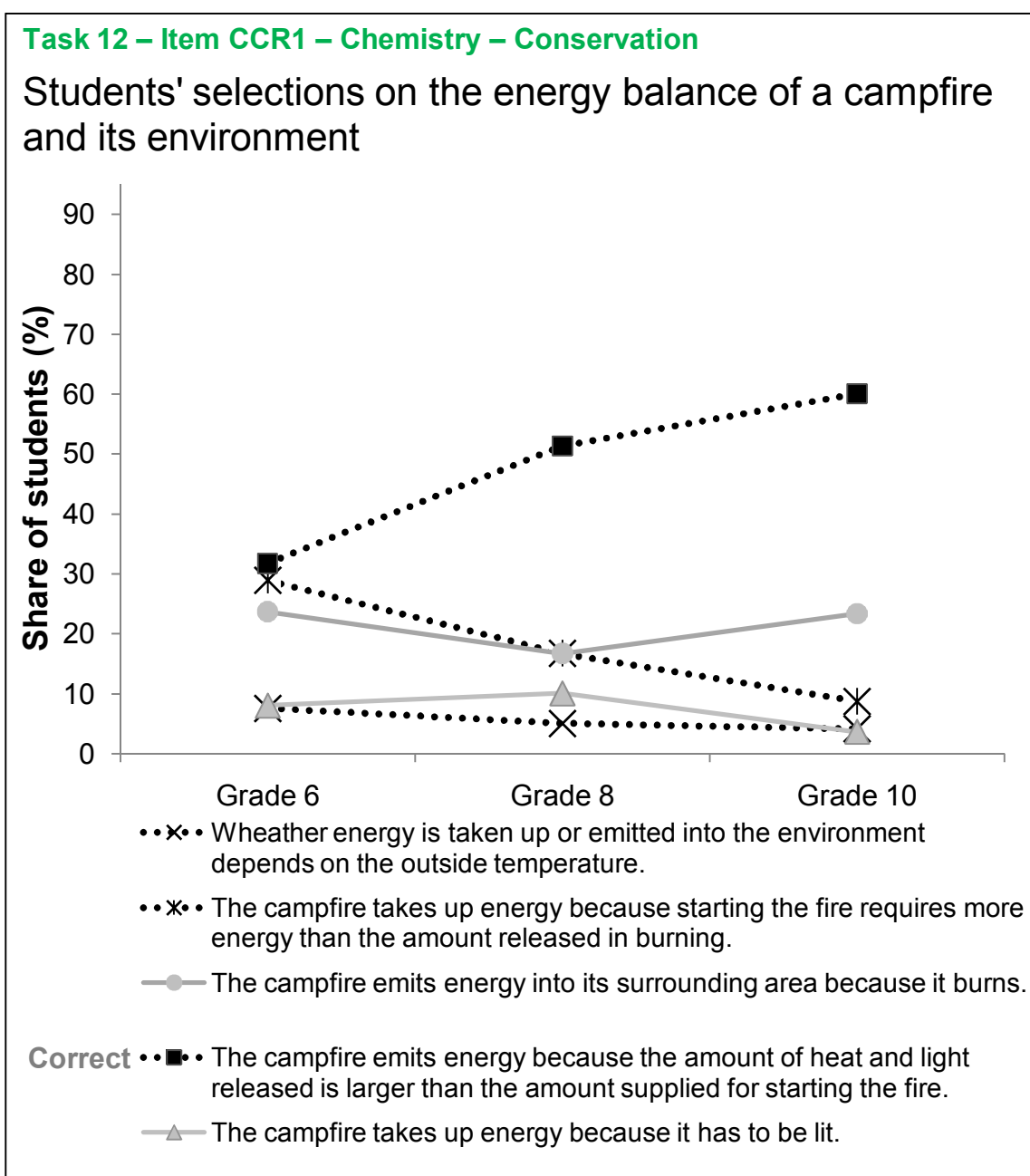
**1 answer is correct!**

- Whether energy is taken up or released into the environment depends on the temperature of the environment.
- The campfire takes up energy because starting the fire requires more energy than the amount of energy released during burning.
- The campfire releases energy into the environment because it burns.
- The campfire releases energy into the environment because the amount of heat and light released is larger than the amount supplied for starting the fire.
- The camp fire takes up energy because it has to be ignited.

**Item parameters for item CCR1**

	Grade 6	Grade 8	Grade 10
<b>Item difficulty (solution <math>p</math>)</b>	0.26	0.49	0.57
<b>Item discrimination</b>	0.20	0.42	0.22

**Distractor/attractor analysis**

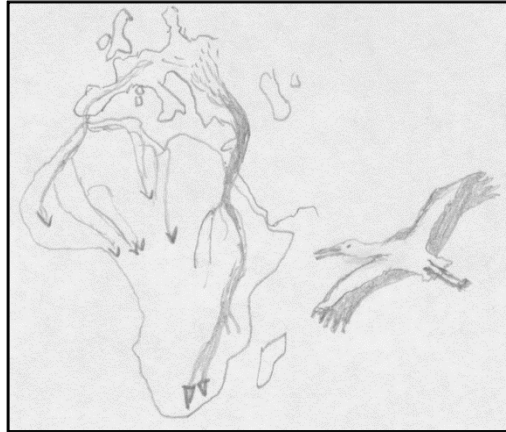


**Discipline:** biology – **Energy aspect:** forms/sources – **Cognitive complexity:** facts

**Correct solutions:** 1 & 5

Task 13

Item 113\_2



As food becomes scarce during the European autumn, storks fly to warmer regions in Africa.

Select the factors that are primarily important for the amount of energy that a stork requires for the flight!

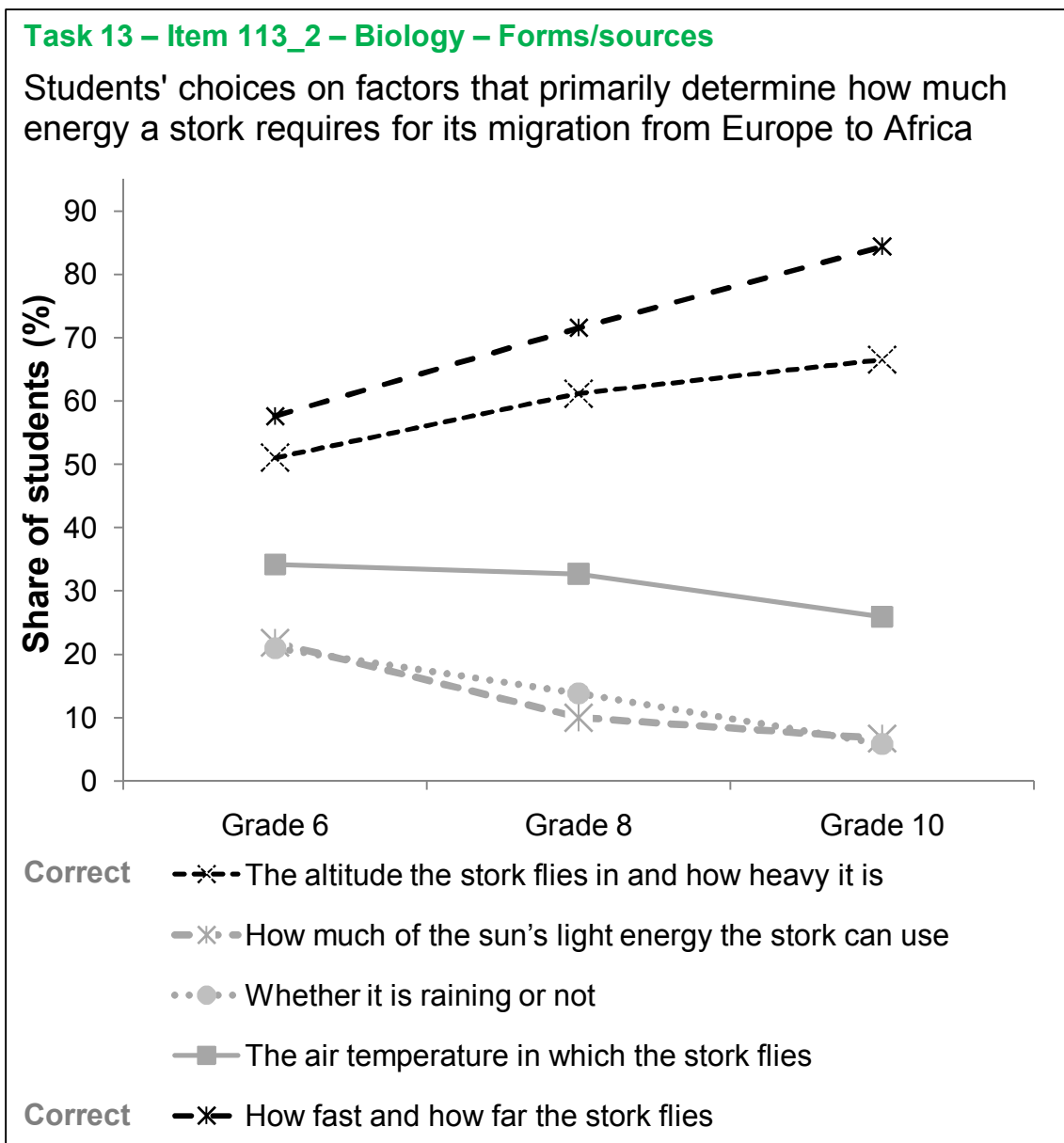
**2 answers**  
are correct!

- The altitude the stork flies in and how heavy it is
- How much of the sun's light energy the stork can use
- Whether it is raining or not
- The air temperature in which the stork flies
- How fast and how far the stork flies

**Item parameters for item 113\_2**

	Grade 6	Grade 8	Grade 10
<b>Item difficulty (solution <i>p</i>)</b>	0.27	0.40	0.55
<b>Item discrimination</b>	0.13	0.17	0.10

**Distractor/attractor analysis**





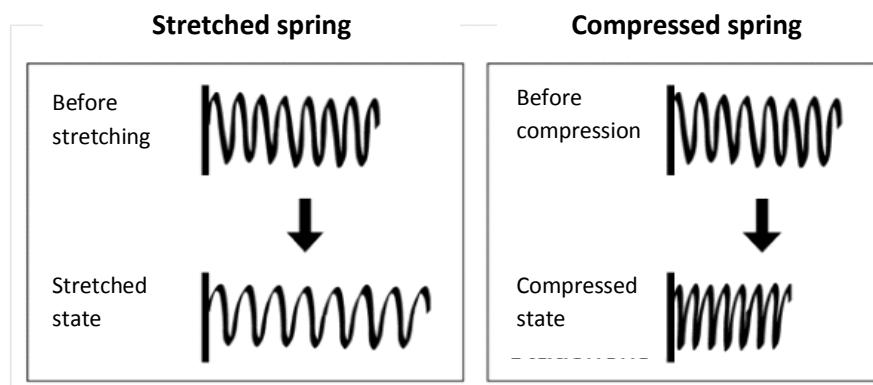
**Discipline:** physics – **Energy aspect:** forms/sources – **Cognitive complexity:** mappings

**Correct solution:** 3

Task 14

Item FM3

A pupil has two identical springs. She stretches one spring and compresses the other.



Which of the following statements correctly describe the elastic potential energy in both springs?

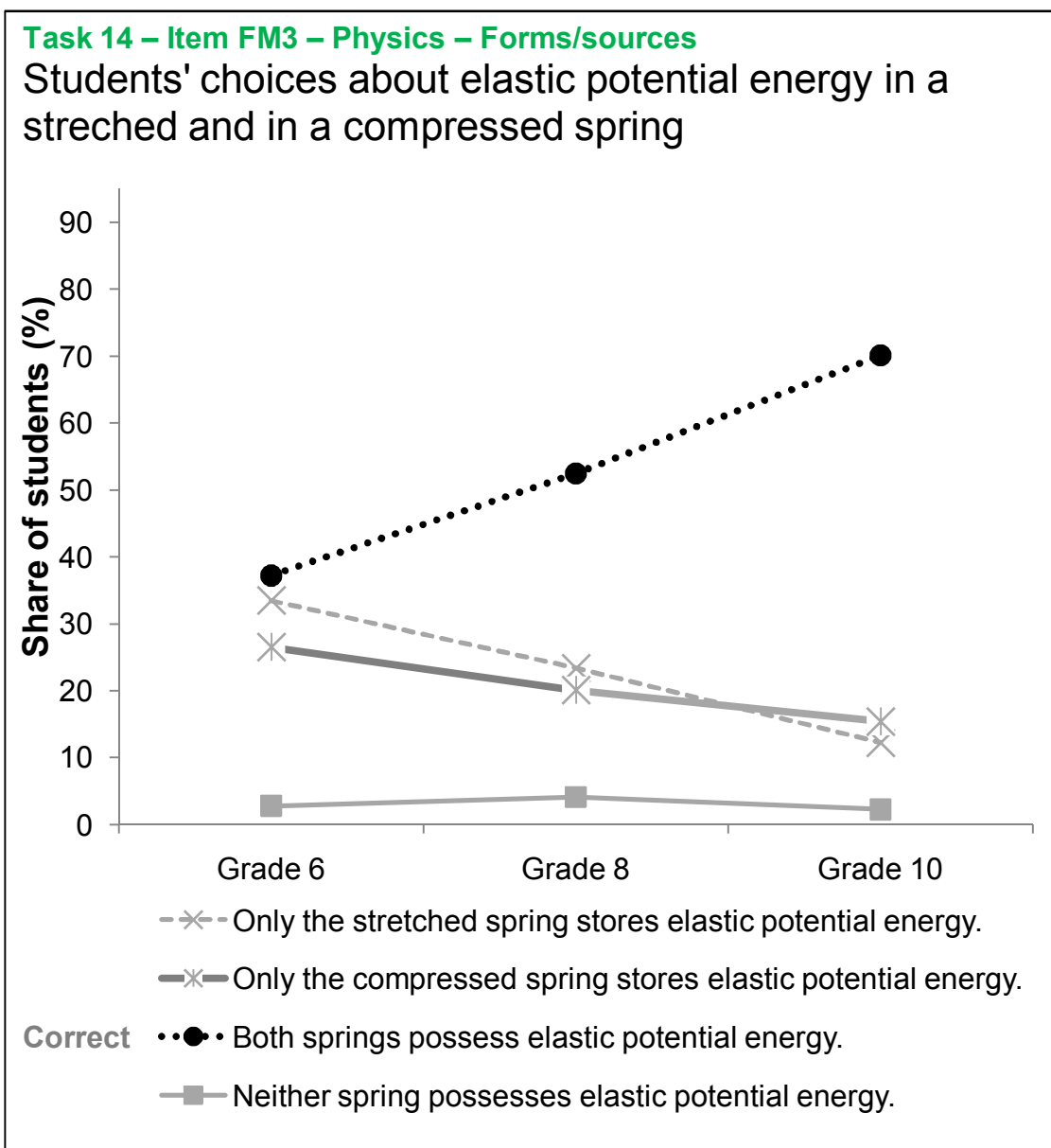
**1 answer is correct!**

- The stretched spring stores elastic potential energy, the compressed one does not.
- The compressed spring stores elastic potential energy, the stretched one does not.
- Both the compressed and the stretched spring possess elastic potential energy.
- Neither the compressed nor the stretched spring possesses elastic potential energy.

**Item parameters for item FM3**

	Grade 6	Grade 8	Grade 10
<b>Item difficulty (solution <math>p</math>)</b>	0.31	0.48	0.68
<b>Item discrimination</b>	0.22	0.31	0.23

**Distractor/attractor analysis**



Attachments  
Attachment B: Online Materials for Chapter 3/Study 2

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THIS IS ONE OF FIVE ITEMS EXCLUDED THROUGH AN INTERRATING FOR BEING DISCIPLINE-UNSPECIFIC ( $k = .81$  for the remaining 43 items – This item: 33% agreement on the intended discipline [chemistry])

**Discipline:** chemistry – **Energy aspect:** forms / sources – **Cognitive complexity:** facts

**Correct solution:** 2

Task 15

Item CFF2

Every day, energy surrounds us in various forms.

Which of the following statements is correct?

1 answer is correct!

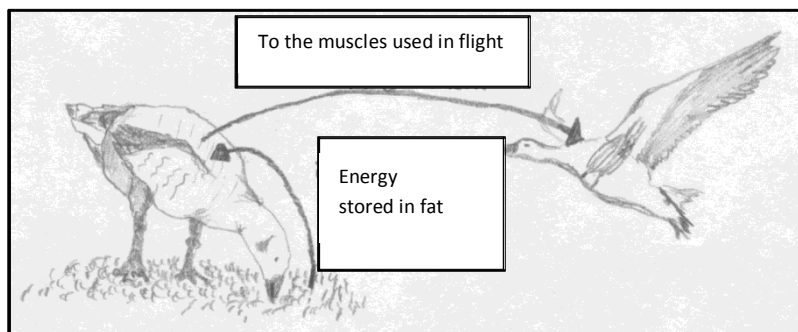
- Fire is a form of energy.
- Electric energy is a form of energy.
- Foods like bread or cheese are a form of energy.
- Fossil oil is a form of energy.
- The sun is a form of energy.

**Discipline:** biology – **Energy aspect:** transfer/transformation – **Cognitive complexity:** mappings

**Correct solutions:** (1) 1/1; (2) 2/2; (3) 3/2

**Task 16**

Item 223\_1



Before they go on their annual migration, birds put on a lot of weight and thereby store a lot of energy in fat stores. To generate movement, energy is passed on from the fat store to the muscles.

For the following three steps, select ...

(A) which pair of energy forms is involved, and ...

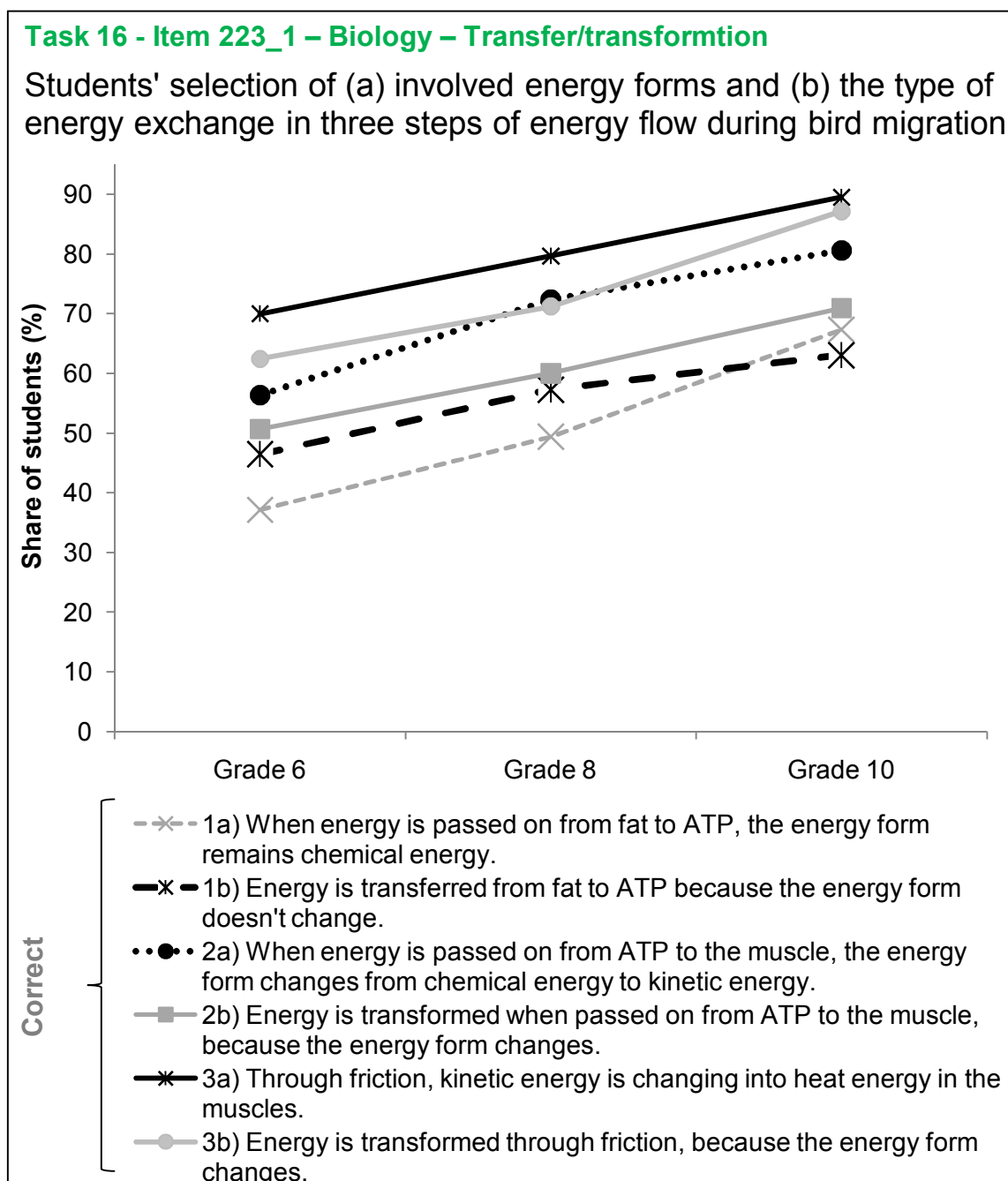
(B) how the energy is passed on!

	(A) Pair of energy forms			(B) How energy is passed on.	
	Chemical energy → chemical energy	Chemical energy → kinetic energy	Kinetic energy → thermal energy	Transfer, because the energy form stays the same	Transformation, because the energy form changes.
<div style="border: 1px solid black; padding: 5px; width: fit-content; margin: auto;">                     For each of the steps, tick <b>one box for (A)</b> AND <b>one box for B.</b> </div>					
<b>Steps</b>					
(1) Chemical energy from the fat store is transported to the muscle and then handed over to the body's energy currency.					
(2) The 'energy currency' causes the muscle to contract. Thereby, the muscle moves.					
(3) The movement also causes friction. Therefore, energy is also passed on as heat.					

**Item parameters for item 223\_1**

	Grade 6	Grade 8	Grade 10
<b>Item difficulty (solution <math>p</math>)</b>	0.03	0.22	0.43
<b>Item discrimination</b>	0.10	0.37	0.48

**Distractor/attractor analysis** (for readability, only correct answers are shown)



**Discipline:** physics – **Energy aspect:** transfer/transformation – **Cognitive complexity:** facts

**Correct solution:** 1

Task 17

Item TF2

Imagine a bouncing rubber ball.

What can be said about the energy of the bouncing rubber ball?

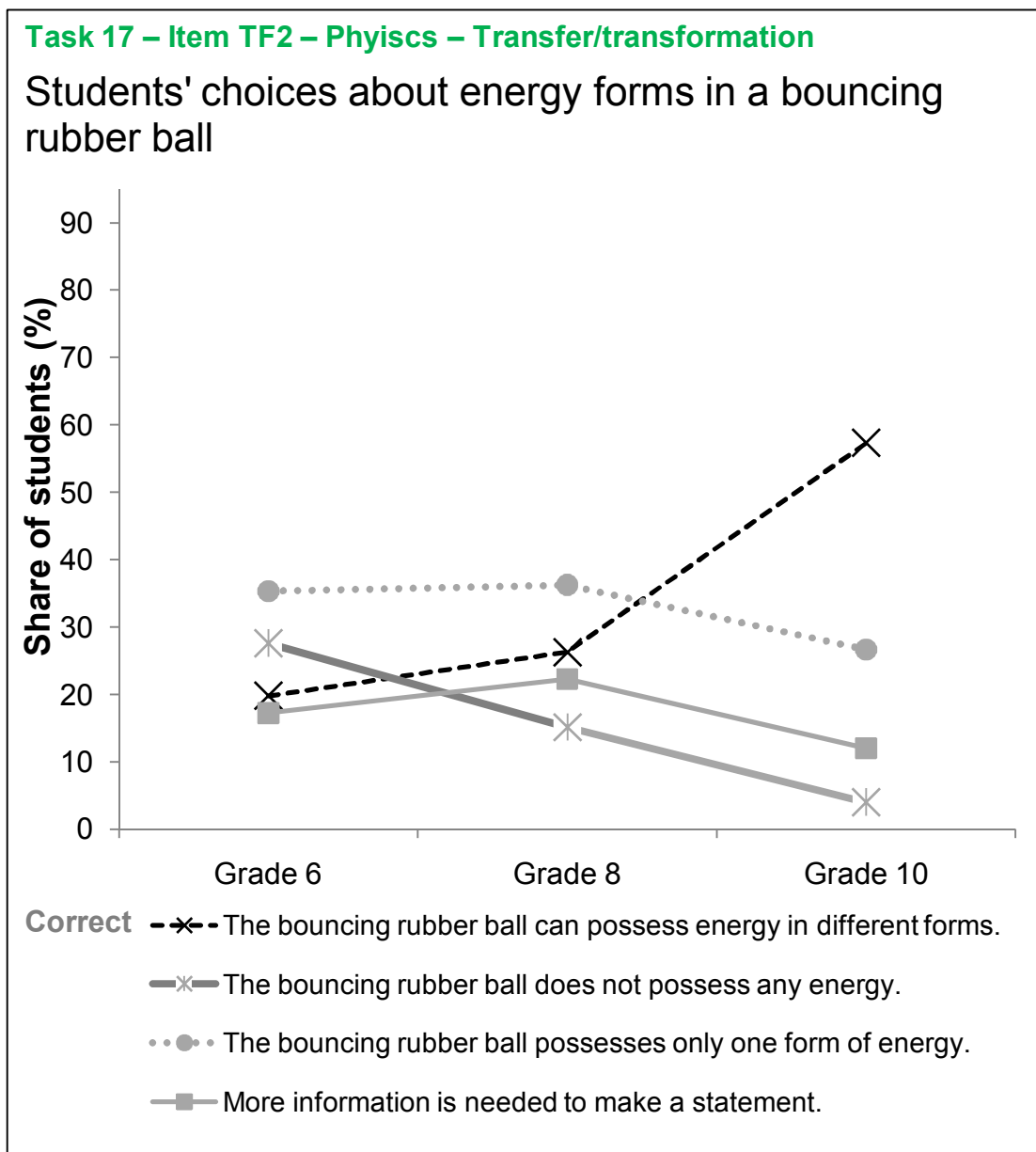
**1 answer  
correct!**

- The bouncing rubber ball can possess energy in different forms.
- The bouncing rubber ball does not possess any energy.
- The bouncing rubber ball possesses only one form of energy.
- More information is needed to make a statement.

**Item parameters for item TF2**

	Grade 6	Grade 8	Grade 10
<b>Item difficulty (solution <math>p</math>)</b>	0.18	0.25	0.56
<b>Item discrimination</b>	0.15	0.20	0.35

**Distractor/attractor analysis**



**Discipline:** chemistry – **Energy aspect:** transfer/transformation –  
**Cognitive complexity:** concepts

**Correct solutions:** 2

Task 18

Item CTC2



When you hurt yourself during sports, a 'cool pack' is often provided to treat the first pain. In the opposite case, you can use a 'hot pack' if you have cold hands. Both packages contain salts and solvents.

Is it possible that similar processes can result, at one point, in heating, while, in other cases, in cooling?

**1 answer is correct!**

- Yes, it depends on how the substances in the packages are brought together.
- Yes, it depends on the number of bonds broken and formed in the salt and in the solvent.
- No, that is impossible. When heating, salt and solvent react with each other, whereas during cooling, the salt merely dissolves.
- No, that is impossible. Energy always has to be supplied for solution processes, as bonds in the salt have to be broken down.
- No, that is impossible. Energy is always released in solution processes, because the breaking of bonds in the salt releases energy.



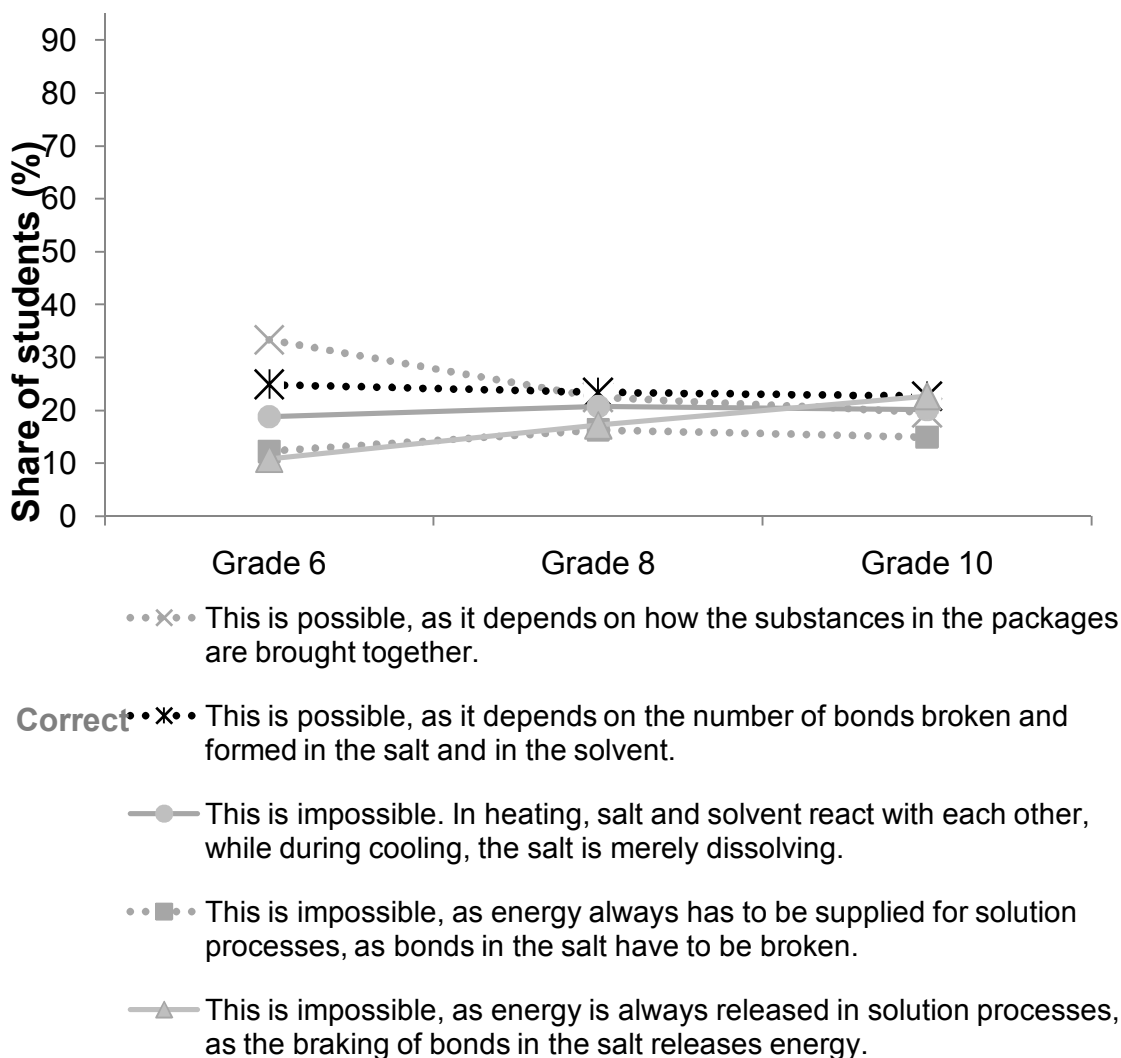
**Item parameters for item CTC2**

	Grade 6	Grade 8	Grade 10
<b>Item difficulty (solution <math>p</math>)</b>	0.21	0.20	0.19
<b>Item discrimination</b>	0.01	0.09	0.05

**Distractor/attractor analysis**

**Task 18 – Item CTC2 – Chemistry – Transfer/transformation**

Students' choices concerning the possibility of both heating and cooling effects through similar reactions

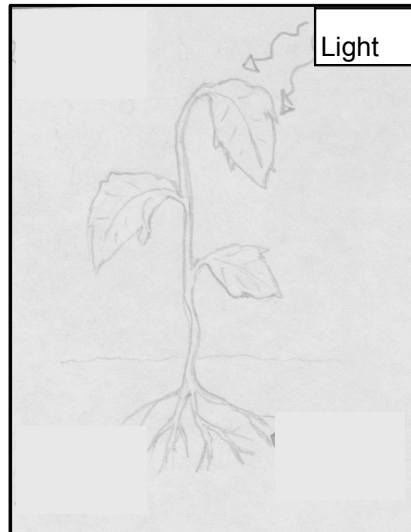


**Discipline:** biology – **Energy aspect:** degradation/dissipation – **Cognitive complexity:** mappings

**Correct solutions:** 1 & 2

Task 19

Item 322\_2



With the help of light energy, a plant produces sugar (chemical energy) from carbon dioxide (CO<sub>2</sub>) in the air. The plant uses the sugar for growth. During that process, energy is 'degraded'.

Select the correct meaning of 'energy degradation' in this process!

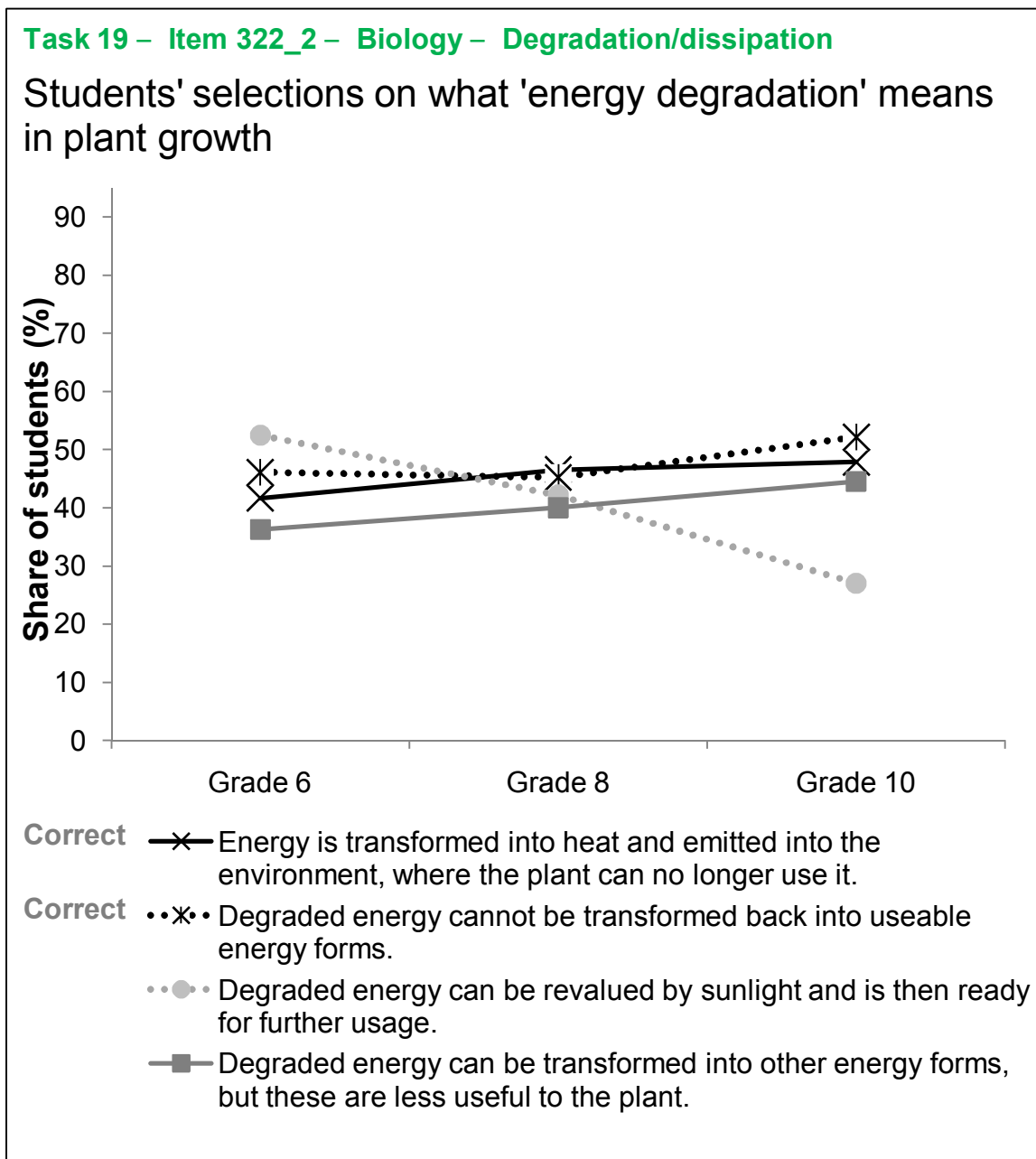
**2 answers** are correct!

- Energy is also transformed into heat, which is released into the environment. The plant can no longer use this heat for further energy transformations.
- Degraded energy (heat) cannot be transformed back into usable energy forms (e.g. chemical energy).
- Degraded energy (heat) can be 're-valued' by more light energy from the sun. It is then once again useable energy.
- Degraded energy (e.g. heat) can be transformed into other energy forms. However, these energy forms have a lower value for the plant.

**Item parameters for item 322\_2**

	Grade 6	Grade 8	Grade 10
<b>Item difficulty (solution <math>p</math>)</b>	0.13	0.15	0.22
<b>Item discrimination</b>	0.21	0.18	0.26

**Distractor/attractor analysis**



Attachments  
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THIS IS ONE OF FIVE ITEMS EXCLUDED THROUGH AN INTERRATING FOR BEING DISCIPLINE-UNSPECIFIC ( $k = .81$  for the remaining 43 items – This item: 8% agreement on the intended discipline [physics])

**Discipline:** physics – **Energy aspect:** degradation / dissipation –

**Cognitive complexity:** relations

**Correct solution:** 4

Task 20

Item DR2

Max and Moritz ride a toboggan run. Whereas Max is braking the whole time, Moritz only brakes once just before the finish.

Who will reach the finish line first, if both kids have the same weight?

1 answer is correct!

- Both will reach it at the same time because both have the same potential energy at the beginning, which is then transformed into kinetic energy.
- Max will reach the finish line faster because his constant braking allows him to drive more skillfully.
- Moritz will reach the finish line first because his entire potential energy is transformed into kinetic energy.
- Moritz will reach the finish line first because the largest part of his kinetic energy is transformed into thermal energy only just before the finish line.

**Discipline:** chemistry – **Energy aspect:** degradation/dissipation –  
**Cognitive complexity:** relations

**Correct solution:** 3

Task 21

Item CDR1

Chemical reactions have an energy turnover.

Which factors influence the scale of the energy turnover?

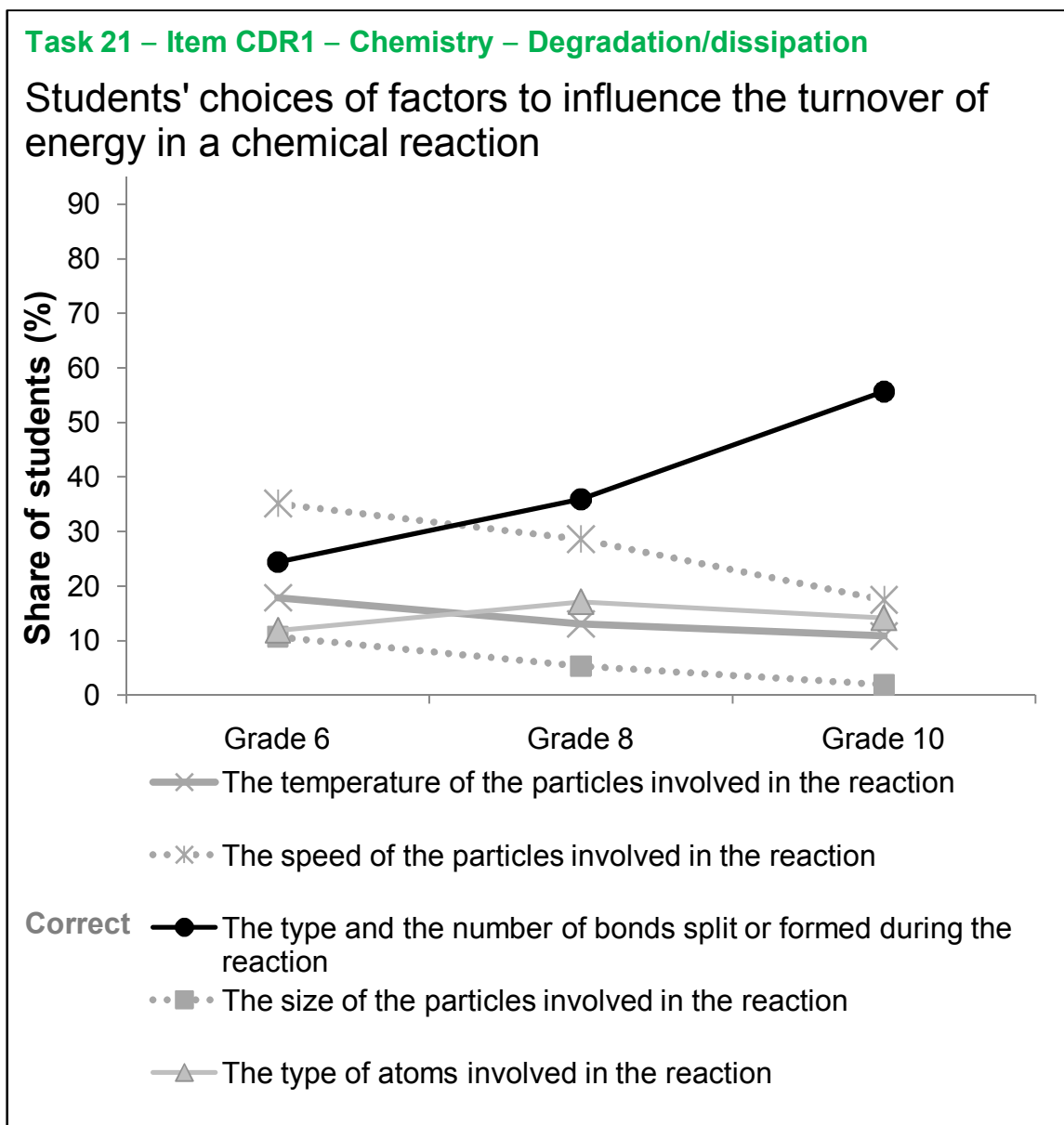
**1 answer is  
correct!**

- The temperature of the particles involved in the reaction
- The speed of the particles involved in the reaction
- The type and the number of bonds split or formed during the reaction
- The size of the particles involved in the reaction
- The type of atoms involved in the reaction

**Item parameters for item CDR1**

	Grade 6	Grade 8	Grade 10
<b>Item difficulty (solution <math>p</math>)</b>	0.16	0.33	0.52
<b>Item discrimination</b>	0.16	0.16	0.23

**Distractor/attractor analysis**

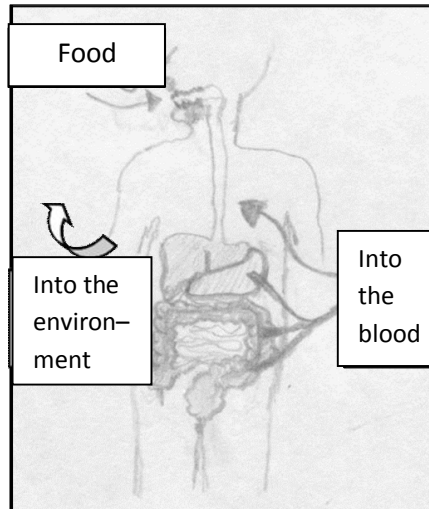


**Discipline:** biology – **Energy aspect:** conservation – **Cognitive complexity:** mappings

**Correct solutions:** (A) 1 – 1 – 2; (B) 3

Task 22

Item 421\_1



A person takes up energy from the environment and transforms it in the body. A part of the energy is released back into the environment, another part remains in the body.

**(A)** In the following three steps, select if the energy is taken up by the body/stored in it, OR, if it's released back into the environment.

In part (A), chose <b>one option for each of the three cases</b> . In part (B), chose <b>one option</b> .	Energy <b>taken up/stored</b> in the body	Energy <b>released</b> by the body into the environment
1) Chemical energy from food	<input type="radio"/>	<input type="radio"/>
2) Chemical energy in growing body parts	<input type="radio"/>	<input type="radio"/>
3) Energy transformed into heat in the body	<input type="radio"/>	<input type="radio"/>

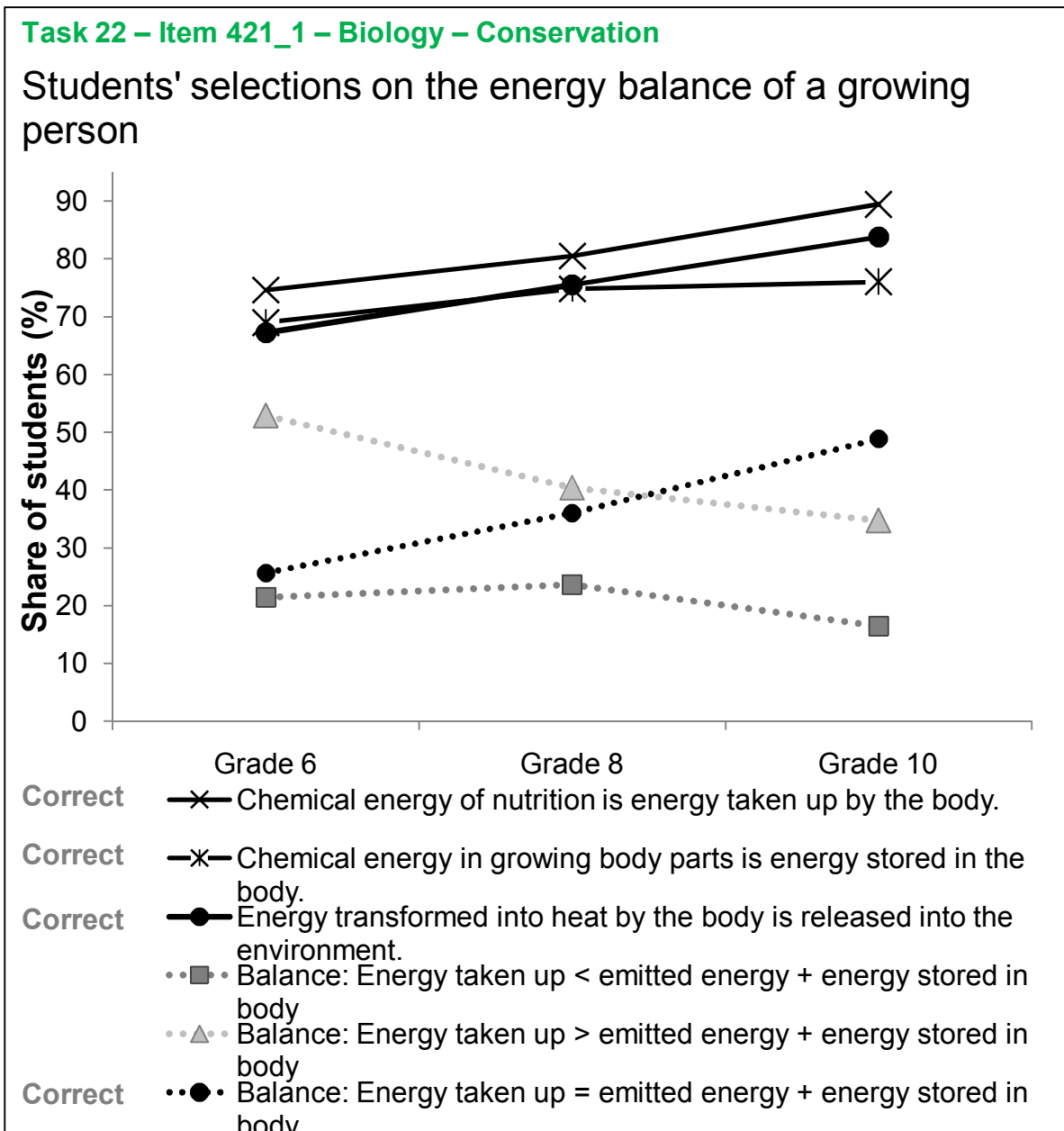
**(B)** Select the correct relation of the given amounts of energy.

The amount of <b>energy taken up</b> is ...	<input type="radio"/> ... <b>smaller than</b> ... <input type="radio"/> ... <b>larger than</b> ... <input type="radio"/> ... <b>equal to</b> ...	... the amount of <b>energy released</b> into the environment <b>AND</b> the <b>energy stored</b> in the body.
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**Item parameters for item 421\_1**

	Grade 6	Grade 8	Grade 10
<b>Item difficulty (solution <math>p</math>)</b>	0.07	0.20	0.33
<b>Item discrimination</b>	0.13	0.39	0.41

**Distractor/attractor analysis** (For readability, only correct answers are shown for part A of the items)





**Discipline:** physics – **Energy aspect:** conservation – **Cognitive complexity:** relations

**Correct solution:** 4

Task 23

Item CR3

A pupil uses a slingshot to shot a chestnut across the classroom.

What can be said for total energy of the classroom, including the pupil, the slingshot and the chestnut?

**1 answer is correct!**

- The total energy increases because the chestnut's kinetic energy and the environment's thermal energy increase. The stored potential energy of the rubber band remains constant.
- The total energy increases because the chestnut's increased kinetic energy plus the thermal energy released into the environment is larger than the decrease in the rubber band's elastic potential energy.
- The total energy decreases because the chestnut's increased kinetic energy plus the thermal energy released into the environment is smaller than the decrease in the rubber band's elastic potential energy.
- The total energy remains the same because the chestnut's increased kinetic energy plus the thermal energy released into the environment equals the decrease in the rubber band's elastic potential energy.

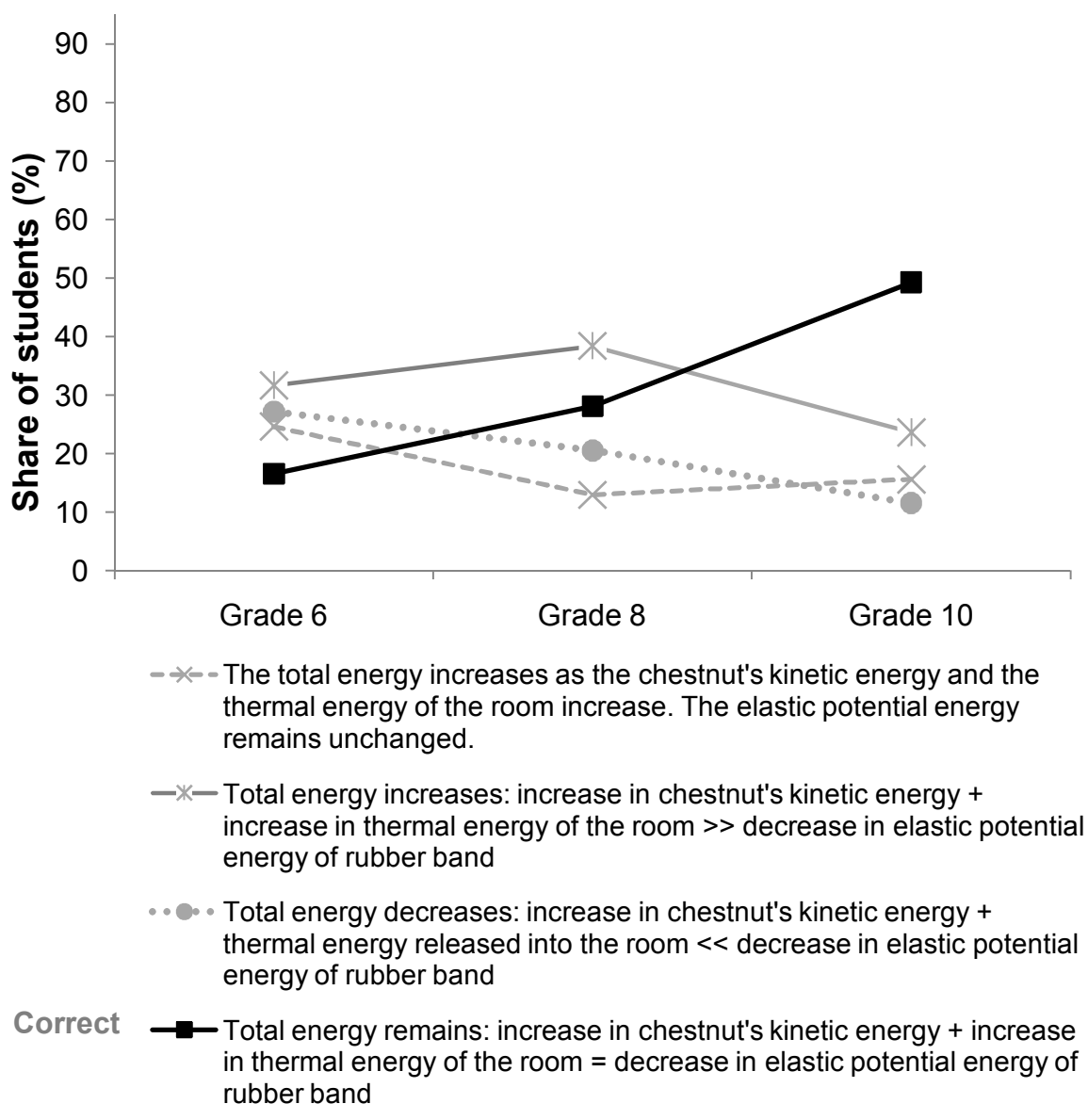
**Item parameters for item CR3**

	Grade 6	Grade 8	Grade 10
<b>Item difficulty (solution <math>p</math>)</b>	0.13	0.24	0.43
<b>Item discrimination</b>	0.18	0.34	0.45

**Distractor/attractor analysis**

**Task 23 – Item CR3 – Physics – Conservation**

Students' selection about the total energy of a classroom, in which a slingshot was used to shoot a chestnut



**Discipline:** chemistry – **Energy aspect:** conservation – **Cognitive complexity:** mappings

**Correct solution:** 4

Task 24

Item CCM1

Chemists explain large parts of the energy balance in chemical reactions through the breaking and forming of chemical bonds, as well as through interactions.

Which of the following statements is correct?

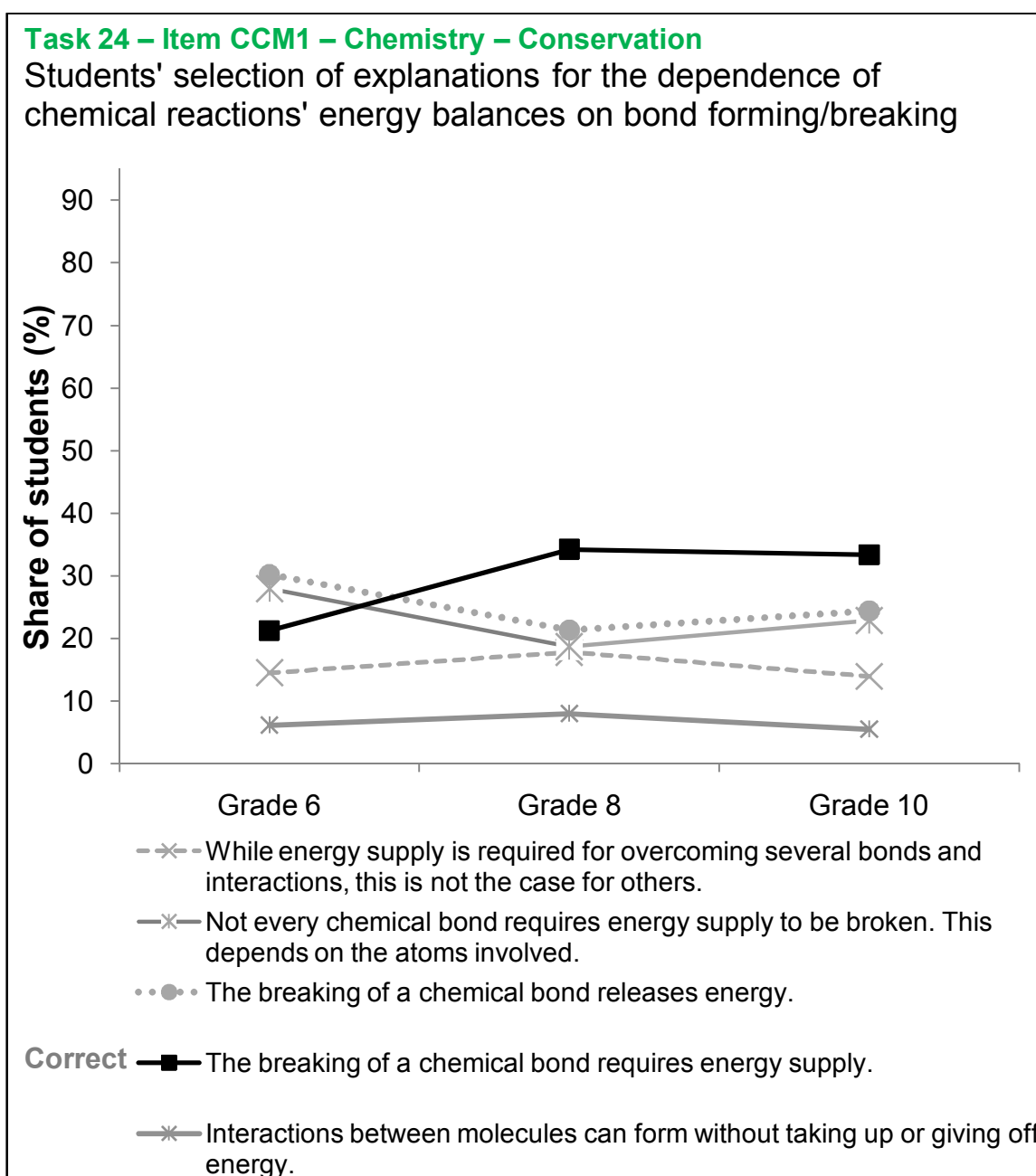
**1 answer is correct!**

- While energy supply is required for overcoming several bonds and interactions, this is not generally valid for all such cases.
- Not every chemical bond requires energy supply to be broken. This depends on the atoms involved.
- The breaking of a chemical bond releases energy.
- The breaking of a chemical bond requires energy supply.
- Interactions between molecules can form without taking up or emitting energy.

**Item parameters for item CCM1**

	Grade 6	Grade 8	Grade 10
<b>Item difficulty (solution <math>p</math>)</b>	0.15	0.29	0.29
<b>Item discrimination</b>	0.16	0.21	0.16

**Distractor/attractor analysis**

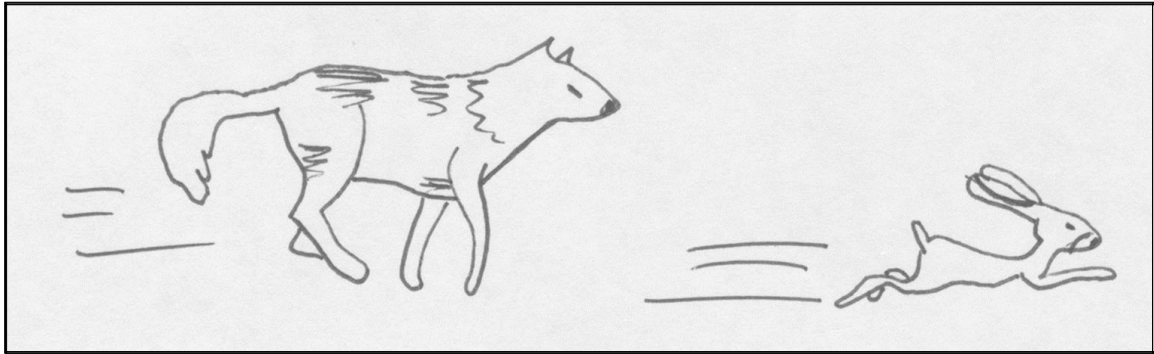


**Discipline:** biology – **Energy aspect:** facts/sources – **Cognitive complexity:** relations

**Correct solutions:** 2 & 3

Task 25

Item 133\_1



Two wolves hunt. Wolf number 1 is hunting in northern Canada, where it's very cold. After 10 hours of hunting, he catches one fat hare. Wolf 2 is hunting for one hour in a summer forest and catches a little partridge.

Select the options that correctly identify what the energy in the wolves' bodies is related to.

**2 answers**  
are correct !

- It is important how much chemical energy from food is stored in the wolf's body. The body does not possess chemical energy without food.
- The chemical energy in the wolf depends on the nature and extent of the stores of chemical energy (fats, sugar, proteins) in foods that are taken up by the wolf with the food.
- The chemical energy in the animals depends on how much chemical energy they give off through excrements and how much energy is transformed in body functions (e.g. movement, body heat) during the hunt.
- It is important how much chemical energy is stored in the digestive tract and in the muscles. There are no stores of energy in other body parts. Therefore, there is substantially more energy stored in wolf 1 than in wolf 2.

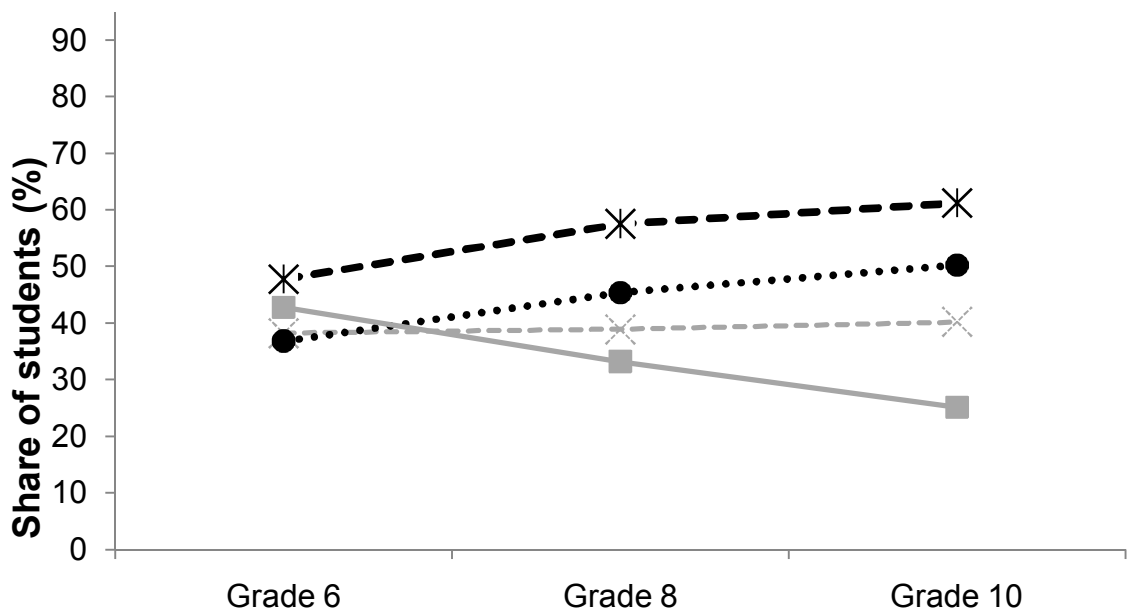
**Item parameters for item 133\_1**

	Grade 6	Grade 8	Grade 10
<b>Item difficulty (solution <math>p</math>)</b>	0.09	0.18	0.24
<b>Item discrimination</b>	- 0.01	0.13	0.20

**Distractor/attractor analysis**

**Task 25 - Item 133\_1 - Biology - Forms / sources**

Students' choices on the relation between chemical energy in the bodies of two hunting wolves, their activity during hunting and the energetic value of their prey



--\*-- It is primarily important, how much chemical energy from food is stored in the wolf's body.

**Correct** -\*• The chemical energy in the wolves depends on the nature and quantity of chemical energy in the prey.

**Correct** ••• The chemical energy in the animals depends on the excretion, as well as on the energy transformation in body functions (movement, body heat) during the hunt.

—■— The chemical energy stored in the digestive tract and in the muscles is important - no energy stores exist in other body parts. Therefore, there is more energy stored in wolf 1 than in wolf 2.

**Discipline:** physics – **Energy aspect:** forms/sources – **Cognitive complexity:** relations

**Correct solution:** 1

## Task 26

Item FR2

Two balls roll at the same speed. The kinetic energy of ball 1 is greater than the kinetic energy of ball 2.

How much is the weight of ball 1 in comparison to ball 2?

1 answer is  
correct!

- Ball 1 weighs more than ball 2 because the kinetic energy of ball 1 is greater.
- Ball 1 weighs less than ball 2. The mass of ball 1 has to be smaller to balance the fact that they roll with the same speed, while the kinetic energy of ball 1 is greater.
- Ball 1 weighs the same as ball 2 because they move at the same speed.
- You need more information to compare the objects' masses.

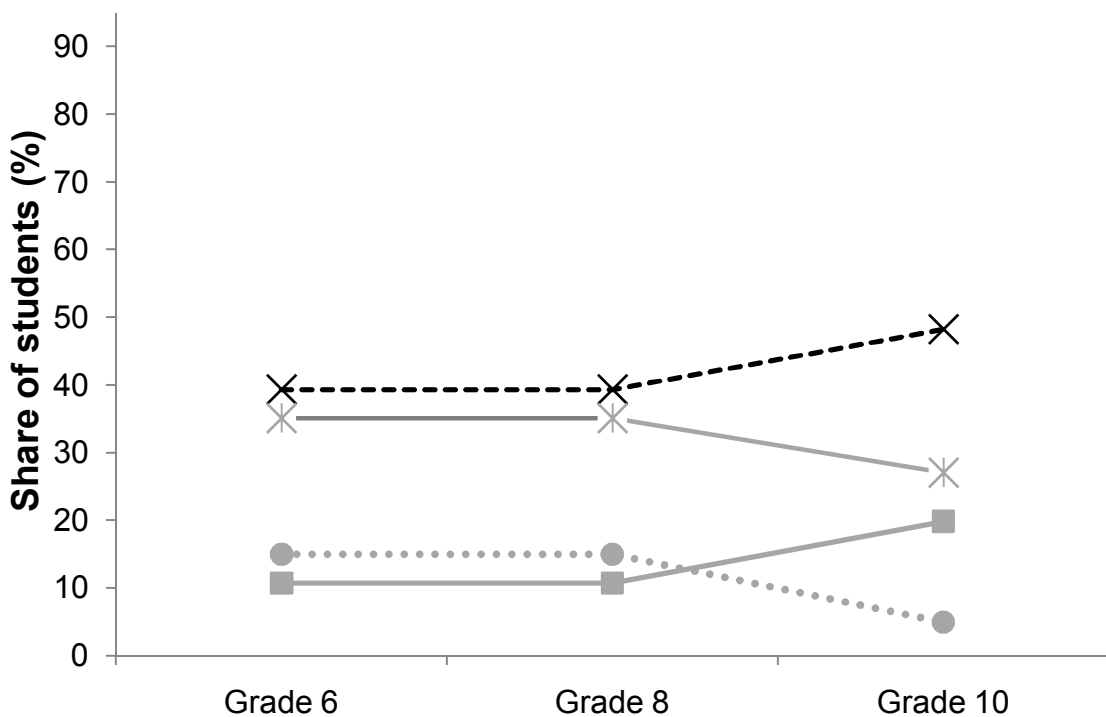
**Item parameters for item FR2**

	Grade 6	Grade 8	Grade 10
<b>Item difficulty (solution <math>p</math>)</b>	0.36	0.40	0.47
<b>Item discrimination</b>	-0.02	0.10	0.17

**Distractor/attractor analysis**

**Task 26 – Physics – Item FR2 – Forms/sources**

Students' selection of explanations for deriving the weight of two rolling balls with equal velocity but different kinetic energy



**Correct** - x - Ball 1 weighs more than ball 2 because the kinetic energy of ball 1 is greater.

- x - Ball 1 weighs less than ball 2. The mass of ball 1 has to be smaller to balance the fact that they roll with the same speed, while the kinetic energy of ball 1 is greater.

••• Ball 1 weighs the same as ball 2 because they move at the same speed.

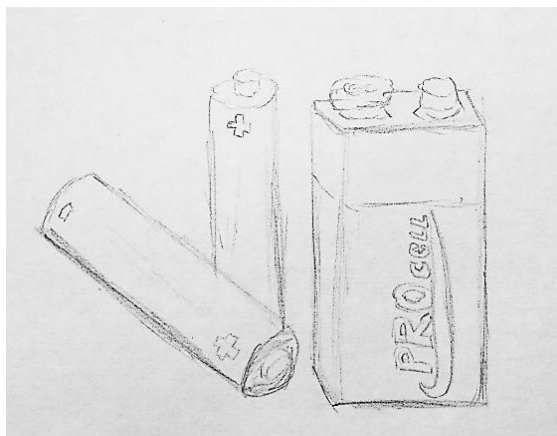


**Discipline:** chemistry – **Energy aspect:** forms/sources – **Cognitive complexity:** mappings

**Correct solution:** 4

Task 27

Item CFM2



It's hard to imagine a life without batteries. They enable us to use electric energy while still being mobile.

Which form of energy is stored in batteries?

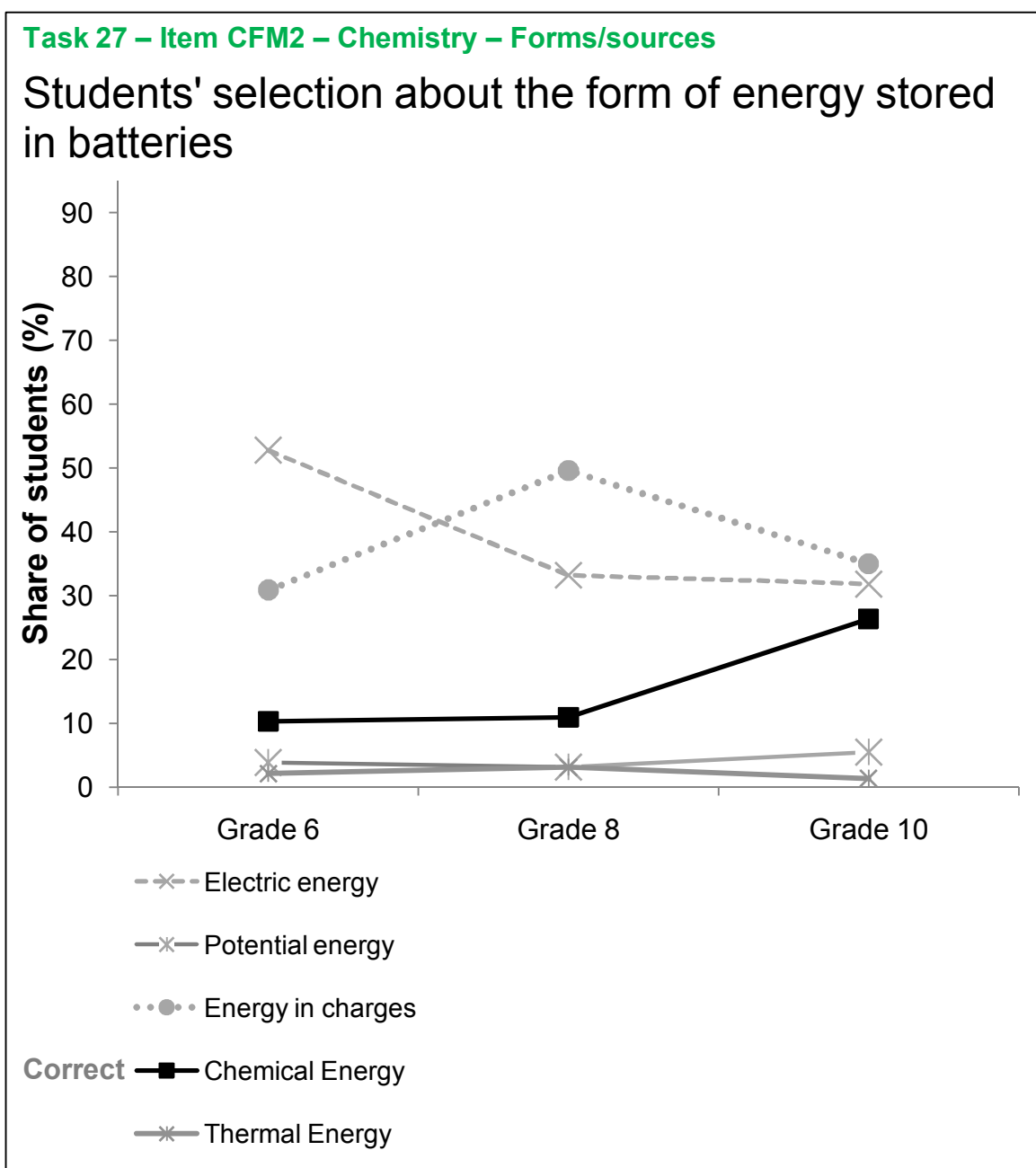
**1 answer is correct!**

- Batteries contain electric energy.
- Batteries contain potential energy.
- Batteries contain energy in charges.
- Batteries contain chemical energy.
- Batteries contain thermal energy.

**Item parameters for item CFM2**

	Grade 6	Grade 8	Grade 10
<b>Item difficulty (solution <math>p</math>)</b>	0.09	0.10	0.25
<b>Item discrimination</b>	0.22	0.14	0.43

**Distractor/attractor analysis**

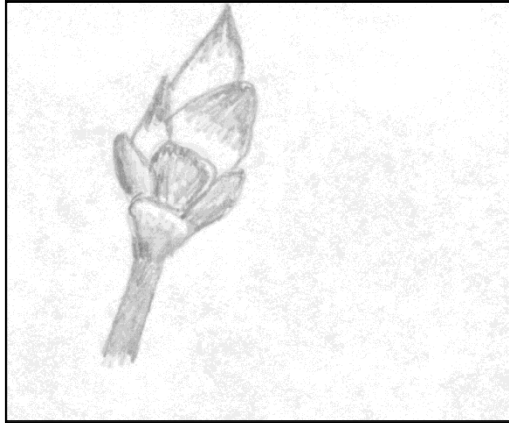


**Discipline:** biology – **Energy aspect:** transfer/transformation – **Cognitive complexity:** concepts

**Correct solutions:** 1 & 4

Task 28

Item 242\_2



Tree buds grow in spring. At this time, the tree does not yet have leaves. The energy needed for the growth therefore does *not* stem from leaves, which could transform energy from sunlight.

Select the statements that correctly describe from where and in what way energy is transferred to the growing tree buds.

**2 answers**  
are correct!

- Leaves are open systems and take up light energy from the sun. In this process, light energy is transformed into chemical energy and sugar is built up as an energy store from carbon dioxide (CO<sub>2</sub>) in the air. The sugar is stored during the winter and is transported to growing tree parts in spring.
- In the leaves, energy particles from the sun are transformed into the 'energy currency' ATP. The ATP is stored in the tree and is transferred onto growing tree buds in spring. The system boundary of the tree prevents stored energy and energy transformed in growth from reaching the environment.
- When the tree buds are in the process of growing, energy is transformed by a process which is inactive at other times. Here, tree buds take up thermal energy from the environment and transform it into chemical energy. The chemical energy can be transformed for growing structures.
- Sugar is built up while the tree has leaves and is then stored as chemical energy. When the tree buds grow, this energy is transferred to growing structures. Without sunlight, growth is limited by the extent of chemical energy stores.

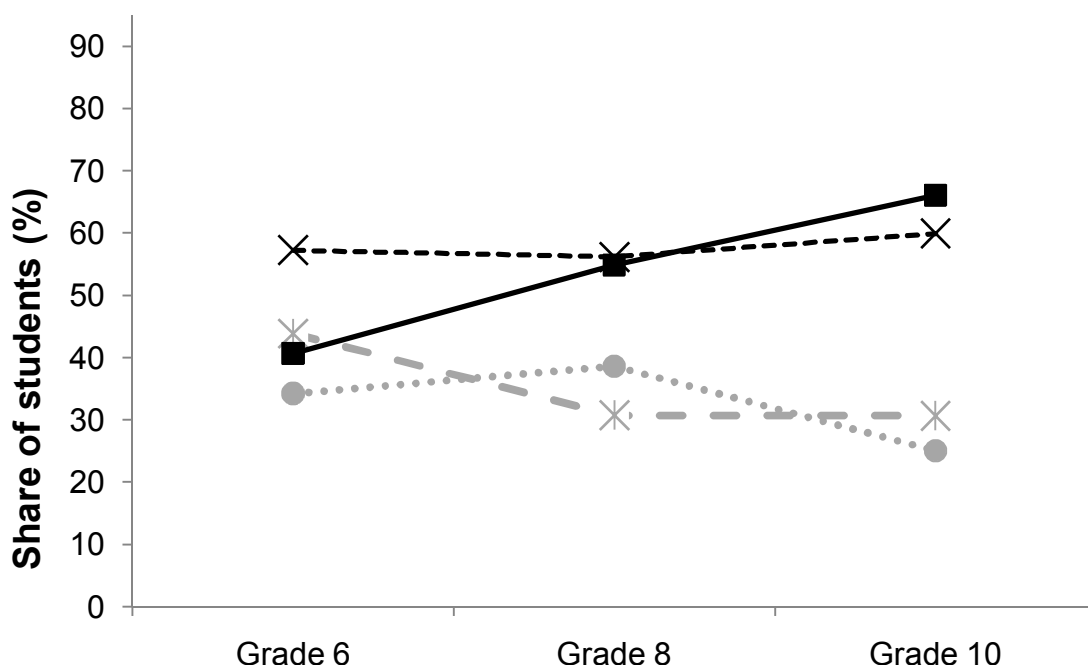
**Item parameters for item 242\_2**

	Grade 6	Grade 8	Grade 10
<b>Item difficulty (solution <math>p</math>)</b>	0.13	0.24	0.33
<b>Item discrimination</b>	0.29	0.21	0.34

**Distractor/attractor analysis**

**Task 28 – Item 242\_2 – Biology – Transfer/transformation**

Students' selection about the energy source of tree buds that grow before the tree has leaves



- Correct** - x - As the tree is an open system, leaves absorb light energy from the sun and CO<sub>2</sub> from the air and transform it into chemical energy. As sugar, the latter is stored during the winter and is transported to growing tree parts in spring.
- x - In leaves, energy particles from the sun are transformed into ATP, which is stored in the tree and transferred onto growing tree buds in spring. The system boundary of the tree prevents energy from reaching the environment.
- ● ● In the tree buds, energy is transformed by a process in which thermal energy from the environment is taken up and transformed into chemical energy, which is used for growing plant structures.
- Correct** - ■ - Sugar is built up while the tree has leaves and is then stored as chemical energy. In spring, this energy is transferred to the tree buds. Without sunlight, growth is limited by the extent of chemical energy stores.

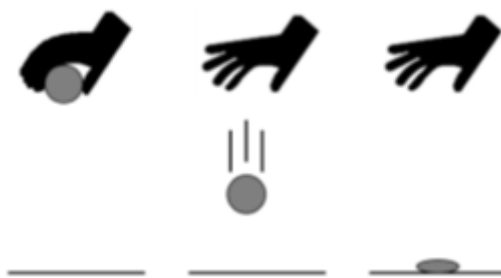
**Discipline:** physics – **Energy aspect:** transfer/transformation – **Cognitive complexity:** relations

**Correct solution:** 1

Task 29

Item TR1

A boy drops a ball of plasticine. During its fall, the plasticine speeds up. When it reaches the ground, it deforms.



Which statement correctly describes the occurring energy transformation?

**1 answer is correct!**

- While the plasticine is falling, its gravitational potential energy is transformed into kinetic energy. When it reaches the ground, the kinetic energy is transformed into thermal energy.
- While the plasticine is falling, its kinetic energy is transformed into gravitational potential energy. When it reaches the ground, the kinetic energy is transformed into thermal energy.
- While the plasticine is falling, its gravitational potential energy is transformed into kinetic energy. When it reaches the ground, its kinetic energy is used up, but it is not transformed into thermal energy.
- While the plasticine is falling, its kinetic energy is transformed into gravitational potential energy. When it reaches the ground, the gravitational potential energy stays the same and it's not transformed into thermal energy.

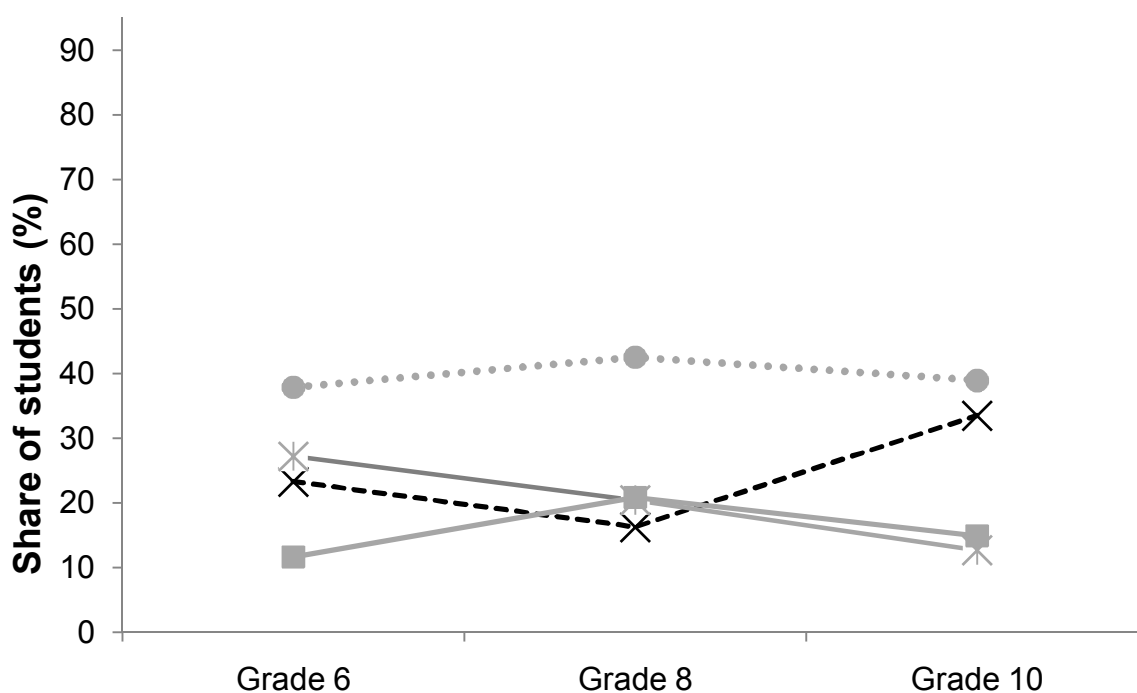
Item parameters for item TR1

	Grade 6	Grade 8	Grade 10
<b>Item difficulty (solution <math>p</math>)</b>	0.19	0.15	0.32
<b>Item discrimination</b>	0.00	0.14	0.30

Distractor/attractor analysis

**Task 29 – Item TR1 – Physics – Transfer/transformation**

Students' choices about the energy transformation occurring when a ball of plasticine is dropped



**Correct** -x- In falling, gravitational potential energy is transformed into kinetic energy, which becomes thermal energy when the plasticine hits the ground.

-x- In falling, kinetic energy is transformed into gravitational potential energy, which becomes thermal energy when the plasticine hits the ground.

●●● In falling, gravitational potential energy is transformed into kinetic energy, which is lost when the plasticine hits the ground. It is not transformed into thermal energy.

■ In falling, kinetic energy is transformed into gravitational potential energy. When it reaches the ground, the gravitational potential energy stays the same. It is not transformed into thermal energy.

**Discipline:** chemistry – **Energy aspect:** transfer/transformation –  
**Cognitive complexity:** facts

**Correct solution: 5**

Task 30

Item CTF1



You can heat a whole flat with an open fireplace. Where does the energy come from that is released during the combustion?

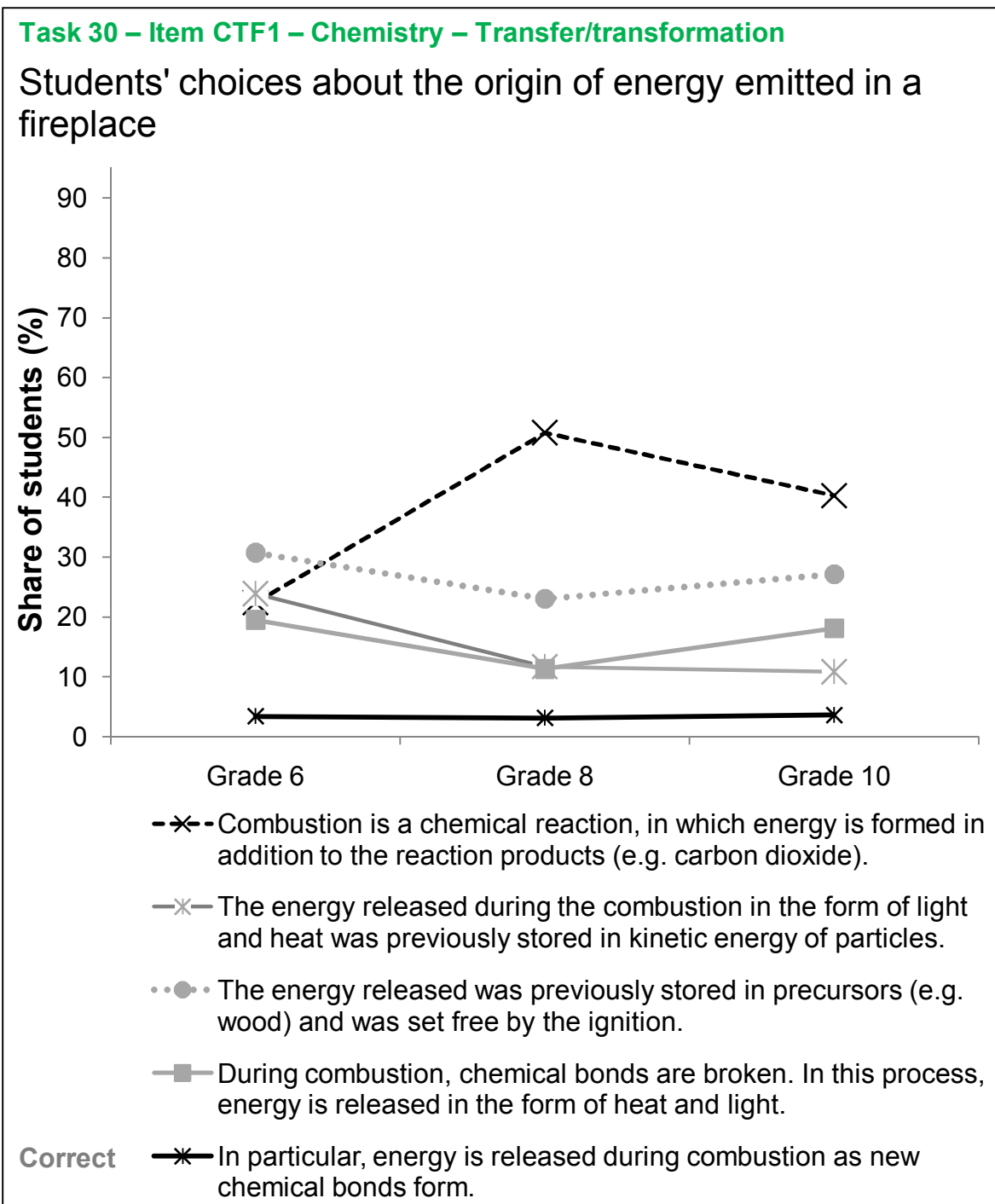
**1 answer is correct!**

- Combustion is a chemical reaction, in which energy is formed besides reaction products (e.g. carbon dioxide).
- The energy released during the combustion in the form of light and heat was previously stored in the kinetic energy of particles.
- The energy released was previously stored in the precursors (e.g. wood) and was set free by the ignition.
- During combustion, chemical bonds are broken. In this process, energy is released in the form of heat and light.
- In particular, energy is released as new chemical bonds form during combustion.

**Item parameters for item CTF1**

	Grade 6	Grade 8	Grade 10
<b>Item difficulty (solution <math>p</math>)</b>	0.03	0.03	0.03
<b>Item discrimination</b>	0.20	0.02	0.04

**Distractor/attractor analysis**



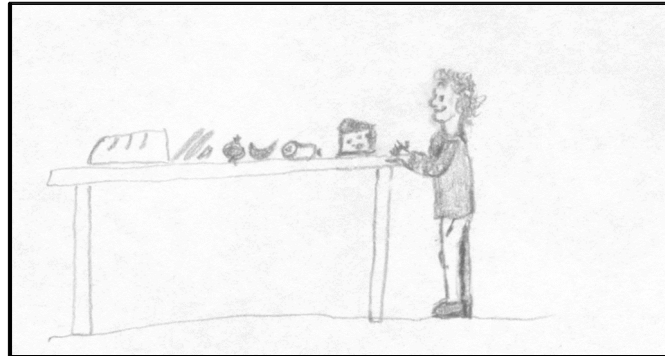


**Discipline:** biology – **Energy aspect:** degradation/dissipation – **Cognitive complexity:** facts

**Correct solutions:** 1 & 3

### Task 31

Item 311\_2



A growing person transforms energy stores from food or from body (fat) for various life processes.

Select, where you can rediscover the energy after the transformation.

**2 answers  
are correct!**

- In new grown body structures, in the person's movement and in undigested parts of the food
- Energy is almost completely stored in new grown body mass (weight). The rest is heat and remains in the body.
- In the heat of the body and the environment
- In the electric currents of nerves which control the body functions
- In heat stores, which the body uses to generate movement

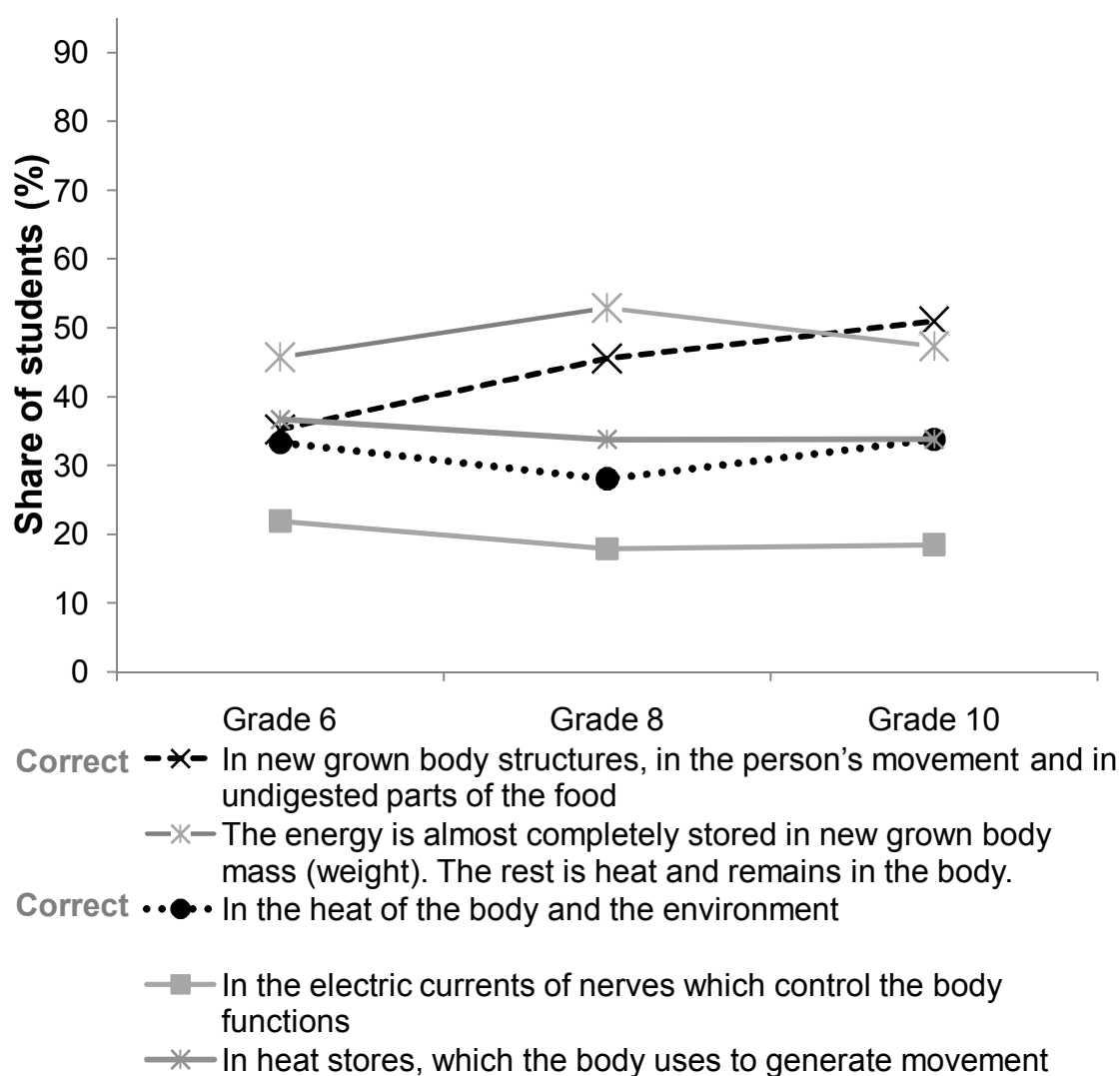
**Item parameters for item 311\_2**

	Grade 6	Grade 8	Grade 10
<b>Item difficulty (solution <math>p</math>)</b>	0.09	0.08	0.15
<b>Item discrimination</b>	0.09	0.04	0.28

**Distractor/attractor analysis**

**Task 31 – Item 311\_2 – Biology – Degradation/dissipation**

Students' choices on where to rediscover energy that was transformed from energy stores in food or body fat



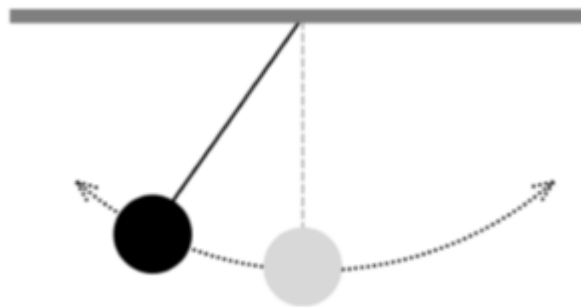
**Discipline:** physics – **Energy aspect:** degradation/dissipation – **Cognitive complexity:** facts

**Correct solution: 2**

Task 32

Item DF1

A pupil is playing with a pendulum. He pushes the pendulum and watches how it swings from one side to the other.



The pendulum stops swinging after some time. Why?

**1 answer is correct!**

- While the pendulum swings back and forth, kinetic energy is used up.
- While the pendulum swings back and forth, the pendulum's kinetic energy is transferred to the air.
- While the pendulum swings back and forth, a part of its kinetic energy is transferred to the air and another part is used up.
- An object only possesses kinetic energy when a person puts it into motion. In this case, the pupil does not put the pendulum into motion again.

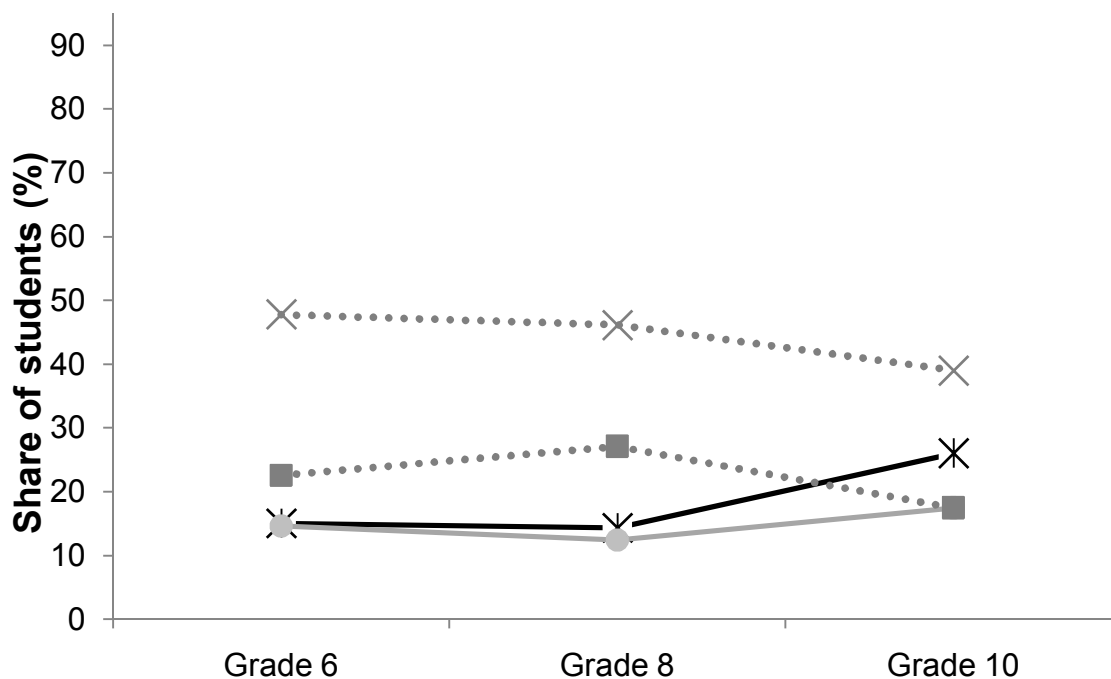
**Item parameters for item DF1**

	Grade 6	Grade 8	Grade 10
<b>Item difficulty (solution <math>p</math>)</b>	0.13	0.14	0.25
<b>Item discrimination</b>	0.09	0.18	0.30

**Distractor/attractor analysis**

**Task 32 – Item DF1 – Physics – Degradation/dissipation**

Students' selections on why a pendulum stops after being put into motion



••x•• In swinging back and forth, kinetic energy is used up.

**Correct** —x— In swinging, kinetic energy of the pendulum is transferred to the air.

—o— In swining, a part of the kinetic energy is transferred to the air, while another part is used up.

••■•• An object only possesses kinetic energy when a person puts it into motion. In this case, the pupil does not put the pendulum into motion again.

**Discipline:** chemistry – **Energy aspect:** degradation/dissipation –  
**Cognitive complexity:** mappings

**Correct solution:** 5

Task 33

Item CDM1



When a candle has burned down, the candle wax has reacted and is gone.

What is the energy balance for this chemical reaction?

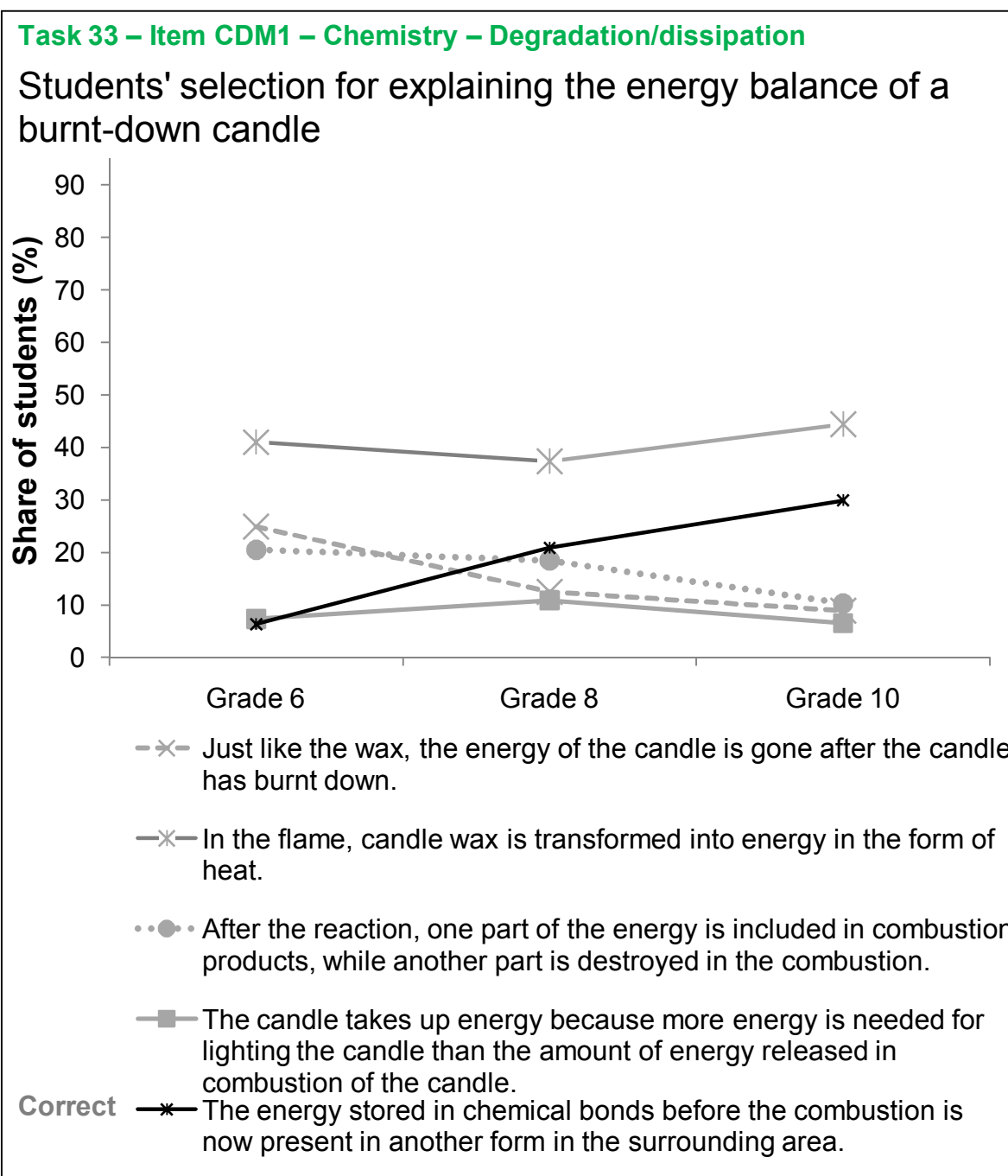
**1 answer is correct!**

- Just like the wax, the energy is gone after the candle has burnt down.
- In the flame, candle wax is transformed into energy in the form of heat.
- After the reaction, one part of the energy is included in combustion products, while another part is destroyed in the combustion.
- The candle takes up energy because more energy is needed for lighting the candle than the amount of energy released in the combustion of the candle.
- The energy stored in chemical bonds before the combustion is now present in another form in the surrounding area.

**Item parameters for item CDM1**

	Grade 6	Grade 8	Grade 10
<b>Item difficulty (solution <math>p</math>)</b>	0.05	0.19	0.28
<b>Item discrimination</b>	0.34	0.27	0.40

**Distractor/attractor analysis**



**Discipline:** biology – **Energy aspect:** conservation – **Cognitive complexity:** mappings

**Correct solutions:** (A) 2 – 2 – 1 (B) 1

Task 34

Item 423\_2



In autumn, reindeers move from regions with plenty of food in northern Canada to the South. In doing so, the animals take up energy, release energy and store energy.

**(A) In the following three steps, select if the energy is taken up by the reindeer, or, if it's energy that is stored in the reindeer/energy that is released into the environment.**

In part (A), chose **one option for each of the three steps**. In part (B), chose **one option**.

Energy **taken up** by the reindeer

Energy **stored** in the reindeer/energy **released** into the environment

1) Kinetic energy (through friction, the latter will eventually become heat)



2) Energy transformed into thermal energy by various processes in the reindeer



3) Chemical energy of food (if the animal feeds before or during migration)



**(B) Select the correct ratio of the given amounts of energy.**

The amount of energy **taken up** is ...

- ... equal to ...
- ... smaller than ...
- ... larger than ...

... the amount of **energy stored** in the reindeer and the **energy released** into the environment.

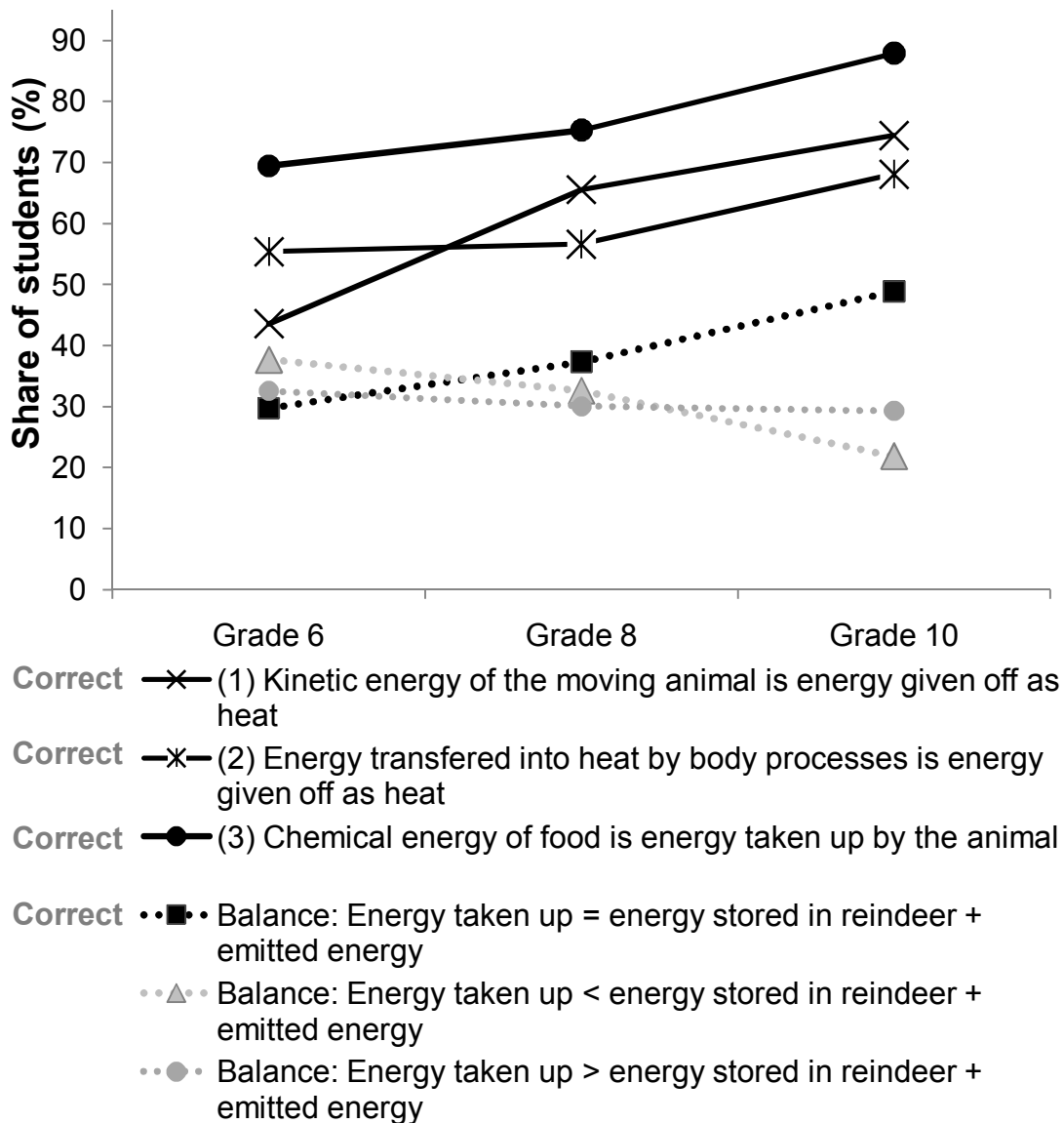
**Item parameters for item 423\_2**

	Grade 6	Grade 8	Grade 10
<b>Item difficulty (solution <math>p</math>)</b>	0.02	0.14	0.24
<b>Item discrimination</b>	0.20	0.48	0.47

**Distractor/attractor analysis** (For readability, only correct answers are shown for part A of the item)

**Task 34 – Item 423\_2 – Biology – Conservation**

Students' selections on the energy balance of reindeer during the annual migration to the south





**Discipline:** physics – **Energy aspect:** conservation – **Cognitive complexity:** forms

**Correct solution:** 1

Task 35

Item CF1

A child skateboards in a halfpipe.



What can be said about the total energy of the child and his/her environment?

**1 answer is correct!**

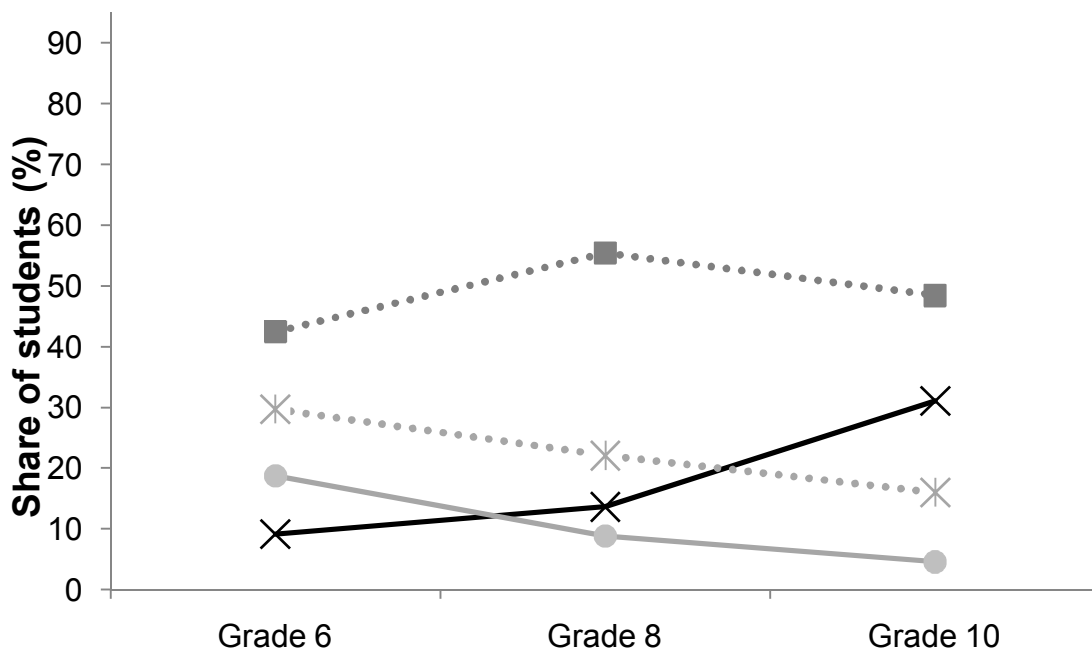
- The total energy remains the same.
- The total energy decreases.
- The total energy increases.
- The total energy changes constantly.

**Item parameters for item CF1**

	Grade 6	Grade 8	Grade 10
<b>Item difficulty (solution <math>p</math>)</b>	0.08	0.13	0.30
<b>Item discrimination</b>	0.03	0.29	0.49

**Distractor/attractor analysis**

**Task 35 – Item CF1 – Physics – Conservation**  
Students' selections on the energy balance of a skater in a half-pipe and his/her environment



- Correct** —X— The total energy does not change.
- \*·· The total energy decreases.
- The total energy increases.
- The total energy is constantly changing.

**Discipline:** chemistry – **Energy aspect:** conservation – **Cognitive complexity:** concepts

**Correct solution:** 1

Task 36

Item CCC2

Many chemists work to develop new catalysts. For their research, chemists have even been awarded the Nobel Prize!

What does the catalyst do that makes it so important?

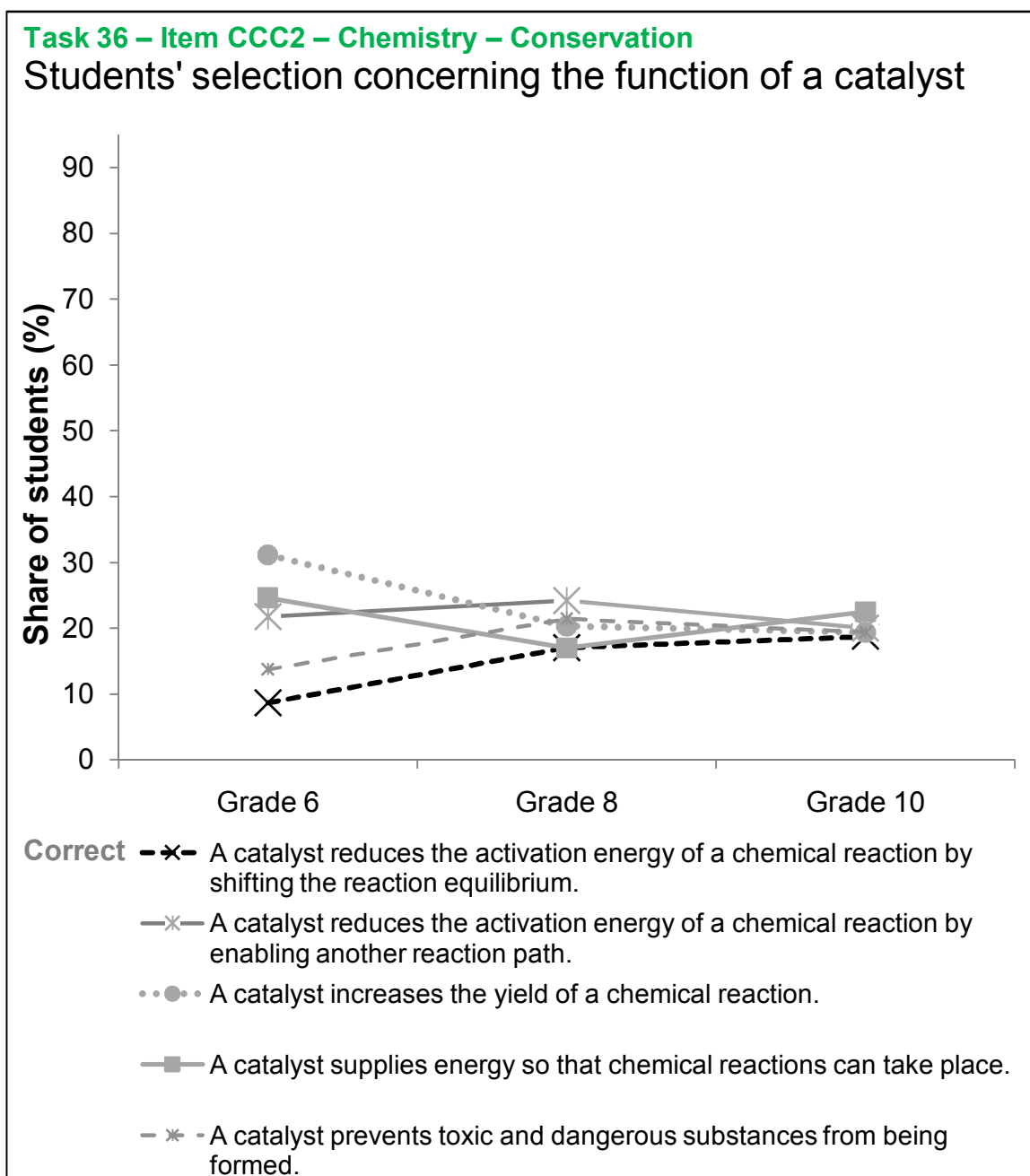
**1 answer is correct!**

- A catalyst reduces the activation energy of a chemical reaction by shifting the reaction equilibrium.
- A catalyst reduces the activation energy of a chemical reaction by enabling another reaction path.
- A catalyst increases the yield of a chemical reaction.
- A catalyst supplies energy so that chemical reactions can take place.
- A catalyst prevents toxic and dangerous substances from being formed.

Item parameters for item CCC2

	Grade 6	Grade 8	Grade 10
<b>Item difficulty (solution <math>p</math>)</b>	0.05	0.12	0.13
<b>Item discrimination</b>	0.17	0.14	0.08

Distractor/attractor analysis



Attachments  
Attachment B: Online Materials for Chapter 3/Study 2

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THIS IS ONE OF FIVE ITEMS EXCLUDED THROUGH AN INTERRATING FOR BEING DISCIPLINE-UNSPECIFIC ( $k = .81$  for the remaining 43 items – This item: 25% agreement on the intended discipline [biology])

**Discipline:** biology – **Energy aspect:** forms / sources – **Cognitive complexity:** mappings

**Correct solutions:** 2 – 4 – 3 – 1

Task 37

Item 121\_1



A person climbs a mountain. The amount of energy required for the climb depends on the influences named in the table.

For each influence, select the correct form of energy!

<div style="border: 1px solid black; padding: 5px; width: fit-content; margin: 0 auto;">                     In each line, <b>one form of energy</b> is correct!                 </div>	Energy form			
	Thermal energy	Kinetic energy	Gravitational potential energy	Chemical energy
<b>Influence</b>				
The person's speed				
The person's body and the food stored in the body				
The height the person is at on the mountain				
The person's body heat				

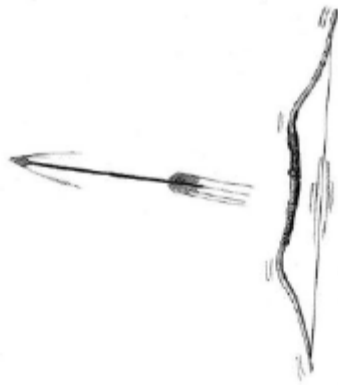
**Discipline:** physics – **Energy aspect:** forms/sources – **Cognitive complexity:** concepts

**Correct solution: 2**

Task 38

Item FC2

An arrow has been shot into the air with a bow.



What can be said about the flying arrow from a physics perspective?

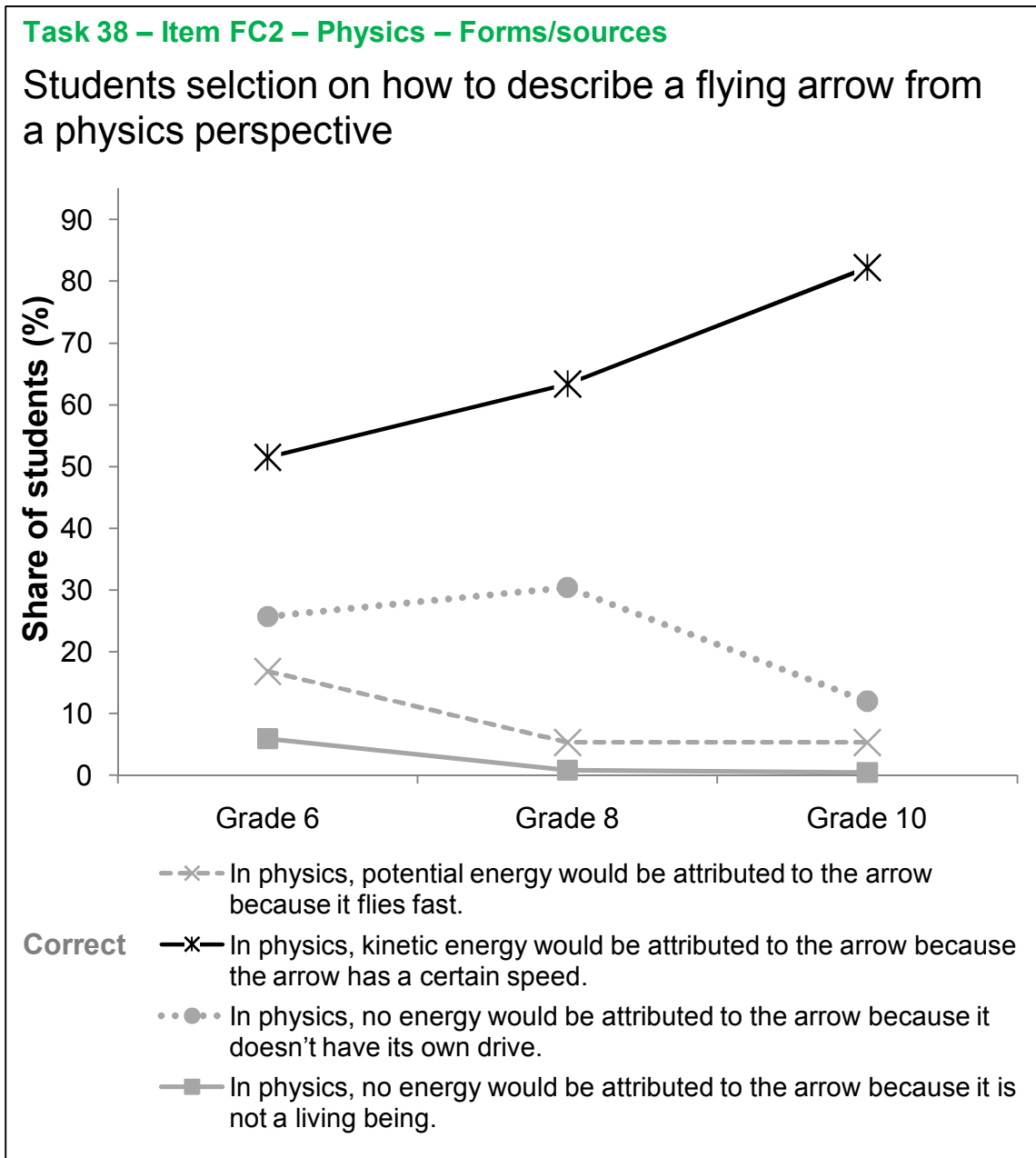
**1 answer is correct!**

- In physics, potential energy would be attributed to the arrow because it flies fast.
- In physics, kinetic energy would be attributed to the arrow because the arrow has a certain speed.
- In physics, no energy would be attributed to the arrow because it doesn't have its own drive.
- In physics, no energy would be attributed to the arrow because it is not a living being.

**Item parameters for item FC2**

	Grade 6	Grade 8	Grade 10
<b>Item difficulty (solution <math>p</math>)</b>	0.41	0.57	0.81
<b>Item discrimination</b>	0.16	0.19	0.23

**Distractor/attractor analysis**

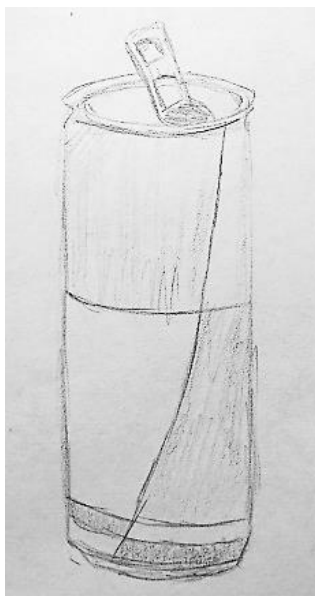


**Discipline:** chemistry – **Energy aspect:** forms/sources – **Cognitive complexity:** relations

**Correct solution:** 3

Task 39

Item CFR3



An energy drink contains the following ingredients: carbonated water, glucose, caffeine, vitamins, and colorant. The calorific value is reported to be 192 kJ per 100 g.

Which ingredient is the determining factor for this calorific value?

**1 answer is correct!**

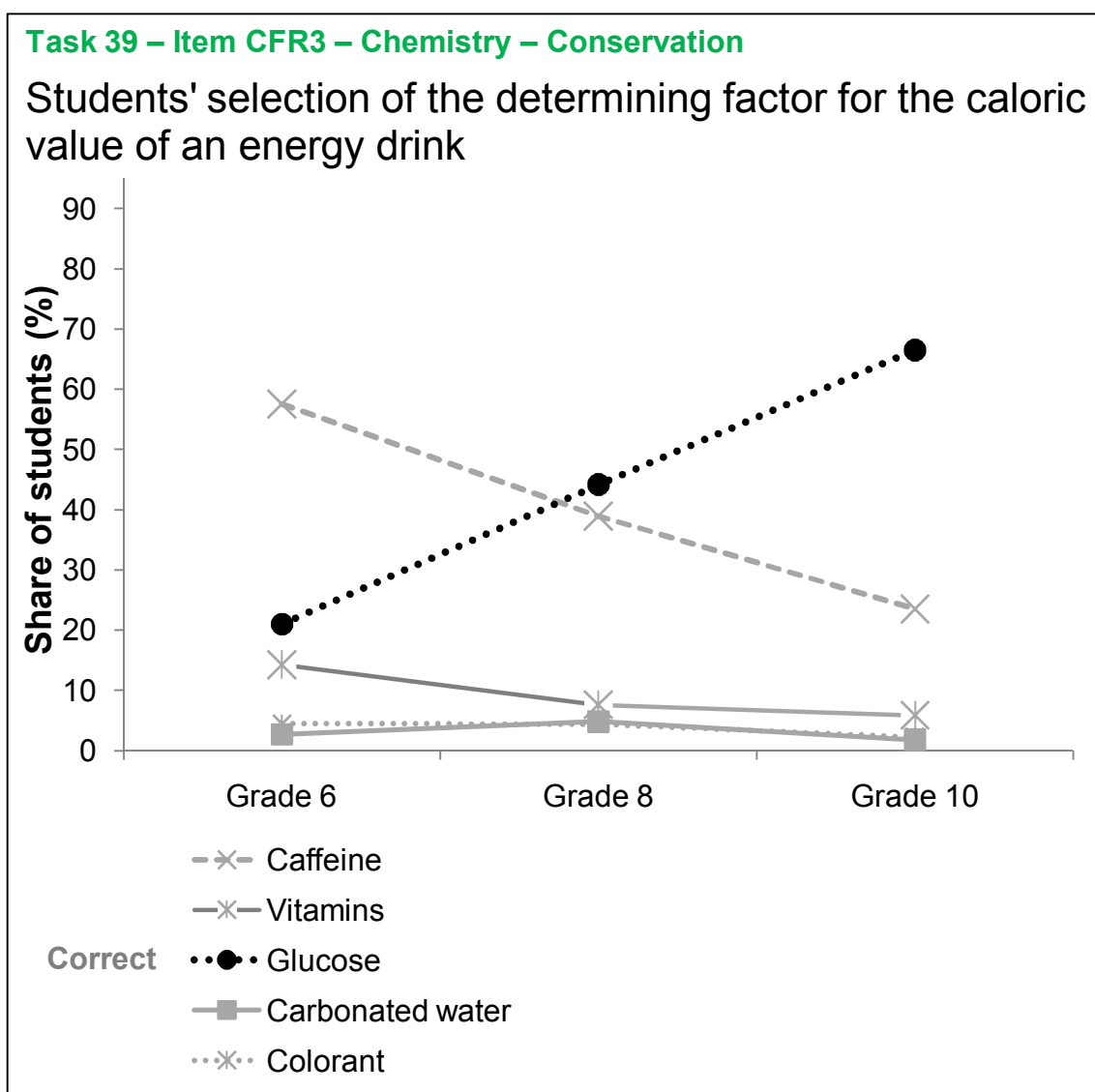
- Caffeine
- Vitamins
- Glucose
- Carbonated water
- Colorant



**Item parameters for item CFR3**

	Grade 6	Grade 8	Grade 10
<b>Item difficulty (solution <i>p</i>)</b>	0.18	0.41	0.64
<b>Item discrimination</b>	0.18	0.31	0.37

**Distractor/attractor analysis**

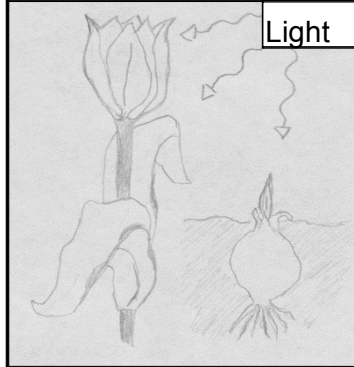


**Discipline:** biology – **Energy aspect:** transfer/transformation – **Cognitive complexity:** mappings

**Correct solutions:** (1) 1/2; (2) 2/1; (3) 3/2

**Task 40**

Item 222\_1



For its growth, a flower can use the sun's light energy, but also the energy stored in its flower bulb.

For the following three steps, select ...

(A) which pair of energy forms is involved, and ...

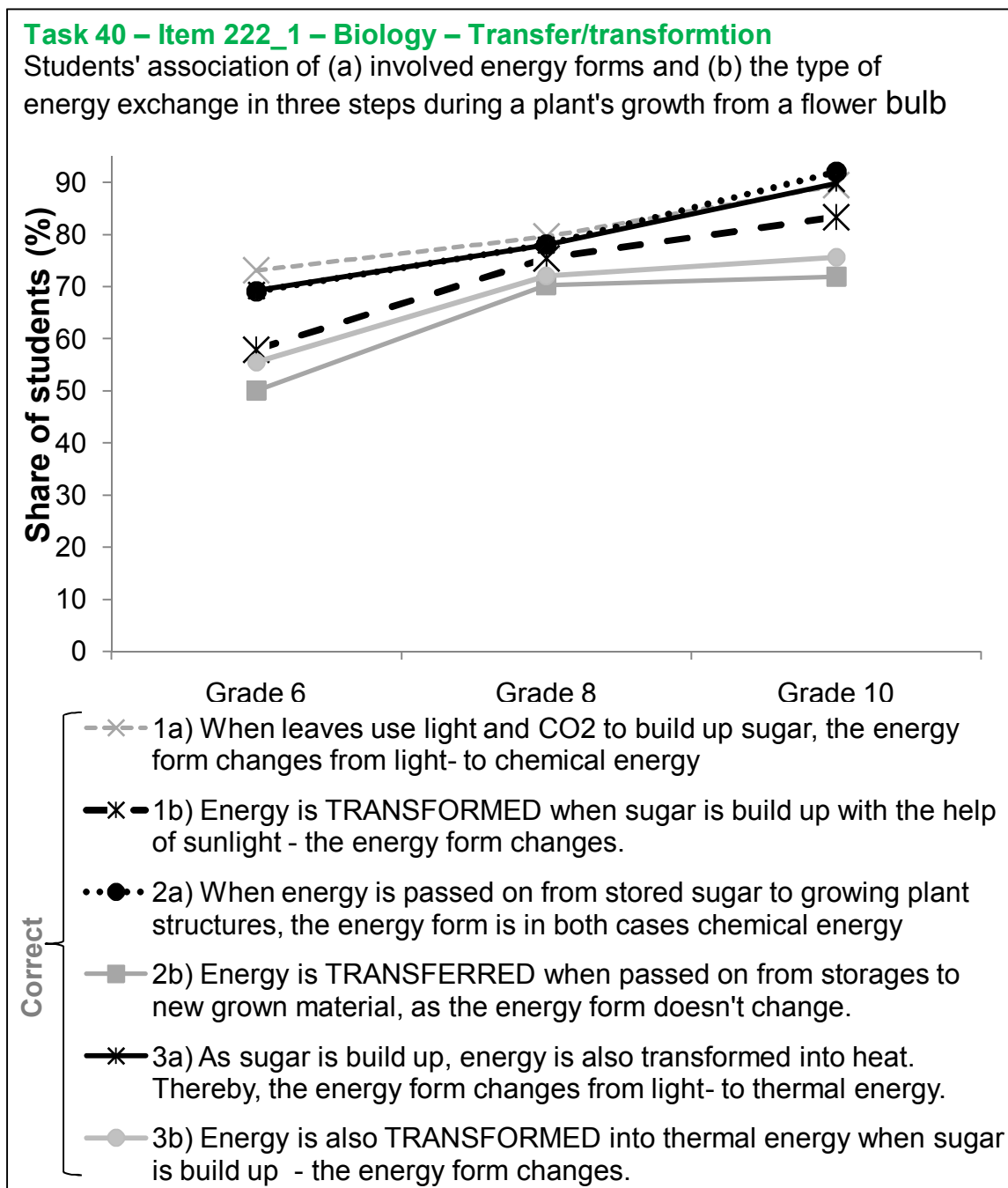
(B) how the energy is passed on!

<div style="border: 1px solid black; padding: 5px; margin-bottom: 5px;">                     For each of the steps, select <b>one box for (A) AND one for (B)!</b> </div> <b>Steps</b>	(A) Energy forms			(B) How energy is passed on	
	Light energy → chemical energy	Chemical energy → chemical energy	Light energy → thermal energy	Transfer, because the energy form remains the same	Transformation, because the energy form changes
(1) With the help of sunlight, the flower's leaves build up sugar from carbon dioxide.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
(2) Sugar, that was stored in the flower bud, is broken down. Its energy is used for the growth of the plant.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
(3) As the sugar is built up, heat is released, too.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

**Item parameters for item 222\_1**

	Grade 6	Grade 8	Grade 10
<b>Item difficulty (solution <math>p</math>)</b>	0.12	0.38	0.52
<b>Item discrimination</b>	0.26	0.56	0.48

**Distractor/attractor analysis** (For readability, only correct answers are shown)



**Discipline:** physics – **Energy aspect:** transfer/transformation – **Cognitive complexity:** relations

**Correct solution:** 4

Task 41

Item TR2

Tom stretches a rubber band and then releases it. The rubber band flies through the room.

Which of the following statements describes what happens to the energy of the rubber band?

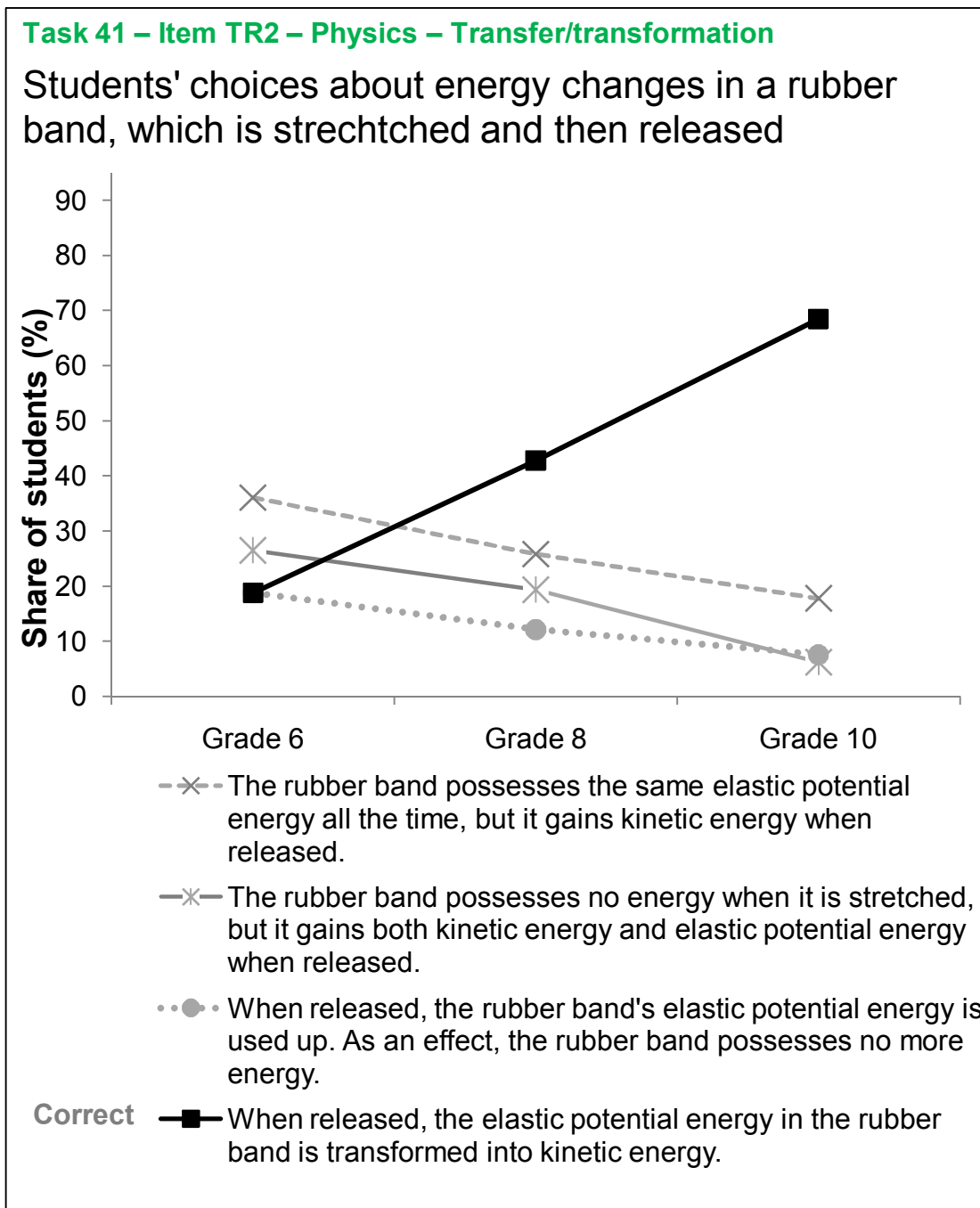
**1 answer is correct!**

- The rubber band possesses the same elastic potential energy all the time, but it gains kinetic energy as soon as Tom releases it.
- The rubber band possesses no energy when it's stretched, but it gains both kinetic energy and elastic potential energy as soon as Tom releases it.
- As soon as Tom releases the rubber band, the elastic potential energy is used up. As an effect, the rubber band has no more energy.
- As Tom releases the stretched rubber band, the elastic potential energy is transformed into kinetic energy.

**Item parameters for item TR2**

	Grade 6	Grade 8	Grade 10
<b>Item difficulty (solution <math>p</math>)</b>	0.15	0.40	0.67
<b>Item discrimination</b>	0.24	0.52	0.38

**Distractor/attractor analysis**



**Discipline:** chemistry – **Energy aspect:** transfer/transformation –  
**Cognitive complexity:** relations

**Correct solution:** 1

Task 42

Item CTR5

What are the changes at particle level when the temperature of a certain amount of gas is increasing?

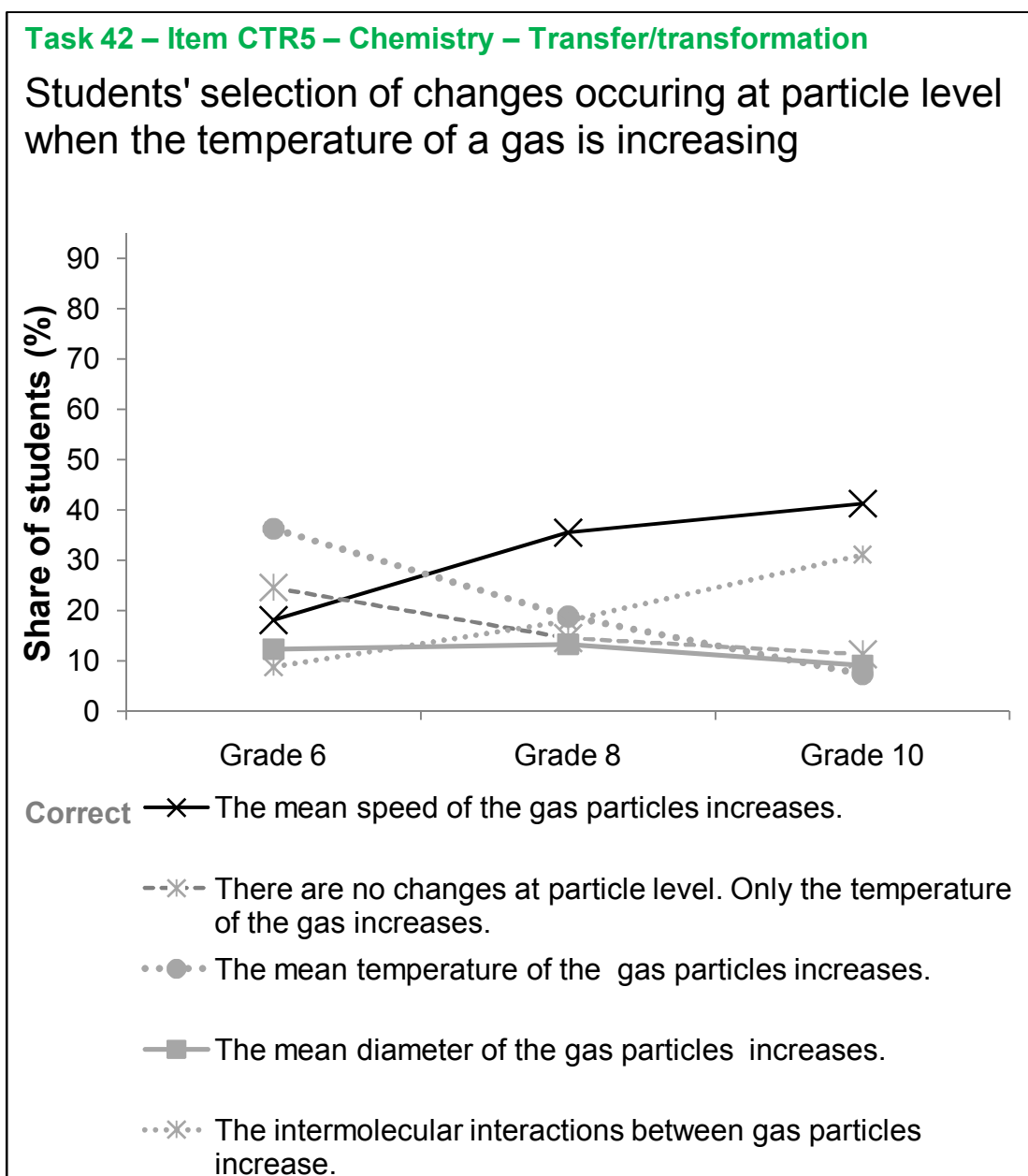
**1 answer is correct!**

- The gas particles' mean speed increases.
- There are no changes at particle level. Only the temperature of the gas increases.
- The mean temperature of the gas particles increases.
- The gas particles' mean diameter increases.
- The intermolecular interactions between gas particles increase.

**Item parameters for item CTR5**

	Grade 6	Grade 8	Grade 10
<b>Item difficulty (solution <math>p</math>)</b>	0.12	0.31	0.32
<b>Item discrimination</b>	0.12	0.32	0.40

**Distractor/attractor analysis**

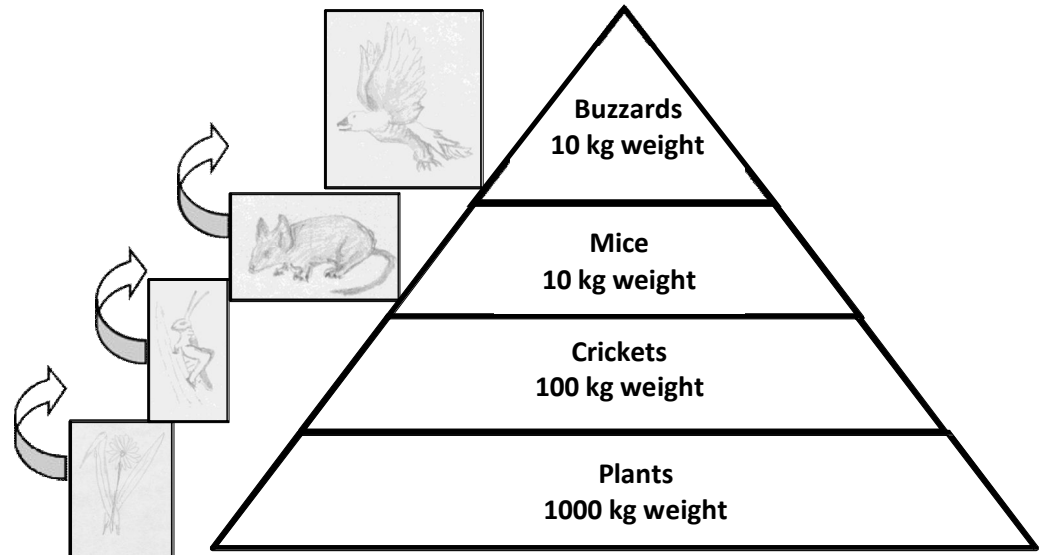


**Discipline:** biology – **Energy aspect:** degradation/dissipation – **Cognitive complexity:** concepts

**Correct solutions:** 2 & 4

Task 43

Item 342\_1



Animals on a higher level in a food chain possess only 10% of the biomass (roughly 'live weight') of the animals/plants they feed on. Therefore, the total weight of the organisms decreases from step to step.

Select the statements which describe the role of energy degradation during the biomass transfer in the food chain!

**2 answers**  
are correct!

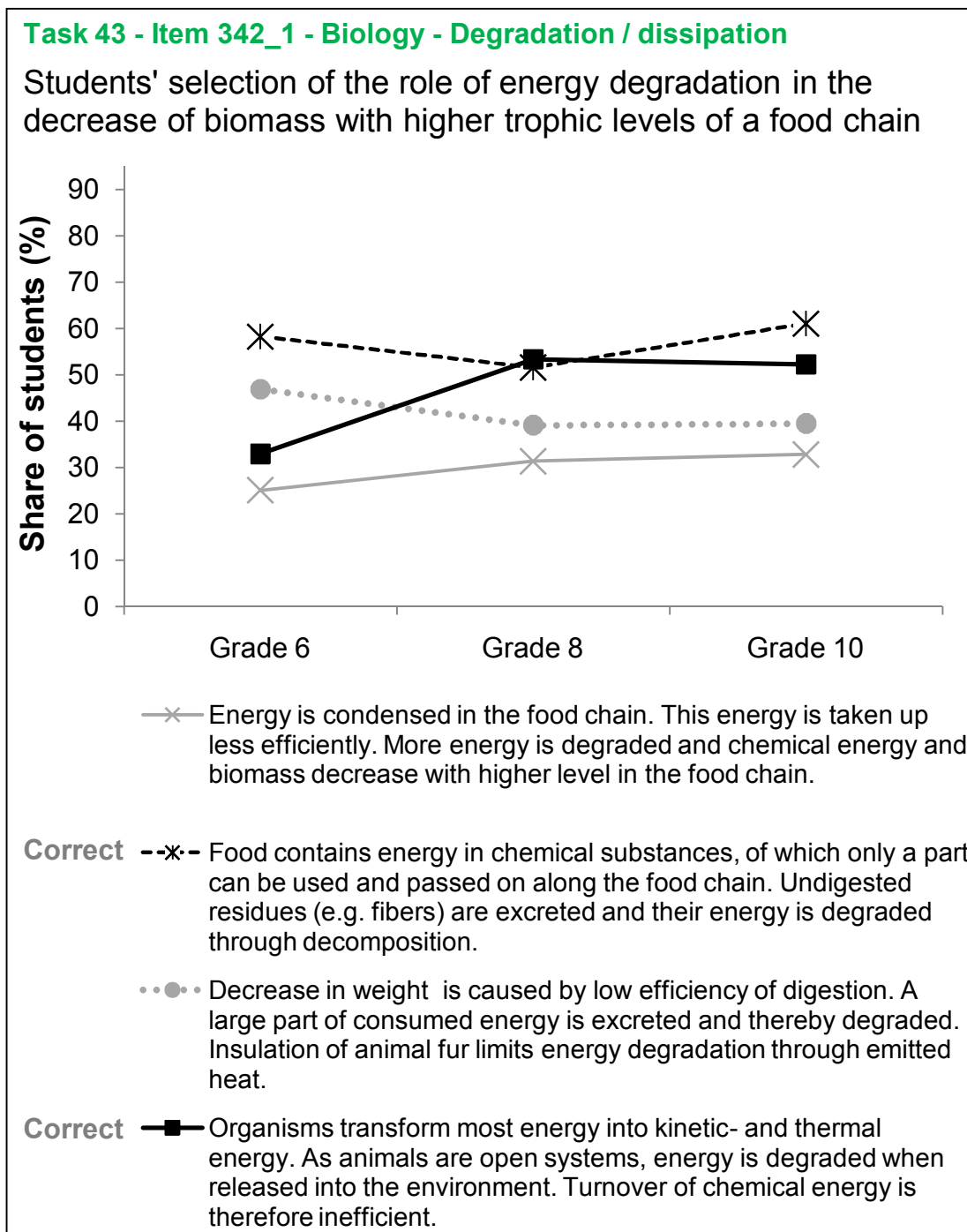
- Through the transfer of chemical energy, energy is condensed at the end of the food chain. Higher concentrated energy can be taken up less efficiently. Therefore, more energy is degraded and chemical energy and biomass decrease with higher levels.
- Food contains energy stored in chemical substances. Only parts of that energy can be used in transformations and thereby be passed on along the food chain. Undigested residues (e.g. fibers) are excreted. In the environment, the energy stored in those residues is degraded through decomposition.
- The decrease in weight from step to step is caused by the low efficiency of the animals' digestion. Here, a large part of the consumed energy is excreted and degraded in this process. Due to the insulation of fur, energy degradation through emitted heat is low in animals.
- All organisms transform a large part of the energy that they take up into kinetic and thermal energy. The latter is then released into the environment as animals are open systems. Energy is degraded during this process. Turnover of chemical energy during growth is therefore inefficient.



**Item parameters for item 342\_1**

	Grade 6	Grade 8	Grade 10
<b>Item difficulty (solution <math>p</math>)</b>	0.14	0.25	0.28
<b>Item discrimination</b>	0.09	0.01	0.27

**Distractor/attractor analysis**



**Discipline:** physics – **Energy aspect:** degradation/dissipation – **Cognitive complexity:** mappings

**Correct solution:** 4

## Task 44

Item DM2

Tea is made in a cup. The cup is then left to stand.



What happens?

**1 answer is correct!**

- The tea cools down after some time, as a part of its thermal energy disappears.
- The tea cools down after some time, as a part of its thermal energy is released into the environment and another part disappears.
- The tea cools down after some time, as all hot things cool down over time.
- The tea cools down after some time, as a part of its thermal energy is released into the environment.

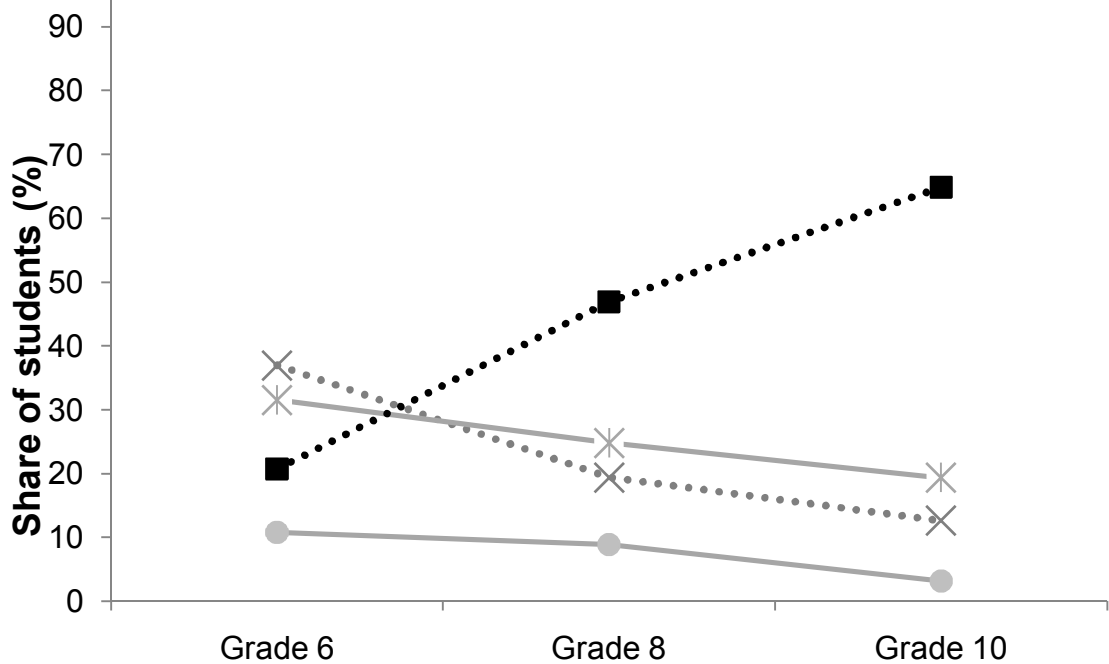
**Item parameters for item DM2**

	Grade 6	Grade 8	Grade 10
<b>Item difficulty (solution <math>p</math>)</b>	0.18	0.45	0.63
<b>Item discrimination</b>	0.07	0.37	0.44

**Distractor/attractor analysis**

**Task 44 – Item DM2 – Physics – Degradation/dissipation**

Students' selections on energy changes in a cooling cup of tea



- ×•• The tea cools down after some time, as a part of its thermal energy disappears.
- ×— The tea cools down after some time, as a part of its thermal energy is released into the environment and another part disappears.
- The tea cools down after some time, as all hot things cool down over time.
- Correct** ••■•• The tea cools down after some time, as a part of its thermal energy is released into the environment.

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THIS IS ONE OF FIVE ITEMS EXCLUDED THROUGH AN INTERRATING FOR BEING  
DISCIPLINE-UNSPECIFIC ( $k = .81$  for the remaining 43 items – This item: 17 %  
agreement on the intended discipline [chemistry])

**Discipline:** chemistry – **Energy aspect:** degradation / dissipation –  
**Cognitive complexity:** facts

**Correct solution:** 1

Task 45

Item CDF1

You can read a lot about the term energy. Unfortunately, not all of this information is correct. Sometimes you can read about 'energy loss', other times you will read about 'energy conservation'.

Which of the following statements is correct?

1 answer is  
correct!

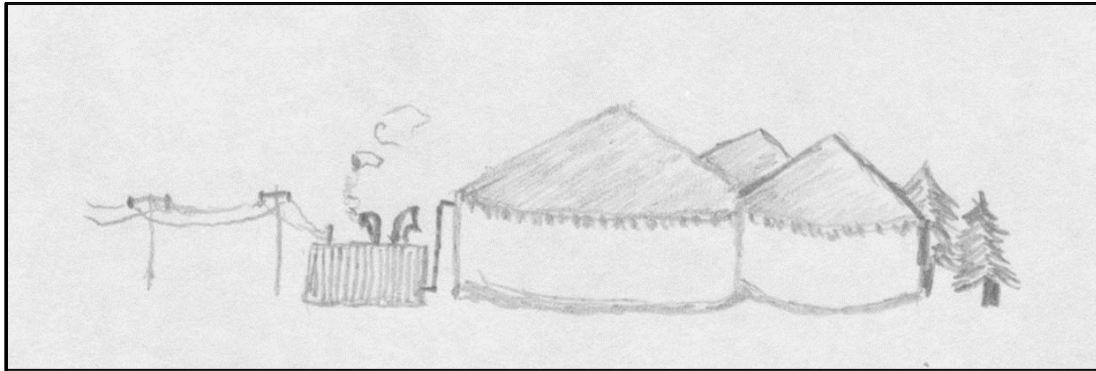
- Energy cannot be lost - it can only be transformed and transferred.
- In general, energy cannot be lost. It can only be used up in chemical reactions.
- Energy can be lost, for example when several electric loads, e.g. TVs, computers etc. are in use.
- Energy conservation applies only to particular technical conditions, but is not applicable in daily life.
- Energy can be generated as a product of chemical reactions.

**Discipline:** biology – **Energy aspect:** conservation – **Cognitive complexity:** relations

**Correct solutions:** 1 & 3

Task 46

Item 432\_1



In the last years, biogas plants (see drawing) have been widely established as small, decentralized power stations to provide a renewable energy source. Assume that a biogas plant is supplied with 2.000.000 kJ (kiloJoules;  $\approx$  480.000 kcal, kilocalories) of chemical energy in plant material ('biomass').

Select the statements that correctly describe how the amount of energy supplied to the biogas plant relates to the amount of energy transformed from it in the plant!

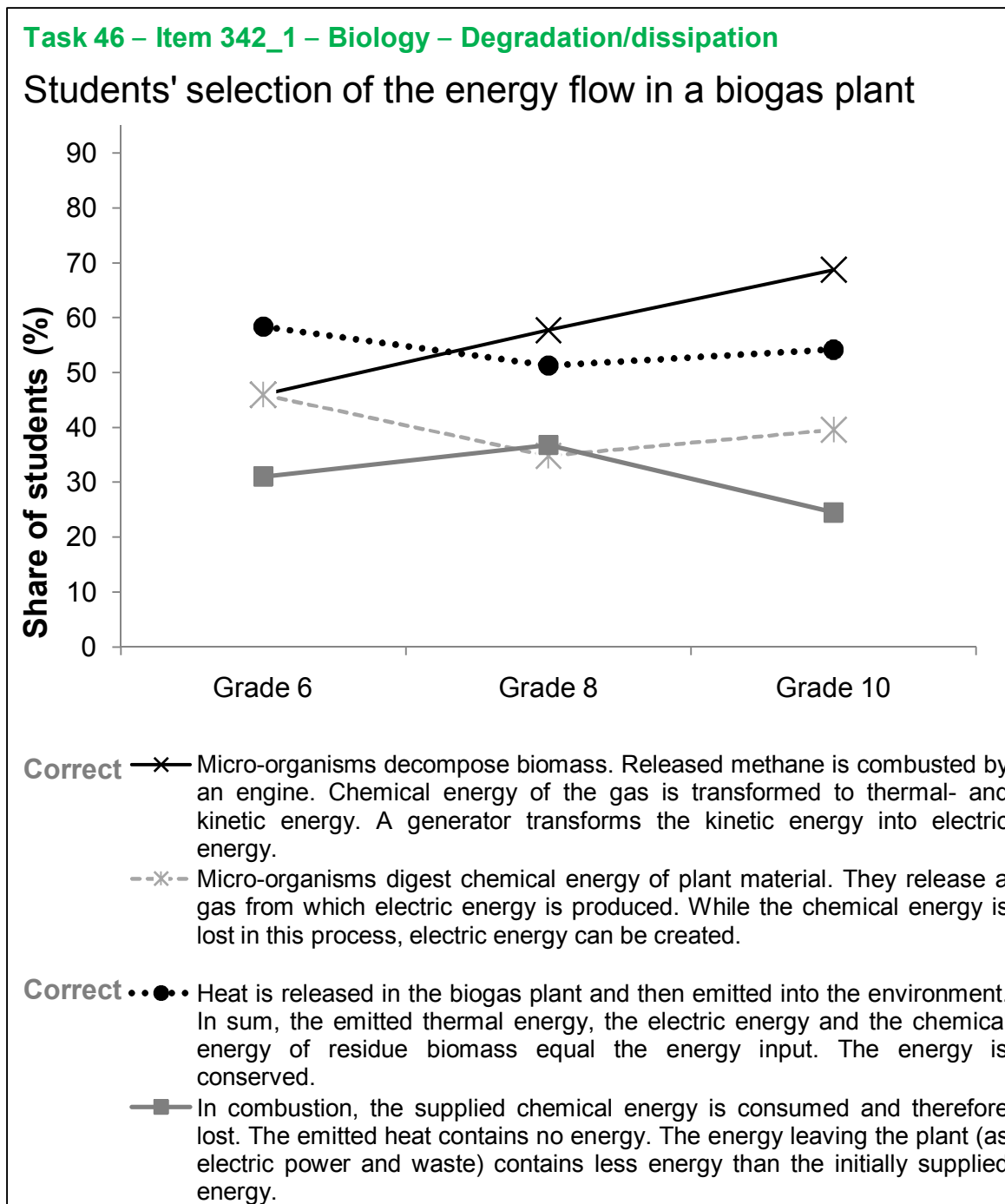
**2 answers**  
are correct!

- Micro-organisms decompose biomass. The hereby released gas (methane) is combusted by an engine. The chemical energy of the gas is transformed into thermal and kinetic energy. A generator then transforms the kinetic energy into electric energy.
- Micro-organisms digest the chemical energy of the plant material. They thereby release a gas from which electric energy is produced. While the chemical energy is lost in this process, electric energy can be created.
- In all transformations in the plant, heat is released. The heat is largely emitted into the environment and then stays unused. In sum, the emitted thermal energy, the electric energy and the chemical energy of residue biomass represent the initial 2.000.000 kJ. The energy is conserved.
- In combustion, the supplied chemical energy is lost, as it is consumed. The emitted heat contains no energy. The energy leaving the plant (as electric power and waste) contains much less energy than the initially supplied energy of 2.000.000 kJ.

**Item parameters for item 432\_1**

	Grade 6	Grade 8	Grade 10
<b>Item difficulty (solution <math>p</math>)</b>	0.18	0.22	0.32
<b>Item discrimination</b>	0.13	0.13	0.31

**Distractor/attractor analysis**



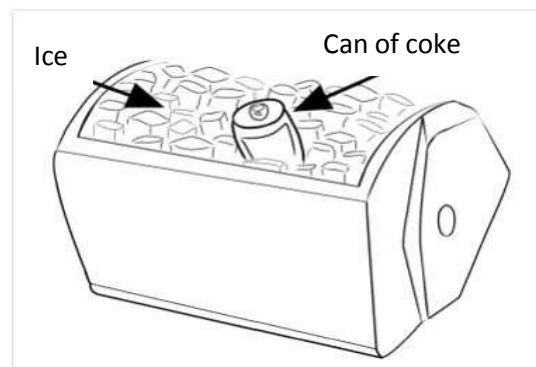
**Discipline:** physics – **Energy aspect:** conservation – **Cognitive complexity:** mappings

**Correct solution:** 3

### Task 47

Item CM2

In the morning, a student puts a warm can of coke into an ice-filled cool box. At noon, the can has become colder. Assume that no heat exchange has taken place between cooler and environment.



Which statement correctly describes the energy of the cooler and its content?

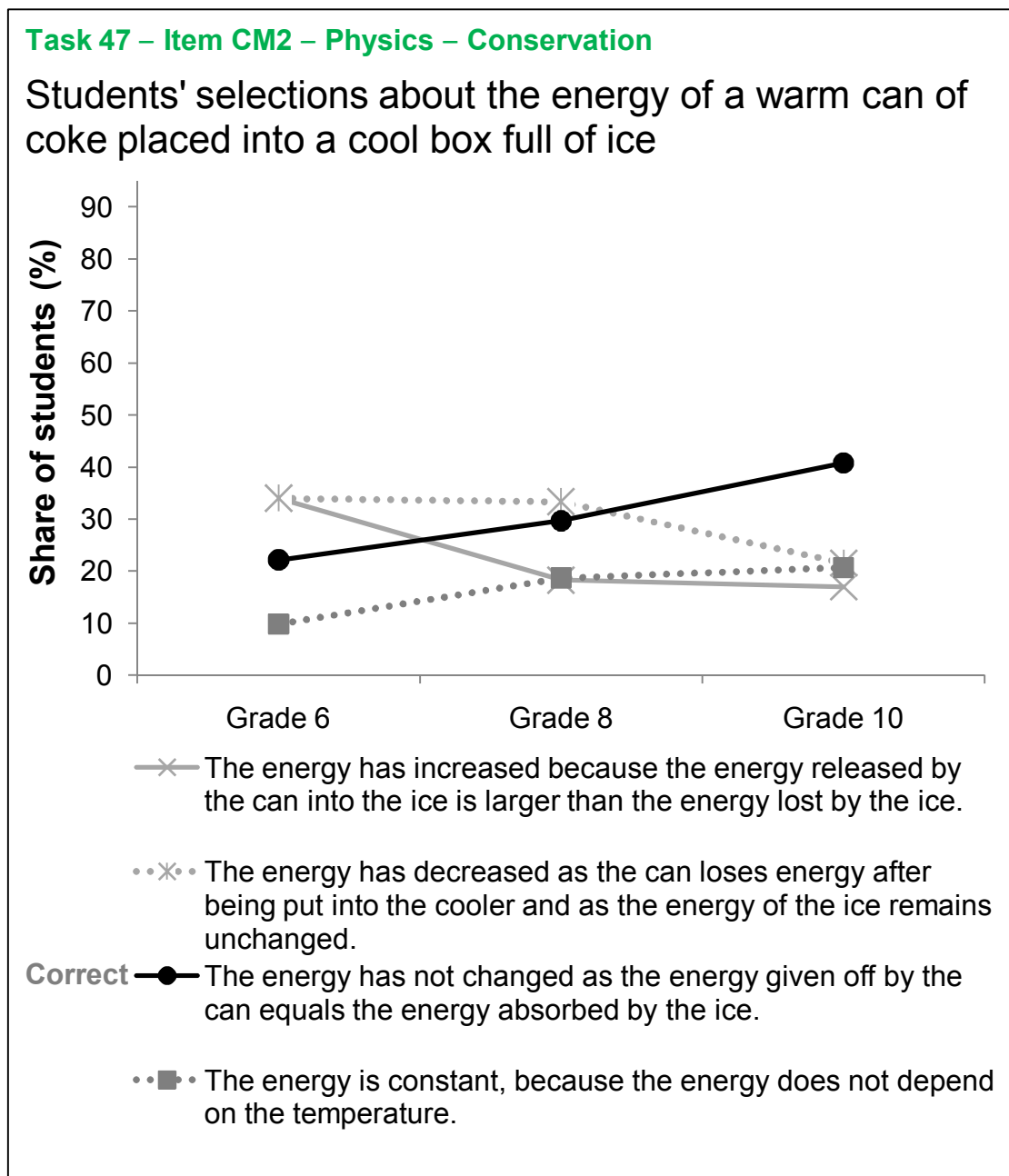
**1 answer is correct!**

- The energy has increased because the energy released by the can into the ice is larger than the energy lost by the ice.
- The energy has decreased because the can has lost energy in comparison to the morning and because the energy of the ice remains unchanged.
- The energy has not changed as the energy released by the can equals the energy taken up by the ice.
- The energy is constant, because it does not depend on the temperature.

**Item parameters for item CM2**

	Grade 6	Grade 8	Grade 10
<b>Item difficulty (solution <math>p</math>)</b>	0.18	0.27	0.39
<b>Item discrimination</b>	0.19	0.19	0.38

**Distractor/attractor analysis**





**Discipline:** chemistry – **Energy aspect:** conservation – **Cognitive complexity:** forms

**Correct solution:** 4

Task 48

Item CCF1

In a chemical reaction, energy can be taken up from the environment or it can be released into it. One can therefore distinguish between endothermic and exothermic processes.

Which of the following definitions is correct?

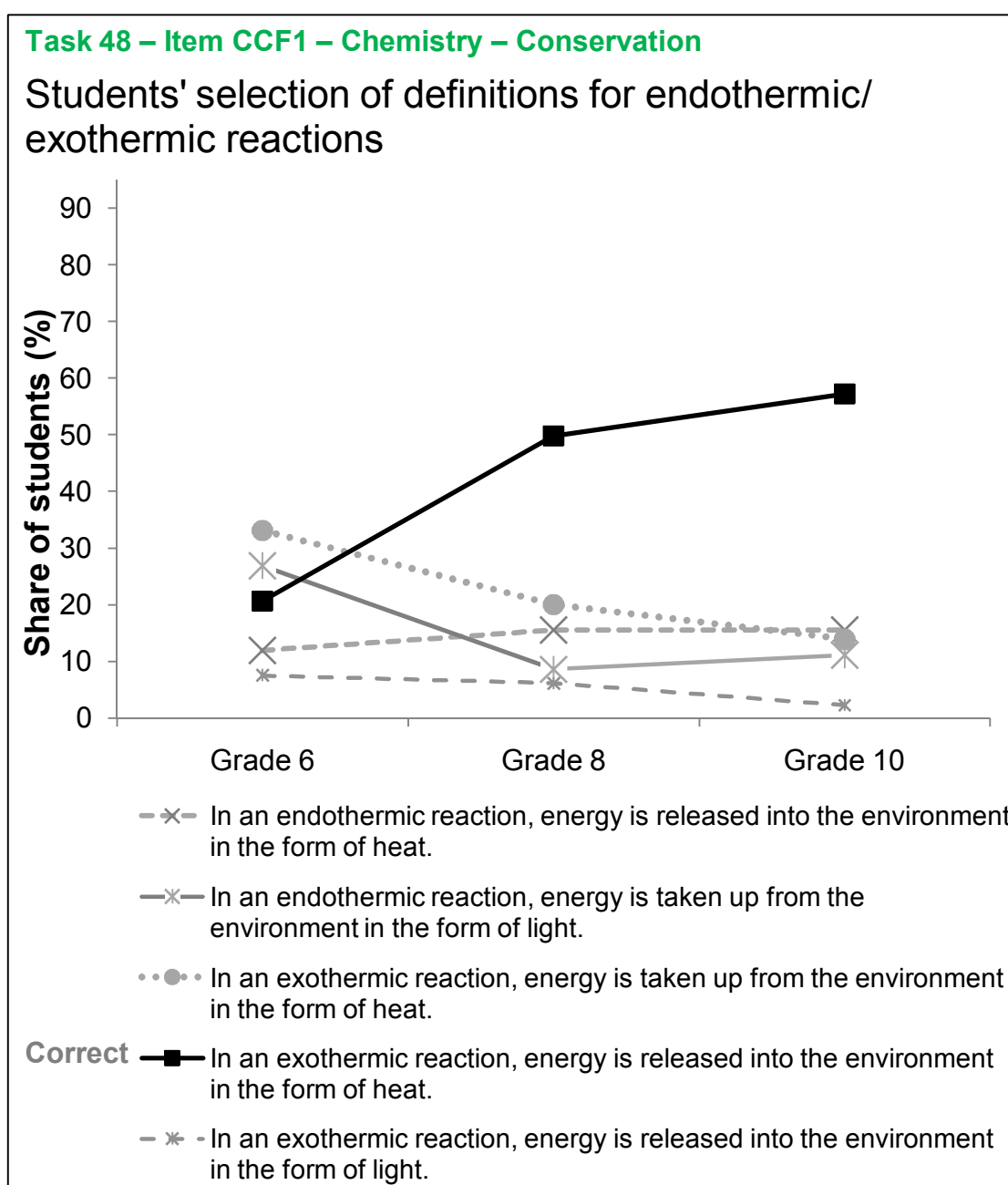
**1 answer is correct!**

- In an endothermic reaction, energy is released into the environment in the form of heat.
- In an endothermic reaction, energy is taken up from the environment in the form of light.
- In an exothermic reaction, energy is taken up from the environment in the form of heat.
- In an exothermic reaction, energy is released into the environment in the form of heat.
- In an exothermic reaction, energy is released into the environment in the form of light.

**Item parameters for item CCF1**

	Grade 6	Grade 8	Grade 10
<b>Item difficulty (solution <math>p</math>)</b>	0.13	0.46	0.45
<b>Item discrimination</b>	0.11	0.27	0.28

**Distractor/attractor analysis**



**Online material 2: Analysis of Differences in Item Types**

Only multiple-choice (MC) items were employed in this study. The item design aimed to vary item difficulties by operationalising a dimension of cognitive complexity in the employed model for item development (Neumann et al., 2013). This process showed that the number of factors that need consideration varies substantially across contexts and disciplines. This variance was taken into account through three types of multiple choice items (MC items), thereby allowing a limitation of the amount of reading load per answering option in more complex items. Besides regular MC items (one correct solution), some items were formatted as two-attractor MC or complex MC items. To minimise confusion over differing items types, students were provided with a help-box that identified the correct number of answering options per item. All students were instructed about the different item types and the help-box at the beginning of testing sessions. To compare the three item types, Table 2 (AttB) presents the share of students choosing an incorrect answering pattern (fewer or more options than indicated) in the three employed item types.

**Table 2 (AttB).** Share of incorrect answering patterns (fewer or more than the correct number of options), as well as the guessing probability of three employed item types (%)

	Grade 6	Grade 8	Grade 10	Guessing probability (%)
<b>Regular MC</b> (1 attractor, 4–5 options) 32 /48 items	.13	.13	.13	25
<b>2-attractor MC</b> (2 attractors, 4–5 options) 10/48 items	9.3	8.8	5.4	5
<b>Complex MC</b> (4–6 attractors, 9–16 options) 6/48 items	11.7	13.3	4.7	≤ 1

From these data, two conclusions can be drawn:

(1) From Grade 6 to Grade 10, the share of students using incorrect answering patterns is relatively constant in all item types, thereby introducing only little variance *across grades*, which is the important dimension for the here presented study.

(2) Even though the share of students who incorrectly answered items is acceptably low, a comparison of the three item types indicates that the 2-attractor and complex MC items were more often answered incorrectly than the regular MC items. However, as the guessing probability was much higher among the regular MC items than among the two other item types, the different item types move closer together in producing construct-irrelevant variance.

In a related analysis of occurring cognitive processes during item answering (think-aloud protocols – see discussion section), consistent differences in item types were not observed. Similar to these findings, the effect of the different item types was found to be small in an earlier study (Opitz et al., 2014). Consequently, it is concluded that the differences in answering format are small enough for the items to be applicable for the scope of this study.

**Online material 3: Energy Learning Opportunities at Schools in Hamburg/Germany**

**Table 3 (AttB).** Learning opportunities that explicitly reference the energy concept in Hamburg/Germany, where testing for the presented study was conducted. The shown contents refer to the compulsory standards for general science classes at primary level (FHH-BSB, 2011a, b; 2014a), middle school at both high-performance (Gymnasium: FHH-BSB, 2011c,d,e) and mixed performance schools (Stadtteilschule: FHH-BSB, 2014b, c, d), as well as in high schools (both school types: FHH-BSB, 2009a,b,c). The referenced standards encompass the German national science standards (KMK, 2005a, b, c) and therefore include energy as a disciplinary core idea and a concept to link the science disciplines.

Due to the large number of learning opportunities, the table does not distinguish between learning opportunities of different school types, as their overlap was considerable. Several points represent summaries of more extensive sections in the standards. Translations are as direct as reasonable and include conceptually critical formulations

Grade level	General science
<p><b>1-4</b> General science at elementary School</p>	<p><i>By the end of grade 2:</i></p> <ul style="list-style-type: none"> <li>- Reasons for energy requirements of humans, animals and plants</li> <li>- Reasons for energy requirements of technical appliances</li> <li>- Possibilities for saving energy in daily life</li> </ul> <p><i>By the end of grade 4:</i></p> <ul style="list-style-type: none"> <li>- Energy requirements and energy transformations in living beings (nutrition and digestion)</li> <li>- Energy transformation in technical appliances (e.g. electricity is transformed into light, heat and movement)</li> <li>- Sources of electrical energy (conventional vs. regenerative)</li> <li>- Measures of saving/cutting down on energy with respect to climate protection</li> </ul>
<p><b>5-6</b> Science / Technology at lower secondary level</p>	<ul style="list-style-type: none"> <li>- Explaining heat by using the particle model</li> <li>- The relationship between heat and energy</li> </ul>

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Attachment B: Online Materials for Chapter 3/Study 2

Grade level	Biology	Chemistry	Physics
<p><b>7-10 / 11</b> (Gymnasium / Stadtteilschule)  Middle school</p>	<ul style="list-style-type: none"> <li>- Matter- and energy transformations in cells and organisms</li> <li>- Matter cycles and energy flow in ecosystems</li> </ul>	<p><b>By the end of grade 8:</b></p> <ul style="list-style-type: none"> <li>- Matter-and energy transformation through particle- and structural reorganization, as well as through the reforming of chemical bonds</li> <li>- Phenomena of matter and energy transformations in chemical reactions</li> <li>- Differentiation between matter-/energy-transformations and physical processes in chemical reactions</li> <li>- Dependence of the energy content of reaction systems on the exchange with the environment</li> <li>- Explaining energetic phenomena in reactions by the transformation of stored energy into other energy forms</li> </ul> <p><b>Additional contents until the end of grade 11:</b></p> <p><i>Competence domain 'content'</i></p> <ul style="list-style-type: none"> <li>- Description of matter-/energy-transformations via changes at particle level and re-formations of chemical bonds</li> </ul> <p><i>Competence domain 'evaluation'</i></p> <ul style="list-style-type: none"> <li>- Value, production and processing of fossil and alternative energy carriers</li> <li>- Applicability of fuel cells for energy transformations</li> </ul>	<p><b>By the end of grade 8:</b></p> <p><i>Competence domain 'content'</i></p> <ul style="list-style-type: none"> <li>- Electrical energy is represented by the dimension voltage and measured by the unit Volt.</li> <li>- Energy appears in different forms, which can be transformed into each other.</li> <li>- Energy can be transferred.</li> <li>- Energy is conserved.</li> <li>- In an electric circuit, energy is transferred from the source to a transducer.</li> </ul> <p><i>Competence domain 'knowledge discovery'</i></p> <ul style="list-style-type: none"> <li>- Description of natural processes by using the energy concept</li> <li>- Possibilities to limit loss of thermal energy</li> <li>- Hints for saving energy in school and everyday life</li> </ul> <p><b>Additional contents until the end of grade 11:</b></p> <p><i>Competence domain 'content'</i></p> <ul style="list-style-type: none"> <li>- Terms: temperature, thermal energy, heat flow, heat conductivity</li> <li>- Comparison of energy transducers respective their electrical properties</li> <li>- Kinetic energy and energy forms during free fall</li> <li>- Gravitational potential, kinetic, electrical potential and thermal energy</li> <li>- Efficiency as a measure of energy degradation</li> <li>- Relation between power, energy and time</li> <li>- Comparison of different types of power stations</li> <li>- Function of energy transducers (e.g. dynamo, combustion engine)</li> <li>- Units of different energy forms and power</li> <li>- Regenerative energy sources and the related energy transformations</li> </ul>

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			<p>- Formulas: <math>E_{\text{pot}} = m \cdot g \cdot h</math>,  <math>E_{\text{kin}} = \frac{1}{2} \cdot m \cdot v^2</math>; <math>Q = c \cdot m \cdot \Delta t</math>;  <math>E = P \cdot t</math></p> <p>- Mass and energy can be transformed into each other.</p> <p><i>Competence domain 'knowledge discovery'</i></p> <ul style="list-style-type: none"> <li>- Application of measurement devices to determine energy consumption, power, as well as amounts and costs of energy</li> <li>- Determination of caloric values</li> <li>- Using energy conservation for argumentation</li> <li>- Application of the above-mentioned formulas in simple problems</li> <li>- Calculation and estimation of efficiencies</li> </ul> <p><i>Competence domain 'communication'</i></p> <ul style="list-style-type: none"> <li>- Representation of energy transformations in block diagrams</li> <li>- Analysis of energy cost and consumption</li> </ul> <p><i>Competence domain 'evaluation'</i></p> <ul style="list-style-type: none"> <li>- Magnitudes of energy consumption in the private sector</li> <li>- Deriving hints for saving energy</li> <li>- Comparing energy transducers respective their efficiencies</li> <li>- Formulating statements for the responsible application of primary energy sources</li> <li>- Climate change with respect to the greenhouse effect and global warming</li> <li>- Application of ionizing radiation in nuclear power with respect to energy and energy utilization</li> <li>- Radiated energy from the sun as a product of fusion reactions</li> </ul>
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<p><b>11 / 12-12 / 13</b> (Gymnasium / Stadtteilschule)  High school</p>	<p><i>Metabolism and energy turnover:</i> - Cell architecture and organelles - Enzyme reactions - Photosynthesis - Respiration and fermentation - Energy transformation in cells and energy transfer via ATP</p> <p><i>Core idea matter- and energy transformations:</i> - Living beings as open systems - Applications concerning photosynthesis, the carbon cycle and energy flow through ecosystems</p> <p><i>Competence domain 'methods'</i> - Application of biology-specific explanatory models, e.g. in the ATP/ADP transfer system - Application of models, e.g. for energy flow</p> <p><i>Competence domain 'communication'</i> - Comprehensible, structured and terminologically adequate presentation of contents, e.g. by using matter cycles or energy flow</p> <p><i>Competence domain 'evaluation'</i> - Evaluation of everyday phenomena from a biological perspective, e.g. respective regenerative natural resources as energy sources</p>	<p>- Energy turnover describes all chemical reactions. - Quantitative and qualitative aspects of understanding the energy concept - Simple reactions and complex reaction systems - Energy und kinetics of chemical reactions</p> <p><i>Competence domain 'content'</i> - Looking at matter transformations from an energy perspective: Influence of catalysts on chemical reactions</p> <p><i>Competence domain 'evaluation'</i> - Impact of applied chemistry on securing food and energy supply - Impact of applied chemistry on the production of materials</p>	<p>Consolidation and integration of contents from the lower secondary grades, especially with respect to:</p> <ul style="list-style-type: none"> <li>- The field concept</li> <li>- The wave concept</li> <li>- The particle concept</li> <li>- The quantum concept</li> </ul>
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## References

- FHH-BSB - Freie und Hansestadt Hamburg Behörde für Schule und Berufsbildung (2009a). *Bildungsplan Gymnasium - Gymnasiale Oberstufe - Biologie*. Hamburg: Behörde für Schule und Berufsbildung.
- FHH-BSB - Freie und Hansestadt Hamburg Behörde für Schule und Berufsbildung (2009b). *Bildungsplan Gymnasium - Gymnasiale Oberstufe - Chemie*. Hamburg: Behörde für Schule und Berufsbildung.
- FHH-BSB - Freie und Hansestadt Hamburg Behörde für Schule und Berufsbildung (2009c). *Bildungsplan Gymnasium - Gymnasiale Oberstufe - Physik*. Hamburg: Behörde für Schule und Berufsbildung.
- FHH-BSB - Freie und Hansestadt Hamburg Behörde für Schule und Berufsbildung (2011a). *Bildungsplan Grundschule - Sachunterricht*. Hamburg: Behörde für Schule und Berufsbildung.
- FHH-BSB - Freie und Hansestadt Hamburg Behörde für Schule und Berufsbildung (2011b). *Bildungsplan Gymnasium - Sekundarstufe I - Naturwissenschaften/Technik*. Hamburg: Behörde für Schule und Berufsbildung.
- FHH-BSB - Freie und Hansestadt Hamburg Behörde für Schule und Berufsbildung (2011c). *Bildungsplan Gymnasium - Sekundarstufe I - Biologie*. Hamburg: Behörde für Schule und Berufsbildung.
- FHH-BSB - Freie und Hansestadt Hamburg Behörde für Schule und Berufsbildung (2011d). *Bildungsplan Gymnasium - Sekundarstufe I - Chemie*. Hamburg: Behörde für Schule und Berufsbildung.
- FHH-BSB - Freie und Hansestadt Hamburg Behörde für Schule und Berufsbildung (2011e). *Bildungsplan Gymnasium - Sekundarstufe I - Physik*. Hamburg: Behörde für Schule und Berufsbildung.
- FHH-BSB - Freie und Hansestadt Hamburg Behörde für Schule und Berufsbildung (2014a). *Bildungsplan Stadtteilschule - Jahrgangsstufen 5 / 6 - Naturwissenschaften / Technik*. Hamburg: Behörde für Schule und Berufsbildung.
- FHH-BSB - Freie und Hansestadt Hamburg Behörde für Schule und Berufsbildung (2014b). *Bildungsplan Stadtteilschule - Jahrgangsstufen 7-11 - Biologie*. Hamburg: Behörde für Schule und Berufsbildung.
- FHH-BSB - Freie und Hansestadt Hamburg Behörde für Schule und Berufsbildung (2014c). *Bildungsplan Stadtteilschule - Jahrgangsstufen 7-11 - Chemie*. Hamburg: Behörde für Schule und Berufsbildung.
- FHH-BSB - Freie und Hansestadt Hamburg Behörde für Schule und Berufsbildung (2014d). *Bildungsplan Stadtteilschule - Jahrgangsstufen 7-11 - Physik*. Hamburg: Behörde für Schule und Berufsbildung.
- KMK - Ständige Konferenz der Kultusminister der Länder in der Bundesrepublik Deutschland (2005a). *Bildungsstandards im Fach Biologie für den Mittleren Schulabschluss - Beschluss vom 16.12.2004*. München: Luchterhand.
- KMK - Ständige Konferenz der Kultusminister der Länder in der Bundesrepublik Deutschland (2005b). *Bildungsstandards im Fach Chemie für den Mittleren Schulabschluss: Beschluss vom 16.12.2004*. München: Luchterhand.
- KMK - Ständige Konferenz der Kultusminister der Länder in der Bundesrepublik Deutschland (2005c). *Bildungsstandards im Fach Physik für den Mittleren Schulabschluss Beschluss vom 16.12. 2004*. München: Luchterhand.

**Online material 4: Additional Statistical Procedures: Multiple Regression Analysis and Rasch Analysis**

**Part A: Results Multiple Regression Analysis**

**Table 1 (AttB).** Resulting models from multiple regression analysis. Steps show the inclusion (forced entry) of grade level and crystallized intelligence as the two major predictors for energy test scores. See 'Note' for model summary. *B* = regression coefficients, *SE B* = standard error of regression coefficient,  $\beta$  = standardized regression coefficients

		<i>B</i>	<i>SE B</i>	$\beta$
<b>Step 1</b>				
	Constant	-.16	.02	
	Grade level	.06	.00	.60**
<b>Step 2</b>				
	Constant	-.20	.02	
	Grade level	.05	.00	.48**
	Crystallized intelligence	.40	.04	.28**
<i>Note: R<sup>2</sup> = .36 (Step 1), p &lt; .001; R<sup>2</sup> = .44, adj. R<sup>2</sup> = .43 (Step 2); ** p &lt; .001</i>				

## **Part B: Methods and Results from Rasch analysis**

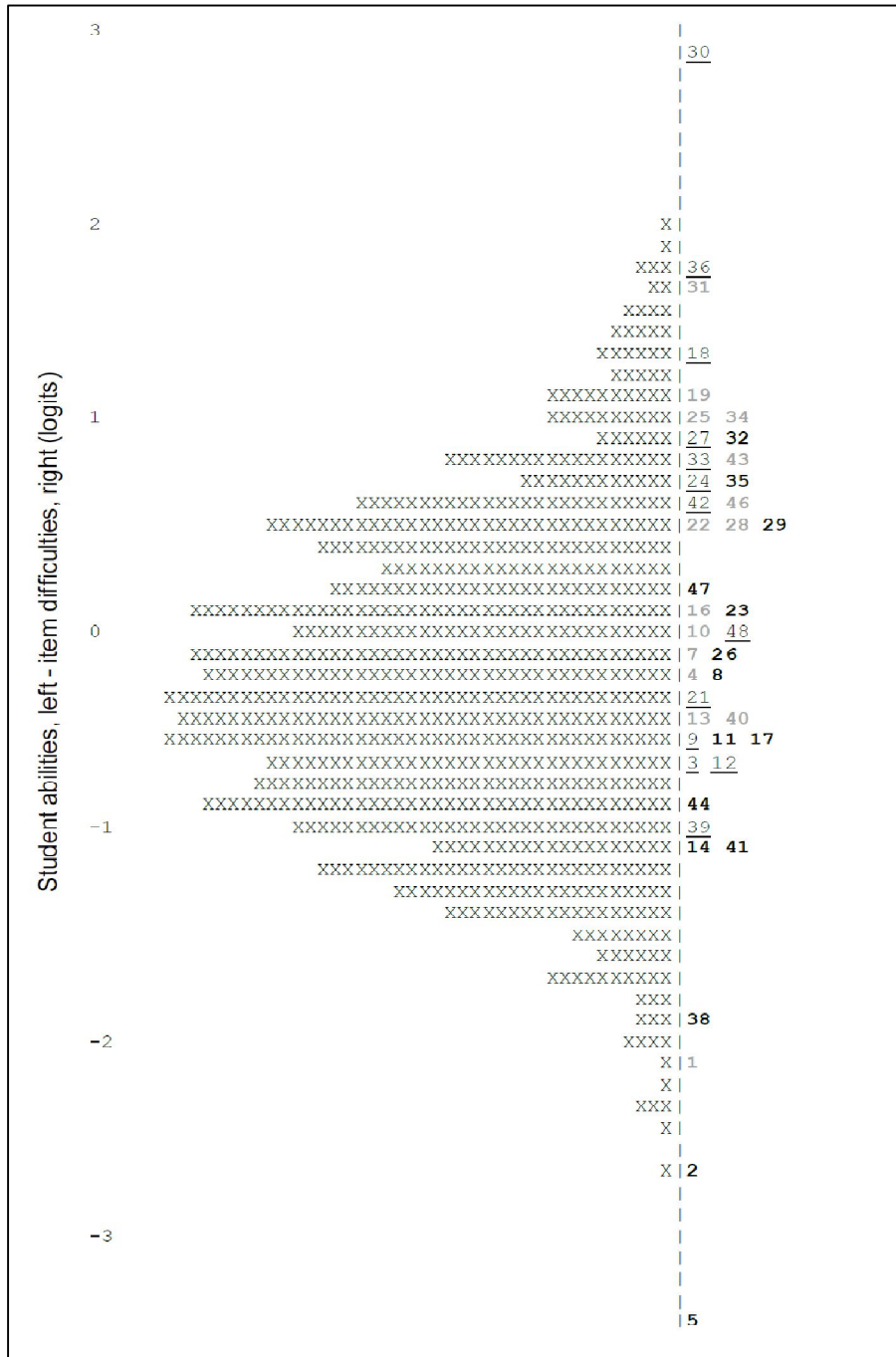
### **1. Methods**

1p/ Rasch models (Wu, Adams, and Wilson, 2007) of students' energy understanding were computed using AcerConquest 2.0. This model was conducted both across grade levels and for grade levels 6, 8, and 10 separately. The instrument adequacy in terms of the fit between item difficulty and students' abilities was analysed using a Wright map. Reliability was computed using WLE person separation indices, which are comparable to Cronbach's  $\alpha$  values (Wright & Stone, 1979; Wu et al., 2007, p. 25, 160). Differential item functioning (DIF, Wu et al., 2007, Ch.8) was used to determine if the developed items were answered differently by male and female students of similar abilities. DIF effects were analysed in relation to commonly used benchmarks (Wetzel, Böhnke, Carstensen, Ziegler, and Ostendorf, 2013).

### **2. Results**

**2.1 Wright map.** Figure 1(Attm B) shows a Wright map with the distribution of item difficulties (right) and students' abilities (left) in the reference group grade 10. The two parameters (student abilities and items difficulties) are presented on a logit scale with high-performing students, respective difficult items at the top, and low-performing students, respective easy items at the bottom. Ideally, item difficulties are spread widely to cover all abilities of the test takers. The distribution of item difficulties should furthermore reflect the distribution of students' abilities. Figure 1(Attm B) shows a sufficiently wide distribution of item difficulties and a reasonable fit between the distributions of item difficulties and student abilities. Thus, the developed instrument fitted students' performance in the reference group well. As the instrument was initially designed to assess energy understanding until high school (grade 12), the resulting instrument was slightly more difficult than grade 10 students' abilities.

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Attachment B: Online Materials for Chapter 3/Study 2



**Figure 1(Attm B).** Wright map of grade 10 student abilities (left) and item difficulties (right). Item numbers refer to numbers in the test booklet (see online material 1). Formats of item numbers indicate disciplines: shaded – biology, underscored – chemistry; **bold** – physics.

**2.2 WLE person separation reliabilities.** Across grades 6–10, WLE person separation reliability was high (.82) for the full test (grade 6: .57, grade 8: .76, grade 10: .83). The respective reliabilities of the disciplinary subtests were sufficient to satisfactory (.58–.62).

**2.3 DIF analysis.** The overall DIF effect of gender was significant and effected 15 items ( $\chi^2 = 13$ ,  $df = 1$ ,  $p < .001$ ). However, only three items showed 'slight to moderate' DIF effects ( $m = .32$  – range of DIF estimators =  $.25 - .38$ ), while the remaining 12 effects proved 'negligible' ( $m = .18$ ; estimators  $< .20$ , see benchmarks by Wetzel et al., 2013). Thus, DIF effects for gender can be considered unproblematic for the items of the developed instrument.

### 3. References

- Wetzel, E., Böhnke, J. R., Carstensen, C. H., Ziegler, M., & Ostendorf, F. (2013). Do Individual Response Styles Matter? *Journal of Individual Differences*, 34(2), 69-81. doi: 10.1027/1614-0001/a000102
- Wright, B. D., & Stone, M. H. (1979). *Best Test Design*. Chicago: MESA Press/University of Chicago.
- Wu, M. L., Adams, R. J., & Wilson, M. R. (2007). *ACER ConQuest version 2.0: generalized item response modelling software*. Camberwell, VIC: Acer Press.

**ATTACHMENT C: ONLINE MATERIALS FOR CHAPTER 4**

**Online material 1: Item and Item Parameters**

→See 'Attachment B, online material 1'

**Online material 2: Energy Learning Opportunities at Hamburg Schools**

→See 'Attachment B, online material 3'

**Online material 3: Item Fits within Parcels**

**Table 1 (AttE).** *1p*/ Rasch models (Conquest) for each of the 12 employed parcels: MNSQ unweighted / weighted as a validation of item fit to employed parcels. The second column refers to item codes as used in the items—see online material 1.

Parcel	Item	Estimate	MNSQ unweighted / outfit	MNSQ weighted / Infit
	122_1	-1.525	1.00	0.99
<b>Biology parcel 1</b>	113_2	0.094	0.98	0.98
Parcel by energy aspect: forms/sources	133_1	1.431	0.93	0.98
	Fourth item excluded in inter-rating on item-specificity for disciplines			
<b>Biology parcel 2</b>	211_1	-0.416	1.10	1.05
Parcel by energy aspect: transfer/transformation	223_1	0.392	0.86	0.96
	242_2	0.463	1.10	1.04
	222_1	-0.439	0.95	1.01
<b>Biology parcel 3</b>	331_2	-0.596	1.05	1.04
Parcel by energy aspect: degradation/dissipation	322_2	0.301	1.02	0.99
	311_2	0.346	1.05	0.98
	342_1	-0.052	1.07	1.01
<b>Biology parcel 4</b>	413_1	-0.48	1.03	1.03
Parcel by energy aspect: conservation	421_1	0.064	0.89	0.97
	423_2	0.624	0.82	0.96
	432_1	-0.208	1.10	1.04

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<b>Chemistry parcel 1</b> Parcel by energy aspect: forms/sources	CFM4	-0.389	0.94	0.98
	CFM2	1.222	1.07	1.05
	CFR3	-0.833	0.93	0.94
	Fourth item excluded in rating on item-specificity for disciplines			
<b>Chemistry parcel 2</b> Parcel by energy aspect: transfer/transformation	CTC2	-0.61	1.01	1
	CTF1	1.426	1.13	1
	CTR5	-0.816	1.01	1
	Fourth item excluded in rating on item-specificity for disciplines			
<b>Chemistry parcel 3</b> Parcel by energy aspect: degradation/dissipation	CDC1	-0.625	1.02	1.01
	CDR1	-0.157	0.99	0.99
	CDM1	0.783	0.87	0.94
	Fourth item excluded in rating on item-specificity for disciplines			
<b>Chemistry parcel 4</b> Parcel by energy aspect: conservation	CCR1	-0.948	0.98	0.99
	CCM1	0.077	0.95	0.97
	CCC2	1.342	0.99	0.94
	CCF1	-0.472	1.01	1.01
<b>Physics parcel 1</b> Parcel by energy aspect: forms/sources	FF1	-0.997	0.95	0.99
	FM3	0.391	1.01	1.01
	FR2	0.755	1.00	1
	FC2	-0.15	0.97	0.97
<b>Physics parcel 2</b> Parcel by energy aspect: transfer/transformation	TM3	-2.535	0.81	0.98
	TF2	0.8	1.09	1.01
	TR1	1.485	1.03	0.98
	TR2	0.249	0.96	0.97
<b>Physics parcel 3</b> Parcel by energy aspect: degradation/dissipation	DR1	-0.444	0.99	0.99
	DF1	1.007	0.97	1.01
	DM2	-0.563	1.00	1.01
	Fourth item excluded in rating on item-specificity for disciplines			
<b>Physics parcel 4</b> Parcel by energy aspect: conservation	CF2	-1.074	1.12	1.09
	CR3	0.206	1.04	1.03
	CF1	0.877	0.93	0.97
	CM2	-0.009	1.01	1.01
<b>Mean</b>			0.994	0.997
<b>Standard Deviation</b>			0.075	0.032

*Criteria for MNSQ weighted/MNSQ unweighted assessment*

(Bond & Fox, 2011, p.243)

High stakes multiple choice tests	$0.8 < \text{MNSQ weighted/unweighted} < 1.2$ ; upper value of $< 1.1$ in large samples ( $N > 1000$ )
Low stakes multiple choice tests	$0.7 < \text{MNSQ weighted/unweighted} < 1.3$



## ATTACHMENT D: ONLINE MATERIALS FOR CHAPTER 5

### Online material 1: Interview Protocol

**Note (see also methods section):** The protocol guided interviews of roughly 60 minutes length. It is structured around three contexts (a running child, a growing tree, a growing child). At the beginning of each of the three interview contexts, students were shown pictures that represented the contexts. These pictures were taken from an interview protocol by Jin and Anderson (2012).

Each of the three contexts contained two interview sections. Section A consisted of more general questions that stemmed from Jin and Anderson's (2012) interview guideline. This section was followed by more specific questions ('Section B') regarding the four energy aspects, i.e. energy forms/sources, transfer/transformation, degradation/dissipation, and conservation. These questions were open-ended adaptations from representative items an earlier quantitative study (Authors, 2015b). For each context, the majority of questions were considered entry level and applied for all students. Advanced questions were skipped if students' had substantial difficulties with respective contents.

To facilitate the organization of the interviews, some questions from the general part Section A were included in Section B. To better identify the background of each question, we use the following formatting style:

- *Questions from the general 'Section A' (Jin and Anderson, 2012) are marked italic.*
- *Advanced questions from 'Section A' are marked grey and italic.*
- Entry-level questions from 'Section B' on the four energy aspects are in regular font.
- Advanced questions from the specific 'Section B' are presented in grey font.

### Context 1: Running Child

#### Section A: General questions (adapted from Jin and Anderson 2012)

#### Enablers [Food, Air, Water, Sleep]

- *What does the child need to be able to run? [Please note down answers!]*
- *How does [enabler, please go through student replies] help the child to run?*
- *What happens with [the enabler; during sleep] in the child's body? Is the [enabler] used up or is it transformed into something else?*

- *[For enablers the students didn't mention, please ask]: We asked other kids at your age this question, too. Some said the child needs [enabler], too, to be able to run. Do you agree? If 'yes', go to questions b and c. If 'no': Why do you disagree?*

**Respiration (CO<sub>2</sub> - O<sub>2</sub> cycle):**

- *Do you think that breathing helps the child to run?*
- *Do you think the movement and the breathing are related processes?*
- *If the student mentions CO<sub>2</sub> in relation to respiration: Do you believe that carbon dioxide, 'CO<sub>2</sub>', contains carbon atoms? If 'yes': Where do these carbon atoms stem from?*

**Energy sources:**

- *Does the child require energy to be able to run? If 'no': Why not?*

**Section B: Specific questions on four energy aspects (adapted from items by Authors, 2015b)**

**Energy forms/sources:**

- *You [other children] said that the kid needs energy to be able to run. Where does the energy stem from that a child uses for running? [Please note down]*
- *What energy form has [enabler – go through the things that the student said the child would need for running]*
- *Why do you believe that the things that you mentioned possess energy?*
- *If the student associates energy with nutrition, ask: What happens with the energy from the food while the child is running?*
  
- *I will not mention some points that are important for how much energy the child needs for running. Could you say what energy form is behind these examples?  
(1) Speed of the running child (2) How much the body of the child warms up  
(3) Food in the child's body (4) Growing body parts]*
- *If the student mentions storage in chemical bonds, ask: Apparently, chemical energy is stored in parts of the human body. What needs to happen to make this energy available for the human body?*
  
- *We are now looking at the 'total energy' of the running child: What is relevant for how much energy the running child possesses in total?*

**Energy transfer and transformation:**

- *As the child is running, energy is being 'transferred' and 'transformed'. What is happening in these two processes?*
- *Can you provide an example where energy is transformed by the running child? If 'yes': What energy form or forms are involved in this example?*
- *And what would be an example for 'energy transfer' in the running girl? If the student provides an example, ask: What energy form or forms are involved in this example?*

- The running child uses chemical energy stored in food or in the child's body in order to be able to run. How does this chemical energy become the kinetic energy of the running child?

**Energy degradation and dissipation:**

- The child uses different energy sources to be able to run. Where can you rediscover this energy after the energy transformations that occur while the child is running?
- If the student names examples: And what energy forms would that be?
- As the child is running, energy is 'degraded'. What is meant by that?
- If the student describes thermal energy/heat, ask: Where does this thermal energy/heat stem from? Is the heat/thermal energy of further use to the child? What happens with the heat/thermal energy in the long run?
- If the student mentions heat/thermal energy transfer into the environment, ask: What happens with the heat/thermal energy in the environment?
- *If the student doesn't reference energy by himself/herself, ask:  
The body of the child is getting warmer while the child is running. What is causing this increase in temperature?*
- *Do you believe that heat is energy?*
- After some time, the running child will start to sweat. The body uses sweating to keep the body temperature constant. Can you imagine what sweating has to do with energy degradation?

**Energy conservation:**

- I will now give you an example where energy plays a role in the running child. Please state for each example, if the energy (a) is taken up, (b) stored in the child or (c) released into the environment. [Please repeat the three options].  
(1) Chemical energy in foods (2) Speed of the running child (3) Energy that the body transforms into thermal energy
- Could you compare the amounts of (a) energy taken up the child with (b) the energy stored in the child AND the energy released into the environment? Are these amounts equally large or is one larger?
- Is energy also getting lost while the child is running? If 'yes': What do you imagine happens when energy is getting lost? If 'no': Why not?
- On the day where we watch the child running, the girl took up 1500 kcal ('calories') of energy through nutrition. Let's assume that all of this energy is transformed by the child's body.
- How many of these 1500 kcal of energy exist after they were used by the running child?
- What is the relation between the energy taken up by the child and the energy transformed from it?
- If the student answers these questions but does not address system boundaries, ask: Energy is always transferred within system boundaries. Where would be the boundaries of the system for analysing energy transfer in the running child?

**Context 2: A growing tree**

**Section A: General questions (adapted from Jin and Anderson 2012)**

**Enabler [Sunlight, water, soil and nutrients, air]**

- *What does the tree need to be able to grow? [Please note down]*
- *How does the [enabler] help the tree to grow?*
- *Is the [enabler] used up by the growing tree or is the [enabler] transformed by the tree into something else?*

*For enablers that the student didn't address, please ask: Some students said that the tree also needs [enabler] to grow. Do you agree?*

*If 'yes': Please ask questions two and three under 'enabler'*

*If 'no': Why is it wrong what the other students said?*

**Nutrition**

- *As you have seen, the tree's weight increases as it grows. Where does this weight come from?*
- *People say that trees 'produce their own food'. What is meant by 'food'?*
- *In how far is our food different or similar to things that plants use in order to grow? [Please provide an example, if the student doesn't understand, e.g., sunlight and carbohydrates]*
- *If the student mentions glucose/starch/cellulose or carbohydrates, please ask: Do you think that the matter that the tree is built from contains carbon atoms? If 'yes': Where do these carbon atoms come from?*
- *If the student mentions the exchange of CO<sub>2</sub> and O<sub>2</sub>, please ask: The tree takes up carbon dioxide and releases oxygen. While carbon dioxide, CO<sub>2</sub>, contains a carbon atom, oxygen, O<sub>2</sub>, does not. What happens to the carbon atom from the CO<sub>2</sub>?*

**Energy sources**

- *Does the tree need energy to be able to grow? If 'no': Why? If 'yes', ask:*
- *Let's now talk about the energy in the wood. Did this energy already exist outside the tree before it was stored in it?*
- *Was any of this energy produced by the tree?*
- *If 'yes': Is the energy that was 'produced' by the tree stored inside the tree?*

*If 'yes':*

- *Where or wherein does the tree store energy?*
- *Is the energy stored in cells or molecules? If yes, could you name them?*

**Section B: Specific questions on four energy aspects (adapted from items by Authors, 2015b)**

**Energy forms and sources:**

- You said that the tree needs energy to grow. Where does the tree get the energy from that it needs to grow? [Please note down student answers]
- What energy form is this? [Name student answers from above.]
- *Why do you believe that the things you mentioned possess energy? [Help student remember the things she/he said]*
  
- I will now list a few things that can have an influence on the tree's growth. Please tell me which form of energy these examples refer to. (1) Temperature of the environment (2) Sugar that the tree built up using sunlight (2) The sunlight itself
  
- The tree in the picture grew a lot. This process required a substantial amount of energy. What does the total energy, i.e. all the energy of the tree, depend on?
  
- If student addresses energy in chemical bonds, ask: Apparently, there are parts of the tree in which energy is stored in chemical bonds. What needs to happen to make this energy accessible?

**Energy transfer and transformation:**

- *Is the tree transforming energy from the sun into something else?*
- When we talked about the running child, we spoke about how energy can be transferred and transformed.
- Can you give an example where energy is transformed in the growing tree? If the student provides an example, ask: What energy form or energy forms are present in the transformation that you described?
- Can you give an example where energy is transferred in the growing tree? If the student provides an example, ask: What energy form or energy forms are present in the transfer that you described?
  
- The tree uses sunlight to grow. In spring, the tree has not yet grown leaves. How does energy from sunlight get into the growing leave buds?
- Can you describe what is happening to the total amount of energy that reaches the tree in the form of sunlight?

**Energy degradation and dissipation**

- *Is it still energy after the light energy was transformed by the tree?*

- The tree takes up energy and uses it for its growth. Where can you rediscover the energy after the tree has used it?
  - Which energy forms are these?
  
  - *Energy is 'degraded' in different life processes in the tree. What does 'energy degradation' mean?*
- If the student states that a part of the energy is transformed into heat, ask:
- Is this heat/thermal energy still of any use to the tree?
  - What happens to this thermal energy/heat on the long run?
  - If the student states that heat/thermal energy is released into the environment, ask: What happens with the heat/thermal energy in the environment?
- If the student does not mention heat/thermal energy, ask:
- The tree is warming up through different life processes. Can you imagine where this heat is coming from?
  - Afterwards, ask the three questions above in grey font.

### **Energy conservation:**

- I will now mention three examples in which energy plays a role in the tree's growth. For each of these examples, please mention if it is about energy that is (a) taken up, (b) stored in the tree, or, (c) if it concerns energy released into the environment. [Please repeat the three options.]  
(1) Sunlight (2) Discarded branches (3) The sugar that the tree builds up using sunlight
  
- Could you compare the amounts of (a) energy taken up by the tree with (b) the energy stored in the tree and the energy released into the environment? Are these amounts equally large or is one larger?
- Is energy also getting lost while the child is running? If 'yes: What do you imagine happens when energy is getting lost? If 'no': Why not?
  
- On a given day, the tree takes up 10.000 kJ of energy via the sunlight. Let's assume that all of this energy is transformed by the tree.
- How many of these 10.000 kJ of energy still exist after they were used by the tree?
- What is the relation between the energy taken up by the tree and the energy transformed from it?
- If the student answers these questions but does not address system boundaries, ask: Energy is always transferred within system boundaries. Where would be the boundaries of the system for analysing energy transfer in the example of the growing tree?

### Context 3: A growing child

#### Section A: General questions (adapted from Jin and Anderson 2012)

##### Enabler [Food, Water, Air, Sports, Sleep]

- *What does the baby need to be able to grow? [Please note down!]*
- *How does [enabler] help the baby to grow?*
- *What happens to [enabler] in the baby's body?*
- *Is the [enabler] used up in the baby's growth or is it transformed into something else by the baby's body?*
- *For enablers not mentioned, ask: Some students said that the baby also needs [unmentioned enablers] to grow? Do you agree? If 'no': Why do they not need it? If 'yes': Ask questions two and three in this section.*

##### Growth as an increase of matter

- *Where does the matter from the increased weight of the growing child come from?*
- *Imagine the child would lose weight: Where would the matter that is responsible for the decrease in weight go? Is the matter used up or is it transformed into something else?*
- *If the student mentions glucose/starch/cellulose or carbohydrates in relation to the child's growth, please ask: Do you think that the body of the child contains carbon atoms? If 'yes': Where do these carbon atoms come from?*

##### Energy sources

- *Does the child's body require energy to be able to grow? If 'no': Why not?*
- *Has the energy in the child's body parts already existed before it become part of the child's body?*
- *Do you think the baby stores energy in its body?*
- *If the student provides ideas: Is the energy stored in cells or in special molecules? If 'yes': Could you name them?*

#### Section B: Specific questions on four energy aspects (adapted from items by Authors, 2015b)

##### Energy forms and sources:

- You said (other kids said) that the child requires energy to be able to grow. Where does the child get the energy from that it uses for growing? [Please note down!]
- What energy forms are behind the things you mentioned?
- If the student does not name sources of energy for growth, ask: Do you think the baby receives energy from air/oxygen (water, nutrients, food) for its growth?
- What is responsible for the total energy of the child? This includes all the energy that can be attributed to the child.

**Energy transfer and transformation:**

- *If the student associated energy with food, ask:*
  - *What happens with the energy from the nutrition in the baby's body?*
  - *Is it used up?*
  - *Is it transformed into something else or is it still energy after the energy was transformed in the child's body?*
  
- Earlier, we already spoke about energy transfer and transformation.
- Can you give an example for an energy transformation that takes place as the child grows? If the student provides an example, ask: What energy form or energy forms are present in the transformation that you described?
- Can you give an example of energy transfer in the growing child? If the student provides an example, ask: What energy form or energy forms are present in the transfer that you described?
  
- What happens to the energy that the child takes up through nutrition? For example, how does the energy get into the muscles of new grown body parts?

**Energy degradation and dissipation:**

- *Are we still looking at energy after the energy was used for growth?*
- *Where would you be able to rediscover the energy after it was used?*
- *Which energy forms are these?*
- *During the child's growth, his/her body also degrades energy in different body processes. What is meant by energy degradation in this example?*
- *If the student addresses that a part of the energy is transformed into heat/thermal energy, ask:*
  - *Where does this heat/thermal energy come from?*
  - *Can the child still use this heat/thermal energy, e.g., for growing?*
  - *What happens with this heat/thermal energy on the long run?*
- *If the child addresses that heat/thermal energy is released into the environment, ask: What happens with the heat/thermal energy in the environment?*
  
- *If the student does not address heat/thermal energy by himself/herself, ask: Especially kids are known for being 'always warm' in winter, e.g., their hands.*
  - *Where does the body's heat/thermal energy come from?*
  - *Ask questions in grey font in the previous paragraph.*



**Energy conservation:**

- *Is energy being lost during the child's growth? If 'yes': What do you imagine happens when energy is lost? If 'no': Why is energy not getting lost in this process?*
- During his/her growth, the child takes up approximately 2 million kcal of energy through nutrition.
- How much of these 2 million kcal of energy are still existing after the child uses the energy for growth?
- What is the relation between the energy taken up and the energy transformed from it?
- If the student does not by herself/himself address system boundaries, ask: Energy transfer is always happening within a system. Where are the boundaries of the system for the energy transferred during the child's growth?

Online material 2: Category System of Students' Conceptions about Energy in Biological Contexts

<b>Online Supplemental Material 2:</b> <i>Category System of Student Ideas Concerning Four Central Aspects of the Energy Concept: Energy forms/sources, transfer/transformation, degradation/dissipation, and energy conservation</i>					
	Grade 5 (n = 12; values 'adapted' to n = 6*)	Grade 7 (n = 6)	Grade 9 (n = 6)	Grade 11 (n = 6)	Total Number of Students (n = 30)
* As the grade 5 sample was twice as large (N=12) as the samples of the upper grades (N=6), the values for grade 5 were divided by two and rounded to facilitate the comparison across grades. Green highlights refer to categories in Figures 2-5, green numbers refer to categories mentioned only in the text. Note: The original short names of the categories have been adapted to allow better readability for researchers who are unfamiliar with the study area.					
<b>100000 Energy forms and energy sources</b>					
110000 Energy forms					
111000 Potential energy					
111100 Potential energy as a reference to position	0	0	0	1	1
111200 Chemical energy					
111210 Students describe the energy in minerals/in the soil as ...					
111211 'Mineral energy'	0	0	1	0	1
111212 'Soil energy'	1	0	0	0	1
111213 'Growth energy'	1	0	0	0	1
111214 No energy	0	0	1	0	1
111220 Students describe the matter of a living being as ...					
111221 An unknown form of energy	1	2	1	1	6
111223 'Body energy'	1	0	0	0	1
111224 'Growth energy'	3	4	4	1	14
111225 'Muscle energy'	1	0	0	0	1
111226 Chemical energy	0	1	1	6	8
111230 Students describe the energy of sugar or nutrition as ...					
111231 An unknown form of energy	4	3	5	0	16
111232 Energy that can be taken up	1	0	0	0	1
111233 'Force energy'	0	0	2	0	2

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111234	'Body energy'/Human energy'	1	0	0	0	0	0	1
111235	'Growth energy'	1	1	0	0	0	0	2
111236	'Production energy'	1	0	0	0	0	0	1
111237	'Food energy'	5	4	1	1	1	1	15
111238	Chemical energy	0	1	3	6	6	6	10
111240	<i>Students describe the energy in water as ...</i>							
111241	An unknown form of energy	2	2	2	2	0	0	7
111242	'Life energy'	1	0	0	0	0	0	1
111243	'Fluid energy'	1	0	0	0	0	0	1
111244	'Growth energy'	0	0	1	0	0	0	1
111245	'Organic energy'	0	0	0	0	1	1	1
111246	'Water energy'	1	2	0	0	0	0	4
111247	Chemical energy	0	1	1	4	4	6	6
111250	<i>Students describe the energy of air/O<sub>2</sub>/CO<sub>2</sub> as ...</i>							
111251	An unknown form of energy	2	3	1	0	0	0	8
111252	No energy	0	0	1	0	0	0	1
111253	'Air energy'	1	0	0	0	0	0	1
111254	'Breathing energy'	1	0	0	0	0	0	1
111255	Chemical energy	0	1	1	3	3	5	5
112000	Kinetic energy							
112100	Radiation energy							
112110	<i>Student describe the energy of sunlight as ...</i>							
112111	An unknown form of energy	2	3	0	0	0	0	7
112112	'Solar energy'	3	0	0	0	0	0	5
112113	Thermal energy	1	3	4	3	3	11	11
112114	Chemical energy	0	0	0	0	1	1	1
112115	Light energy/radiation energy	2	2	5	3	3	13	13
112200	Thermal energy							
112210	<i>Students describe the energy behind the body's/the environment's temperatur as ...</i>							
112211	An unknown form of energy	2	1	0	0	0	0	5
112212	No energy	1	0	1	0	0	0	2
112213	'Rapid-access energy'	1	0	0	0	0	0	1
112214	'Sweating energy'	1	0	0	0	0	0	1
112215	'Body energy'	1	0	0	0	0	0	1

Attachments  
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112216	'Temperature energy'	2	1	0	0	0	4
112217	Thermal energy	3	6	6	6	6	24
<b>112300</b>	<b>Kinetic energy</b>						
<i>112310 Students describe the energy of a running person as ...</i>							
112311	An unknown form of energy	1	1	0	0	0	3
112312	'Power/Sportsmanship'	1	1	0	0	0	2
112313	'Panting energy'	0	1	0	0	0	1
112314	'Running energy'	0	1	0	0	0	1
112315	'Body energy'	1	0	0	0	0	1
112316	'Friction energy'	0	0	1	0	0	1
112317	'Velocity energy'	2	2	0	0	0	5
112318	'Mechanical energy'	0	0	0	0	1	1
112319	'Kinetic energy'	1	1	5	6	6	14
1123110	'Propulsion energy'	1	0	0	0	0	1
<b>113000</b>	<b>Alternative ideas</b>						
<b>113100</b>	<b>Students attribute sleep as...</b>						
113110	An unknown form of energy	0	1	0	0	0	1
113120	A source of power	0	2	0	0	0	2
113130	A source of 'recreational energy'	1	0	0	0	0	1
113140	A source of chemical energy	0	0	1	0	0	1
		0					
<b>113200</b>	<b>Students equate energy and power</b>	1	0	0	0	0	2
<b>120000</b>	<b>Energy sources</b>						
<b>121000</b>	<b>The sun is the original source of all energy used by plants/animals.</b>	0	0	0	0	1	1
<b>122000</b>	<b>Energy sources for human movement</b>						
<b>122100</b>	<b>Unknown</b>	1	0	1	0	0	2
<b>122200</b>	<b>Sleep or rest</b>	2	3	0	0	0	7
<b>122300</b>	<b>Internal energy stores</b>	1	0	1	1	1	3
<b>122400</b>	<b>Sunlight</b>	0	0	0	0	1	1
<b>122500</b>	<b>Air</b>	2	1	1	1	2	7
<b>122600</b>	<b>Water</b>	3	0	1	1	2	9
<b>122700</b>	<b>Nutrition</b>	4	6	2	2	5	21

123000	Energy sources for plant growth								
123100	Air	4	2	1	1	1	1	12	
123110	Air (undifferentiated)	3	0	1	1	0	0	6	
123120	Carbon dioxide	1	2	0	0	0	0	3	
123130	Oxygen	1	0	0	0	1	1	3	
123200	Sun or sunlight	5	6	4	4	5	5	24	
123300	Water	3	4	1	1	3	3	14	
123400	Soil	3	0	1	1	1	1	7	
123500	Nutrients	0	3	0	0	2	2	5	
123600	Roots	0	0	1	1	0	0	1	
123700	'Heat' (from the sun)	0	0	0	0	2	2	2	
124000	Energy sources for human growth								
124100	Sun	1	2	1	1	2	2	6	
124200	Sleep	3	1	1	1	0	0	8	
124300	Fluids								
124310	Water	1	2	0	0	3	3	6	
124320	Fluids (other than water)	3	1	1	1	0	0	8	
124400	Air	3	3	1	1	2	2	9	
124500	Nutrition (incl. nutrients')	5	4	5	5	4	4	23	
130000	Energy stores								
131000	Energy in matter and light								
131100	No knowledge why something possesses energy	1	1	1	1	2	2	6	
131200	Nutrients/vitamins/water are responsible for the energy value of nutrition	1	1	1	1	0	0	4	
131300	Energy is necessary for the existence of stars	0	1	0	0	0	0	1	
131400	Matter possesses energy if it supports life or growth	3	5	1	1	2	2	14	
131410	Vital substances possess energy	2	4	1	1	1	1	10	
131420	Growth requires energy	1	2	0	0	0	0	4	
131430	Every life form possess energy	1	0	0	0	1	1	2	
131500	Light does not possess energy	1	0	0	0	0	0	2	
131600	Light possesses energy because it is warm and bright	2	0	2	2	0	0	5	
131700	Energy is stored in chemical bonds	0	0	0	0	1	1	1	

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Attachment D: Online Materials for Chapter 5/Study 4

131800	Matter always contains energy	0	0	0	0	0	0	2	2	2
131900	A complex flow of energy endows things with energy	0	0	0	0	0	0	1	1	1
132000	The human body stores energy in ...	1	1	1	0	0	0	2	2	4
132100	The human body (undifferentiated)	0	0	2	2	0	0	2	2	6
132200	Organs	0	1	1	2	1	2	0	2	5
132210	Organs (undifferentiated)	0	1	1	1	0	0	0	0	2
132220	Muscles	0	1	1	0	0	0	0	0	1
132230	Bones	0	1	1	1	0	0	0	0	2
132240	Skin	0	1	1	0	0	0	0	0	1
132250	Hair	0	1	1	0	0	0	0	0	1
132260	Brain	0	1	1	0	0	0	0	0	1
132300	Blood	0	2	2	1	0	0	0	0	3
132400	Cells	1	0	0	1	1	3	3	6	6
132500	Outside cells	0	0	0	0	0	0	1	1	1
132600	Water	0	1	1	0	0	0	1	1	2
132700	Carbohydrates (e.g. sugar)	0	0	0	0	0	0	2	2	2
132800	Fats	0	0	0	3	4	7	4	7	7
133000	A plant stores energy in ...	2	2	1	1	1	3	3	8	8
133100	Unknown, where a plant stores energy	1	0	0	0	0	0	2	3	3
133200	The plant (undifferentiated)	3	3	3	4	3	3	3	15	15
133300	Wood/bark/roots	1	4	4	3	3	3	3	12	12
133400	Leaves	1	5	5	3	3	3	3	13	13
133410	Leaves (undifferentiated)	0	0	0	1	1	1	1	2	2
133420	Chlorophyll									
133500	Cells	4	1	1	3	2	13	2	13	13
133600	Water	0	1	1	0	0	0	0	1	1
133700	Fruits	0	1	1	1	1	1	1	3	3
133800	Sugar	0	0	0	2	2	2	2	4	4
200000	Energy transfer and energy transformation									
210000	Energy transfer									

Attachments  
Attachment D: Online Materials for Chapter 5/Study 4

211000	Energy transfer is unknown.	2	3	1	1	9
212000	Energy transfer is a spontaneous transfer of heat.					
212100	Spontaneous transfer from warm to cold	0	0	1	1	2
212200	Spontaneous transfer from cold to warm	0	0	1	0	1
213000	Energy transfer is a change in energy form.	1	0	1	1	4
214000	Energy transfer means moving an object to another location.	2	2	3	0	9
215000	Energy transfer means the transfer of energy to another object.	4	4	2	3	17
216000	In energy transfers, the energy form remains unchanged while the object or location changes.	1	3	4	5	14
2200000	Energy transformation					
221000	Energy transformation is unknown.	5	1	0	1	11
222000	Light enables energy transformation.	0	0	1	1	2
223000	Energy transformation means energy is transformed into activity.	1	0	0	0	1
224000	In an energy transformation, matter is transformed into other matter.	2	1	2	0	6
225000	In an energy transformation, matter is transformed into energy.	1	0	1	0	2
226000	In an energy transformation, energy is transformed into matter.	2	1	1	1	7
227000	In an energy transformation, energy is transferred onto another object.	0	0	1	0	1
228000	The product of an energy transformation is also energy.	1	3	3	4	11
229000	Energy transformation entails a change in energy form.	3	5	5	6	22
2210000	In an energy transformation, the chemical structure changes.	0	1	3	5	9
2210100	Unknown how energy is released from a bond	0	0	0	2	2
2210200	Changes in a bond release energy.	0	1	3	5	9

Attachments  
Attachment D: Online Materials for Chapter 5/Study 4

2210300	To release energy from a chemical bond, the energy has to be detached from it.	0	0	1	0	0	1
2211000	In transformations, the change in energy occurs independently from the form of energy.	0	1	0	0	0	1
2300000	Energy as a part of matter cycles						
2310000	Energy cycles.	1	0	1	1	1	3
2320000	Energy is 'transported' along matter cycles.						
2321000	Transfer of energy in the human body is unknown.	2	0	0	0	1	4
2322000	In a tree, energy is transported in a network	0	2	1	1	1	4
2323000	In humans, nerves transport energy from the brain to the muscles.	0	1	0	0	0	1
2324000	Energy is transported via the muscles.	1	0	0	0	0	1
2325000	Energy is filtered from the body and is then transported to its destination.	1	1	1	1	2	5
2326000	In the human body, energy is transported via blood.	3	4	5	4	4	18
2330000	Storage of energy in matter cycles						
2331000	Energy supply in winter						
233110	Unknown, how trees maintain energy supply in winter.	2	0	0	0	0	4
233120	In winter, trees can use photosynthesis without having leaves.	1	0	0	0	0	2
233130	In winter, trees take up energy from the ground.	1	0	0	0	0	2
233140	In winter, trees use previously stored energy.	3	6	1	1	1	13
2332000	Sunlight is stored as chemical energy.						
2333000	Trees store sunlight in the form of light energy.	0	0	1	3	3	4
2334000	Humans store excessive energy in body fat.	0	1	0	0	0	1
2340000	Usage of energy in matter cycles						
2341000	Unknown usage of energy in the human body.	3	1	0	0	0	6
2342000	Unknown destiny of used energy.	1	1	0	0	0	3
2343000	Nutrition provides power and power allows activity.	1	0	0	0	0	1
2344000	During activity, energy is used, and this energy changes.	1	0	0	0	0	2
2345000	As part of matter cycles, energy is transformed into body substance.	3	2	2	3	3	13
2346000	As part of matter cycles, energy is transformed into thermal energy.	0	2	0	1	1	3
2347000	As part of matter cycles, energy is transformed into kinetic energy.	0	2	0	2	2	4
2350000	Energy release as part of matter cycles.						
2351000	Energy is released into the environment as a substance.	3	1	1	1	1	8



235200	The body can release transformed energy.	1	1	0	3	6
300000	<b>Energy degradation and energy dissipation</b>					
310000	Energy transformation or energy transfer of degraded energy					
311000	Energy degradation is a result of energy transfer.	2	2	4	6	16
311100	An energy source is degraded by taking energy from it.	0	0	1	0	1
311200	Energy degradation is caused by releasing energy.	2	0	0	3	6
311300	Energy degradation is caused by releasing matter that contains energy.	1	2	3	5	11
312000	Energy degradation is a result of energy transformation.	6	6	6	6	30
312100	Heat is released as an effect of energy degradation.	6	5	6	4	27
312110	Unknown cause for heat release	4	2	1	0	11
312120	Released heat stems from the environment.	2	0	0	1	5
312130	Activity releases heat.	4	3	1	2	13
312140	Friction releases heat.	1	2	0	2	6
312150	Pressure releases heat.	0	1	0	0	1
312160	Using energy releases heat.	2	2	0	4	9
312170	Transformation processes release heat.	2	0	5	6	14
312180	Combustion releases heat.	0	0	1	0	1
312200	Energy degradation depends on energy transformation.	0	1	0	2	3
320000	Energy degradation is unknown.	5	3	2	1	15
330000	Irreversibility of energy degradation					
331000	Energy degradation means that energy is 'lost'/consumed'.	4	3	2	2	14
332000	Usefulness of degraded energy					
332100	Usefulness of degraded energy (heat) is unknown.	1	3	0	0	5
332200	The quality of energy decreases if the energy is used.	2	0	0	0	3
332300	Degraded energy can be used by humans/plants.	6	6	5	6	29
333310	Heat can be transformed (by humans, trees)	3	4	2	3	15
333320	Heat can be stored.	3	2	2	2	11

333330	Heat enables life processes.	4	2	1	5	15
333340	Heat accelerates reactions.	0	0	1	0	1
333350	Heat is used to warm the body	2	3	2	4	13
333360	Heat supports the immune system.	1	0	2	0	3
333370	Degraded energy can be re-valued.	1	0	0	0	1
332400	Degraded energy cannot be used by humans/plants.	3	6	6	5	23
333410	Degraded energy has no further use.	2	2	4	2	11
333420	Thermal energy is not used by the human body.	3	5	5	5	21
333000	Heat is connected to energy degradation and has the lowest energy value.					
333100	Unknown destiny of heat/degraded energy	2	0	0	0	3
333200	Heat is used up.	1	0	0	0	1
333300	Heat becomes CO <sub>2</sub> .	0	1	0	0	1
333400	Thermal energy is released into the environment	5	6	5	6	26
333500	Energy released into the environment is taken up by another body.	2	1	0	1	6
333600	'Heat cools down and spreads in the environment'	2	3	3	4	13
333700	Thermal energy cannot be degraded any further.	0	0	0	1	1
340000	Degraded energy can be stored/bound.	0	0	0	2	2
350000	Energy degradation is a results of energy usage.	1	2	2	1	7
400000	Energy conservation					
410000	Energy 'consumption' and energy 'production'					
411000	Energy cannot be consumed/created.	6	5	6	6	29
411100	Energy exists before it is taken up by an organism.	4	4	3	3	17
411200	Energy cannot be created ('produced'/'generated').	4	2	3	4	16
411300	Energy cannot be consumed ('used up').	5	3	3	3	19
411400	Energy cannot be lost.	2	4	4	3	15
412000	Energy can be consumed/created.					
412100	Unknown, if energy can be consumed/created.	1	0	0	0	1
412200	Energy can be created ('produced'/'generated').	5	5	1	3	19

412300	Used energy is transformed into something else.	2	1	1	1	1	6
412400	Using energy consumes the energy	4	3	3	1	1	14
412500	Energy can be 'lost'.	6	6	4	4	4	25
412510	Unknown destiny of lost energy.	2	1	0	0	0	4
412520	Energy is lost if energy is redistributed.	1	0	0	0	0	1
412530	Energy loss means that energy does not exist any more.	3	1	2	0	0	9
412540	Energy is lost in energy transformations	2	2	1	0	0	6
412550	Energy is lost if energy is released.	3	2	3	3	3	13
412560	Energy is lost through energy degradation.	1	0	0	1	1	2
420000	Energy balances within system boundaries						
421000	The total energy of a human being depends on ...						
421100	The condition of the body	5	5	4	4	4	27
421110	Movement	5	4	3	4	4	21
421111	Movement (undifferentiated)	3	1	1	2	2	9
421122	Breathing frequency	0	1	0	0	0	1
421123	The person's effort and/or strain	0	1	0	0	0	1
421124	Speed of the person	1	3	1	1	1	7
421125	Kinetic energy of the person	2	2	2	2	2	10
421120	Sleep	2	2	1	1	1	7
421130	Air resistance	0	1	1	0	0	2
421140	Natural disposition/genetic disposition	0	1	2	0	0	3
421150	The person's power	1	0	0	0	0	1
421200	Matter/parts of the person's body	6	4	3	4	4	22
421210	Weight/size	2	1	2	2	2	8
421220	Body fat	1	0	0	1	1	2
421230	Legs	1	0	0	0	0	1
421240	Muscles	0	2	1	1	1	4
421250	Blood	1	0	0	0	0	1
421260	Organs	1	0	0	1	1	2
421270	Body (undifferentiated)	4	3	0	3	3	14
421300	The metabolism of the person	4	5	6	4	4	19
421310	The amount of energy taken up	0	0	3	1	1	4
421320	The amount of energy released	0	0	0	0	1	1

421330	Fluids that are part of the metabolism	3	2	3	0	10
421340	Nutrition	4	5	4	4	21
421350	Metabolism (undifferentiated)	0	0	0	1	1
421360	The process of growing	1	1	0	0	3
<b>421400</b>	<b>The environment</b>					
421410	The person's total energy is independent from his/her position in space	3	2	3	1	18
421420	The person's position in space	3	3	0	0	8
421430	Environment (undifferentiated)	2	1	0	1	6
421440	Heat	0	1	1	0	2
421450	Air	4	5	2	1	15
421451	Released CO <sub>2</sub>	3	1	1	0	8
421452	Air (undifferentiated)/breathing	0	0	1	0	1
421453	Oxygen	2	1	0	0	5
		1	0	0	0	2
421460	Sun	0	1	0	0	1
422000	The total energy of a tree depends on ...					
422100	Unknown	0	2	0	0	2
422200	The condition of the tree	2	1	0	1	5
422210	The tree's age	0	1	0	0	1
422220	Height of the tree	1	1	0	1	4
422230	'Power' of the tree	1	0	0	0	1
		0				
422300	Matter/parts of the tree	4	2	1	5	15
422310	The number of energy stores in the tree	0	0	0	1	1
422320	The capacity of energy stores in the tree	0	0	0	1	1
422330	Mass of the tree	2	0	0	4	7
422331	Mass (undifferentiated)	0	0	0	2	2
422332	Leaves	2	0	0	1	4
422333	Stem/wood/roots	2	0	1	2	6
422340	The entire tree	3	2	0	0	7
422350	'Heart' of the tree	1	0	0	0	1
422400	The tree's 'growth energy'	0	0	1	0	1
422500	The tree's metabolism	2	1	2	3	9
422510	The tree's ability to take up and release energy	0	0	1	2	3

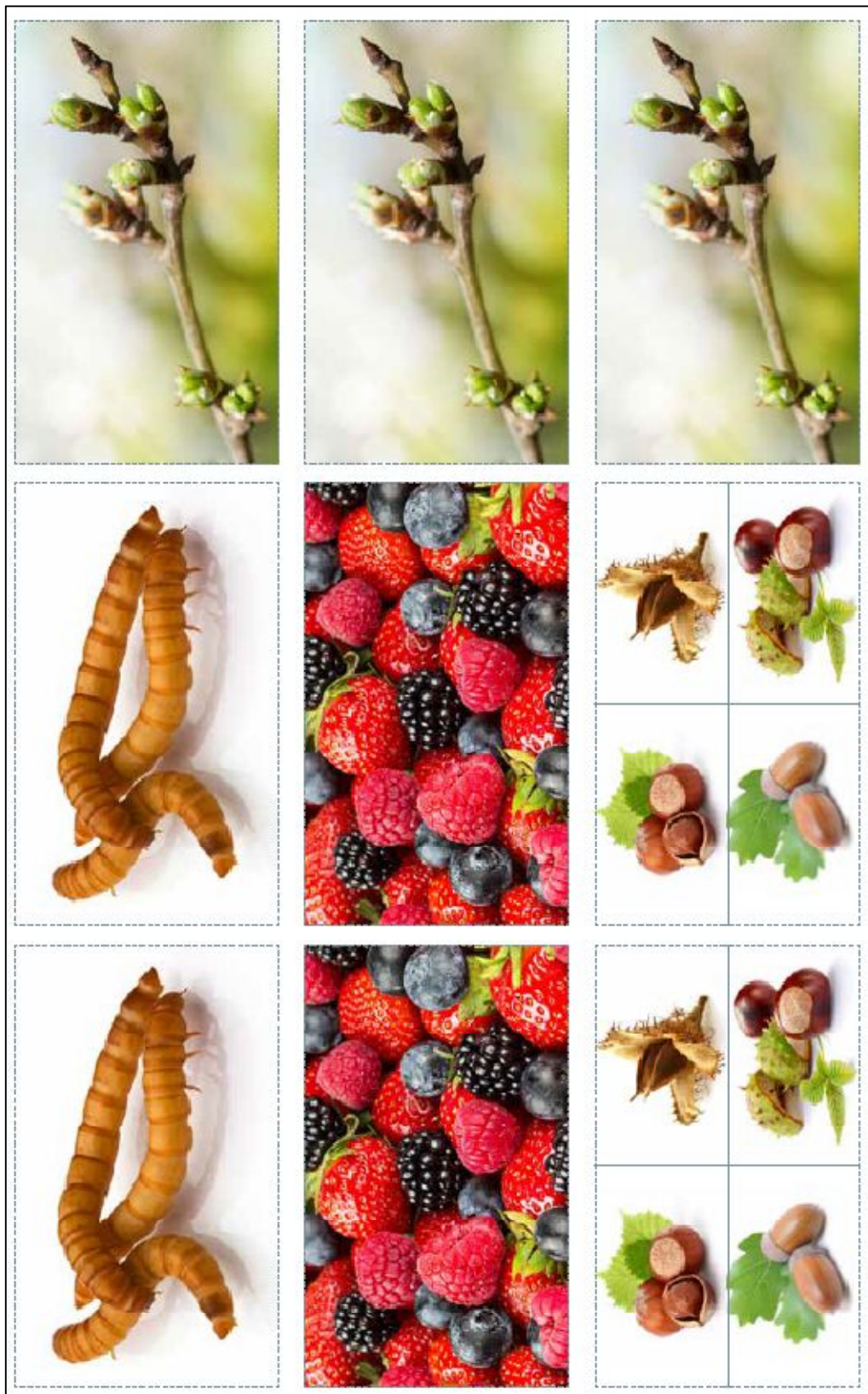
422520	Metabolism (undifferentiated)	0	0	0	0	0	1	1	1
422530	Food energy'	1	1	1	0	0	0	0	2
422540	Air	1	1	1	1	1	0	0	4
422550	Stored energy	1	0	0	0	0	0	0	1
422560	Energy uptake	1	0	0	0	0	0	0	1
422600	The tree's environment	3	2	2	4	4	3	3	15
422610	Energy from the sun	2	0	0	0	0	1	1	4
422620	Water supply	3	1	1	3	3	0	0	10
422630	Availability of light	1	1	1	4	4	0	0	7
422640	Availability of nutrients/minerals	1	0	0	2	2	1	1	5
422650	Thermal energy	2	1	1	1	1	1	1	6
422660	The tree's position in space	0	0	0	0	0	1	1	1
422670	The soil/ground	1	0	0	0	0	0	0	2
423000	Student ideas concerning the system boundaries for analyzing energy.								
423100	System boundaries are unknown.	1	1	1	2	2	0	0	4
423200	The boundaries of a body part	1	0	0	0	0	0	0	2
423300	The boundaries of the body	1	1	1	4	4	4	4	11
423400	The direct environment of the body/tree	1	0	0	1	1	2	2	5
423500	The earth and the atmosphere	0	1	1	2	2	3	3	6
423600	There are no closed systems.	0	0	0	1	1	0	0	1
424000	Energy balances								
424100	Drawing up energy balances								
424110	Energy uptake < Energy storage + Energy release	3	2	2	2	2	0	0	10
424220	Energy uptake = Energy storage + Energy release	5	5	5	5	5	6	6	25
424330	Energy uptake > Energy storage + Energy release	4	3	3	4	4	1	1	15
424200	Drawing up energy balances is unknown	1	1	1	0	0	0	0	3
424300	Energy uptake occurs through ...								
424310	Energy that was transformed into heat	1	0	0	0	0	0	0	1
424320	The speed of a person	1	0	0	0	0	0	0	1
424330	Sugar, that a tree builds up from sunlight	1	2	2	0	0	1	1	5
424340	Energy from sunlight that the tree takes up	2	3	3	6	6	6	6	19
424350	Chemical energy taken up with food	2	4	4	3	3	4	4	15
424400	Energy is stored through/in ...								

424410	Kinetic energy/speed of a person	1	0	1	0	0	3
424420	Energy in shed plant material	2	2	1	1	1	8
424430	Energy in sunlight	2	2	1	0	0	7
424440	Chemical energy in nutrition	2	2	4	2	2	12
424450	Thermal energy	3	3	1	1	1	10
424460	Sugars that were built up from sunlight	2	3	6	5	5	18
424500	Energy is released through ...						
424510	Light energy	3	0	0	0	0	5
424520	Thermal energy	3	6	6	5	5	23
424530	Energy in nutrition	3	3	1	0	0	9
424540	Stored energy in sugar	2	0	2	1	1	6
424550	Stored energy in shed plant material	4	2	5	5	5	19
424560	Kinetic energy/speed	4	5	4	6	6	23

**ATTACHMENT E: ONLINE MATERIAL FOR CHAPTER 6**

**Online material: Game Cards**









# Acknowledgement

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# Curriculum Vitae

## 1 Personal Data

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Nationality: German  
Date of birth: August 14<sup>th</sup>, 1985  
Place of birth: Gießen/Germany

## 2 Professional Activity

Since 05/2016 Visiting Scholar at the CREATE for STEM Institute at Michigan State University, USA

10/2014–  
01/2015 Research stay at the Weizmann Institute of Science, Israel  
(Work group of Prof. David Fortus)

10/2011–  
04/2016 PhD students at the Leibniz Institute for Science and Mathematics Education (IPN), Biology Education, Kiel University, Germany

- Participation in the multi-disciplinary 'Leibniz Research Alliance Energy Transition' (Germany)

## 3 University

09/2008–  
07/2009 Studies of Biology and English at the University of Aberdeen, UK;  
- Erasmus scholarship by the European Union (2 semesters)

10/2006–  
07/2011 Studies of Biology and English at Kiel University, Germany;  
- Degree for higher secondary education (State Diploma—equivalent to Master's degree; final grade: very good, 1.5) (8 semesters)

- Travel scholarship by the Schönhauser Stiftung Kiel for a presentation at the 2011 World Conference on Marine Biodiversity (Aberdeen, UK)

04/2006–  
09/2006 Law studies at Kiel University, Germany (1 semester)

10/2005–  
04/2006 Law studies at the University of Jena, Germany (1 semester)

## 4 School

- 04/2005 High School Diploma ('Abitur')
- 2004–  
2005 German high school at Tokyo/Yokohama, Japan
- 08–10/2001 Student exchange to Saskatoon, Canada  
- Travel scholarship by the federal state of Schleswig-Holstein,  
Germany
- 1996–  
2004 High school at Bad Bramstedt, Germany
- 1992–  
1996 Elementary school at Hamburg, Germany

## 5 Publications

### Peer review - published

**Opitz, S.**, Harms, U., Neumann, K., Kowalzik, K., Frank, A. (2015). Students' Energy Concepts at the Transition between Primary and Secondary School. *Research in Science Education*, 49(5), 691-715. doi 10.1007/s11165-014-9444-8

Appelhans, Y., Thomsen, J., **Opitz, S.**, Pansch, C., Melzner, F., & Wahl, M. (2014). Juvenile sea stars exposed to acidification decrease feeding and growth with no acclimation potential. *Marine Ecology Progress Series*, 509, 227–239. doi: 10.3354/meps10884

### Intended for peer review publication

**Opitz, S.**, Harms, U., Neumann, K., Bernholt, S. (re-submitted after major revision, 02/2016). How Do Students Understand Energy in Biology, Chemistry, and Physics? Development and Validation of an Assessment Instrument. *International Journal of Science Education*.

**Opitz, S.**, Harms, U., Neumann, K., Bernholt, S. (submitted 01/2016). Students' progressing energy understanding across contexts from biology, chemistry, and physics. *Research in Science Education*

**Opitz, S.**, Blankenstein, A., Harms, U. (in preparation for the *Journal of Biological Education*). Characteristics of Students' Progressing Energy Understanding in Biological Contexts.

## Non-peer review

**Opitz, S., & Opitz, M.-T.** (2016). Winterschlaf: Energiesparen als Überlebensstrategie [Hibernation: Energy Saving as a Survival Strategy]. *Unterricht Biologie*, 40(411), 18-23.

**Opitz, S.** (2011). *Vergleichende Untersuchungen über den Einfluss von erhöhtem Seewasser  $p\text{CO}_2$  auf den gemeinen Seestern *Asterias rubens* L. in der Ostsee* [Comparative Analysis on the Influence of Increased Sea Water  $p\text{CO}_2$  on the Common Starfish, *Asterias rubes* L. in the Baltic Sea], Staatsexamensarbeit [Master thesis equivalent], Helmholtz Center for Ocean Research Kiel/Germany, 112 pages

<http://oceanrep.geomar.de/12620/>

## **Declaration**

I hereby declare that the work presented in this thesis is my own in both form and content. With the exception of the supervision by Prof. Dr. Ute Harms and Prof. Dr. Knut Neumann, I have received no other help than the referenced sources in this work. This is my first dissertation and the work has never been used in any other dissertation attempts. The dissertation complies with the standards for good scientific practice proposed by the German Research Foundation (DFG). As indicated at their respective beginnings, the five articles presented in this doctoral thesis have been published, submitted, or are intended for submission at scientific journals.

Kiel, April 26<sup>th</sup>, 2016

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Sebastian Opitz