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DOES "THINKING IN SYSTEMS" FOSTER A CROSSDISCIPLINARY UNDERSTANDING OF ENERGY?

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Abstract

In school education the concept of energy should be a unifying element between all natural science disciplines. Still, many characteristics of living systems appear to be in contradiction to the laws of physics. Physics often refer to energy conservation in a closed system, whereas biology is dominated by open ecological or physiological systems with a "dynamic equilibrium". This makes the underlying, crosscutting scientific concept of energy hard to understand. Our study investigated, if the idea of an open energy system (with an in- and output of energy), located within an "idealized" closed system (in which the total amount of energy is conserved), offers the potential for a cross-disciplinary understanding. We developed a learning environment and applied interviews to identify students' ability to think in open and closed systems. Four teaching experiments with focus groups of three students each (9th grade, secondary school, males = 10) were carried out. Within the learning environment a scaled model demonstrated processes in a biogas plant and illustrated the idea of an open system that is in direct exchange with the environment. Students easily described the conversion of energy within the scaled model, but faced severe difficulties when the energy was emitted into the environment. Consequently they showed scientifically wrong conceptions when energy could not be perceived through phenomena anymore. We propose the particle model to illustrate energy and to bridge the apparent macro- microscopic gap.

Keywords: Conceptual development, particle model, open system, closed system

Introduction

Energy plays a central role in our everyday lives, as well as in science. Concepts of energy are crosscutting and intersect all natural science disciplines. Worldwide, societies have recognized the central role of schools within energy education and responded with a curricular implementation of energy concepts across all branches and years of schooling (e.g. NRC 2012). However, in science class the topic of energy is generally being taught focusing on the respective discipline. Rarely previous knowledge from other disciplines is incorporated, making the underlying, crosscutting scientific concepts hard to understand. Cooper & Klymkowsky critiqued that „we are failing our students by not making explicit connections among the ways energy is treated in physics, chemistry, and biology.“ (2013, p. 309). Between disciplines energy consumption, degradation and conservation often appear to be contradicting and are regarded as specific learning hurdles (e.g. Neumann et al. 2013). Only a few studies applied a multidisciplinary perspective in the discourse about a better understanding of energy (Cooper & Klymkowsky 2013; Dreyfus et al. 2015; Lancor 2014, 2014; Nagel & Lindsey 2015; Redish et al. 2014). Until now, empirically validated strategies are missing. We present our theoretical model of "thinking in systems" for an interdisciplinary understanding of the concept of energy in science class. In relation to the respective discipline, the "system nature" of the concept of energy (Duit 2014) is often either perceived within a closed or an open system. Lancor stated, that "the principle of energy conservation needs to be introduced in tandem with the idea of a clearly defined system." (2014, p. 1263). In reference to the 2nd law of thermodynamics, physics refer to energy conservation within a closed system, e.g. in terms of calculations. In contrast to these "idealized systems" (Nordine et al. 2010, p. 670) it is stated, that „nonequilibrium systems, such as those found in living organisms, are open in terms of energy" (Cooper and Klymkowsky 2013, p. 307). Within biological structures, that are in direct exchange with each other, energy circulates (e.g. within physiological or ecological systems). This approach is incorporated, for instance, in the research field of biological or biochemical thermodynamics (Alberty, 2006; Haynie, 2001).

Already in 1950 Von Bertalanffy developed the interdisciplinary "Theory of Open Systems in Physics and Biology“. He criticized that „so far, physics and physical chemistry have been concerned almost exclusively with processes in closed reaction systems, leading to chemical equilibria. (…) We need, therefore, an extension and generalization of the principles of physics and physical chemistry, complementing the usual theory of reactions and equilibria in closed systems, and dealing with open systems, their steady states, and the principles governing them.“ (1950, p. 23). More than sixty years later we are using his considerations of a "dynamic equilibrium" by taking open and closed systems for an interdisciplinary teaching approach into account.

This approach combines both systems - with the idea of an in- and output of energy in open systems that are located within an “idealized” closed system. The closed system stands for a constancy of the total amount of energy amidst the change of energy within the open systems (c.f. Hiebert 1962; Elkana 1974).

The model of “thinking in systems”

“Thinking in systems” deals with a theoretical model. Hereby open systems have to be defined previously; they can be enlarged to more complex systems or reduced to a lower level of complexity. Energy can be transferred from one part of a system to another part, as well as from one system to another.

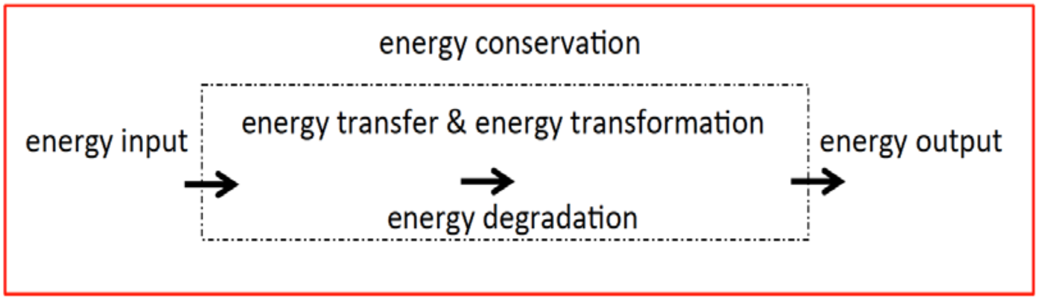

Fig. 1: The schematic representation of an open system within a closed system combines key ideas of energy. The black dashed line indicates the open system and the red continuous line the idealized closed system. Note, that Fig. 1 is simplified, taking only one single open system into account.

Fig. 1 shows a schematic representation: Within the closed system (red continuous line) energy is conserved and can move between open systems (indicated by a black dashed line). The total amount of energy remains unchanged. The connection of both systems relates energy conservation (closed system) with its input and output (open systems). Inside the open system (dashed line) energy is transferred, transformed, thereby degraded and emitted into the environment. The black line is dashed to indicate that open systems always interact with the overarching system; hence they are exposed to external forces, inter alia expressed by gravitational energy (cf. Doménech et al. 2007). As a consequence the open system should not be considered independently from the surrounding systems.

The application of our theoretical model of “thinking in systems” should connect open and closed systems within a learning environment. Thus it should foster an understanding of interdisciplinary key ideas of the concept of energy. We developed a learning environment, which is based on the idea of “thinking in systems” and analysed the effects on students` understanding of the concept of energy.

Sample and Procedure

Four teaching experiments were conducted and audiotaped, with focus groups of three students each. Learners were aged between 15 and 16 years (grade 9, secondary school). It is important to note that many aspects of the concept of energy have already been addressed in the classroom. Teaching experiments consisted of a pre-interview, an intervention and a post-interview. The same person conducted all teaching experiments and interviews that lasted on average 35 minutes. An open interview guide enabled us to rephrase original questions and to add questions to identify „mis“conceptions. Altogether twelve participants (males = 10) were interviewed. The learning environment (schematically shown in Fig. 2) should demonstrate the idea of an energy exchange between an open system (consisting of a scaled biogas model) and the idealized closed system (environment).

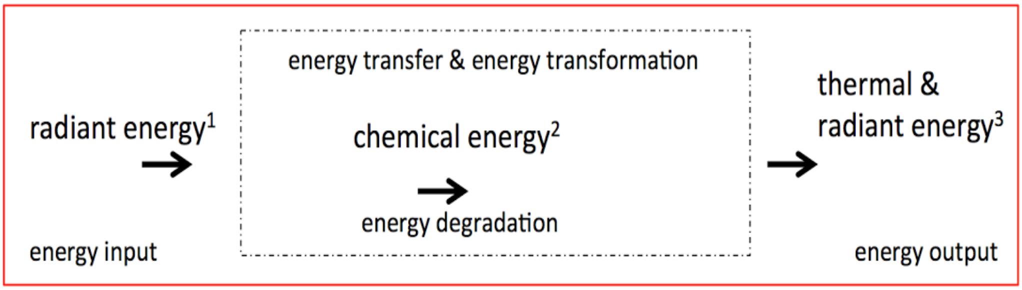

Fig. 2: Schematic representation of the practical implementation of “thinking in systems” within a learning activity. Transformation processes are indicated by numbers and explained in more detail below. The black dashed line indicates the open system and the red continuous line indicates the idealised closed system (cf. Fig. 1).

1. Energy input by biomass (as a source of energy).
2. Production of biogas via fermentation of biomass by bacteria (using liquid manure and corn) in a scaled biogas model (based on Jaeckel & Parchmann 2010)
3. Ignition of biogas and emission of thermal and radiant energy indicated by light and heat. Emitted heat could be measured with a digital infrared thermometer.

Pre-interview: Students explained – contextless - six predefined key ideas of the energy concept (input, transformation, transfer, degradation, output and conservation of energy)

Intervention: The scaled model was introduced and the interviewer explained the idea of “thinking in system” in relation to the model, including the idea of an energy exchange between the open system (represented by the model) and the closed system (represented by the environment).

Post-interview: Students should describe the six predetermined key ideas (input, output, transformation, transfer, degradation and conservation of energy) of the energy concept in reference to the open system (represented by the model) and the closed system (represented by the environment).

Data Evaluation

Firstly we evaluated the scientific connectivity of the students’ descriptions. Secondly we analysed the students’ „mis“conceptions and tried to detect underlying schemata to identify causes for possible learning obstacles. Our understanding of students` conceptual development is based on the theoretical assumption of an “embodied mind“ as the origin of cognitive schemata and is grounded on the theory of Experientialism (Lakoff & Johnson 1999): Lakoff and Johnson assume that we understand new matter on the basis of the known and familiar and rely on schemata that already have been established in early childhood (Lakoff 1987). They are assigned and help to structure concepts (Lakoff & Johnson 2008). Hereby energy as an abstract concept is understood imaginatively, because directly meaningful concepts and schemata are used (cf. Niebert & Gropengießer 2014).

Results

Scientific connectivity of students’ descriptions

Pre-interview: In the pre-interview students mainly named definitions that already have been addressed in the classroom - interestingly they all referred to physics education. Stated descriptions of the predetermined key ideas (including input, transformation, transfer, degradation and output of energy as well as energy conservation) were not always scientifically correct at first, but have been elaborated and improved during the group discussions.

Post-interview/open system: Without difficulties students were able to transfer the key ideas to the open system. They easily identified different manifestations of energy and connected transfer and transformation processes. Hereby they explained the in- and output of energy and the degradation of energy along with energy conservation.

Post-interview/closed system: Although students could state that energy is not destroyed and still exist within the environment, they could not detect the conversion of energy outside of the open system. Learners knew that thermal and radiation energy is released into the environment and is still existent, but they could not perceive any manifestations of energy. “Mis”conceptions occurred when energy was no longer experienced by phenomena.

Exemplary „mis“conceptions

The question of the whereabouts of energy within a closed system leaded to extensive learning difficulties. Students answered to the question “What happens with the energy output of the glowing lamp?” and tried to explain the conservation of energy. Two “mis”conception, named during the post interview, exemplarily demonstrate the students’ attempts to identify the remaining energy (Tab. 1). David perceived the earth as a closed system; simultaneously he tried to identify energy through its effects. For Sarah energy re-circulated between the earth and the sun. Inquiring closer, Sarah compared energy with a water cycle.

Tab. 1: Students „mis“conceptions when energy was no longer experienced by phenomena

“Mis”conception	**Example**
Energy causes changes	“Thermal energy accumulates and contributes to global warming” (David, 15 years).
Energy is cycling	“Thermal energy is absorbed by the sun and re-radiated. Radiation energy passes on to plants and is further used for photosynthesis” (Sarah, 15 years).

Discussion

Overall, students’ concepts seemed to be quite sophisticated, if they had to reproduce key ideas of the concept of energy and applied them to the open system. It is important to note that the discussion itself (without any intervention) proved to be very conducive to learning. Contrary to our assumption, energy conservation together with the degradation or in- and output of energy did not appear to be contradicting for the students (c.f. Ogborn 1990; Trumper 1996; Neumann et al. 2013). Already before the intervention, students had a scientific understanding of energy as quantitatively stable, but subject to qualitative change. However, we identified the shift from the open to the closed system as a specific obstacle for the students.

In the post interview students could easily apply the key ideas of energy, as long as energy could be detected through its effects. They could also describe the transfer of energy into the system and out of the system. It has already been shown that the observation of energy-related phenomena fosters an experience-based understanding of energy (Brook & Wells 1988, Driver et al. 2013, Nordine et al. 2010). Thus the change from “visible” energy (open system) to “invisible” energy (closed system) could be detected as a difficulty. It seemed to be contra-inductive for the learners to believe that the “released” (thermal and radiation) energy is still there, because it could not be sensed anymore. They knew that energy could not be destroyed, though they were not able to apply this idea in a “real world” context. This seems comprehensible as our understanding of the world is based on our experiences.

Causes for “mis”conceptions and underlying schemata

“Energy causes changes“: In accordance with literature, participants of our study only recognized energy by visible changes (Goldring & Osborne 1994; Trumper 1996; Van Heuvelen & Zou 2001) and transformation processes when they could be observed (Trumper 1998; Goldring & Osborne 1994). David`s “mis”conception that thermal energy accumulates and contributes to global warming (due to energy conservation) is representative. Students lacked the concept that (at the atomic level) heat is kinetic energy that is transferred by atoms - consequently energy “gets lost“ in the atmosphere.

“Energy is cycling”: Sarah`s “mis”conception, that thermal energy is “absorbed” by the sun and re-radiated, demonstrates students’ attempts to identify an in- and output of energy. The schema of an in- and output (of energy) is directly and intuitively understandable, because of our daily life experiences (cf. Gropengießer 2007, p.109).

The closed system is counterintuitive

The idea of the conversion of energy within a closed system is based on a physical ideal that cannot be experienced directly in daily life (Nordine et al. 2011, p. 670). In real life we perceive a barrier between the in- and outside (of the system) (cf. “container schema” Johnson 1987, p. 126; Lakoff 1987, p. 267). The idea of a closed system that simultaneously is contiguous is a completely new idea that cannot be understood within common schemata. Unlike open systems, e.g. ecological or physiological systems, an idealized closed system is based on a mental image that must be accepted on the basis of physical laws.

We present the particle model as a possible solution that leads to a conceptual development: All matter is composed of discrete, energetic particles. Perceiving energy from a molecular perspective - transmitted by particles - offers the opportunity to relate to the “mis”conception “energy causes changes“ also if these changes are not perceptible on a macroscopic scale. Energy can appear - simplified - as a mixture of kinetic energy, potential energy and radiation energy. Other forms of energy can be derived from this (c.f. NRC 2012; Lancor 2014, p. 1256).

Particle models of matter are widely recognised as being fundamental in science education and pupils' understanding benefits from the introduction of a "particle level" (e.g. Papageorgiou & Johnson 2005). Understanding the structure and properties of matter is an essential part of science literacy (Tytler, Peterson & Prain 2006; Merritt & Krajcik 2013).

"A vast array of biological, chemical and physical phenomena can only be explained by understanding the changes in the arrangement and motions of atoms and molecules." (Harrison & Treagust 2003, p. 189). The suitability for learning of the display of molecular movements and bonds has been shown in different contexts. In science education the model is used "to explain material properties, the states of matter and phase changes, chemical reactions, the water cycle, diffusion, DNA and cell biology." (Harrison & Treagust 2003, p. 189). Still, besides the identified learning effectiveness, significant difficulties have been found. Although it is easy to inspire students at a macroscopic level, it is a pedagogical challenge to create the same fascination at the submicroscopic and symbolic level (Othman, Treagust & Chandrasegaran 2008). Additionally a progression in thinking within particle models is generally only attained over periods of some years (Garcia Franco & Taber 2009).

Conclusion

In contrast to (physical) closed systems that refer to the second law of thermodynamics, living systems are open systems that are never in true equilibrium. Von Bertalanffy (1950) speaks of a "dynamic equilibrium". Our interdisciplinary approach of "thinking in systems" presents an opportunity to link both systems. Within an open system key ideas of energy could be easily experienced (by sophisticated students) using the phenomena it produces. Though, we identified specific learning obstacles that are connected with energy conservation within closed systems. Outside of the open system energy is not conceptually tangible and cannot be perceived by its effects anymore. We propose the particle model to bridge the macroscopic (visible) –molecular (invisible) gap. Future studies should investigate if the conception of discrete, energetic particles and the display of molecular movements and bonds foster an understanding of the way energy is transformed and conserved, if it cannot be perceived through phenomena anymore.

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