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Young children's ideas of energy compared with the scientific energy concept: Results of a video study with interviews about children's own drawings

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For accessing young children's intuitive ideas about energy, twenty-five first and second graders of Swiss elementary schools (age 6–8 years, M=7 years 6 months) were asked to draw or write what they associated with energy and subsequently interviewed about their drawing or written note. The responses were videotaped. The children's responses, including gestures and other nonverbal responses, were analyzed using qualitative content analysis (QCA). A concept-driven approach was used to uncover links between the children's ideas and the core aspects of the scientific energy concept: forms/manifestations, transformation, transfer, dissipation/degradation, and conservation, and a corresponding coding frame was developed. Though the participating children had not encountered energy or topics like electricity or human nutrition in formal schooling, almost all (N=24) knew the term energy and used it in the interview. The findings indicate that already young children have nuanced ideas on how energy manifests and behaves that can be expressed by means of drawings/notes and verbally. These ideas refer to energy as an inherent feature of certain objects, as a causal agent, or as a kind of substance and are expressed in association with humans, electric sources and consumers, and vehicles, and their activities or features. The developed category systems summarize how young children express themselves about energy and enable comparison of these ideas with all core aspects of energy. The findings of this study indicate how the very first "steppingstones" for energy learning in early science classrooms might look like, and where "blind spots" or aspects that need further attention should be expected. The detailed analysis of the children's statements with the developed coding frames is a first step towards reconstruction of the children's mental models of energy and may serve as a basis for the development of educational and diagnostic tools.

KEYWORDS

energy, pre-instructional conceptions, elementary education, drawings, interviews

1. Introduction

To foster meaningful and sustainable science learning, disciplinary core ideas and crosscutting concepts are widely regarded as important contents for science teaching at the elementary and middle school level (National Research Council, 2007). "Big ideas" such as the concepts of matter, interactions and energy guided the development of science curricula in many countries, for example in Germany, Switzerland, and the United States

(Kultusministerkonferenz, 2005; Gesellschaft für Didaktik des Sachunterrichts, 2013; NGSS Lead States, 2013; Deutschschweizer Erziehungsdirektoren-Konferenz, 2016). The scientific energy concept is one of these "big ideas": The conservation of energy is a fundamental principle in physics that constrains how systems of the real world can evolve (National Research Council, 2012; Quinn, 2014). Hence, arguments based on the conservation principle are a powerful tool that allows analyzing phenomena from a broad variety of science contexts, describing them in unified terms and discovering commonalities among them, for example, energy flows or source-receiver relations (Feynman et al., 1965; National Research Council, 2012; Tobin et al., 2018). Energy is thus considered a disciplinary core idea in physics as well as a crosscutting concept in the natural sciences. Therefore, many elementary school curricula, or frameworks for such curricula, include energy as a topic of instruction already for young learners (Yuenyong and Yuenyong, 2007; AAAS, American Association for the Advancement of Science, 2009; Gesellschaft für Didaktik des Sachunterrichts, 2013; NGSS Lead States, 2013; Deutschschweizer Erziehungsdirektoren-Konferenz, 2016).

However, there is no common understanding what *young* children from kindergarten to second grade (K-2) are capable of and expected to learn: According to the Swiss curriculum, by the end of grade 2 of elementary school, children shall be able to *"perceive and talk about processes of energy transfer* (e.g., *the wound up spring drives the wind-up car* […])*"* and to *"describe the occurrence and use of energy in everyday life* (e.g., *food delivers the energy we need* […])*"* (stages a and b of the competence NMG.3.2; Deutschschweizer Erziehungsdirektoren-Konferenz, 2016). While stage a focuses on phenomena, stage b already includes the use of the term energy. The U.S. Next Generation Science Standards, on the other hand, recommend developing the idea of energy as a scientific concept *not at all* in K-2 education and only very generally in grades 3–5 (National Research Council, 2012, p. 120ff). Therefore, specifically in Switzerland, the question arises which aspects of the complex energy concept are accessible for children in the last year(s) of stage K-2, i.e., when the children are about 6–8 years old, and how age-adequate instruction can be designed.

Within the theoretical framework of conceptual change, students' pre-instructional conceptions are widely regarded as a key factor for successful teaching and learning (Posner et al., 1982; Duit and Treagust, 2003; Amin et al., 2014; Vosniadou, 2019). Based on their everyday experiences, individuals develop conceptions which act as mental models of reality and thereby enable orientation in everyday life; often, they are inconsistent, unstable and contextualized (Greca and Moreira, 2000; Johnson-Laird, 2013). Learning can be seen as a cognitive process in which learners actively change their conceptions, thereby, ideally, gradually approaching a scientific concept. As summarized for example by Vosniadou (2013, 2019) or Amin et al. (2014), there are different views about the structure of students' conceptions that have different instructional implications. In this study, it is assumed that students' conceptions are constituted by a variety of knowledge elements that are shaped by children's real-life experiences, language and social interactions and are more or less integrated to form conceptual models (Amin et al., 2014, p. 68ff). Simplified, learning can be seen as activation, organization, and re-organization of knowledge elements and thereby a development from very contextualized and simple to gradually more abstract and complex conceptual models. Consequently, the initial conceptions and the knowledge elements characterizing them, including the contexts they refer to and the language used to express them, can be regarded as important resources for learning.

Learning progressions play an important role in the design of instructional settings: Learning progressions can be understood as empirically testable hypotheses of in which stages the learning of a scientific concept may typically occur. They identify a targeted scientific concept (upper anchor), "typical" initial conceptions (lower anchor), and intermediate conceptual models that may act as steppingstones between the lower and upper anchor (Amin et al., 2014, p. 75; National Research Council, 2007; Neumann et al., 2013). Characterizing initial conceptual models and proposing age-adequate sequences of steps towards the targeted scientific concept are thus aims of learning progression research.

Consequently, it is necessary to characterize the initial conceptions as well as the targeted scientific concept with a similar level of detailedness. As suggested in the literature (diSessa et al., 2004, p. 855ff), such a specification should not only include existential aspects, e.g., associations with a scientific term, but also ontological aspects, specifically, as what a concept like "force" or "energy" is conceived of, how it relates to objects of the real world and how it behaves in time and space. The present study is based on a specification of the scientific energy concept that is widely used in science education literature. It will be described in the next paragraph.

Energy is one of the most fundamental, but also most subtle concepts in science. Since energy is not directly observable, the scientific energy concept can be regarded as a model for describing phenomena of the real world (Feynman et al., 1965; Papadouris and Constantinou, 2011; Tobin et al., 2018). To structure the complex energy concept, the following interdependent core aspects of energy have been identified (Duit, 1986, 2014; Driver et al., 1994; Liu and McKeough, 2005; Neumann et al., 2013; Lacy et al., 2014; Nordine, 2016; Herrmann-Abell and DeBoer, 2018; Tobin et al., 2018):

- *Manifestations/forms of energy*. Energy is not directly observable but its presence, form and amount are inferred from observations of indicators of energy (Nordine et al., 2011, p. 696) that are associated with an element of a system, e.g., an object. For example, moving objects are said to have kinetic energy. Despite there being several indicators of energy, all energy is fundamentally the same.
- *Transformation*. When system elements interact, correlated gains and losses of different indicators may occur. A falling ball, for example, gains velocity while it loses height. This is modelled by the transformation of one form of energy into another (in this example gravitational potential energy into kinetic energy).
- *Transfer*. In interactions, correlated gains and losses of indicators associated with different system elements may occur. A moving marble that collides with a resting one, for example, slows down while the other speeds up. This is modelled by the transfer of energy between these elements (in this example kinetic energy).
- *Dissipation and degradation*. Because of friction and other "losses," real-world processes cease. This is modelled by the transformation of energy into less "useful" forms (degradation, e.g., into thermal energy) and/or by energy transfer to the environment (dissipation).
- *Conservation*. The net energy remains constant in a closed system.

Learning the scientific energy concept, therefore, means developing a conceptual model of what energy is, how it relates to observable phenomena, and how it behaves. More specifically, students should eventually learn to infer the presence of energy from observations, track correlated gains and losses of energy within the system of interest, and describe the observed processes using all core aspects of energy. In this report, these inferences are designated as "looking through the energy lens" (see also Lacy et al., 2014, 2022; Tobin et al., 2018).

Since energy is entirely abstract, the *conceptualization* of energy has been introduced as an additional aspect that needs to be considered (Duit, 1986, 2014). This denotes references to energy, for example, as an abstract accounting quantity, a substance-like entity (substance metaphor), or the ability to cause changes, that are used in instruction (Duit, 2014). Especially the substance metaphor of energy is deemed to support an understanding of energy transfer and conservation, and is therefore often used in instruction (Scherr et al., 2012; Lancor, 2014; Nordine et al., 2018).

The importance of the energy concept, and the difficulty of learning it, is reflected by a large body of research on energy learning (see for example, Chen et al., 2014). Secondary students' conceptions of energy have been largely investigated since the 1980s; reviews can be found in the literature (Nordine et al., 2011; Duit, 2014). Students have been observed to hold and use simultaneously various "alternative frameworks" of energy that are influenced by the use of the term energy in everyday language and are only partly compatible with the scientific view (Solomon, 1983; Watts, 1983; Lijnse, 1991; Trumper, 1993). Recent research on learning progressions in grades 4–12 indicates that even older students are often unable to apply the conservation principle, which is central to productive use of the energy concept, to everyday phenomena (Herrmann-Abell and DeBoer, 2018). On the other hand, this study suggests that there are no principal boundaries to energy learning in grades 4–12; all core aspects of energy can principally be developed at all grade bands with adapted sophistication (Herrmann-Abell and DeBoer, 2018).

Only a few studies address kindergarten or elementary students' energy ideas: Two studies from the English language area in kindergarten (Hook et al., 2008) and third grade (Lacy et al., 2014) report associations with living beings (human), motion or activities like running or playing, to a smaller extent also with batteries and other electric devices. According to Lacy et al. (2014, p. 245), the interviewed third-grade students considered energy an inherent 'either-or' property of animates or certain self-propelled technical objects ("human-centered framework" (Watts, 1983), while none of the other "alternative frameworks" were observed. Yuenyong and Yuenyong (2007) assessed Thai first- to sixth-graders' energy ideas. All participants had previously been introduced to energy in school. Most of the students in grades 1 and 2 referred to technical objects and motion but did not associate humans or food with energy. The authors report that the students implicitly referred to several forms of energy and energy transformations but that they did not distinguish forms and sources of energy and did not mention aspects of energy conservation and degradation. Two German studies (Haider, 2016; Reimer, 2020) addressed fourth-graders' ideas about energy. All students had previously attended science classes, and some had also received instruction on energy. Both authors report a predominantly technical notion of energy, strong associations with electricity and only a minor role of associations with humans. Haider (2016) analyzed the students' answers regarding correct references to the core aspects of forms, transfer, transformation, and conservation, but did not assess intuitive ideas within these aspects.

In summary, learning about energy means developing a conceptual model of energy, using eventually all of the above-mentioned core aspects of the scientific energy concept (Tobin et al., 2018). However, as the brief literature review shows, little is known about what German-speaking children in lower elementary school, i.e., in grades 1 and 2, think about energy before formal science teaching commences. Consequently, there is no empirical basis for proposing a learning progression for that age, and/or for developing age-adequate instruction. Furthermore, no instrument that is suited for analyzing young children's statements through the lens of the complex scientific energy concept has been proposed so far. Hence, the purpose of this study is to describe what Swiss first and second graders associate with and think about energy before receiving formal science instruction, and to categorize their explanations with respect to the different aspects of the scientific energy concept.

The following research questions are addressed:

RQ 1: What do children associate with energy, specifically, what objects and/or features/activities can be identified in children's drawings/notes and explanations of something they associate with energy, and how do these ideas relate to the core aspect *manifestations/ forms* of the scientific energy concept?

RQ 2: How do children describe what energy "is" and how it "behaves," and how do these ideas relate to the further core aspects of the scientific energy concept *transfer*, *transformation*, *dissipation/ degradation*, *conservation*, and to *conceptualizations* of energy for instruction?

RQ 3: To which contexts do the children refer when explaining their associations with energy?

This study summarizes children's ideas with respect to all core aspects of the scientific energy concept. Thereby, it describes children's knowledge elements, including the contexts they refer to and the language they use to express them, as resources or building blocks toward a more sophisticated understanding of energy. The category systems as main result of this study show links between the children's ideas and the different aspects of the scientific concept. In future research, they may be used to reconstruct children's conceptual models by correlating, say, the phenomena children refer to with the children's ideas of what energy "is" and how objects "get" energy.

2. Materials and methods

2.1. Methodology and context

This study reports findings from a drawing/writing activity of a larger investigation of Swiss first and second graders' ideas about energy. The methodology and research design of the larger investigation as well as considerations to ensure the validity of the findings have been described in a method-centered publication (Detken and Brückmann, 2021). Below, key aspects of that investigation are summarized to illustrate the context of the present study.

There is no established research methodology for investigating young children's ideas about complex scientific concepts. To arrive at valid conclusions, the employed methods of data collection and analysis should mediate between the structure of the scientific concept and the young age of the participating children [structural/content and cognitive aspects of validity according to Messick (1995)]: Structural validity requires assessing children's conceptions in depth such that links between their ideas and all aspects of the scientific concept, here energy, can be established. Regarding cognitive validity, the children's everyday world, their concentration span, and their abilities to express themselves need to be considered. To mediate between both requirements, the larger investigation used a multi-method approach (Greenfield, 2015) with single interviews (Clark, 2005; Einarsdóttir, 2007; Hadzigeorgiou, 2015) in combination with child-friendly methods, such as working with objects, role-play and children's drawings (Rennie and Jarvis, 1995; Brooks, 2009; Ehrlén, 2009). A *first interview* focused on three phenomena from different contexts without the interviewer using the term energy. A *second interview* addressed children's understanding of the term energy. Before the second interview, the children attended to a drawing task: They were asked if they knew the word energy and if yes, to draw or write something they associated with it. The children who knew the term energy were then interviewed about their associations, i.e., they were asked to explain what they drew or wrote and were asked what they otherwise associated with energy. Subsequently, they attended to a sorting task, discussed the phenomena of the first interview in terms of energy and were asked to explain to a friend how to become an "energy detective." A specific interview guideline was used repeatedly throughout the second interview to target the above-mentioned core aspects of energy, including the conceptualization (*cf.* Supplementary material and Detken and Brückmann (2021)). The guiding questions of this protocol are based on the "Energy Tracking Lens" (Lacy et al., 2014; Tobin et al., 2018; Lacy et al., 2022). They address, for example, what an object has to do with energy, whether its energy changes, how or from where it "gets" energy and what happens to the energy later.

This study focuses on the drawing task: It analyses the children's drawings/written notes about their associations with the term "energy" and their explanations of their associations in the second interview.

Drawings are generally considered a suitable and genuine mode of communication for young children, though expressing ideas by means of a drawing is a complex process involving several cognitive and motoric skills. Several studies make use of children's drawings for eliciting their ideas in science (Vosniadou and Brewer, 1992; Rennie and Jarvis, 1995; Reiss and Tunnicliffe, 2001; Tay-Lim and Lim, 2013; Dai, 2017). However, researchers emphasize that young children's drawings should not be considered a mere representation of their ideas; rather, the meanings children give to their drawing and communicate while drawing or by referring gesturally to the drawing should be foreground (Wright, 2007; Brooks, 2009; Ehrlén, 2009; Einarsdottir et al., 2009). Hence, this study uses children's drawings/notes mainly as a "door-opener" and as a communication aid for the interview. The drawings/notes are analyzed only regarding certain aspects of the energy concept (i.e., the phenomena they refer to), while the main focus of the analysis is the interview.

2.2. Sample and data

Initially, the sample comprised 25 children (13 girls, 12 boys) of the first and second grades (ages 6–8 years, $M = 7$ years 6 months) of two elementary schools in two neighborhoods with medium to upper socio-economic standards in the city of Zurich, Switzerland. Since one girl from the first grade did not know the term energy, the sample of this study comprises only the 24 children (12 girls, 12 boys) who knew the term energy and participated in the second interview.

The participants were recruited by convenience sampling; to ensure a heterogeneous sample, the classroom teacher selected children with different school performances. The school language in Zurich, German, was used for the interviews. Though many of the participating children had a multilingual background, all were able to understand the interviewer and responded in German or the Swiss German dialect. The study was approved by the responsible education board; the children volunteered, and their legal guardians' consent was obtained prior to the interviews.

The study was conducted in the first quarter of the school year after only few weeks of elementary schooling for the first graders and slightly more than one year for the second graders. No science content such as energy, electricity or human nutrition had been taught during elementary schooling. Previously, the children had attended two years of compulsory kindergarten, where they had been familiarized with classroom routines in playful learning environments. As the children came from several kindergarten classes and as there is no common science content for these two years, it is not known which science topics were addressed in kindergarten, if any.

This study analyses 22 drawings and/or written notes (11 drawings, 7 drawings with text, 4 text only) and 24 interview sections (duration 1–13 min, $M = 5$ min 8 s, $SD = 2$ min 51 s) in which the children explained their associations with energy and responded to the interviewer's questions. Two children did not draw or write about their associations, though they knew the term energy and participated in the interview. The responses in the interview were videotaped and transcribed, including gestures, references to the drawings and other non-verbal modes of expression. Examples of the drawings/notes and the responses are provided in the results.

2.3. Analysis

2.3.1. General approach

Qualitative Content Analysis, QCA, (Schreier, 2012; Kuckartz, 2018) was applied to analyze the drawings/notes and the interviews, using a QDA software (VERBI Software, 2020). By QCA, subjective conceptions of test persons are extracted in a highly systematic yet flexible way from qualitatively interpretable texts and summarized by coding frames.

A concept-based approach, guided by the core aspects of energy including the conceptualization, was used to define the main categories for analysis. Table 1 gives an overview of the main categories, their relation to the scientific energy concept and the guiding questions for the evaluation of the data: The main category "System Elements" summarizes which objects and/or phenomena children describe when they explain their associations with energy; the main category "Characteristics" summarizes the features and/or activities the children refer to. By categorizing observable elements of

TABLE 1 Overview of the main categories, the research interest, and the relation to the scientific energy concept.

Main category	Research interest/guiding question for analysis	Aspects of the energy concept
System elements	Which entities (e.g., objects or phenomena) are described?	Manifestations/Forms
Characteristics	Which observable features and/or activities of these entities are described?	Manifestations/Forms
Nature of energy	What "is" energy (ontology, causality, relation to real-world objects)?	Conceptualization
Transfer ideas	How or from where do entities "get" energy?	Transfer
Transformation ideas	Are different "characteristics" related to one another? Can energy change its "guise"?	Transformation
Conservation ideas	What happens to the energy after a process?	Dissipation/Degradation conservation

the real world and their properties, these two main categories provide links to the core aspect *manifestations/forms*. The main category "Nature of Energy" summarizes children's "ontologies" of energy, e.g., what energy "is" and/or how it relates to real-world objects; it thus provides links to the *conceptualization* of energy. The other three main categories can be linked to the core aspects of *transfer*, *transformation*, *dissipation/degradation* and *conservation*: The main category "Transfer Ideas" summarizes children's ideas about how or from where objects get energy and thus provides links to core aspect *transfer*. The "Transformation Ideas" summarize ideas if and/or how different features or activities, e.g., light and electricity, are related to one another; thereby, it provides links to the core aspect *transformation*. Ideas about the "fate" of energy after the end of a visible process, e.g., if it is "just gone" or somewhere else, are summarized in the main category "Conservation Ideas." Hereby, links to the core aspects *dissipation/degradation* and *conservation* can be identified.

Structuring the material of this study by QCA makes it possible to (a) describe children's ideas by categorizing and summarizing their drawings/notes and statements in view of the different core aspects of the scientific energy concept, (b) determine the frequencies of subcategories, and (c) to identify which combinations of subcategories occur. Comparison with the corresponding scientific core aspects of energy allows for identifying ideas that may act as steppingstones towards a (more) scientific understanding of energy and ideas that are not compatible with the scientific view (step a). Frequent subcategories indicate which of these ideas are typical, less frequent or missing categories indicate "blind spots" (step b). Eventually, a first step towards the reconstruction of children's intuitive models of energy can be made by analyzing frequent combinations of subcategories (step c).

2.3.2. Development of coding frames

For the development of subcategories, a concept-based approach was taken for the first two main categories (Detken and Brückmann, 2021; Detken, 2023): The subcategories within the "System Elements" are based on an ontological tree (Chi, 2013, p. 58), those within the "Characteristics" are based on energy indicators (Nordine et al., 2011, p. 696). Data-based additions and modifications account for ideas that do not fit into these subcategories, such as references to the physical or mental state of a being.

For the main categories "Nature of Energy," "Transfer Ideas," "Transformation Ideas," and "Conservation Ideas" no analytical instrument adapted to young children at the age of 6–8 years was known. Here, coding frames were developed in a mainly data-based process, by oscillating between the interview data and ideas described in the literature for older students [e.g., learning progressions for upper elementary school (Lacy et al., 2014; Herrmann-Abell and DeBoer, 2018), secondary students' "alternative frameworks" of energy (e.g., Watts, 1983; Duit, 2014) and the "dimensions" of children's energy ideas described by Nicholls and Ogborn, 1993]. The developed coding frames are characterized by three features: First, they summarize young children's ideas independent of the context, i.e., the object or phenomenon the children talk about. For example, ideas that humans "get" energy from food or electric devices from a power supply, have both been summarized in the subcategory *source/flow* within the main category "Transfer Ideas." This has the advantage that context-dependencies of ideas about the nature or the behavior of energy can be determined at a later stage (*cf.* 2.3.1, step c). Second, they distinguish between the different core aspects of energy by using the guiding questions of Table 1 as "lenses" for the analysis. Third, they include "alternative" ideas expressed by young children at the age of six to eight. As will be outlined in the results and discussion, this approach provides a comprehensive picture of what ideas regarding the core aspects *transfer*, *transformation*, *dissipation/degradation,* and *conservation* the participating young children express.

2.3.3. Analysis of the drawings

For the analysis of the 22 written documents (drawings, notes), only the main categories "System Elements" and "Characteristics" were used, because in most cases the drawings/notes did not reveal ideas about the nature or the behavior of energy. For example, without the explanation of the child, it cannot be distinguished whether a human being was drawn because it has to do with energy, has itself energy or needs energy.

Codes of these two main categories were applied to thematically coherent coding units. The definition of the coding units ($n = 36$) was guided by the assumed main themes/subjects of the drawing or written note. Figure 1 gives an example: The drawing of a boy (shortcut "Is") from first grade depicts two human beings and a flashlight. Coding unit 1 comprises the flashlight and was coded with *electric user* (System Elements) and *electricity* (Characteristics). Coding unit 2 comprises the two characters and was coded *human being* (System Elements) and *physical activity/state* (Characteristics).

2.3.4. Analysis of the interviews

The coding units defined in the interviews comprise thematically coherent segments of the transcripts, typically one or more sentences, including the interviewer's questions. As expected, the children did not always express themselves clearly and coherently. Consequently, the definition of coding units was a compromise between capturing new ideas while preserving context information, and thus entails a certain degree of subjectivity.

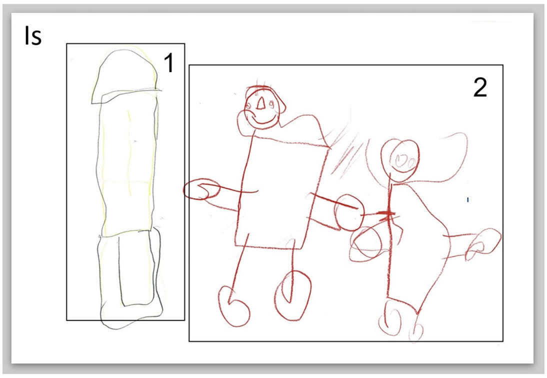

FIGURE 1
Energy drawing of a first grader (Is) with two coding units (1: flashlight, 2: human beings).

Codes of all six main categories have been assigned to each of the 119 coding units of the interview. Multiple coding were permitted only in the main categories “System Elements” and “Characteristics,” otherwise exactly one code had to be assigned. Since it could not always be distinguished if a child mentioned something because of energy or as an element of the general situation, specific “System Elements” and “Characteristics” codes were assigned whenever a child described the respective object, feature, or activity. While ideas about the “Nature of Energy” were identified in appr. 80% of the coding units, relevant ideas about transfer, transformation or dissipation/degradation/conservation could be identified only in 15–25% of these; all other coding units were assigned to the residual categories. Examples for the coding of two coding units are given below; the statements of a boy from the first grade, “Is,” refer to the drawing in Figure 1. All excerpts are translated from German or the Swiss German dialect preserving the statement’s original character. Gestures and further information are included in parentheses. The letters indicate the child, the numbers the paragraph in the transcript.

Coding unit 1 (Is, 6–14):

> “Here are my arms (*whoosh*-sound, points to drawing) and there is someone else. I tell you, if I have too much energy, I want to do things that I am not allowed to do. […] I have too much energy in my body, and then I beat, if I (have) so much energy (*whoosh*-sound, gets up and beats into the air).”

Coding unit 2 (Is, 18–24):

> “Lightenergy, battery. […] We talked about that yesterday. Here is the light and the battery is also the energy for the light (points to elements in the drawing). The battery is like energy for the light.”

Coding unit 1 was coded with *human being* (System Elements), *physical activity/state* (Characteristics), and *substance idea* (energy contained *in* the body; Nature of Energy). As coding unit 1 does not refer to multiple characteristics and does not contain ideas about where energy comes from or goes to, the residual categories were assigned in the other main categories. Coding unit 2 was coded with *electric user* and *electric source* (references to the flashlight and the battery; System Elements), *electricity* and *light* (Characteristics), *causal agent* (energy *for operating* the flashlight; Nature of Energy), and *causal relation* (*if* electricity, *then* light; Transformation ideas); in the other main categories, the residual categories were assigned. The subcategories are explained in the results section.

TABLE 2 Intercoder reliabilities for the main categories.

Main categories	κ_n Drawings/notes	κ_n Interviews
System elements	0.86	0.93
Characteristics	0.89	0.92
Nature of energy	–	0.73
Transformation ideas	–	0.49
Transfer ideas	–	0.72
Conservation ideas	–	0.80

2.3.5. Quality management

A subset of six drawings/notes and six interview sections (appr. 25% of the data set) was independently coded by the author and a trained research assistant. The intercoder reliabilities, Brennan and Prediger’s κ_n (1981), were determined, using the QDA software (VERBI Software, 2020). According to Rädiker and Kuckartz (2019, p. 303) with reference to Landis and Koch (1977), Brennan and Prediger’s κ_n, can be interpreted like Cohen’s Kappa, wherein values above 0.61 indicate a substantial and those above 0.81 an almost perfect agreement. According to Table 2, mostly good agreements were achieved for both types of data.

3. Results

In this section, the developed category systems are presented and trends in the data are described. The category systems show that young children at the age of six to eight already have detailed ideas about energy that can be related to the different core aspects of energy and its conceptualization. The depth and richness of the children’s statements are illustrated with selected excerpts and drawings. This section is organized as follows: The first part addresses the children’s associations, i.e., the objects and features/activities described by the children in the drawings and in the interviews (RQ 1). Subsequently, the developed category systems for the other main categories are presented (RQ 2). In the last section, the category systems for the main categories “System Elements” and “Characteristics” are used to determine the main contexts of the children’s associations (RQ 3). The coding frames with anchoring examples are included in the Supplementary material.

3.1. Objects and features described in association with energy: Main categories “System elements” and “Characteristics” (RQ 1)

Table 3 shows an excerpt of the coding frame for the main categories “System Elements” and “Characteristics” and the frequencies of documents (children) that have been assigned a specific subcategory, both for the interviews and the drawings/notes.

TABLE 3 Coding systems for the main categories system elements and characteristics (excerpts, *cf.* Detken and Brückmann, 2021) and frequencies of documents (interviews and drawings/notes) with assigned subcategories.

Main category	Subcategories	Definition	Interviews (*n*=24)	Drawings/notes (*n*=22)
System elements	Human being	Humans and parts of the human body	19	14
	Electric user	Technical device that operates on electric current	7	5
	Electric source	Electric supply, e.g., cable, battery, power socket	7	1
	Food	Food and drinks (including water)	6	2
	Vehicle	Vehicles and their parts (including toys)	6	3
	Gaseous substance	Gaseous substance, e.g., air, breathing	3	–
	Fuel	Fuels	2	–
	…			
Characteristics	Physical activity/state	Physical activity and/or state of living beings	19	14
	Electricity	Closed electric circuit, working on electricity	9	9
	Chemical	Presence, appearing or disappearing of substances, growth	9	3
	Light	Emission of light, shining	7	5
	Motion	Motion of inanimate objects	4	4
	Force	Strength or force of an inanimate object	3	–
	Functioning	Ability to operate in unspecified ways	2	–
	…	…		

Humans, *food*, *electric users* and/or *electric sources*, and *vehicles* are the most frequent "System Elements" subcategories in both the drawings and the interviews. The sun, other primary energy sources and power plants, which are frequent associations of older students (Reimer, 2020), were described only by single children or not at all. The small number of subcategories indicates that young children associate energy only with a limited number of phenomena or objects, while, from a scientific perspective, energy can be assigned to virtually any object in the real world. In the main category "Characteristics," about 80% of the children described the *physical activity and/or state* of living beings, mostly humans (data-based category), while only four children referred to the motion of inanimate objects. *Electricity*, *light* and phenomena that involve substances (*chemical*), such as breathing or eating, were mentioned by about one-third of the children. Characteristics that are indicators of forms of potential energy, such as *temperature*, *height*, *deformation*, and *sound*, were described by single children only or not at all. These findings indicate which of the scientific indicators of energy are "seen" by the children, and what alternative features children consider indicative of or related with energy.

Generally, the interviews are more diverse than the drawings/notes: The code counts are higher in the in the interviews than in the drawings/notes (e.g., two drawings/notes vs. six interviews were coded with *food*), and some subcategories were only found in the interviews (e.g., *gaseous substance*, *functioning*).

The most frequent categories are described below and illustrated with examples from the drawings/notes and the interviews.

3.1.1. "Humans" and "physical activity/state"

14 of the 22 *drawings/notes* referred to humans and/or human activities, e.g., sports. Examples are given in Figures 1, 2. Re and Ju are girls from the first grade, both refer only to humans. The text in Ju's drawing (Figure 2B) means *"if one has energy one can do relay run or climbing or balancing."* Je and Sr. are second-grade girls; both refer to several objects, including humans. The texts read *"animals need energy – current needs energy – a bike needs energy – a human being needs energy – a car needs energy"* (Je, Figure 2C) and *"battery, force, sports, food"* (Sr, Figure 2D).

In the *interviews*, even 19 of the 24 children (about 80%) described human beings and/or human activities. The children also referred to the physical condition, such as being fit, strong, trained or having "force" or "power." Examples: *"That he can move (points to the character with dashes). This one can move and run (moves arm up and down), I think, that is energy"* (Re, 2; *cf.* Figure 2A); *"[…] sports is… if one hears the word (energy) and then the word force, one thinks about sports, because one needs force to do sports"* (Sr, 6, explaining the word "Sport," *cf.* Figure 2D). For some children, being inactive or tired corresponded to a state of little or no energy, e.g., *"if one does not do sport for a long time, then one gets lazy and then one has less energy"* (Ro, 54). Several children used the terms force, strength, fitness, or power (or respective adjectives) synonymously with energy, e.g., *"the force… your energy is like your fitness"* (Is, 102, *cf.* Figure 1).

The idea that energy characterizes the physical state of a being was also articulated by those children who associated fictional creatures with energy. Additionally, some children referred to the mental state to describe energy – being excited or concentrated with energy, being sad or bored without.

3.1.2. "Electric users" and "electricity"

In nine of the 22 *drawings/notes* references to electricity and/or electric users/sources were found, such as batteries, cables, devices working on electric current and written statements like in Je's drawing or Sr's notes (Figures 2C,D). Further examples are given in Figure 3: An and Ja are first-graders (boy/girl), Be and Ke are boys from second grade. The text in Be's drawing (Figure 3C) reads *"the car needs electronic energy."* Ke (Figure 3D) wrote *"Änergi"* (energy).

In the *interviews*, these nine children referred to electric current and described a variety of electric users, such as lamps, mobile phones, cameras, microphones, and computers, and/or electric sources like batteries, cables and power sockets. The children's explanations ranged from vague associations with electricity –" *energy means the strengths of electronic"* (Ke, 10, *cf.* Figure 3D) – to more nuanced statements as in the following example (Ja, 4–6, *cf.* Figure 3B):

> Ja: And then I thought, a lamp and a flashlight have to do with energy.
>
> I: What does it have to do with energy?
>
> Ja: This has to do with energy, well, because it shines it has energy. It has to do with energy because it shines and has a battery inside, because that has also energy, like, inside.

Like in the following example of An (*cf.* Figure 3A), cables and batteries often served as indicators to recognize energy: *"This has to do with energy because it has a cable, and this as well (points to mobile phone and computer) and this because it is hot, and this as well (points to oven and frying pan)"* (An, 6). Some children used the terms energy and electric current or batteries synonymously, explained that energy is contained in current and/or believed that current and energy are identical or similar. Example: *"Because it is the same: energy, current"* (No, 4).

3.1.3. "Vehicles" and "motion"

Three *drawings* depict vehicles, i.e., (toy) cars and a bike (*cf.* Figures 2C, 3C). In the *interview*, altogether six children mentioned vehicles, including planes, boats and railroad engines. Like in the following examples, most of these justified the vehicle's relation with energy with the presence of batteries, current or electric energy (subcategory *electricity*): *"A car because it needs like electric energy. If you go by car and a human is inside, then the human is perhaps also like a sort of energy because it sets everything up and helps"* (Be, 4–6, with reference to his drawing, *cf.* Figure 3C). *"These two I drew because of current, and because the current needs energy [...]. Because the car needs current and current has energy [...]"* (Je, 2, with reference to the bike and the car in her drawing, *cf.* Figure 2C). Others mentioned vehicles in a rather loose association with electric current, e.g., *"with electronic things: lamps, mobile phones... planes, no idea... for example, what else? Houses with energy, like current, or cars or planes or boats"* (Ke, 22–27, explaining the flash symbol in his drawing, *cf.* Figure 3D).

Though four children described moving vehicles, just one child explicitly used *motion* as an indicator of energy (An, 43–49):

FIGURE 2
Four drawings/notes of associations with energy that (partly) refer to human beings. A: drawing only, B & C: drawing and text, D: text only.

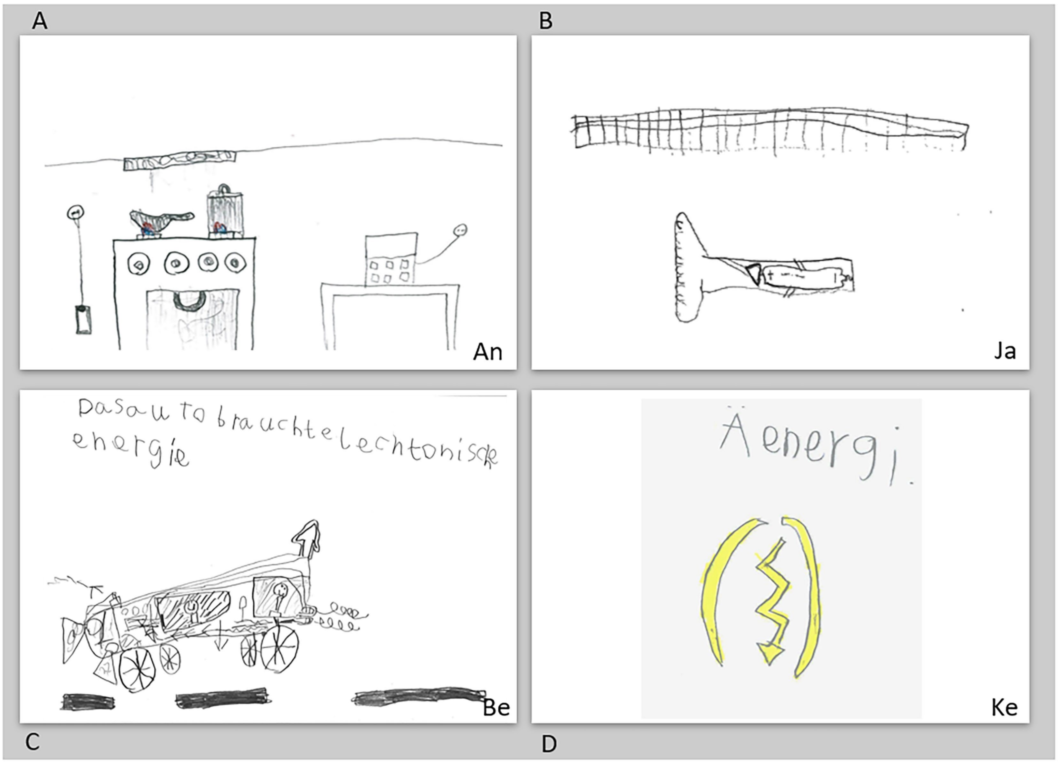

FIGURE 3
Four drawings/notes of associations with energy that (partly) refer to electric devices or electricity. **A** & **B**: drawing only, **C** & **D**: drawing and text.

> An: A railroad engine is also energy.
>
> I: What is energy there, regarding the railroad engine?
>
> An: That it drives. And the car as well. And the bike as well.

Observations from other interview parts indicate that a motor or a fast, controlled, or unusual movement, e.g., rising instead of falling, is required to produce an association, while motion as such is not sufficient.

3.1.4. "Food," "fuel," and "chemical"

Only three *drawings/notes* were coded with *chemical*, a subcategory summarizing references to substances. In two cases the children wrote the term "food" (*cf.* Sr., Figure 2D), the third occurrence is Be's drawing of a car with exhaust gas (*cf.* Figure 3C). In the *interviews*, references to substances were more frequent; 9 of 24 children mentioned food, air, fuel and/or water or described breathing, eating and/or drinking, e.g., *"it (the energy) goes away, and then it comes back, if you eat or sleep"* (Is, 126, *cf.* Figure 1). Only one child (Sr, 33–34; *cf.* Figure 2D) explained that food has energy:

> I: You also wrote 'food'. Does food have energy, or not?
>
> Sr: I think it does.

Most of the other children explained that food or other substances, like air or water, were important for gaining energy. As the following example shows, this does not necessarily imply that food as such has energy: *"One needs energy to do sports. I think, perhaps, if one eats or drinks, it becomes energy in one's belly"* (Sa, 6).

3.2. Children's ideas about the nature and the behavior of energy: Main categories "nature of energy," "transfer ideas," "transformation ideas," and "conservation ideas" (RQ 2)

The above-mentioned examples show that children's reasoning is nuanced, diverse and on different levels of complexity. Many of the children described energy and its behavior in various ways during the interview. These ideas have been summarized within the main categories "Nature of Energy," "Transfer Ideas," "Transformation Ideas," and "Dissipation/Degradation/Conservation Ideas" (Table 4).

3.2.1. Nature of energy

The main category "Nature of Energy" summarizes children's ideas about what energy "is," it can be linked to the *conceptualization* of energy (Table 1). The children explained that the objects or phenomena had, needed, expended, were, or had to do with energy. They also used expressions like fitness, power, force, or current as synonyms for energy.

The most prominent idea about the "nature" of energy, expressed by 14 of the 24 children, is energy as *causal agent*, i.e., as an enabler for processes and/or a kind of fuel that humans or devices need always or for being active (Table 4). Examples are *"one needs energy for running"* (El, 2), *"a flashlight needs energy for shining"* (Iv, 4), or a child's definition of energy *"energy is like a support, it helps that one does not*

TABLE 4 Coding systems for the main categories nature of energy, transfer ideas, transformation ideas and conservation ideas, and frequencies of interviews with assigned subcategories.

Main category	Subcategories	Definition (italics: typical responses)	Interviews (*n*=24)
Nature of energy	Causal agent	Functional notion of energy; energy as a kind of "fuel": *X needs energy for Y*	14
	Feature of certain states	Energy as something a system element has only in certain states: *X has energy, if it is/does Y, and no/less energy, if not*	10
	Substance idea	Energy as a substance-like entity: *X has energy inside; X gets energy from Y*	8
	Intrinsic feature	Energy as a feature of certain system elements: *X has energy (because of Y)*	7
	Being energy	Energy is the same as a system element or a feature thereof: *X is (like) energy*	5
	Generated	Energy as a product: *X becomes/makes energy*	2
	General/unclear	Residual category for a positive relation with energy	12
Transfer ideas	Process	Energy is generated by a process or an activity of the energy-using system element.	10
	Flow/source	Energy comes from a source and/or moves.	6
	Incorporation	A system element gets energy by incorporating an object that has or is (like) energy.	1
	Product	Energy is generated by an interaction/reaction.	1
	None/unclear	Residual category (no/unclear answer or no relation with "getting energy")	22
Transformation ideas	Causal relation	causal relation between two characteristics, no indication of conversion: *if x, then y; the more x, the more y*.	10
	Implicit transformation	One characteristic is converted into another or into energy. Energy changes its "guise."	2
	None/unclear	Residual category (no/unclear answer, segments with only one characteristic)	23
Conservation ideas	Gone or used up	Energy is used up or gone when the visible process ends.	10
	Somewhere else	Energy is somewhere else when the visible process ends.	2
	Conservation	Energy is somewhere else but is "reusable."	2
	None/unclear	Residual category (unclear answer, no information regarding the "fate" of energy)	23

hang around lazily or bored […]" (Be, 67). Further examples can be found in the excerpts in section 3.1 (Be, 4–6; Sa, 6).

Other statements indicate that energy is conceived as a side-effect of a state of activity of humans or devices, for example being fit, running or in operation. The amount of energy can change and is associated with certain observables. To summarize such ideas, the subcategory energy as a *feature of certain states* has been defined; it was coded in about 40% of the interviews. The following excerpt gives an example (Re, 9–16; *cf.* Figure 2A):

> I: Does he always have energy, or not always?
>
> Re: Always. Sometimes he needs a break if he cannot go on.
>
> I: If he cannot go on, does he still have energy, or not?
>
> Re: Then he has less.

Statements like having energy inside/contained, wasting, expending, or saving on energy, or descriptions of energy "flow," suggest that energy is conceptualized as a kind of substance that is different from the object that "has" energy. The statement *"the energy is in the battery"* (No, 18) indicates that energy is conceived of as an entity that is contained in batteries. Such ideas, identified in one-third of the interviews, were summarized in the subcategory *substance idea*. In the following example, a girl from first grade describes energy as a substance-like entity that moves through a flashlight (Ja, 45–49, *cf.* Figure 3B):

> Ja: The energy comes from this tiny curly tail (points to the contact spring in her drawing). It goes up into the battery, then it goes up and then it shines (indicating the path in the drawing).
>
> I: Where does it come from before it enters the curly tail?
>
> Ja: It comes from the batteries. Well, actually, it is like a bit electronic, and then it comes (moves finger along the battery in the drawing), there it has like energy inside, and then something can shine.

Like in this statement, some children described "substance" as well as "enabler" ideas; in this case, the subcategory *substance idea* was coded.

Some children also described energy as something that certain objects had *per se* or because they had certain features such as working on electricity, e.g., *"[…] if I am tired, then I do not have much force in everything (in the whole body) and then I have almost no energy […]"* (Ro, 40). These ideas have been summarized in the subcategory *intrinsic feature*.

3.2.2. Transfer ideas

The main category "Transfer Ideas" summarizes children's ideas about how or from where objects "get" energy; this can be linked to the core aspect *transfer* (Table 1). When explaining their drawing/note, many of the children described combinations of objects that, from a scientific perspective, act as sources and receivers of energy. However, such source-receiver relations were not always recognized by the children. Rather, various ideas about how or from where objects "get" energy were observed (Table 4). About 75% of the coding units did not contain relevant information and were thus assigned to the residual category.

Ten of the 24 children referred to certain activities when asked where the energy of a system element came from (subcategory *process*). Especially when talking about human beings, regenerative processes, such as resting, sleeping, eating, drinking, and/or breathing or doing sports, were frequently mentioned, for example (Re, 21–24, continuation of the statement in section 3.2.1):

> I: How does he get back energy, to be able to run again?
>
> Re: By taking a break. About ten minutes, then he has got back energy.

The subcategory *flow/source*, coded in 25% of the interviews, summarizes ideas about moving/flowing energy and/or energy that comes from an external source. The following statement is an example of energy "flow" in human beings without reference to an external source: *"My fitness, my energy, then it enters here (points along his arm to his hand) and then – whoosh – I can beat with full force (beating gesture)"* (Is, 104, with reference to his drawing, *cf.* Figure 1). Especially when talking about electric devices, children described that energy is delivered to electric *via* cables or by batteries that contain and release energy. Ja's statement (see section 3.2.1) is an example of energy "flow" in electric devices. Both examples illustrate how "flow" ideas were expressed verbally and with gestures.

Sa's statement (*cf.* section 3.1.4) is an example of the idea that energy is generated from certain ingredients (subcategory *product*), more specifically, in the human body from food. This idea was observed in only one interview; however, observations in the other interview parts and from pre-studies indicate that this is not an isolated idea.

3.2.3. Transformation ideas

The main category "Transformation Ideas" summarizes children's ideas about how observable characteristics are related to one another; this can be linked to the core aspect *transformation* (Table 1). About 75% of the coding units did not contain relevant information (residual category, Table 4). However, in many of the statements wherein the children described phenomena with multiple characteristics such as *electricity* and *light* or *motion*, or *physical activity* and *chemical* (food), a causal relation between the characteristics on the phenomenological level was described, such as the need for electric current to generate light or to move something (e.g., Ja, 45–49, *cf.* section 3.2.1). Such ideas were summarized in the subcategory *causal relation*. As described in the introduction, according to the core aspect *transformation* the increase of one indicator of energy is correlated with the decrease of another, which is modelled by the conversion of "forms" of energy into one another. Such ideas were not observed. Only two children described some sort of conversion, such as the "digestion" of energy in form of food or fuel, e.g.: *"Yes, because fuel is like car energy, like our food, it is food for the cars. […] It is like with humans – it (the fuel) is digested, just in the car […]"* (Be, 22–28, *cf.* Figure 3C). These ideas have been summarized in the subcategory *implicit transformation*.

3.2.4. Conservation ideas

In the main category "Conservation Ideas," children's ideas about the "fate" of energy are summarized (Table 4). This category can be linked to the core aspects of *dissipation/degradation* and *conservation* (Table 1). When asked what happened to the energy after a process, the children mostly stated that they did not know (residual category, appr. 85% of the coding units). Ten children explained that it was spent or just gone (subcategory *gone/used*), e.g., *"there is energy in the battery, and one uses the energy for that (the flashlight) and then, eventually, there is no energy anymore and then the flashlight does not work anymore"* (Sr, 16, *cf.* Figure 2D). Only a few statements were observed suggesting that energy is still present (subcategory *somewhere else*), or even reusable, after the termination of the observable process (*conservation idea*), e.g., *"[…] but if you press the button, it switches off because then the energy goes back (moves hand towards her body) and there are batteries inside, and then it stays there until you press the button again […]"* (Ja, 51, *cf.* Figure 3B).

3.3. Contexts of the children's associations (RQ 3)

Coding of the data with this coding frame enables identifying ideas which occur frequently in combination. This can be a first step towards a characterization of young children's mental models of energy. To show the potential of such an analysis, frequent combinations of subcategories of the main categories "System Elements" and/or "Characteristics" at the same coding units of the interview data were determined (*cf.* Supplementary material). Thereby, objects and/or features/activities that are frequently mentioned together in the same coding unit can be identified. This indicates which *contexts* the children refer to when explaining their associations with energy. The following tendencies were observed:

- 19 of the 24 children described *humans* and *physical activity/state*. Of these 19 children, only six additionally described *food*. References to other objects were rare. One example of an additional object is air (subcategory *gaseous substance*): two children mentioned air or breathing while describing humans (*cf.* section 3.1.4).
- Nine of the 24 children refer to the feature *electricity* in combination with *electric sources* and/or *electric users*. The subcategory *electricity* often occurred together with the subcategories *light* and *motion* (six and three children, respectively).
- The subcategory *vehicle* was coded in six interviews, mostly in combination with *fuel* and/or *electric sources*. Four children described *motion* when explaining their associations with *vehicles*, also, references to *electricity* were made in the same coding unit.

These tendencies suggest that the spontaneous associations of the participants of this study refer to three main contexts: human beings, electric devices (including sources and users), and vehicles. A Venn diagram (Figure 4) illustrates how the children's associations relate to these contexts: The contexts are symbolized by big circles; each child is symbolized by a small circle. The shadings indicate which of the five most frequent "Characteristics" subcategories – *physical activity/state,* *electricity, light, chemical*, and *motion* – were assigned to the child's interview. Re, for example, referred only to humans and to their physical activity/state. Ja described only electric devices, light and electricity. Be described humans, vehicles and electric devices as well as features of all five subcategories. This focus on the interview documents shows that all except two of the participating children argued in at least one of these three contexts, most of them (19) in the context of humans (i.e., 19 interviews contained at least one coding unit that was coded with *humans* and *physical activity/state*). Eight children (one-third of the participants) referred to two or three contexts. Two children associated only fictional creatures with energy. Nine children focused exclusively on human beings when explaining their drawing/notes. The other 10 children described humans in combination with food, water and/or air (subcategory *chemical*) but mostly without indication that these substances might have energy. Two or more subcategories of the main category "Characteristics," e.g., *electricity* and *light* and/or *motion*, were mostly assigned in connection with electric devices.

4. Discussion

This study shows that the participating children – at the age of 6–8 years and prior to formal science schooling – are able to engage in a conversation about energy, wherein they express ideas about what objects of the real world have to do with energy, and about energy as such. Hence, they have developed a conceptual model, or several models, of energy (Tobin et al., 2018). The coding frame with its six main categories structures the children's statements with respect to the core aspects of the scientific energy concept. By contrasting the ideas summarized in the main categories with the related core aspects of the scientific energy concept (*cf.* Table 1), children's resources for energy learning can be identified, in particular "productive" elements that provide a basis for more scientific ideas, and "alternative ideas" that might need further attention. This will be discussed below with respect to research questions 1 and 2, by way of example of selected subcategories. The detailed analysis with the coding frames allows to determine contexts of children's associations; these will be discussed with respect to research question 3.

4.1. RQ 1: "System elements" and "characteristics" vs. manifestations/forms

This research suggests that young children at the age of 6–8 years mainly associate humans and human activities, to some extent also technical objects, such as electric devices and cars, and their features (electricity, light, motion). The children's references to activities or features, such as doing sports (subcategory *physical activity/state*) or working on electric current (subcategory *electricity*), indicate that most participants recognized energy by looking at observable characteristics of real-world entities. This can be a basis for introducing energy as something that is inferred from observations (core aspect *manifestations/forms* of energy). However, not all the features and/or activities described by the children correspond to a scientific indicator of energy (Nordine et al., 2011), and not all the scientific indicators have been mentioned directly or indirectly by the children:

Children's references to light, batteries, cables and/or electric current, for example, can be linked to the scientific indicators of radiation and electric energy, i.e., the emission of light and a closed electric circuit, respectively. Hence, such ideas can constitute a basis for introducing these energy forms. The features and/or activities summarized in the subcategories *physical activity/state* and *motion*, on the other hand, deserve attention: By including references not only to human motion but also to various other human activities and/or subjective feelings of being fit or energetic, the ideas summarized in data-based subcategory *physical activity/state* are much broader than the scientific view. Moving objects, on the other hand, were to some extent described, but mostly not linked with energy. These observations indicate that the idea that all moving objects have energy needs to be introduced carefully. Rarely, the participating children described features that are not associated with activities or the operation of technical devices. Hence, there are blind spots, especially regarding forms of potential energy, and their scientific indicators, for example, temperature, deformation, and elevation.

The participating children's frequent references to humans are consistent with the prior studies with kindergarten and older elementary students, that were conducted in the English language area (Nicholls and Ogborn, 1993; Hook et al., 2008; Lacy et al., 2014). However, there are differences to the findings of the two studies with German fourth-graders, where the children mostly described associations with electric or other technical devices and only to a smaller extent with humans and other living beings (Haider, 2016; Reimer, 2020). Since the German students were 2–3 years older and had attended science classes, this could be an effect of prior schooling and/or age.

4.2. RQ 2: Further relations to the energy concept

In this section, selected subcategories will be discussed with reference to the further core aspects of energy (*transfer*, *transformation*, *dissipation/degradation*, *conservation*) and its *conceptualization*.

4.2.1. "Nature of energy" vs. conceptualization

Within the category "Nature of Energy," various ideas about what energy "is" have been observed. Knowing these intuitive "ontologies" is important for the development of age-adequate instruction because the abstract entity energy needs to be represented in class. The children's intuitive ideas of what energy "is" are therefore resources to determine which *conceptualization* of energy might aid an understanding of energy.

According to the core aspect *manifestations/forms*, energy is something that is attributed to objects based on certain observable indicators (Lacy et al., 2014; Tobin et al., 2018). Accordingly, children's statements like "*… has energy, because (or if) …*," as summarized in the subcategories *intrinsic feature* and *feature of certain states*, can be considered helpful language for talking about energy. In particular, the subcategory *feature of certain states* is interesting because children correlated the amount of energy with observable features, e.g., the fitter a person is, the more energy it has. Though the content of such a statement (e.g., correlating fitness with energy) may be incorrect, thinking of energy as a feature of certain states may constitute a starting point for introducing the general idea that the presence and

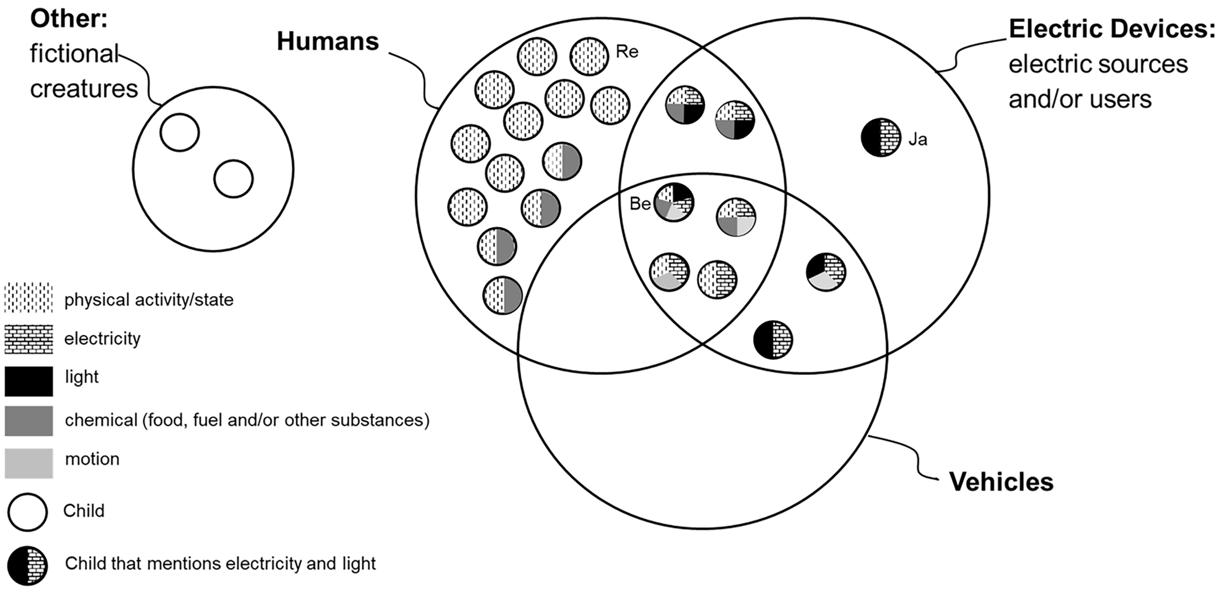

FIGURE 4
Venn diagram of the participants' spontaneous associations with energy.

amount of energy are inferred from observations (core aspect *manifestations/forms*).

Immanent in many of the children's statements is the idea that energy is an enabler that an actor needs and expends for certain purposes and activities (Jin and Anderson, 2012). Children described this enabler as some sort of inner resource that certain entities have and use without being material itself (subcategory *causal agent*), or as a kind of substance that is contained in and delivered by – or is the same as – electric current, batteries, fuel, or food (subcategory *substance ideas*). The "enabler concept" does not correspond to the scientific view, and is especially not compatible with the core aspect of conservation, because an enabler is normally used up or gone after fulfilling its purpose (Jin and Anderson, 2012). Nevertheless, "enabler" ideas may constitute a basis for introducing more abstract ideas like energy as the ability to cause changes or to do work (Duit, 2014).

Children's substance ideas can be a basis for introducing the core aspects *transfer* and *conservation* by using the "substance metaphor" of energy in instruction (Scherr et al., 2012; Lancor, 2014). However, attention should be paid that children do not equalize energy with food, current or other material entities. Also, not all children appear to consider energy something (quasi-)material and might thus have difficulties connecting to instructional models that rely on the substance metaphor.

4.2.2. "Transfer ideas" vs. transfer

In the category "Transfer Ideas," children described energy as a moving entity and partly also described chains of objects between which energy is passed on (subcategory *source/flow*). Though the children were not always correct about the causality or confused energy with, say, current or light, such ideas can provide steppingstones towards an understanding of energy transfer between sources and users of energy in a system.

Ideas of the subcategory *process* seem further away from the scientific view. However, it may be argued that children describing how, for example, human beings get energy by resting, focus on the object, its energetic states and the processes causing transitions between these states. These children might lack the understanding that the described processes also include interactions with other entities. More knowledge about the phenomena on a systemic level may help to see that "state changes" of the described objects are caused by interactions with other objects. Thereby, a basis may be provided for – eventually – regarding these objects as elements of a system wherein energy transfers and transformations take place when looking through the "energy lens."

4.2.3. "Transformation ideas" vs. transformation

If children described two characteristics, they were in many cases also aware of a causal relation between them (subcategory *causal relation*). However, they rarely described the conversion of one feature into another or into energy (subcategory *implicit transformation*). References to correlated gains and losses of indicators, that are modelled by energy *transformation* in the scientific view, were not observed. This indicates that children can describe the phenomena they associate with energy in terms of observations. However, they do not "see" energy transformation when viewing these phenomena through the energy lens. Hence, the idea of *transformation* of energy between different forms seems far away from what children think intuitively about energy.

For developing the core aspect of *transformation*, settings should be provided where children have the chance to observe several energy indicators as well as correlated changes of these indicators. Furthermore, children need to learn suitable terminology.

4.2.4. "Conservation ideas" vs. dissipation/degradation and conservation

Most of the children had no idea what might have happened to the energy in or after a process or stated that energy was gone or consumed. These intuitive ideas about the "fate" of energy are consistent with the idea of energy as an enabler of processes (*cf.* section 4.2.1). They are also understandable from the children's experiences: The aspects of dissipation, degradation, and conservation are based on very subtle changes in observable characteristics of a system, such as the temperature, which are far removed from what children can experience in daily life without knowing what to look for. Hence, it appears important to include thermal phenomena in energy learning, especially those where energy "losses" to the environment are tangible.

Nevertheless, some participants appeared to at least consider that energy is still somewhere else. Though some statements might be *ad hoc* constructs, the emergence of such ideas indicates that they can be developed also with young children and that questions like "where does the energy go to" (Tobin et al., 2018; Lacy et al., 2022) might help to do so.

4.3. Contexts

This research suggests that young children's associations with energy are likely to relate to objects or phenomena from the contexts of humans, electric devices, and vehicles. The analysis of structures in the data (section 3.3) indicates that each of these contexts has its merits and drawbacks for introducing energy:

Humans is a context where young children can be expected to have rich ideas of what it means to "have" energy, but where the everyday notion of energy as (human) vigor appears foreground. The findings indicate that many of the children focused only on humans and their activities or their physical state, while further system elements as sources and receivers of human energy (e.g., food, manipulated objects) were rarely described. As children appear to mainly "see" human beings when looking at a phenomenon involving humans through the energy lens, more advanced ideas like energy transfer or transformation might not be easily accessible in the context of humans.

In the contexts of electric devices and vehicles, on the other hand, the participants directly or indirectly described sources and receivers of energy, for example, a flashlight and batteries, or a car and fuel, as well as several characteristics that are a basis for scientific energy indicators, e.g., light, motion, and substances (*chemical*). These contexts could thus be a basis for introducing the core aspects of energy transfer and transformation. However, it appears likely that not all young children associate electric phenomena with energy, and those who do so, might confuse energy with electric current and/or fuel.

While there appears to be no single, ideal context, the context of humans could be a suitable starting point for energy learning in the early grades of elementary school. However, already in an early stage, instruction should attempt to expand the children's intuitive human-centered view. For example, by exploring what humans can do with their energy, such as "lift, squeeze, stretch and twist" objects (Hook et al., 2008), children should learn that also in animates can have energy. To do so, the general idea of energy transfer between sources and users of energy, e.g., from a human being to an inanimate object, needs to be developed (see RQ 2). Students should eventually also learn that motion rather than vitality is an indicator of energy, and that energy can manifest in various further phenomena, not all of which are associated with obvious activities or observable changes. Especially the technical contexts like electric devices and/or vehicles appear suited to introduce different manifestations of energy and to explore source-receiver relations, which might be more obvious here than in the human context (Tobin et al., 2018, p. 1140).

4.4. Method and limitations

The method has been discussed in detail in an earlier publication (Detken and Brückmann, 2021). Here, selected aspects of relevance for this study are described.

Though it was expected that children might have difficulties finding a representation of something as abstract as energy, almost all the children that knew the term energy (22 of 24) also drew and/or wrote something related to their notion of energy. The drawings/notes as such indicate which objects the children associated with energy. A comparison of their analysis with the analysis of the interviews shows that codes of more subcategories have been assigned to the interviews than to the drawings in the two main categories "System Elements" and "Characteristics." Hence, the drawings give an idea of the general direction of children's associations but may, as such, underestimate the scope of the children's associations. In addition, ideas about further core aspects of the energy concept (e.g., main categories "Nature of Energy" and "Transfer Ideas") are not accessible by drawings/notes as such. Consequently, the interview is needed to access more subtle aspects of the energy concept. Nevertheless, the drawings have an important function in this study: Not only did they serve as a "door opener" for the interview – they helped many of the participants express their ideas by interacting with their drawing/note (*cf.* Ja's statement, section 3.2.1). This highlights the importance of using and supporting multiple child-friendly modes of expression to elicit young children's ideas, e.g., verbally, by drawings and by gestures. As a consequence, video recordings are important to capture young children's full accounts, specifically speech and gestures.

This analysis does not consider the interviewer's input. This leads to uncertainty about to what extent children's ideas are a result of the situation. Nevertheless, many of the children responded differently to the same questions. This indicates that their responses are also based on individual dispositions. In a next step, the interviews could be analyzed in greater detail to find out which prompts can be helpful to elicit or even evoke certain ideas about energy.

The dynamic character of the children's statements constituted a challenge for the rigorous analysis of the data. Hence, the definition of the coding units as well as the coding itself is subject to uncertainties. The intercoder agreements indicate that young children's statements can nevertheless analyzed by a complex QCA with trustworthy results. Since some categories have been defined based on just a few statements and the focus of the present analysis was the participants' spontaneous (unprompted) associations with energy, it might be necessary to refine the identified categories when evaluating more data. Because of the small sample and data set, the results of this study should primarily be understood as empirically based hypotheses about young children's energy ideas that need to be tested using a larger sample. To that end, one main contribution of this study is the coding frame as an analytical tool for evaluating young children's statements with respect to all core aspects of energy.

5. Conclusion and outlook

This study describes, perhaps for the first time, the energy ideas of young children in the first two grades of elementary school with respect to all core aspects of the scientific energy concept, including the *conceptualization* of energy. The developed coding frames as such are interesting information because they categorize children's ideas and link them to the core aspects of the scientific energy concept. Thereby, productive elements and aspects that need further attention can be identified. The present findings show that young children are likely to have rich and diverse resources for energy learning that refer to all core aspects of energy. However, there are also many "blind spots," especially regarding energy in phenomena that are not associated with obvious changes or activities and more sophisticated energy aspects like *dissipation/degradation* and *conservation*.

For developing age-adequate instruction, it is necessary but not sufficient to know children's ideas about the different aspects of energy. We also need to know how and in which situations children use the corresponding knowledge elements, e.g., in which contexts children express what ideas about the nature of energy or about energy transfer. To this end, the developed coding scheme is a tool for analyzing children's statements in view of all the core aspects of energy. Though such an analysis may appear "atomistic," it allows one to distinguish the objects, phenomena and/or contexts children refer to from the way they explain the "behavior" of energy. Hence, this analysis can serve as a first step towards the reconstruction of children's conceptual models of energy; in this study, it served to identify the main contexts of the children's associations by analyzing frequent codes and code combinations within the main categories "System Elements" and "Characteristics." To further characterize children's mental models of energy, future research should address the question, whether certain ideas about the nature of energy accumulate in certain contexts and/or occur preferably in conjunction with certain transfer ideas.

In this respect, some tendencies were observed, e.g., that children tended to describe energy as substance-like and coming from a source when talking about electric phenomena, while the notion of energy as human vigor, and thus as a feature of an "energetic" state, that can be regenerated by certain activities, is foreground in the human context. For a more thorough analysis of such correlations, more data are required. Hence, in a next step a bigger data set should be analyzed, specifically the complete interviews, and frequent constellations of categories should be determined to characterize typical mental models of young children. Based thereon, learning progressions for the lower elementary school may be proposed and tested empirically.

As the coding frames are very complex, future research should proceed in a quantitative direction to uncover structures in the data of a larger sample validly and reliably. To this end, the described categories may serve as a basis for the development of quantitative test items that are adapted to how young children express themselves about the various core aspects of energy.

The young participants of this study expressed very detailed ideas about energy though they had not received formal instruction on science topics in school. Accordingly, the observations indicate how important implicit energy learning, by children's experiences and the use of the term energy in their everyday lives, is for the development of their intuitive energy ideas. Though more research is needed about age-adequate instruction, already now the importance of teachers using the term energy sensitively and correctly in school, ideally even before the formal introduction of the energy concept in science class, is obvious. Furthermore, children are likely to benefit from a good knowledge of various phenomena for being able to see objects as interacting elements of systems which, later, can be viewed through the "energy lens."

Data availability statement

The datasets presented in this article are not readily available because of the instructions of the board that approved this study. Selected interview excerpts can be made available upon request. Requests to access the datasets should be directed to franziska.detken@phzh.ch.

Ethics statement

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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Conflict of interest

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/feduc.2023.1035066/full#supplementary-material

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