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Accessing Young Children's Ideas about Energy

Franziska Detken [1,*] and Maja Brückmann [2]

[1] Department of Elementary Education, Zurich University of Teacher Education, 8090 Zurich, Switzerland
[2] Department of Educational and Social Sciences, Carl von Ossietzky University Oldenburg, 26111 Oldenburg, Germany; maja.brueckmann@uol.de
* Correspondence: franziska.detken@phzh.ch

Abstract: We present a multi-method design for elucidating young, mostly illiterate children's (grades 1 and 2 of Swiss elementary school, ages 6–8) ideas about energy. The design uses semi-structured interviews and video recordings as the main methods of data generation and collection, respectively. A plurality of tasks, including drawing, sorting and a newly developed picture stories task, target core aspects of the scientific energy concept in selected contexts. These tasks provide various opportunities for the children to connect to their prior experiences and express ideas verbally and non-verbally in age-adequate ways, e.g., by gestures or drawings. We illustrate the level of detail and complexity of the children's responses and show how these reflect the children's associations with energy and their patterns of argumentation. These rich data enable analysis regarding various aspects of the scientific energy concept, including sources, users, forms, and the transfer of energy, and the identification of possible starting points for early energy instruction.

Keywords: energy; young children; conceptual understanding; elementary (primary) education; video; interviews; drawings; assessment; validity

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1. Introduction

Energy is one of the most fundamental concepts in science and an important socio-economic issue. This has been recognised by policy makers: energy as a topic of instruction has been implemented in elementary science curricula around the world, in some countries already in K-2 education (e.g., the United States and Switzerland [1,2]). However, little is known about which aspects of the scientific concept of energy are accessible at a young age. It is thus an open question of how age-adequate instructional approaches for lower elementary school can be designed, on which phenomena they should focus and when it is advisable to introduce the term, energy.

A key to successful instruction is knowledge about the learners' pre-instructional conceptions. While there exists a large body of research on secondary students' energy conceptions, studies in elementary school or kindergarten are rare and do not provide a clear picture of younger children's energy ideas [3–8]. It is generally assumed that elder students' *pre*-instructional energy conceptions reflect how the term energy is used in the everyday language [9,10]. However, it is not clear if this also applies to children at the start of elementary schooling. Do they really hold ideas about something as abstract as energy? If yes, how can we build bridges between these ideas and the scientific concept?

In order to elucidate what energy "is" for such young children and how these conceptions relate to real-life phenomena and to the scientific energy concept, we have set out to address the following research questions:

RQ1: What do children in the first and second grade of elementary school associate with the term energy?

RQ2: How do children argue about energy, and which relations to the scientific energy concept can be identified in their statements?

RQ3: Is there a relationship between children's energy ideas and their understanding of selected phenomena?

Generating empirical data to answer these questions is not straightforward. On the one hand, first and second graders cannot be assessed like older students, but the research design must reflect the specifics of research with young (illiterate) children [11–15]. On the other hand, we need rich data that are suited to inform about various aspects of the highly abstract scientific energy concept. As a matter of validity, the research design must mediate between these two poles—the cognitive resources of young children vs. the sophistication of the scientific energy concept.

In this paper, we present a methodology to elucidate young children's energy conceptions and discuss our considerations and measures to ensure the validity of the findings. We show by way of example how we access surface structures of children's ideas (objects/situations and their characteristics deemed indicative for energy, RQ1) as well as deeper structures (ideas about the "nature" of energy, e.g., quantitative, spatial and temporal aspects, which can reveal relations to the scientific concept; RQ2). The results of the study will be presented elsewhere.

2. Background

2.1. The Scientific Concept of Energy

Energy is not only a concept of substantial social and economic relevance, but thanks to the conservation principle it is the perhaps most fundamental—and most subtle—concept in science. The scientific energy concept is special in that energy as such is not observable or measurable as other physical quantities are, e.g., mass or voltage. Instead, it can be seen as a model that provides a lens through which virtually all phenomena can be viewed [16–18].

More specifically, virtually any phenomenon in the natural sciences can be described on the level of observations (involved system and system elements, characteristics thereof, changes, and underlying mechanisms) and with energy terms (sources and/or receivers of energy, forms of energy, energy transformations and/or transfers). The description in terms of energy might not always explain why things happen, but energy arguments based on the conservation principle allow for grasping a system's behaviour, without needing to address complex mechanisms on the phenomenological side. For using such energy arguments, students need to understand the following interdependent core aspects of energy, which have been identified by science educators [6,9,19–22]:

1. Manifestations (forms) of energy;
2. Transformation;
3. Transfer;
4. Dissipation and degradation;
5. Conservation.

In addition, the "conceptualisation", i.e., as what the transferred or conserved quantity is thought of, is an important aspect of the energy concept from an educational perspective [19].

The abstract model character makes learning about energy difficult [19]. At the same time, this is one of the reasons why early energy instruction is considered in the first place. As a tool to analyse phenomena from a wide range of contexts, energy is a crosscutting concept with the potential to foster scientific literacy and integrated understanding [2]. Thus, science curricula that explicitly or implicitly draw on core concepts also include energy for elementary and kindergarten stage; for example, in Switzerland [1].

2.2. Accessing Young Children's Ideas about Science

2.2.1. Approaches to Access Younger Children's Energy Ideas

Only a few studies investigate kindergarten and elementary students' energy ideas as main focus of the research [4,7,8], in the context of an intervention [3,5] or within research on learning progressions, which includes upper elementary school [6,20,23].

An intervention study in kindergarten used semi-structured single interviews (n = 20) with material prompts (e.g., mechanical toys and a flashlight) [5]. Questions like "what is energy", "what is energy used for", "does ... have energy", and "how can you give energy to ... " were asked. In the pre-study, most children responded with "I do not know" or one-word responses. The authors attribute these observations to the children's limited vocabulary to communicate their understanding, and to "limited prior experience and knowledge of how things work". No details were provided about the analysis of the interview data.

In the context of research on learning progression, Lacy et al. [5] conducted qualitative clinical interviews with eight pairs of third-grade students to access their intuitive ideas and to find out what new ideas about energy in motion events could be developed in the conversation. A range of hands-on activities relating to mechanical phenomena and "questions about what it means to 'have energy'" were used. The authors do not describe how the student's responses were analysed.

Clinical interviews were also conducted by Yuenyong and Yuenyong [7] with elementary students (grades 1 to 6, n = 30) from Thailand; the authors used a set of image cards ("interview about instances" [24]) and asked the participants if the depicted objects had to do with energy and to explain their decisions. Using data-driven content analysis, the authors identified five "frameworks" (electrical energy, potential energy, mechanical energy and forces, heat energy, fuel). The authors did not investigate if the children's responses could be linked to other energy aspects than energy forms.

Reimer [4] used a questionnaire with written responses to assess German fourth-graders ideas about energy (n = 121); in addition, she conducted qualitative interviews with 21 pairs of selected children. As in the study of Yuenyong and Yuenyong, the children were presented a set of images (e.g., a banana, a sleeping child, a fire) representing several forms of energy. The written and verbal responses were analysed with content analysis (data-driven approach), and a complex set of categories was developed to capture various aspects of the children's ideas regarding selected images.

As a part of his intervention study in German elementary school (fourth grade, n = 202), Haider [3] used a complex questionnaire with open and multiple-choice (MC) answer formats to assess the participants' understanding of energy. The questionnaire comprised a task requesting a drawing with description, a definition/explanation of energy and several items that addressed core aspects of energy-like forms, transfer, and transformation. The open responses and the drawings were coded with a coding frame that included categories relating to core aspects of the energy concept. For the MC items, the number of correct answers was determined. In his analysis, the author focused on how often certain categories were assigned and correct answers were given before and after the intervention. The author did not analyse which intuitive ideas were expressed by the drawings and their descriptions.

Using a questionnaire that required only yes/no answers, Nicholls and Ogborn [8] assessed how fourth graders (n = 32, ages 10–11) characterised a variety of objects by their relation with energy (e.g., having, needing, giving energy). The decision for this method was based on their observation that students had difficulties in expressing their ideas in interviews, and that the students' answers were hard to understand and to analyse.

Research on learning progressions, which included upper elementary school (grade 3 and higher), used MC items addressed to core aspects of energy in various contexts [20] and biological contexts [23], respectively.

This review shows that most of the prior studies have been conducted with students of grade 3 and higher, while the stage K-2 is addressed in only two studies. Two main methods—clinical interviews and questionnaires—have been used in these studies, the latter only with students in upper elementary school. For accessing children's energy ideas with a questionnaire with open answers, as in the fourth-grade studies of Haider [3] and Reimer [4], the children need to at least be able to write, which cannot be assumed in grades 1 or 2. Questionnaires with a closed-answer format, as used in some learning progression studies [20,23], can cover a broad range of energy aspects and contexts. Yet, there are no well-established instruments for younger children, and their development requires knowledge of how young children think about energy and careful validation. Accordingly, we decided against using questionnaires in the present study.

Interviews, especially in conjunction with material prompts, such as objects or image cards, appear to be a more productive approach for younger children, and are thus pursued in this study. However, the earlier studies indicate that the abstractness of the energy concept (younger children might not understand the questions or lack words to express their ideas) and its broad scope (difficulty to access different energy aspects systematically) may cause problems in data collection and analysis [5,8]. Using similar instruments for the collection of their interview data, Reimer [4] and Yuenyong and Yuenyong [7] developed data-driven coding schemes with very different levels of complexity; both do not provide easy access to children's ideas about aspects of the scientific energy concept. Following Hadzigeorgiu [12], we conclude that it is advisable to ground our methods of data collection and analysis on a framework that reflects the structure of the energy concept. Additionally, we need to ascertain that the interview setting, including the verbal and material prompts, meets the children's cognitive resources. We, therefore, continue with a brief review of research methodologies for children in preschool and lower elementary school in other contexts than energy with a focus on interviews.

2.2.2. Methodologies to Elicit Younger Children's Perspectives

Research with young children is challenging, because their abilities, e.g., concentration span, memory, and language abilities, differ greatly from those of adults. Nevertheless, several authors emphasise that children are, just like adults, capable of speaking for themselves and thus of participating in research about their perspectives—if the "right" methods are used, e.g., [11,15,25,26].

Which methods are considered suitable, as well as the conclusions drawn from the empirical data, depend on the researchers' perspectives on cognition and learning. In this study, we take a socio-cultural view on learning, in which we assume that children hold certain everyday conceptions about scientific concepts, but that these ideas are highly contextualised, and their expression is thus very sensitive to the assessment situation.

In this view, suitable child-friendly methods engage the children in the research process by inviting them to reveal their perspectives on the topic of interest. Generally, it is recommended to use multiple methods that "suit their competence, knowledge, interest and context" [15] and generate rich data (see also [14], and for science education [13,27]). Such methods comprise observations, interviews, questionnaires, structured activities (e.g., role-play), and multi-sensory approaches that give more weight to the children's non-verbal expressions (e.g., drawings, children's photographs, tours through the environment) [14,15].

Interviews, as the main method of data acquisition of this study, are—besides observations—the most common method in early childhood research in general [14,15] and in science education [12,28]. However, several aspects can affect the validity of inferences made from interview data, if the situational nature of children's knowledge is not reflected by the methods of data acquisition: Children might not understand the interviewer, especially if words for abstract concepts are used, or the children's responses might be misinterpreted, e.g., taken literally instead of metaphorically [5,11,12]. If children cannot relate to the task they might be unable to access their implicit knowledge by connecting to their everyday experiences; thus, they cannot show their full potential [12,15]. Finally, children have been observed to align with the interviewer, resulting in the emergence of ad hoc constructs, [11,14,15,29], or they may be hesitant to respond to questions if they do not feel comfortable in the situation [14,15].

Therefore, it has been suggested to use various "tools", e.g., drawings, images or objects, that support children in expressing their ideas [14,15]:

Drawings, as a familiar cultural tool, are used in many research endeavours investigating young children's perspectives, e.g., [26,30,31], and also in science education, e.g., [32–37]. Rennie and Jarvis [35,38] found that drawings generally reflected the range of their 7–11-year-old participants' ideas about technology, though they under-represented the scope of some children's conceptions. Other authors regard children's drawings as having limited informative value, but deem an analysis in combination with the children's explanations fruitful [36,37]. Hence, the main benefit of drawings is seen in assisting children to communicate their ideas, rather than constituting an independent body of data [14,26,30,31].

Material prompts, such as image cards and/or objects, are also often used to assist students in expressing their ideas regarding the existence and the scope of an abstract concept, e.g., in an "interview about instances/events" [24]. In order to produce valid data when using such methods to engage younger children in a conversation, it is important to choose prompts to which children can relate to [11,12].

We conclude that interviews are a reasonable choice to elucidate young children's ideas in science, if combined with techniques that aid children in expressing their thoughts verbally and non-verbally. This requires an instrument with a setting that is as authentic as possible, and the use of material prompts that are suited to activate the children's prior knowledge. The interview protocol and the person conducting the interview play a major role, because the way the interview is conducted greatly affects the richness of the children's accounts; open questions, encouragement and the appreciation of the children's contribution are important [29]. Because of the situated nature of children's knowledge, the influence of the interviewer on the children's responses is to be expected. Pramling [11], therefore, suggests conceptualising the children's answers in an interview as the "collaborative unfolding of sense between interviewer and child" rather than the child's "pure" understanding.

2.3. Summary and Further Organisation of This Report

To access young children's energy ideas in depth, we thus need a "Swiss army knife"—a research setting reflecting the structure and contextual scope of the energy concept as well as providing authentic settings that offer different possibilities for children to connect to their prior experiences and to express their ideas in familiar, age-adequate ways.

We describe the development of a suitable research design in Section 3 with an emphasis on data collection and present our considerations to ensure validity by mediating between the complexity of the energy concept and specifics of conducting research with young children. In Section 4, we provide "thick, rich" descriptions of selected situations, which show how children acted in the setting. These indicate, by way of example, that our method elicits rich responses; we outline how these accounts can be related to several aspects of energy and provide an empirical basis for answering the research questions of our study (these findings will be presented elsewhere). In Section 5, we discuss how decisions in the design process and our observations support the validity of this research.

3. Methodology and Materials: The Research Design and Its Development

Our research design, as shown in Figure 1, is a multi-method design with single interviews. It comprises a set of age-adequate and theoretically substantiated activities. These have been designed to invite young children to express themselves in various ways about energy and exemplary phenomena. More specifically, we target:

- Associations with the term energy (surface structures);
- Patterns of argumentation—ideas about the "nature" of energy and about further aspects of the scientific energy concept (deeper structures);
- Understanding of selected real-world phenomena (observations and ideas about underlying mechanisms).

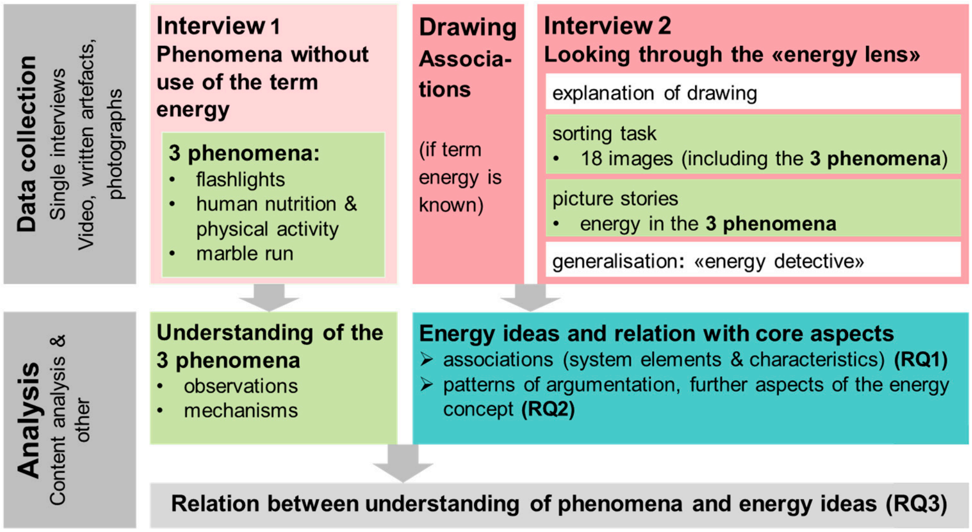

Figure 1. Research design.

Three main contexts and phenomena are used in both interviews:

- Electricity—shining and fading flashlights;
- Humans—physical exercise and nutrition;
- Mechanics—ball rolling down an inclined rail (marble run).

The children's responses were videotaped and analysed with content analysis. Details of the research design are described in Sections 3.2 and 3.3.

In view of the "content" aspect of validity [39], we verified the coherence between the research questions, methods of data collection and analysis, and data generated [40,41] by using the scientific energy concept as a common point of reference (Section 3.1). The appropriateness for young children as one element of the "substantive" aspect of validity [39] was ensured by developing the methodology in an iterative process, including two pre-studies with elementary school children (n = 22, grades 1–3, ages 7–10), one pre-study in kindergarten (n = 17, ages 4–6) as well as discussions with science educators and early childhood experts. Additionally, we adapted the procedure situationally during data collection (researcher responsiveness [40,41]).

3.1. Framework

To ensure methodological coherence we developed a framework that guides data collection and analysis (Figure 2). The framework reflects (a) the core aspects of the scientific energy concept; (b) the character as a crosscutting concept with applicability in various contexts and across disciplines ("contexts"); (c) the model character with its strong link between observable phenomena ("phenomena lens") and their description and analysis in terms of energy ("energy lens") (cf. Section 2.1). For this study, we divided the core aspect "manifestations (forms) of energy" into two more specific ideas: "system elements" designate objects, or object-like entities, such as air, involved in phenomena. "Characteristics" designate observable features or activities, e.g., motion as an indicator for kinetic energy [20,42]. We also merged "dissipation, degradation" and "conservation" into one aspect "dissipation/conservation".

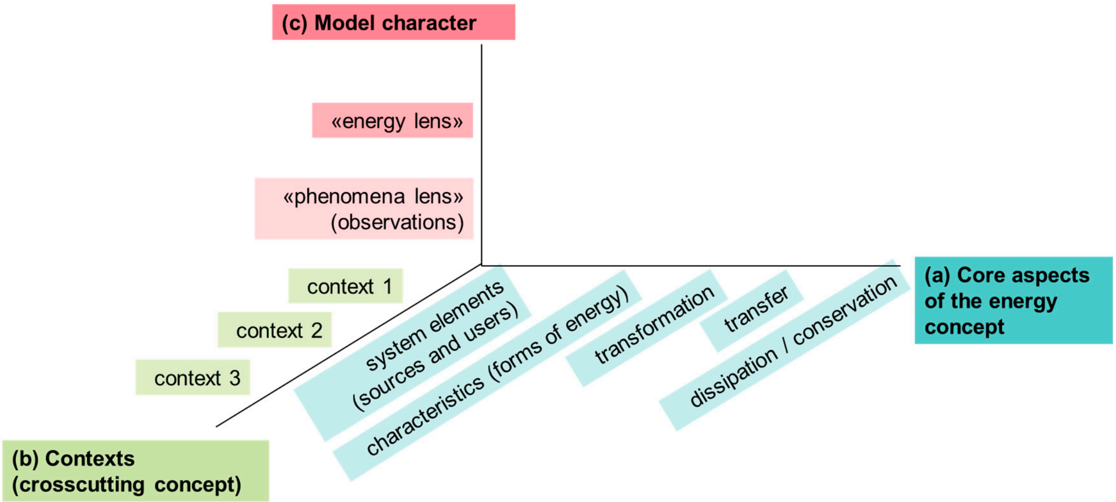

Figure 2. Framework for accessing and analysing energy conceptions.

The following example from the context of electricity (fading flashlight) illustrates the application of this framework and the relation with the research questions: On the phenomenological level ("phenomena lens"), the system "flashlight" comprises a light bulb, a battery, and conductors arranged in an electric circuit. One can observe and/or measure the emission of light, the voltage of the battery, the current in the closed circuit, and—less obvious—the temperature of the environment. One can also observe changes in these characteristics over time, e.g., fading brightness and decreasing voltage. Viewed through the "energy lens", this process can be described by energy transfer from the battery as the energy source to the light bulb as the user and further to the environment. The energy form changes from chemical to electrical, light and finally thermal energy (transformation and degradation). Thermal energy spreads out (dissipation), but the total energy, including the environment, remains constant (conservation). By this "translation" into energy language, no information is added.

In our study, we are interested in whether children "see" energy when they view this and other phenomena through the "energy lens", what system elements and characteristics they describe, and to which further aspects of the scientific energy concept their accounts relate (RQ1&2). For example, do they identify light as an indicator for energy, or the battery as a source of energy? We are also interested if the understanding of the structure and general function of a flashlight has an impact on these ideas (RQ3). For example, do children express transfer ideas, if they know that there is an interaction between the battery and the light bulb? Table A1 (Appendix A) summarises the application of this framework to the three main phenomena.

3.2. Data Collection

The research design implements this framework by comprising two parts which focus on the two "lenses". The parts are linked by the same three main phenomena and include activities that are suited to reveal ideas about various core aspects of energy (Figure 1). We use videotaped semi-structured single interviews as the main data source and children's artefacts (drawings, worksheets) as an additional source of data. Both interviews are modified "interviews about instances/events" [24]. To account for the children's cognitive resources, we implemented a multi-method approach as considered adequate for this age group [13,27]. These multiple methods are situated in authentic, familiar contexts. They offer a broad spectrum of activities that trigger different cognitive processes, have varying levels of openness, and allow multiple modes of expression. Many of these activities include material prompts, such as objects, images, and worksheets. The research protocols of both parts are summarised in Tables A2 and A3 (Appendix B). Figure 3 illustrates selected tasks that relate to the phenomenon "fading flashlight".

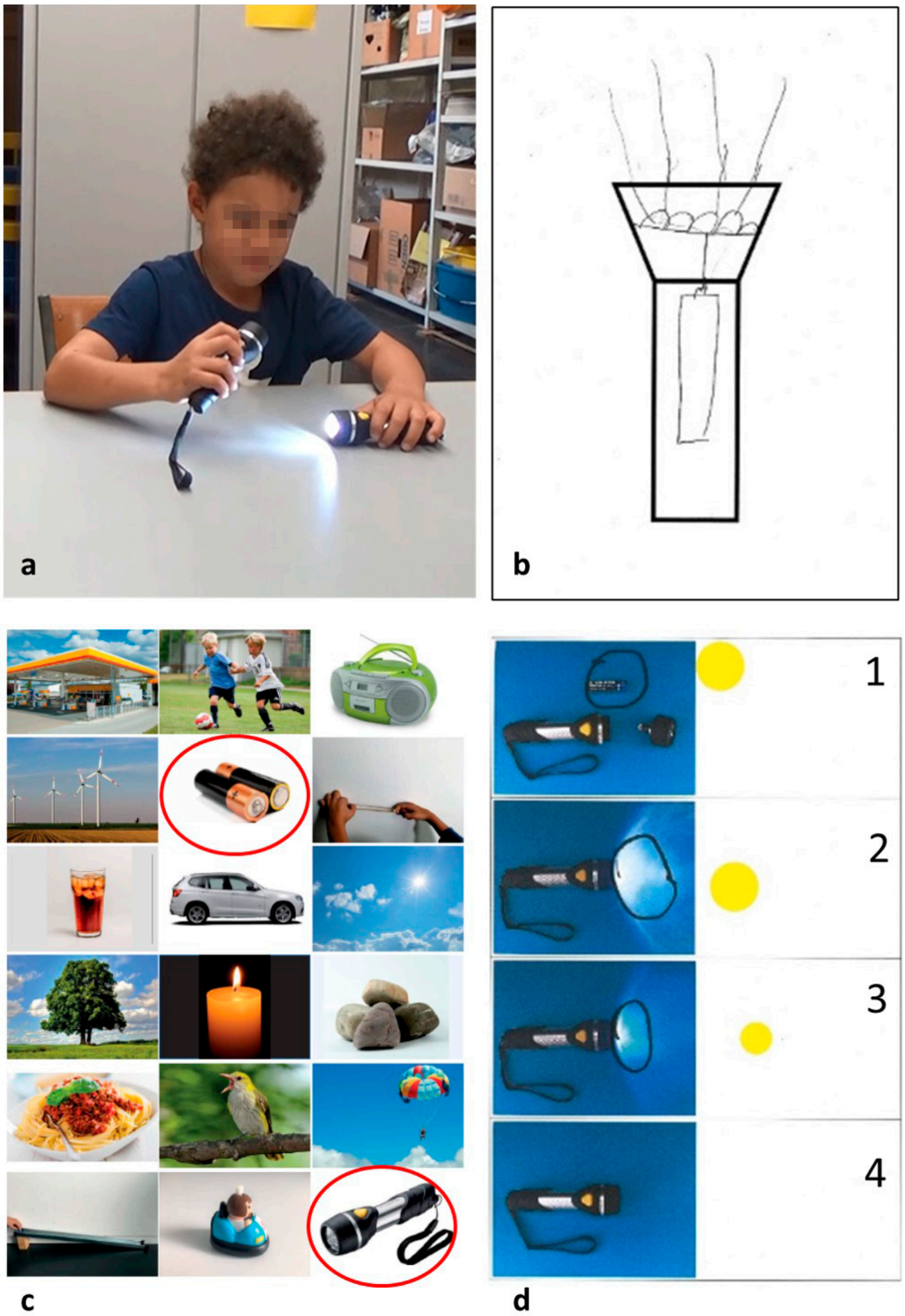

Figure 3. The phenomenon "fading flashlight" as a link between the two interviews: (**a**) discussing the phenomena, here flashlights, in Interview 1; (**b**) a child's illustration to explain how a flashlight makes light (Interview 1); (**c**) images used in the sorting task of Interview 2 (objects relating to the flashlight task from Interview 1 encircled); (**d**) picture story of a fading flashlight with a child's indication where (black circles) and how much (yellow dots/stickers) energy can be found (Interview 2).

3.2.1. Part 1 (Interview 1): "Phenomena Lens"

Interview 1 addresses the children's understanding of the main phenomena. It comprises three tasks which generally have the same sub-structure. First, the children encounter the phenomenon, e.g., by exploring flashlights (Figure 3a), doing physical exercise, or constructing a marble run. These immediate experiences provide a starting point for the conversation, wherein we first focus on the children's observations: We target the children's ability to identify system elements and characteristics and to describe the processes. Then we probe the children's ideas about the underlying mechanisms: for example, the children are asked to explain their ideas while completing scaffolds showing contours ("black boxes") of a flashlight (Figure 3b) and the human body [34] to assess their understanding of the electric circuit and digestion, respectively. An example is described in Section 4.1.

At the time of Interview 1, the children did not know that the study was about energy; we did not use the term energy unless the child did.

3.2.2. Part 2 (Drawing Task and Interview 2): "Energy Lens"

Part 2 addresses what children "see" when they look through the "energy lens". Before Interview 2, the children are asked individually if they had heard the word energy before, and if yes, to draw something they associate therewith, and/or to write. If they know the word energy, the children proceed to Interview 2 which comprises four tasks:

1. Drawing task [35–38]: The children are asked to explain their drawings or written notes ("unprompted" associations with energy).
2. Sorting task [4,7]: 18 images are presented to the children (Figure 3c). The children are asked to name the depicted objects; selected images are explained by showing the children the corresponding real objects. Then, the children are asked to slip into the role of an "Energy Detective" who looks for energy. The children categorise the images depending on their relation with energy (yes, no, not sure). Hereby, we target the children's "prompted" associations regarding a broader spectrum of phenomena.
3. Picture stories: The three phenomena of Interview 1 are presented as picture stories with 4–5 images (Figure 3d). The children are asked to retell the story of the level of observations. As "Energy Detectives", they are then asked to look for energy, to mark the corresponding parts of the images, and to indicate with stickers how much energy there is. We developed this task to address the process character of the main phenomena and to access spatial and temporal aspects of energy in these processes.
4. Generalisation: At the end of the interview, children are asked to explain to a friend how to become an "Energy Detective". Thereby, the verbal scaffold "if you want to find energy, look for all things that … " was used. With this task, we target the children's ability to explicate criteria for a relation with energy.

The role of the "Energy Detective" was developed to introduce the "energy lens" in a child-adequate way, since searching games (e.g., "spot the … " pictures) as well as pretend play are familiar activities for young children.

To probe children's ideas about selected objects (e.g., objects depicted in the own drawing or in selected image cards) in depth, we repeatedly used a set of "energy lens" questions that target both surface and deeper structures of children's conceptions. Table 1 shows an excerpt, and Table A4 (Appendix B) shows the full set; an example is given in Section 4.2. The set is based on the "Energy Tracking Lens" [6,18], which was developed for instructional purposes. We added questions to reduce suggestiveness, e.g., regarding substance and transfer ideas.

Table 1. Interview guideline (excerpt) for children's explanation of their drawings and their decisions in the sorting task, with the targeted aspects of energy.

Question		Research Interest
What does … have to do with energy?	Relation of energy with objects	Surface structures; associations: System elements and characteristics (RQ1)
Does … have energy (or not)?	Relation of energy with objects	
Does … always have energy (or not)?	Temporal aspects	Deeper structures; patterns of argumentation: Transfer, transformation, dissipation/conservation (RQ2)
How does … get energy?	Spatial and temporal aspects	
Where does the energy come from?	Spatial aspects	
What happens to the energy (after…)?	Spatial and temporal aspects	
Where does it go to?	Spatial aspects	

We chose the three main phenomena and 13 additional auxiliary phenomena for the sorting task (total 18 images, five of these referring to the main phenomena, cf. Figure 3c) according to the following criteria:

- Meaningfulness for young children, e.g., daily routines and experiences, toys, hobbies.
- Access points to various energy aspects across disciplines, e.g., different forms, users, and sources of energy (see Appendix A, Table A1).
- Relevance from an educational perspective: topics of elementary school science, known pre-instructional conceptions of younger students [4–6].
- Variance: different categories of objects (e.g., natural–artificial, living–inanimate, small–big), different timescales of processes (e.g., tree growth vs. rolling marble).
- Ability to trigger interesting conversations, openness.

3.2.3. Sample, Ethics and Procedure

The participants were recruited from two elementary schools in the city of Zurich, Switzerland. The sample consisted of 25 children (13 girls, 12 boys) which were 6 to 8 years old (mean 7.5 years). In total, 13 children attended the first grade, 12 the second. Based on the teachers' estimation, children with different language and cognitive abilities were selected. In total, 14 children had a foreign language background. All were able to understand the interviewer, who spoke standard German, and to express themselves in standard German (school language) or the Swiss German dialect.

Before entering elementary school, the participants had attended the compulsory 2-year kindergarten training, where they had been acquainted with classroom routines and playful learning environments but had not been formally introduced to reading, writing, or calculating. At the time of the study, only two months after the start of the new school term, the children had not received any formal instruction regarding energy, electricity, human body, and mechanics. The topics of kindergarten instruction are unknown.

The children volunteered; parental permission was obtained. The main study was approved by the education board. To avoid bias, the children and their parents knew that the study was about science but did not know the topic "energy". All names are pseudonyms.

The participants were interviewed during school hours in a separate room in the school. After each task, they had the opportunity to stop or interrupt. The interviewer explicitly expressed her interest in and pleasure about the children's thoughts, regardless of "right" or "wrong", and encouraged the children to also express uncertainties and "new" thoughts. Almost all children were very engaged in the conversation and seemed eager to share their ideas; none wished to terminate and some continued after a break.

3.3. Data Analysis

3.3.1. Types and Processing of Data

Transcripts of the videotaped interviews constitute the main body of data that underwent an in-depth analysis with the QDA program MaxQDA [43]. Additionally, the children's artefacts (drawings, worksheets, video stills of the completed sorting task) were secondary data that help us to understand the children's verbal and nonverbal statements in the videos. Table 2 displays the collected types of data and further analytical steps. Figure 4 shows exemplary drawings, Table 3 the corresponding interview excerpts and sample codings.

Table 2. The different types of data collected and their further processing and analysis.

Data Collection	Original Data	Processing	Data Analysis
Interview 1	video recordings (*n* = 25; duration 18 to 40 min, mean 32 min)	transcription (TIMMS transcription rules [44] modified to include gestures)	rating (understanding of phenomena) spontaneous use of term energy
	sketches of a flashlight (*n* = 24 *) and the human body (*n* = 24 *)	scanning	secondary data to assist analysis of Interview 1
Drawing task	drawings and/or written notes (*n* = 22 **)	scanning	content analysis with coding frame (system elements and characteristics)
Interview 2	video recordings (*n* = 24 ***; duration 28 to 61 min, mean 40 min)	transcription (cf. Interview 1)	content analysis with coding frame (a) system elements and characteristics (b) patterns of argumentation, other aspects of the scientific energy concept
	video stills/photographs of the result of sorting task (*n* = 24 ***)	spreadsheet	frequency analysis (yes, no, do not know per image)
	picture stories of the three processes (*n* = 3 × 24 ***, including those left blank)	spreadsheet	frequency analysis (no, little, medium, much energy per image)

* In each case, one child did not use this scaffold; ** 2 children knew about energy, but did not draw, 1 child did not know about energy; *** all 24 children knew about energy.

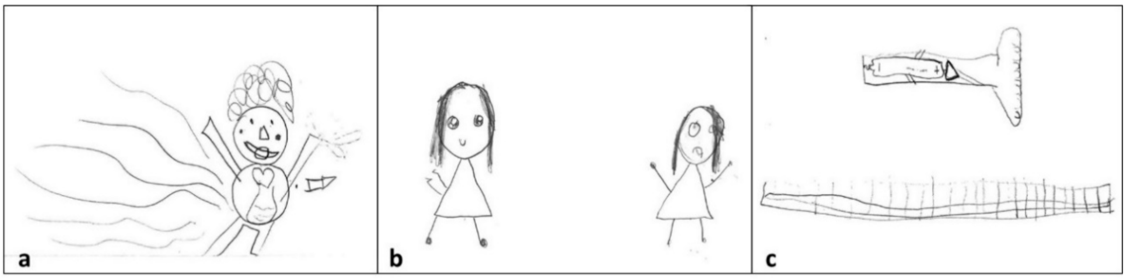

Figure 4. Three drawings of something that has to do with energy (all girls, 1st grade): (**a**) "Energy is speediness" (text on the drawing), (**b**) having energy and having no energy, (**c**) flashlight and ceiling light.

Table 3. Four excerpts the beginning of the second interview (children's explanations of their drawings) and sample codings of *system elements* (**bold**) and *characteristics* (underlined). *Italics* indicate codings that have only been applied to the transcript.

Excerpt	Transcript (Verbal, Gestures)	Drawing	System Elements	Characteristics
1	**She** runs, and then **the heart** beats fast and then she expends a lot of energy. And then **she** is weaker and needs to take a deep **breath** {gestures indicate beating heart and breathing}.	Figure 4a	Human *Gaseous substance*	Physical activity/state *chemical*
2	**She** runs and has much energy {points to figure on left side}. And **she** cannot run because she has no energy {points to other figure}.	Figure 4b	Human	Physical activity/state
3	And then I thought, a **lamp** and a **flashlight** have to do with energy. [. . .] 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.	Figure 4c	Electric user *Electric source*	Electricity Light
4	**One** needs energy to do sports. [. . .] I think, perhaps, if **one eats or drinks**, then this becomes energy in the belly, perhaps.	No drawing (boy, 2nd grade)	*Human food*	*Physical activity/state chemical*

3.3.2. Development of a Coding Frame for Interview 2

The framework of Figure 2 also guides data analysis. To this end, Qualitative Content Analysis (QCA), using a concept-driven approach with the data-based addition of categories [45,46], provides the best alignment of our research interest with the types and contents of the collected data. The coding frame comprises dimensions that are directed to the surface structures ("system elements" and "characteristics", RQ1) and the deeper structures (patterns of argumentation, RQ2).

Presently, the codes for the dimensions "system elements" and "characteristics" have been developed and applied to the drawings and the corresponding interview parts. The initial categories of the dimension "system elements" were derived from Chi's ontological categories [47], those of the dimension "characteristics" from the indicators for forms of energy described by Nordine et al. [42]. Data-driven additions, for example, physical or mental activity/state or a general notion of "functioning", were developed in an iterative process. Since we generally coded all objects and activities that were mentioned by the children in the interview, the codings serve mainly to structure the data for further analysis, for example, to analyse whether all children that mention food actually believe that food itself has energy.

Table 3 shows exemplary interview excerpts with assigned "system elements" and "characteristics" codes. The coding frames (Tables A5 and A6) and our considerations to ensure the quality of the analysis can be found in Appendix C. The intercoder reliabilities indicate a good agreement (dimension system elements: drawings $\kappa = 0.86$, interviews $\kappa = 0.97$; dimension characteristics: drawings $\kappa = 0.89$, interviews $\kappa = 0.87$; κ-value according to Brennan and Prediger [48] as implemented by MaxQDA [43]; 6 of 24 cases). Regarding the aspects system elements and characteristics of the scientific energy concept, this agreement indicates content validity as the main validity criterion of a concept-driven QCA [49].

As shown in the excerpts of Table 3 and Section 4, children argue in various ways when describing the phenomena. We observe patterns that can be related to energy aspects, such as transfer or transformation, or to the "nature" of energy. Excerpts 1, 4 and 5, for example, indicate that these children may think of energy as a "causal agent", i.e., something that is needed for operating or performing an activity and thereby expended. Excerpts 3, 6 and 7 suggest the notion of energy as a substance-like entity that is contained in and/or can be transferred between objects (" … has energy … inside", "gets stuck", "comes out"). Though energy transformation is not explicitly described, Excerpts 4–6 indicate that the children are aware of causal relations between characteristics, e.g., food and physical activity, or the state of the battery and the emission of light. A coding frame for these and other patterns is currently under development and will be presented elsewhere. These patterns of argumentation cannot be derived from the drawings; similarly, we need the interviews to clarify what is drawn (system elements) for what reasons (characteristics). The codings in italics in Table 3 demonstrate that the interview allows us to access this substantial information.

4. Description of Selected Situations

In this section, we present a "thick" description of four situations from the context of electricity that further illustrate the procedure, material and verbal prompts used and children's responses. The situations show, by way of example, how some children were able to provide very detailed accounts that allow an in-depth analysis of their ideas, while others had difficulty to relate to individual tasks. We also indicate how we intend to proceed with the further analysis of the deeper structures of children's energy ideas.

Situations 1–3 show how the two interviews are aligned with each other to address first the main phenomena and then to look at them through the "energy lens". Situation 4 illustrates how the scaffolds helped a girl to express her ideas in Interview 2.

4.1. Situation 1: What Do Flashlights Need to Shine?

As the first activity in Interview 1, the interviewer (I) passes the children two flashlights, wherein one of them is not working. Norman (first grade), obviously surprised (Figure 3a), suggested that the battery was "empty". Excerpt 5 begins after the battery was replaced by a fresh one:

I: Ok, what was your assumption?

N: Well, that this was empty and the other one was not empty.

I: Ah, ok. And what does that mean, the battery is empty?

N: That it has no Akku * inside anymore. (*colloquial for a rechargeable battery or its "pep")

I: What does that mean?

N: That one cannot use it anymore. And with a charger one can recharge it.

I: If you say, it is empty, does that mean that something was inside before? Or what does that mean, it is empty?

N: There is something inside. And the flashlight needs it to be able to shine.

I: Ok. What could that be, there inside?

N: Current.

I: Current. Does the flashlight need current?

N: (nods)

I: Ok. And how did that become empty?

N: If you use . . . and if you leave it switched on, then it can, then the current can go down, because the flashlight needs energy to be able to shine.

Norman describes the system element battery, the characteristics electricity and light, and the process that current/energy "goes down" when the flashlight shines. Using the contour of a flashlight as a scaffold (Figure 3b), Norman describes and draws further system elements (battery, cable, light bulbs) and states that the light bulbs "get a signal and start to shine" after the current went from the battery to the light bulbs.

This situation shows that Norman can identify elements of the system "flashlight" and causal relations therebetween, including the idea that current is transferred from the battery to the light bulb. Not surprisingly, he does not know the mechanism. Like Norman, 12 of the 25 children of our sample spontaneously mentioned "energy" in Interview 1 (all 12 in the context of humans, and 3 of these 12 additionally in the context of electricity). We conclude that this task is suited to elucidate the children's understanding of the process "shining and fading flashlight" on the phenomenological level, and that the setting represents a situation that some children spontaneously associate with energy.

4.2. Situation 2: Probing Aspects of the Energy Concept

In Interview 2, after explaining their drawing, the children attend to the sorting task. Prior to the episode from Excerpt 6, Andy (first grade) decided that the images "flashlight" and "battery" (cf. Figure 3c) have to do with energy, because batteries in general "can do something", and because the flashlight has a battery inside. Excerpt 6 shows how energy ideas are probed using the questions of Tables 1 and A4 (these questions being underlined in the excerpt). Figure 5 illustrates Andy's gestures.

I: And what do you think, is there always energy or not always?

A: Not always.

I: So when?

A: When one switches it on. (pushes an imaginary button)

I: Ok. And where does the energy come from? If it was not there before one switches it on?

A: From the battery.

I: Ok, you mean, the energy was in there? (points to image "battery")

A: Yes.

I: And then, when you switch on the lamp?

A: Then it comes out of there. (moves finger from the image "battery" to the image "flashlight")

I: Ok, that is interesting. And what happens with it then?

A: Eh, it gets stuck there (points to the light bulb in the image "flashlight", Figure 5a) and then it comes out of there eventually (moves finger away from the light bulb, Figure 5b).

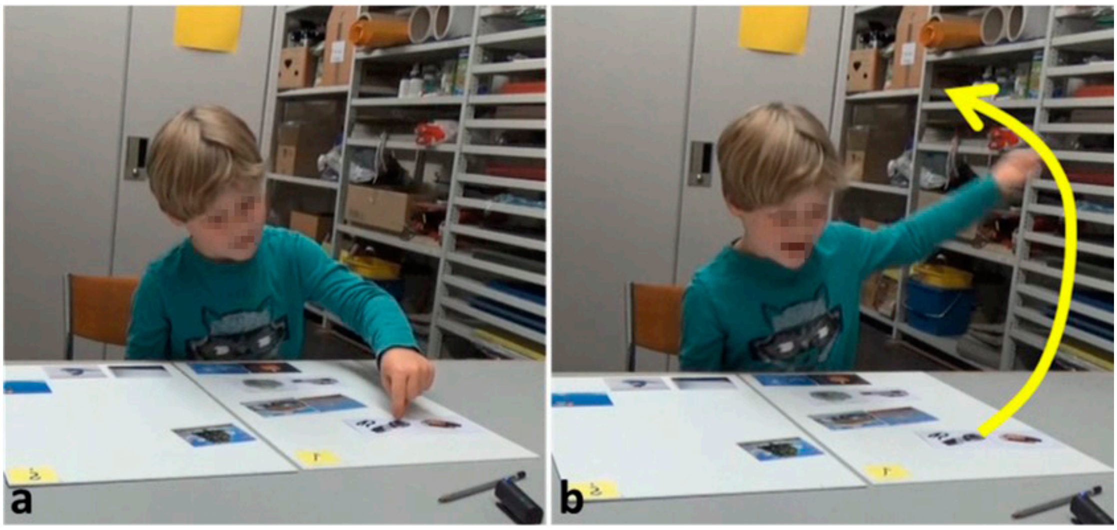

Figure 5. Using the image card "flashlight", (**a**) Andy indicates where the energy "gets stuck", (**b**) where it goes to when it leaves the flashlight.

The sorting task allows us to assess which objects or situations are associated with energy and why. This excerpt illustrates how a child uses different modes of expression as well as different patterns of argumentation: First, when answering to the question "always or not always", Andy describes energy as a feature of the state of being "switched on". Then, in response to the question "from where", he expresses verbally and with gestures (Figure 5) the idea of energy as a transferable substance-like entity.

Excerpt 6 shows how children's answers reveal ideas about "deeper structures" of energy, here substance and transfer ideas ("gets stuck", "comes out"), and how these ideas can emerge in response to the questions of Table 1. It highlights that video recordings enable capturing the children's full account and that the interviewer's input should be considered in the analysis.

4.3. Situation 3: Picture Story "Flashlights"

Excerpt 7 concerns the picture story task and begins after Elena (first grade) completed the worksheet (Figure 3d). Again, questions probing deeper structures are used (cf. Tables 1 and A4, questions from these tables underlined)

I:Ok, you say energy is here where the battery is, and here where the light is (points to encircled positions in the first two images, Figure 3d). Do you have an idea how it gets there?

E: The battery has energy first. Then you insert it there, then you close the lid, and later the energy from the battery comes out of there (moves hand in Image 1 from the battery to the flashlight, then in Image 2 from the body of the flashlight linearly to the light).

I: It comes out of there, interesting! And then? Here is much and there is medium, how does that happen? (points to encircled positions in Images 2 and 3)

E: Yes, because here it shines strongly (points to Image 2), and then, I think, one leaves it switched on, and then, I think, it gets less and less and then the battery has no more energy.

Excerpt 7 illustrates that the picture story task is a further approach to find out which objects or characteristics within an observed process are deemed indicative for the presence of energy. In the worksheet (Figure 3d), Elena identifies the battery as the initial location of energy (Image 1) and the light as the subsequent location (Images 2 and 3), and she infers the amount of energy from the intensity of the light (Images 2–4). This suggests that Elena recognises light as an indicator of energy. The interview adds further information: Elena's verbal statements and gestures indicate the idea of a "transferable substance" ("comes out"). Though she does not explicitly describe a correlation of the energy loss of the battery with the energy gain of the light, she displays an understanding that energy can have varying amounts and that the energy of the battery is related to the energy of the light (last paragraph). We conclude that the picture stories can be used as a starting point to access students' ideas about characteristics, transfer, transformation, and dissipation/conservation.

4.4. Situation 4: No Drawing

Two children knew the term energy but had no idea for a drawing. The following *Excerpts 4 and 5* illustrate how Aileen (2nd grade), one of these two children, was able to express increasingly specific ideas about energy in Interview 2. Excerpt 8 corresponds to the beginning of Interview 2.

I: You told me that you heard the word energy before. (Aileen nods) Then perhaps you can tell me what comes to your mind when you hear the word?

A: Hm ... (self-conscious, looks to the window)

I: (after waiting about 10 s) What comes to your mind?

A: For writing (gestures writing letters in the air and smiles to the interviewer).

I: (misunderstands Aileens's gestures) You can tell me. You do not need to write it down.

A: Hm ... (looks to the window) For running (tiny gesture moving fists back and forth, smiles to the interviewer).

I: For running? What do you mean by that?

A: Hm ... I do not know.

I: But running has to do with energy, do you mean that?

A: *(nods)*

I: Can you think of other things?

A: No.

In the subsequent sorting task, Aileen chose all image cards except for the "ice tea", and stated that these images "have energy". She explained this by a variety of characteristics, for example, physical activity (use of legs, getting energy by carrying a big stone), presence of batteries (e.g., in the wind-up car), light or fire, motion and "being a lucky tree".

Excerpt 9 illustrates how Aileen described energy in the process "marble run"; it starts after interviewer and child had clarified the images by referring to the real marble run known from Interview 1 (Figure 6a), and after Aileen had completed the worksheet (Figure 6b).

> **Ai:** Here it stops a little ... it waits (points to the ball in Image 2). And here it moves a little faster (moves finger along the ball's path in the Image 3). And here it will brake slowly (points to Image 4). And here ... (points to Image 4) eh ... here it brakes again.
>
> **I:** Hm?
>
> **Ai:** It will brake again.
>
> **I:** There it is not rolling anymore. Why did you choose "much energy" here? (refers to Image 5)
>
> **Ai:** Because it brakes a bit faster.
>
> **I:** But if it just rests here (points to the ball in Image 5) and has stopped rolling. Do you think it still has energy or ... is the energy somewhere else?
>
> **Ai:** Somewhere else.
>
> **I:** Where could it be?
>
> **Ai:** Somewhere here (points to the inclined plane in Image 5).

This situation shows how the image cards and worksheets can help children to express their ideas about energy. Though Aileen expressed only vague ideas at the beginning of the second interview (drawing task), she was able to explain her thoughts in more detail in the sorting and picture stories tasks. Therein, for example, the stickers aided the verbalisation of her ideas. The excerpt also shows the importance of avoiding suggestive questions: Aileen's response to the question " ... or is it somewhere else" is probably an ad hoc construct to align with the interviewer.

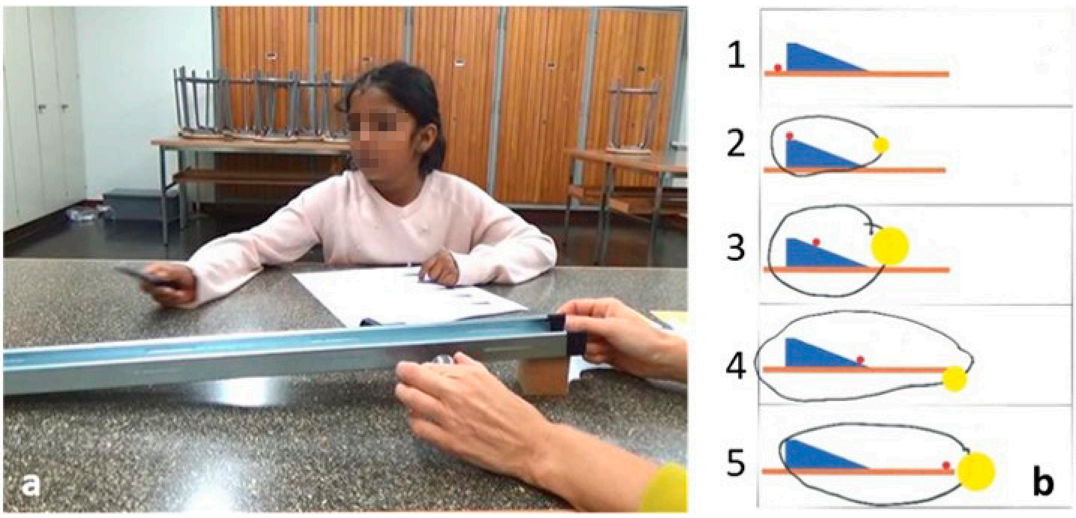

Figure 6. (**a**) Ensuring a common understanding of the "marble run" picture story; (**b**) worksheet with locations and amounts of energy.

5. Discussion

5.1. The Collected Data Reveal the Targeted Aspects of the Children's Ideas

Our aim was to invite young children to express themselves in various ways about energy and underlying phenomena. The data show that our young participants accepted this invitation. Using various tasks in different contexts, we were able to collect rich empirical data which reveal the targeted aspects of children's ideas:

- *Associations with the term energy (surface structures)* are assessed as a side-effect in Interview 1 ("spontaneous" associations) and in Interview 2 through the drawing task ("unprompted" associations), the sorting task ("prompted" associations) and the picture stories. Figure 4 shows by the way of example that the drawings as such are diverse and enable the identification of system elements and characteristics (RQ1). However, the children's explanations in the interviews are necessary to find out which aspects are considered indicative for energy (cf. Table 2). The three other tasks complement this information.
- *Patterns of argumentation (deeper structures)* of children's ideas are accessible in the conversation with the children in Interview 2. Table 3 indicates that some children spontaneously express ideas about the "nature" of energy when explaining their drawings. Excerpt 6 shows by the way of example that the "energy lens" questions of Table 1 are suited to probe such ideas. It also shows how observed patterns can be related to further aspects of the energy concept, e.g., transfer (RQ2). The same applies to the conversation about the picture stories (Excerpts 7 and 9).
- *Understanding of selected phenomena* is addressed in Interview 1 (RQ3). Here, the contexts and tasks allow us to assess which objects, characteristics, and relations the children are aware of, and what ideas about the mechanisms they have (Excerpt 5).

5.2. Multiple Methods with Multiple Modes of Expression Elicit Rich Responses

Collecting this rich data was enabled by a complex setting with multiple methods [13,27]. The interview durations (Table 2) and the excerpts indicate that we were able to engage the children in the one-to-one conversation with the interviewer and to elicit rich responses. The drawings and the material prompts served as scaffolds to express thoughts verbally and non-verbally and encouraged the children to interact with the material rather than focusing on the interviewer. As in Excerpts 6, 7 and 9, many of the children used the images of the sorting and picture stories task to indicate where energy is or how it moves. Additionally, the picture stories make these ideas tangible by enabling the visualisation of changing amounts and locations of energy. Combining these approaches with the "energy lens" questions (Table 1) enables us to access the surface and deeper structures of children's conceptions. This indicates that the single interviews are generally also a suitable approach for young children, if used in combination with child-friendly methods, such as drawing, sorting and picture stories, and that video recordings and children's artefacts (drawings, worksheets) are appropriate techniques for data collection.

5.3. Drawings Can Help Children Expressing Themselves but Do Not, as Such, Reflect Their Understanding

The children were asked to draw in both interviews with different purposes:

The "black-box" drawing tasks in Interview 1 (Figure 3b) were used to direct the children's attention to the inner structures of the human body [34] and of a flashlight and to help them express ideas about the involved processes verbally and with gestures. Though the example shown in Figure 3b enables the identification of elements of the flashlight, most "black-box" drawings show the structures only vaguely and do not reflect processes. This corresponds to findings of earlier studies [36,37] and confirms that it is fruitful to let the children draw during the interview and to focus the analysis on their explanations.

The "energy drawings" (Figure 4) used in Interview 2 served as an indication, if the child knew the word energy and what it associated with energy; they were also used to start the conversation about energy. Our data show that most of these drawings (including responses in writing) could be categorised without the children's explanations with respect to the subject of the drawing (dimension system elements) and potential indicators for forms of energy (dimension characteristics). As in the earlier technology-related study [35,38] drawings of "something associated with . . . " are thus suited to determine the contexts of children's "unprompted" associations. However, the drawings do not tell us why the child chose the respective object or situation (cf. Table 3). Accordingly, the interview is needed to access this aspect and deeper structures of children's thinking, which is in line with earlier studies [36,37].

Another purpose of the "energy drawings" was easing the start of the conversation. While most of the children seemed to enjoy explaining their drawing, a few were reluctant, and two did not draw at all but were able to explain their ideas verbally.

We conclude that "energy drawings" can constitute a good starting point for conversations about energy but should not be used as the only way to elicit children's ideas, e.g., in science class. An alternative less demanding approach to the children's "unprompted" associations in future studies could be letting children identify real-life objects or situations that have to do with energy, e.g., by taking photographs in their environment [15].

5.4. The Sorting Task Enables Probing a Wider Range of Phenomena

We observed that the children had pleasure attending to the sorting task and experienced no difficulties. As Situation 4 shows, by the way of example, many of the children expressed a broader understanding of energy in the sorting task than in the drawing task. This is contrary to findings of the earlier technology-related study [35,38], where a general consistency between children's drawings and/or written notes and the decisions in a "picture quiz" has been reported. We hypothesise that tasks that require a judgement (sorting) rather than a production of an own example (drawing) are less demanding and that this difference might have a stronger impact here, because energy is less tangible than technology.

We experienced that images are useful to probe children's understanding across a wider range of phenomena. To this end, we believe that presenting the image cards as a set adds value to an "interview about instances" approach as used in earlier studies [4,7]. The children in our study could interact with the cards, choose with which card they would like to start, and group related cards—all this helped to involve them more actively than just talking about the images one after the other. Grouping related cards can be the first step towards identification of source-receiver relations (cf. Excerpt 6), or of generalised indicators for a relation with energy; however, many children had difficulties to generalise their ideas.

The resulting structure (objects on the yes/no/unsure plates) indicates which of the objects are or are not associated with energy, but the children's explanations in the interview are necessary for elucidating the reasons for those decisions and further energy ideas. Changes as important indicators of energy transfers and transformations are generally difficult to capture by static images. Hence, the process character of some of the depicted phenomena, especially slow changes like plant growth, is hidden, and the discussion about energy transfers and transformations in these phenomena is thus on a very abstract level. Consequently, the sorting task does not allow to address all energy aspects in all depicted phenomena equally well.

5.5. Picture Stories Unfold the Process Character of Phenomena

The picture stories were designed to address aspects of transfer and transformation of energy by highlighting the process character of selected phenomena, thus mitigating limitations associated with the sorting task. Since the children were familiar with these phenomena from Interview 1, their representation as series of photographs was understood by all children, and the children responded as expected by encircling the locations of energy and indicating the amounts with stickers (Figures 3d and 6b). The worksheets show which of the depicted objects (e.g., flashlight, light, battery in the "flashlight" picture story) are considered indicative of energy and indicate if the child thinks of energy as an entity that can have varying amounts. However, the worksheets, as such, do not allow for inferring if energy is transferred or transformed, or if it just appears or disappears. To address these aspects of children's energy ideas, the interview is needed.

The children's responses in the interview indicate that two of the stories—"flashlight" and "human nutrition/physical exercise"—were useful to direct the conversation to aspects of energy sources and receivers, transfer, and conversation, while the "marble" run was less productive, as there is no visible source of energy.

5.6. The Interview Is Necessary to Access Relevant Information

As discussed, the children's artefacts (drawings, chosen image cards, picture-stories worksheets) enable accessing situations where energy exists, but the children's explanations are necessary to access deeper structures of children's thinking. Situation 2 shows by the way of example that the *"energy lens"* questions (Table 1) are suited to probe selected energy aspects. However, the repeated use of these questions may already teach the children how to talk about energy; this will have to be addressed during the further analysis of the data. Besides, some children became tired of responding to these questions. To avoid such issues in future studies, we suggest using the full set of "energy lens" questions (Table 1) only to discuss few selected images.

As a part of our effort to conduct the interviews in a *child-friendly manner* we selected and adapted the verbal and material prompts based on careful observation of the children's reactions. To ensure that the prompts are understood as intended and evoke the targeted behaviour, we asked the children to name the objects and images used and/or asked, *"do you have . . . at home?"*, *"have you ever seen . . . ?"*. We also generated experiences in situ as starting points for the conversation, e.g., by doing an exercise and then asking, "what do *you* need to do *these star jumps*?" in Interview 1, by letting children play with a real wind-up car in the sorting task, or by referring to the experiences from Interview 1 in the picture stories task. Another fruitful approach to help the children understand the tasks was to let them adopt the role of the "Energy Detective" throughout Interview 2. We conclude that it is not only necessary to check beforehand how fruitful the prompts are, but also to invest some of the precious interview time in ensuring this common understanding, or in finding alternatives that work for the individual child.

5.7. The Selected Contexts Are Adequate for Young Children and for the Energy Concept

The contextuality of the research design is pivotal since the phenomena must be both meaningful for young children and exemplary for the energy concept. The children's concentration span was the main limiting factor for the duration of the interviews and determined indirectly the number of phenomena we could use as main phenomena (Interviews 1 and 2) and auxiliary phenomena for the sorting task (Interview 2). As the analysis of the selected phenomena under the framework of Figure 2 shows (cf. Appendix A), some forms and core aspects of energy have received more weight than others in the final set of phenomena; in particular, thermal phenomena that can reveal dissipation and degradation ideas, are only represented by the sorting task. Since any selection is inevitably incomplete because of the broad scope of the energy concept and, since we expect children's ideas to be contextualised anyway, we considered it more important to assess children's ideas in depth—with different methods in few contexts—than trying to address a larger quantity of phenomena. Though we cannot determine in this setting how strongly a child's ideas are contextualised, the selected contexts are rather diverse, mitigating uncertainty about a limitation to specific contexts. Since the children responded well and even used the term energy spontaneously in Interview 1 in two of the main contexts (cf. Section 4.1), we conclude that the contexts and phenomena used in this study provide fruitful starting points to access energy conceptions of young children with similar cultural backgrounds.

5.8. The Situational Nature of Children's Conceptions Has Implications

Despite the recurring phenomena, we observed that not all children could connect equally well to each task and the children's ideas are not always consistent. For example, some children did not draw though they knew the term energy (cf. Situation 4 and Table 3); others did detect energy in the "flashlights" picture story, but not in the corresponding images of the sorting task. Though we used the children's wording and/or offered alternatives, e.g., "*does it* . . . , or *doesn't it* . . . ?" (cf. Table A4, Appendix B), some responses might also have been influenced by the interviewer's input and the material prompts. It is likely that the children learned in the setting.

However, inconsistencies and an influence of the interview situation are to be expected because of the situational and highly contextualised nature of children's conceptions. Our observations support Pramling's view that the research interview should be "reconceptualised as a social practice, where the collaborative unfolding and meaningful exchange between interviewer and child is foregrounded" [11]. They also underpin Wilkening and Cacchione's view that "batteries of tasks of varying content, of varying information-processing demands, of varying shares of cognition and action, and of varying motivational appeal" are needed to assess children's ideas in science, while pure, context-free conceptions are likely not to exist [27].

Since we assessed the children's ideas redundantly by different tasks—while referring to the same phenomena—we can compare and triangulate these ideas. We can find out which ideas are expressed by many children in and across contexts. On the level of the individual, we can find out which ideas are stable, and how others might be influenced by the setting. Both the expressed ideas and the prompts that affect them are important information for instruction; for example, it indicates which ideas can emerge in classroom discussions. This is subject to further analysis and will be presented elsewhere.

5.9. Outlook: The Analysis of Rich Data

Collecting rich data with multiple methods is adequate for young children, but as earlier studies show [3,4,7], the analysis of such data is a challenge. The categorisation should be neither too coarse, nor too fine-grained and should enable the identification of links to the scientific energy concept. In addition, the quality of the analysis must be ensured.

Though the analysis of our data was not the focus of this publication, the first steps reported above (cf. Section 3.3.2) indicate that a concept-driven QCA—guided by the same framework as the data collection, but with data-driven additions—is a suitable approach. We were able to categorise the children's responses with respect to surface structures of their energy ideas in a reliable way and to identify links to the core aspects "forms" of the scientific energy concept. Similarly, our analysis of selected excerpts indicates that a categorisation of the patterns of argumentation on a concept- and data-driven basis (e.g., energy as a substance-like entity, "scientific" and "alternative" transfer ideas) is a viable approach.

6. Conclusions

As a key to valid findings, we implemented age-adequate activities and interview questions, which are based on a thorough analysis of the energy concept (framework of Figure 2). Given the children's young age, the courage to leave gaps and responsiveness regarding the children's reactions is equally important—less is more. The research design is based on careful consideration of both aspects of validity and engages young children in an intense and yet playful conversation about energy and related phenomena. Specifically, letting children adopt the role of an "Energy Detective", who looks at phenomena "through the energy lens", and making children's ideas and decisions visible by suitable familiar activities, e.g., drawing, sorting, or marking "energy" in picture stories, have proven fruitful. Using the generated artefacts, various aspects of energy can then be "probed" with a set of recurring "energy lens" questions (Tables 1 and A4). We assume that an adapted setting is also promising to access young children's ideas about other scientific concepts, for example, force.

Considering the abstractness of the term energy, the richness of detail of the children's accounts goes far beyond what we expected from such young children. Generally, we are not aware of other studies that collected such detailed data on elementary students' ideas about energy, even at an older age. Hence, we believe that the findings of this study will provide a comprehensive insight into young children's thinking and a sound empirical basis for the development of age-adequate energy instruction.

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Informed Consent Statement: Informed consent was obtained from all subjects involved in the study. It included the guardians' permission for publishing the children's photographs (Figures 3a, 5 and 6a).

Data Availability Statement: The data presented in this study are available on request from the first corresponding author and are not publicly available to ensure the privacy of the participants and to comply with the instructions of the board that approved this study.

Conflicts of Interest: The authors declare no conflict of interest

Appendix A. Selection of the Phenomena

Table A1 shows how the finally selected three main phenomena can be described in terms of observations ("phenomena lens"), and in an "energy language", and shows which energy aspects are covered. The "characteristics" are based on Nordine et al.'s indicators for energy forms [42]; the transfer mechanisms have been described by Herrmann-Abell and DeBoer [20]. This table served as a basis for the development of concrete tasks and activities.

Appendix B. Interview Protocols

Tables A2 and A3 summarise the interview protocols. Table A4 indicates the guidelines to probe deeper structures of children's energy ideas, using an amended "Energy Tracking Lens" [6,18].

Appendix C. Coding Frame and Procedure for the Drawings and Corresponding Interview Sections

The initial coding was carried out by one of the authors by applying the codes to the main elements of the drawings and to thematically coherent segments of the interview, respectively. In defining these coding units, a compromise had to be found between identifying new ideas in children's reasoning and preserving context information. This process involved a certain degree of subjectivity. The segments coded by the researcher constituted the coding units that were subsequently coded by a trained research assistant [50]. A subset of the data (six drawings and corresponding interview sections) was double coded and the intercoder reliability calculated.

Table A1. Energy ideas in the three selected phenomena, viewed through the "lenses" of phenomena (observations) and energy (description with energy terms, *italics*).

Energy Ideas	Electricity: Flashlights		Humans: Nutrition, Physical Activity		Mechanics: Marble Run	
system elements	lamp battery elements of electric circuit	*user* *source* *(cf. transfer)*	human food, air (environment)	*user* *source*	ball gravitational field (earth)	*user* *source*
characteristics (features, activities)	light (brightness) complete circuit and voltage source ("full" battery)	*light energy* *chemical energy* *electric energy*	motion (activity, fitness) substances appear or disappear (ingestion, breathing)	*kinetic energy* *chemical energy*	height velocity	*gravitational potential energy* *kinetic energy*
transformation	battery becomes "empty" when lamp emits light	*electric (chemical) energy > light energy*	human eats and breathes to maintain bodily functions	*chemical energy > chemical/kinetic energy*	height decreases, marble accelerates	*gravitational potential energy > kinetic energy*
transfer (mechanism)	electric current in closed circuit	*by electric current*	in-/digestion, cellular respiration	*by transfer of matter*	gravitation	*by gravitational force*
conservation, dissipation, degradation	environment gets warmer, visible process terminates	*thermal energy is dissipated, total amount is conserved*	human gets tired/hot, environment gets warmer, visible process terminates	*thermal energy is dissipated, total amount is conserved*	environment gets warmer, visible process terminates	*thermal energy is dissipated, total amount is conserved*

Table A2. Summary of guidelines for Interview 1.

Task	Material	Activity and Focus
		Electricity
exploration	flashlight with fresh battery flashlight with "flat" battery	invite the child to use the two flashlights conversation about what might have happened to the non-working flashlight, e.g., what makes the flashlight "go", how the battery "lost pep" (observations)
mechanism	worksheet with contour of flashlight	ask the child to explain ideas about how the flashlight makes light by completing contour (internal structure and mechanism, e.g., closed circuit)
		Human body
exploration 1	-	invite the child to do physical exercise (star jumps) conversation about what she/he needs to do this (observations)
exploration 2	sketch of two human characters (low/high BMI)	conversation about what might have happened to the depicted person such that it gained or lost weight (observations)
mechanism	worksheet with contour of human body	ask the child to explain ideas about what happens to food in own body by using contour (internal structure and mechanism, e.g., food moves through the digestive system)
		Mechanics
exploration	wooden blocks, rails, marbles of different sizes and materials	ask child to build a marble run conversation about what happens and how this can be influenced, e.g., by varying height, slope, mass of the marble (observations)
mechanism	-	conversation about what makes the marble go down (mechanism, e.g., earth pulls ball down)

Table A3. Summary of guidelines for Interview 2.

Task	Material	Activity
explanation of drawing	drawing produced by child	conversation about what is depicted and why; properties of energy (questions of Table A4)
sorting task	three plates with symbols for yes, no, do not know eighteen image cards arranged on the "do not know" plate (same order as in Figure 3c) objects for clarification (wind-up toy, rubber band, marble run)	introduction "being an energy detective" ask the child to name depicted objects/situations; clarification with objects ask the child to find all objects/situations that have (or have not) to do with energy and to place them on the corresponding plates ask the child to group cards that have been selected for similar reasons conversation about the decisions, properties of energy (questions of Table A4)
picture stories	three worksheets with picture stories stickers in 3 sizes objects for clarification (flashlights, marble run)	ask the child to describe the story introduction of task "detect energy" and "indicate amount" probe spatial and temporal aspects of energy (e.g., "how did it happen that . . . ")
generalisation	-	ask the child to explain to a friend how to become an "energy detective" offer prompts like "look for all things that . . . "

Table A4. Interview guideline for students' explanation of their drawings and their decisions in the sorting task. Because of the children's young age, it was neither possible nor intended to follow the guidelines in a strict and exhaustive manner.

Research Interest	Questions
surface structures; associations: system elements and characteristics (RQ1)	Why does this come to your mind if you hear the word energy/why did you chose this picture/what does it have to do with energy? *Further clarification questions using the student's wording, e.g.,:* How do you notice that it has (to do with) energy? Why does it need energy?
deeper structures; patterns of argumentation: further energy ideas (RQ2)	Does it have energy, or does it not have energy? *If answer 'has energy', continue:* Does it always have energy, or does it not always have energy? *If answer 'not always', continue:* How do you notice this? How does that happen, that sometimes it has (much) energy, and sometimes not (less)? *If answer does not indicate that energy comes from somewhere, continue:* How does . . . get energy? *If answer indicates that energy comes from somewhere, continue:* Where does the energy come from? What happens to the energy (after . . .)? How does it happen that . . . ? *If answer indicates that energy is gone, continue:* Is the energy just gone or does it go somewhere? Where does it go to?

Table A5. Coding frame for the dimension system elements.

Dimension 1: System Elements **Definition:** Entities associated with energy (objects and object-like elements) [47] Drawing: one main subject per coding unit Interview: all objects mentioned in the coding unit, regardless of the child justifying the relation with energy therewith		
Category	**Definition and *special rules***	**Examples (bold:** indicator for choice of category)
humans	humans parts of the human body human activities (in written notes)	human, heart, body, human superheroes (including pronouns) words "sports", "football", "running" (in written notes) "**One** needs energy to do sports."
electric user	technical device that operates on electric current *category vehicle precedes*	lamp, computer, mobile phone, gaming console, camera drawing: object with battery, cable, power socket interview: any object that needs a battery or current in the child's view "A **lamp** and a **flashlight** have to do with energy." "The **oven** has to do with energy, because it has a cable."
electric source	electric supply *also coded when the child uses term 'battery' as an analogy*	battery, power socket
vehicle	vehicles and their parts (including toys), regardless of their drive (electric, fuel)	car, engine, bike, motorbike, RC car, motor, wheels, tank "A **car**, because that needs like electric energy."
fuel	fuels	fuel "**Fuel** is like car-energy; like our food, it is food for the cars."
food	food and drinks (including water) *Also coded when process eating and/or drinking is mentioned*	food, water, eating, drinking "Running makes energy; **eating** and **drinking**." "By **drinking** water"
gaseous substance	gaseous substance *also coded when breathing is mentioned*	smoke, air, evaporated fuel, steam, breath "The **exhaust** is also part of the energy."
...	...	
other	residual category	fictional creatures, undefined objects, term "force" in notes, flash (symbol)

Table A6. Coding frame for the dimension characteristics.

Dimension 2: Characteristics
Definition: (Observable) features and/or activities of entities [42]
Drawing: 1–2 main visible or inferred features per coding unit
Interview: all features mentioned in the coding unit, regardless of the child justifying the relation with energy therewith

Category	Definition and *special rules*	Examples (**bold:** indicator for choice of category)
physical activity or condition *	physical activity and/or state of humans and other animate beings *also coded if child describes how humans are without energy*	running, doing sports; fitness, power; being strong/fit, having muscles; being tired, weak without energy “One needs energy for **running**.” “If one does not have energy, one **collapses**.”
electricity	closed electric circuit, device working on electricity (indicator for electric energy) *Always coded if object categories ‘electric user’ or ‘electric source’ are assigned*	battery, cable, flash symbol in drawing; (working on) current, electric, electronic, electric cable, battery, power socket “This has to do with energy because it has a **cable**.” “Energy means the strength of **electronic**. That’s energy *(clenches his fists)*.”
light	emission of light	lamp and/or light ‘rays’ in drawing; shining, light “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.”
chemical	appearing or disappearing of substances, growth *always coded if object categories ‘food’ or ‘fuel’ are assigned*	eating, drinking; running on fuel “The energy comes back if one **eats** or **sleeps**.”
motion	motion of inanimate objects *Motion of animate objects is coded as physical activity/condition*	driving, moving, being able to go/move “The car needs energy to be **able to go**.”
functioning *	ability to operate in unspecified ways	“The battery needs force to drive something. And force is similar to the word *(refers to “energy”)*.” “The camera would not **work** if it had no energy inside.”
temperature	temperature	hot, warm, cold, heating up “This has to do with energy because it is **hot**.”
. . .	. . .	
other	*residual category*	
none	*coded if no characteristic is mentioned*	“just like that”, “I don’t know”

* data-driven addition.

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