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Young children's pre-instructional ideas of energy – steppingstones or stumbling stones for learning the scientific concept of energy?

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Structured Abstract

Background: Energy is a core concept in science and has great socio-economic significance. Meanwhile, many countries have included energy as a topic of instruction in their elementary school curricula. In Switzerland, energy learning is supposed to start in K-2 education, i.e., when children are four to eight years old (Deutschschweizer Erziehungsdirektoren-Konferenz, 2016). Students' pre-instructional conceptions are considered a core element for successful learning. While there exists a large body of research on secondary students' energy conceptions, little is known about young children's ideas about energy (Detken & Brückmann, 2021).
Purpose: The present study aims at eliciting young children's energy ideas and identifying therein resources for learning the scientific concept of energy.
Sample/setting: The sample comprised 24 children (12 girls, 12 boys, ages six to eight years) of two first- and two second-grade classes in two schools in the city of Zurich, Switzerland. The children had not received instruction on energy or related topics.
Design and Methods: Single interviews with multiple child-friendly methods and tasks, such as drawing, sorting images, picture stories, were conducted. By references to everyday objects/phenomena and by using a specific protocol, the participants were invited to express themselves in-depth about all core aspects of energy (forms, transfer, transformation, dissipation/degradation, conservation). The interviews were videotaped for capturing speech and non-verbal modes of communication, transcribed, and analysed by qualitative content analysis with a multi-dimensional coding frame based on the structure of the scientific concept of energy.
Results: The results show that the interviewed children have rich and diverse ideas about energy. Children's resources for energy learning are identified by linking selected categories to the different core aspects of the scientific energy concept. For example, the children describe several indicators of energy, such as electricity, motion, and light; these ideas may serve as "steppingstones" for introducing energy forms such as electrical, kinetic or radiation energy. Children's frequent references to human activities or their physical state do not correspond to a scientific indicator of energy; such ideas, therefore, deserve attention when designing age-adequate instruction (a possible "stumbling stone" for introducing more scientific ideas). Many of the categories of the coding frame are found in many of the analysed interviews, though children have individual preferences. The first step towards the reconstruction of the children's mental models of energy is made by analysing frequent combinations of categories.
Conclusions: Young children can be expected to have rich ideas about what energy is and how it behaves that constitute resources for energy learning. Hence, a great diversity of energy conceptions is to be expected in the classroom, both on the level of the individual child and in the learning group. This has impacts on the design of suitable learning environments; particularly, there is not "the ideal" context for energy learning. Methodologically, this study shows that valid inferences about young children's conceptions of an abstract science concept can be made from children's explanations in a child-friendly multi-method setting. The developed coding frame and the children's statements can serve as a basis for the development of quantitative test items. Future research should focus on reconstructing children's conceptional models of energy from the various ideas described in this study.
Keywords: *energy, young children, elementary school, child-friendly methods, conceptions, mental models*

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1 Introduction

The Swiss "Lehrplan 21" (Deutschschweizer Erziehungsdirektoren-Konferenz, 2016) is a competence-oriented spiral curriculum for all subjects of compulsory education, i.e., kindergarten to grade 9, in 21 Swiss cantons. In the subject *Natur, Mensch, Gesellschaft* (science and social studies) the curriculum is based on core science concepts such as matter, interactions, or energy. Specifically, energy has been introduced as a topic of instruction already for kindergarten and lower elementary school (*NMG.3.2*, n.d.).

However, as extensive research literature on energy learning in higher grades shows, even older students often have difficulties understanding the complex scientific concept of energy (Duit, 2014; Herrmann-Abell & DeBoer, 2018). Hence, the fundamental question arises about how energy learning can succeed with even younger children. This study therefore investigates first and second graders' conceptions of energy as an important aspect of their learning prerequisites. It shows that young children's intuitive conceptions of energy offer multiple links to the scientific energy concept and therefore constitute resources that can be used in early science classrooms.

2 Research Background

2.1 The scientific energy concept from a PCK perspective

Energy is considered a core concept in science with the potential to foster meaningful learning (NGSS Lead States, 2013; Wodzinski, 2011). Using the scientific energy concept as a common framework, phenomena from different disciplines, e.g., physics and biology, can be described in unified terms and commonalities among these phenomena can be identified. Based on the conservation principle, predictions about the development of real-world systems can be made without knowing the mechanisms on the phenomenological level. Hence, the scientific concept of energy can serve as a tool for analysing real-world phenomena. Since energy is a complex concept, a set of core aspects of energy have been identified in science education literature (Duit, 1986, 2014, Herrmann-Abell & DeBoer, 2018; Liu & McKeough, 2005; Neumann et al., 2013; Nordine, 2016; Tobin et al., 2018). These core aspects are illustrated in Fig. 1 and summarised below:

- Forms: Energy is not directly perceptible. It is an abstract quantity that is assigned to a real-world system and to its elements/constituents based on certain indicators. For example, two marbles on the floor can be considered a system, and the marbles and the environment (floor, air) the system elements; if the first marble moves and the second rests, the first has kinetic energy and the other does not have energy (indicator velocity). Despite references to different *forms* of energy, all energy is fundamentally the same.
- Transfer: Interactions between these elements can change the magnitude of an indicator. For example, if the first marble collides with the second, the second speeds up and the first slows down. This is described by the *transfer* of energy between these system elements.
- Transformation: During processes, different indicators of energy can change, e.g., an object loses height when falling (the indicator of gravitational potential energy, height, decreases) but accelerates (the indicator of kinetic energy, velocity, increases). This is described by the *transformation* between different forms of energy.
- Dissipation and degradation: Processes cease, mostly due to friction. These "losses" are described by the transformation of energy into thermal and other "less useful" forms (*degradation*) and their transfer into the environment (*dissipation*). In the example of the colliding marbles, a part of the energy is transformed into sound energy (indicator sound) and thermal energy (a subtle increase in temperature) which then dissipate in the environment.
- Conservation: In a closed system the sum of all forms of energy is constant at any time, energy cannot be generated or destroyed but is *conserved*. "Closed" means that the system's boundaries are impermeable for matter and energy.

These core aspects are interconnected: For example, for an understanding that all energy is fundamentally the same (core aspect *forms*), the core aspects *transfer and transformation* are necessary. Understanding *transformation*, on the other hand, requires knowledge of different *forms* of energy. Understanding core aspect *conservation* is only possible if the *form* thermal energy and the energy *transfer* to the environment is acknowledged (*degradation, dissipation*).

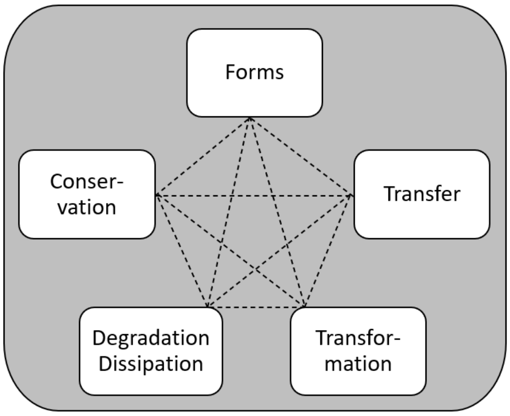

Fig. 1. Schematic representation of the structure of the energy concept with its interconnected core aspects (based on Duit, 1986, p. 96)

Since energy is not directly perceptible or measurable but is inferred based on observations, the scientific concept of energy can be considered a model (Feynman et al., 1965; Nordine et al., 2011; Tobin et al., 2018). Learning about energy thus means developing a conceptual model of energy, which includes ideas about how energy manifests, how it "behaves" and knowledge about how one can talk about energy, i.e., what kind of questions can be answered with energy considerations (Tobin et al., 2018). Specifically, students should learn to infer the presence of energy from observations in the real world based on certain indicators of energy (core aspect *forms*), track correlated gains and losses of these indicators within the system of interest and describe these observations by energy transfer, transformation, dissipation, degradation, and conservation. Consequently, the aim of energy instruction in school is to help children developing conceptual models of energy that – eventually – include all five interconnected core aspects of energy (Fig. 1). In this text, such a description of real-word phenomena with energy terms will be referred to as "looking through the energy lens" (Lacy et al., 2014, 2022; Tobin et al., 2018).

According to Duit (1986, 2014), the *conceptualisation*, i.e., how the abstract entity called "energy" is described or represented in the classroom, is another important aspect that needs to be distinguished. Conceptualisations include, for example, energy as the ability to perform work, as an abstract accounting quantity, or as quasi-material (substance metaphor) (Duit, 1986, 2014). Since energy is entirely abstract, there is no single "scientifically correct" conceptualisation, but different conceptualisations may highlight different core aspects of energy and obscure others. The substance metaphor, for example, is deemed to support an understanding of energy transfer and conservation (Nordine et al., 2018; Scherr, Close, Close, et al., 2012; Scherr, Close, McKagan, et al., 2012). However, it might obscure that energy is not a real substance.

2.2 Importance of pre-instructional conceptions for learning

Already in their first years of life, children develop conceptions about the physical or biological world (Smith & Wiser, 2013; Wilkening & Cacchione, 2010). Based on everyday experiences, these conceptions are very plausible in specific situations or contexts, but not generalisable and often far away from the scientific view. In this study it is assumed that students' conceptions are constituted by a variety of highly contextualised knowledge elements that are shaped, for example, by real-life experiences, language, and/or social interactions (Amin et al., 2014, p. 68ff). These knowledge elements are more or less integrated to form conceptional models as mental representations of reality.

According to theories of conceptual change, learning, simplified, means that children actively change these conceptional models by organisation and re-organisation of existing and new knowledge elements to gradually form more abstract and complex conceptional models; ideally, thereby they successively approach the scientific concept (Amin et al., 2014; Duit & Treagust, 2003). There is a mutual relationship between the scientific concept and everyday conceptions in this learning process: The scientific concept facilitates the incorporation of everyday experiences into a framework of scientific ideas, while everyday ideas related to concrete situations can fill the abstract scientific concept with life and thus prevent learning of "empty words" (Fleer, 2015, p. 15ff; Halldén et al., 2013). Consequently, the initial (everyday) conceptions are important resources for learning.

Teachers should therefore not only take learners' conceptions into account when planning lessons, but also repeatedly gain insights into children's thinking (Duit & Treagust, 2003; Möller, 2018; Schecker & Duit, 2018). Since this is highly demanding for teachers (Duit & Treagust, 2003), it has been proposed to base instruction on empirically validated learning progressions. Learning progressions describe typical (idealised) initial and intermediate conceptual models that may act as steppingstones towards a targeted science concept, as well as conceptual shifts that are necessary to progress from one steppingstone to another (Amin et al., 2014, p. 75; National Research Council, 2012; Neumann et al., 2013).

For the development and implementation of age-adequate energy education it is therefore important to know young children's energy conceptions, including the knowledge elements they are built from, the contexts they refer to, and the language used to express them.

2.3 Empirical findings on young children's conceptions about energy

Conceptions of energy among secondary school students have been intensively researched since the 1980s; reviews are provided, for example, by Duit (2014) and Nordine et al. (2011). In contrast, little is known about children's energy conceptions at the elementary or kindergarten level. The few recent studies show that children can express ideas about energy at an early age and typically associate humans, electricity, and/or technical devices with energy (Haider, 2016; Lacy et al., 2014; Reimer, 2020; Van Hook & Huziak-Clark, 2008; Yuenyong & Yuenyong, 2007). Most of these studies did not address the core aspects of energy systematically: In a U.S. interview study in kindergarten, the children were asked from where objects, e.g., toys, get energy; mostly, they had no idea (Van Hook & Huziak-Clark, 2008). In a German intervention study in fourth grade (Haider, 2016), children's responses to a questionnaire were evaluated to determine whether correct references were made to the core aspects of energy; any "alternative" ideas of the children were not analysed and documented. In an interview study in Thailand, where the topic of energy is taught from first grade onwards, energy conceptions of children from first to sixth grade were summarised within a set of data-based categories (Yuenyong & Yuenyong, 2007). Besides dominant associations with electricity, the authors report only implicit references to various forms and transformations of energy, but not to energy sources, transfer, and conservation.

These recent studies use different methods of data collection and analysis, come from different educational contexts and language areas, and investigate mostly ideas of children that have received formal instruction about energy and/or related science topic like electricity. Hence, there is no clear picture of how young children's intuitive energy conceptions look like in the first years of elementary school and before formal science teaching, and of how these conceptions relate to the scientific energy concept with its interconnected core aspects.

2.4 Context and aim of this study

The aim of this qualitative video-based study is therefore to investigate first and second graders' conceptions about energy systematically and with respect to all core aspects of energy. The method, design and first results are described in an earlier publication (Detken & Brückmann, 2021). The development of the coding frame and its application to a part of the data will be reported separately. This study reports results from the analysis of a more comprehensive data set, more specifically, the interview data of the so-called "energy interview". It characterises what young children describe when they "look through the energy lens", and summarises typical ideas (knowledge elements) such that possible links to the core aspects of the scientific energy concept become visible. Additionally, I took a first step towards a characterisation of children's conceptional models of energy, by analysing whether certain ideas occur in combination, e.g., are context-dependent. Specifically, the following research questions will be addressed:

> **RQ1**: What ideas regarding the core aspects of energy can be identified in children's explanations of energy?
>
> **RQ2:** To what extent can inferences about children's conceptional models of energy be made (and which)?

3 Methods

Conceptions are not directly accessible but can only be inferred based on a child's utterances and/or actions (Hartinger & Murmann, 2018; Schecker & Duit, 2018). Valid inferences require here that the methodology is adapted to the complex structure of the energy concept as well as to the target group (validity aspects *content* and *substantive* according to Messick (1995)): Given the young age of the children, child-friendly methods are necessary. These methods must allow the child to connect to his or her everyday knowledge and to activate the respective knowledge elements through different stimuli; they also take into account language barriers, lack of literacy skills, and attention span (Clark, 2005; Einarsdóttir, 2007; Hadzigeorgiou, 2015; Pramling, 2015). The scientific perspective requires that children must be able to express themselves about energy comprehensively enough that inferences about all core aspects of energy as well as its conceptualisation can be made.

3.1 Design and data collection

Such a compromise mediating between the complex and abstract energy concept and the requirements for research with young children is described in an earlier publication (Detken & Brückmann, 2021): To elicit in an age-appropriate way what children see "through the energy lens", single interviews were conducted in which children worked on different child-friendly tasks (Brooks, 2009; Einarsdóttir, 2007; Kübler, 2017; Reimer, 2020): First, they were asked whether they had heard the word energy before, and if yes, were asked to write or draw something that came to their mind when hearing the word. They subsequently attended to a sorting task with impulse pictures, wherein they were asked to sort the pictures according to their relation with energy (yes, no, uncertain, Fig. 2a). The last task used picture stories of three exemplary processes; the children were asked whether the objects or phenomena had to do with energy, to highlight where in the picture(s) they "detected" energy and to indicate the amount of energy (Fig. 2b). The children were instructed to act as "energy detective" throughout the interview, i.e., they were asked to look for "hints" for energy in the real-world phenomena of the impulse pictures and the picture stories, and to explain their thoughts and decisions.

In terms of content, the structure of the energy concept guided the data collection and analysis: for example, everyday phenomena from different contexts (e.g., car, sun, flashlight), which can be described in scientific terms by several forms, transfers, and transformations of energy, were selected for the impulse pictures. The aim was to find out which of the various indicators of energy (e.g., motion, height, light) represented in the pictures were recognised by the children. The picture stories addressed the presence of energy and energy changes in processes. Here, three exemplary phenomena were selected (eating and playing football, shining flashlights, marble run). For addressing the different core aspects of energy, recurring questions were asked throughout all tasks, for example, how the child recognised a relation with energy (core aspect *forms*), whether energy was always present or not, how something might "get" energy (core aspect *transfer*), and what happened to it after a process (core aspects *dissipation/degradation* and *conservation*). The interviews were videotaped to capture the children's answers integrally, including verbal and nonverbal modes of communication (e.g., gestures). More information on the design, the interview protocol and the prompts, as well as examples of the children's statements can be found in the earlier publication (Detken & Brückmann, 2021).

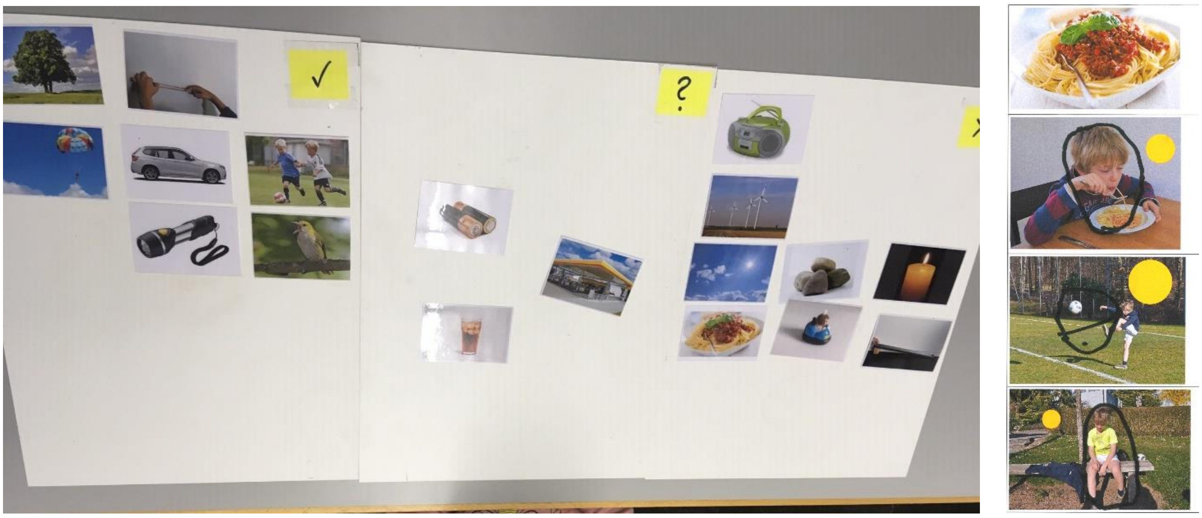

Fig. 2. (a, left) Impulse pictures sorted on three panels according to their relation with energy: yes (✓), uncertain (?) and no (x); (b, right) picture story "eating and playing football", the child encircled "locations" of energy and indicated the amounts of energy with stickers of different sizes

3.2 Sample and data

The sample comprised 24 children (12 girls, 12 boys) from two first and two second Swiss primary school classes (age 6-8 years, M=7.5 years). The children were selected together with the classroom teacher to achieve a heterogeneous sample (school performance according to the teacher's estimation). The interviews were conducted in German, the language of schooling, and the children responded in German or the Swiss German dialect. Many of the participants had a multilingual background.

The children participated voluntarily and with the consent of their legal guardians. They were able to interrupt or end the interview at any time. Despite the abstract subject matter, most of them were eager to share their thoughts. The study was approved by the responsible school board. Clearance by an ethics committee was not required at the time of data collection in Switzerland.

The study was conducted in the first quarter of the school year. At that time, all children had attended the compulsory two-year kindergarten. According to the classroom teachers, no science content relevant to the topic of energy, such as electricity or nutrition, had been taught since school entry. Topics covered in kindergarten are unknown.

The following analysis is based on 24 videotaped and transcribed energy interviews with a length of 28 to 61 minutes (M=41 min, SD=8 min). Children's gestures and other nonverbal utterances, e.g., their references to the drawings or the impulse pictures, were included in the transcripts. Children's drawings and worksheets were used to better understand what children meant but were not analysed as an independent body of data.

3.3 Analysis

The children's young age constituted challenges for the analysis: The statements are very rich but the children often did not finish their sentence, jumped from one idea to another and/or contradicted themselves; some also had difficulties in verbalising their thoughts and used neologisms, their hands and/or the material prompts to explain what they meant (Detken & Brückmann, 2021). To identify links to the scientific energy concept, these statements needed to be contrasted with all core aspects of energy. Hence, like the data collection, also the analysis is based on a compromise between the specifics associated with the young age of the children (e.g., vagueness, inconsistencies, language skills) and the complex scientific concept. Since no analytical instrument was known, a coding frame adapted to young children and all aspects of energy was developed (Detken, under review). Key aspects of this analysis are summarised below:

The very rich data were analysed using qualitative content analysis (Kuckartz, 2018; Mayring, 2015; Schreier, 2012). In an iterative process (Mayring, 2015, p. 50ff), five dimensions were defined that refer to a guiding question and can be linked to the core aspects of energy and the conceptualisation (Tab. 1). Within these dimensions, children's statements were summarised in concept- and/or data-based categories. These categories summarise ideas contained in the children's statements that refer to one of the core aspects of energy. From these ideas, the "knowledge elements" from which children's mental models are built (section 2.2) can be inferred. The dimension "characteristics", for example, includes concept-based categories corresponding to the scientific indicators of energy (Nordine et al., 2011, p. 696) as well as data-based categories without a clear reference to one of the scientific indicators, for example *physical activity/state*. The ideas summarised in this dimension thus relate to the core aspect "forms". The categories of the other dimensions are mainly data-based but were inspired by literature on older student's conceptions, e.g., the "alternative frameworks" identified by Watts (1983) and Trumper (1993), aspects of the grade 3-5 learning progression proposed by Lacy et al. (2014), or the response options (e.g., *have/use/give* energy) used by Nicholls & Ogborn (1993). Selected categories are explained in the results section and illustrated with examples. The coding frame with anchoring examples is found in the supplementary materials.

Tab. 1. System of categories, research interest (guiding question) and links to the core aspects of the scientific energy concept.

Dimension	Research interest	Categories	Core aspects of the energy concept
characteristics	Which observable features and/or activities of entities are described?	physical activity/state electricity light chemical motion functioning temperature … unclear (residual)	forms
nature of energy	What "is" energy (ontology, causality, relation to real-world objects)?	intrinsic feature feature of certain states causal agent substance idea being energy generated general/unclear (residual) no relation with energy uncertain relation with energy	conceptualisation
transfer ideas	How or from where do entities "get" energy?	incorporation flow/source product process none/unclear (residual)	transfer
transformation ideas	Are described features and/or activities related to one another? Can energy change its "guise"?	causal relation implicit/explicit transformation none/unclear (residual)	transformation
conservation ideas	What happens to the energy after a process?	gone/used somewhere else conservation idea none/unclear (residual)	dissipation/degradation conservation

Thematically coherent segments of the interview were chosen as coding units – though "coherence" is relative in young children's accounts. Typically, these segments comprise a question and its answer. A total of 1019 segments (M 42, SD

13) were categorised with respect to all five dimensions using the software MAXQDA 2020 (VERBI Software, 2020). Multiple coding was allowed only in the dimension "characteristics", in all other dimensions exactly one code per dimension was applied.

To ensure the quality of the analysis, six of the 24 interviews (25%) were coded by a second rater, and the coding frame was iteratively refined. The kappa coefficients according to Brennan and Prediger (1981) as a measure for interrater reliability have values between 0.67 ("transformation ideas") and 0.87 ("conservation ideas"). According to Rädiker and Kuckartz (2019, p. 303) with reference to Landis and Koch (1977), these values indicate a substantial agreement between the raters.

An example of the coding of the interview is shown in Tab. 2, using a first grader's explanation of his drawing (Fig. 3).

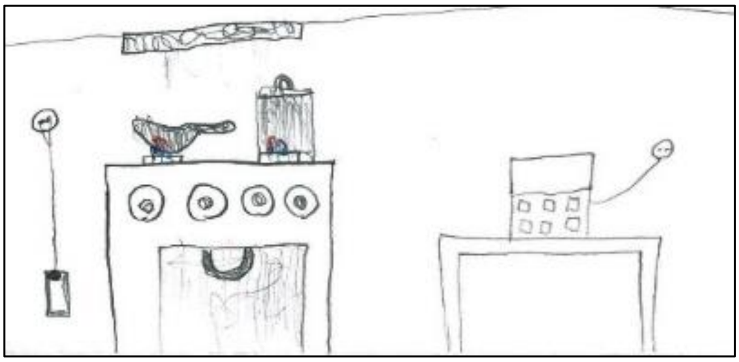

Fig. 3. A first grader's associations with energy: Mobile phone, oven with pans and extractor hood, computer, and cables/sockets

Tab. 2. Example for the coding of the interviews: Interview excerpt, structured into three coding units, and codes assigned in the five dimensions

Interview excerpt (An, 6-14)[1]	**Coding** *italics: remarks and indicators for the choice of the categories*
An: This is a mobile phone with a cable, and an oven, and this (is a thing that) is frequently above the oven, and also a computer (points to elements in the drawing: mobile phone, extractor hood, computer). […] I: What does this have to do with energy? An: 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 the oven and the frying pan).	**Characteristics:** electricity *(reference to cable)*, temperature *(reference to heat)* **Nature of energy:** general/unclear *("has to do with energy")* **Transfer ideas:** none/unclear *(not asked, no information)* **Transformation ideas:** none/unclear *(no relation between the mentioned characteristics)* **Conservation ideas:** none/unclear *(not asked, no information)*
I: Is there always energy or not always? An: If you switch it off, it is not there, and if you switch it on, it is there.	**Characteristics:** see above **Nature of energy:** feature of certain states *(has energy if…, otherwise not)* **Transfer ideas:** process *(switching on initiates the "energetic" state)* **Transformation ideas:** none/unclear *(no relation between characteristics)* **Conservation ideas:** none/unclear *(not asked, no information)*
I: Where, do you think, does it come from? An: Through an electric cable. […] A cable comes out of the floor (moves hands upwards) and then it goes in there (moves hands downwards and points to the oven).	**Characteristics:** see above **Nature of energy:** substance ideas *(energy is independent of the cable or the devices)* **Transfer ideas:** flow/source *(energy moves through cables)* **Transformation ideas:** none/unclear *(no clear relation between characteristics electricity and temperature)* **Conservation ideas:** none/unclear *(not asked, no information)*

[1] The letters indicate the child, the numbers the paragraph in the transcribed interview. "I" designates the interviewer.

Structuring the material using this rather complex category system allows to determine frequent and to contrast the corresponding ideas ("knowledge elements") with the related core aspects of the scientific energy concept – which ideas correspond to an aspect of the scientific concept, which are "alternative" ideas, which aspects of the scientific concept have no counterpart in the children's ideas (section 4.1)? It also allows to compare the frequencies of categories in individual interviews with those of the overall sample (section 4.2). In a next step, frequent combinations of categories can be determined (Kuckartz, 2018, p. 118). The latter is interesting because it is the first step towards a reconstruction of "typical" patterns of ideas. This may serve as a basis to identify contexts (section 4.3) or to infer how children's conceptional models of energy look like (section 4.4). Only the dimension "characteristics" addresses features of objects or phenomena of the real world, while the other dimensions summarise children's ideas independent of to which object/phenomenon they refer. As will be shown below (section 4.4), this distinction allows to analyse children's ideas in the dimensions "nature of energy", "transfer ideas" etc. in different contexts. Tab. 3 summarizes the steps of the present analysis.

The dimension "nature of energy" has a dual function: On the one hand, it summarises children's ideas about what energy "is" and links it to conceptualisations of energy (Tab. 1). On the other hand, it serves to structure the data depending on whether children see a relation with energy or not or are uncertain about such a relation. To that end, all categories except for "no/uncertain relation with energy" have been summarized into a structuring category "positive relation with energy (yes)".

Tab. 3. Overview of the present analysis

	Analytical step	Research interest/aim	Results
1	Determination of frequencies of categories	Identification of "typical" ideas and comparison with the core aspects of energy	Section 4.1
2	Comparison of individual children with the overall sample	Analyse individual preferences and identify "typical" combinations of categories	Section 4.2
3	Determination of frequent combinations of categories within the dimension "characteristics"	Identification of contexts of the children's associations, i.e., features that are described in combination (basis for analysing context-dependencies in step 4)	Section 4.3
4	Determination of frequent combinations of categories within the dimension "characteristics"	Analysis of context-dependencies of ideas in the dimensions "nature of energy" and "transfer"	Section 4.4

4 Results

In this section, the analytical steps performed (Tab. 3) are described and the respective results are presented. A detailed discussion follows in section 5.

4.1 Step 1: Analysis of frequencies – "typical" ideas

A total of 1019 coding units (segments) from 24 interviews were coded in all five dimensions and differentiated with respect to their relation with energy (yes, no, and uncertain) using the "nature of energy" codes. In 819 of the 1019 coding units, children describe something that has to do with energy, in 39 units children are not sure about a relation with energy, and in 161 units children deny a relation with energy. In the material structured in this way, the frequencies of interviews and segments with assigned categories were determined. Tab. 4 shows the results: The column "categories" lists the identified categories in the five dimensions. The column "interviews" shows in how many of the interviews the respective category was found in total, and depending on the relation with energy (yes, no, and uncertain). The column "coding units" shows how many of the coding units were assigned a certain category, again in total and depending on the relation with energy (yes, no, and uncertain).

The frequencies in the dimension "characteristics" indicate that the children refer to many features or activities when talking about energy, though there are clear preferences for the first five categories (*physical activity/state, electricity, motion, chemical, light*). The most frequent category *physical activity/state*, for example, summarises children's references to human activities, like doing sports or operating devices, or to their physical condition, e.g., their fitness, their muscles or being tired. The category *electricity* was coded whenever children referred to electric current, batteries, cables, or electrical devices. It was not distinguished whether a child mentioned a feature because it considered it indicative of energy or as a general element of the situation. Examples are given in the supplementary materials and will be reported separately (Detken, under review).

The frequencies in the dimension "nature of energy" indicate that children describe what energy "is" in various ways. Here, energy as a *causal agent* is a frequent category. It was coded when children explained that energy (or a synonym used by the child, e.g., force, current, power) is required for activities or to maintain a certain state, or that something cannot be done without energy. Example: *"There (points to picture "CD player") one needs force that one can somehow push the button […]"* (Ro, 91). Besides the residual category, also *substance ideas* have been observed frequently. These have been assigned when a child described that energy is different from the entity that has energy. Example: *"The camera has energy inside"* (Ja, 16); *"[…] Because energy is also, resides also inside your body"* (Is, 2). The category *feature of certain states* summarises ideas that energy is present only when certain conditions are fulfilled, e.g., someone is active, a device is in operation, and otherwise not. Example: *"(…) because if we run much, we have much energy, (and) if we do not run at all, we do not have energy"* (Di, 285; see also Tab. 2).

In the dimensions "transfer ideas", "transformation ideas" and "conservation ideas" most of the segments have been assigned to the residual categories. A reason may be that these topics are rather complex (Herrmann-Abell & DeBoer, 2018; Neumann et al., 2013) but also that questions like "where does the energy come from / go to", that tackle such ideas, have not been asked in all segments.

The dimension "transfer ideas" summarises children's statements regarding how objects "get" energy. Ideas relating to the flow of energy or to energy coming from a source or delivered to a receiver (category *flow/source*) were expressed by almost all children. Examples: *"This (points to picture "tree") makes air for us, and from the air, it takes energy and water"* (Je, 129); *"because the battery is new and there is already a lot of energy and then here comes out a lot (indicates the path on the picture of a shining flashlight)"* (Ay, 501). To a lesser extent, children also expressed the idea that energy is gained by certain activities or processes. Example: *I: "Where do these boys get their energy from (points to picture "playing football")?" Ju: "By sleeping or staying fit"* (Ju, 113).

The dimension "transformation ideas" addresses relations between several observable characteristics and/or forms of energy. Though in 580 of the 819 energy-related segments no or unclear statements (residual category) were found, children describe *causal relations* or, to a much lesser extent, *implicit transformations* in about 80% of the segments that have been coded with two or more characteristics codes (about 35% of all coding units with reference to energy, see section 4.3). This means that children mostly describe causal relations when they talk about phenomena with two or more observable features. Example: *"Here (points to the picture of a shining flashlight) it has a battery to be able to shine"* (Iv, 292). The conversion of one feature into another or into energy (implicit transformation) is much rarer. Example: *"And then you can use it (i.e., energy provided by wind turbines and delivered by cables) as light"* (An, 199).

The dimension "conservation ideas" summarises ideas regarding the "fate" of the energy after a process. Most children stated nothing or that the energy was gone or used up (*gone/used*). A few statements included the idea that energy might still exist (*conservation*). Example: *"It (energy) goes away from us. Perhaps it goes into another body. Then it comes back, if you ate well, slept well and so on"* (Is, 128).

Tab. 4. Frequencies of interviews (children, n=24; middle column) and coding units (segments, n=1019; right column) with a certain category, distinguished by the relation with energy (yes, uncertain, no).

Categories		Interviews (n=24)				Coding units (n=1019)			
		total[a]	yes	uncertain	no	**total**	yes (n=819)	uncertain (n=39)	no (n=161)
Characteristics	Physical activity/ state (humans)	**24**	23	5	10	**294**	271	7	16
	Electricity	**24**	22	3	15	**260**	221	4	35
	Motion	**24**	21	3	15	**236**	198	3	35
	Chemical	**24**	23	7	13	**228**	193	8	27
	Light	**24**	22		8	**125**	115		10
	Functioning	**10**	9	1		**21**	20	1	
	Force (non-human)	**9**	9		1	**22**	20		2
	Deformation	**16**	13	1	4	**24**	19	1	4
	Sound	**14**	9	1	5	**25**	18	1	6
	Fire, flame	**16**	8	1	10	**32**	17	1	14
	Life, nature	**9**	6		3	**20**	17		3
	Temperature	**8**	7		2	**16**	12		4
	Height	**7**	6		2	**12**	10		2
	Mental activity/ state (humans)	**7**	6	1	1	**10**	8	1	1
	Good, healthy, ecological	**4**	4	1	2	**13**	7	1	5
	Residual	**21**	17	2	11	**56**	39	2	15
	No characteristic	**17**	14	7	16	**88**	33	21	34
Nature of Energy	Causal Agent	**22**	22			**207**	207		
	General/unclear (residual)	**22**	22			**179**	179		
	Substance idea	**19**	19			**126**	126		
	Feature of certain states	**24**	24			**124**	124		
	Intrinsic feature	**22**	22			**107**	107		
	Generated	**17**	17			**42**	42		
	Being energy	**10**	10			**34**	34		
	Uncertain relation with energy	**14**		14		**39**		39	
	No relation with energy	**22**			22	**161**			161
Transfer Ideas	Flow/source	**21**	21	1[b]		**112**	110	2[b]	
	Process	**18**	18			**64**	64		
	Incorporation	**18**	18			**48**	48		
	Product	**12**	11			**25**	25		
	None/unclear (residual)	**24**	24	14	22	**770**	572	37	161
Transformation Ideas	Causal relation	**24**	23	2[b]	8[b]	**237**	226	3[b]	8[b]
	Implicit transformation	**7**	7			**13**	13		
	None/unclear (residual)	**24**	24	13	22	**769**	580	36	153
Conservation Ideas	Gone/used	**21**	21			**75**	75		
	Somewhere else	**8**	8			**25**	25		
	Conservation	**5**	5			**6**	6		
	None/unclear (residual)	**24**	24	14	22	**913**	713	39	161

[a] This number may be less than the sum of the preceding columns because a child may speak of the same characteristic in segments with different relation to energy.
[b] Relevant statements were made though the child sees no relation with energy.

4.2 Step 2: Comparison of the whole sample with selected children – individual preferences

Tab. 4 shows that many of the categories have been assigned to many of the interviews. This indicates that the individual children describe energy inconsistently in many ways. On the other hand, strong personal preferences were noticed, e.g., for references to humans or electric devices, on the level of the individual interview. Hence, I compared the code frequencies in the interviews of three children, chosen by way of example because they argue very differently from one another, with the frequencies in the overall sample. Tab. 5 shows that there are considerable differences between the four data sets: Though all three children "use" almost all selected categories, child 1 refers mostly to *electricity*, child 2 to *motion*, and child 3 to *physical activity/state* in the dimension "characteristics"; similarly, they have different preferences in the other dimensions. Implications of these observations will be discussed in section 5.

Tab. 5. Frequencies and percentages of coding units coded with selected categories in the three dimensions "characteristics", "nature of energy" and "transfer ideas" in interviews of three children in comparison with the overall sample (only positive relation with energy, most frequent category per dimension highlighted; percentages refer to the total number of segments per child and in the overall sample and are included to enable comparison of the four data sets).

	Categories	**Coding units with a positive relation with energy**							
		Child 1 (n=45)		Child 2 (n=40)		Child 3 (n=36)		All children (n=819)	
Characteristics	Physical activity/ state (humans)	6	13%	15	38%	**28**	**78%**	**271**	**33%**
	Electricity	**19**	**42%**	7	18%	6	17%	221	27%
	Motion	8	18%	**18**	**45%**	7	19%	198	24%
	Chemical	4	9%	7	18%	1	3%	193	24%
	Light	6	13%	3	8%	3	8%	115	14%
Nature of Energy	Causal Agent	1	2%	9	23%	**23**	**64%**	**207**	**25%**
	General/unclear (residual)	12	27%	3	8%			179	22%
	Substance idea	**14**	**31%**	1	3%	3	8%	126	15%
	Feature of certain states	7	16%	**18**	**45%**	3	8%	124	15%
	Intrinsic feature	3	7%	8	20%	3	8%	107	13%
	Generated	4	9%	1	3%	1	3%	42	5%
	Being energy	4	9%			3	8%	34	4%
Transfer ideas	Flow/source	**13**	**29%**	2	5%	3	8%	110	13%
	Process	7	16%	5	13%	1	3%	64	8%
	Incorporation	1	2%	6	15%			48	6%
	Product	1	2%	2	5%			25	3%
	None/unclear (residual)	**23**	**51%**	**25**	**63%**	**32**	**89%**	**572**	**70%**

4.3 Step 3: Analysis of constellations in the dimension "characteristics" – contexts

Three contexts of children's "spontaneous" associations with energy were determined earlier by analysing the interview sections in which children explained their drawings for frequent codes and code combinations in the dimension "characteristics" – the only dimension where multiple coding was permitted. These contexts are *human beings*, *electric devices,* and *vehicles* (Detken, under review). This analysis was repeated for the whole data set by determining the code constellations in the 819 segments with a positive relation with energy. This analysis shows that constellations with one or two "characteristics" codes account for 94% of these segments (ca. 58% one code, 35% two codes). Segments coded with at least one of the three most frequent characteristics *physical activity/state*, *electricity,* and *motion* account for about ¾ of the segments in which children refer to energy. The most frequent constellations are as follows:

- *Physical activity/state* alone (in appr. two thirds of the 271 segments coded with *physical activity/state*) or in combination with *chemical* (appr. one quarter of these segments)
- *Electricity* alone (appr. one third of the 221 segments coded with *electricity*) or in combination with *light* (appr. one quarter) or *motion*
- *Motion* alone ((appr. one third of the 198 segments coded with *motion*) or with *chemical* or *electricity*

Hence, the three contexts identified before, appear also important when children are prompted with pictures that refer to other features than human activity, electricity, or motion. The analysis further shows that only ten segments refer to both *physical activity/state* and *electricity*, while there is more overlap between *electricity* and *motion*. Hence, the two contexts of *human beings* and *electric devices* are almost distinct, and the categories *physical activity/state* and *electricity* can serve to distinguish these contexts. This was used to analyse context dependencies (section 4.4).

4.4 Step 4: Analysis of constellations between the dimension "characteristics" and the dimensions "nature of energy" and "transfer ideas" – context dependencies

Table 5 shows that the three children's preferences for certain phenomena (dimension "characteristics": child 1 *electricity*, child 3 *physical activity/state,*) are accompanied by certain preferences in the dimension "nature of energy" (child 1 *substance ideas*, child 3 *causal agent*). This might be an indication of context-dependent ideas about the nature of energy. However, table 5 does not specify whether these ideas occur in the same statement. I, therefore, proceeded with an analysis of selected code correlations at the same segments (coding units) in the overall sample.

To determine whether the children's ideas depend on the contexts *human beings* and *electric devices*, the 271 and 221 energy-related units coded with *physical activity/state* and *electricity*, respectively (in total 60% of the 819 energy-related coding units), were analysed for occurrences of categories of the dimensions "nature of energy" and "transfer ideas". Table 6 shows that the category *causal agent* occurs more frequently in combination with *physical activity/state* (context *human beings*) than with *electricity* (context *electric devices*) and within the overall sample. Similarly, there seem to be more *substance ideas* when children speak about *electricity*. Since many segments have been assigned to the residual category in the dimension "transfer ideas", there is no clear picture regarding a context-dependency here. The distribution in the non-residual categories indicates that *process* ideas might be preferred in the context of *human beings*, while children describe sources or flow of energy in the context of *electric devices*.

Tab. 6. Frequencies of coding units coded with *physical activity/state* and *electricity* in the two dimensions "nature of energy" and "transfer ideas" (only positive relation with energy, most frequent category per dimension highlighted, percentages refer to the total number of coding units with the respective characteristics code; they are included to enable comparison of the three data sets).

	Categories	**Coding units with positive relation with energy**					
		Physical activity/state (n=271)		Electricity (n=221)		All children (n=819)	
Nature of Energy	Causal Agent	**111**	**41%**	35	13%	**207**	**25%**
	General/unclear (residual)	53	20%	46	17%	179	22%
	Substance idea	18	7%	**71**	**26%**	126	15%
	Feature of certain states	41	15%	23	8%	124	15%
	Intrinsic feature	26	10%	29	11%	107	13%
	Generated	14	5%	7	3%	42	5%
	Being energy	8	3%	10	4%	34	4%
Transfer ideas	Flow/source	18	7%	**49**	**18%**	**110**	**13%**
	Process	**51**	**19%**	3	1%	64	8%
	Incorporation	9	3%	30	11%	48	6%
	Product	12	4%	4	1%	25	3%
	None/unclear (residual)	**181**	**67%**	**135**	**50%**	**572**	**70%**

In addition, correlations between the categories of the dimensions "nature of energy" and "transfer ideas" were determined (Tab. 7). Most of the coding units comprise combinations of a "nature of energy" category with the residual category *none/unclear transfer idea* (rightmost column). Apart from these combinations, there are the following trends: Ideas about flowing energy or external sources of energy (*flow/source*) seem to be associated with *substance ideas* of energy. Ideas concerning gaining energy by a *process* are expressed when children describe energy as a *causal agent* or a *feature of certain states*. *Incorporation* seems to be associated with the idea that energy is an *intrinsic feature* of objects, and the idea that energy is gained by a reaction (*product*) is associated with the conceptualisation of energy as something that is *generated*.

Tab. 7. Frequencies of coding units coded with combinations of categories in the two dimensions “nature of energy” and “transfer ideas” (only positive relation with energy, most frequent combinations (except residual categories) highlighted).

	Categories	total counts	Transfer ideas: Flow/source	Process	Incorporation	Product	None/unclear (residual)
	Total counts		**110**	**64**	**48**	**25**	**572**
Nature of Energy	Causal agent	**207**	7	**19**	7	5	168
	General/unclear (residual)	**179**	14	5	6	3	151
	Substance idea	**126**	**78**	4	13	1	29
	Feature of certain states	**124**	3	**19**	4	2	96
	Intrinsic feature	**107**	4	5	**16**		82
	Generated	**42**	3	12	1	**14**	12
	Being energy	**34**	1				33

5 Discussion

The present study investigated what young children describe when looking “through the energy lens” and what resources for developing an understanding of the scientific energy concept can thus be expected in early science classrooms. In the first section, I will show that various knowledge elements (as summarised in the categories of the five dimensions) can be identified in the interviewed children’s rich and diverse statements about energy. By contrasting selected categories with the core aspects of energy, I will identify “links” to the scientific energy concept as resources for energy learning but also “blind spots” and aspects that need further attention. In the second section, I will show how the complex system of categories can be used to uncover structures in the data that indicate how children’s conceptional models might look like.

5.1 Links of the children’s ideas to the core aspects of the scientific energy concept – possible steppingstones and stumbling stones (RQ 1)

The frequencies of the individual categories allow conclusions about what young children are likely to see (or not see) when looking through the “energy lens”. Based on the observations in this study, I will discuss possible resources and stumbling stones for energy learning in children’s intuitive ideas.

The dimension “characteristics” summarises the features and activities of real-world objects or phenomena children refer to when they talk about energy. The respective ideas (as summarised in the categories of this dimension) can be linked to the core aspect *forms*, more specifically, to the scientific indicators of energy (Nordine et al., 2011, p. 696). Although a greater variety was offered through the materials used (impulse pictures, picture stories), the results suggest that the participating children recognised a connection with energy in only a few phenomena. The five most important characteristics described by almost all children - *physical activity/state, electricity, movement, chemical* and *light* (Tab. 4) - represent possible steppingstones for introducing kinetic, electrical, radiation and chemical energy. Thus, contexts in which these characteristics and their changes are readily observable, for example, the contexts of humans, electric devices, and vehicles, could serve as starting points for energy learning. However, the category *physical activity/state* summarises ideas that refer not only to human movements but also to their physical condition, such as being fit or tired. Consequently, the most important feature children refer to when describing energy, physical activity and/or the physical state of human beings, does not have a scientific equivalent. Here, one must pay attention that motion and subjective feelings are distinguished: children should eventually learn that only motion/velocity is an indicator of energy in the scientific sense, while “feeling energetic” is not. Other indicators of energy such as *height*, *temperature*, *sound*, or *deformation* (Nordine et al., 2011, p. 696) were also mentioned but much less frequently clearly associated with energy. This indicates that children do not recognise energy in many real-life phenomena, which are described with forms of potential or inner energy (e.g., gravitational potential, elastic, thermal, chemical energy) by scientists. One reason for this may be the notion of energy as a *causal agent* expressed by many children and used in German everyday language: If children see energy as a precondition that something happens, they may fail to recognise energy, if nothing perceivable happens. Hence, the indicators *height*, *temperature*, *sound*, or *deformation* should be carefully introduced and suitable phenomena should be included in (early) energy learning.

The dimension "nature of energy" refers to children's intuitive conceptualisations of energy. Representations or analogies are needed in instruction – otherwise, it is impossible to speak about energy or to make the abstract entity "energy" tangible (Duit, 1986, 2014). Though there is no right or wrong conceptualisation, analogies and/or representations should match with the children's ideas to avoid misunderstandings (Wernecke et al. (2018) regarding older students). As Tab. 4 shows, the children most frequently describe energy as a *causal agent*, i.e., as a requirement or "enabler" of processes. While this idea provides a basis for introducing energy as the ability to do work (Duit, 2014), difficulties can be expected in learning the core aspects of transfer, transformation, and conservation, because an "enabler" is normally gone after fulfilling its purpose (Jin & Anderson, 2012). In contrast, understanding energy as a *feature of a certain state* can be a basis for introducing the idea that energy is inferred from certain indicators (Tobin et al., 2018). I, therefore, consider statements such as "X has energy, if/because..." to be rather helpful; however, care should be taken that children – in the long run – learn to also consider characteristics that are not associated with obvious activities. Children's *substance ideas* could be a basis for using the substance analogy of energy in class and to support an understanding of conservation (Nordine et al., 2018; Scherr, Close, McKagan, et al., 2012). However, the present results show that some children do not express substance ideas at all, even when asked where energy comes from, and others describe energy as a substance but might confuse it with current or fuel. Hence, attention is required when using the substance metaphor in class (a possible stumbling stone).

The dimension "transfer ideas" summarises children's ideas about how an object "gets" energy. Ideas of the category *flow/source* can provide an initial basis for describing a system and its development by means of energy flows between different system elements (sources and receivers of energy). As with children's *substance ideas*, care should be taken that the children do not equalise energy with real substances like air, fuel, or food, or with electric current. In the category *process*, on the other hand, the child appears to focus on a single object and its changes and not on interactions with other system elements. Thus, it is rather an incomplete than wrong picture, which has equivalents in physics (e.g., energy level diagrams). For (eventually) introducing the ideas of external sources and receivers of energy, a more systemic view of phenomena might be productive. For example, it can be explored what humans need from an external source to regenerate or how they manipulate objects while getting tired and "losing" energy.

The children's frequent descriptions of a *causal relation* between features in the dimension "transformation ideas" indicate that there is a good basis for starting to investigate also correlated gains and losses of certain indicators and to describe these – eventually – by the transformation of energy.

Among the "conservation ideas", the residual category is dominant (Tab. 4). However, the few segments coded with *conservation* show that the idea of conserved or even recyclable energy can also be developed with young children.

5.2 Patterns in the children's answers (RQ 2)

There are tendencies in the data the following discussion is based on: First, almost all categories can be found in almost all interviews (Tab. 4, middle column). Second, there are preferred categories and combinations of categories (Tab. 5 to 6). These observations indicate that children's conceptual models of energy are generally situational and flexible, while there are also indications of deeper-rooted and more stable conceptions.

Throughout all dimensions and in most of the interviews, many of the categories were assigned at least once (Tab. 4, middle column). Nevertheless, as Tab. 5 shows by way of example of three children and selected categories, there are considerable differences between individuals. Comparison of the respective frequencies reveals that these three children "use" almost all categories but that their individual "signatures" can differ from one another as well as from the distribution in the overall sample: There are preferred phenomena in which these children recognise energy and preferred and context-dependent ways to describe what energy is and where it comes from: Frequent combinations of categories are, for example, energy as a substance in combination with the idea of energy flow between sources and receivers (child 1), energy as a feature of an active state of moving objects (child 2), or energy as a causal agent needed for human activities (child 3). These and other combinations (e.g., *substance ideas* with *flow/source*, or *motion* with *feature of certain states*) are also found in the total sample (Tab. 6 and 7).

Based on these observations, trends for the following patterns can be identified: Energy as a *causal agent* or as a *feature of certain states* (e.g., when active) is associated with the idea that objects "get" energy by certain activities (*process*), i.e., by themselves rather than from an external source; this pattern can be expected in the context of *humans*. Energy as a substance-like entity (*substance ideas*) is associated with the idea of energy flow or delivery from an external source (*flow/source*); this pattern may be expected in the context of *electric devices*. A third pattern might be the notion of energy as *an intrinsic feature* of objects, which is transferred by *incorporation* of one object with energy into another; this pattern may be associated with the context of *electric devices*.

These patterns are consistent with the use of the term "energy" in everyday German, specifically, with the notion of energy as human vigour or "life force" and of electric current, and are likely to reflect children's experiences with their own body and with electric devices: Humans and other living beings need "life force" (energy) for their activities (energy as *causal agent*) and regain this "life force" by regeneration (*process*); getting or using energy might involve other objects, e.g., food, but these objects are invisible "through the energy lens" as they are not alive or themselves active. Electric devices use electric current (energy) for motion, the emission of light, or for other modes of operation; they get current/energy via cables or by batteries (energy as a *substance*, *flow*/*source*).

5.3 Method and limitations

Methodically, this study shows one way of investigating young children's conception about an abstract science concept, here energy: Using a fine-grained system of categories to categorise the children's statements, knowledge elements relating to the different (isolated) core aspects of the scientific energy concept were identified. The data structured in this way was used to identify frequent and missing references to these core aspects as well as "alternative" ideas. By determining frequent combinations of selected categories in the data set, indications for "patterns" of how selected knowledge elements were used in combination were identified. I consider this a first step towards a reconstruction of the children's conceptual models.

There are some limitations associated with the analysis: Since the children did not always express themselves clearly and coherently, the definition of the coding units as well as the coding itself is subject to uncertainties. Nevertheless, the high interrater agreement shows that the children's ideas can be reliably categorised with the suggested coding frame (see section 3.3) – the emerging picture of the children's energy ideas might be blurred but is still clear enough to infer what children "see through the energy lens". However, the exact code counts should not be overrated. The results also indicate that some answers may be ad-hoc constructs in response to the interviewer's question (Tab. 2). They may also be biased by the material prompts provided in the interviews, especially by the choice of the pictures and the phenomena of the picture stories. In my view, both cannot be avoided: Children likely learn in situations like the interview (Pramling, 2015, p. 118). Given the broad scope of the energy concept and the limited interview time, a selection of relevant phenomena had to be made. A limitation of this study is that I did not take the interviewer's verbal/material input into account when analysing the children's responses. Such an analysis of the interactions would give further valuable insights into how productive learning environments could be designed, and I suggest further research in this direction.

The presented analysis was only possible because I had been able to collect very rich data in in a child-friendly multi-method setting that invited the children to express themselves in-depth about energy (Detken & Brückmann, 2021). Gaining access to the children's ideas in a respectful, ethical, and yet effective way necessitated a qualitative approach. This, however, implies that generalisable conclusions are not possible at the moment. Hence, the results of this study should be understood as empirically substantiated hypotheses that should be tested and refined in a larger-scale investigation. To this end, I consider the used tasks, and the defined categories, including the language used in the children's concrete answers, a good basis for the development of quantitative test items enabling an investigation of larger samples.

6 Conclusion and Outlook

This study shows what young children see when they "look through the energy lens": They most likely know the term energy and have various ideas about what energy is, to which real-world objects or phenomena it relates and how it "behaves" in space and/or time. Hence, it should be assumed that even young children have developed a conceptual model, or several models, of energy before they receive formal instruction about energy or related phenomena in school. The observed patterns, e.g., energy as *causal agent* and *process* ideas in the context of *human beings*, or energy as a flowing substance in the context of *electric devices*, indicate how typical conceptional models of energy of young children may look like. These patterns resemble the use of the term energy in everyday German (as "life force" or "electric current") and suggest that children's experiences in everyday contexts in which they hear or are exposed to the term energy shape their conceptual models. Though the participating children did not see a complete and correct picture when "looking through the energy lens", these conceptual models and the knowledge elements they are built of can constitute steppingstones towards a more scientific understanding of energy and should be considered resources for energy learning:

According to the findings of this study, it can be assumed that many children associate energy with humans and/or electric devices. Hence, the contexts *human beings* and *electric devices* can be starting points for formal energy learning, though the observed patterns also suggest that there are some context-specific "stumbling stones": In the context of *human beings*, young children can be expected to have rich ideas of what it means to have energy. Especially those ideas that link the presence of energy with observable features, such as the physical activity, are a good basis for introducing energy as something that is inferred from observations. However, many of the children appear to focus solely on humans without considering interactions with, say, food or other objects when talking about energy. This anthropocentric view is normal for young children, but it might obscure ideas that need to be introduced for a more general understanding of energy, for example, that also inanimate objects can have energy, and that there are several indicators of energy besides (human) motion. In the context of *electric devices*, the participants' references to various energy indicators and to sources and users of energy can be used as steppingstones for introducing different *forms/manifestations* of energy and the core aspects of energy *transfer* and *transformation* (Tobin et al., 2018). However, a focus on electricity could promote the identification of energy with electric current. Consequently, multiple contexts should be used in instruction. To foster an understanding of energy as crosscutting concept, commonalities between phenomena from different science contexts, such as source-receiver-relations, should be highlighted. Age-adequate analogies, such as "humans get energy from food as electric devices get energy from batteries", may help to transfer productive ideas expressed in one context to another.

A good knowledge of various phenomena from a systemic perspective is required for – eventually – describing them in terms of energy *transfer*, *transformation*, *dissipation/degradation* and *conservation*. These foundations for energy learning can, in my view, be laid from the very beginning of formal science instruction in kindergarten or elementary school by letting children explore phenomena from different contexts with a focus on interactions and changes within the system of interest. Specifically, a good knowledge of the human body and its interactions, e.g., with food, air, and/or a football, and of the general operation of electric devices appears beneficial, since these contexts are intuitively associated with energy. In addition, children should make experiences with phenomena where they can observe indicators of further, non-intuitive manifestations of energy, such as temperature, deformation, elevation or sound. Finally, the results of this study suggest that a moderate and correct use of the term energy by teachers before a formal introduction of the energy concept, i.e., when exploring the above-mentioned phenomena in early science classrooms, can have a positive impact on the children's conceptual models of energy.

The knowledge of children's conceptional models of energy is important for the development of learning progressions for lower elementary school and/or the design of age-adequate instruction. Hence, future research should aim at describing patterns, like the correlations between categories identified in this study, more comprehensively and should identify conceptual shifts that children must make to proceed towards a deeper understanding of energy. To this end, the findings of this study can aid the development of quantitative test items that enable investigating such patterns more thoroughly.

Which instructional approaches might be productive requires further research and development. Given the diversity of the children's conceptions in this study, it can be supposed that "the one" effective teaching approach does not exist. Rather, I suggest aiming at multi-perspective, methodologically diverse, and individualised instruction, which fits well with the intentions of the subject *Natur, Mensch, Gesellschaft*.

Finally, instruction aiming at an understanding of the scientific energy concept is not possible without a corresponding professionalisation of teachers: In order to be able to speak correctly about energy and to recognise and use children's resources, teachers must understand and apply the core aspects of energy themselves. At least in Switzerland, subject science currently plays a minor role in the training of future primary teachers. Teachers, therefore, need support not only in terms of subject didactics (teaching materials, etc.) but also for their own subject-specific understanding of energy.

Supplementary Materials

Category systems for the five dimensions.

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