Fields in middle school energy instruction to support continued learning of energy

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Science education research has repeatedly revealed students' problems with understanding the energy concept, in particular, their understanding of potential energy. Newer research suggests that teaching students fields as a means to store potential energy may promote a more consistent understanding of the energy concept. Yet, it is presently unknown if the helpfulness of fields is limited to particular manifestations of potential energy or if the conceptualization of potential energy as energy stored in fields may constitute a coherent approach that supports students' continued learning on energy. To address this issue, we carried out a quasiexperimental pre-post-test study with $N = 64$ students from grade 6, with students being assigned to one of two conditions (fields-based vs nonfields-based approach to energy instruction). We also compared students continued learning in a subsequent unit on electric energy. Our findings suggest that students in the fields approach not only outperformed students in the nonfields approach, they were, in particular, able to use their understanding of potential energy to make better sense of electric energy, a form of energy previously unknown to them. The results of our study imply that fields can help students develop a deeper understanding of energy, in particular potential energy, and support continued learning about energy; that is, the learning about additional forms of energy.

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I. INTRODUCTION

An understanding of energy is important to address the most pressing issues societies are facing in the 21st century such as modern societies growing hunger for energy. Understanding the difficulties associated with storing energy generated by wind or solar power plants, for example, requires understanding the issues associated with the transport of (electrical) energy over longer distances (e.g., how electrical energy dissipates in its transport). Accordingly, policy documents such as the Framework for K-12 Education [1] and the PISA Framework [2] identify energy as a core idea in science.

Science education research has repeatedly found that students have difficulty understanding energy [3–8], in particular, potential energy. Students often refer to potential energy as a kind of label for a certain range of phenomena but fail to understand what potential energy really is [9,10]. Additionally, students often struggle with assigning potential energy to a location. Researchers have suggested that conceptualizing potential energy as stored in fields may help to address this issue [11,12]. More specifically, fields are expected to provide potential energy with a location and thus can help students to productively use potential energy to explain phenomena.

Recent findings confirm that teaching students fields as a means to store potential energy in an introductory unit on energy may promote a better understanding of potential energy and the energy concept as a whole [13]. Yet, it is presently not clear whether the inclusion of fields is limited to support learning about different manifestations of potential energy or if it sets the stage for students to develop a conceptual understanding of potential energy. Such conceptual understanding of potential energy should help students in their continued learning about energy. In this paper, we describe a study in which we explored whether incorporating fields into an introductory middle school energy unit supports continued learning about energy in a subsequent unit on electricity, which was enacted several months later. By comparing students learning in fields- and nonfields-based energy instruction,

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this study aims to empirically investigate the longer-term effects on students' learning when fields are included in energy learning.

II. THEORETICAL BACKGROUND

A. Learning about energy

There is broad consensus that students need to learn about five aspects in order to develop an understanding of energy: (i) energy manifests itself in different forms, (ii) energy can be transformed from one form into another, (iii) energy can be transferred from one place to another, (iv) whenever energy is transformed or transferred a part of the energy is dissipated and no longer available for further use, and (v) that the total amount of energy is conserved (for an overview, see [14]). Several large-scale studies have investigated how students build an understanding of these five energy aspects over time. Namely, students seem to progress in their understanding by first mastering the idea that energy is manifest in different forms, then progress in their understanding that energy can be transformed and/or transferred; the ideas of energy dissipation and conservation come later and many students fail to demonstrate a deep understanding of these ideas by the end of secondary school [3–5]. It is important to note that these studies provide information regarding students' ideas about energy in the course of "typical" energy instruction.

Energy is typically introduced using a forms-based approach. In this approach, energy is introduced as a quantity that manifests itself in different forms such as gravitational, kinetic, elastic, and electric energy. This approach has been taken up by many curriculum researchers [15–17] and is the de facto standard in school physics instruction today [18]. Findings suggest that while forms-based approaches are successful in fostering an understanding of how energy manifests itself in different forms and how different forms of energy are transformed from one into another, students still commonly struggle to develop a conceptual understanding of the energy concept as a whole [16,17,19]. Researchers have suggested that this is due to the forms-based approach emphasizing the use of forms as labels instead of fostering a deeper understanding of what energy forms truly are [11] and that this may in fact be a hindrance to continued learning (i.e., students developing a complete understanding of energy through K12 as defined by the learning progression [4]) about energy [20].

Energy can manifest itself in the real world in two fundamentally different forms: kinetic energy and potential energy. Kinetic energy is the energy of motion. It is stored in the motion of objects. Students readily accept this [21]. Potential energy manifests itself in different forms such as gravitational, magnetic, elastic, and electric potential energy. It is the energy of fields and the energy is stored in the field between objects that interact at a distance [22]. Potential energy, however, is difficult for students because they struggle with the idea that nonmoving systems have energy [23]. For students, potential energy becomes apparent only when transformed into kinetic energy. Potential energy seems not to be real [9,24], but potential energy is every bit as real as kinetic energy. Furthermore, students often (incorrectly) associate potential energy with a single physical entity instead of a system of interacting objects [10,25]. Traditional approaches are typically silent about the location in that potential energy is stored until it is transformed into kinetic energy leading students to the wrong idea that it is stored in a single object [9,12,16,20]. Because of the lack of a location to which potential energy can be assigned, students make up their own choice. As students assign kinetic energy to a single object, they often also wrongly say that a single object "has" potential energy. This language is a common practice by scientists and in students' textbooks and is accepted as an intermediate step toward a more technically adequate wording [20]. Yet this wording entails problems. Experts use this wording as a shortcut. When saying that an object has potential energy, they are inherently aware that this assignment always refers to a system, namely the system of interacting objects. The system is just not made explicit. With novice students, however, this is different. When students say that a single object has potential energy, they often do not think about the system that underlies this assignment. But potential energy is fundamentally connected to systems since one always has to consider the relative position of an object in a force field or the configuration of that object in relation to other objects. Disregarding the system to which potential energy is related leads to students' misconceptions of potential energy.

As one of two fundamental forms of energy, the understanding of potential energy plays a crucial role in the understanding of the energy concept as a whole. In the course of instruction, potential gravitational energy is typically introduced after kinetic energy as the first manifestation of potential energy. If students do not understand this form of potential energy correctly, other difficulties in understanding can quickly arise at the beginning of the energy instruction. These difficulties may continue in the learning of other, new forms of potential energy leading to students exhibiting little progress in building a coherent understanding of the energy concept, i.e., well-connected ideas of the energy concept [26,27]. The reason may be that students fail to conceptualize potential energy productively throughout energy instruction. However, this conceptualization is fundamental to build coherence and successfully continue learning about potential energy. In typical energy instruction, students seem to only acquire isolated knowledge about one form of potential energy [16] and fail to recognize that potential energy is a concept on its own. When students do not recognize the underlying principles of the concept of potential energy, it may be that each new form of potential energy appears to be an entirely new form for them. Students may only label the new energy forms but may not be able to identify the underlying ideas that connect all forms of potential energy and that could help them to understand other forms of potential energy better. Students' problems with conceptualizing potential energy appropriately may therefore cause problems in learning energy as a whole [10,25] and hinder learning about energy over time [20].

B. Promoting continued learning about energy with fields

Introducing fields into energy instruction may help address the problems students have with potential energy and better support their continued learning about energy as a whole. Fields and potential energy are closely related: potential energy can be conceptualized as stored in a field between at least two objects that interact at a distance. This perspective is consistent with the recommendation of the Framework for K-12 Science Education [1] (p. 124) that energy "can be modeled as either motions of particles or as stored in fields." This language of energy stored in a field is commonly used in the research field [11,12] and also Feynman used this wording in his lectures [28]. Introducing fields leads to a more complete and consistent view of potential energy. When introducing potential energy to students, connecting potential energy to fields may address students' difficulties in assigning potential energy to a location. Assigning potential energy to the field between a system of interacting objects gives energy a home [11,12]. With the help of fields, students realize that potential energy is fundamentally connected to systems.

Nordine *et al.* [29] developed an approach to middle school energy instruction where the fields and energy concepts are tightly connected. The so-called "systems-transfer approach" is focused on modeling energy transfer between systems. The authors introduced fields as a system. Energy can be transferred to the fields system or energy can be transferred from the fields system to another system. Investigation of the systems-transfer approach suggests that students can successfully relate energy and fields when explaining phenomena [30–32]. Most of the researchers who advocate for the inclusion of fields into energy instruction at the same time advocate for a focus on energy transfer, while avoiding energy forms (see also [11]). To explore whether the results reported by Fortus *et al.* [30] also apply to a forms-based approach (the more common way of teaching energy) incorporating fields, we developed an approach to introductory energy instruction that introduces potential energy as stored in fields. The results show that students can learn fields in addition to energy during a forms-based energy unit. The students showed a significant gain in their understanding of energy as a result of forms-based instruction including fields [$t(92) = 10.66$, $p < 0.001$, $d = 2.20$]. The findings of this study suggest that the inclusion of fields could lead to a better understanding of energy [13] when students understand fields. Students in this study learned about potential energy through the examples of magnetic and gravitational energy. Using fields could help students learn about other forms of potential energy, such as electric energy. Once students have learned that gravitational energy is energy stored in the gravitational field between two objects with a mass, electrical energy may be effectively introduced as stored in the field between two charges [33]. It is promising that the prior knowledge of potential energy may support learning about another, third manifestation of potential energy. Fields may provide a good explanation of particular forms of potential energy.

However, the impact of fields on students' learning of energy might go far beyond a simple improvement of students' knowledge of one or several manifestations of potential energy. The conceptualization of potential energy as stored in fields could promote a conceptual understanding of potential energy and set the stage for continued learning about energy. The findings of [3–5] suggest that a conceptual understanding of how energy manifests itself in different forms is the foundation for developing an understanding of the other aspects of the energy concept (i.e., transformation and transfer, dissipation and degradation, as well as conservation). As one of two fundamental forms of energy, an understanding of potential energy is an essential part of fully understanding the energy concept and being able to use the energy concept to make sense of phenomena. Fields may play a key role in helping students to use potential energy not just as a label [20], but to understand the underlying principles of potential energy, thus helping students to make connections between the various manifestations of potential energy. Fields represent a unifying underlying concept for all manifestations of potential energy as they provide conceptual simplicity and consistency. While potential energy manifests itself in various forms, the underlying principles are the same for every manifestation. For every manifestation of potential energy, students should learn that, in every phenomenon that involves potential energy, fields (i) mediate the interaction of objects at a distance and (ii) store potential energy with the amount stored depending on the distance between objects. Using the same set of underlying principles in learning about a range of potential energy manifestations may support students in developing a well-organized set of ideas about potential energy and thus a better understanding of potential energy (see [34]). In this way, the conceptualization of potential energy as energy stored in fields may constitute a coherent approach that unifies the various manifestations of potential energy. Such a coherent approach provides learners with opportunities to use the same set of ideas in a variety of contexts, which sets the stage for continued domain-specific learning [19,35]. diSessa and Wagner [26] argued that continued learning within a domain is enhanced when learners' knowledge is well connected around a small set of central ideas. In an empirical investigation, Nordine *et al.* [16] found that better-connected ideas about the energy concept promoted students' ability to make sense of other energy-related phenomena and to continue learning about energy over time. The conceptual consistency by conceptualizing potential energy as energy stored in fields may facilitate students' continued learning about new, yet unknown manifestations of potential energy. Accordingly, conceptualizing potential energy as stored in fields represents a promising approach to promote continued learning about energy—supporting evidence, however, has until now been largely lacking.

C. Research question

The inclusion of fields can lead to a better knowledge of gravitational and magnetic potential energy when students understand fields [13], i.e., introducing fields can promote students' knowledge of potential energy in two of its manifestations. Building on this work, we hypothesize that fields may contribute to students' developing of a coherent understanding about energy [11] and thus support continued learning about energy [16]. To investigate to what extent this is the case, we ask the following research question:

To what extent does the inclusion of the fields concept in a forms-based energy instruction support continued learning about energy in the context of electrical potential energy?

III. METHODS

A. Research design and sample

In order to answer our research question, we employed a repeated quasiexperimental pre-post-design (see Fig. 1). After being introduced to energy in one of two conditions during an introductory unit on energy, students' continued learning about energy was investigated as a function of a subsequent unit on energy. During an introductory unit, students were taught in two conditions: one group learned about magnetic and gravitational potential energy with fields (the fields group) and the other group learned about these two forms without fields (the nonfields group). Quantitative data on students learning have been collected by a respective test before (T1) and after the introductory unit (T2). In the subsequent unit, students' continued learning was assessed by their understanding of electric energy as another manifestation of potential energy. The introductory unit consisted of ten lessons of instruction across five weeks. After the introductory unit on energy, students received instruction on optics, which did not include any energy ideas. The subsequent unit on electric energy started four months after the introductory unit and constituted the next explicit learning opportunity about energy. Again, students were taught about energy in the two conditions, both following a forms-based approach. The

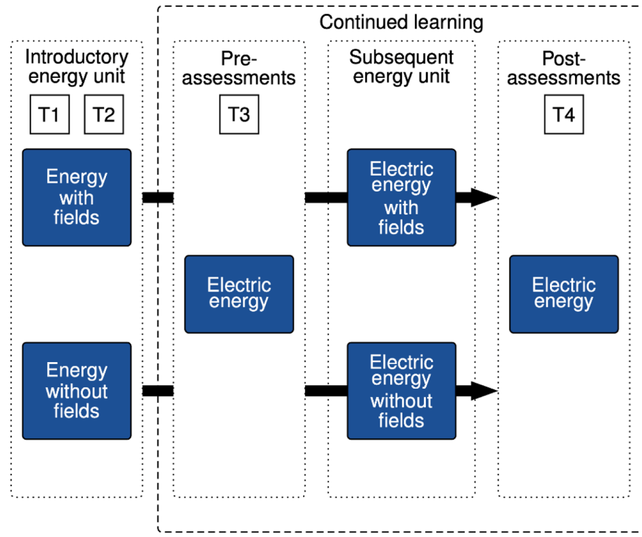


FIG. 1. Study design as a quasiexperimental pretest-post-test design with two intervention groups (fields and nonfields) and assessments before and after the interventions.

fields group was taught using a forms-based approach that included fields, and the nonfields group was taught using a forms-based approach without fields. Quantitative data have been collected by a test before the beginning (T3) and directly after the conclusion of the subsequent unit (T4).

The study took place during April and May 2019 with $N = 64$ students from a school in Northern Germany. The students were all in grade 6 and hence in their first year of learning physics. Students distributed to two fields groups ($N_{\mathrm{f}} = 46$) and one nonfields group ($N_{\mathrm{nf}} = 18$). Each fields group was taught by a different teacher. One of these teachers also taught the nonfields group. This design—that is, working with students from one school and having one teacher teach one of the fields groups and the nonfields groups, and one teacher teach another fields group—helped us control the influence of school-level variables across intervention groups, examine the effect of teacher-level variables between fields groups, while controlling for these variables between (one of the) fields and nonfields groups, effectively mimicking a laboratory study design that allowed us to evaluate the actual potential of the fields approach for students learning before taking it to regular instruction. The school in which our study took place was a public school in Kiel, the capital city of Schleswig-Holstein, Germany's most northern state. Students attending the school come from various parts of the city and represent different social classes. Since we sampled all students from 6th grade, no specific selection bias was introduced. However, the school was a gymnasium that is the more academic of the two school tracks in Schleswig-Holstein. Again, this helped us understand the principle potential of the fields approach for students' learning about energy. We acknowledge that we cannot make any claims about the extent to which our findings generalize to any

TABLE I. Overview of lesson contents during the units for both groups.

Lesson	Subject focus: Fields group	Subject focus: Nonfields group
1	Students explored the electric field as a store for electric energy and compared it to the gravitational and the magnetic field.	Students investigated phenomena that contained electric energy.
2 + 3	Students investigated the transformation of electric energy to light and thermal energy in a circuit. Students used a model representing a conveyor belt in order to explore electric energy transport.	

students' learning about energy. We have, however, no reason to believe the school is not representative of a typical gymnasium-level school in Germany. In order to ensure comparability of the groups, we assessed students' cognitive abilities and prior knowledge about electric energy before instruction (i.e., at pretest time, T1). Students' cognitive abilities were assessed using the nonverbal cognitive abilities test by Heller and Perleth [36]. This test indicated no significant differences between groups, $t(62) = -0.3$, $p = 0.77$, $d = 0.08$. Students' prior knowledge about electric energy was assessed using the same test utilized to assess their learning about energy (see the "Instruments" section for a detailed description). The comparison did not exhibit any significant group differences $t(62) = -0,\ 2,\ p = 0.82$, $d = 0.06$. Note: Effects sizes, despite being negligible, are provided in terms of Cohen's d [37].

B. The instructional units

The instructional units in this study built on the respective conceptualizations of energy students were introduced to in the introductory energy units. The introductory units introduced the energy forms of magnetic energy, gravitational energy, kinetic energy, and elastic energy, and the unit of the fields group included the magnetic field and the gravitational field into the energy forms of magnetic energy and gravitational energy. Energy transformation was also part of both units.

The subsequent units used in this study introduced electric, light, and thermal energy without investigating the latter two in-depth. Both units contained the same phenomena and energy forms and required the same time of instruction. Students received three lessons within two weeks. The distribution of topics among lessons, by group, can be seen in Table I. Both units were based on the same design principles to support knowledge in use. The units followed a guided inquiry. Students investigated phenomena by focusing on energy transformations between one energy form and another. They developed explanations of phenomena in a semiquantitative way, by tracking energy increase and decrease in one form which was always connected to a decrease or increase in another form.

During the units, students generated an explanation of the phenomenon of a light bulb in a circuit by a transformation of electric energy, provided by the power supply, into light and thermal energy. Both groups used the model of a conveyor belt (see Fig. 2) in order to explain why a light bulb in a circuit glows. A conveyor belt transports plastic balls on a higher level. Through a connecting element, the plastic balls reach a ramp that is studded with nails at regular intervals. The plastic balls roll down the ramp and collide with the nails. Through a connecting element, they return to the conveyor belt. Students compared the processes in an electric circuit and electric energy to the processes of the conveyor belt and gravitational energy. The belt itself represented the power supply, the plastic balls the electrons, the ramp represented the light bulb, and the nails the atoms in the light bulb.

The nonfields group was expected to develop the following explanation: Electrons are on a higher level of electric energy when leaving the power supply. While passing through the light bulb, they are speeding up and this kinetic energy is transformed into thermal and light energy when they hit the atoms. Students in the fields group were expected to use the conveyor belt model and the model of the electric circuit in Fig. 3 to explain a glowing light bulb as such: in the power supply, electric energy is stored in the electric field as charges are in a high-energy

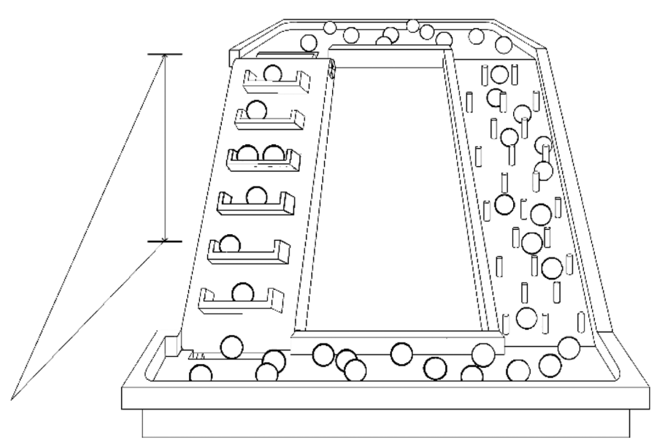


FIG. 2. Model of a conveyor belt used to establish an analogy between the transformation of gravitational energy in the conveyor belt circuit and the transformation of electric energy in an electric circuit.

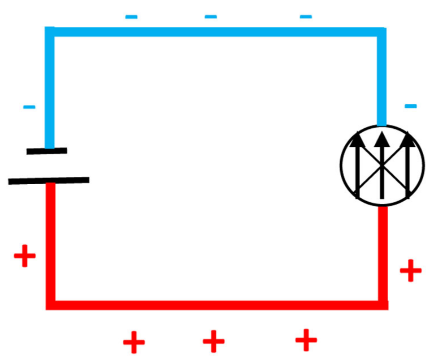


FIG. 3. Model of the electric circuit used in the fields groups to visualize the electric field in an electric circuit.

configuration. In the light bulb, the electric energy of the electric field is transformed into kinetic energy of moving electrons which is transformed into light and thermal energy when the electrons hit the atoms. By using the electric field in their explanation of why a light bulb in a circuit glows, students in the fields group can use the same field's framework to conceptualize gravitational energy (in the analogy of the conveyor belt) and electric energy (in circuits). Fields serve as a conceptual bridge between the two manifestations of potential energy. In contrast, the explanation of students in the nonfields group is limited to the analogy to gravitational energy. They do not have the conceptual bridge between the two manifestations of potential energy.

Using the conveyor belt model in our approach comes with a cost. In the model, electrons are speeding up and slowing down in the light bulb, while in a circuit, the speed of the electrons and with it the current remains nearly the same. We recognize that there may be a risk to misrepresent current. This technically incorrect intermediate step is accepted in favor of avoiding the frequently developed misconception that energy is transported from the electrons through the wires to the bulb. Instead, we initiate the idea that the energy is transported from the battery to the lamp by a field. In higher grades, this idea can be taken up to teach students about the transport of energy via electromagnetic fields. By using the conveyor belt model, we made a pedagogical choice. We would like to invite teachers to take up current in the following lessons in order to avoid misconceptions.

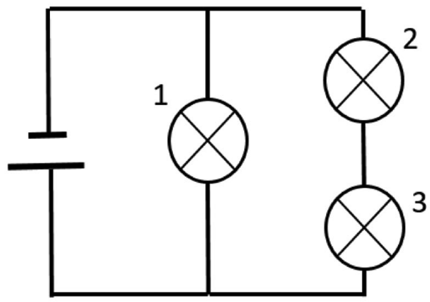
To construct the explanation of a glowing light bulb, students in the fields group should build on their knowledge from the introductory unit. There are especially two aspects from the introductory unit that are important to understand potential energy: (i) Fields mediate the interaction of objects at a distance and (ii) fields store potential energy with the amount stored depending on the configuration of objects. Students could use their knowledge to understand the new energy form: potential electric energy. In the case of electric energy, the electric field mediates between charges at a distance, it stores electric energy, and the amount of electric energy stored in the electric field depends on the configuration of the charges. To focus on and remind students of these underlying principles of the potential energy concept, the unit started with the electric phenomenon of a small stick containing a Van de Graaff generator that repelled figures made of aluminum. Students were asked to construct an explanation of the phenomenon. As they knew already that fields mediate action at a distance, they should be able to reactivate their knowledge by guessing that there must be a field between the generator and the figure. Students readily accept that this field is not the magnetic field since no permanent magnets were involved.[1] It could not be the gravitational field either, because the figure was repelled by the stick and not attracted by the Earth. That is how the electric field was introduced and with it electric energy. We tended to strengthen the analogies between the new form of potential energy, electric energy, and the already-known forms of magnetic and gravitational potential energy. To do so, students investigated the representations of the fields of all three forms and identified the two aspects of the fields concept that are important to understand potential energy for electric energy. With these activities, students were supported to use the same powerful ideas (fields as a store for potential energy with the amount depending on the configuration) across a range of contexts.

C. Instruments

To assess students' understanding of energy and in particular electric energy during the subsequent units, we developed a written electric energy test. To be able to compare students' understanding of energy before and after the subsequent units, the test before and after the subsequent units were identical. To ensure the sufficient psychometric quality of the test, we extensively drew on existing test instruments [38–40]. We selected tasks from these tests that focused on electric energy phenomena and adapted them to fit the content of the subsequent units where necessary. We also newly developed several tasks as needed. In developing the test, we have paid particular attention not to advantage either the fields or nonfields group. Students were not required to use fields to solve the tasks and the phenomena and models used in the test were equally part of the instruction in both groups. Overall our instrument contained seven multiple-choice and four open-ended tasks. The multiple-choice items of the test offered four answer options, one of which is correct. For choosing the correct answer option, the task was coded with one, otherwise with zero. The open-ended tasks were scored

[1]This logic is not technically correct since there is no permanent magnet needed to have a magnetic field. Still, it is acceptable at this grade level to allow students to eliminate the magnetic field based upon this criterion.

In the figure you can see a lamp (1) connected in parallel with a series connection of two lamps (2 and 3).



a. What can you say about the brightness of the lamps?
- ❑ Lamp 1 shines brighter than lamp 2 and 3, which are equally bright.
- ❑ Lamp 1 shines the brightest, then lamp 2, then lamp 3.
- ❑ All lamps shine equally bright.
- ❑ Lamp 1 lights up, lamp two and three remain dark.

b. Justify your answer using energy. (Hint: Consider the distance in the conveyor belt model).

FIG. 4. Example of an item in the electric energy test.

using partial credits based on a coding manual developed for the test. We carefully designed scoring rubrics so that they did not favor either instructional approach. Rubrics were designed in a way that a higher level of sophistication and connection of energy ideas led to a higher score. Responses were awarded one point for presenting facts like identifying energy forms. Two-point responses connected two or more ideas of the energy concept, for example, linking the decrease in one energy form to an increase in another energy form. Three-point responses provided a complete explanation by both connecting two or more energy ideas and applying them correctly to the present phenomenon. Even though students in the fields group were able to show a more sophisticated understanding by explaining in more depth the processes occurring in the electric circuit by using fields, they did not gain more points than a student in the nonfields group who also gave a correct explanation. The test did therefore not favor students in the fields group. The test was coded independently by two raters at the pretest and post-test time points. Interrater reliability for the open-ended tasks was good, with a Cohen's kappa of $\kappa \geq 0.98$. An example item from the electric energy test is given in Fig. 4.

The reliability with which energy understanding was measured was assessed using Cronbach's alpha. The internal consistency of the electric energy test at the pretest time (T3) was low with Cronbach's $\alpha = 0.42$ and at the post-test time (T4) acceptable with $\alpha = 0.64$. Because of the low reliability of the pretest, we did not consider it as a covariate in our analyses (see below). Reliabilities at the post-test time were sufficient for group comparisons [41] (p. 14).

D. Data analysis

To investigate the extent to which the inclusion of the fields concept supports continued learning about energy in the context of electric potential energy, we compared the fields and the nonfields group in terms of their understanding of electric energy. Students' understanding of electric energy was measured before (T3) and after the subsequent units (T4) using the electric energy tests. For an initial overview of students understanding in both groups, we wanted to obtain an overview of group differences in students' understanding of electric energy over time. For this purpose, a paired t test was calculated for each group with students' scores on the electric energy test at pretest time (T3) and post-test time (T4). We furthermore compared students' understanding of electric energy at post-test time by calculating Welch's two-sample t test (a generalized and even more robust version of the t test, see, e.g., [42]) with students' scores on the electric energy test at post-test time. We then analyzed the group differences in greater depth.

Differences in students' performances in the electric energy test at post-test time (T4) may be influenced by two factors other than the group influence. First, students may have a different understanding of the energy concept based

TABLE II. Results of both groups in the tests on electric energy, energy from the introductory unit, and cognitive abilities.

		Fields group ($N = 46$)		Nonfields group ($N = 18$)	
Results	Time	*M*	*SD*	*M*	*SD*
Cognitive abilities test score	T1	17.02/25	6.19	16.50/25	6.72
Energy score (post, introductory unit) in %	T2	48.56	16.84	53.19	16.41
Electric energy score (pre)	T3	5.88/18	2.28	5.75/18	1.54
Electric energy score (post)	T4	7.96/18	2.89	6.83/18	2.38
Gain in electric energy score		2.08	3.27	1.08	1.75

on whether fields were included in the introductory unit. Students in the fields group should conceptualize potential energy as energy stored in fields while students in the nonfields group learned potential energy in a traditional way without fields. These differences in the conceptualization of potential energy may affect students' continued learning about potential energy forms and therefore also about electric energy. We controlled for students' prior knowledge on energy using the data of students' energy understanding at post-test time (T2) of the introductory unit as a covariate. The energy post-test had a good reliability with Cronbach's $\alpha = 0.74$. Second, students' performance in the electric energy test at post-test time (T4) may also depend on their cognitive abilities. Students' cognitive abilities were measured at the pretest time (T1) of the introductory unit. Students' cognitive abilities were assessed using the N1 nonverbal subscale of the cognitive ability test (KFT) [36]. The reliability of the subscale used was good with a Cronbach's α of 0.90. To control for the influence of these two factors, prior knowledge about energy (T2), and cognitive abilities, we conducted an analysis of covariance (ANCOVA), using the electric energy scores at the post-test time (T4) as the dependent variable, and the group factor, prior knowledge about energy (T2), and cognitive abilities as the independent variables. The statistical methods that we used in our study are considered robust against small sample sizes [43]. Further, the diagnostics of the ANCOVA showed no reasons for concern, e.g., residuals of the ANCOVA were normally distributed.

IV. RESULTS

A descriptive overview of students' scores on the electric energy test before the unit (i.e., at pretime, T3) and after the subsequent units (i.e., at post-time, T4) is provided in Table II. Students' score in the energy test after the introductory unit (i.e., at post-time, T2) is shown in percent because the number of tasks differed between pretime (T1) and post-time (T2). All other measures are given in absolute points. For those measures (separated by a slash), the maximum achievable score is also given. Students' cognitive abilities test scores were assessed before the introductory unit (i.e., at pretime, T1). The correlations between students' total scores in all measures are provided in Table III. Students' scores in the electric energy test after the subsequent units (T4) correlate with their scores in the cognitive abilities test and students' scores in the energy test after the introductory unit (T2). Students differed in neither their cognitive abilities (T1) nor their prior understanding of electric energy before the subsequent units (T3).

For each group, we examined students' progress in understanding electric energy as a result of the subsequent units. To do so, we compared their electric energy scores in the pretest and post-test. The results indicate that students in both groups progressed substantially in their understanding of electric energy. Students' scores in the fields group on the electric energy test increased significantly from pretime to post-time with a large effect size [$t(45) = 4.30$, $p < 0.001$, $d = 0.80$]. In the nonfields group, students' scores also increased significantly from pre to post, this time with a medium effect size [$t(17) = 2.63$, $p = 0.01$, $d = 0.54$]. Comparison of students' scores on the post-test reveals slightly higher scores on the electric energy test after the subsequent units (T4) for students in the fields group (see Fig. 5); a difference that is not statistically significant [$t(37.49) = -1.59$, $p = 0.119$, $d = 0.41$]. However, in our study, we were not exclusively interested in students' learning about electric energy, but more specifically their continued learning about energy in the context of—fields- or nonfields-based—instruction on electric energy.

In order to investigate students' continued learning about energy as a function of fields- and nonfields-based energy

TABLE III. Correlations between all measures.

	Electric energy score (pre, T3)	Electric energy score (post, T4)	Energy score (post, T2)
Electric energy score (post, T4)	0.40, $p = 0.001$		
Energy score (post, T2)	0.22, $p = 0.076$	0.55, $p < 0.001$	
Cognitive abilities test score (T1)	0.37, $p = 0.002$	0.25, $p = 0.037$	0.38, $p = 0.002$

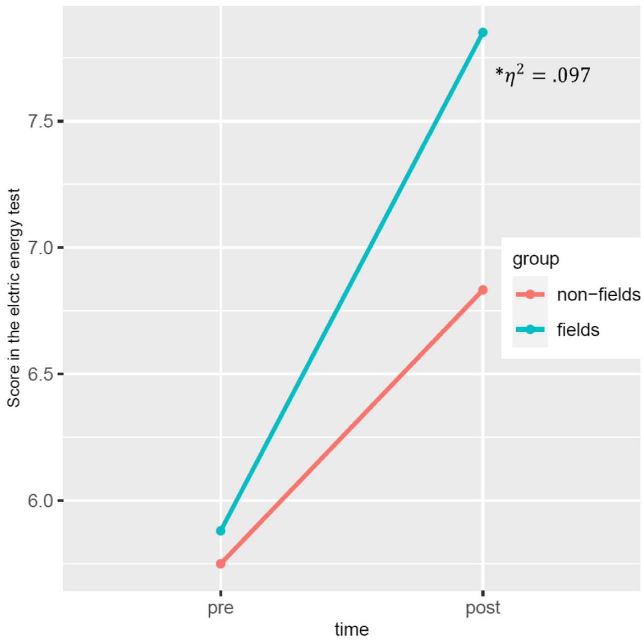


FIG. 5. Students mean scores on the electric energy test before (pre, T3) and after (post, T4) the subsequent unit for both groups.

teaching, we conducted an ANCOVA. In this ANCOVA, we examined students understanding of energy measured by the electrical energy test at post-test time (T4). We included the type of intervention group (i.e., fields vs nonfields), adjusting for relevant covariates including students' prior understanding of energy measured by the energy test immediately post the introductory unit (T2). We further included students' cognitive ability as a covariate (see Table IV for an overview of the variables included in the ANCOVA). The results of the ANCOVA suggest that when controlling for cognitive ability scores (T1) and energy test scores post the introductory unit (T2) [$F(1, 60) = 6.4$, $p = 0.014$, partial $\eta^2 = 0.097$], students in the fields-group outperform students in the nonfields group; that is, students learning about energy in fields-based instruction showed better continued learning.

V. DISCUSSION

Our findings suggest that the inclusion of the fields concept in a forms-based energy instruction successfully supports continued learning about energy in the context of electric potential energy. After being introduced to energy in a first unit (with or without fields), students significantly improved their understanding of electric energy in a subsequent unit (with or without fields). Moreover, accounting for prior knowledge and cognitive abilities students in the fields group demonstrated a better understanding than their counterparts in the nonfields group.

The inclusion of fields into energy instruction has long been recommended by scholars [1,11,12,29] in order to give potential energy a location when not manifested in motion [12]. When potential energy is located in fields, students are less likely to perceive it as hidden or not real [9,24]. Before the students in the fields group learned about electric potential energy, they learned about other potential energy forms in an introductory energy unit. In this introductory unit, the potential energy forms of magnetic and gravitational energy were introduced as being stored in fields, with the amount of energy being stored depending on the configuration of two objects. After being introduced to energy, students from the fields group did not exhibit a better understanding of energy. In fact, the fields group scored slightly worse on the energy test post the introductory unit compared to the nonfields group, see [13]. We argued that this is due to the fact that students were exposed to two complex constructs (energy and fields) at the same time, which could have been overwhelming for some students. However, when it comes to students' continued learning, the fields group outperformed the nonfields group in terms of their energy understanding. We interpret this as a positive long-term effect of the fields approach. Fields no longer seemed to create an additional load but, on the contrary, seemed to help students learn about energy in a different area of physics, electricity.

Bransford, Brown, and Cocking [34] argue that the foundation of competence in a domain is well-connected knowledge organized around the central concepts of that domain. Including fields into the concept of potential energy could promote conceptual understanding because the underlying principles of the concept are the same: For every manifestation of potential energy, fields mediate interaction at a distance and store different amounts of energy based upon the configuration of objects that interact via fields. Fields could therefore help students to better understand and connect the underlying principles of the potential energy concept that promotes a more coherent understanding of energy. diSessa and Wagner [26] argue that well-connected (coherent) ideas of a concept promote students' ability to apply their prior understanding to

TABLE IV. Results of the ANCOVA with students' understanding of electric energy after the subsequent units (T4) as dependent variable.

Independent variable	Sum of squares	df	Mean square	F	p	Partial η^2
Cognitive abilities test score (T1)	3.03	1	3.027	4.701	0.034	0.001
Energy score (post, T2)	17.19	1	17.192	26.696	<0.001	0.334
Group (0 = nonfields group, 1 = fields group)	4.14	1	4.145	6.437	0.014	0.097

understand other contexts. Presenting the same set of ideas of a concept in a variety of contexts promotes students' likeliness to apply their prior understanding to other contexts [35]. In the subsequent energy unit on electric energy in the present study, students in the fields group learned about electric energy as the third manifestation of potential energy. Once again, electric energy has been introduced as stored in a field, i.e., the electric field, with the amount of energy stored depending on the configuration of charges. With electric energy, students got another learning opportunity to learn about potential energy and fields that helped them to understand the underlying principles of the concept of potential energy. Students could use fields as a unifying underlying concept for all manifestations of potential energy that sets the stage for continued learning about energy.

Our findings support our hypothesis that students in the fields group would more successfully build a more coherent understanding of potential energy. Students seemed to be able to use their prior understanding on potential energy and fields to understand another manifestation of potential energy. Therefore, learning about the electric field seemed to support learning about electric energy. We argue that students were able to make the connection between potential energy and fields after having experienced them in several of its manifestations. Using the same set of powerful ideas in several manifestations of potential energy seemed to promote students' continued learning.

There is much discussion in the literature about whether the inclusion of fields in energy instruction can help students better understand energy [11,12,30]. By testing this idea in class with students, we wanted to contribute to this discussion, which has so far been rather theoretical. Our findings provide a small-scale demonstration that fields can promote continued learning about energy and that it has merit to further investigate the role of fields in energy instruction. In our future research we aim to substantiate the findings of this study with a greater sample. A greater number of students and teachers is needed to minimize effects that are due to factors such as the teachers' teaching style or the socioeconomic status of the students. The results in the present study should therefore be interpreted as the first evidence of the potential benefits of the inclusion of fields into introductory energy instruction. While the study occurred in a specific context and involved a relatively small sample size, our findings nonetheless point to a clear benefit of connecting fields to potential forms of energy as a part of students' first encounter with energy ideas. Contrary to the assumption that including fields in introductory energy instruction may unnecessarily complicate students' learning about an already abstract concept (energy), we found that students who began to conceptualize potential forms of energy in terms of fields developed better-connected ideas that seemed to set the stage for continued learning.

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