Middle school students using energy analysis in diverse phenomena

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ABSTRACT

Teaching and learning about energy, especially in the elementary and middle school grades, constitutes a challenging topic that has received much attention within the science education research literature. Despite this, it is important to notice the lack of consensus on a range of relevant issues (e.g., whether - and how - to address the nature of energy as a scientific construct). In this study we briefly discuss the challenge inherent in introducing and elaborating energy in school science and the inadequacy of conventional teaching approaches in addressing this challenge effectively. Next, we outline the rationale underlying a novel teaching proposal and the corresponding curriculum materials. The remaining part of the paper presents a portion of the results of the analysis of preliminary data that have emerged during the implementation of the curriculum materials with a group of 28 students aged 12-14. These results demonstrate the potential of the curriculum materials to help students construct understanding about the transphenomenological, unifying nature of energy and also to develop the ability to employ energy for analyzing simple, unknown physical systems so as to derive qualitative accounts for system changes.

KEYWORDS

Energy, epistemological awareness, scientific constructs, trans-phenomenological aspect, system analysis

Résumé

Enseigner et apprendre l'énergie, en particulier dans les classes des écoles élémentaires et des collèges, constitue un sujet difficile qui a reçu beaucoup d'attention dans la littérature de recherche en didactique des sciences physiques et naturelles. Malgré cela, il est important de noter l'absence de consensus sur une série de questions pertinentes (par exemple, si - et comment - d'aborder la nature de l'énergie comme un concept scientifique). Dans cette étude, nous discutons brièvement les défis inhérents à l'introduction et l'élaboration de l'énergie dans l'enseignement des sciences et de l'insuffisance des approches pédagogiques classiques pour relever ce défi de manière efficace. Ensuite, nous décrivons la logique qui sous-tend une proposition d'enseignement innovatrice et les matériels pédagogiques correspondants. Enfin, nous présentons une partie des résultats de l'analyse des données préliminaires qui ont émergé au cours de la mise en œuvre d'une intervention d'enseignement avec un groupe de 28 élèves âgés de 12-14 ans. Ces résultats démontrent le potentiel des matériels pédagogiques utilisés pour aider les élèves à construire la compréhension de la nature trans-phénoménologique et unificatrice de l'énergie et aussi de développer la capacité d'utiliser l'énergie pour l'analyse des systèmes physiques simples et inconnus de manière à dériver une approche qualitative des changements du système.

Mots-Clés

Énergie, prise de conscience épistémologique, constructions scientifiques, aspect trans-phénoménologique, analyse systémique

Introduction

Teaching and learning about energy has attracted much attention in the science education research literature (Driver & Millar, 1985; Solomon, 1992; Doménech et al., 2007). This seems to be directly related to the abstract nature of this construct and the need for appropriate teaching transformations. Despite the useful insights that have been published in the research literature about students' conceptual difficulties (Duit, 1984; Driver & Warrington, 1985; Lawson & McDermott, 1987; Solomon, 1992) and the useful ideas pertinent to the teaching elaboration of various aspects of energy (Schmid 1982; Arons 1990; Boohan & Ogborn, 1996; Van Heuvelen & Zou, 2001; Doménech et al., 2007; Nordine, Krajcik & Fortus, 2011) we are still lacking substantial progress and there is clearly a need for further research on the development of relevant teaching innovations. We have sought to contribute towards meeting this need by developing a teaching approach for the introduction and elaboration of energy in the lower middle school grades (students aged 11-14). In this paper we report on the results of an empirical study intended to provide preliminary indications as to the potential effectiveness of this approach.

Theoretical Background: Underlying Rationale and Research Questions

Understanding about energy is widely recognized as a major learning objective of science teaching, starting from the upper grades of the elementary school (AAAS, 1993). However, the abstract and purely quantitative nature of this construct tends to confound attempts to introduce and elaborate energy in school science. Addressing these difficulties, calls for teaching transformations that can productively adapt the depth of teaching elaboration, so as to help students develop a qualitative account of energy.

Existing research literature has demonstrated that conventional teaching approaches fall short of addressing this instructional challenge in an effective manner. For instance, it indicates that students do not emerge with an articulated notion of energy (Duit, 1984). Instead they tend to use various ideas and terms associated with energy in a rather loose, and often invalid, manner (Solomon, 1992). Another indication of the failure of conventional teaching approaches to bring about coherent understanding of energy relates to the energy conservation principle. Existing research indicates that despite the significant attention that is usually paid to this idea, students do not typically emerge with functional understanding (Duit, 1984; Driver & Warrington, 1985; Solomon, 1992).

We take the perspective that any attempt to teach about energy needs to address the fundamental epistemological question “what is energy, why is it useful and how do we use it?”, in an effective manner. We believe that a potentially productive way of approaching this question, includes shifting away from a conceptually-oriented approach towards a philosophically-informed perspective. Specifically, one could begin with the idea that in science we formulate theoretical frameworks so as to account for observations and phenomena. Once this idea has been sufficiently elaborated, energy could then be introduced as a theoretical framework that has been invented in science so as to enable the unified analysis of the operation of diverse physical systems. The emphasis could then be shifted to its gradual elaboration, through the introduction of the various features of energy, namely transfer, transformation, conservation, degradation, and its application for the qualitative analysis of systems. We have developed teaching and learning materials (TLMs) along this line and we have implemented them in the classroom environment so as to empirically explore their potential to help students develop understanding of energy. In this study we specifically seek to address the following research questions:

To what extent does students' interaction with the TLMs help them:

a. appreciate the unifying, transhpenomenological nature of energy?
b. develop the ability to use the features of energy for deriving qualitative accounts of system changes?

Research Methods

Overview of the TLMs

The TLMs, which are mostly web-based, involve three main sections. The first includes a series of activities intended to introduce certain aspects of the Nature of Science (NOS), including the distinction between observation and inference and the role of invention in scientific inquiry (Lederman, 2007). These aspects are intended to provide a working framework that could support the initial introduction of energy as an invented theoretical framework and inform its elaboration throughout the TLMs. The second section presents students with a variety of physical systems and engages them with identifying the parts of the system in each case and the change it undergoes. The focus is then shifted to the value of a single unifying interpretation that could account for all the changes presented in this section. At that stage, energy is introduced as a construct that has been invented in science so as to serve this purpose. The third section, seeks to gradually elaborate the theoretical framework of energy and help students appreciate its power in terms of facilitating the qualitative analysis of system behavior. Specifically, this section introduces the main features of energy (i.e., energy transfer, form conversion, conservation and degradation), in a progressive manner with an emphasis on revealing how each contributes to the interpretive and predictive capability of the theoretical framework. Also, in this section students are introduced to the idea of *energy chain* as a model for facilitating the derivation of qualitative accounts of system changes. This model consists of arrangements of rectangles (denoting forms of energy) and arrows (denoting energy transfer processes), which can describe, in a graphical form, the operation of physical systems in terms of energy transfer and transformation (see figure 2 for examples). During instruction, energy chains were constructed by students using a specially designed electronic tool that was embedded in the TLMs. This tool provided a space that allowed students to construct energy chains by selecting and arranging (in a "drag and drop" manner) the specific forms of energy (rectangles) and energy transfer processes (arrows) they deemed relevant to the system under analysis[1].

1 This scaffolding was removed in the last session.

Instructional context

The TLMs have been tested in the context of an extracurricular school science club. Participants were 28[2] students aged 12 to 14 years old, who volunteered to take part. Students met with the instructors twice a week for 90-minute sessions over a period of six weeks. The teaching approach used with the activity sequence was based on the *Physics by Inquiry* pedagogy (McDermott et al., 1996). Students routinely worked in groups and interacted with the learning materials without being exposed to lecturing or teacher-directed instruction. At certain points throughout the activity sequence, each group of students separately discussed with the instructor and reflected on what they had done in the preceding activities. During these discussions, the instructor avoided to offer direct answers to students' questions or comments. Instead, the emphasis was placed on helping students articulate their thoughts and negotiate the various difficulties they were encountering.

Data Sources

Prior to and after the implementation of the TLMs we collected data so as to assess students for potential learning gains and, thereby, derive a preliminary measure for the potential effectiveness of the TLMs. Assessment involved two open-ended tasks. The first (Figure 1) pertains to students' understanding of the transphenomenological nature of energy and its facility to provide a unifying framework for the interpretation of different changes. It presented students with two pairs of physical systems (first pair: electric blades & wind blades; second pair: electric drill & manual drill) depicting certain

FIGURE 1

First pair of systems	Second pair of systems

First pair of systems	Second pair of systems
• Provide an interpretation for the rotation of the electric blades. • Provide an interpretation for the rotation of the wind blades. • Provide a single interpretation that accounts for both the rotation of the electric and wind blades.	• Provide an interpretation for why the electric drill spins. • Provide an interpretation for the rotation of the manual drill. • Provide a single interpretation that accounts for the operation of both, the electric and the manual drill.

Overview of Task I

2 Some of the students were absent during the administration of the pre- and post-tasks. Specifically, the total number of students who participated in the initial assessment was 23. The corresponding numbers for the final assessment were 26 (Task I) and 24 (Task II).

changes (rotation of the blades in the first pair and rotation of the drill bit in the second pair). In each case students were asked to, firstly, account for the two individual changes independently, and, secondly, to provide a single interpretation that could account for both changes (Koliopoulos, 1997). The first pair of systems was administered before and after the teaching intervention while the second was only given as a post-test.

Any single system can be analyzed without resorting to energy, by employing physical quantities drawn from the corresponding field of physics (e.g., electric current and force in the cases of the electric blades and the wind blades, respectively). What makes energy a powerful interpretive framework is its unifying character, which enables the analysis of different systems, drawn from diverse domains, using the same perspective. In this light, even though we expected an increase in the frequency of energy-based responses to the first probe (i.e., interpretation of individual changes), the main change that we anticipated as a result of students' interaction with the activity sequence is primarily concerned with the second probe (i.e., single interpretation for a pair of changes). Specifically, we assumed that while students might not be able to meaningfully construe this question during the initial assessment, their interaction with the TLMs would help them appreciate energy as a framework for the unified interpretation of changes and, hence, lead them to provide more informed responses.

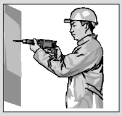
The second task pertains to students' ability to describe the energy transfers and form conversions that relate to specific changes occurring in physical systems. Students were presented with two physical systems and were asked to specifically concentrate on a certain change depicted in each of them. The first system included a worker using an electric drill to perforate a wall and the second showed a woman striking a ball with a golf club. The changes that students were asked to account for in the two systems include the acceleration of the drill bit and the ball, respectively, from rest. The two systems also depicted additional changes (e.g., sound, dust coming out from the wall etc.). Even though we did not explicitly ask students to account for those, we encouraged them to do so. It is important to note that neither of the two systems was analyzed by the students during the implementation of the TLMs. Figure 2 shows the energy chain that students were expected to provide for the specified change in each system.

Data processing

The coding of students' responses to the first task was largely informed by a previous study that involved the collection of data from a large sample of students using this same task (Papadouris, Constantinou & Kyratsi, 2008). That study reported a categorization scheme, which was found to adequately fit our data and, therefore, we decided to rely on that for coding students' responses. In the case of the second task,

FIGURE 2

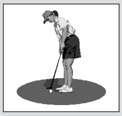
The worker switches on the drill and the drill bit starts rotating



Expected energy chain

Chemical potential energy → Electricity → Kinetic energy

The woman strikes the ball with the golf club and it starts sliding



Expected energy chain

Chemical potential energy → Mechanical work → Kinetic energy

Energy chains for the systems in Task II that could be deemed appropriate

students' responses were processed so as to evaluate the extent to which they were able to provide energy-based accounts for the changes under consideration and to evaluate their accuracy and completeness, as discussed later.

RESULTS

Below we present the results that emerged from processing students' pre- and post-test responses to the two tasks. Each task is discussed in a separate subsection.

Task I

First probe: Interpretations of changes in individual systems

Students' responses to the first probe were clustered in four categories shown in table 1. The first category involves energy-based responses that sought to account for the changes in terms of energy transfer or transformation. The second category entails responses that referred to energy in a vague manner. The next category includes the responses that drew on constructs of physics other than energy. Finally, the fourth category involves the cases in which students refrained from employing either energy or any other construct and instead relied on phenomenological aspects of the systems under analysis. Specifically, these students relied on either individual system objects or processes taking place within the systems. Table 2 shows the distribution of student pre-test responses across these categories for each of the two systems.

Table 1

Categories of students' responses to the first probe of Task 1

Category of response	Illustrative student response
Energy-based responses drawing on the idea of energy transfer	*"There is energy transfer from the battery to the blades, which keeps them rotating."*
Energy-based responses: vague reference to energy	*"The blades spin because of energy."*
Responses drawing on constructs of physics other than energy	*"The drill functions because of the force exerted by the hand of the woman."*
Phenomenologically-oriented responses	*"The woman spins the drill with her hand. This makes the drill perforate a hole on the wood."*

Table 2

Categorization of students' pre-test responses to the first probe of Task 1

	Electric blades		Wind blades	
	N	%	N	%
Energy-based responses drawing on the idea of energy transfer	11	48	1	4
Energy-based responses: vague reference to energy	9	39	-	-
Responses drawing on constructs of physics other than energy	2	9	5	22
Phenomenologically-oriented responses	1	4	17	74

One important observation about table 2 relates to the significant variation between the distributions of the students' responses in the two systems. Specifically, it seems that a significant proportion of students who referred to energy in accounting for the change in the electric system failed to do so in the mechanical system. Instead, they preferred to draw on phenomenological aspects of the system. This implies that the extent to which students selected to employ energy for the interpretation of changes was influenced by the characteristics of the system. The relatively high percentage of students (87%) who provided energy-based responses in the electric system might have been triggered by specific characteristics of that system, including the presence of a clearly discernible source and receiver of energy and the physical connection between them. In this light, this high frequency should not be perceived as a reliable indication of students' appreciation of the interpretive power of energy.

Table 3 shows the corresponding distributions of students' post-test responses. The comparison between tables 2 and 3 indicates a marked increase in the percentage of energy-based responses (from 46%, to 75%, overall) and a decrease in the percentage of responses that relied on phenomenological aspects of the systems (from 39% to 17%, overall). This provides an encouraging indication as to the improvement in students' appreciation of energy as an interpretive scheme for changes in physical systems.

TABLE 3

Categorization of students' post -test responses to the first probe of Task 1

	Electric blades		Wind blades		Electric drill		Manual drill	
	N	%	N	%	N	%	N	%
Energy-based responses drawing on the idea of energy transfer	22	84	7	27	18	69	10	38
Energy-based responses: vague reference to energy	2	8	7	27	4	15	8	31
Responses drawing on constructs of physics other than energy	–	–	3	11	2	8	3	12
Phenomenologically-oriented responses	2	8	9	35	2	8	5	19

Second probe: unified interpretation for a pair of changes

Table 4 illustrates the categories of response that we were able to discern with respect to the second probe. The first three categories were also encountered in the case of the first probe. These include, energy-based responses drawing on the features of energy transfer or transformation, vague energy-based responses and responses that relied on constructs of physics other than energy. The next category includes the cases in which students failed to come up with a single interpretation and, instead, dealt with each change independently. Finally, the fifth category includes irrelevant responses that essentially failed to address the question at hand.

As shown in table 5, most students in the pre-test (60%) failed to come up with a single interpretation for both changes and, instead, dealt with each independently. This percentage was significantly lower in the post-test responses (31% in the first pair of systems and 19% in the second pair of systems). Additionally, there was a considerable increase in the percentage of responses that relied on energy transfer or transformation (38% in each of the two pairs in the post-test compared to 4% in the pre-test).

TABLE 4

Categories of response to the second probe of Task I

Category of response	Illustrative student response
Energy-based interpretations drawing on energy transfer or transformation	*"In both cases energy that is stored in the system is transferred to the blades and this makes them spin."*
Energy-based responses: vague reference to energy	*"The blades of the windmill spin because of the energy in the wind and the blades of the electric motor because of the energy of the battery."*
Responses drawing on constructs of physics other than energy	*"In both cases the blades rotate because of force; the force of the wind and the force of the battery."*
Two distinct interpretations	*"The blades of the windmill spin because of the wind and the blades of the electric motor spin because of its connection to the battery."*
Irrelevant responses	*"The blades spin because something makes them do that."*

TABLE 5

Categorization of students' pre- and post-test responses to the second probe of Task I

	First pair of systems Pre-test		First pair of systems Post-test		Second pair of systems Post-test	
	N	%	N	%	N	%
Energy-based interpretations drawing on energy transfer or transformation	1	4	10	38	10	38
Energy-based responses: vague reference to energy	4	18	6	23	8	31
Responses drawing on constructs of physics other than energy	4	18	1	4	2	8
Two distinct interpretations	14	60	8	31	5	19
Irrelevant responses	–	–	1	4	1	4

Integrated perspective into students' responses to both probes

Another measure that was employed for the assessment of students' (emerging) appreciation of the facility of energy to provide a unifying framework for the interpretation of changes relies on the combination of their responses to the two probes involved in Task I. Students' responses were scored dichotomously depending on whether they relied on energy or not (1 or 0). Table 6 summarizes the results of

TABLE 6

Distribution of students' energy-based responses to the two probes in Task I

Energy-based response for at least one of the two individual changes	Energy-based response for the pair of changes	Pre-test (first pair of systems)	Post-test (first pair of systems)	Post-test (second pair of systems)
0	0	2 (9%)	2 (8%)	3 (12%)
1	1	4 (18%)	16 (61%)	18 (69%)
1	0	16 (69%)	8 (31%)	5 (19%)
0	1	1 (4%)	–	–

Notes: a. The second pair of systems was administered as a post-test only
b. For the first two columns, 1 indicates Yes and 0 indicates No.

this coding procedure. The first two columns denote whether students provided energy-based responses for the first and the second probe, respectively. Each row represents a different combination of the two levels of these dichotomous variables. The last three columns show the frequency and percentage of students' responses for each of these combinations. The most informative part of the table is its third line, which refers to the students who resorted to energy-based responses for one (or both) of the individual changes (1) but failed to do so in providing a single interpretation for both (0). The percentage of these cases decreased from 69% to 31% in the first pair of systems and 19% in the second pair of systems. This notable decline provides an additional encouraging indication as to students' increased appreciation of the unifying value of energy.

Task II

Prior to the implementation of the TLMs, students were not in a position to meaningfully employ energy for accounting for the two system changes, involved in Task II. Twenty of the students (87%) in the first system and eighteen students (78%), in the second system, merely cited a sequence of objects they deemed relevant to the process under consideration. For example, a common response in the case of the electric drill system was that "*energy goes from the plug to the drill*". It is important to note the total absence of references to any of the features of energy or to the terminology associated with forms of energy, which is usually emphasized by conventional teaching of energy. Most of the remaining students provided irrelevant responses such as *"the drill will perforate a hole on the wall"* whereas only a small number of them explicitly referred to energy transfer.

After the implementation of the TLMs there was an interesting shift in students' responses. In seven cases (15%) students cited a sequence of objects involved in the energy transfer process and additionally indicated either one or more of the forms in which energy was stored during the operation of the two systems or the relevant energy transfer process. For instance, one of these students stated that *"Energy was transferred from the woman to the golf club and then from the club to the ball causing it to move (kinetic energy)"*. In five cases (10%) students constrained themselves to merely describing observations relevant to the two systems (e.g., *"the woman hit the ball and it started moving"*) and one student (2%) provided an energy-based interpretation for the change under consideration without explicitly mentioning any forms of energy or energy transfer processes (e.g., *"energy was transferred to the drill and it made it operate and perforate the hole on the wall"*). In the remaining 35 cases (73%) students attempted to provide an energy chain representing the changes under consideration (sixteen students, 67%, in the case of the first system and nineteen students, 79%, in the second system).

The responses of the students who pursued energy-based accounts were coded according to their accuracy and completeness. Specifically, each response was accorded one point for each component of the targeted energy chain (see figure 2) that was correctly identified and incorporated in the analysis (either the verbal account or the energy chain). Thus, the responses were coded into an ordinal scale with a maximum possible score of three, in cases when both forms of stored energy and also the corresponding energy transfer process were correctly identified and incorporated in the energy chain, and a minimum score of zero, in cases when none of these components was properly incorporated in the energy chain. Table 7 shows the distribution of students' responses across the four levels of this ordinal scale. It is interesting to note the significant percentage of students who attained the maximum score (38%[3] in the first system and 53% in the second) after the implementation of the TLMs. Table 8 shows three indicative energy chains. It is important to note that in

Table 7

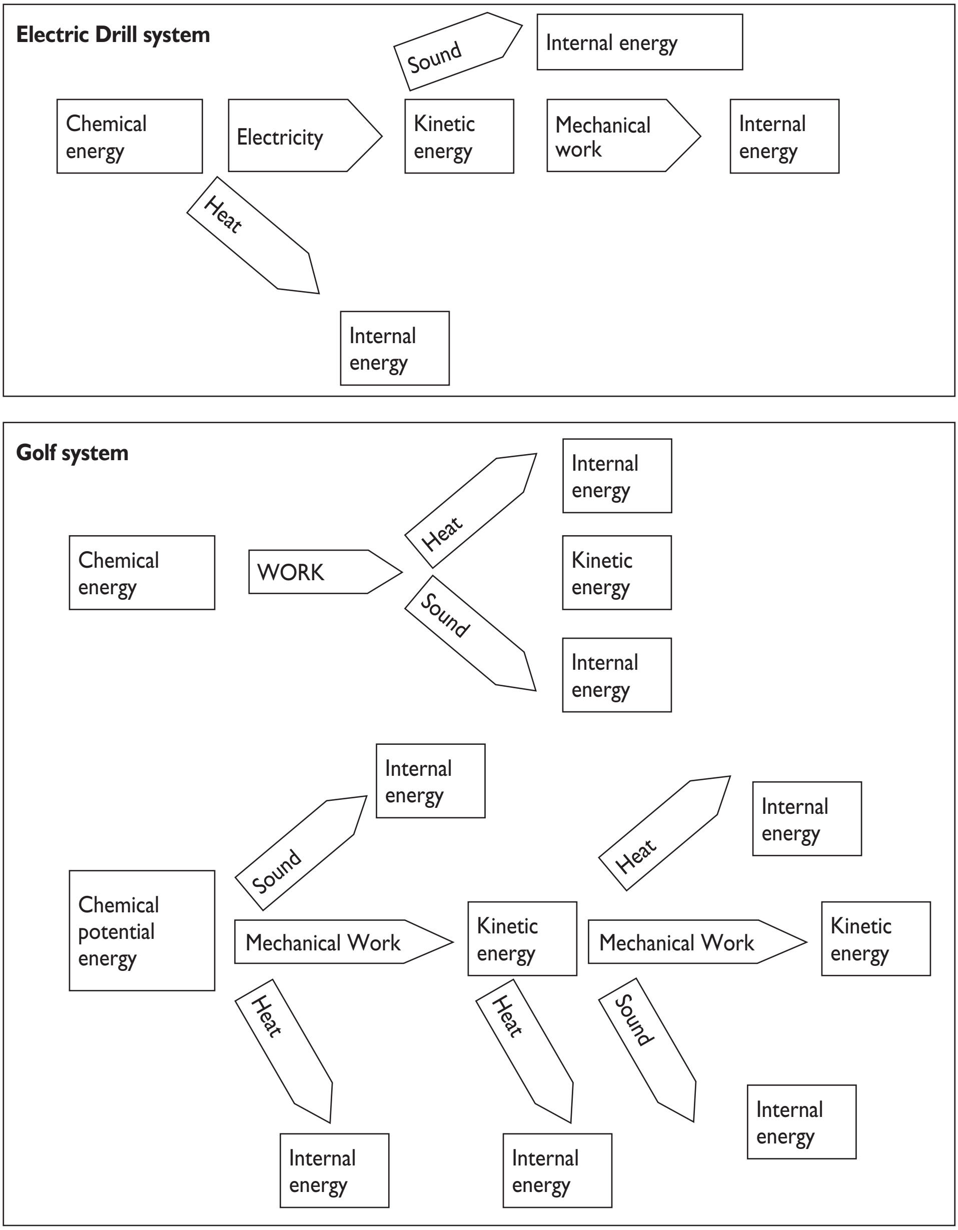
Correctness of students' energy chains for the two changes (post-test)

Number of components that were correctly identified and integrated in the proposed energy chains	First System		Second System	
	N	%	N	%
0	1	6	1	5
1	2	12	4	21
2	7	44	4	21
3	6	38	10	53

3 One point that should be noted, which might have perplexed the measurement in the case of the first system, relates to the difficulty associated with the identification of the power station as a part of the system and, hence, the recognition of the form in which energy was initially stored (chemical energy in the fuel-oxygen system).

TABLE 8

Examples of student generated energy chains



these cases, students went beyond the main change they were explicitly asked to account for and also incorporated further aspects of the systems. These examples could give a flavor of what could be achieved by students at this level in terms of energy-based system analysis.

One issue that needs to be noted pertains to the mismatch between the way students analyzed systems during the implementation of the TLMs, on the one hand, and the assessment, on the other. Specifically, for the most part of the teaching intervention students' attempt to construct energy chains was scaffolded by an electronic tool, which, as discussed earlier, significantly reduced the level of difficulty associated with analyzing system changes. During assessment, students were not scaffolded in any way. In view of this important deviation between these two situations and given that the two systems were not studied by students during the implementation of the TLMs, the relatively high percentage of students who were in a position to synthesize the appropriate forms of energy and energy transfer processes into coherent energy chains, provides a very encouraging indication as to the extent to which they were able to productively employ energy and its features for qualitative system analysis.

Concluding Remarks

This study has yielded promising results for the potential of the TLMs, and the underlying teaching approach, to promote students' understanding of energy. One of the main findings relates to the marked improvement in students' appreciation of the transphenomenological and unifying nature of energy. This is an important aspect of energy as a construct, which, however, is typically ignored by conventional teaching. Our data demonstrate that when this idea is addressed in an explicit manner students are likely to achieve significant learning gains. The available data also provided positive indications concerning students' ability to use energy and its features (energy transfer and form conversion, in particular) in a coherent manner for the (qualitative) analysis of system changes. As shown in the pre-test data, despite the emphasis given by conventional instruction to the ideas of forms of energy (and the corresponding technical terminology) (Millar, 2000), those were totally absent from students' responses. The emphasis placed by the TLMs on formulating a coherent structure for the introduction and elaboration of the features of energy in a manner that stresses their contribution to system analysis seems to have helped students to meaningfully employ them for deriving qualitative analysis of system changes.

One limitation of this study relates to the rather small size of the sample and also the characteristics of the students it comprised. Clearly, this limitation underscores the need for a wider implementation of the TLMs and a more extensive evaluation of student learning outcomes. However, this limitation notwithstanding, this empirical study has provided important findings, which should not be dismissed.

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