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# How Should Energy Be Defined Throughout Schooling?

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**Abstract** The question of how to teach energy has been renewed by recent studies focusing on the learning and teaching progressions for this concept. In this context, one question has been, for the most part, overlooked: how should energy be defined throughout schooling? This paper addresses this question in three steps. We first identify and discuss two main approaches in physics concerning the definition of energy, one claiming there is no satisfactory definition and taking conservation as a fundamental property, and the other based on Rankine's definition of energy as the capacity of a system to produce changes. We then present a study concerning how energy is actually defined throughout schooling in the case of France by analyzing national programs, physics textbooks, and the answers of teachers to a questionnaire. This study brings to light a consistency problem in the way energy is defined across school years: in primary school, an adapted version of Rankine's definition is introduced and conservation is ignored; in high school, conservation is introduced and Rankine's definition is ignored. Finally, we address this consistency problem by discussing possible teaching progressions. We argue in favor of the use of Rankine's definition throughout schooling: at primary school, it is a possible substitute to students' erroneous conceptions; at secondary school, it might help students become aware of the unifying role of energy and thereby overcome the compartmentalization problem.

**Keywords** Definition of energy · Teaching progression · Conservation of energy · Rankine

## Introduction

Energy is a fundamental concept of physics that enables the explanation and prediction of many phenomena and contributes to the unification of various branches of physics.

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For this reason, it can be considered one of the “big ideas” that should be taught in school (National Research Council 1996, Lee and Liu 2010; Eisenkraft et al. 2014). However, energy is also a difficult concept to understand and to master. It is highly abstract (Warren 1982; Millar 2005), and its meaning in physics differs from that found in everyday life (Solomon 1983; Lijnse 1990). There is a subtle distinction among sources, forms, and modes of transfer of energy (e.g., work and heat being occasionally mistaken as forms rather than modes of transfer of energy, see Cotignola et al., 2002, Jewett 2008b; Papadouris and Constantinou 2011). Energy must also not be confused with other closely related quantities such as force, temperature, power, and entropy. For example, force and energy are often confused (Watts 1983, Trellu and Toussaint, 1986), as are heat and temperature (Lewis and Linn 1994, Harrison et al. 1999). Finally, the concept is inseparable from the principle of energy conservation, and few students at the end of secondary school can apply this principle correctly (Duit 1981; Driver and Warrington 1985; Solomon 1985; Trumper 1990; Neumann et al. 2013). How energy should be taught, therefore, remains a topical question. Since the 1980s, many teaching strategies have been proposed and discussed (for an overview, see Millar 2005, Doménech et al. 2007, Bächtold & Guedj 2014).

More recently, it has been highlighted that students cannot learn about energy in one attempt but must follow several conceptual steps. Some authors have attempted to determine empirically students’ actual “learning progression” (i.e., the conceptual steps students are actually following across school years); in the light of these studies, these authors and others have also discussed what might be the most adequate teaching progression throughout schooling (i.e., what features of energy should be taught, and how, at each grade) (Liu and McKeough 2005; Lee and Liu 2010; Nordine et al. 2011; Colonnese et al. 2012; Neumann et al. 2013; Lacy et al. 2014; Duit 2014; Bächtold et al. 2014). There is an important question in this new context that has been minimally addressed to date (Colonnese et al. 2012; Bächtold et al. 2014): should teachers provide their students with a definition of energy, and, if so, what definition should they provide and at what level of the science curriculum should it be provided? This question is problematic insofar as the very question of how to define energy remains debated in the field of physics. Although the concept of energy is now used in all domains of physics, some physicists, following Feynman (1963), believe that “in physics today, we have no knowledge of what energy *is*” (4-2); thus, no satisfactory definition is available. However, this view is not endorsed by all physicists, and in the field of physics education, several approaches have been proposed concerning how energy could be defined (Lehavi et al. 2012). However, this question of the definition of energy has rarely been discussed from the perspective of a teaching progression for energy.

This paper addresses the question of how to define energy throughout schooling. First, we examine more carefully whether and how energy can be defined in the field of physics. Two main approaches are distinguished: the conservation approach and Rankine’s approach. Second, we present a study concerning how energy is actually defined throughout schooling (in the case of France) and whether either of the previously mentioned approaches are employed. This case study brings to light what we call the “consistency problem.” Finaly, we address the problem of consistency by investigating the way energy could be defined in a coherent manner across school years.

## What Does Physics Tell us About Energy?

Before studying how energy is or could be defined in school ("The Consistency Problem: a Case Study" and "Toward a Coherent Teaching Progression with Regard to Energy Definition" sections), it is useful to clarify what physics tells us about energy, i.e., how it can be described and defined.

### Nominal and Operational Definitions of Energy

To begin with, we can spell out the points of agreement concerning the description of energy in physics:

(1) Energy is a variable state quantity (i.e., a quantity associated with a physical system and determined by its state).
(2) In SI units, energy is measured in joules (J).
(3) There are different forms (or types) of energy (kinetic, potential, thermal, chemical…).
(4) Energy can be converted from one form into another.
(5) Energy can be transferred from one system to another.
(6) There are different means of transferring energy (work, thermal transfer, light…).
(7) Energy can be dissipated (or degraded).
(8) Energy is a conserved quantity (i.e., it can be neither created nor destroyed).

Two additional features of energy must be expressed in a negative manner:

(9) Energy cannot be directly measured (i.e., it can be evaluated only indirectly by means of the measurement of other quantities which arise in the mathematical formula of given forms of energy).
(10) There is no mathematical formula for energy in general (although formulas do exist for the different forms and modes of transfers of energy).

Finally, it must be stressed that a definition of energy, which was given by Rankine in the middle of the nineteenth century, is endorsed by some physicists but rejected by others:

(11) Energy is the capacity of a system to do work.

To clarify the status of the different points expressed above, we can make use of the distinction between "nominal" and "operational" definitions of physical concepts. This distinction was proposed by Margenau (1950) and expressed by Galili and Lehavi (2006) as follows:

> A nominal definition seeks to establish the meaning of a concept by relating it to other concepts and by listing its characteristic features; it matches theory. An operational definition, on the other hand, defines the concept in terms of a particular measurement, indicating the apparatus, the conditions of measurement, and possibly, also, the units. (p. 524)

In the case of energy, two points mentioned above, namely points 2 and 9, contribute to an operational definition of this concept. The other points can be related to its nominal definition.

Let us consider them one by one. Point 1 can be viewed as a nominal definition but as a relatively general one; it does not differentiate energy from other quantities because there are several variable state quantities. Points 3 to 8 correspond to a set of characteristic features of energy. Although they describe the properties of energy, they do not say what this quantity *is* or what it *represents*. In this respect, they do not constitute what we may call a "formal" nominal definition of energy. On the contrary, point 11 (Rankine's definition) is such a definition. However, this definition is controversial.

The disagreement on Rankine's definition is a strong one. This point leads us to distinguish two main approaches with respect to defining energy. Below, we present the various arguments in favor of and against each of them.

## Conservation as a Fundamental Property

A first approach supports the points that there is no satisfactory formal definition of energy and that we take conservation as a fundamental property. This approach is endorsed by Feynman (quoted above), in line with another famous scientist, Poincaré (1902), who claimed, "As we cannot give energy a general definition, the principle of conservation of energy simply means that there is *something* that remains constant."

Let us consider the statement "energy is what has the property of being conserved." This can be viewed as a nominal definition. However, is this definition sufficient? In spite of the fact that conservation is a fundamental property of energy, it is unable to differentiate it from other quantities. For example, linear momentum and angular momentum are also conserved quantities. Surprisingly, the fact that conservation is not a discriminating property has hardly been emphasized in the literature.

A possible means of discriminating energy from other conserved quantities is to specify the whole set of its properties, namely points 3 to 8. This set of properties constitutes a more complete nominal definition of energy and has the advantage of differentiating it from all other quantities. Nevertheless, it may still appear unsatisfactory insofar as it does not explain what this quantity is or what it represents.

## Rankine's Definition

The second approach to defining energy consists of making use of Rankine's (1855) definition of energy as the "capacity of a system to do work" (where "work" refers to the quantity defined in mechanics in terms of force and displacement of a system). Let us stress that this formal nominal definition was never fully accepted. Today, only one some of the academic textbooks in physics mention it. As an example, Hobson (2004) surveyed 22 introductory physics textbooks and found that 6 defined energy as the "capacity of a system to do work." During the last three decades, the relevance of this definition has been debated. Note that this debate has occurred in the physics education literature, and not merely in that of theoretical physics. Although the authors contributing to this debate are ultimately concerned with the question of how to make sense of energy to students, they have also discussed Rankine's definition from the point of view of physics. In the remainder of this section, we discuss this definition only from this point of view. We return in the "Option with Conservation and Rankine's Definition" section to the relevance of this definition to energy teaching.

According to Warren (1982, 1991), the notion of the form of energy and the conservation property have no meaning without the definition of energy as the capacity of a body for doing work. For instance, a system can be said to have kinetic energy equal to $\frac{1}{2}mv^2$ only if one conceives the possibility that this system can transfer energy to another system without dissipation *by means of work.* Indeed, the value $\frac{1}{2}mv^2$ is obtained by calculating the work produced by the system if brought to rest with respect to a given observer. Similarly, McIldowie (2004) argues,

> Energy and work form a duality. A *system* can be said to possess energy, and when energy is transferred, work is done. A true description of what goes on in any transfer of energy inevitably involves both concepts. […] All energy is potential work." (pp. 213–214) As Hobson (2004) writes, "Quantitatively, a system's energy is the amount of work it can do. (p. 260)

It must be emphasized that Rankine introduced his definition at the same time as he and Thomson proposed to explain the conversion processes in terms of energy transformation and conservation (i.e., in the 1850s). This historical context is significant. Indeed, Rankine's definition provided a simple justification for viewing different quantities, say *A* and *B*, as instances of the same quantity, as "forms of energy" (e.g., kinetic energy, thermal energy…): quantities *A* and *B* can be conceived as instances of the same quantity because some value *a* of *A* and some value *b* of *B* are equivalent with respect to the capacity of the systems under consideration to produce the same physical changes (e.g., the increase of temperature or the change in velocity of a body). Identifying these quantities as forms of energy in turn enabled describing the conversion processes as transformations of energy with the total amount of energy being conserved.

Sexl (1981), Duit (1981), and Trumper (1991) challenge Rankine's definition by claiming that it is refuted by the second law of thermodynamics. This argument is expressed by Sexl (1981) as follows: "The statement that 'energy describes the capacity of a system to perform work' is not satisfactory because it cannot be used in thermodynamics. Thus, the internal energy of a system cannot be transformed completely into work (p.287). Let us make the last step of this argument explicit: if the energy of a system cannot entirely be transformed into work, this energy cannot be equated with the work the system is actually able to produce.

Warren (1982) and Hobson (2004) both reply that Rankine's definition is not a claim that, *in all conditions*, the whole amount of energy of a system can be used to produce work. Indeed, this is not possible in cyclic processes. Rather, according to the second law of thermodynamics, this definition means that we can always imagine ideal conditions for which this is possible. As Hobson (2004) stresses, "The definition should be understood as referring to the amount of work a system *could* do under *ideal* conditions" (p. 260).

Another objection has been advanced by Duit (1981, 2014) concerning the scope of Rankine's definition: it is not sufficiently general in its reference to merely mechanical effects, i.e., effects in terms of work. According to Duit (1981),

> the energy concept as expressed in the above definition [i.e., Rankine's definition] is limited to mechanics. […] this energy concept does not possess universal validity (energy is not only the ability for doing work but also a precondition for many other processes such as heating, lighting etc.). (pp. 292–293)

A possible answer amounts to the claim that any type of effect in principle can be converted into a mechanical effect; hence, its value can be expressed in terms of work. There is another means of evading this objection, which consists of slightly modifying the definition, replacing "work" with "transformations" (Doménech et al. 2007) or "changes" (Bunge 2000; Bächtold & Guedj 2014)—these two terms being understood tacitly as referring to *physical* transformations and changes.

With respect to this definition in terms of "changes," energy acquires a very wide scope: it is applicable in all the domains of physics. As such, it is in accordance with the unifying role of energy, which contributed, in the middle of the nineteenth century, to making energy a fundamental concept in the field of physics. As emphasized by Harman (1982), "the fundamental status of energy is derived from its immutability and convertibility and from its unifying role in linking all physical phenomena within a web of energy transformations" (p. 58).

Against Rankine's definition in terms of "changes," Duit (1981) argues it is not able to distinguish energy from other quantities: "The ability to bring about changes can also justifiably be attributed to a number of other physical concepts (for example, force and torque)."

There is a possible answer to this argument. The physical changes associated with a force or a torque are simultaneous to their application, whereas the physical changes a system can produce by virtue of its energy are only potential. For instance, in some cases, if a force is applied on a body, the latter is set in motion. The application of the force does not endow the body with some capacity to move, it makes it move at the very time it is applied. Therefore, only energy can be said, strictly speaking, to describe the "capacity" or "ability" of the system to produce physical changes.

More recently, Coelho (2014) has stated another argument against Rankine's definition of energy as "the capacity of doing work." According to him, the problem with this definition is that it leads to a substantialist conception of energy:

> Another common definition of energy in textbooks is 'energy is the capacity of doing work.' The subject of the previous sentence is energy. Therefore, energy has this ability. If this is the case, then energy must be something real. So real, that it is able to act, namely to do work. (p1362)

This last objection can be addressed by answering that Coelho misinterprets the sentence "energy is the capacity of doing work" by changing it into the sentence, "energy *has* the capacity of doing work." Now, the sentence "energy is the capacity of doing work" should be considered a shortened version of "energy is the capacity *of a system* to do work." The definition expressed in this manner does not compel us to hypostatize energy; rather, it describes this quantity as the property of a system, and only the system is *something* able to do work.

## Discussion

Thus far, we have distinguished two main approaches with respect to the definition of energy: the conservation approach and Rankine's approach. While both approaches have been subject to various objections in the literature, the second one was argued to have more advantages. Let us recall that the conservation approach faces a major problem: conservation is not a discriminating property (i.e., other quantities are also conserved). As for Rankine's definition, it offers a way to grasp the meaning of energy: it helps to understand what makes it different from other conserved quantities and provides a justification for viewing the different quantities as being instances of the same quantity, as being "forms of energy." Moreover, this definition has a very wide scope, making it valid in all the domains of physics, in accordance with the unifying role of energy. Furthermore, it appears that all the objections against Rankine's definition can be challenged. The advantages of this definition may provide arguments in favor of introducing it at school in the frame of energy teaching. Before considering these arguments ("Toward a Coherent Teaching Progression with Regard to Energy" section), let us turn to what is currently done at school.

## The Consistency Problem: a Case Study

The question of how to define energy throughout schooling has received little attention so far. No clear proposal has been made in the science education literature. It is therefore likely that the authors of national programs as well as teachers do not consider this question. Given that the very definition of energy is debated in the field of physics, one can expect that there is no consistency in the way energy is defined across years of instruction. This might cause difficulties for students in their learning of energy—an aspect that, to date, has not been stressed in the literature. So as to better understand what we shall call the "consistency problem," it would be helpful to know how energy is actually defined throughout schooling. Is either of the two above approaches favored in school? If so, is this the case across grade levels? Or is there a change of approach depending on the grade? We examined these questions by carrying out a survey in one country, namely France. One reason for this choice is that the French middle school program makes an explicit reference to Rankine's definition.

### Method, Part 1

We examined the French national programs from grades 3 to 12. It must be stressed that teachers in France are compelled to follow the programs precisely. Although they have some capacity to choose their pedagogical methods, they officially have no freedom to change either the content to be taught or the teaching progression described in the programs. Therefore, the analysis of these programs provides us with an insight concerning how energy is defined throughout schooling in France. We also examined a selection of physics textbooks from grades 3 to 12 (extending the study presented in Bächtold et al. 2014). These textbooks suggest a variety of possible approaches to interpreting the programs by giving specific formulations of the items of the programs and additional content. These formulations correspond to possible ways teachers themselves interpret and implement the programs. Moreover, being read and used by teachers, the textbooks influence teachers' approaches to teaching. Hence, analyzing these textbooks provides a complementary insight into how energy is actually defined across years of instruction.

Our analysis consisted of searching for occurrences of formal definitions of energy and also for statements referring to the various features of energy, thereby providing an indirect definition of energy. We checked systematically if there were statements in line with Rankine's definition and formulations of the conservation property. We characterized these definitions as being either nominal or operational. We also made use of one subcategory of nominal definitions, namely "lexical definitions," which are described by Galili and Lehavi (2006) as including "figurative statements, 'non-formal terms', […] casual expressions only vaguely related to theory [and] concepts […] related to common experiences, sensations, or ideas" (pp. 525–526).

**Table 1** Definitions of energy provided by the French national programs and a selection of textbooks

| | French national programs | Physics textbooks ($N = 28$) |
|---|---|---|
| Grades 3 to 5 | No formal definition, but the following statement:<br>"The use of an energy source is necessary to heat, to light, to set in motion."<br>Conservation of energy is not mentioned. | ($N = 8$)<br>5 textbooks out of 8 provide a definition:<br>"Energy is what enables to heat (calorific energy), to produce light (luminous energy), to produce electricity (electrical energy) and to set in motion (mechanical energy)"<br>"Energy: possibility for matter or an object to provide heat, light or motion"<br>"Energy makes it possible for an object to set itself in motion, to produce light or heat."<br>"Energy can modify the state of things, make them change their shape, make them move, or make them work."<br>"Every object of our everyday environment needs energy to work […] energy can be used to light (lamp), to set in motion (car, train, boat), to move, to heat (fire, radiator), to communicate (phone)."<br>No textbook mentions conservation of energy. |
| Grades 6 to 9 | Two definitions are provided in the introduction of the physics and chemistry programs (grades 6 to 9):<br>"Energy appears as the capacity of a system to produce an effect."<br>"The energy possessed by a system is a quantity which characterizes its ability to produce actions."<br>Conservation of energy is not mentioned. | Grades 7 and 8 ($N = 3$)<br>1 textbook out of 3 provides a definition:<br>"Energy: an object has energy if it can produce actions or effects."<br>No textbook mentions conservation of energy.<br>Grade 9 ($N = 7$)<br>2 textbooks out of 7 provide a definition:<br>"Scientists define energy as the capacity to produce work" (definition of 'work' is provided in this textbook).<br>"Energy: physical quantity which is conserved. An object which has energy can produce actions: heat, light, set in motion, etc."<br>3 textbooks out of 7 mention conservation of energy:<br>"Energy: physical quantity which is conserved."<br>"The most remarkable characteristic of energy is that is it always conserved."<br>"Energy can neither be created nor lost. Energy is conserved." |
| Grade 11<br>Scientific pathway<br>(Note: around half of students at high school follow this particular pathway) | No definition.<br>An item of the program:<br>"Principle of conservation of energy" | ($N = 5$)<br>4 textbooks out of 5 provide a definition, but each is different:<br>- "Energy is a quantity characterizing the capacity of a system to modify its state, its position or its motion."<br>- "To each system, one can associate a quantity called energy which can take different forms: mechanical (kinetic or |

**Table 1** (continued)

| | French national programs | Physics textbooks ($N = 28$) |
|---|---|---|
| | | potential), chemical, nuclear, electrical, etc."<br>- "[Energy has the following] essential properties […]: It can be stored […] it can be transferred […] it is conserved."<br>- "Energy describes the state of a system under the action of one or several of the four fundamental interactions."<br>The principle of conservation of energy is expressed in every textbook. |
| Grade 12<br>Scientific pathway | No definition<br>Conservation of energy is not mentioned. | (N = 5)<br>No textbook provides a definition.<br>1 textbook out of 5 mentions conservation of energy:<br>"The total energy of an isolated system is conserved." |

The parentheses "(…)" are those of the original author, whereas the square brackets "[…]" are ours

## Outcomes, Part 1

We present in Table 1 the definitions of energy provided by the French national programs from grades 3 to 12 and a selection of physics textbooks ($N = 28$, see references in Appendix 1). We also report the cases in which conservation of energy is mentioned. Note that energy is not mentioned in the programs of physics and chemistry in grades 6 and 10 and that energy is only a secondary item in those of grades 7 and 8. As no differences were found with respect to the definition of energy and conservation of energy for grades 3 to 5 and for grades 7 and 8, the outcomes concerning these grades are presented in a single line of the table of Table 1.

A primary school level (grades 3 to 5), the majority of textbooks provide a definition of energy corresponding to an adaptation of Rankine's definition in terms of "changes." These definitions can be considered lexical definitions. They are partly in line with a sentence that can be found in the national programs, which nonetheless refers to "energy source" rather than to "energy." Some of them retain the notion of capacity (e.g., "possibility," "makes it possible"); the others remove this element of Rankine's definition. Note that one definition is reifying energy by making it the subject of actions ("energy can modify the state of things…"). This definition, disputed by Coelho, is in fact a fallacious transformation of Rankine's original definition (see above, "Rankine's Definition" section). The conservation of energy is mentioned by neither the national program nor the textbooks.

At middle school level (i.e., grades 7 to 9), the national programs introduce Rankine's definition in terms of "changes" (using the expressions "effects" or "actions" rather than "changes"). A few textbooks follow the program in this respect and provide this definition or an adaptation of it. Although there is no reference to conservation of energy in the national programs in these grades, some textbooks take the initiative to mention this property and present it as fundamental.

At high school level (grades 11 and 12), the national programs do not refer to Rankine's definition or to any other definition of energy. Nonetheless, in grade 11, most of the textbooks provide a nominal definition. The proposed definitions are of various types: Rankine's definition, but also definitions in terms of the properties of energy and a definition referring to the fundamental forces of physics. The fact that these textbooks propose a nominal definition may be explained by the fact that energy is presented as a key concept in the national program of physics and chemistry in this grade. In grade 12, none of the textbooks we examined provided a definition.

The principle of energy conservation is central in grade 11, both in the national program and in the textbooks. However, no further reference is made to this principle in grade 12. Few textbooks present conservation as the fundamental property of energy.

## Method, Part 2

Our goal being to obtain a quantitatively significant picture of how energy is actually defined in school, we chose to make use of a questionnaire. To build a meaningful questionnaire, we attempted to anticipate the possible practice of the teachers concerning the definition of energy. Therefore, the questionnaire was built by taking into account how energy is actually defined in the French national programs and the selected physics textbooks. It consisted of a few questions focused on how teachers define energy in the frame of their teaching and their reasons for doing so. Two versions of the questionnaire were produced: one suited for primary teachers, the other for secondary teachers (see Appendix 2). It is important to stress that in France, secondary teachers in physics and chemistry have undergraduate training in science before being trained on science teaching methods, contrary to most primary teachers.

In both versions, the first question (labelled Q1 for primary teachers/Q*1 for secondary teachers) was open and general: "How do you describe energy to your students when teaching this concept?" Teachers had no access to the other questions and accordingly could not be influenced by the information they contain concerning the definition of energy and the property of conservation. In this first question, we chose not to ask expressly for a definition of energy so as to see what teachers were answering spontaneously: they were free to provide a formal definition, and/or a description of the properties of energy, and/or to mention how it may be measured, its unit, and so on. We considered that what they spontaneously mentioned in their answers to this first question are important features of energy according to the teachers. When analyzing their answers, we identified whether they spontaneously expressed:

- a nominal definition of energy, and especially a definition in line with Rankine;
- an operational definition of energy (i.e., reference to the way energy is measured, to its units);
- the conservation of energy;
- some difficulty in defining energy.

The other questions were closed-ended. We asked explicitly whether they make use of a definition in line with Rankine (without mentioning the name "Rankine," which is probably not known by most teachers) (Q2/Q*2) and whether they tell their students that energy is a conserved quantity (Q5/Q*6). In the case of a positive answer to these questions, we wanted to know if teachers consider them important and useful elements of the description of energy in their teaching. We avoided asking this directly using a question such as "Is it an important feature of energy in your teaching?" with a Likert scale, because the word "important" is rather subjective. Instead, to investigate this aspect, we asked if these are features of energy their "students must write down in their science (resp. physics and chemistry) notebooks and must memorize" or "which [they] provide to [their] students only in discussion and which they do not need necessarily to memorize" (Q3/Q*3). They could also provide their own answer.

In the case of a negative answer to these questions, we wanted to know the teachers' reasons for not introducing these features. When asking them why they do not introduce a definition of energy in line with Rankine (Q4/Q*5), we anticipated possible reasons (partly based on the literature): "it does not help students to understand what energy is," "it is too abstract," and "you did not know this definition." They could also provide their own answer. When asking them why they do not introduce the conservation of energy (Q7/Q*8), we anticipated other possible reasons (also partly based on the literature): "students cannot understand it," "it is not an item of the program" (in the case of primary school and grades 7 to 9), "you did not know this property" (in the case of primary teachers) or "there are many items in the program and it is not a priority to discuss this property" (in the case of secondary teachers). Again, they could also provide their own answer.

## Outcomes, Part 2

The questionnaire was submitted electronically to primary teachers and secondary teachers of physics and chemistry throughout France. In the case of the primary teachers, the questionnaire was submitted through the intermediary of school inspectors in 12 regional education authorities to an indeterminate number of schools. The number of answers was $N = 61$. Note that, in practice, energy is not taught by all teachers; those who answered this questionnaire may be only those who actually teach energy. In the case of the secondary teachers, the questionnaire was submitted by means of a mailing list with about 1500 subscribers. The number of responses was $N = 116$ (32 teaching grades 7 to 9 and 84 teaching grades 11 and 12).

The answers were gathered automatically by means of the software used to submit the questions and transferred into a spreadsheet. The free-choice answers to the first open question were analyzed manually according to the grid presented in the "Method, Part 2" section, while the answers to the closed-ended questions were processed so as to yield percentages.

Let us consider first the answers of the primary teachers. When asked whether they provide their students with an adapted version of Rankine's definition, i.e., "energy is what is necessary to heat, to light, to set in motion" (Q2), 90 % answer "yes." Among those answering "yes," a majority consider it an important element of the description of energy to provide in primary school: 54.5 % of these teachers ask their students to write it down in their science notebooks and to memorize it; the others only mention it in discussion. When analyzing their answers to the first open question (Q1), we observed that 42 % of the teachers spontaneously provided a nominal definition in line with Rankine's definition and said that they introduce it in their teaching of energy (see examples in Table 2). When expressing this definition, few of them mentioned the notion of capacity or the system with which energy is associated. Among the teachers who answered that they do not provide their students with an adapted version of Rankine's definition, one third considered it too abstract, one third considered that it does not help students to understand what energy is, and the remaining one third did not know this definition.

When asked whether they tell their students that energy is conserved (Q5), 29.5 % of the primary teachers answer "yes." Remember that energy conservation is not an item of the primary school programs. Among those answering "yes," a minority consider it an important

**Table 2** Selection of some teachers, answers to the open question asking for a description of energy

Open question: How do you describe energy to your students when teaching this concept?

| Answers of primary teachers (extracts) | Answers of secondary teachers of physics and chemistry (extracts) |
|---|---|
| Adapted versions of Rankine's definition:<br>"Energy is necessary in order to move, to heat, to light"<br>"Energy is the source of motion, heat or light"<br>"'Element' which enables the producing of motion, heat, light."<br>"That which enables producing work"<br>"Possibility (invisible capacity) of a system to produce work (a force?) that enables moving, transforming itself, to create heat, light, electricity" | Rankine's definition or adapted versions of it:<br>"Capacity of a system to cause moving, deformation, or to produce light or heat"<br>"Quantity which enables quantifying the capacity of a system to move, to heat, to radiate"<br>"A body has energy if it can produce work"<br>"Ability to produce an effect such as to lift or to accelerate an object, to increase the temperature, to make electricity flow…" |
| Conservation of energy:<br>No teacher spontaneously referred to conservation. | Conservation of energy:<br>"A physical quantity which is conserved"<br>"A physical quantity for which one cannot give a definition, but which is always conserved on condition that the system is correctly defined"<br>"As Lavoisier tells it, which can be applied to the principle of energy conservation: 'Nothing is lost, nothing is created, all is transforming'" |
| | Energy defined as belonging to the field of mechanics, in relation to work (without being associated with Rankine's definition):<br>"It is the work of a force"<br>"Energy is all that is related to mechanical work"<br>"In relation to the notion of work" |
| Other types of description or definition:<br>"I describe it in terms of energy being renewable or not, of transformations, of pollution"<br>"Tool for comfort"<br>"These are the elements which enable living or non living beings (machines) to work"<br>"Energy is something which allows motion"<br>Non-scientific definitions of energy:<br>"Energy is a force which enables to obtain light or sound"<br>"It is a force which enables to move, to transform, to produce something"<br>"Energy is a type of 'fuel' which allows a set in motion, an action" | Other types of description or definition:<br>"A 'thing' associated with an object, which it can exchange, accumulate, lose…"<br>"Quantity [which is] the product of power x time"<br>"Something which always changes its form"<br>"Something which is exchanged"<br>"It is a quantity which enables quantifying the motion, the position or the state of a system"<br>"Energy is not an object. Energy is an abstract concept created by scientists to describe various situations." |
| Energy is difficult to describe:<br>"I do not address this topic because I do not have enough knowledge"<br>"I do not describe it, there are several energies. Fossil, renewable, natural, artificial…" | Energy is difficult to describe/define or cannot be described/defined:<br>"It is very complicated to define"<br>"Energy is a concept and therefore cannot be 'described'"<br>"I do not discuss energy in general, but tackle along the program the energies related to motion, to electrical current, to nuclear reactions…"<br>"As varied as there are forms of energy. No definition of energy 'alone'" |

element of the description of energy: only 27 % of these teachers ask their students to write it down in their science notebooks and to memorize it, whereas the majority only mention it in discussion. When analyzing their answers to the first open question (Q1), we observed that none of the primary teachers spontaneously mentioned conservation of energy as being part of their description of energy in their teaching. Among the teachers who answered that they do not mention it to their students, 37 % argued that it is beyond the scope of primary students, 28 % answered that it is not an item of the primary school program, and 44 % admitted that they did not know this property.

Moreover, in their answers to the first open question (Q1), no primary teacher provided an operational definition of energy; there was no reference to the fact that energy can be measured only indirectly and no mention of the unit of energy. However, some teachers proposed nominal definitions of energy that were not in full agreement with the scientific concept; some confused energy with force or power or described it as a type of fuel (which may correspond to a chosen teaching strategy, i.e., describing energy as a quasi-material substance, see Duit 1987). Some teachers answered that energy is difficult to describe (see examples in Table 2).

Let us turn now to the answers of the secondary teachers. When asked whether they provide their students Rankine's definition in terms of changes (Q*2), 26 % answered "yes" (37.5 % in middle school, 21 % in high school). Among those answering "yes," a minority considered Rankine's definition an important element of the description of energy, whereas 67 % only mention it in discussion without necessarily expecting their students to memorize it. When analyzing the secondary teachers' answers to the first open question (Q*1), we observed that 43 % of these teachers spontaneously mentioned Rankine's definition as being part of their description of energy in their teaching (see examples in Table 2). A majority of them expressed the definition in terms of "changes," whereas the others expressed it in terms of "work." Most of the teachers providing Rankine's definition answered that they take time in their teaching to discuss its meaning, either by providing examples of "effects" a system can produce by virtue of its energy (83 %) and/or by explaining that the term "capacity" means that these "effects" are only potential or possible (43 %). Among the teachers who answered that they do not provide their students with Rankine's definition, 53 % considered it too abstract, 40 % believed that it does not help students to understand what energy is, and 39 % did not know this definition.

When asked whether they tell their students that energy is conserved (Q*6), 94 % of the secondary teachers answered "yes" (without a significant difference between middle and high school teachers). Remember that energy conservation is not an item of the middle school programs. Among those answering "yes," a majority considered it an important element of the description of energy to provide in secondary school: 81.5 % of these teachers ask their students to write it down in their physics and chemistry notebooks and to memorize it, whereas the others only mention it in discussion. However, when analyzing their answers to the first open question (Q*1), we observed that only 21 % of these teachers (without a significant difference between middle and high school teachers) spontaneously mentioned conservation of energy as being part of their description of energy in their teaching (see examples in Table 2).

Moreover, in their answers to the first open question (Q*1), few secondary teachers (7 %) provided an operational definition of energy by referring to the fact that energy can be measured only indirectly and/or by mentioning the unit of energy.

Finally, some secondary teachers answered that energy is difficult to define or cannot be defined. Several teachers explained that they do not define it, but only introduce the forms of energy in different parts of the program (see examples in Table 2).

### Discussion of the Outcomes

As expected, this survey shows a lack of consistency in the way energy is defined throughout schooling. More precisely, the outcomes reveal trends with respect to the approach being favored. At primary school, Rankine’s approach (which consists of providing Rankine’s definition or an adaptation of it) is favored by the programs, by most of the textbooks and by most of the teachers. At middle school, Rankine’s approach remains favored by the programs, but only some textbooks and some teachers are following the programs; other textbooks and teachers favor the conservation approach (which amounts to emphasizing merely the conservation property), although conservation is not an item of the programs. At high school, Rankine’s definition is mentioned neither by the programs nor by the textbooks, but some teachers nonetheless make use of it. In grade 11, the conservation approach is favored by the programs, the textbooks and a majority of teachers.

In brief, in the early grades, an adapted version of Rankine’s definition is provided to students and conservation is ignored, while in the higher grades, conservation is put forward and Rankine’s definition is ignored. We can observe here a lack of “curricular coherence” (Fortus et al. 2015, p. 2) with respect to the question of how to define energy: the definition of energy is not “built incrementally” (ibid.); energy is not given a more sophisticated definition across school years (for instance, first Rankine’s definition, then Rankine’s definition *and* conservation); rather, students are taught a different definition (i.e., first Rankine’s definition, then conservation). It is likely that this lack of consistency causes difficulties to students and hinders their understanding of energy.

The lack of curricular coherence may be avoided if the authors of the national programs are the same for all the grades. This seems to be the case, for instance, with the US Next Generation Science Standards (NGSS Lead States 2013), which describe the teaching progression for “disciplinary core ideas” including energy, from kindergarten to high school. Nevertheless, this document neither provides a formal nominal definition of energy, at any grade (the item called “definitions of energy” referring to the definitions of the various forms of energy and not to a general definition of energy), nor does it indicate explicitly that such a definition should be excluded. Accordingly, nothing prevents some textbooks and teachers at some grades from introducing a nominal definition of energy. Without a strong commitment of the national programs to a specific teaching progression regarding the definition of energy, curricular coherence will be difficult to secure.

## Toward a Coherent Teaching Progression with Regard to Defining Energy

We propose to address this consistency problem by investigating the way energy could be defined in a coherent manner across school years. Given the fact that conservation is a fundamental property of energy we exclude the option of a teaching progression putting aside this property. Broadly speaking, two main options remain possible: one that focuses on conservation and does not introduce Rankine’s definition, and another that introduces both Rankine’s definition and conservation. Let us discuss the advantages and disadvantages of each.

## Option with Conservation Only

Consider first a teaching progression stressing conservation and ignoring Rankine's definition. It is important to recall that the principle of energy conservation is very difficult for students to master (as noted in several studies: Duit 1981; Driver and Warrington 1985; Solomon 1985; Trumper 1990; Neumann et al. 2013). Why is this the case? Several explanations have been advanced. First, the everyday meaning of the concept of energy appears to be in contradiction with the idea of conservation. In everyday life, the energy used to make an object work (e.g., a lamp or a car) seems to vanish; in everyday language, energy refers to something which can be "produced" and "consumed" (Duit 1981; Lijnse 1990; Solomon 1983, 1985, Vince and Tiberghien 2012, Bächtold & Munier 2014). Hence, students face two different ways to think about the term "energy." Second, fully understanding energy conservation requires the integration of many other ideas (Lee and Liu 2010). These ideas include not only the transformation and transfer of energy but its of dissipation (Duit 1984; Solomon 1985; Goldring and Osborne 1994; Neumann et al. 2013; Duit 2014; Lacy et al. 2014) and the distinction between the system under study and its environment (Trellu and Toussaint 1986; Arons 1999; van Huis and van den Berg 1993; Jewett 2008a). Third, according to some authors, mastering the principle of energy conservation implies also mastering mathematical equations (e.g., Warren 1982, 1991).

How should these challenges be considered? At least three sub-options are conceivable within the frame of the conservation approach. The first one amounts to deferring teaching energy until after secondary school (or even after high school). This is the option supported by Warren (1982, 1991), who argues that the concept should be taught only when students have mastered the mathematical tools that allow them to apply the principle of conservation of energy. However, this option to negate the very idea of a teaching progression for energy. Moreover, it allows students' misconceptions to and become ingrained, being unchallenged at an earlier age.

The second option consists of developing a teaching progression for energy that postpones the study of the principle of conservation to the end of this progression. This is the option favored more recently by Neumann et al. (2013). First, teaching should focus on the sources and forms of energy (and avoid confusion between both features), followed by ideas of transformation and transfer of energy, and then the ideas of dissipation and conservation should be taught. However, such a teaching progression faces at least three problems. First, if no formal definition of energy is provided to students, they may rely on their initial conceptions, which are therefore more likely to persist. Recall that most initial conceptions of energy are in disagreement with the scientific concept and, in particular, with the conservation principle (Watts 1983; Duit 1984; Gilbert and Pope 1986; Trumper 1993). Second, according to the teaching progression suggested by Neumann and his colleagues, the forms of energy should be taught before the notion of transformation and hence, in a first step, independently of it. The intention of these authors is understandable; they propose to deconstruct the conceptual system associated with energy, which is very complex, and to teach its elements step by step. However, to describe phenomena in terms of "forms of energy" without considering the transformations of these forms of energy seems to be problematic; doing so does not help to explain or predict phenomena. In the history of the concept of energy, physicists did not first identify various forms of energy and then discover possible transformations of them. Instead, they first observed processes connecting different types of phenomena (e.g., electricity and movement, or movement and heat), viewing them as "conversion processes." They then attempted to make sense of such processes in terms of the transformation of a quantity conserved during these conversions, named "energy" (Kuhn 1959; Elkana 1974; Harman 1982; Smith 2003). To avoid this problem, an alternative teaching progression could consist of introducing both notions of form and transformation of energy from the beginning. This is what Colonnese et al. (2012) proposed in their teaching progression from primary to secondary school. Finally, Neumann and his colleagues face a third problem: according to their teaching progression, the fundamental feature of energy, namely its conservation, is only introduced at the end. Consequently, until the last part of schooling, students must make use of energy without being told of the feature supposed to give meaning to the concept.

A third option within the frame of the conservation approach, which avoid the last problem, amounts to introducing the conservation property in primary school but qualitatively. This is the option supported by Colonnese et al. (2012), who argue it is important, at this level, to "lay the groundwork for a more quantitative treatment of energy in later studies in middle and high school" (p. 27). This option is also favored by Lacy et al. (2014), who contend that conservation is at the core of the "energy lens," that is, the lens through which scientists examine phenomena and that students must integrate. Recall that the empirical study presented in "The Consistency Problem: a Case Study" section highlights that some primary teachers (29.5 % in our study) do indeed choose to hint at the conservation property to their students. Nevertheless, a problem with this option is that understanding the notion of conservation implies understanding a whole set of other notions, as stressed above, which makes the learning task very ambitious for young students, even in the frame of a qualitative approach. In line with this view, 37 % of the primary teachers of our study who do not introduce conservation consider it to be beyond the scope of their students.

## Option with Conservation and Rankine's Definition

Let us turn now to a teaching progression introducing both conservation and Rankine's definition. More specifically a coherent teaching progression with respect to the definition of energy could consist of introducing Rankine's definition at primary school, making use of it throughout, and introducing conservation in the second or last part of schooling. For reasons discussed in the "Rankine's Definition" section, we will consider here Rankine's definition in terms of "changes" (rather than in terms of "work"). The formulation of this definition could be adapted and become more sophisticated across grade levels.

What are the advantages of providing students with Rankine's definition throughout schooling? At the early grades, students often have conceptions of energy that are scientifically incorrect (as mentioned above). Explaining to them that their conceptions are incorrect (e.g., energy is not a substance, energy is not a force…) without proposing another one is unlikely to be sufficient to help them modify these initial conceptions. In this respect, introducing Rankine's definition in an adapted manner can be very helpful as a possible substitute to students' erroneous conceptions. Note that Liu and McKeough (2005) have performed an empirical study showing that students can develop an understanding of such a definition at grades 3 and 4.

At high school, when no formal definition of energy is given to students, most of them tend to conceive energy only in relation to one domain of physics, for instance, as a type of force (in relation to mechanics) or as molecular agitation (in relation to the study of heat) (Bächtold & Munier 2014). This leads to the "compartmentalization" problem (Papadouris and Constantinou 2016, see also Jewett 2008c): students may consider that energy is a quantity relevant only in one domain (e.g., mechanics) and be unaware of the unifying role of energy (see "Discussion" section). One possible consequence is that students confuse the principle of energy conservation with the conservation of mechanical energy (which holds only in the specific case of the absence of friction) and therefore not apply the principle correctly

(Bächtold & Munier 2014). A means to avoid the compartmentalization problem and its consequences is to make use of Rankine's definition. As stressed in the "Rankine's Definition" section, this definition has a very wide scope: it can be applied across all domains of physics. Indeed, the physical changes a system can produce by virtue of its energy can be, for instance, variation of its speed, emission of light, variation of the temperature of a body, change in its physical state, or a mechanical deformation. Considering this definition and studying its meaning might help students become aware of the unifying role of energy. However, there is also a disadvantage in the fact that Rankine's definition in terms of "changes" is a general definition: it may appear very abstract to students. Recall that this is the main reason why the majority of secondary teachers in our case study do not make use of this definition. The three notions involved in Rankine's definition—change, system, and capacity—might all contribute to its abstractness. Let us consider them one by one and discuss possible strategies for avoiding the abstractness for which they are responsible. The notion of change is itself very general. One can think of two strategies to make this notion less abstract. First, teachers should not provide their students with the definition of energy as "the capacity of a system to produce changes" without giving them various examples of changes. In fact, according to our case study, most teachers introducing Rankine's definition in secondary school provide students with examples of changes. Another possibility amounts to simply avoiding use of the word "change" and just providing a list of examples of changes. Perhaps this second solution is best suited for students in primary school, whereas the first option is preferable for students in secondary school. Note that the textbooks and teachers' answers analyzed in our case study are consistent with such a progression.

The notion of system is also an abstraction, requiring one to mentally isolate a part of the physical world to model its properties and the relationships with its environment. A teaching progression with respect to this notion is also conceivable. The word "system" could be included in Rankine's definition only in a second step, in secondary school. In a first step, in primary school, the word "system" could be avoided. Two options remain possible. The very notion of system (and not only the word "system") could be set aside (e.g., "Energy is what is needed to set in motion, to heat, or to light"). Alternatively, teachers could express the definition for specific cases of systems that are well known by the students (e.g., "A lamp needs energy to light").

Finally, the notion of capacity is perhaps the most abstract and the most difficult for students to understand: to say that energy is the *capacity* of a system to produce changes means that it is a "potential" property (McIldowie 2004). In other words, it refers to changes which *could* be produced under certain conditions. If the term "capacity" is used, it seems important to discuss with students what it means. According to our study, almost half of the secondary teachers using the word when they introduce Rankine's definition explain the meaning of the term "capacity." In at primary school level, the term "capacity" is most likely too difficult to understand even when explained by teachers. A means to avoid using the term "capacity" without misrepresenting Rankine's definition, teachers could use the word "allow:" "Energy is what allows something to make changes. For example, energy is what allows a car to move motion, a radiator to heat, or a lamp to light." At secondary school level, when the notion of system has been introduced, the following definition can be given: "Energy is what makes a system able to produce physical changes, such as setting in motion, heating or lighting."

In this teaching progression, the principle of energy conservation is not ruled out. One can well consider that both Rankine's definition and energy conservation are essential features of the teaching of energy. The discussion in the "Option With Conservation Only" section suggests that the property of conservation should be introduced either in middle or high school: students must have already acquired knowledge concerning the forms of energy (to be distinguished from the sources of energy), transformations and transfers of energy (to be distinguished from forms of energy), as well as an understanding of the system/environment distinction, and their "cognitive maturation" (Liu and McKeough 2005) must enable them to combine all these features of energy and to make use of mathematical equations. Rankine's definition of energy can be useful at this point. As stressed above, it may help students become aware of the unifying role of energy and consequently apply more correctly the principle of energy conservation: by not reducing it to the conservation of mechanical energy and by taking into account all the forms and transfers of energy in a given situation.

## Conclusion

In this paper, we first examined what physics can tell us about the question of how to define energy. We identified and discussed two main approaches: the conservation approach and Rankine's approach. We then investigated if one or both of these approaches is actually endorsed in schools in the case of France. This study brought to light a consistency problem in the way energy is defined across school years. At primary school level, in accordance with the French national programs, most teachers introduce an adapted version of Rankine's definition but not conservation. At high school, it is the other way round: still in accordance with the national programs, most teachers introduce conservation and ignore Rankine's definition.

This study was carried out using a questionnaire. There might be some discrepancy between what teachers answered and their actual teaching practices. So as to get a more detailed and accurate picture of how energy is defined in schools, we could undertake classroom observations at all the grades and look at what teachers are actually telling their students. However, there would be the practical problem of making such observations in a sufficiently significant number of classrooms. In addition, our case study represents only one country. A similar study could be performed in various countries in order to determine the extent of the consistency problem.

In the last part of the paper, we addressed the consistency problem by discussing two ways energy could be defined throughout schooling: one that focuses on conservation and does not introduce Rankine's definition, and another that introduces both Rankine's definition and conservation. We stressed that a problem with the conservation approach is that it leaves students without any formal definition of energy, which can lead them to rely on their initial, erroneous conceptions. We therefore argued for the second option. At the primary school level, an adapted version of Rankine's definition offers a possible substitute to students' erroneous conceptions. At the secondary school level, this definition can help students become aware of the unifying role of energy and thereby overcome the compartmentalization problem, which may hinder the proper application of the principle of energy conservation.

Finally, the main recommendation made in this paper, at variance with the French national programs and teachers' declared practice, is to make use of Rankine's definition in secondary schools, especially high school. Although we made several proposals for teachers to avoid the abstractness of this definition, we did not provide concrete examples of teaching lessons. To assess the effectiveness of making use of Rankine's definition in high school, new teaching sequences could be built, implemented, and tested. We believe that the question of how to define energy across school years is important with respect to the teaching and learning of energy and deserves to be investigated further.

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## Appendix 1. The programs and textbooks analyzed in the study

**Table 3** The programs and textbooks analyzed in the study

| The French national programs | |
|---|---|
| MEN (Ministère de l'Education nationale, France). (2008a). Programmes d'enseignement de l'école primaire, Bulletin Officiel de l'Education Nationale, hors série n°3 du 19 juin 2008.<br>MEN. (2008b). Programmes du collège: programmes de l'enseignement de physique-chimie. Bulletin Officiel de l'Education Nationale, spécial n° 6 du 28 août 2008.<br>MEN (2010). Programme d'enseignement spécifique de physique-chimie en classe de première de la série scientifique. Bulletin Officiel de l'Education Nationale, spécial n°4 des 9 et 30 septembre 2010.<br>MEN (2011). Programme de l'enseignement spécifique et de spécialité de physique-chimie, classe terminale de la série scientifique. Bulletin Officiel de l'Education Nationale, spécial n°8 du 13 octobre 2011.<br>MEN (2012). Progressions pour le cours élémentaire deuxième année et le cours moyen, sciences expérimentales et technologie. Bulletin Officiel de l'Education Nationale, 5 janvier 2012. | |
| The textbooks | |
| Grades 3 to 5 | Boëche, S. (ed.) (2011). Les reporters, Sciences, CE2, CM1, CM2. Toulouse: Sedrap.<br>Courdant, A. (ed.) (2012). Les cahiers de la luciole, sciences expérimentales et technologie : CE2, CM1, CM2. Paris: Hatier.<br>Giordan, A. (ed.) (2008). Toutes les sciences: cycle 3. Paris: Nathan<br>Guichard, J. (ed.) (2010). Sciences expérimentales et technologie: CM. Paris: Hachette Education.<br>Morvan, A. et al. (2014). Le développement durable: cycle 3. Paris: Belin.<br>Rolando, J.-M. et al. (2014). Sciences expérimentales et technologie, tout le programme en 24 enquêtes: CE2, CM1, CM2. Paris: Magnard.<br>Tavernier, R. (ed.) (2013). Sciences expérimentales et technologie: CE2. Paris: Bordas.<br>Vilaro, C. & Fritz, D. (2015). Les découvreurs, sciences expérimentales et technologie : CM. Paris: Istra. |
| Grades 7 and 8 | Carré-Montréjaud, H. (ed.) (2010). Physique Chimie: $5^{ème}$. Paris: Nathan.<br>Parisi, J.-M. (ed.) (2010, 2011). Physique Chimie: $5^{ème}$, $4^{ème}$. Paris: Belin.<br>Vento, R & Regaud, D. (ed.) (2011). Physique Chimie: $5^{ème}$, $4^{ème}$. Paris: Bordas. |
| Grade 9 | Carré-Montréjaud, H. (ed.) (2008). Physique Chimie: $3^{ème}$. Paris: Nathan.<br>Cheymol, N. & Hoff, M. (ed.) (2008). Physique Chimie: $3^{ème}$. Paris: Magnard.<br>Collectif de Professeurs (2008). Physique Chimie: $3^{ème}$. Paris: Hachette.<br>Dirand, B & Ruffenach, M. (ed.) (2011). Physique Chimie: $3^{ème}$. Paris: Bordas.<br>Durandeau, J.-P. (ed.) (2008). Physique Chimie: $3^{ème}$. Paris: Hachette Education.<br>Jourdan, J. (ed.) (2008). Physique Chimie: $3^{ème}$. Paris: Hatier.<br>Parisi, J.-M. (ed.) (2008). Physique Chimie: $3^{ème}$. Paris: Belin. |
| Grade 11 Scientific pathway | Bataille, X. et al. (2011). Physique Chimie: $1^{re}$ S. Paris: Belin.<br>Dulaurans T. & Durupthy A. (ed.), Barde, M. et al. (2011). Physique Chimie: $1^{re}$ S. Paris: Hachette.<br>Le Maréchal, J.-F. (ed.) (2011). Physique Chimie: $1^{re}$ S. Paris : Hatier.<br>Prevost V. & Richoux B. (ed.) (2011). Physique Chimie: $1^{re}$ S. Paris: Nathan.<br>Ruffenach, M. (ed.) (2011). Physique Chimie: $1^{re}$ S. Paris: Bordas. |
| Grade 12 Scientific pathway | Antczak, S. & Le Maréchal, J.-F. (ed.) (2012). Physique Chimie: TS. Paris: Hatier.<br>Bataille, X. et al. (2012). Physique: TS. Paris: Belin.<br>Dulaurans, T. & Durupthy, A. (ed.) (2012). Physique Chimie: TS. Paris: Hachette.<br>Prevost, V. & Richoux, B. (ed.) (2012). Physique Chimie: TS. Paris: Nathan<br>Ruffenach, M., Cariat, T. & Mora, V. (ed.) (2012) Physique Chimie: TS. Paris: Bordas. |

## Appendix 2. The two versions of the questionnaire submitted to the teachers

**Table 4** The two versions of the questionnaire administered to the teachers

| Questionnaire submitted to primary teachers | Questionnaire submitted to secondary teachers of physics and chemistry |
|---|---|
| Q1: How do you describe energy to your students when teaching this concept? | Q*1: How do you describe energy to your students when teaching this concept? |
| Q2: Do you tell your students that energy is what is “necessary so as to heat, to light, to set in motion” (quotation from the national program of 2012)?<br>yes/no | Q*2: Do you tell your students that energy is “the capacity of a system to produce an effect” (quotation from the national program of 2008)?<br>yes/no |
| If teachers answered yes to Q2:<br>Q3: The definition of energy as what is “necessary so as to heat, to light, to set in motion” is a definition:<br>A1: your students must write down in their science notebooks and must memorize.<br>A2: which you provide to your students only in discussion and which they do not need necessarily to memorize.<br>A3: other answer: … | If teachers answered yes to Q*2:<br>Q*3: The definition of energy as “the capacity of a system to produce an effect” is a definition:<br>A1: your students must write down in their physics and chemistry notebooks and must memorize.<br>A2: which you provide to your students only in discussion and which they do not necessarily need to memorize.<br>A3: other answer: … |
| | Q*4: When you express this definition:<br>(several answers can be given)<br>A1: you provide examples of “effects” a system can produce by virtue of its energy (e.g., set in motion, increase in temperature, deformation…).<br>A2: you explain that the term “capacity” means that the “effects” (a system can produce by virtue of its energy) are only potential or possible.<br>A3: I do not take time to explain it.<br>A4: other answer: … |
| If teachers answered no to Q2:<br>Q4: You do not provide the definition of energy as what is “necessary so as to heat, to light, to set in motion” because:<br>(several answers can be given)<br>A1: it does not help students to understand what energy is.<br>A2: it is too abstract.<br>A3: you did not know this definition.<br>A4: other answer: … | If teachers answered no to Q2:<br>Q*5: You do not provide the definition of energy as “the capacity of a system to produce an effect” because:<br>(several answers can be given)<br>A1: it does not help students to understand what energy is.<br>A2: it is too abstract.<br>A3: you did not know this definition.<br>A4: other answer: … |
| Q5: Do you tell your students that energy is conserved (or can be neither created nor destroyed)?<br>yes/no | Q*6: Do you tell your students that energy is conserved (or can be neither created nor destroyed)?<br>yes/no |
| If teachers answered yes to Q5:<br>Q6: Conservation of energy is a property:<br>A1: your students must write down in their science notebooks and must memorize.<br>A2: which you provide to your students only in discussion and which they do not need necessarily to memorize.<br>A3: other answer: … | If teachers answered yes to Q*6:<br>Q*7: Conservation of energy is a property:<br>A1: your students must write down in their physics and chemistry notebooks and must memorize.<br>A2: which you provide to your students only in discussion and which they do not necessarily need to memorize.<br>A3: other answer: … |
| If teachers answered no to Q5: | If teachers answered no to Q*6: |

**Table 4** (continued)

| Questionnaire submitted to primary teachers | Questionnaire submitted to secondary teachers of physics and chemistry |
|---|---|
| Q7: You do not introduce conservation of energy because:<br>(several answers can be given)<br>A1: primary students cannot understand it.<br>A2: it is not an item of the primary school program.<br>A3: you did not know this property.<br>A4: other answer: … | Q*8: You do not introduce conservation of energy because:<br>(several answers can be given)<br>A1: your students cannot understand it.<br>A2: it is not an item of the program (if you teach in grades 7 to 9).<br>A3: there are many items in the program and it is not a priority to discuss this property.<br>A4: other answer: … |

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