History and Philosophy of Science: A Lever to Teach Energy at High School

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Learning Difficulties and Issues

Energy is both a fundamental concept of physics and a major component of current socio-scientific issues. Accordingly, this concept lies at the core of the science curricula in numerous countries (Lee and Liu 2010; Eisenkraft et al. 2014). For instance, in the USA energy is considered as a "crosscutting concept" which helps to "organize" the "disciplinary core ideas" (NGSS Lead States 2013). However, understanding this concept is far from obvious. Energy does not depict a particular phenomenon but can be applied to a wide range of phenomena in all branches of physics; it is therefore very abstract (Warren 1982; Millar 2005). Although a definition of energy is available, namely, the one proposed by Rankine (see below), this definition remains disputed and is not always introduced in classrooms; often, energy is defined merely as a conserved quantity (Bächtold 2018). As a matter of fact, students develop a variety of erroneous conceptions (Watts 1983; Duit 1984; Gilbert and Pope 1986; Trumper 1993). Moreover, energy is embedded in a highly complex conceptual network: first, energy has several associated sub-concepts, such as the sources, forms and modes of transfer of energy; second, it is closely related to other quantities, such as force, temperature or power. As a consequence, students tend to make several kinds of confusions: e.g. they often wrongly consider work and heat as forms of energy (Cotignola et al. 2002; Jewett 2008); they tend to confuse energy and force (Watts 1983; Trellu and Toussaint 1986) or heat and temperature (Lewis and Linn 1994; Harrison et al. 1999). Finally, the principle of energy conservation is very difficult to master (Driver and Warrington 1985; Solomon 1985; Trumper 1990; Neumann et al. 2013). To apply it accurately, students need

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first to master the ideas of energy transformation and transfer; they also have to understand the notion of dissipation (Duit 1984; Solomon 1985; Lacy et al. 2014), and they must be able to identify the relevant system and distinguish it from its environment (Arons 1999; Van Huis and van den Berg 1993). As a consequence of all these learning difficulties, teaching energy appears to be a great challenge. Since the 1980s, several teaching strategies have been proposed (for a review, see Millar 2005; Doménech et al. 2007). Some of them are opposed, e.g. either for or against introducing the notion of energy transformation (Nordine et al. 2011; Falk et al. 1983; Brewe 2011) and either for or against introducing energy as a "quasi-material substance" (Duit 1987; Colonnese et al. 2012). However, no systematic empirical comparison between the proposed strategies has been performed yet. Nonetheless, a "learning progression" of energy has been identified, thanks to several empirical studies (Liu and McKeough 2005; Lee and Liu 2010; Nordine et al. 2011; Neumann et al. 2013): first, students tend to master several forms and sources of energy, then the notions of energy transformation and transfer and eventually the notion of dissipation and the conservation principle. These outcomes supply landmarks for organizing a teaching programme for energy throughout schooling. However, the following question remains: what specific teaching strategies should be developed at each stage of the learning progression so as to help students to overcome their difficulties and acquire a deeper understanding of energy?

The Contribution of History and Philosophy of Science

Several authors have highlighted the interest of history and philosophy of science (HPS) for the teaching of energy (De Berg 1997; Cotignola et al. 2002; Coelho 2009; Rizaki and Kokkotas 2013; Papadouris and Constantinou 2016; Lehavi and Bat-Sheva 2018). On the one hand, HPS can provide an accurate insight into the meaning of the concept of energy and help to conceive relevant teaching sequences. For instance, based on a "historiographical analysis" of the concept which puts forward the "causal and the unifying characters of energy", Rizaki and Kokkotas (2013) developed an original teaching approach for primary school. On the other hand, some elements of HPS can be introduced directly into the classroom. For instance, some historical experiments can be presented to students; following de Berg (1997), we consider that the historical reconstruction designed for the classroom can omit some experimental or mathematical details; what matters is to present the historical context and in particular the scientific problems, which enable students to understand why the scientists performed their experiments and how they could interpret the outcomes.

Research Questions

In line with the authors cited above, we undertook a collaborative work with teachers to build a new teaching strategy for energy at high school which relies on HPS. In this study, we aim at investigating the usefulness of HPS and more specifically the two following research questions: (i) Does a collaborative work aimed at introducing HPS in the teaching of energy help high school physics teachers to understand the issues of energy teaching and change their view concerning the role of HPS in this respect? (ii) To what extent does a teaching strategy built in the light of HPS and introducing some elements of HPS allow students to overcome the learning difficulties and reach a deeper understanding of the concept of energy? In the following sections, we present the way we built our HPS-based teaching strategy, the method for assessing it, before discussing our main results.

Building an HPS-Based Teaching Strategy

So as to build a relevant HPS-based teaching strategy for energy, we first carried out (1) a review of the literature in science education so as to identify students' learning difficulties which have to be taken into account; (2) an analysis of the French national programmes and of the French science textbooks in order to adapt the teaching strategy to the context of the country in which the study is undertaken; and (3) a historical and epistemological study concerning energy with the aim to get a new insight on the meaning of the concept and in particular to understand why the concept has entered the field of physics in the middle of the nineteenth century. Steps 1 and 2 are presented in Bächtold et al. (2014) and step 3 in Bächtold and Guedj (2014). We summarize here the main outcomes of the historical and epistemological study (step 3), which was based on secondary (and some primary) historical and philosophical sources concerning energy (e.g. Meyerson 1908; Kuhn 1959; Poincaré 1968 [1902]; Elkana 1974; Lindsay 1975; Harman 1982; Bunge 2000; Smith 2003). It is well-known that energy as we understand it today was introduced in physics when the principle of energy conservation was established; for this reason, many physicists consider that conservation is a fundamental property of energy (Balibar 2010). Nevertheless, there is another important part of the story which is less known. Let us present it in few words. Before the very notion of energy was introduced, in the first part of the nineteenth century, physicists performed a whole set of new experiments which could be viewed as "conversion" processes between different kinds of phenomena, that is, phenomena which were usually handled in different branches of physics (e.g. Faraday's electric motor experiment in 1821 which links electricity and movement or Joule's paddle wheel experiment in 1845 and 1847 which links movement and heat). In this context, energy was introduced as a unifying conceptual tool which allowed an explanation of how these phenomena were linked together, that is, how heterogeneous quantities (e.g. living force and heat) could be converted into one another: Thomson and Rankine proposed viewing these quantities as instances of the same quantity, namely, energy, and describing each conversion process in terms of energy transformation – the amount of energy being constant during the process. Moreover, to conceive the convertible quantities (e.g. living force and heat) as instances of the same quantity, they defined energy as the "capacity of a system to perform changes" (this definition being known as "Rankine's definition"): these quantities are equivalent with respect to the capacity of the systems under consideration to produce the same changes (e.g. the increase of temperature in the case of Joule's experiment). This historical and epistemological study brings to light two important points: the unifying function of energy and the role of Rankine's definition.

The fourth step of the research consisted in building, implementing and assessing a new teaching strategy for energy that relies on HPS and in particular on the points stressed above. We chose to focus on high school, at grade 11, a school year in France during which energy has to be studied in several teaching sequences of physics and chemistry. Taking into account the contents clarified in the previous steps of our research (steps 1–3), we came to develop a teaching strategy consisting of (a) a teaching sequence beginning with the study of a historical text of Joule (Joule 1847b) and centred on Joule's paddle wheel experiment (Joule 1847a) and Rankine's definition (Rankine 1855); (b) a prestructured conceptual map of energy (called "ID card") to be filled in by students during the school year, which is intended in particular to help them to differentiate various concepts associated to energy that are often confused (i.e. sources, forms, transformations and transfers of energy); and (c) the introduction of the conservation principle the first time the quantity energy is dealt with during the school year, followed by multiple applications of this principle. We would like to emphasize that the choice of introducing Joule's experiment was motivated by the fact this experiment can illustrate in a simple manner the notion of transformation between two energy forms (i.e. kinetic energy and thermal energy) which, moreover, are usually studied in two separate branches of physics (i.e. mechanics and thermodynamics). The relevance of introducing this experiment in the frame of energy teaching has also been stressed recently by Lehavi et al. (2016).

Following the "design experiment" method (Cobb et al. 2003, Sandoval 2013), we then undertook collaborative and iterative work involving teachers: collaborative so as to build teaching sequences meaningful for teachers, not too far from their usual practices, and compatible with the constraints of the school environment, iterative, that is, with two loops of implementation and assessment, in order to improve the teaching sequences.

In accordance with the national programme for grade 11, a total of eight teaching sequences involving the concept of energy (either as a central or a secondary item) were designed and implemented in each class. Let us describe in more details the HPS-based teaching sequence centred on Joule's paddle wheel experiment and Rankine's definition. This sequence consisted of three activities and had a total duration of around 4½ h. In the first activity (around 1½ h), teachers first provide a document describing the scientific and technical context at the time of Joule. Students are then asked to study a historical text of Joule published in 1847 (an extract from "On matter, living force, and heat"). The first part of the text deals with the notion of living force and is used as a support for a discussion with students about the difference between force and energy. The second part explains the problem faced by Joule concerning the disappearance of living force and sets out the solution he proposed (i.e. interpretation in terms of conversion of living force into heat; experiences performed to support this interpretation). Teachers then describe Joule's paddle wheel experiment in terms of energy transformation (i.e. kinetic energy into thermal energy). Finally, they formulate and discuss Rankine's definition of energy (i.e. they discuss the terms "capacity" and "changes") paying attention to the unifying role of energy. In the second activity (around 2 h), the teachers ask students (in small groups of 3–5 students) to conceive a similar experiment with current materials available at home or in the teacher's laboratory, to perform it and to present and discuss their outcomes. In the last activity (around 1 h), students complete an exercise with mathematical calculations concerning Joule's experiment which compels the use of the notions of energy dissipation and energy conservation.

Method

The teaching sequence has been implemented in grade 11 classrooms for 2 consecutive years, with three experienced high school teachers (T1, T2 and T3) during the first loop of implementation and assessment (year 1) and two teachers (T1 and T2) during the second loop (year 2). To address our first research question (i), related to teachers' view on HPS-based teaching of energy, we analyse the two implementations. As regards the effectiveness of the teaching strategy (research question (ii)), we restricted our analysis to the results of the 2nd implementation, those concerning the first experimentation being presented in Bächtold et al. (2016). During the second year, T1 implemented the teaching strategy in 1 class (27 students) and T2 in 2 classes (35 students and 33 students). Both teachers described the students of the second year as having overall a "rather low level" in physics compared to the students in the classes they had taught in the past.

To address the two research questions, we collected the following data. The HPS-based sequence was videotaped, and evidence of students' activities was collected. Note that the detailed analyses of the videos are presented elsewhere (Bächtold & Munier, submitted). As regards teachers, three working meetings were audio-recorded in the context of which we performed semi-structured interviews, on the basis of selected video extracts of classroom activities. At the end of the school year, in the context of a final meeting with the teachers, we also gathered complementary information concerning the other teaching sequences where the quantity energy was involved, concerning the way the ID card of energy was used and the number of applications of the conservation principle.

As regards students, they were asked, during the teaching sequence, to perform an experiment similar to the one carried out by Joule ("raise as much as possible the temperature of a quantity of water in 10 minutes, starting with kinetic energy") and to make a short video of this experiment presenting the protocol and discussing the outcomes. These videos (15 video recordings of students' experiments, each 1 of an average duration of 2′30″) were analysed, focusing on students' use of the notion of energy transformation. We also proposed written pre- and post-tests to assess the evolution of pupils' knowledge about energy.

The pretest (N=95) consisted of five open-ended questions. Six questions were added in the post-test (N=87), one open-ended question and five multiple-choice questions adapted from the questionnaire of Neumann et al. (2013). This questionnaire was distributed by these authors to a large number of pupils, which allows us to have a reference level when we analyse the answers and assess the level of the students involved in our experiment. These six further questions dealt with quantities and notions which were introduced during the school year, so we considered it meaningless to include them in the pretest.

In question 1, students were asked to describe in terms of energy the following situation: a person turns the crank of a flashlight, which emits some light. We wanted to determine whether pupils were able to describe this situation in terms of forms and transformations of energy. In question 2, to determine whether students confuse energy with other quantities closely related to energy (e.g. force and power), students were asked to provide all of the energy units they know. Question 3 addressed the unifying role of energy. We remind students that the curriculum for their level emphasizes the concept of energy, and we ask them whether they have an idea about the reasons for this emphasis. We want to determine whether students spontaneously mention the unifying role of energy. In questions 4 and 5, students were asked to explain what energy is for them and what the properties of energy are. These two questions were analysed together in order to determine if students are able to provide Rankine's definition and if they spontaneously mention energy transformation and the conservation principle. The remaining questions were included only in the post-test. Question 6 concerned the gap between how energy is addressed in physics and in everyday life. We remind students that in everyday life, we often speak of "production" or "consumption" of energy before asking them whether, from the point of view of physics, energy could be produced or consumed and to justify their answer. We want to determine whether students are capable of translating these expressions into scientific terms (e.g. in terms of "transformation" or "dissipation") and what is the status they grant to energy conservation. Questions 7–11 were multiple-choice questions addressing concrete physical situations. In Question 7, the picture of a marble held at the top of a bowl is presented, and students must choose between several statements claiming that the ball has or does not have various forms of energy. We wanted to determine whether students confuse the different forms of energy or whether they associate energy with motion or with a human action. In questions 8 and 9, the picture of a ball dropped and making round trips in a bowl is presented. Question 8 aims at determining whether students are able to correctly describe the situation in terms of transformation of a form of energy into another, whereas question 9 examines whether they can explain the slowing down of the ball in terms of energy dissipation without dismissing the conservation principle. Questions 10 and 11 concern the working principle of a wind turbine that produces electricity. We aim at knowing whether students are able to explain its functioning in terms of energy transfer and of energy transformation and are capable of analysing the situation in terms of dissipation and conservation of energy. The complete questionnaire and the detailed coding grid are presented in a paper currently under review (Bächtold and Munier 2018).

Results

With regard to our first research question, the classroom video recordings and the collective semi-structured interviews with teachers yielded the following outcomes. The interviews brought out that the three teachers were enthusiastic concerning the activity based on Joule's experiment. Teachers stressed that students were very motivated to conceive their own experiment, to perform it and to film it. They then considered the activity based on Joule's experiment as a very good tool for raising students' interest for energy. They also consider that performing their own experiment allows students to make the idea of energy transformation more concrete for them, helping them to understand the notion of energy transformation.

The three teachers were also enthusiastic with respect to the introduction of history of science in their classrooms via the study of the historical text. They stressed that such an activity can contribute to the cultural literacy of their students. At the end of year 1, the teachers viewed the historical text as "too long" and some parts of it as too difficult for students to understand. They viewed the expression "living force", used by Joule, as confusing for students. This feedback led us to adapt the activity for year 2 by removing parts of this text, reformulating the questions aimed at guiding the students and proposing a slide to be projected at the end of the activity to summarize the difference between force and energy. Recall that our assumption is that the discussion of the expression "living force" is a good opportunity to clarify the distinction between force and energy. At the end of year 2, the two remaining teachers no longer considered the text too long or difficult.

Concerning Rankine's definition, at the end of year 1, teachers did not appear to understand well its role in the strategy for teaching energy. Thus, in their classrooms, they only mentioned it in passing (as we could see in the video recordings). In year 2, after longer discussions about the role of this definition in the understanding of energy, we decided with the teachers to devote more time to the discussion of this definition in the classrooms. In the interview at the end of year 2, both T1 and T2 agreed that the introduction of Rankine's definition, by discussing the terms "changes" and "capacity", was more meaningful.

The three teachers were very positive regarding the training their received through this collaborative work. They initially ignored how energy was introduced in the history of physics and had no idea of the unifying role fulfilled by this quantity.

Our meetings helped them to understand this point. At the end of the second year, the two remaining teachers emphasized that the ID card of energy was very useful in order to integrate this unifying role in their classrooms. This tool was described as a "guideline" so as to establish links between the various lessons during the year where energy is at play. The word "guideline" was used both by T1 and T2. In the view of T2, this tool could also be very helpful for his students during their next year (grade 12), as it provides an overview concerning all the aspects of energy that have been studied during this year. According to T1, the ID card "has a role of binder […], it gives a meaning to energy throughout the school year, [this meaning being] hidden in some words, in some chapters;" otherwise, the chapters appear as merely "juxtaposed". Note that the teachers proposed adding a timeline in the ID card and using this as a means of constructing historical landmarks concerning the contribution of famous physicists (e.g. Joule, Rankine, Planck, Einstein, etc.) to the history of energy in the various domains of physics.

Finally, taking into consideration the low results concerning the application of the conservation principle year 1, we chose to introduce it earlier year 2. Teachers were in favour of this strategy, but in their view, the mastery of this principle by their students seemed to be only one pedagogical goal among others, and not the overarching goal of energy teaching.

Concerning the efficiency of the teaching strategy (research question ii), the answers to the pre- and post-tests are summarized in Table 1.

Let us provide details on some of the outcomes provided in Table 1. In question 1, the number of students providing a description in terms of energy transformation, at least of one element of the chain, increases significantly.

Concerning question 2, we note that the percentage of students able to name one or more correct units of energy without also stating an incorrect unit increases from 7% to 39%. However, the number of students providing an erroneous unit remains important. In particular, the number of students providing a unit of force remains similar between the pretest and the post-test (difference not statistically significant), which suggests that confusion persists between energy and force. Concerning question 3, the percentage of students able to mention spontaneously the unifying role of energy increases, but the difference is not statistically significant. When they are asked to provide a definition of energy (Q4), Rankine's definition or a distorted but acceptable version of this definition (e.g. with the idea of capacity) is more frequent after teaching than before, by an amount that is statistically significant.

Answers to question 6 show that a large percentage of students after teaching is able to interpret correctly the expressions "production" and "consumption" of energy, namely, in terms of energy transformations.

According to answers to questions 7–9, most students, in the specific situation of a marble in a bowl, have acquired well the notions of kinetic and potential forms of energy and are able to describe this situation accurately in terms of energy transformation. In this case, the difference from students assessed by Neumann et al. (2013) is statistically very significant. Nevertheless, the outcomes concerning the notion of energy transformation are comparable with the outcomes of Neumann et al. in the case of another physical situation (i.e. wind turbine generating electricity (Q10 and Q11)).

Table 1 Students' answers to the pre- and post-tests (year 2)

	Physical situation	Kind of question	Skills and confusions assessed	Answers to the pretest	Answers to the post-test	Outcomes from Neumann et al. (2013) (details given in private communication)
Q1	A crank flashlight	Open	Notion of energy transformation	Description with a clear idea of transformation		
				26%	54%	
				Significant evolution (χ^2=14.58)		
Q2	Not specified	Open	Measurement units of energy	Correct(s) measurement units without erroneous unit		
				7%	39%	
				Significant evolution (χ^2=26.17)		
				Confusion with force		
				11%	7%	
				Non-significant evolution (χ^2=0.75)		
Q3	Not specified	Open	Unifying role of energy	16%	28%	
				Non-significant evolution (χ^2=3.75)		
Q4 and Q5	Not specified	Open	Definition of energy	Rankine's definition or distorted but acceptable versions of this definition (e.g. with the idea of capacity)		
				5%	40%	
				Significant evolution (χ^2=30,85)		
			Notion of energy transformation	Idea of transformation		
				23%	48%	
				Significant evolution (χ^2=12.57)		
			Conservation principle	Conservation principle		
				5%	53%	
				Significant evolution (χ^2=51.04)		
Q6	Not specified	Open	Energy "production/consumption" interpreted in terms of energy transformations		61%	
Q7	A marble held at the top of a bowl	Closed	Notion of kinetic and potential forms of energy		86%	45%

(continued)

Table 1 (continued)

	Physical situation	Kind of question	Skills and confusions assessed	Answers to the pretest	Answers to the post-test	Outcomes from Neumann et al. (2013) (details given in private communication)
Q8	A marble rolling in a bowl	Closed	Notion of energy transformation		88%	48%
			Confusion between energy and force		6%	/
Q9		Closed	Conservation principle with the relevant system		37%	20%
			Confusion between energy and mechanical energy conservation		16%	/
Q10	A wind turbine generating electricity	Closed	Identification of various forms of energy and notion of energy transformation		42%	49%
			Confusion between energy and force		35%	/
Q11		Closed	Conservation principle and notion of dissipation		51%	31%
			Confusion between energy and force		38%	/

Answers to questions 9 and 11 show that the percentage of students mastering the principle of energy conservation is higher in our study than in the one of Neumann et al. (2013), this difference being statistically significant. This is the case in a situation in which they might confuse it with the conservation of mechanical energy and in which they must identify the relevant system (Q9), as well as in a situation in which dissipation must be considered (Q11). Another outcome that must be emphasized is that the force-energy confusion remains latent for many students. For example, although few of them appear to confuse these two quantities in the situation of a marble in a bowl (6%), more than one-third experience this confusion in the situation of the wind turbine.

Let us turn finally our attention to students' videos. Our analysis shows that 5 groups out of 15 spontaneously described the experiment in terms of energy transformation, 4 groups spoke about kinetic energy and heat without using explicitly the idea of transformation and 6 did not even mention the notion of energy. More details concerning this analysis are given in Bächtold and Munier (2018).

Discussion and Conclusions

Let us recall our first research question: Does a collaborative work aimed at introducing HPS in the teaching of energy help high school physics teachers to understand the issues of energy teaching and change their view concerning the role of

HPS in this respect? Our case study suggests that teachers can be very receptive to the contribution of HPS. The three teachers participating in this study particularly acknowledged the insight that HPS gave them into the unifying role of energy in physics. Understanding this unifying role was very helpful for them to give meaning to the high school programme of physics and chemistry, which involves numerous chapters dealing with energy without apparent relationships. This new insight for teachers into their understanding of energy has been manifest in the interest they showed for the ID card of energy.

Overall, the teachers in this case study were very involved in the collaborative work, not only for the implementation of the teaching sequence but also for its design by making several proposals (e.g. they proposed to add a timeline in the ID card that students provide a video recording of their experiment and changes concerning the selected historical texts). This commitment can be viewed as evidence they considered the introduction of HPS meaningful in their teaching.

More specifically, although the teachers did not assign a major role to Rankine's definition, they were very positive concerning the study of Joule's paddle wheel experiment and its replication with their students. It has been identified not only as a good means for raising their interest concerning energy but also, and more fundamentally, as a meaningful illustration of the idea of energy transformation. As further evidence, let us note that one of the two teachers who took part in our study the second year is still implementing the HPS-based sequence (with Joule's experiment) 3 years later and outside the frame of our research (the other one is now teaching students at other grades).

These outcomes are in line with previous studies which emphasize the interest generated by providing science teachers with training about HPS. As Matthews (1994) argues: "many examples have been given where HPS can contribute to better, more coherent, stimulating and critical teaching of specific curriculum topics" (pp. 200–201). Irrespective of the introduction of HPS in classrooms, training teachers about HPS can give them an insight into the meaning and the role of experiments and concepts they teach.

Concerning our second research question about the effectiveness of the teaching strategy, data analysis shows that the implemented teaching strategy allowed a large proportion of students to identify correctly and distinguish the energy forms and to apply accurately the notion of energy transformation in various situations. However, this level of mastery seems dependent on the forms of energy involved: students seem to master the potential-kinetic energy transformation, two forms of energy with which they have been familiar for several years and which can be more easily associated with a system. They have more difficulties with light and electrical energy, "forms" which are not consensually defined in the scientific community and which are more difficult to associate to a system.

The comparison with the results of Neumann and colleagues shows that the teaching strategy seems more effective than a classical one for helping students to apply correctly the conservation principle without confusing it with the conservation of mechanical energy, taking into account dissipation and identifying the relevant system. It seems to confirm the relevance of introducing this principle from the first time energy is studied in the school year and applying it several times during the year (and not only after having studied mechanical energy).

Results are more mixed concerning the energy-force confusion; depending on the context, up to a third of students made this confusion. The study of a historical text designed to discuss this confusion can be an interesting tool but can also have a possible counterproductive effect with less skilled students.

A limitation to the assessment of the teaching strategy is the relative gap between the sequence as it was envisaged by the researchers and the sequence actually implemented, due to various uncontrollable constraints of the school environment. By carrying on the iterative process of implementation and adjustment of the sequence, we may reduce this gap, better determine the relevance of the strategy and imagine possible improvements.

Even if we do not claim that HPS should be introduced systematically in science teaching, this research points out its usefulness for building new science teaching strategies and illustrates how HPS may be introduced in classrooms. Indeed, the historical and epistemological study carried out as a preliminary step of this research provided us with a new insight into the meaning of energy: in particular, it brought to light both the unifying function of the concept and the important role of Rankine's definition. These two points have been decisive in the development of our teaching strategy. Concerning the introduction of some elements of HPS directly into the classroom, Joule's paddle wheel experiment appears to be a simple and easily understandable experiment and, at the same time, a powerful illustration of the notion of energy transformation. Thereby our research shows that historical experiments can help students to understand better the scientific contents and possibly play the role of a paradigmatic example. In this regard, HPS does not merely supply a cultural extra to the study of the scientific knowledge; it appears as a reservoir of potentially fruitful tools for teaching and learning this knowledge.

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