Chapter 8
Teaching Energy Informed by the History and Epistemology of the Concept with Implications for Teacher Education

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8.1 Introduction

What can Epistemology and the History of Science and Technology (EHST hereafter) contribute to the field of teaching energy? Is it enough simply to evoke them as a way of broadening the learning after teaching the concept, that is, once students have mastered it, in order to offer them a few historical reference points and to spark off philosophical debate on the subject? That is not our point of view. On the contrary, we think that EHST could play a fundamental role in teaching energy, especially in regard to teacher training. Beynon wrote in 1990: 'I have no doubt at all that the problem of teaching energy will remain insoluble until teachers, themselves, have a clear understanding of the concept of energy' (1990, p. 316). We share this point of view. Indeed, for students to successfully understand and correctly apply the concept, it seems essential that their teachers themselves first master it, which is far from given. The highly abstract nature of the concept of energy (which is inseparable from the principle of energy conservation), its many possible forms (e.g. kinetic energy, thermal energy, nuclear energy), the distortions of meaning to which it is subject in everyday use (e.g. saying that energy can be 'produced' and 'consumed') all make it difficult to define the concept.

As we will try to demonstrate in this article, EHST provides the keys to understanding what energy is and, in particular, to at least begin to answer these three questions:

- 'What is the origin of the concept of energy?'
- 'What is energy?'
- 'What purpose does the concept of energy serve?'

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This is why our strategy consists of developing a training programme for teaching energy based on EHST. We start by discussing how teaching energy is covered throughout schooling (in the case of France), the learning difficulties associated with the concept and the main strategies presented in science education literature to teach the concept (Sect. 8.2). Then we outline our methodology and our two lines of research:

(i) EHST as part of teacher training for teaching energy
(ii) EHST as a means of rethinking how energy is taught (Sect. 8.3)

In the context of the first line of research, we present a framework for teacher training on the concept of energy based on EHST (Sect. 8.4). The second line of research will be addressed in a future article.

8.2 Teaching Energy: A Brief Overview of the Current Situation

8.2.1 Institutional Expectations and Teaching Energy: The Case of France

Energy appears as a concept across physical science programmes from primary through secondary school. Its progressive introduction throughout primary and secondary education has two main strands: the scientific approach to the concept and its implication in current social issues. Generally speaking, the emphasis is on a qualitative approach that prioritises the nature, role and properties of a concept that, although part of daily life, remains difficult to tackle.

In primary school (MEN 2008a), this qualitative approach is based on an introduction that aims to present energy via questions related to using and saving energy. In the further learning and consolidation stage, this does not involve introducing the scientific concept, but rather increasing pupils' awareness of the diverse situations that require a source of energy (using everyday vocabulary), identifying the principal sources of energy and distinguishing those that are renewable from those that are not. In addition, the concept of thermal insulators and conductors is first introduced, with the home providing a good illustration of this approach. The main goal of this initial contact with the concept of energy, which provides the opportunity for projects on the Industrial Revolution introduced in the history programme of the further learning stage, is to contribute to the education of the student as a future citizen.

This same goal also pertains to the educational programme at *collège* (the first stage of secondary school, age 10–14), which equally stresses a qualitative approach to energy; however, at this stage, the scientific concept is introduced and a definition given. The concept of energy, used as an example in the 'unity and diversity' theme that underlies the college (MEN 2008b) programme, is at the heart of the curriculum. It is presented as an essential concept in core knowledge and skills and is treated as a subject that provides a focal point.

The two main strands mentioned above are fully formulated at this stage. The definition is formulated as follows: 'energy is the capacity of a system to produce an effect' – it can be transformed and conserved. This first scientific approach to the concept proves necessary in order to introduce in a logical way a wide range of events that bring energy into play (e.g. day-to-day use of electric circuits, heat exchange, analysis of how living organisms function) and also constitutes essential knowledge for future citizens who need to be aware of the issues around energy that are central to debates in modern society.

In continuity with *collège*, the first year of *lycée* (high school, i.e. the second stage of secondary school, age 15–18) (MEN 2010a) calls for scientific learning and citizenship that will aid all students to succeed, while in the scientific stream of the two final years of *lycée* (MEN 2010b, 2011), the approach concerns vocational preparation to allow students to work towards careers in science. The emphasis is on acquiring skills in the discipline, encouraging interest in the sciences and making connections between science and society.

The final year of the scientific stream in *lycée* is structured around three axes: 'observe, understand,ct'. The purpose of these points of access to the scientific approach is to illustrate its main steps, giving a central role to the concept of energy, which is a sort of unifying theme throughout the 2 years of the course. In this way, the axis 'understand', dedicated to laws and models, presents energy as a common denominator of all basic interactions and the principle of conservation as an explanatory and predictive tool that allows awareness of the evolution of systems (second year of *lycée*). In addition, the study of the transfer of energy at different scales allows the introduction of the basic concept of thermodynamics (internal energy, thermal transfer, work, heat capacity) and a discussion of the irreversibility of phenomena and the causes of dissipation associated with these transfers (final year of *lycée*). This approach underlines the universality of the laws of physics, for which energy is presented as a unifying principle.

In this initial introduction, which highlights the nature, role and properties of the principle of conservation, the educational programme introduces the social and environmental issues related to energy. This includes knowledge about the variety of energy resources and saving energy, problems related to the production of electricity and the transport and storage of energy as well as the environmental impact of energy choices; all these subjects combine scientific knowledge and current issues in society. The axis 'act' sets out to develop this aspect.

The goal of the educational programme is the progressive construction of scientific knowledge and the development of skills suitable for initiation to experimental methods and practice. To help achieve this goal, the programme recommends making use of the history of science. Creating a historical perspective is structured around two axes: one concerning the nature of science and the other the scientific method. The aim, by emphasising the process of how knowledge is constructed, is to show that scientific truth has a particular status; it is the result of a codified process for which mistaken concepts and incorrect hypotheses are common. The history of science demonstrates that science is a social activity that is part and parcel of the culture in which it develops and that new ideas sometimes collide with tradition or dogmatism. These elements should be taken into account to contextualise science and '*mettre la science en culture*' (establish its place in a culture) (Lévy-Leblond 1973). This in turn should help to develop critical thinking, rethink the role of error and present the diversity of scientific methods, which cannot be reduced to a simple sequence of 'observation–modelling–verification', with the last having mainly a heuristic value.

8.2.2 A Difficult Concept to Grasp and Master

Although in general use, the concept of energy is abstract, difficult to define and subject to numerous recurrent conceptions noted by many writers.[1] The origins of these ideas are mainly found in everyday language, which contributes to the formation of imprecise or even mistaken concepts. The different meanings the term 'energy' and other related words take on in ordinary language are distant from or sometimes even incompatible with scientific concepts. In French, as well as in English, for example, it is common to associate the terms *energy* and *energetic* with strength and vigour. These words are often employed to describe a highly active person. Whereas in physics, the quantity of energy associated with a system may be very low. Moreover, energy may be in a form that is not even noticeable (this is the case for potential energy).[2]

In general discourse at least, people frequently speak about using, consuming, buying or selling energy, sometimes referring to fossil fuels themselves as 'energy'. This creates confusion between sources and forms of energy and presents a real obstacle in the acquisition of the principle of conservation.

Apart from language, daily experience can also prove to be a source of confusion, particularly for the youngest pupils. The ease with which it is possible to make an appliance function simply by plugging it into a socket implies that something can be obtained without anything being consumed. In the same way, obtaining electricity in hydroelectric or thermal power stations (especially nuclear power stations) takes on a magical character in which electricity seems to be stored.

The diversity of concepts related to energy makes it difficult to provide an exhaustive overview. Thus, we have chosen to mention only those, often cited by writers, which seem to be the most recurrent. Watts (1983) groups these according to seven categories:

- The anthropocentric conception, in which energy is associated with what is living.

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[1] See Solomon (1982, 1983, 1985), Watts (1983), Gilbert and Watts (1983), Duit (1984), Driver and Warrington (1985), Agabra (1985, 1986), Gilbert and Pope (1986), Trellu and Toussaint (1986), Trumper (1993), Ballini et al. (1997), and Bruguière et al. (2002).

[2] Fact sheet for Cycle 2 (basic learning in first years of primary school) and Cycle 3 (further learning in last years of primary school) (MEN 2002, p. 29)

- The conception of energy as a causal agent, in which energy is perceived as the cause of an event, as that which makes something happen. In this scenario, in which energy can be stored, the movement of a falling stone or a thrown ball is explained by the presence of potential and kinetic energy, respectively.
- The conception of energy as a product deriving from a process, a product that rapidly disappears and is not conserved.

To these three ideas, identified by Trumper (1990) as the most frequent, Watts adds the following four concepts. Energy can be perceived as an 'element' that lies dormant in certain objects and is released by a trigger. When energy is systematically associated with movement, Watts refers to the concept of 'activity' energy. This can be 'combustible' energy, where energy is equated to its source (oil, coal, natural gas and petrol are seen as energy), or 'fluid' energy, where energy is equated to a fluid that can be exchanged and transported. When this idea of energy as a fluid, i.e. as something 'quasi-material', is taken as an analogy only, it may be a fruitful tool for initially grasping the concept and the principle of its conservation (Duit 1987; see also below). However, the danger of making use of it in physics education is that students may take it literally and thereby endorse a non-scientific conception that is very hard to overcome (Warren 1982).

In the same vein, Robardet and Guillaud (1995) synthesise the work of other writers to summarise the most common conceptions, grouping these in three broad categories: energy as life (anthropocentric conception), energy as source (i.e. as cause of phenomena), and energy as product (i.e. as consequence of phenomena). This overview highlights the fact that energy is more noticeable when the effect produced is visible and even more so when the effect has a practical aspect or is associated with comfort. Thus, potential energy is little recognised by students (this point will be dealt with in Sect. 8.4.2).

These different conceptions result in several frequent and persistent errors, even after traditional learning (Trumper 1990). Without listing them all, we can cite, for example, the substantialisation of energy, confusion between the form and mode of transfer of energy; between force, speed and energy; and between heat, temperature and internal energy.

8.2.3 The Main Teaching Strategies

While educational programmes from primary to secondary school grant an increasingly large place to energy, the diversity, origin and consequences of mistaken ideas present a major obstacle to learning the scientific concept. Since the 1980s, the trickiness of teaching the concept has led certain educators to seek ways to facilitate its acquisition by taking into account related preconceptions. Generally speaking, traditional teaching is judged dogmatic and abstract (Lemeignan and Weil-Barais 1993), reducing the concept to a group of systematic technical procedures stripped of physical meaning.

The main teaching strategies are based on taking into account students' preconceptions during the application of the principle of conservation of energy. Thus, Trumper (1990, 1991, 1993), in the context of a constructivist approach, leads students to identify any conflicts between their own ideas and the properties required to establish the principle of conservation.

In the same spirit, the work of Agabra (1986) as well as Trellu and Toussaint (1986) promotes the concept of 'objective–obstacle' defined by Martinand, who suggests linking educational objectives with students' ideas, making the obstacles associated with the various preconceptions explicit and in each case indicating a specific way to surmount them.

Also in the constructivist framework, the work of Lemeignan and Weil-Barais (1993), extended by Robardet and Guillaud (1995), aims at constructing the concept of energy and its conservation by encouraging conceptualisation and only subsequently introducing classical formalism. The objective is to define, step by step, the semantic relationships that connect each object in the system studied with the next (e.g. an alternator powers a lamp in an overall system). By progressively establishing the semantic relationships, the energy exchanges that take place in the studied system can be defined.

Another teaching strategy consists of introducing energy as a 'quasi-material' substance. The supporters of this approach, which is in line with students' ideas of energy, justify their choice in pointing out the eminently abstract character of energy. Based on this idea, Duit (1987) and Millar (2005) suggest examining the different types of energy in a qualitative manner before tackling a quantitative, mathematical approach. This is a controversial choice of strategy, whose opponents underline the risk of perpetuating an entrenched false idea (Warren 1982).

Finally, writers agree on the terminological pitfalls, due in large part to everyday language – the meanings and uses of the term 'energy' vary considerably between informal and scientific contexts. Solomon (1985), Chisholm (1992) and Bruguière and colleagues (2002) argue that this problem could be mitigated by simplifying the vocabulary.

To this brief outline, it is fitting to add the work of Koliopoulos and Ravanis (1998), who group the various teaching strategies according to three categories. Their approach differs from those described previously as their classification is based on collected curricula from various countries and not directly on research results. This categorisation thus includes the aims of institutions and the issues that they consider important. So curricula qualified as 'traditional', 'innovative' and 'constructivist' are representative of these orientations.

The traditional curriculum corresponds to a classical mode of exposition in which energy, generally introduced as a concept derived from work, does not have a status in its own right. As a consequence, each field of study in physics requires a specific presentation of the concept, reflecting its many meanings.

The curriculum described as 'innovative' is based on ideas influential in the 1960s that promote the concept of energy by giving it a structural character and granting it a central place in the educational programme. This approach also introduces a social dimension to the learning of the concept.

The constructivist curriculum takes into account the current research orientations presented above. It is characterised notably by the construction of models of the energy chain and draws on students' prior conceptions.

In addition to the strategies outlined above, some writers suggest marshalling the history and philosophy of science in order to facilitate teaching energy. For the most part, the proposals revolve around aligning the difficulties confronted by scientists in the context of the emergence of the concept and students' ideas about energy. This is the case of Trellu and Toussaint (1986), who compare teaching centred on the conservation or transfer of energy; of Agabra (1986), who returns to the various models of heat; and of Duit (1987), who proposes that students could follow the same train of thought as certain nineteenth-century scientists; that is, start from a quasi-material conception of energy (see Sect. 8.4.2).

In contrast, Coelho (2009) draws from the work of Mayer and Joule to propose teaching centred on the notion of equivalence (e.g. heat and work), excluding the question of substantiality, which he supports is a source of confusion (see Sect. 8.4.2).

Generally speaking, the main aim of these proposals is to introduce elements of the history and philosophy of science in order to compare the difficulties of students to those confronted by scientists in the nineteenth century. History is employed here as a useful didactic tool, but little place is given to the cultural and scientific context.

8.3 Methodology for Designing a Teacher Training Programme for Teaching Energy

8.3.1 A New Strategy: Starting with Teacher Training

Although the range of strategies for teaching energy indicates its interest and these strategies contain innovative ideas, none has really managed to impose itself over the others. Teaching energy is considered complex and fragmented. This fragmentation is a result of the lack of connection between the fields of study concerned, which tends to obscure the principal properties of energy and precludes an understanding of the role of the principle of conservation. There seem to be as many meanings of the term *energy* as there are uses and fields of study.

In fact, teachers themselves feel ill-prepared when they have to take on this subject. This is notably referred to in the study mentioned above (Koliopoulos and Ravanis 1998), which aims to identify how experienced teachers teach the concept of energy. While this study shows that the majority of teachers choose traditional teaching methods, it indicates that strategies similar to those described as innovative and constructivist are also used. The latter two strategies are motivated, respectively, by the desire to underline the role of energy, in particular its unifying character, and by the necessity of taking into account students' prior ideas. However, some of the teachers who opt for an innovative approach in fact focus mainly on mechanical phenomena and eventually come back to a traditional approach that introduces energy by deriving it from work, while teachers opting more for a constructivist approach consider themselves poorly armed for incorporating students' conceptions in their teaching.

Furthermore, teachers themselves are not without mistaken conceptions concerning energy, especially in the case of primary school teachers (see, e.g. Summers and Kruger 1992; Trumper et al. 2000). Regarding secondary school teachers or students with science training, Pintó and colleagues (2004) and Méheut and colleagues (2004) highlight confusions regarding irreversibility and real phenomena, cyclical processes and reversibility as well as difficulty in conceptualising the dissipation of energy in the context of its conservation (thus, energy dissipation and conservation seem contradictory).

These various factors regarding teachers' ideas about energy and how it is learned prompt us to delve more deeply into what acts as an obstacle to implementing effective teaching and bring our attention to how teachers themselves are trained. It seems indispensable for teachers to be sufficiently at ease with the concepts to be able to undertake a critical analysis of their teaching practice and to rethink how energy is taught.

Clarifying the concept seems an essential first step to dispel any ambiguities related to the definitions of terms and the properties of the various concepts brought up. The concept of energy is complex, abstract and polymorphous, and the principle of conservation that characterises it is a unifying principle, a 'super law'[3] that structures physics. Explaining the properties and role of the principle leads back to the context of the emergence of the latter in the nineteenth century, to theoretical problems (questions relating to the dissipation of energy and the nature of heat), to experimental situations (the issue of increasing the profitability of machines), to mathematical formalism (the analytic expression of heat required to express the outcome during a Carnot cycle of operations) as well as to the philosophical context, the period being the subject of many debates regarding the founding concepts of physics (Freuler 1995).

This clarification of the concepts should allow the subsequent construction of teaching that highlights the fundamental characteristics of the principle of conservation of energy, defines the concepts related to energy and takes into account, with appropriate vocabulary, the social orientations given by official educational guidelines.

In this context, EHST seems to us an effective and fertile field for elucidating the concept of energy and rethinking how it is taught (on this point, see also Bächtold and Guedj 2012).

8.3.2 EHST in Teacher Training: The Case of France

The role of EHST in teacher training has long interested those who promote a full and authentic science education. In France, in 1902, the institutionalisation of science teaching in secondary school was coupled with the university-level

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[3] This expression comes from Michel Hulin (1992) in his book entitled *Le mirage et la nécessité: pour une redéfinition de la formation scientifique de base*.

development of a general history of science aimed mainly at teachers. Later, in the 1970s, reforms stressed the necessity of transmitting historical knowledge in university programmes as well as in teacher training, including for primary teachers. In mathematics, these reflections were largely the realm of the newly created IREMs.[4] The SFHST,[5] since its creation in 1980, has supported EHST initiatives, which have continued to develop.

In what she describes as the ‘long march’ of EHST education, Fauque (2006) points out that in the 1980s, the concerns of French researchers on the subject were shared abroad. She notes the reach of Bevilacqua’s work at the University of Pavia, leading to numerous educational publications that introduced elements from the history of science based on local archives (primary sources and scientific instruments) into science teaching. In 1983, under the impetus of Bevilacqua and Kennedy,[6] the first international conference was held in Pavia. Many others would follow: at the *Deutsches Museum* in Munich, at *La Cité des Sciences et de l’Industrie* in Paris and in Cambridge, to mention only the first three conferences.

This impetus also resulted in the production of literature by specialist organisations, which allowed teaching proposals to be supplemented by reports on the results of experiments. This was notably the case of the French Physicists’ Union (*Union des Physiciens en France*) and the Association for Physics Education (*Associazione per l’insegnamento della fisica*) in Italy. The work of Shortland and Warwick (1989) in Britain was in the same spirit, with their publication (under the aegis of the British Society for the History of Science) of *Teaching the History of Science*, as was that of Matthews[7] with the creation of the journal *Science & Education*, as well as another work dedicated to this question (Matthews 1994/2014). Although far from comprehensive, this overview testifies to a shared wish to integrate EHST in science education.

Likewise, in France, the place given to EHST in school programmes increased, with its inclusion in core knowledge and skills,[8] in recruitment examinations as well as in the guidelines for teachers’ skills,[9] all aspects of the same approach.

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[4] *Instituts de Recherche sur l’Enseignement des Mathématiques* (Research Institutes for Teaching Mathematics).

[5] *Société Française d’Histoire des Sciences et des Techniques* (French Society of the History of Science and Technology).

[6] P. J. Kennedy was professor at the University of Edinburgh.

[7] University of New South Wales, Sydney.

[8] The core skills are those considered essential to master by the end of compulsory education. The section dedicated to scientific and technological knowledge emphasises: ‘The presentation of the history and the development of concepts, drawing from resources in all the disciplines concerned, is an opportunity to tackle complexity: the historical perspective contributes to providing a coherent vision of science and technology as well as their joint development’ (pp. 12–13).

[9] Secondary school teachers should be able to ‘situate their discipline(s) within its history, its epistemological issues, its didactic problems and the debates that affect it’. *Framework of reference for teachers’ professional skills* (extract from the decree of 19 December 2006 containing guidelines for teacher training, MEN 2007).

In 1999, Lecourt (1999) submitted his report concerning the role of teaching the history and philosophy of science in French universities in which discussed the many factors related to its instruction. Noting the disaffection with studying science, he stressed the necessity of breaking away from the highly technical nature to which science study is often reduced, emphasising the need to give meaning to scientific knowledge and situating it within other types of knowledge – humanising it. Lecourt denounced the harmful effects caused by a lack of EHST education in the curriculum, leading students to adopt an implicit philosophy close to scientism. Several studies reveal the frequent adoption of scientism, whether by students (Désautels and Larochelle 1989) or teachers (Abd-El-Khalik 2001). In the same vein is Paty's (Paty 2000–2001, pp. 56–57) assertion that EHST is essential for discussing the value of scientific truth, while the discourse in society tends to equate revealed truth and scientific truth. Paty reminds us that although scientific truth is relative in the sense that it is incomplete and prone to modification, it has a specific status resulting from a mode of attribution of proof that is clearly identified.

A central element in reflecting on the sciences, in terms of content, methods and links with other fields of knowledge, EHST is essential for reintegrating science in culture. 'Putting science (back) into culture', in the words of Lévy-Leblond (2007), is not a question of creating effective means of transmitting scientific results to the wider public; it is rather about rethinking the sciences, their practice and their methods, in order to produce new, innovative knowledge. Taking up this challenge involves developing critical thinking, too often neglected according to this writer, and prompts consideration regarding the training of scientists. Although referring to the latter, the statement that follows could equally serve as an explanation for the guidelines for teacher training mentioned above:

> Can we continue to train professional scientists without giving them the least element of comprehension of the history of science – concerning their discipline first of all – and of the philosophy, sociology and economy of science? The tasks they now face in practicing their occupation, and the social responsibilities that they can no longer ignore, require them to have a broad conception of scientific work. How can we believe any longer that science is different in this regard than art, philosophy or literature, fields of human activity that no one would imagine teaching independently from their history? (Paty 2000–2001, pp. 13–14)

Training future scientists and educating the citizens of tomorrow necessitate bringing together diverse skills, which we should remember are already widely present in school programmes. Martinand (1993, p. 98) comes to the same conclusion when he emphasises shortcomings in future teachers uninformed about the practices and culture of science: 'The "mission" of the history and the epistemology of science is to enrich research and reflection about its practice, evolution and foundation, without an immediate didactic aim.'

Lastly, in a more specific way, EHST education supports the teaching of scientific disciplines through an epistemological examination of problems, concepts and theories. In the study previously mentioned, Martinand points out that thanks to its critical and prospective function, EHST allows encountered problems to be clarified and teaching content to be questioned in order to better understand its integration in school programmes. Epistemology ‘at the service of education’ should supplement the orientations developed above.

8.3.3 The Proposed Approach

In the context of the study of energy, the aforementioned approaches lead to a re-examination of the foundations of the concept and its emergence in order to understand its role, properties and functions. This should allow the concept, its principle of conservation and its related concepts (in particular, work, force and heat) to be clarified. All of these steps are essential for teachers. The development of this approach, which enlists the acquisition of ‘scientific culture’, is a first line of research. Using EHST at the service of teaching energy will be a second, future line of research.

8.3.3.1 EHST in Teacher Training for Teaching Energy

The rest of this article (see Sect. 8.4) will focus on the first line of research. How should teacher training based on EHST be designed to help teachers acquire scientific culture around energy? To develop the beginning of a response to this, we have drawn from many existing works, not only in the field of EHST,[10] but also in science education.[11] Based on these works, we have created a general framework for teacher training on energy, which aims to include all the aspects of the concept and to introduce them according to the most logical progression of ideas possible. We have striven to avoid the pitfall of drowning teachers in an overly complex and detailed history and epistemology of the concept of energy. In particular, the cultural and scientific contexts are not examined in detail, as they would be in a historical study.[12] The aim is to make the use of history and epistemology functional and accessible to teachers. Furthermore, to be both relevant and enlightening, such a historical and

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[10] Several historical and epistemological studies on energy were published by scientists and/or philosophers of science at the end of the nineteenth century and the beginning of the twentieth century (e.g. Mach, Planck, Poincaré, Meyerson and Cassirer). Later, Kuhn’s (1959) article encouraged science historians to carry out new investigations on the emergence of the concept in the nineteenth century (e.g. Elkana 1974; Truesdell 1980; Hiebert 1981; Smith and Wise 1989; Caneva 1993; Smith 1998; Ghesquier-Pourcin et al. 2010). It should be noted that the history of the concept of energy over the course of the twentieth century, with the advent of the theory of relativity (special and general relativity) and of quantum mechanics, as well as the importation of the concept in many other fields (chemistry, biology, economics, arts, etc.), has not yet been well studied.

[11] See in particular the literature indicated in Sect. 8.2.

[12] For further information on these aspects, see the references in the previous footnote.

epistemological introduction must be centred on physical content. Hence, we suggest the teacher training programme could be organised around three points[13]:

What is the origin of the concept of energy?
The investigation of this question aims to challenge the idea that the concept of energy, with the meaning attributed to it today, was always available for scientists. The goal of teacher training here is not only to make teachers aware that the current accepted scientific understanding of the concept only stabilised in physics in the middle of the nineteenth century but also to supply teachers with information to help them understand why it stabilised at this time and how the process of this stabilisation came about.

What is energy?
So that teachers can fully grasp the meaning of the concept of energy, teacher training should clarify all characteristics of the concept (i.e. energy is a quantity associated with a system, it can take different forms, it can be transformed and transferred; see Sect. 8.4), rather than reducing it to the principle of conservation of energy. When dealing with this question, it also seems appropriate to discuss incorrect ideas that can be obstacles to learning the concept.

What purpose does the concept of energy serve?
So that teachers understand and can explain to students the omnipresence of the concept of energy in the curriculum, teacher training should clarify the different functions that this concept allows to be performed in scientific work.

This framework, which will be elaborated upon in Sect. 8.4, makes up the first step of the creation of a teacher training programme, which can then be enriched with examples of possible course outlines and teaching sessions on energy (see the second line of research presented below) and added to allowing for constraints on the ground (type of teacher, available time, equipment and resources, etc.). We then plan an experimentation phase for the training programme in order to assess its impact and attain an empirical response that will enable us to improve it.

8.3.3.2 Using EHST to Rethink the Teaching of Energy

The second line of research mentioned above, that is, EHST at the service of teaching energy, is the subject of a study currently in progress that will be expounded in an upcoming article. Our first hypothesis, which is the basis of this study, is that a teacher training programme on energy based on EHST should profoundly redefine

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[13] The inspiration here is from Papadouris and Constantinou (2011, p. 966), who ‘take the perspective that any attempt to promote students’ understanding about energy should primarily address the question ‘What is energy and why is it useful in science?’. However, we diverge from these writers’ approach on several points: we maintain that it is pertinent to include the question of the origin of the concept of energy; we suggest approaching the three questions drawing on EHST; and, lastly, we do not provide the same answers to the questions posed.

the way in which teachers themselves envisage teaching about energy. More specifically, this teacher training programme should lead teachers towards:

- A new insight into educational programmes (a better global overview as well as an understanding of the relationship between the different sections of these programmes)
- A reflection on their own ideas about energy and its related concepts (e.g. work, heat)
- A new way of taking into account students' prior conceptions
- A review of practices in teaching energy (in terms of the coherence of planned teaching sessions, the organisation of the content, the method used to develop knowledge and, in particular, the relationship between theory and experimentation and the formulation of problems)

The objective of this research study is to come up with concrete proposals for course outlines and teaching sessions on energy making use of EHST. In these proposals, we intend to supply examples of teaching about energy that do not call on the history of science as an optional extra (the 'add-on' approach; see Matthews 1994, p. 70), but rather place it, and epistemology, at the centre of instruction. Our second hypothesis, which remains to be tested, is that such teaching should allow the many difficulties related to the acquisition of the concept of energy to be more easily overcome (see Sect. 8.2).

8.4 Framework for Teacher Training on Energy Based on the History and Epistemology of the Concept

8.4.1 What Is the Origin of the Concept of Energy?

The absence of historical perspective encourages the illusion of the immutable nature of scientific concepts and theories, as if these have always been available for scientists and cannot be challenged or revised in the future. The same is true for the concept of energy. The fact that today it is omnipresent in physics and the other sciences makes it difficult to imagine that only 200 years ago it was not yet fully part of the armoury of physics. So that teachers understand the concept of energy and can grasp its meaning and utility (see Sects. 8.4.2 and 8.4.3), it seems crucial that beforehand they are clear about its origin: where does the concept of energy come from – or, in other words, why and how was this concept introduced in physics?

The first fundamental point that should be emphasised is:

> In its accepted scientific meaning, the concept of energy is inseparable from the principle of its conservation which was established in the middle of the nineteenth century.

This point is expressed by Balibar (2010, p. 403) in this way: 'The concept of energy only became a physics concept from the moment it was irreversibly established that a law of energy conservation exists'.

This initial point guides the rest of our discussion, since it leads us to replace the question 'What is the origin of the concept of energy?' with 'What is the origin of *the principle of conservation* of energy?' This latter question can be approached from two perspectives: one centred on the people who participated in the emergence of the principle and the second centred on the epistemic factors that played a role in this emergence, namely, experimentation and reasoning. These two perspectives should be combined to avoid the risk of a truncated answer.

Concerning the first perspective, the history of energy is particularly instructive for teachers, whose historical idea of science often consists merely of a succession of 'discoveries' made by isolated geniuses – discoveries that are considered independently of context (scientific, technological, philosophical, etc.) (see, e.g. Gil-Pérez et al. 2002, pp. 563–564). The case of the principle of conservation of energy is illustrative of this. The historical study of its emergence is an opportunity to challenge and enrich the vision that teachers have about the history of science.

> The principle of conservation of energy emerged in the middle of the nineteenth century following different research projects led by several scientists (among others, by Mayer, Joule and Helmholtz) influenced by their scientific, technological, philosophical and religious context.

Three points merit emphasising to teachers. Firstly, the principle was not discovered by an isolated genius. This point was underlined by Kuhn (1959), who lists no less than 12 scientists that 'simultaneously' participated in the 'discovery' of the principle.[14]

Secondly, the term *emergence* is more relevant than discovery, because the latter suggests an image that does not comply with the history of the principle – as if it pre-existed all scientific research and was suddenly revealed. This misleading image obscures the work of *construction* carried out by scientists. In fact, energy with all its properties (see Sect. 8.4.2) is not directly observed in nature. Before scientists could accept energy as a physical reality, they first had to construct and stabilise the concept. This construction was progressive, not the result of one action. During the seventeenth and eighteenth centuries, the precursors of the energy conservation principle (e.g. Leibniz, Huygens, Jean Bernoulli, Lagrange) prepared the groundwork for this construction in the field of mechanics by forging and developing the concepts of *vis viva* or living force (the ancestor of kinetic energy) and *vis mortua* or dead force (the ancestor of potential energy) and by establishing as a theorem, in the middle of the century, the conservation of these two quantities in idealised and isolated mechanical systems – this theorem being identified a century later as a particular case in the energy conservation principle (see Hiebert 1981, pp. 5 and 95). It should also be pointed out that in the middle of the nineteenth century, scientists that contributed to the emergence of the principle 'were not saying the same things' (Kuhn 1959, p. 322) or, as Elkana notes (1974, p. 178), they came up with solutions

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[14] In the order of occurrence in Kuhn's text: Mayer, Joule, Colding, Helmholtz, Carnot, Séguin, Holtzmann, Hirn, Mohr, Grove, Faraday and Liebig. This list is not meant to be exhaustive, and other scientists could be added, such as W. Thomson (Lord Kelvin) and Rankine, whose contributions came later but were no less conclusive.

to ‘different problems’. It was only progressively, over the course of the 1850s, that the different quantities of living force, work, heat, etc. were identified as examples of the same quantity – that is, energy – and that the new ideas defended by these scientists were recognised as equivalents, bringing to light the conservation of this quantity (see Elkana 1974, p. 10, Guedj 2010, p. 118).

Thirdly, the emergence of the principle cannot easily be understood independently of its scientific, technological, philosophical and religious context. In terms of the scientific context, the decisive elements were of both a theoretical and experimental nature. As we mentioned above, the principle of conservation of living force and dead force was established in the middle of the eighteenth century. However, this principle had limited impact and fell within the framework of nonconservative rational mechanics, which took into account the existence of an observed loss of living force during collisions. It was not until a new generation of engineers (Navier, Coriolis, etc.) proposed a molecular approach that rational mechanics would be transformed to conservative mechanics, in which the loss of living force is considered only apparent. This was an essential step towards the construction of a general principle of energy conservation (on this point, see Darrigol 2001). To these concerns related to mechanics must be added those regarding heat. In the first half of the nineteenth century, the idea that living force could be converted into heat (today we refer to the conversion of kinetic energy into thermal energy) appeared. During this period, many other conversion processes were experimentally brought to light, establishing the relationships between different fields (heat science, mechanics, chemistry, electricity, magnetism, animal physiology, etc.).

The technological context also had a major influence. The development of steam engines and electric machines played a significant role in the theoretical developments of the first part of the nineteenth century. For example, the scientific concept of work, essential in the formulation of the principle of energy conservation, was derived by scientists from accumulated experiments in the field of mechanical engineering (see Kuhn 1959; Elkana 1974, pp. 40–41; Vatin 2010).

Lastly, historians of science also accept the influence of the philosophical and religious context, although these are more complex to grasp. The metaphysical idea[15] of the equality of cause and effect, as formulated in particular by Leibniz, was shared by many of those involved in the emergence of the principle (e.g. Mayer, Helmholtz) and motivated them to search for a conserved physical quantity (see Mach 1987 [1883], pp. 474–475; Meyerson 1908, pp. 181–184; Kuhn 1959). Nor are religious considerations absent from scientific reasoning. Citing, for example, Joule:

> We might reason, *a priori*, that such absolute destruction of living force cannot possibly take place, because it is manifestly absurd to suppose that the powers with which God has endowed matter can be destroyed any more than they can be created by man’s agency. (Joule 1847)

This perspective centred on the participants involved contributes vital information about the origin of the principle of conservation of energy and situates it in its context. However, it also seems important to combine this perspective with one

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[15] By ‘metaphysical’, we mean an idea that precedes any scientific research.

centred on epistemic factors, namely, reasoning and experimentation, so that teachers have a full understanding of the nature of the principle. The question of the origin of the principle could be posed in the following terms: (i) Is the principle an empirical law (an a posteriori law) resulting from experimental investigation or (ii) is it a metaphysical principle (an a priori principle) established by reasoning?[16] Teachers are inclined to opt for option (i), in accordance with the inductivist 'naïve' conception of the scientific approach that they tend to spontaneously adopt.[17] However, the history of science reveals that neither of these alternatives 'conforms to the historical truth', as Meyerson states (1908, p. 175). The response is found midway between them:

> The principle of conservation of energy is the result of a mutual adjustment between an a priori question posed by scientists searching for a quantity conserved during all transformations and the experimentation that allowed what this quantity is to be determined.

How can this interrelationship between the empirical aspect and the a priori aspect in the emergence of the principle be illustrated in teacher training? Taking our inspiration from Meyerson (1908, pp. 175–190), we suggest first examining option (i) in light of Joule's experiments and then option (ii) in light of the principle of the equality of cause and effect.

In an article from 1847, Joule claimed to have established on the basis of several experiments that living force can be converted into heat and that, inversely, heat can be converted into living force,[18] without anything being lost during the two conversions:

> Experiment […] has shown that, wherever living force is *apparently* destroyed, an equivalent is produced which in process of time may be reconverted into living force. This equivalent is *heat*. […] In these conversions nothing is ever lost. (Joule 1847, pp. 270–271)

This idea of mutual convertibility without loss is not strictly equivalent to the principle of conservation of energy, but is an important step towards it: it was yet to be accepted that living force and heat were two examples of the same quantity – energy – or to generalise the specific case of mutual convertibility without loss between living force and heat to all possible conversions between different forms of energy. Two of Joule's experiments could be presented in teacher training to illustrate mutual convertibility: the first demonstrating the conversion of living force to heat (the famous experiment during which a falling mass rotates paddles in a liquid and through the effect of friction causes the

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[16] It should be noted that advances in the mathematical sophistication of the laws of physics were a necessary precondition for the emergence of the principle.

[17] See, for example, Robardet and Guillaud (1995, Chap. 3), Gil-Pérez et al. (2002, p. 563), Johsua and Dupin (2003, pp. 215–217) and Cariou (2011, pp. 84–86). A survey of teachers would be worth carrying out to corroborate this hypothesis regarding their choice of option (i).

[18] In accordance with current terminology, one should speak of the mutual convertibility between kinetic energy and thermal energy (a form of energy, as distinct from heat, or 'thermal transfer', which is a mode of energy transfer).

temperature of the liquid to rise) and the second demonstrating the inverse conversion (the experiment on the expansion of heated air).

These two experiments carried out by Joule indeed demonstrate the mutual convertibility between living force and heat. The problem is that they do not prove the absence of loss during each conversion. To do this, the first experiment would need to establish that a given quantity A of living force always results in exactly the same quantity B of heat, while the second experiment would need to establish that quantity B of heat always results in exactly the same quantity A of living force. Yet for the first experiment, Joule's initial results in the 1840s were marred by significant dispersion and were obtained on a temperature scale too small to be accepted. This explains why, as Truesdell points out (1980, p. 180), Joule's contemporaries, such as W. Thomson, Helmholtz and Rankine, 'were reluctant to accept his early results'. In the second experiment, the problem was even more serious: as W. Thomson (1852) indicated, 'full restoration' of heat in living force (Thomson speaks of 'mechanical energy') is in practice 'impossible' because of the phenomenon of the 'dissipation' of energy. For this reason, contrary to what he asserts in his writings, Joule was not in a position to be able to experimentally establish the mutual convertibility *without loss* between living force and heat. This examination of the case of Joule suggests the dismissal of option (i): historically, the principle of energy conservation was not drawn directly from experiments.

Turning to option (ii), according to which the principle was established by a priori reasoning, several scientists that contributed to the emergence of the principle (e.g. Mayer, Helmholtz) presented the principle of energy conservation as a consequence of the principle of the equality of cause and effect. For example, here is what Mayer wrote in 1842:

> Forces are causes: accordingly, we may in relation to them make full application of the principle: *Causa aquet effectum*. […] In a chain of causes and effects, a term or a part of a term can never […] become equal to nothing. This first property of all causes we call their indestructibility. […] Forces are therefore indestructible, convertible, imponderable objects. (Mayer 1842, quoted and translated by Truesdell 1980, p. 155)[19]

The principle of equality of cause and effect can certainly be interpreted in terms of the conservation of a quantity in a relationship of cause and effect (a quantity that is instantiated first in the cause and then in the effect), but does not in any way determine what this conserved quantity is. In fact, different options have been favoured by scientists through history: in the seventeenth century, Descartes thought it was the 'quantity of motion' (the ancestor of momentum)[20]; soon after, Leibniz suggested

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[19] As stressed by Caneva (1993, pp. 25–27, 46 and 323), Mayer came to this idea of the conservation of 'force' (an ancestor of energy) by making an analogy with the conservation of matter (the latter being still implicit in physics and chemistry at the time of Mayer and made explicit by him). This 'guiding analogy' can also be considered as an a priori reasoning towards the principle of conservation of energy.

[20] Unlike momentum as it is defined today, Descartes' 'quantity of motion' (*quantité de mouvement*) was a scalar and not a vector quantity. See Descartes (1996 [1644]).

it was living force[21]; throughout the eighteenth century, scientists preferred Leibniz's proposition; from the second half of the eighteenth century, Lavoisier put forward the caloric theory (the caloric being conceived as a conserved 'fluid' that is the 'cause of heat')[22]; it was finally in the middle of the nineteenth century that a new concept of energy, conceived as a more general quantity capable of taking the form of living force and of heat, was accepted as the conserved quantity. In other words, although scientists indeed had an a priori idea of the existence of a quantity conserved during any transformation, energy could not be identified as the quantity sought without the aid of experiments and, in particular, without the many conversions demonstrated in the first half of the nineteenth century.

One last point concerning the origin of the principle of conservation of energy warrants clarification for teachers so that they grasp its role in the theoretical structure of physics. It should be noted that it was first described as one of the two 'principles' of *thermodynamics* (as first formulated in the 1850s) before being considered as a principle of *physics* (i.e. of thermodynamics but also of other physics theories that developed later, such as electrodynamics, special and general relativity and quantum mechanics). Establishing the conservation of energy as a principle has two implications: (a) this proposition is asserted as true without requiring that it be demonstrated by other propositions, and (b) it acts as an axiom on which other propositions in physics are based.

Points (a) and (b) each give rise to the questions: 'What justifies that the proposition of the conservation of energy is asserted as true?' and 'Why adopt this proposition as an axiom of physics?' The history of energy that we have just outlined in broad strokes leads to an initial answer to the first question: although neither experiments nor reasoning allows conclusive proof of the truth of energy conservation, both offer elements that corroborate this conclusion. A second answer can be found in Cassirer's analysis (1929 [1972], p. 508) of the relationship between a principle and an experiment: it is legitimate to accept the 'validity' of a principle on the strength of the accordance of all the consequences that can be derived from experimentation. To the second question, a possible answer is the following: scientists choose the conservation of energy as an axiom of physics because of its functional character (see Sect. 8.4.3).

8.4.2 What Is Energy?

It is difficult to describe what energy is and to give it a definition that encompasses a consensus. For this reason, some scientists put forward the minimal definition that describes energy as a quantity that is conserved. Thus, Poincaré argues (1968 [1902], pp. 177–178): 'As we cannot give energy a general definition, the principle

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[21] On the controversy between Descartes and Leibniz on this point, see, e.g. Iltis (1971).

[22] See Lavoisier (1864 [1789]).

of conservation of energy simply means that there is *something* that remains constant.' Likewise, Feynman writes:

> There is a fact, or if you wish, a *law*, governing all natural phenomena that are known to date. There is no known exception to this law—it is exact so far as we know. The law is called the *conservation of energy*. It states that there is a certain quantity, which we call energy, that does not change in the manifold changes which nature undergoes. That is a most abstract idea, because it is a mathematical principle; it says that there is a numerical quantity which does not change when something happens. […] It is important to realize that in physics today, we have no knowledge of what energy *is*. (Feynman 1963, 4.1–4.2)

It is true that the principle of conservation of energy is the integral core of the concept of energy. It is also true that the concept of energy is very abstract: not only does it describe a quantity of which we have only very indirect experimental access through the intermediary of the measurement of other quantities (such as speed or temperature), but additionally, it does not refer to a particular type of phenomena (e.g. mechanical or thermal), but to all phenomena. This is why certain science education writers, such as Warren (1982, 1991), argue the concept should not be taught in primary school, but only when students have mastered the mathematical tools that allow them to apply the principle of conservation of energy.

We believe that teaching energy by defining it uniquely as a conserved quantity and limiting it to mathematical operations of the principle of its conservation is largely inadequate for understanding its meaning. Teacher training should explicitly identify, explain and relate all the characteristics of energy (we distinguish eight) that remain implicit in traditional teaching. It seems useful, at the same time, to point out the recurrent incorrect ideas of students and teachers – on the one hand, so that they grasp what energy is *not* and, on the other hand, so that they are aware of the stumbling blocks of learning the concept. History and epistemology of the concept of energy should be included in teacher training as these bring valuable perspective on its different characteristics. Below we set out the eight characteristics of energy and outline one possible way to approach them. The first is:

(1) Energy is a quantity associated with a system.

We suggest introducing this characteristic in a discussion of the substantialist conception of energy, which is the idea that is most recurrent and most ingrained in students' and teachers' minds and thus also the most difficult to overcome. The merit of the substantialist conception is that it allows us to think more easily about the conservation of energy. This is why, rather than dismissing this conception out of hand, one could imagine taking advantage of it. The history of science is here a source of inspiration. As Duit notes (1987, pp. 140–141), referring to Planck (1887), the analogy of the conservation of energy to the conservation of matter played an important role in the acceptation of the former. According to Duit, introducing students to the conception of energy as something 'quasi-material' allows this quantity to be presented as something more 'concrete' or 'tangible' and so aids in understanding it (see also Millar 2005). This proposal seems useful in the context of teacher training. However, it is important to stress to teachers, first, that this conception is an *analogy* and, second, its limitations.

The first limitation of the substantialist conception is in fact characteristic (1): energy is a physical quantity associated with a system; that is, it does not exist autonomously, independent of a system. Or as Bunge writes (2000, p. 459): ‘All energy is the energy of something.’ In order to avoid the erroneous conception that a system plays the role of a reservoir of energy (the ‘depository model’; see Watts 1983), it should be emphasised, as by Millar (2005, p. 4), that energy is not *in* a system, i.e. it is not ‘contained’ or ‘stored’ by it, as can be gasoline in a tank, for instance. In physics, it is a question of the energy *of* a system, i.e. energy is a ‘state quantity’, a variable quantity determined by the state of the system and indicating the system’s capacity to produce change (see characteristic 3).

The second limitation of the substantialist conception concerns the two components of mechanical energy that are characterised by a second level of relativity. Kinetic energy is relative to the frame of reference considered (because speed, which features in the expression of kinetic energy, is itself relative to the frame of reference). The potential energy is doubly relative: it depends on the presence and the position of other systems but also on the choice of the coordinate system used to determine its value.[23] This double relativity of potential energy was put forward by Hertz (1894), who noted that a quantity capable of assuming negative values would not be able to be interpreted as representing a substance.[24]

We should add that, in the framework of special relativity, this second limitation is generalised to the total energy of a system, which is relative to the frame of reference considered.

To sum up, comparing energy with matter appears to be a useful analogy favouring the acquisition of the principle of conservation of energy. Nevertheless, as is the case for any analogy, this quasi-material concept has some limitations: energy is not an autonomous substance and its value is not absolute. To avoid teachers taking this concept literally, it is essential to emphasise that it is only an analogy and explain its limitations.

The concept of ‘system’ used here may seem self-evident. However, as several science education writers have emphasised (Trellu and Toussaint 1986, pp. 68–69, Arons 1999, p. 1066, van Huis and van den Berg 1993), in order to understand the conservation principle and be able to unambiguously describe energy exchange, it is essential to clearly define what a system is and to specify the boundaries of the system for each situation considered. In particular, when defining a system, it is important to stress the distinction between the system, which is the object (or group of objects) that we want to describe, and its ‘environment’, with which it can interact, and thus exchange energy (see characteristics 6 and 7), and/or with which it can exchange matter.

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[23] Note that, in classical mechanics, potential energy depends only on the relative distances between the interacting bodies. Therefore, if all these interacting bodies are included in the system, the potential energy of this system no longer depends on the choice of the coordinate system.

[24] Hertz actually rejected potential energy, emphasising the role of the kinetic energy of hidden masses.

The second characteristic of energy is an extension of the first:

(2) Energy is a universal quantity: it is associated with all systems and all fields of science.

As Bunge writes (2000, p. 459): 'Energy is the universal physical property.' However, he restricts the field of application of this property to material objects only. Yet it is important to underline that energy is also a quantity associated with all electromagnetic radiation. In addition, this quantity has a universal character due to the fact that it applies to all fields of science: physics, chemistry, biology, geology, physiology, etc.[25]

When we express the universality of the quantity of energy in this way, it is important to draw attention to a possible inversion that should be avoided regarding the historical process. Scientists did not first identify energy in a particular branch of physics and then discover that this quantity was also associated with systems being studied in other branches of physics as well as in other scientific fields. On the contrary, it was the connection between the different branches of physics and other scientific fields (in particular, heat science, mechanics and physiology) that led to the emergence of the concept of energy (see Kuhn 1959). Its universality and its correlative function of unification (see Sect. 8.4.3) are the constituent features of the concept.

For us, this partly explains the abstract nature of the concept of energy: if it is abstract, this is notably because of its universal reach. Indeed, the concept must achieve a certain level of abstraction in order to subsume all forms of energy and be universal. In other words, it was through a process of abstraction based on concrete phenomena in each branch of physics and field of science that the concept of energy was formed.

Saying that energy is a quantity associated with a system is still a very limited characterisation of energy and does not enable it to be distinguished from other quantities. Certain science education writers (e.g. Warren 1982, 1991) argue that the energy of a system should be defined as its 'capacity for doing work', because this definition is necessary for thinking about the different forms of energy, as well as the conservation of energy. Other writers (e.g. Sexl 1981; Duit 1981; Trumper 1991) disagree with this definition as it is restricted to the field of mechanics; in other words, it suggests that the effects or changes a system is able to produce by virtue of its energy are merely mechanical (i.e. work). This criticism is understandable. But why not retain the definition of the energy of a system as its capacity to produce *change*? The main objection of Duit (1981, p. 293) is the following: 'The ability to bring about changes can also justifiably be attributed to a number of other physical concepts (for example, force and torque).' However, this objection is not admissible in our view. First, energy is a quantity that is the property of *one* system, while the quantities mentioned by Duit, such as force and

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[25] It should also be noted that energy is equally employed in the social sciences: economics, psychology, sociology, etc. However, the meaning of the concept of energy and the uses made of it are not necessarily the same as in the physical sciences.

torque, model the action of one system on another. Second, the changes produced by force or torque occur simultaneously with its application, while the changes a system can produce by virtue of its energy are only potential: that is, only energy describes the *capacity* of a system to produce change.

Even if slightly different definitions of energy may be available (namely, in terms of work or in terms of change), it is essential to provide teachers and students with this definition of the capacity to produce change. It not only aids in clarifying the physical meaning of the concept of energy and thus in distinguishing it from other physical quantities but is also necessary for thinking about characteristics (4)–(8) of energy. Taking our inspiration from several writers, such as Chisholm (1992), Bunge (2000), and Doménech and associates (2007), without following them exactly,[26] and in line with French *collège* programmes (see Sect. 8.2.1), we propose the following definition, which we identify as the third characteristic of energy:

(3) The energy of a system is its capacity to produce change (within the system or in other systems).

Now let us turn to the other characteristics of energy and show why this definition is necessary to understand them properly. The fourth characteristic can be expressed as:

(4) Energy can take different forms.

Here it is worth restating the possible inversion of the historical process as mentioned above, though expressed in slightly different terms. Scientists did not first discover energy as a well-defined quantity appearing in a particular form (e.g. kinetic energy) before searching for and discovering the other forms in which it can also appear (e.g. thermal energy, electric energy). They first defined distinct quantities representing distinct physical realities (e.g. living force, work, heat), before making the connections between them and conceiving of them as examples of the same quantity.

Only by defining the energy of a system as its capacity to produce change gives meaning to the idea that distinct quantities representing distinct physical realities are examples of the same quantity. In fact, the only point in common between these different quantities lies in their capacity to produce the same changes. For this reason, in our view, it is the equivalence of these quantities in terms of the capacity to produce the same changes that justifies considering them as different expressions of one and the same quantity – energy.

The following historical fact supports our argument: the identification in the 1850s of the different quantities of living force, work, heat, etc. as examples of energy

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[26] Chisholm (1992, p. 217) writes: ‘Energy […] produces changes.’ Bunge (2000, p. 458) identifies energy with ‘changeability’. For us, these two definitions do not adequately elucidate the idea of capacity. Doménech et al. (2007, p. 51) define energy ‘as the capacity to produce transformations’. We criticise this definition for the use of the term ‘transformation’ rather than ‘change’. The latter term is more general than the former and, in particular, can include variation in the value of a quantity (such as temperature or speed), which is not usually described as a ‘transformation’.

recognised as being the conserved quantity is concurrent with the introduction of the definition of energy as the 'capacity to effect changes' or 'capacity for performing work' (Rankine 1855, pp. 125 and 129).[27]

The adoption of this definition of the energy of a system as its capacity to produce change led to the reconsideration in a new light of the common conception of kinetic energy as 'actual energy' (to use Rankine's term, 1855), a form that would appear directly to us through the movement of a material system. Certainly, the speed v and mass m of a studied system determine its kinetic energy, and we have relatively direct experimental access to these quantities. Yet that which justifies considering the formula $\frac{1}{2}mv^2$ as the expression of *energy* is not the manifestation of the movement itself, but rather the potential effects of this movement, or in other words, the capacity of the system driven by this movement to produce change (e.g. the ascent of the system up a slope or the deformation of a second system following a collision). This is why we challenge the assertion of certain writers (see Agabra 1985, pp. 111–112) that the concept of potential energy is much less accessible than that of kinetic energy. Although learners may easily accept the statement that a material system in movement possesses 'kinetic energy', that does not mean that they have understood the meaning of the concept of energy. Unless they recognise potential energy as a possible form of energy in the same right as kinetic energy and this by virtue of their common capacity to produce change, it is not guaranteed that the term 'kinetic energy' means anything else to them apart from movement (that is to say, a form of activity).

In addition, so that teachers have a global view of the forms of energy, we think it is important to eliminate the boundary raised in secondary and university education between energy in mechanics and energy in thermodynamics, which is at odds with the historical origin of the concept. As too few textbooks (e.g. Pérez 2001, pp. 90–92) or science education writers (e.g. Cotignola et al. 2002, p. 283) point out, the total energy of a material system is the sum of its mechanical energy (itself equal to the sum of the kinetic energy and the potential energy of the system considered at the macroscopic level and in relation to other systems) and its internal energy (equal to the sum of the molecular kinetic energy, or thermal energy, and the potential energy of interactions, such as chemical or nuclear energy, of the system considered at the level of its microscopic constituents and independently of other systems). In mechanics, if only mechanical energy is considered, this leaves out, on one hand, the processes of thermal transfer between the studied system and its environment and, on the other hand, the changes in the internal makeup of the system. In thermodynamics, if only internal energy is considered, this leaves out, on one hand, the movement of the system considered at the macroscopic level and, on the other hand, the external fields to which the system is subjected. As for electromagnetic radiation, the form of energy associated with this is unique – electromagnetic energy (which is the sum of the energy of the constituent photons in radiation).

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[27] As observed by Roche (2003, p. 187), 'Rankine attributes this definition to Thomson', who 'in 1849, in an almost casual way […] first used the term energy in print more generally to mean the amount of work any system can perform.'

The definition of energy in terms of capacity to produce change helps to give meaning to characteristic (4) and, in correlation, to the following characteristic:

(5) Energy can be transformed or, in other words, can change form.

Certain writers' main concern is to avoid establishing or reinforcing the substantialist conception of energy in learners' minds. To this end, Coelho (2009, p. 978) suggests describing conservation in conversion processes solely in terms of equivalence. In his view, in Mayer's and Joule's experiments on the conversion of work into heat, conservation can be understood simply through the idea that a quantity (of work) is converted into an *equivalent* quantity (of heat). The idea of the 'indestructibility' and the 'transformability' of the same entity (energy), thus acquiring the characteristic of a substance, is simply not needed. The problem with this minimal approach appears when we pose the question: in what way are the quantities of work and heat equivalent? In our point of view, the only possible response is that they are equivalent in regard to the capacity to produce change.

These experiments on the conversion of work into heat can be described as transformation experiments, or of changing one form of energy into a new form of energy. However, in the absence of a clear distinction between *form of energy* and *mode of energy transfer*, confusion could arise in learners' minds. This type of confusion is often found in certain textbooks in relation to the concept of heat (see Cotignola et al. 2002, pp. 284–286, Papadouris and Constantinou 2011, p. 970). Work and heat are modes of energy transfer. Although in Joule's experiment there was indeed conversion from one form of energy into another, it was the transformation of kinetic energy into thermal energy, occurring simultaneously to a transfer of energy (namely, from the 'paddle' system to the 'liquid' system). The possibility of energy to be transferred or exchanged should thus be considered as a characteristic independent of its possibility to be transformed:

(6) Energy can be transferred from one system to another.

Given that the ideas of heat as a property of a body (a form of energy of a body) or as an independent substance (a sort of fluid) are very frequently held by students and can also persist in some teachers (see Gilbert and Watts 1983, pp. 78–79, Driver et al. 1994, pp. 138–139), it seems essential to explicitly discuss them in teacher training. Three themes seem worth developing. The first simply involves pointing out that the term 'heat' can be replaced by 'thermal transfer'. The second consists of emphasising the meaning of each term in the usual mathematical formula of the first law of thermodynamics: $\Delta U = Q + W$. The term on the left describes the change in internal energy U, which includes the internal forms of energy *of the system*, while the two terms on the right describe the modes of energy exchange (Q is thermal transfer and W is work performed on the system by its surroundings) *between the system and its environment* that are responsible for a change in the internal energy of the system (see Arons 1989, p. 507, van Huis and van den Berg 1993 and Cotignola et al. 2002, p. 287). A third theme consists of exploring the history of the theories of heat (see Brush 1976) stressing four stages: (i) the first part of the nineteenth century, a period of confrontation between the substantialist conception in terms of a fluid (a conserved substance distinct from living force) and the mechanistic conception in terms of the movement of the constituent particles of a body; (ii) the rise and fall of the wave theory in the 1830s (one relic of which is the mistaken idea that heat can be propagated by electromagnetic radiation in the same way as conduction or convection); (iii) the interpretation of the experiments of the conversion of work into heat in the 1840s, contributing to the abandonment of the substantialist conception in favour of the mechanistic conception but with the idea that heat is a form of energy rather than a mode of energy transfer (there was still no clear distinction between 'thermal energy' and 'thermal transfer', the latter term being a synonym of 'heat'); and (iv) the microscopic interpretation of heat in terms of microscopic work at the molecular level in the context of the kinetic theory of gases, allowing heat to be eventually understood as a mode of energy transfer. This historical approach allows teachers to consider the two recurrent mistaken conceptions mentioned above and to clarify why they have been ruled out, rather than simply asserting that they are incorrect.

As energy can be transferred from one system to another, it is possible that the energy of a system can be transferred to and, by the same token, split between large numbers of subsystems in its environment. In this case, one refers to 'dissipation':

(7) Energy can be dissipated in the environment.

Several writers (Solomon 1985, p. 170, Duit 1984, p. 65, Goldring and Osborne 1994, p. 30) have suggested that students' difficulty in understanding the idea of the conservation of energy can be surmounted (at least in part) by first introducing the concept of the dissipation of energy.

To deal with this concept of dissipation in teacher training, we suggest starting from the problem of loss that Thomson confronted and tried to resolve in his articles from 1851 to 1852 (Thomson 1851, 1852, see Guedj 2010): in steam engines, it is observed that only part of the heat is converted into useful work[28]; the other part is lost or 'wasted'. What happens to the part that is lost? Is it a question of 'absolute waste', that is, the destruction of part of the heat? Thomson's response came in two stages. In his 1851 article, he developed Joule's idea according to which energy can never be *destroyed* ('mechanical energy' in his words), but only *transformed*. Therefore, the apparent loss of energy is a loss for human beings (who want to use it in machines) and not an absolute loss: the energy in question is 'lost to man irrecoverably; but not lost in the material world'. In his 1852 article, Thomson further clarifies his response by introducing the fundamental concept of *dissipation*. In a steam engine, part of the mechanical energy dissipates via heat because of friction between different parts of the engine, which are inevitable in practice. As it is 'dissipated', that is, divided between large numbers of subsystems of its environment, this energy is 'irrecoverably wasted'. This historical approach has at least two points to recommend it. First, in experiments that they carry out and/or study, teachers are constantly confronted by this problem of the apparent

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[28] In the viewpoint of current physics, it is a question of the transformation of 'thermal energy' into 'mechanical energy'.

disappearance of energy. Second, Thomson's reasoning allows the clear distinction between the utilitarian aspect (loss of energy for the operation of a machine) and the physics aspect (dissipation of energy in the environment).

All of the elements are now in place to introduce the final characteristic:

(8) The energy of an isolated[29] *system is conserved.*

This characteristic can only be fully understood in light of the other characteristics detailed previously, in particular those relating to transformation and transfer. As Duit writes (1984, p. 59): 'When energy is transferred from one system to another, or when energy is converted from one form to another, the amount of energy does not change.'

Let's reiterate these different characteristics and our definition. The conservation of the energy of a system can only be understood if the conversion between different quantities (what is today called 'kinetic energy', 'thermal energy', etc.) is interpreted as the transformation of the same quantity into different possible forms, that is, different possible expressions. If these different expressions can be seen as expressions of the same quantity, we argue that this is because they represent the same capacity to produce change. Additionally, the conservation of the energy of a system can only be understood as an idealised case where the system does not interact with its environment. When it interacts with its environment, the system exchanges energy. In particular, in the presence of friction, part of the energy of the system dissipates in the environment. In order to avoid the obvious contradiction with the principle of conservation of energy, the total energy of the system and the environment with which it interacts should be considered: if this system and its environment are considered as isolated (which is also an idealisation), then their total energy is conserved, although this is not the case of the energy of the system being studied.

8.4.3 What Purpose Does the Concept of Energy Serve?

Why grant so much importance to the concept of energy in teaching? Why do students need to learn to use it? Ultimately, what purpose does this concept serve? To enable teachers to respond to these questions, teacher training should identify and explain the functions that the concept fulfils in science practice. The description of the emergence of the scientific concept of energy (see Sect. 8.4.1) and what energy is (see Sect. 8.4.2) offers a glimpse of these functions. Here we try to make them explicit:

(F1) *Energy is an unvarying focal point for thinking about variations observed in phenomena.* This point was put forward by Mach as early as the end of the nineteenth century. Speaking about the principle of energy conservation, he wrote: 'An isolated variation that is linked to nothing, without a fixed point of comparison, is inconceivable and unimaginable' (1987 [1883], p. 473). Or as

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[29] An 'isolated system' is defined here as a system that does not interact with its environment.

Papadouris and Constantinou emphasise more recently (2011, p. 966): 'Energy [is] a theoretical framework that has been invented in science so as to facilitate the analysis of changes occurring in physical systems regardless of the domain they are drawn from.' More precisely, describing phenomena in terms of *transformation*, *transfer* and *conservation* of energy allows us to think about observed variations.

(F2) *Energy is a unifying focal point for referring to a large variety of phenomena and making links between them.* This point distinctly emerges from the history of the development of the principle of conservation of energy (see Sect. 8.4.1). To quote Cassirer (1929 [1972], p. 520), energy can be described as 'a point of unity to grasp by pure thought'.

(F3) *The principle of conservation of energy allows predictions to be made.* This predictive function occurs at two possible levels. (i) The principle allows quantitative predictions to be made *in the context of a theory*. For example, in mechanics, the principle of conservation of mechanical energy allows the prediction of the speed of a body at time t_2 given the position and speed of the body at a previous time of t_1. (ii) The principle also allows predictions to be made *in the development of theories*, which can be described as a 'heuristic function'. A famous example of this is that of the role of the principle in the anticipation of the existence of the neutrino. We could also mention the no less important examples of the development of special relativity and quantum mechanics, in which the principle played an explicit role (see, e.g. Einstein 1905; Heisenberg 1972 [1969], pp. 91–92). This heuristic function was emphasised as early as the nineteenth century, for example by Maxwell (1871) who attributes the principle as it was formulated by Helmholtz with an 'irresistible driving power' (see Truesdell 1980, p. 163). More recently, Feynman (1965, p. 76) justifies the recourse to the principle in new fields in this way: 'If you will never say that a law is true in a region where you have not already looked you do not know anything.'

8.5 Conclusion

As we have established in the case of France, energy is an omnipresent concept in school programmes from primary to the end of secondary education and has two main aims: educating students from a scientific point of view and preparing them as future citizens to enable them to take part in social issues that involve the concept of energy. Yet science education literature has shown that the concept of energy is particularly difficult to define and to teach. This is due to the concept itself, principally to the fact that it is highly abstract and polymorphous and thus difficult to define. The difficulties in defining the concept lead to a multiplicity of conceptions (anthropocentric, substantialist, etc.) and confusions (force/energy, forms of energy/modes of energy transfer, etc.) that are equally obstacles to learning. Several teaching strategies have been proposed in science education literature over the last thirty years as alternatives to traditional teaching methods deemed too formal and dogmatic. However, none has distinguished itself as the most convincing method and been retained over the course of time in school programmes.

The new strategy that we advocate differs from previous proposals in two major ways. Firstly, we propose turning the attention to teacher training, which seems an essential precondition to teaching energy, given the complexity of the concept. The aim is thus to develop a teacher training programme that allows educators to better grasp the meaning of the concept, the role it plays in science and to be clear about all the characteristics of energy as well as the recurrent mistaken ideas about it. Secondly, our strategy grants a central role to EHST. We think EHST provides effective ways to throw light on the different aspects of the concept and should be a feature of teacher training. In this article, we have recommended a framework for teacher training based on EHST structured around three main questions: 'What is the origin of the concept of energy?', 'What is energy?' and 'What purpose does the concept of energy serve?'

We have highlighted several points that seem essential to include in teacher training. In particular, it is important that teachers understand that the concept of energy, as currently accepted, has not always been available for scientists and only became stable with the emergence of the principle of conservation of energy, itself resulting from a mutual adjustment between theory and experimentation. We have also tried to show that the definition of the energy of a system as its capacity to produce change is required in order to be able to understand that energy can take different forms and can be transformed. These characteristics, along with the transfer and dissipation of energy, allow the fundamental characteristic of the conservation of energy to be understood. Finally, it seems very important that teachers are aware of three operational roles that the concept of energy plays in scientific activity: its role as an unvarying focal point for thinking about variation, its unifying role and its predictive role.

The teacher training framework on energy presented here needs to be further enriched (with examples of course outlines and teaching sessions on energy) and detailed (to allow for constraints on the ground) and to be subjected to experimentation. Our hypothesis is that this teacher training should lead teachers to profoundly rethink the way in which they approach teaching about energy: in terms of their interpretation of programmes, of their own ideas and those of their students and of their teaching practice. If teachers are clear about the concept of energy and adopt, in light of EHST, a new position regarding how to teach it, it becomes possible to envisage a teaching approach itself based on EHST that can thus truly distance itself from a formal, dogmatic approach. Our wager is that this type of teaching will enable the difficulties in mastering the concept of energy to be overcome more easily. This teaching has yet to be developed.

References

Abd-El-Khalick, F. (2001). Embedding nature of science instruction in preservice elementary science courses: abandoning scientism, but…. *Journal of Science Teacher Education*, 12 (2), 215–233.

Agabra, J. (1985). Energie et mouvement: représentations à partir de l'étude de jouets mobiles. *Aster*, 1, 95–113.

Agabra, J. (1986). Echanges thermiques. *Aster*, 2, 1–41.

Arons, A. (1989). Developing the Energy Concepts in Introductory Physics. *The Physics Teacher*, 27, 506–517.

Arons, A. (1999). Development of energy concepts in introductory physics courses. *American Journal of Physics*, 67(12), 1063–1067.

Bächtold, M. & Guedj, M. (2012). Towards a new strategy for teaching energy based on the history and philosophy of the concept of energy. In O. Bruneau, P. Grapi, P. Heering, S. Laubé, M.-R. Massa-Esteve, T. de Vittori (eds.), *Innovative methods for science education: history of science, ICT and inquiry based science teaching* (pp. 225–238). Berlin: Frank & Timme GmbH.

Balibar, F. (2010). Energie. In D. Lecourt (ed.), *Dictionnaire d'histoire et philosophie des sciences* (pp. 403–408). Paris: Presses Universitaires de France.

Ballini, R., Robardet, G. & Rolando, J.-M. (1997). L'intuition, obstacle à l'acquisition de concepts scientifiques : propositions pour l'enseignement du concept d'énergie en Première S. *Aster*, 24, 81–112.

Beynon, J. (1990). Some myths surrounding energy. *Physics Education*, 25(6), 314–316.

Bruguières, C., Sivade, A. & Cros, D. (2002). Quelle terminologie adopter pour articuler enseignement disciplinaire et enseignement thématique de l'énergie, en classe de première de série scientifique. *Didaskalia*, 20, 67–100.

Brush, S. (1976). *The kind of motion we call heat: a history of the kinetic theories of gases in the 19th century, Volumes I and II.* Oxford: North-Holland Publishing Company.

Bunge, M. (2000). Energy: between physics and metaphysics. *Science & Education*, 9, 457–461.

Caneva, K. (1993). *Robert Mayer and the conservation of energy*. Princeton: Princeton University Press.

Cariou, J.-Y. (2011). Histoire des démarches en sciences et épistémologie scolaire. *Revue de Didactique des Sciences et des Techniques*, 3, 83–106.

Cassirer, E. (1929 [1972]). *La philosophie des formes symboliques 3: la phénoménologie de la connaissance* (tr. fr.). Paris: Les éditions de Minuit.

Chisholm, D. (1992). Some energetic thoughts. *Physics Education*, 27, 215–220.

Coelho, R. (2009). On the concept of energy: how understanding its history can improve physics teaching. *Science & Education*, 18, 961–983.

Cotignola, M., Bordogna, C., Punte, G., & Cappannini, O. (2002). Difficulties in learning thermodynamic concepts: are they linked to the historical development of this field? *Science & Education*, 11, 279–291.

Darrigol, O. (2001). God, waterwheels, and molecules: Saint-Venant's anticipation of energy conservation. *Historical Studies in Physical Sciences*, 31(2), 285–353.

Descartes, R. (1996 [1644]). *Les principes de la philosophie.* In *Œuvres de Descartes*. Paris: Vrin/CNRS.

Désautels, J., and Larochelle, M., (1989). *Qu'est ce que le savoir scientifique? Points de vue d'adolescents et d'adolescentes*. Québec: Les Presses de l'Université de Laval.

Doménech, J.-L., Gil-Pérez, D., Gras-Marti, A., Guisasola, J., Martínez-Torregrosa, J., Salinas, J., Trumper, R., Valdés, P. & Vilches, A. (2007). Teaching of energy issues: a debate proposal for a global reorientation. *Science & Education*, 16, 43–64.

Driver, R., Squires, A., Rushworth, P. & Wood-Robinson, V. (1994). *Making sense of secondary science: research into children's ideas*. London and New York: Routledge.

Driver, R. & Warrington, L. (1985). Student's use of the principle of energy conservation in problem situation. *Physics Education*, 5, 171–175.

Duit, R. (1981). Understanding energy as conserved quantity. *European Journal of Science Education*, 3(3), 291–301.

Duit, R. (1984). Learning the energy concept in school – empirical results from the Philippines and West Germany. *Physics Education*, 19, 59–66.

Duit, R. (1987). Should energy be introduced as something quasi-material? *International Journal of Science Education*, 9, 139–145.

Einstein, A. (1905). Ist die Trägheit eines Körpers von seinem Energieinhalt abhängig? *Annalen der Physik*, 17, 639–641.

Elkana, Y. (1974). *The discovery of the conservation of energy*. London: Hutchinson Educational LTD.

Fauque, D. (2006). La longue marche d'un enseignement de l'histoire des sciences et des techniques. *Tréma*, 26, 35–47.

Feynman, R. (1963). *The Feynman lectures on physics, vol. I: mainly mechanics, radiation, and heat*. California Institute of Technology.

Feynman, R. (1965). *The character of physical law*. Cambridge (Mas.), London: MIT Press.

Freuler, L. (1995). Major trends in philosophy around 1900. In M. Panza & J.-C. Pont (eds.), *Les savants et l'épistémologie vers la fin du XIXè siècle* (pp. 1–15). Paris: Albert Blanchard.

Ghesquier-Pourcin, D., Guedj, M., Gohau, G. & Paty, M. (2010). *Energie, science et philosophie, Vol. 1: l'émergence de l'énergie dans les sciences de la nature*. Paris: Hermann.

Gilbert, J. & Pope, M. (1986). Small group discussions about conception in science: a case study. *Research in Science and Technological Education*, 4, 61–76.

Gilbert, J. & Watts, D. (1983). Concepts, misconceptions and alternative conceptions: changing perspectives in science education. *Studies in Science Education*, 10, 61–98.

Gil-Pérez, D., Guisasola, J., Moreno, A., Cachapuz, A., Pessoa, A., Martinez-Torregrosa, J., Salinas, J., Valdés, P., Gonzalez, E., Gené, A., Dumas-Carré, A., Tricarico, H. & Gallego, R. (2002). Defending constructivism in science education, *Science & Education*, 11, 557–571.

Goldring, H. & Osborne, J. (1994). Students' difficulties with energy and related concepts. *Physics Education*, 29, 26–31.

Guedj, M. (2010). Du concept de travail vers celui d'énergie: l'apport de William Thomson. In Ghesquier-Pourcin, Guedj, Gohau & Paty (2010, pp. 103–125).

Hertz, H. (1894). *Die Prinzipien der Mechanik: in neuen zusammenhange dargestellt*. Leipzig: Barth.

Heisenberg, W. (1972 [1969]). *Le tout et la partie: le monde de la physique atomique* (tr. fr.). Paris: Flammarion.

Hiebert, E. (1981). *Historical roots of the principle of conservation of energy*. New York: Arno Press.

Hulin, M. (1992). *Le mirage et la nécessité: pour une redéfinition de la formation scientifique de base*. Paris: Presses de l'École Normale Supérieure and Palais de la Découverte.

Iltis, C. (1971). *Leibniz and the vis viva controversy*. Chicago: The University of Chicago Press.

Johsua, S. & Dupin, J.-J. (2003). *Introduction à la didactique des sciences et des mathématiques*. Paris: Presses Universitaires de France.

Joule, J. (1847). On matter, living force, and heat. Published in the Manchester *Courier* newspaper, May 5 and 12. Reprinted in *The Scientific Papers of James Prescott Joule*, Vol. 1, 1884 (pp. 265–276). Taylor & Francis.

Koliopoulos, D. & Ravanis, K. (1998). L'enseignement de l'énergie au collège vu par les enseignants. Grille d'analyse de leurs conceptions. *Aster*, 26, 165–182.

Kuhn, T. (1959). Energy conservation as an example of simultaneous discovery. In M. Clagett (ed.), *Critical Problems in the History of Science* (pp. 321–56). Madison (Wis.): The University of Wisconsin Press.

Lavoisier, A.-L. (1864 [1789]). *Traité élémentaire de* chimie. In *Œuvre de Lavoisier, tome premier*. Paris: Imprimerie impériale.

Lecourt, D. (1999). L'enseignement de la philosophie des sciences. *Rapport au ministre de l'Éducation nationale, de la Recherche et de la Technologie*.

Lemeignan, G. & Weil-Barais, A. (1993). *Construire des concepts en physique*. Paris: Hachette.

Levy-Leblond, J. M. (1973). *(Auto)critique de la science (Textes réunis par Alain Jaubert et Jean-Marc Lévy-Leblond)*, Seuil.

Levy-Leblond J. M. (2007). (Re)mettre la science en culture: de la crise épistémologique à l'exigence éthique. *Speech at the inauguration of the Institute for Scientific Methodology (ISEM), Palermo, March 2007*. Online at <http://www.i-sem.net>.

Mach, E. (1987 [1883]). *La mécanique: exposé historique et critique de son développement* (tr. fr.). Paris: Gabay, 1987.

Martinand, J.-L. (1993). Histoire et didactique de la physique et de la chimie: quelles relations? *Didaskalia*, 2, 89–99.

Matthews, M. (1994/2014). *Science teaching: the role of history and philosophy of science*. New York, London: Routledge.

Maxwell, J.C. (1871). *Theory of heat*. London: Longmans, Green, and co.

Mayer, J. (1842). Bemerkungen über die Kräfte der unbelebten Natur. *Annalen der Chemie und Pharmacie*, 42, 233–240.

Méheut, M., Duprez, C. & Kermen, I. (2004). Approches historique et didactique de la réversibilité. *Didaskalia*, 25, 31–62.

Meyerson, E. (1908). *Identité et réalité*. Paris: Alcan.

Millar, D. (2005). Teaching about energy. Department of Educational Studies, research paper 2005/11. Online at <http://www.york.ac.uk/media/educationalstudies/documents/research/Paper11Teachingaboutenergy.pdf>.

MEN[30] (2002). *Fiches connaissances : cycles 2 et 3*. Collection 'Document d'application des programmes'. CNDP. Online at <http://www2.cndp.fr/archivage/valid/38285/38285-5692-5495.pdf>.

MEN (2007). Cahier des charges de la fomation des maîtres en Institut Universitaire de formation des maîtres. *Bulletin Officiel de l'Education Nationale*, spécial n°1 du 4 janvier 2007. Online at <http://www.education.gouv.fr/bo/2007/1/MENS0603181A.htm>.

MEN (2008a). Horaires et programmes de l'école primaire. *Bulletin Officiel de l'Education Nationale*, hors-série, n°3 du 19 juin 2008. Online at <http://www.education.gouv.fr/bo/2008/hs3/default.htm>.

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. Online at <http://media.education.gouv.fr/file/special_6/52/7/Programme_physique-chimie_33527.pdf>.

MEN (2010a). Programmes de physique-chimie en classe de seconde générale et technologie. *Bulletin Officiel de l'Education Nationale*, spécial n°4 du 29 avril 2010. Online at <http://media.education.gouv.fr/file/special_4/72/9/physique_chimie_143729.pdf>.

MEN (2010b). 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. Online at <http://www.education.gouv.fr/cid53327/mene1019556a.html>.

MEN (2011). Programme d'enseignement spécifique et de spécialité de physique-chimie de la série scientifique : classe terminale. *Bulletin Officiel de l'Education Nationale*, spécial n°8 du 13 octobre 2011. Online at <http://media.education.gouv.fr/file/special_8_men/99/0/physique_chimie_S_195990.pdf>.

Papadouris, N. & Constantinou, C. (2011). A philosophically informed teaching proposal on the topic of energy for students aged 11–14. *Science & Education*, 20, 961–979.

Paty, M. (2000–2001). Histoire et philosophie des sciences. *Sciences Humaines*, 31, 56–57.

Pérez, J.-P. (2001). *Thermodynamique: fondements et applications*. Paris: Dunod.

Pinto, R., Couso, D. & Gutierrez, R. (2004). Using research on teachers' transformations of innovations to inform teacher education: the case of energy degradation. *Science Education*, 89, 38–55.

Planck, M. (1887). *Das Prinzip der Erhaltung der Energie*. Leipzig: Teubner.

Poincaré, H. (1968 [1902]). *La science et l'hypothèse*. Paris: Flammarion.

Rankine, W. (1855). Outlines of the science of energetics. *The Edinburgh New Philosophical Journal*, July-October 1855, Vol. II, 3, 121–141.

Robardet, G. & Guillaud, J.-G. (1995). *Éléments d'épistémologie et de didactique des sciences physiques: de la recherche à la pratique*. Grenoble: Publications de l'IUFM de Grenoble.

Roche, J. (2003). What is potential energy? *European Journal of Physics*, 24, 185–196.

Sexl, R. (1981). Some observations concerning the teaching of the energy concept. *European Journal of Science Education*, 3(3), 285–289.

Shortland, M. & Warick, A. (eds.) (1989). *Teaching the History of Science*, Basil Blackwell, Oxford.

---

[30] *Ministère de l'éducation nationale* (Ministry of education, France)

Smith, C. (1998). *The science of energy: a cultural history of energy physics in Victorian Britain*. London and Chicago: The Athlone Press.

Smith, C. & Wise, N. (1989). *Energy and empire: a bibliographical study of Lord Kelvin*. Cambridge: Cambridge University Press.

Solomon, J. (1982). How children learn about energy, or Does the first law come first? *School Science Review*, 63 (224), 415–422.

Solomon, J. (1983). Learning about energy: how pupils think in two domains. *European Journal of Science Education*, 5, 49–59.

Solomon, J. (1985). Teaching the conservation of energy. *Physics Education*, 20, 165–170.

Summers, M. & Kruger, C. (1992). Research into English primary school teachers' understanding on the concept of energy. *Evaluation & Research in Education*, 6, 95–111.

Thomson, W. (1851). On the dynamical theory of heat: with a numerical result deduced from Mr Joule's equivalent of a thermal unit, and M. Regnault's observations on steam. *Proceedings of the Royal Society of Edinburgh*, 3, 48–52.

Thomson, W. (1852). On a universal tendency in nature to the dissipation of mechanical energy. *Proceedings of the Royal Society of Edinburgh for April 19, 1852*.

Trellu, J.-L. & Toussaint, J. (1986). La conservation, un grand principe. *Aster*, 2, 43–87.

Trumper, R. (1990). Being constructive: an alternative approach to the teaching of the energy concept, part one. *International Journal of Science Education*, 12(4), 343–354.

Trumper, R. (1991). Being constructive: an alternative approach to the teaching of the energy concept, part two. *International Journal of Science Education*, 13(1), 1–10.

Trumper, R. (1993). Children's energy concepts: a cross-age study. *International Journal of Science Education*, 15, 139–148.

Trumper, R., Raviolo, A. & Shnersch, A. M. (2000). A cross-cultural survey of conceptions of energy among elementary school teachers in training — empirical results from Israel and Argentina. *Teaching and Teacher Education*, 16(7), 697–714.

Truesdell., C. (1980). *The tragicomical history of thermodynamics (1822–1854)*. New York, Heidelberg, Berlin: Springer.

Van Huis, C. & van den Berg, E. (1993). Teaching energy: a systems approach. *Physics Education*, 28, 146–153.

Vatin, F. (2010). Travail. In D. Lecourt (ed.), *Dictionnaire d'histoire et philosophie des sciences* (pp. 1109–1114). Paris: Presses Universitaires de France.

Watts, D. (1983). Some alternative views of energy. *Physics Education*, 18, 213–217.

Warren, J. W. (1982). The nature of energy. *European Journal of Science Education*, 4(3), 295–297.

Warren, J. W. (1991). The teaching of energy. *Physics Education*, 26(1), 8–9.

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(2006) *Du concept de travail vers celui d'énergie : l'apport de Thomson.* Revue d'histoire des sciences, janvier-juin 2006, tome 59–1, pp. 29–51

(2008) *À propos de l'ouvrage d'Helmholtz « Über die erhaltung der ktaft » sur un principe limité de la conservation de l'energie*. Philosophia Scientiae, Vol 11 Cahier 2 Novembre 2007, pp. 1–25

(2010) *William Thomson et l'emergence du principe de conservation de l'energie, in* Energie, sciences et philosophie aux tournants des XIXème-XXeme siecles, (dir.) D. Ghesquier-Pourcin, M. Guedj, G. Gohau et M. Paty, Hermann, Paris

(2010) *L'equivalent mécanique de la chaleur chez Sadi Carnot entre Reflexions, doutes, notes et énergie, in* Energie, sciences et philosophie aux tournants des XIXème -XXème siècles, (dir.) D. Ghesquier-Pourcin, M. Guedj, G. Gohau et M. Paty, Hermann, Paris

(2010) *L'introduction du principe de conservation de l'energie dans l'enseignement secondaire français, vue à travers quelques manuel,* in Energie, sciences et philosophie aux tournants des XIXème -XXème siècles, (dir.) D. Ghesquier-Pourcin, M. Guedj, G. Gohau et M. Paty, Hermann, Paris

(2010) *Ernst Mach sur les mesures des grandeurs de la mécanique et la théorie des dimensions*, *in* Le sens des nombres, (dir.) A. Bernard, G. Chambon et C. Ehrhardt, Vuibert, Paris