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# Introducing Joule's Paddle Wheel Experiment in the Teaching of Energy: Why and How?

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**Abstract**

History of science provides access to a reservoir of meaningful experiments that can be studied and reproduced in classrooms. This is the case of Joule's paddle-wheel experiment which displays the potentiality to help students improve their understanding of the concept of energy. This experiment has been mentioned in many physics textbooks during the twentieth century. Recently, it has received renewed attention by several researchers in science education. However, the accounts of Joule's experiment proposed by these researchers are at variance with each other: either in terms of equivalences, in terms of energy change, or in terms of energy transformation and Rankine's definition. This raises several questions: What is their respective contribution to the understanding of the historical emergence of the energy concept, and to the understanding of the very meaning of this concept? Are these accounts concurrent? Eventually, how can they help for the teaching energy? To investigate these questions, historical details concerning this experiment are first considered. It is stressed that Joule did not made use of the concept of energy, and instead described his experiment in terms of conversion of living force into heat. The three accounts of Joule's experiment are then presented and their respective contribution discussed. By emphasizing different aspects of this experiment, they are shown to suggest different strategies for teaching energy. For all that, they are not contradictory and, considered together, they bring to light the great potential of Joule's experiment to foster students understanding of this concept.

**Keywords** Joule · Science education · Energy teaching · Energyaccount transformation

## 1 Introduction

History of science provides access to a reservoir of experiments of which some might be studied and reproduced in classrooms to help students improve their understanding of science. Not all experiments from the history are suited to being introduced in the frame of science teaching. Especially, since the twentieth century, many experiments display a growing complexity, involving sophisticated materials and several layers of theories

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(Galison 1987; Hacking 1983; Pickering 1995). In contrast, many experiments in the early history of science were based on more basic equipment and were described in more simple terms, so that they can be more easily understood by students (Gauld 2014). Those experiments may be replicated either as close as possible to the originals ("historical replications"), or merely by displaying the same phenomena in a physical sense without paying to much attention to the historical details ("physical replications") (Chang 2011). If the aim of replicating a past experiment is to provide students with new insight into the knowledge at play, then these details may be ignored (de Berg 1997) and the historical steps should be rearranged so as to become comprehensible for students (de Hosson 2011). What might be illuminating for them in the first place when studying a past experiment is the principle at the core of this experiment as well as the historical context which allows understanding its contribution to solve a well-defined problem faced by scientists at a given time in the history.

The paddle-wheel experiment performed by James Prescott Joule (1818–1889) in the 1840s appears to be such an experiment with a potentiality to help students improve their understanding of the concept of energy. As matter of fact, it has been mentioned and described in many physics textbooks during the twentieth century (Bécu-Robinault and Tiberghien 1998). Recently, it has received renewed attention by several researchers in science education. However, the accounts of Joule's experiment yielded by these researchers are at variance with each other. In particular, three different accounts have been proposed, which are expressed respectively in terms of equivalence between different quantities (Coelho 2009, 2014), in terms of energy change (Lehavi et al. 2016, Lehavi and Eylon 2018), and in terms of energy transformation and Rankine's definition (Bächtold and Guedj 2014; Bächtold and Munier 2019). This raises several questions: what is their respective contribution to the understanding of the historical emergence of the energy concept, and to the understanding of the very meaning of this concept? Are these accounts concurrent? Eventually, to what extent are they helpful for the teaching energy? To investigate these two questions, the historical details concerning this experiment will first be considered: the scientific context, Joule's motivations, the experimental setup and results, their interpretation by Joule, and the implications. The three accounts of Joule's experiment, in terms of equivalence, of energy change, and in terms of energy transformation and Rankine's definition, will then be presented and discussed. We will pay attention both to the understanding of energy from an historical and epistemological perspective and to the issues concerning the teaching and learning of energy.

## 2 Joule's Paddle-Wheel Experiment: Scientific Context, Issues and Implications

The scientific context surrounding the paddle-wheel experiment in the 1840s can be grasped to some extent by considering how Joule himself depicted the state of the art in physics at this time. In a lecture entitled "On matter, living force, and heat" given at St. Ann's Church in Manchester and published in 1847, he starts by explaining how matter is currently described. He assigns two essential properties to matter: "In our notion of matter two ideas are generally included, namely those of impenetrability and extension. By the extension of matter we mean the space which it occupies; by its impenetrability we mean that two bodies cannot exist at the same time in the same place" (Joule 1847a, b, c, p.

265[1]). He describes the other properties of matter in terms of different kinds of force (Joule 1847a, b, c, pp. 265–267):

- the attractive "force of gravitation" which is assumed to hold together the component parts of all solid bodies;
- other attractive forces and also repulsive forces such as those related to electric or magnetic phenomena;
- the "living force" which is assumed to be "possessed by moving bodies" or in other words which is "carried by the body itself, and exists with it and in it, throughout the whole course of its motion," and which is expressed mathematically as proportional to the mass of the body and to the square of its velocity (as such, living force can be viewed as precursory of kinetic energy but still as conveying a confusion between force and what will soon be identified as energy).

To complete this state of the art, he also recalls how heat is conceived by most scientists, excluding himself: "the most prevalent opinion, until of late, has been that it is a *substance* possessing, like all other matter, impenetrability and extension" (Joule 1847a, b, c, p. 273).

Having clarified how matter is commonly described in physics at his time, Joule comes to spell out a major scientific problem, namely the problem of the apparent destruction of living force: "until very recently the universal opinion has been that living force could be absolutely and irrevocably destroyed at any one's option. Thus, when a weight falls to the ground, it has been generally supposed that its living force is absolutely annihilated, and that the labour which may have been expended in raising it to the elevation from which it fell has been entirely thrown away and wasted, without the production of any permanent effect whatever […] in almost all natural phenomena we witness the arrest of motion and the apparent destruction of living force" (Joule 1847a, b, c, pp. 268–269). This apparent destruction of living force is identified as problematic with regard to an a priori idea of conservation: "We might reason à 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 that they can be created by man's agency" (Joule 1847a, b, c, pp. 268–269). This problem was not new but already identified during the eighteenth century in the frame of mechanics, when scientists were dealing with the inelastic collisions of moving bodies. This has been pointed out by Hiebert (1981, p. 101): "By the middle of the eighteenth century it was commonly believed that the observed losses for inelastic collisions were to be considered as apparent and not real… And so came about that the early natural philosophers began to grapple with the question of mechanical energy losses. Their speculations reveal the beginnings of a deep-felt desire for a much wider generalization in the conservation idea. Positive success in this venture was however first accomplished only one hundred years later when it became known that the mechanical losses could in most processes be accounted for by equivalent thermal effects."

According to Joule, the solution to this scientific problem is given by a whole set of experiments among which the paddle-wheel experiment: "experiment has enabled us to answer these questions in a satisfactory manner; for it has shown that, wherever living force is *apparently* destroyed, an equivalent is produced which in process of time may be

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[1] The pagination used for all Joule's quotations is the one of *The Scientific Papers of James Prescott Joule,* Vol. 1, 1884, Taylor & Francis.

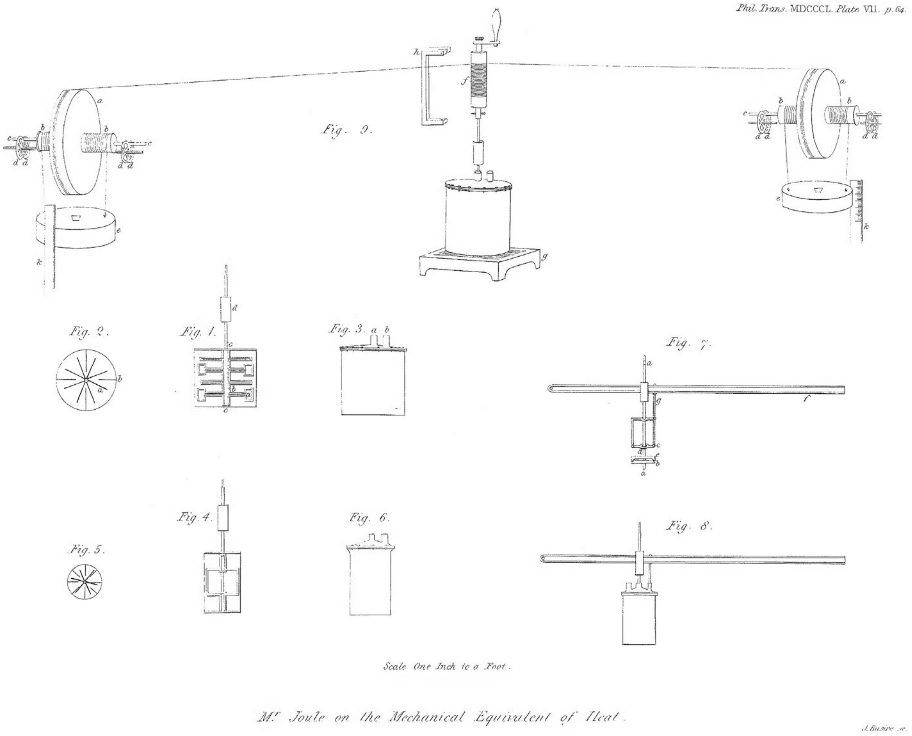

**Fig. 1** Device used by Joule to perform his so-called "paddle-wheel experiment" ( *source* Joule 1850)

reconverted into living force. This equivalent is *heat*. Experiment has shown that wherever living force is apparently destroyed or absorbed, heat is produced" (Joule 1847a, b, c, p. 269).

Let us have a closer look at the the paddle-wheel experiment. To conceive his device (Fig. 1), Joule has been inspired by the paddle-wheel used in 1831 by the British engineer George Rennie (1791–1866) to study the friction of water (Joule 1845, p. 203, note). The principle of Joule's experiment can be summarized as follows: falling weights cause the rotation of a paddle-wheel in a vessel of water, which in turn causes the rise in the temperature of the water.

Joule performed a first series of measurements presented before the British Association at Cambridge and published in a short paper in 1845 (Joule 1845), and a second series of experiments "under more favourable circumstances, and with a more exact apparatus, and [employing] sperm-oil as well as water" (Joule 1847b) presented before the British Association at Oxford and published in a extended paper in 1847 (Joule 1847b). In this second paper, Joule describes the experiment as follows: "The brass paddle-wheel employed had […] a brass framework attached, which presented sufficient resistance to the liquid to prevent the latter being whirled round. In this way the resistance presented by the liquid to the paddle was rendered very considerable, although no splashing was occasioned. The can employed was of copper, surrounded by a very thin casing of tin. It was covered with a tin lid, having a capacious hole in its centre for the axle of the paddle, and another for the insertion of a delicate thermometer. Motion was communicated to the paddle by means of a drum fitting to the axle, upon which a quantity of twine had been wound, so as by the intervention of delicate pulleys to raise two weights, each of 29 lb.[ca. 13 kg], to the height of about 5¼ feet [ca. 1.6 m]. When the weights in moving the paddle had descended through that space, the drum was removed, the weights wound up again, and the operation repeated. After this had been done twenty times, the increase of the temperature of liquid was ascertained" (Joule 1847b, p. 278).

Note that Joule attached great importance to the "precision" of the instruments, especially for measuring the temperature. In a paper published in 1850, he describes the thermometers used in the paddle-wheel experiment: "the thermometers employed had their tubes calibrated and graduated according to the method first indicated by M. Regnault. Two of them […] were constructed by Mr. Dancer at Manchester; the third […] was made by M. Fastré of Paris. The graduation of these instruments was so correct, that when compared together their indications coincided to about 1/100 of a degree Fahr." (Joule 1850, p. 302). As stressed by Sibum, such thermometrical skills were unusual in the Victorian physics community, but were widely distributed in the brewing community to which Joule belonged (Sibum 1995, p. 74). Joule worked for the brewery of his family and this cultural context is of importance to understand "Joule's exceptional experimental practice" (Sibum 1995, p. 74).

This experiment had several important implications. First, as mentioned above, it contributed to solve the scientific problem of the apparent destruction of living force: living force is not destroyed but converted into heat.

Second, this experiment yielded an accurate value for the "mechanical equivalent of heat:" "the equivalent of a degree of heat in a pound of water was therefore found to be 781.5 lb., raised to the height of one foot" (Joule 1847b, p. 280), or in terms of grams and meters, the equivalent of a degree of heat in a gram of water was therefore found to be 428.8 g, raised to the height of one meter (Joule 1847c, p. 283). This value was useful in the engineering domain, especially concerning the functioning of steam engines, which were developed at this time. This was stressed by Joule when considering the reverse equivalence: "The knowledge of the equivalency of heat to mechanical power is of great value in solving a great number of interesting and important questions. In the case of the steam-engine, by ascertaining the quantity of heat produced by the combustion of coal, we can find out how much of it is converted into mechanical power, and thus come to a conclusion how far the steam-engine is susceptible of further improvements" (Joule 1847a, p. 271).

Let us notice that several kinds of experiments were carried out by Joule to determine the value for the mechanical equivalent of heat. Among them, he chose the paddle-wheel experiment to make the most precise determinations of the value. Because of the simplicity of this experiment, the relation between living force and heat was more straightforward, and therefore easier to acknowledge by other scientists: "the drum and paddle experiment, Cardwell writes, was the best one on score of simplicity; it was open to fewer objection than the […] other methods" (Cardwell 1989, p. 76).

Third, Joule's paddle-wheel yielded new evidence against the current conception of heat as a substance: if heat can be produced, as this experiment shows, then heat cannot be considered as a conserved substance. Joule writes for instance "I had proved that heat was generated by the friction of water produced by the motion of a horizontal paddle-wheel" (Joule 1847b, p. 277). In his view, evidences for the possibility to produce heat were already yielded by a whole set of observations and experiments, among which the one of Benjamin Thompson (Count Rumford, 1753–1814) who observed the "very great quantity of heat excited by the boring of cannon" (Joule 1850, p. 299). However, scientists endorsing the substance conception of heat were unable to acknowledge these evidences: “From the explanation given by Count Rumford of the heat arising from the friction of solids, one might have anticipated, as a matter of course, that the evolution of heat would also be detected in the friction of liquid and gaseous bodies.[…] Nevertheless the scientific world, preoccupied with the hypothesis that heat is a substance […] have almost unanimously denied the possibility of generating heat in that way” (Joule 1850, pp. 301–302).

Because of the third implication, Joule’s paddle-wheel experiment was immediately recognized as an important contribution. After hearing Joule’s presentation at the British Association at Oxford in 1847, William Thomson (Lord Kelvin, 1824–1907) writes in a letter to his father: “[Joule] seems to have discovered some facts of extreme importance, as for instance that heat is developed by the friction of fluids in motion” (quoted by Cardwell 1989, p. 85). Joule’s experiment could harly go unnoticed; it had a disturbing effect on all scientists like Thomson who were endorsing Carnot’s theory of heat. As emphasized by Harman, “while remaining publicly committed to Carnot’s theory, Thomson recognised that the hypothesis of the conservation of heat, which he considered to be Carnot’s ‘fundamental axiom,’ was called into question by Joule’s experiments” (Harman 1982, p. 51). Indeed, two years following Joule’s presentation, Thomson stresses that his experiments challenge the idea of heat conservation described as “the foundation” of the commonly acknowledged theory of heat developed by Carnot: “The extremely important discoveries recently made by Mr Joule of Manchester, […] that heat is *generated* by the friction of fluids in motion, seem to overturn the opinion commonly held that heat cannot be *generated*, but only produced from a source, where it has previously existed either in a sensible or in a latent condition” (Thomson 1849, p. 543). Note that Thomson did not endorsed Joule’s claim concerning the reverse conversion process of heat into living force. This is described by Smith as follows: “Unconvinced, however, by Joule’s complementary claim that such heat could in principle be converted into work, Thomson remained deeply perplexed by what seemed to him the irrecoverable nature of that heat” (Smith 2003, p. 296). Thomson came to resolve this issue by developing the idea of energy dissipation (Thomson 1852) which was missing in Joule’s description of his experiments.

Let us stress that in his 1847 paper Joule did not make use of the term “energy.” The very concept of energy was introduced only after Joule performed the paddle-wheel experiment, by Thomson and William Rankine (1820–1872) in the 1850s (Thomson 1851; Rankine 1853). Joule also did not expose an interpretation of his paddle-wheel experiment in terms of a unique conserved quantity, which could be considered as a precursor of energy. Although Joule’s work is generally considered as a significant contribution for the establishment of the principle of energy conservation, he did not formulate this principle. His interpretation of the paddle-wheel experiment is based on the idea of “conversion” of living force into heat. What is conserved in his view is the total amount of both quantities. This point is well explained by Hiebert: “The experimental demonstration of a constant relationship between the quantity of mechanical work which disappears and the quantity of heat which appears in a system isolated from its surroundings was made in the 1840s. The quantity of heat was conveniently expressed according to a linear relationship which equates the heat produced and the work expended in terms of mechanical work equivalents. The arithmetic sum of heat and work was seen to be constant for all possible conditions” (Hiebert 1981, p. 1). The principle of energy conservation was first stated in its whole generality by Hermann von Helmholtz (1821–1894) (see Elkana 1974, p. 115). Regarding its mathematical foundation, it was developed by Rudolf Clausius (1822–1888) who attempted to overcome the contradiction first emphasized by Thomson between Joule’s experiment and Carnot’s theory of heat, by discarding the assumption of heat conservation and by introducing a new function able to encompass both heat and living force (Clausius 1850). This function, noted *U*, came to be coined "energy" by Thomson and Rankine, and was progressively acknowledged by scientists as describing a new physical quantity. This is explained by Clausius himself some years later: "The function U which I introduced is capable of manifold application in the theory of heat, and, since its introduction, has been the subject of very interesting mathematical developments by W. Thomson and by Kirchhoff […]. Thomson has called it 'the mechanical energy of body in a given state,' and Kirchhoff 'Wirkungsfunction.' Although I consider my original definition of it, as representing the sum of the heat added to the quantity already present and of that expended in interior work, starting from any given initial state […], as perfectly exact, I can still have no objection to make against an abbreviated mode of expression.[…] the term energy employed by Thomson appears to me to be very appropriate.[…] I have no hesitation, therefore, in adopting, for the quantity U, the expression energy of the body." (Clausius 1867, footnote p. 226, pp. 251–252).

We should underline, moreover, that the experimental evidences for the existence of "conversion processes" (Kuhn 1959, p. 73) such as the one yielded by Joule can be considered as an intermediary step towards the unification of physics allowed by the concept of energy. Recall that in the beginning of the nineteenth century, new kinds of phenomena (e.g., thermal, electric, magnetic…) were discovered and led to the development of new branches of physics. In this respect, the concept of energy fulfilled a unifying function (Harman 1982, pp. 1–4), or in Cassirer's words (1929 [1972], p. 520), provided "a point of unity." The unified description of physics in terms of energy could be developed on the basis of the conversion processes experimentally established in the first half of the nineteenth century. Indeed, the latter brought to light relations between the various kinds of phenomena, and thereby suggested possible connections between the different branches of physics. Joule's experimental contribution to the unification of physics was not fortuitous. As described by Forrester (1975, pp. 279–280), his aim was to confirm a unified theory of electricity, chemistry and heat he developed in the beginning of the 1840s.

## 3 Three Contemporary Accounts Of Joule's Experiment

The paddle-wheel experiment has recently been highlighted as worthwhile to be studied in the classrooms so as to help students understand the concept of energy. To what extent can Joule's experiment be useful to grasp the meaning of energy? As mentioned above, three different accounts of Joule's experiment related to the concept of energy have been proposed: in terms of equivalence (Coelho 2009, 2014), in terms of energy change (Lehavi et al. 2016, Lehavi and Eylon 2018), and in terms of energy transformation and Rankine's definition (Bächtold and Guedj 2014; Bächtold and Munier 2019). How do they contribute to the understanding of the historical emergence of the energy concept, and to the understanding of the very meaning of this concept? Are these accounts contradictory or do they share some ideas? How can they help for the teaching energy? To investigate these questions, we will first consider the three accounts one by one.

### 3.1 Equivalence

After describing the paddle-wheel experiment, Coelho comes to clarify Joule's own account in terms of conversion: "Joule considers the experiment as a phenomenon of conversion from mechanical power into heat. The phenomenon of conversion must have taken place within the can. However, no observation is made to verify what happened within it.[…] no specific information of the process of conversion is used" (Coelho 2009, pp. 971–972). Coelho considers that this idea of conversion is only an account. In his view, the underlying observed phenomenon is a numerical equivalence between living force (or "mechanical power") and heat: "Concerning the question of what Joule discovered, posed in the introduction, it could be said that he found *experimental methods for determining the mechanical equivalent of heat*. Joule measured the mechanical power, the heat evolved, established a numerical relation and determined the mechanical equivalent of heat. The justification of this, as conversion from the observable motion of the weights into the unobservable motion of which heat would consist, is account" (Coelho 2009, p. 972). According to Coelho, the notion of equivalence is essential in Joule's experiment, it is even sufficient to understand its meaning. In this respect, he refers to a so-called "principle of equivalence" which was pointed forward by several physicists between the 1860s and the beginning of the twentieth century, including Verdet and Poincaré (Coelho 2009, p. 978; Coelho 2014, p. 1375).

Coelho does not ignore the interpretation of Joule's experiment in terms of conversion, nor its possible account in terms of a conserved quantity. Regarding this second account, he discusses several experiments carried out by Robert Mayer (1814–1878) which establish for instance connections between heat and motion, or between electricity and motion. In Coelho's view, Mayer made two kinds of contribution in relation to these experiments: first, he found a new "methodology" which amounts to verify a cause-effect relationship between two kinds of phenomena, to translate this relationship into an equation, and thereby "to establish a numerical relationship between domains, which were until then separated" (Coelho 2009, p. 966), or in other words "*equivalences* between different domains" (Coelho 2009, p. 977); second, he developed a new theory "based on the indestructibility and transformability of force," which was precursory of the "concept of energy as a substance" (Coelho 2009, pp. 977–978). Yet, it is well possible to dissociate both contributions and put aside the second one: "Let us now suppose that we use the other part of Mayer's contribution: his methodology for dealing with phenomena. We are then aware that we are applying a methodology to a process, to a phenomenon, where there is a cause-effect relationship, as Mayer said. Let us consider, therefore, the measured quantity concerning the 'initial' part of the process equivalent to the 'final' one. As we know, then, that an equivalence is established by us between those quantities, we do not need the 'indestructibility' of an entity to express that the quantity does not change. This is now a mere consequence of our dealing with the measured quantities. As we establish an equivalence between different domains, as is the case in general, we do not need to suppose the 'transformability' of the same entity. We know in advance that we are dealing with different measurement processes and units" (Coelho 2009, p. 978).

Coelho's concern is the substantialist conception of energy. Referring to several researchers in science education, like Duit (1987), Beynon (1990) or Doménech and colleagues (2007), he draws attention to students' confusions associated to the conception of energy as a "real existing thing;" in particular, they tend to develop "alternative ideas, such as 'Energy is fuel' or 'Energy is stored within objects'" (Coelho 2009, p. 979). According to Coelho, experiments such as the paddle-wheel experiment should be interpreted merely in terms of equivalences between different quantities. That is to say, the equivalence account provides a means in physics teaching to avoid strengthening the misleading conception of energy as a substance.

### 3.2 Energy change

Let us turn to the "energy change" approach developed by Lehavi and his colleagues (Lehavi et al. 2016; Lehavi and Eylon 2018). Like Coelho, these authors also consider the main contribution of Joule's experiments, and especially his paddle-wheel experiment, as being the numerical relations established between different phenomena or in other words, their equivalence. Their historical account on this point differs slightly insofar as they view temperature rise (or heating) as a base phenomenon: "[Joule's] remarkable experimental skills allowed him to find quantitative relations between temperature change and other phenomena: electrical, chemical, gas expansion and change in speed.[…] The heating/cooling phenomenon served Joule as a standard against which he compared the results of measuring chemical affinity, electromotive and electro-magnetic forces and even the passage of water through narrow tubes. Finally, his famous paddle wheel experiment enabled him to regard a mechanical process as just another heating phenomenon and thus equivalent to other phenomena that result in a temperature rise" (Lehavi et al. 2016, p. 9).

According to Lehavi and his colleagues, it is worthwhile to replicate Joule's paddle-wheel in science teaching to make students understand the existence of such empirical equivalences: "because of the great importance of Joule's conclusion with regard to the generality of his standard measure of different phenomena, it is highly desirable to reproduce his main empirical conclusions in a teaching context" (Lehavi et al. 2016, p. 10). For this purpose, they present in their paper a very simple experiment setup replicating the principle of Joule's experiment (i.e., heating caused by the downward motion of a weight).

Their account of Joule's experiment is not restricted to the idea of equivalence as is the case of Coelho's account. They also regard Joule's experimental work as an important step towards the emergence of the energy concept with its unifying function: "although at Joule's times many concepts were used to describe different processes and phenomena (e.g., living force, heat, power), his experiments laid the groundwork for using energy as one entity that can be employed in analyzing different phenomena, otherwise considered to be disconnected" (Lehavi and Eylon 2018, p. 337). They argue that temperature rise is the base reference allowing the description of different kinds of phenomena in terms of one and the same concept: "further pursuing Joule's approach, if one measures *separately* how each process (the change in height, speed, electric charge distribution, chemical constituents in bio and non-bio systems, temperature of bodies in contact, radiation or even nuclear masses) affects the change in temperature, one can combine all such processes under one concept. Note that this aligns well with Joule's own account and enables regarding heat (the change in energy of an object that interacts with another object having a different temperature) and work as not distinct from each other" (Lehavi and Eylon 2018, p. 338).

Having in mind Joule's experiments, they come to develop a new way to understand the concept of energy by putting forward the idea of energy change: "The various processes by which a system can change are characterized by a change in variables such as height, temperature, and speed, among others. The change in value (increase or decrease) of each of these variables characterizes a specific change (process) in the system. Such changes of the characterizing variables, each corresponding to a certain process, indicate a corresponding change (increase or decrease) in the value of the energy of the system" (Lehavi and Eylon 2018, p. 338).

This way of dealing with the concept of energy is intended to be used with students. The aim is to counterbalance the misleading language in terms of "forms" of energy, which, according to some authors (Brewe 2011, p. 3, Falk et al. 1983, p. 1076), is assumed to conflict with the idea of energy as a unitary quantity. Lehavi and Eylon do not suggest putting aside this forms-based language, but rather to clarify its meaning: "It follows that energy, like any other scientific entity, can change only by its value. Thus, changes in kinetic energy, in height energy, in chemical energy etc., do not represent changes in different forms of energy. These 'forms' are just labels that refer to the different processes by which the value of the energy of a system can increase or decrease" (Lehavi & Eylon, 2018, p. 339).

### 3.3 Energy transformation

We will consider now the third account of the paddle-wheel experiment. In the papers proposing this account (Bächtold and Guedj 2014; Bächtold 2019), we also put forward the fact that Joule's experiment established a connection between living force and heat, and thereby brought to light the relationships between two different branches of physics. However, we consider that his interpretation in terms of "conversion" is only an intermediary step and appears in fact problematic: how can living force be converted into heat given that both quantities are completely different in nature? Indeed, they refer to different kinds of phenomena and are defined with different units. Although Joule did not explicitly formulate this problem, it seems to have motivated him looking for a physical explanation at the microscopic level. Based on a model developed in 1844 which describes heat in terms of the momentum of the electrical atmosphere surrounding atoms, he proposed an explanation summarized by Forrester as follows: "when mechanical force became heat at the macro-level the corresponding change at the micro-level was from *general* motion of matter to a rotational motion associated with individual atoms" (Forester 1975, p. 294). Being too speculative, this explanation did not draw much attention. By contrast, the description of Joule's experiment in terms of energy transformation proposed by Thomson and Rankine in the beginning of the 1850s (Thomson 1851; Rankine 1853) was much easier to accept. Although they introduced a new concept, namely energy, their description remained at the macroscopic level and did not involve any speculation concerning the processes at the underlying microscopic level. Furthermore, their description was simple, consistent, and allowed to overcome the conceptual problem related to the conversion of one kind of quantity (i.e., living force) into a completely different quantity (i.e., heat): the conversion of living force into heat could be understood merely as a transformation of energy. This is why, in our view, there are two important steps to be considered in the history of the account of Joule's paddle-wheel experiment: "first, Joule interpreted his experiment in terms of conversion of living force into heat, addressing them as two distinct quantities defined in two distinct domains of physics; then, Rankine introduced the concept of energy and reinterpreted the experiment in terms of transformation of kinetic energy into thermal energy, addressing them as two forms of the same quantity" (Bächtold and Munier 2019, p. 779). By means of this notion of energy transformation, the relationships between the different branches of physics suggested by Joule's experiments could be integrated into a unified picture. In other words, the unifying role of energy is allowed to some extent by this notion. This is put forward by Harman: "The fundamental status of energy derived from its immutability and convertibility, and from its unifying role in linking all physical phenomena within a web of energy transformations" (Harman 1982, p. 58).

Nevertheless, having resolved the conceptual problem concerning the conversion of living force into heat, a new problem appears: "it was yet to be accepted that living force and heat were two examples of the same quantity" (Bächtold and Guedj 2014, p. 226). In this respect, the following historical fact should be emphasized. At the same time Thomson and Rankine proposed to interpret Joule's experiments in terms of energy transformation, they introduced the following definition of energy, today called "Rankine's definition:" energy is the capacity of a system to produce changes (Thomson 1851; Rankine 1853, 1855). The term "changes" refers here to all kinds of physical processes: temperature rise, change of velocity, change of state, emission of light… This definition provides a simple justification for viewing different quantities as instances of the same quantity, as "forms of energy." In the case of the paddle-wheel experiment, living force can be conceived, just like heat, as a form of energy insofar as it can increase the temperature of water.

With regard to energy teaching, it may be insightful for students to study Joule's experiment by considering the three layers of theory discussed above, associated respectively to the notion of conversion, the idea of energy transformation and Rankine's definition. Being easy to understand and bringing into connection two usually separated branches of physics, this experiment seems to have great potential for helping students understand the energy concept; especially it "can play the role of a paradigmatic example of the idea of energy transformation" (Bächtold and Munier 2019, p. 793).

In our view, this idea of energy transformation should be at the core of energy teaching for three reasons: "First, this notion is required for a proper application of the principle of energy conservation. Second, it is a powerful tool for describing qualitatively all types of physical processes, particularly everyday phenomena […]. Third, in the frame of [socio-scientific issues] teaching, understanding both conservation and energy transformation might be helpful to avoid misunderstanding expressions such as 'energy production' or 'energy consumption.' From a scientific point of view, these expressions do not mean absolute creation or destruction of energy but rather transformation of one form of energy into another, with the total amount of energy being constant" (Bächtold and Munier 2019, p. 767).

As for Rankine's definition, it deserves to be introduced to students since it provides them with a possible "substitute" for their erroneous conceptions, such as the substantialist conceptions mentioned above (Bächtold 2018, pp. 360 and 362; Bächtold and Munier 2019, p. 789). Moreover, because of its general scope, this definition also allows considering energy as a quantity with the same meaning in all the branches of physics, and thereby avoiding "compartmentalization of the teaching of energy to isolated domains" (Papadouris and Constantinou 2016, p. 120).

## 4 Discussion

Let us now compare the three accounts and discuss their possible implications for energy teaching. An important idea put forward by all three accounts is that the paddle-wheel experiment yielded empirical evidence for the relation between two different kinds of phenomena (i.e., motion and heat), and thereby brought to light the possible connection between two different branches of physics. This point is of importance in the frame of physics teaching, since the two kinds of phenomena under consideration, i.e., motion caused by a force and heat, are usually studied separately in two distinct courses of physics, which at university are traditionally referred to as respectively as "mechanics" and "thermodynamics." Joule's experiment offers a means for bridging the gap between these two branches of physics and helps students avoid developing a compartmentalized view of physics.

Note however some differences between the three accounts concerning this empirical evidence for the relation between two kinds of phenomena. Both Coelho and Lehavi et al. are laying emphasis on the quantitative aspect of this relation, but in two different ways. Coelho considers that Joule's experiment exemplifies a new "methodology" for establishing "numerical" relations between apparently disconnected phenomena, and that this methodology avoids making use of the misleading conception of energy as a substance. As for Lehavi and his colleagues, such quantitative relations established by means of experiments provide the basis for developing the notion of "energy change," which corresponds to a new conception of energy assumed to help students understand it as a unique quantity putting into relation variations of all kinds of quantities. In the frame of our account of Joule's experiment, the relation between two kinds of phenomena established by this experiment is first considered in a qualitative manner: what has to be stressed with students, in our view, is first of all the fact that different kinds of phenomena, and thereby different branches of physics, can be connected. The quantitative aspect of this relation is not neglected, but can be taken into consideration in a second phase, if the teacher aims at making students apply the conservation principle to the paddle-wheel experiment, which in this respect provides a new opportunity of application (Bächtold and Munier 2019, p. 793).

Another important difference between Coelho's account, on the one hand, and the account of Lehavi et al. and ours, on the other, concerns the introduction of the energy concept to interpret Joule's experiment. The approach developed by Coelho can be described as "minimal:" in his view, what should be retained from this experiment is only the quantitative relation between two kinds of phenomena and the methodology thanks to which Joule ascertained this relation; the concept of energy should be discarded. This minimal approach sticks to the phenomena and therefore can be characterized as lying at the "phenomenal" level. It provides insight into the understanding of the relations between the phenomena, but not into the understanding of energy. In contrast, the approach developed by Lehavi et al. describes this phenomenal level as laying the ground for giving meaning to the concept of energy: the changes of the various quantities, of which the relations have been established empirically, are viewed as changes of the same quantity, i.e., energy. According to our approach, the phenomenal level also offers the ground for giving meaning to the concept of energy. However, instead of developing the idea of energy change, we are putting forward the notion of energy transformation: the relations between the various quantities, which have been established empirically, can be interpreted in terms of "transformations" of energy, that is to say, in terms of changes of the "forms" of the same quantity. In our view, the notion of forms has no meaning without the idea of transformation: without admitting that a form of energy can be transformed into another form of energy, these forms are mere "labels" assigned to the phenomena (to take the term of Lehavi et al.). Nevertheless, in both approaches (the one of Lehavi et al. and ours), energy is introduced as a unifying quantity. In other words, the shared idea is that Joule's experiment provides support for making students understand the unifying role of energy.

A further point of disagreement between the three accounts concerns the notion of equivalence. Indeed, Coelho merely supports that the paddle-wheel experiment shows the equivalence between living force and heat. He does not consider meaningful to say something more concerning this equivalence: its meaning relies on the numerical relation between living force and heat. On the contrary, in the frame of the two other accounts, the notion of equivalence is specified. Indeed, according to Lehavi et al., living force is "equivalent" to heat insofar as it can produce temperature rise. Our approach agrees with this idea but stresses that temperature rise can be encompassed in the broader notion of change: living force is "equivalent" to heat insofar as it can produce the same change, which, in the case of the paddle-wheel experiment, is temperature rise. From this point of view, the notion of equivalence can be related to Rankine's definition. Therefore, to provide students with the whole picture concerning energy would consist in introducing Rankine's definition explicitly.

Eventually, it appears that the three accounts of Joule's experiment are not contradictory. Rather they emphasize different aspects of this experiment. As a consequence, they are suggesting different strategies for energy teaching based on the paddle-wheel experiment: paying attention to the phenomenal level, constructing the notion of energy change, or giving meaning to the notion of energy transformation. Each strategy allows dealing with some of the issues related to energy learning. Accordingly, they can be considered as complementary. Together they bring to light the great potential of Joule's experiment to foster students understanding of this concept.

## Compliance with ethical standards

**Conflict of interest** The author declares that he has no conflict of interest.

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