Chapter 9

Integrating Science Education Research and History and Philosophy of Science in Developing an Energy Curriculum

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9.1 Introduction

Traditionally, the role of the nature of science (NOS) in curriculum development is manifested by asking how history and philosophy of science (HS and PS, respectively) should be integrated into the curriculum (Rudolph 2000), whereas ideas from science itself are often regarded as the final and desired goal of students' understanding. The findings from science education research (SER) are used to inform the curriculum designers about how students learn a certain subject, what difficulties they (and sometimes their teachers) have, and what methods are most suited for constructing the students' desired understanding. How the four disciplines – HS, PS, Science, and SER - are considered in curriculum design may vary, reflecting the curriculum developers' different educational perspectives. For example, disciplines such as the history and philosophy of science (HPS) can be used to supplement the curriculum, aimed at adding cultural information or human interest, or past scientists' views on natural phenomena could be set alongside students' views as other perspectives for consideration (Monk and Osborne 1997). Class and lab activities can be used to emphasize methodological concerns, such as the identification and control of variables, to encourage students' motivation and curiosity or, alternatively, to determine "how, with what confidence, and on what bases, scientists come to know what they do" (Shapin 1992). Results from education research

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can be used to elicit students' prior knowledge or to put constraints on the ways by which new scientific ideas can be conveyed.

Thus, the strong interrelations among science, its philosophy, and its teaching (Elkana 2000, Matthews 2015) call for considering in conjunction all four disciplines when planning a curriculum design: Philosophy of Science, its History, Science Education Research, and Science itself (PHES). This view is in accordance with the suggestion of viewing didactics as a discipline that utilizes contributions from different scholarly fields in order to improve science education (Adúriz-Bravo and Izquierdo-Aymerich 2005). Although the four disciplines often overlap and cannot be completely distinguished from each other, each of them has its own unique contribution to curriculum decision making and therefore will be discussed here separately.

In this regard, energy serves as a very good example, since scientists, philosophers of science, and science educators (e.g., Poincare 1903/1952, ch. VIII; Feynman 1964; Bunge 2000; Wolter and Martin 2002) have all been involved in the ongoing long discussion regarding the meaning of energy and its special language (Bevilacqua 2014). Evidently, the lack of consensus with regard to what is energy, its level of abstraction and what is meant by energy types/forms, conversion/transformation, transfer and conservation presents a great challenge for an energy curriculum designer who strives for coherence and consistency. For us, the philosophical discourse with regard to the experiment-theory relationship and the meaning of scientific concepts, with special emphasis on their definitions, provides essential and rich support in making curriculum development decisions.

Thus, our approach integrates all four disciplines in developing a coherent, consistent, spiral curriculum for teaching energy. We exemplify this approach by discussing how considerations based on each of the four disciplines were integrated in making curricular decisions in the development and implementation of a curriculum for teaching the concept of energy in Israel. This approach follows and extends the suggestion that HPS should be used in order to address the teaching of the concept of energy and especially with regard to teachers' training (Bächtold and Guedj 2012, 2014). Our approach led us to shift the focus of the curriculum and to put more emphasis on quantitative change in energy rather than on energy itself. The importance of focusing on changes in energy (as one concept) rather than viewing it in a static way in teaching energy has been recognized in the past (Chisholm 1992).

Our curriculum development was based on the assumption that the difficulties reported by SER are strongly related to the above-mentioned lack of consensus with regard to the "language of energy". We not only examined past studies—we also conducted our own research, with regard to teachers' concept image of energy, to help us in making curricular decisions. In order to address the challenges that our research raised, we considered all four components of PHES in constructing a new curriculum for teaching energy in Israel.

9.2 The Integrated Approach to Curriculum Design

As described above, the design of the energy curriculum was based on four pillars: (1) History of science; (2) Science; (3) Philosophy of science, and (4) Science education research. We will describe how we employed each of these disciplines in designing our curriculum.

9.2.1 History of Science (HS): Adopting Joule's Approach

With regard to the history of science, we followed the approach to curriculum design that addresses scientific ideas in their original context of discovery (Monk and Osborn 1997). Applying this approach to energy was manifested by adopting Joule's approach.

During the nineteenth century, scientists developed the idea that the creation of a certain 'power' requires the exhaustion of another. However, to become a conservation law, this co-variation in different directions of 'power' required measurable relations to a given standard (Kuhn 1977, p. 79–82). Such relations, using change in temperature of a standard object, were established by several scientists at the middle of the nineteenth century (Kuhn 1977, p. 89) with the prominent contribution of Joule who wished to compare different processes:

> In accordance with the pledge I gave the Royal Society some years ago, I have now the honour to present it with the results of the experiments I have made in order to determine the mechanical equivalent of heat with exactness. (James Prescott Joule 1850)

Thus, Joule's approach[1] led him to arrive at quantitative relations between different phenomena rather than to characterize a new entity and to attribute it with qualities such as being indestructible. Owing to his remarkable experimental skills, he discovered quantitative relations between temperature change and other phenomena: electrical, chemical, gas expansion, and change in speed (Coopersmith 2015, p. 245–252). 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 (Kuhn 1977, p. 77). The heating 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.

Furthermore, Joule succeeded in finding equivalence between different processes by which a system can change by measuring the change in temperature of an object due to such processes:

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[1] We named this approach after Joule although he was one of many who contributed to the effort to arrive at a unified concept of energy via experiments (see especially Bevilacqua 2014 and Coopersmith 2015).

A change (by various processes) → ΔT (of a certain object)

Thus, for each changing variable in his experiments, Joule could relate a certain change in temperature. This, as is well known, enabled him to relate different processes to each other and to suggest a means to compare them. One can therefore interpret Joule's approach as an endeavor to quantify different processes by the same operation of measurement.

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,[2] temperature of bodies in contact, radiation or even nuclear masses)[3] affects the change in temperature, one can combine all such processes under one concept. Note that this aligns well with Joule's own interpretation 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.

Thus, HS provided us with the means to clarify in our curriculum *why* we can use *energy change* as one concept for different kinds of processes. It also led us to develop low-cost classroom experiments that can be used to demonstrate Joule's approach (Lehavi et al. 2014a, b, 2016). This unitary view of energy is crucial for presenting it as a crosscutting curricular concept.

9.2.2 Science: Interpreting the First Law of Thermodynamics and Energy Conservation

Our guiding principle in employing the scientific ideas was to consider them not only as the goal of teaching but also for guiding curriculum design decisions.

This principle was manifested in interpreting the first law of thermodynamics $\Delta E = W - Q$) as representing the change in energy (left side) corresponding to different processes (right side) and making this change the focus of the curriculum (Eylon and Lehavi 2014). Thus, the 1st law was not taught at the middle school level, but rather, it served as a means of organizing the curriculum.

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 in 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. Such an interpretation of the first law of thermodynamics is in accordance with both Joule's approach (although he did not use the concept of energy as such) and the scientific view of

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[2] Recall Lavoisier and Laplace's calorimetric experiment that showed how processes in animals are energetically (and chemically) similar to a combustion reaction.

[3] Although many of these phenomena were not known to Joule, his approach is often used for measuring the heating/cooling they induce.

energy as one entity (Moore 1993). It follows that energy, like any other scientific entity, can change only by its value. Thus, changes in kinetic energy, height energy, and chemical energy, among others 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.

Science puts emphasis on changes and processes and employs changes in the value of energy to describe them. Notably, science provides no definite method by which the energy value of a system can be determined. In fact, the energy value of a system is relative and can be determined up to an arbitrary constant (Fermi 1936). However, this ambiguity does not affect the first law of thermodynamics, since this law is not concerned with the energy value but instead, with the quantitative changes in this value. Thus, from a scientific point of view, although energy itself cannot be determined without ambiguity, since it has no absolute zero value, a change in the quantity of energy[4] can be measured and thus, it is of physical importance.[5] A good example of this view adopted by science is that the rest mass of the objects within a system is not often mentioned (e.g., in an electric circuit or when an apple falls), although it is responsible for most of the energy related to the system. This mass cancels out since only changes in energy matter (Quinn 2014, p. 18).

It is apparent from our discussion that the 1st law is not regarded by us as representing the energy conservation law. We adopted the view that in certain systems (termed isolated since any change within them is not accompanied by any change in their surroundings and vice versa) any increase in energy related to one or more processes is counterbalanced by a decrease in energy related to one or more other processes. Such a balance can be the subject of an empirical inquiry *after* we arrived at a good quantification of energy change in processes characterized by changes in different variables. In this respect, energy conservation becomes a refutable law.

9.2.3 Philosophy of Science (PS): The Meaning of Scientific Concepts and Theory-Experiment Relationships

Science teaching should have a have deep commitment to philosophy (Gilbert 2006, p. 5; Matthews 2015). Pleasingly many philosophers recognize the place of philosophy in science teaching:

> It is well known that there is a strong interaction between the philosophy of science and the science of each generation. It is less often stated clearly that there is also an interaction between these two and the teaching of science in so far as it is the philosophy of science which molds the general attitudes which form the foundations of the various theories of science teaching. (Elkana 2000 p.463)

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[4] In the literature, energy change is often used as a synonym for energy transformation. Here we use the term solely to describe the change in the *value* of energy: its increase or decrease.

[5] See: Fermi 1936; Quinn 2014, p. 18; Reif 1967, p. 202; Reif 1965, p. 129.

However, Feigl and Brodbeck (1953, p. 5) claimed that philosophy of science was concerned mainly with describing the structure of science itself. The structure of science, not surprisingly, has also been the concern of prominent science educators:

> By linking concept clusters that have common physical variables, one can create larger structures that ultimately encompass all of physics. The approach to definitions, empirical relationships, and theoretical relationships has to be consistent among the clusters that are linked…. there is considerable freedom in the choice of quantities to be defined and derived. The exact choices that are made will determine the structure that is obtained. (Karplus 1983, p. 240)

Elkana further supports this view:

> In whatever light we see this interaction, one thing will be admitted by all; in every age it is the philosophy of science which forms the image of science in the eyes of the masses,... It is not less important that it is this philosophy which determines what is 'good science' and thus determines how it should be taught. (Elkana 2000 p.464–465).

The importance of providing meaning to data brings back Schwab's observation that the epistemology of science is not only about its procedures—it is heavily based on interpretation. This, as stressed by Monk and Osborne (1997), has implications for curriculum development since curriculum developers should be obliged to focus not merely on scientific inquiry skills but also on interpretive discussions of the data found. The curriculum should therefore include grounds on how "scientists come to know what they do" (Shapin 1992).

Karplus'comment with regard to the freedom a curriculum planner has in choosing which concepts to define and which to derive led us to also consider, in addition to developing inquiry skills, the meanings provided to concepts and how such meanings are gained. This naturally brings to fore concepts definition and their connection to theory-experiment relationships. The context of science education also calls to interrelate it to PS by stressing the important role of theories and by addressing explicitly the nature of science in the curriculum (Duschl 1985, 1990, 2000)

Moreover, since science presents a culture, learning of science presumes enculturation from inside and/or outside (Tseitlin and Galili 2005). Expanding the practicing of science presents enculturation from inside. During such a process, conceptual knowledge is constructed by experience in many contexts. Explicit and concise articulation and contemplation of concept meaning might seem less important than application of physical knowledge. This attitude is, however, natural for "normal science" (Kuhn 1970) rather than for revolutionary research. In the latter, the concept's meaning might represent the major issue of interest (Bridgman 1952).

9.2.3.1 Addressing Scientific Concepts in Relation to Their Definitions

We adopted Elkana's approach that philosophy of science can assist in choosing the 'teaching theory' for curriculum development design:

> …We should also aim at grounding our theories of science teaching in that philosophy of science which at present seems to us the most advanced. (Elkana 2000)

Traditionally, philosophy of science was largely concerned with the meaning of the scientific concepts, with special attention given to their definitions (Bridgman 1964; Copi and Cohen 1990; Hempel 1966, 1970; Margenau 1950). Schwab (1964) stressed the importance of concept definitions with regard to the structure of a scientific discipline, as well as in educational scientific epistemology (comprising syntactic knowledge and its relation to measurement) and in scientific content (substantive knowledge). He regarded concept definitions as necessary for the coherent presentation of a subject in science owing to their role in the organization of scientific knowledge.

Thus, philosophy of science was considered in our curriculum development approach since science education requires clarity with regard to the meaning of the concepts used. The scientific activity also requires the use of concept definitions in order to make such concepts useful for scientific endeavors:

> A concept is useless if it does not appear in relation to other concepts, or if we fail to support it with clear definitions. (Holton 1985, p. 221)

Many types of definitions were found to exist (Angeles 1981). However, only two of them, nominal (theoretical) and operational (epistemic), are in accordance with the fundamental schools of scientific thinking: rationalism and empiricism (Margenau 1950; Matthews 2015).

A nominal definition seeks to establish the meaning of a concept by relating it to other concepts and by listing its characteristics. Within the nominal definitions, one can distinguish between several types: textual (such as "the weight of the body is the gravitational force acting on it"), "definitory formula" (Braithwaite 1955) (such as W = mg), and characteristics (such as "weight is a vector").

Positivist philosophy recognized that the explanation of nature - unlike in mathematics - requires more than just theoretical definitions of the concepts involved. This development, which was apparent in Einstein's (1905) use of the concepts of time, simultaneity, and length, led to an appreciation of the fundamental role of the operational definition of physical concepts (Bridgman 1923/1964, p. 36). Thus, an operational definition defines the concept in terms of a particular measurement, indicating the apparatus and the conditions of measurement. Such a definition constitutes the concept's epistemic aspect:

> Ideally, each concept used in physical sciences can be made clear in terms of some such definition, and that is the mechanism whereby mutual understanding among scientists is made possible. For it is clearly more difficult to misinterpret action than words. (Holton 1985, p. 222)

Karplus (1981) claimed that operational definitions have a didactical advantage in that they are more accessible to students but warns about their weakness with regard to the structure of physics:

> The extensive use of operational definitions relates concepts directly to the students' experience and more-or-less familiar objects. Yet physics relationships among concepts must then be obtained from experiments that are carried out with the errors and uncertainties of such procedures, from teacher claims about such experiments that have been carried out by

> others (i.e., researchers in physics), or by means of theoretical derivations and “thought” experiments. (Karplus 1981, p. 240)

Note how in that claim Robert Karplus relates to science, science education research, science philosophy and, by referring to ‘researchers in physics’, also to the history of science. Hence, his approach was for us a way to interrelate all four disciplines.

However, Bunge realized that the operational definitions of physical concepts are not clear without any theory (Bunge 1963 pp. 60–61). Therefore, both theoretical (constitutional) and operational (epistemic) definitions should be employed in defining a given concept (Margenau 1950 pp. 220–244).

In the context of science education, the quality of definitions was regarded as an indicator of coherence (Bächtold & Guedj 2014; Galili and Lehavi 2006). Swartz (1999) drew attention to the many flaws in definitions, such as applying circular reasoning in connection with Newton’s Second Law, found in textbooks of which teachers should be aware. Stinner (1992) and Hestenes (1998) stressed the essential contribution of definitions to the effectiveness of instruction. Operational definitions of physical concepts have been strongly advocated by several leading researchers in physics education (Arons 1965, 1999; McDermott 1996, 1997; Reif 1965). With regard to energy, providing a definition was found to be important in supporting teachers and increasing their confidence (Kruger 1990, Stylianidou and Ogborn 1999).

Teachers and textbooks were found to provide additional types of definitions to the theoretical and the operational (Galili and Lehavi 2006). Lexical (descriptive) definitions (Copi and Cohen 1990) were identified as a subcategory of the nominal definitions. Definitions in this subcategory describe concepts informally, as in a general dictionary, but not in a manner sufficient for a rigid discipline. The concepts were usually related to common experiences, sensations, or ideas and they used non-formal terms. For example, energy is often defined by relating it to fuel, sun’s light, or electricity. The reliance on a descriptive rather than a quantitative approach might cause difficulties (Mclldowie 1995). Textbooks have rarely followed the advanced texts (e.g., Landau and Lifshits 1960) and they related energy to time symmetry and thus avoided its mere postulation. Such definitions were often far from accurate and never referred to measuring operations.

9.2.3.2 Addressing Experiment-Theory Relationships

The experiment-theory relationship is another strand of the philosophy of science discourse that can influence curriculum design, especially when considering whether to construct a concept’s understanding deductively or inductively. With regard to energy, such a consideration can assist when one needs to decide how concrete (vs. abstract) energy should be presented in a curriculum.

According to the generative view (Koponen and Mäntylä 2006), adopting the epistemology of experiments requires an inductive justification of knowledge that can foster and guide students’ own knowledge construction. It was claimed that the epistemological role of experiments in physics may help to reconstruct the use of experiments in their historical perspective. Thus, insights from history and philosophy of physics should be taken into account if one wishes to design an experimental-based curriculum and train teachers accordingly.

9.2.3.3 Implications for Energy Curriculum Design

Several approaches for addressing the challenge posed by the problems of defining energy have been suggested: (a) Avoiding a definition (Poincare 1903/1952, p. 167; Feynman 1964), (b) A mechanical definition as “the ability to do work”, (c) A definition as “the cause of events” (Millar 2000), (d) A definition based on an operational definition of energy change (Karplus 1981),[6] and (e) Developing energy transfer and transformation as a theoretical framework that accounts for changes in very different systems (Bächtold and Guedj 2014; Papadouris et al. 2008).

It is apparent that in most cases if a definition of energy is provided, it would be formulated as a nominal theoretical definition rather than an operational one. The first two approaches seem to provide no or an incomplete answer to the question what is energy. The third definition, a causal definition of energy, as discussed by Ogborn (1986) and Millar (2000), is incorrect since it is entropy (or free energy), that can be said to ‘make things happen’. The ‘work’ definition of energy could hinder our goal of unifying the concept of energy because it is hardly applicable for non-mechanical processes such as light absorption or chemical reactions. In fact, any mechanical-based definition of energy (e.g., through motion) will fail to unify such phenomena and therefore, it will be limited in rendering the idea of energy conservation plausible.

Consider, for example, using a pendulum in order to convey the energy conservation idea. Any classroom observation will demonstrate that the pendulum “loses height” as it swings until it stops its motion. This will happen even in vacuum. Therefore, if one relates energy to motion, the direct interpretation of observing the pendulum’s motion will be that it lost its energy. In order to start looking for the “lost” energy, one assumes that energy is conserved and then one is also compelled to relate energy to phenomena other than motion. Hence energy dissipation and energy conservation are inseparable (Solomon 1982). However, following such an argumentation, students may find the unification of energy difficult and may view the structure of science as being based on cyclic reasoning.

Furthermore, the fact that students are very familiar with such non-mechanical processes stresses the didactic weakness of employing the mechanical definition.

Approaches (c) – (e) share in common the emphasis they put on processes and changes. The last two approaches, (d) & (e), seem to complement each other; however, they share an epistemic difference: (d) employs an operational definition of energy change, whereas (e) presents energy as an abstract, trans-phenomenological concept.

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[6] Karplus suggested defining operationally the energy of a system *relative* to a system of ice and water at 0 °C as: “the mass of ice melted as the system comes to equilibrium with a mixture of ice and water”. We consider this as a definition of the *change* in energy rather than the energy itself, since the result of such a measurement also depends on the relative motion and position of the measured system and the ice-water system.

Note that although energy does not lend itself to an operational definition (or, perhaps to any definition), a change in the energy of a system does. Therefore, keeping in mind Karplus'educational insights with regard to the advantage of using such definitions from the students' perspective, we decided to design the curriculum for middle school level around an operational definition of energy change.

Approaches (d) & (e) naturally directed us to follow Joule's approach and to establish a list of different processes (e.g., a change in height, a change in speed, and a chemical change) that share their capability to produce the same effect: changing the temperature of a certain object.[7] Choosing the temperature change of a standard object as our 'ruler' for measuring energy change, rather than some mechanical device, also enables, beyond the unification of the energy concept mentioned above, to avoid the difficulties posed by the 2nd law of thermodynamics, i.e., that a mechanical process can terminate with heating as the only final result but not vice versa (Arons 1999).

According to the operational approach, the teachers would have a valid rationale to *justify* the unification of the concept of energy change for cases where a change in temperature occurs:

Changes in characterizing variables (of certain processes) → ΔT (of a standard object) $\equiv \Delta E$

The generalization to other processes is left for the next steps of the procedure. This approach enabled us to provide a definition of *energy change* as a quantification of processes:

> 'Energy change', corresponding to some process, is the maximal change in the temperature of a standard object that this process can induce.
>
> Or, less formally: 'Energy change' is the capability of a process to induce warming or cooling.

'Energy change' thus, provides a measure of the change in a system when it goes from one state to another through some process. The details of the process are not significant - only the difference between the different states. Note that the role of a system is greatly emphasized according to this approach. In addition, our definition enables to *quantify* energy change when a system undergoes a process and therefore, it differs from defining the energy of a system as its capacity to produce a change (Bächtold and Guedj 2014).

It should be clarified that the operational definition does not mean that the energy of a system does not change if there is no (or very little) change in temperature when a characterizing variable of a process changes. It only means that if one wishes to ascribe energy change to such a process, one has to refer to a measurement in which the change in temperature is the only change corresponding to the changing variable. Thus, if one wishes to analyze the swinging of a pendulum in terms of change in energy from the beginning of the swing to some intermediate position, one has first to ascribe independently, via measurement, energy change to the change in

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[7] Karplus'suggestion has merit in that the change in the ice mass is the only change in an ice-water system, whereas using a thermometer also involves volume changes. However, carrying out a measurement such as that suggested by Karplus is not feasible in most classrooms.

height and the change in speed. One can then arrive empirically to the idea that the decrease in energy related to the decrease in height almost equals the increase in energy related to the increase in speed.

9.2.4 Science Education Research (SER): Studying Students' and Teachers' Pertinent Knowledge and Difficulties

Science education research provides information about students' and teachers' known pertinent knowledge and difficulties regarding various scientific concepts and ideas. Furthermore, analysis of textbooks can shed light on how a certain subject is planned to be presented and taught. The presentation can be categorized with respect to the different aspects of the concept on hand.[8] With regard to the special concept of energy, SER found that it presents a great challenge for teaching. The literature indicates that students lack a proper understanding of: (I) what energy is (its definition) and what is the meaning of: (II) energy forms, (III) energy transformation and transfer, and (IV) energy conservation (Duit 1984, 1985).

SER also indicates several additional challenges. Students have difficulties to relate quantitative and qualitative knowledge (Goldring and Osborne 1994) with regard to energy and difficulties related to the interrelation of work and energy and to the role of a system in this regard (Lindsey et al. 2009, 2012). The definition of energy seems to pose difficulties even to teachers (Trumper 1998, Galili and Lehavi 2006). In the past, many doubts were raised about the use of 'forms of energy' in teaching. Millar (2000, 2014) points out that very often energy forms serve as a list of labels to be remembered by pupils and that such forms add little, if at all, to explanations and understanding of phenomena. He further argues that energy forms may also complicate explanations by adding unnecessary variables and can even lead to incorrect analyses of processes. Most important to our approach, energy forms may hinder the importance of processes and weaken the unifying image of energy (Ellse 1988; Mak and Young 1987; Summers 1983).

Commonly, graduate-level physics textbooks define energy through a gradual construction: First, work is defined and then, when applied to various forces (e.g., gravitation or elastic), different expressions are obtained by defining the corresponding types of energy (Galili and Lehavi 2006). This method shows that many "types" of energy are based on the definition of work. However, this approach, as discussed above, may face difficulty in addressing heat or radiation. Hence, such phenomena are often postulated as additional options of energy transfer.

The concept of energy is rarely given a universal definition to which the learner can refer when considering something called "energy". Thus, energy cannot be well distinguished from other concepts (e.g., force) and is not sufficiently inclusive to account for its different "types". Therefore, the definitions of energy often lack the

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[8] With regard to energy, see the comprehensive summary of Michelini and Stefanel (2010).

requirement of the scientific method, namely that a definition of a concept will differentiate it from other concepts and clarify its essence (Cohen and Nagel 1939, p. 232, 238). This, possibly, impedes a systematic exploration of the subject matter (e.g., the application of energy rather than force to chemical or biological systems).

Parallel to these deficiencies, there is a lack of consensus among physics educators as to the proper language by which energy should be described (Wolter and Martin 2002). In particular, the meaning of the above-mentioned four aspects is not agreed upon (Michelini and Stefanel 2014). For example, whereas energy is considered not to be a substance, the language used to describe some of its aspects (mainly energy transfer) may suggest a substance interpretation of energy.

Official international education standards and national curricula often leave much room for interpreting the meaning of the four aspects of energy. For example, the New Framework for K-12 Science Education uses terms like *energy generation* (e.g., pp. 9, 43), *energy flow*, and *energy transfer* (e.g., pp. 84, 89, 92, 93), energy storage (e.g., pp. 96, 121) without explicating their meaning (National Research Council 2012). Under the headline “What is energy?” the framework states: “That there is a single quantity called energy is due to the remarkable fact that a system’s total energy is conserved”. Such a statement clarifies the unitary aspect of energy but not the meaning of the concept (there are other conserved entities in science). The fact that various forms of energy still exist in the framework may also weaken the unitary statement. Energy as a quantitative property of a system is mentioned only once (p. 123) without specifying how its value can be determined. Moreover, scrutinizing the framework reveals that energy is predominantly mentioned with relation to its changes during processes due to transfer, interactions, and reactions, rather than its value within a system. This may provide a hint as to the importance of using energy changes rather than energy to describe and analyze processes and changes, as suggested by Hecht (2007).

The SER literature suggests that although forms of energy or its transformations do not have a solid scientific status, they are very useful in science teaching. Thus, in designing the curriculum we were challenged to develop teaching materials in order to address the students’ difficulties and the teachers’ need to possess a clear view regarding the meaning of the concepts they teach.[9] In designing these materials, we gave special attention to the unitary nature of energy and to the coherent meaning of such terms as energy “forms”, “transfer”, “transformation/conversion”, and conservation.

In order to follow the goals of coherence and consistency, the curriculum design *required us to make didactical choices with regard to which definition to choose,* whether to focus on energy or on energy change to refer to energy forms or to avoid them, among other choices. We will demonstrate later possible ramifications of making different curricular choices with regard to the example of the energy change related to changes in speed (“kinetic” energy).

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[9] It is not surprising that the Framework (pp. 95,96) calls for the need to have “a common use of language about energy and matter across the disciplines in science instruction” and that “the language of energy needs to be used with care so as not to further establish misconceptions”.

Consequently, we had to make decisions concerning how to interweave the content and the means to support students in constructing their pertinent knowledge and understanding.

One can observe that many of the difficulties regarding the understanding of energy, as reported by SER, may be related to the "language of energy" as described above. These observations are summarized in the following table. We formulated the difficulties that were found to puzzle learners in terms of questions, and categorized them according to the corresponding energy curriculum challenges:

9.3 Teachers' Concept-Image of Energy

In parallel to our curriculum design, we conducted research on teachers' concept images of energy. It revealed that their concept image may pose a great challenge for curriculum design (Lehavi and Eylon 2014). We found that many teachers declared that energy is one entity, but, at the same time, many also did not agree with the statement that energy only changes in its value. Moreover, regarding energy transformations in general, the extent of agreement among the teachers regarding the unity of energy was considerably less. A similar picture of teachers' views was observed in their responses regarding specific cases of energy forms or types. There is an apparent gap between the teachers' statements regarding the unity of energy and their opinion regarding energy transformations and forms. This gap may indicate that the idea that energy is a unified concept is not fully accepted and is not clearly related to terms such as energy transformations and forms.

Most of the teachers indicated that the energy of an object is a relative quantity. However, their responses to questions that addressed specific cases revealed that many abandoned this idea in favor of the idea that energy is a property pertaining to a single object that is absolutely determined. This view ignores the systemic view of energy as is apparent in the case of an object's height energy, which disregards the Earth as a part of the system. In addition, most of the teachers hold the view that energy is contained within an object, which further weakens the relativistic view of energy. Only a few teachers agreed with the statement that a single procedure of measurement can be used to measure energy changes, and with regard to measuring energy itself, most of them did not respond. This may indicate that the teachers are confused with regard to the idea of unifying the concept of energy via measurement or they may even reject it. This, together with the confusion regarding the possibility of measuring energy changes by a single procedure, may have implications regarding the ability of many teachers to teach their students about the unification of energy.

With regard to energy conservation, our findings indicate that the energy conservation law (ECL) is perceived as an irrefutable law. This is supported by teachers' views of the limitations of measurement with regard to energy. Such a view of the conservation law assigns it a special status as a scientific law. Furthermore, the view that energy cannot be created or destroyed does not support the systemic view of the energy conservation law and might actually strengthen the material view of energy.

We found that the two aspects - energy conservation and energy transformations - nearly mirror each other in the teachers' views. Apparently, one is the reason for the other and, at the same time, its result. This view may suggest that some teachers regard ECL not as a basic law but as being derived from energy transformation. Such views possibly hinder a coherent justification of both energy transformation and the energy conservation law.

These findings may indicate the difficulties one may face in fostering a coherent teaching of the energy concept in such a way that energy forms (or types) together with energy transformation and transfer will be consistent with the unity of energy and its conservation (Eylon and Lehavi 2014).

9.4 Curriculum Design Decisions

Here we will depict the framework we employed in developing an 'energy change approach'. We will describe the points considered in this development and will provide specific examples from the curriculum.

It should be stressed that we focused on the teachers' concept image of energy. We therefore decided to support the unitary image of energy by regarding energy types/forms as *labels of different processes* in which the value of energy changes (i.e., increase or decrease) rather than perceiving the *existence* of different types of energies. The notion of energy increase/decrease assisted us in providing coherent meaning to confusing concepts such as energy transformations, energy transfer, and energy conservation. The finding that the teachers' declarative knowledge was not always in accordance with their deep-rooted beliefs and knowledge led us to construct ideas and activities that support their declarative knowledge. For example, the teachers' doubts regarding whether it is possible to construct an energy concept on the basis of experiments led us to generate simple and easy-to-use Joule-like experiments (Lehavi 2014; Lehavi et al. 2014a, b, 2016). Thus, we aimed at focusing the teachers' attention on the following observations:

9.4.1 Central Observations

As pointed out previously (Table 9.1), we opted in the energy curriculum to provide meaning to energy forms, transformations, conversions, transfer, and conservation. This required us to draw the students' attention throughout their learning to the following observations:

A. Co-variance of Changes An observation of various processes in nature revealed that they cannot be described by the change in one variable only. For example, when an object falls, its height decreases and its speed increases; when an object absorbs light there is less light and the object heats up.

Table 9.1 Energy teaching challenges and their relations to energy curriculum challenges[a, b]

Teaching challenges	Curriculum challenges
(a) Is energy a material entity?	**(I)** How can a definition be employed in order to provide meaning to energy?
(b) Is energy related to living things only?	
(c) Is energy a force?	
(d) How can we distinguish the energy scientific content from its everyday meaning?	
(e) What makes energy one concept and not many?	
(f) Is energy an absolute or relative entity?	
(g) Can we measure energy or is it only an abstract concept?	
(h) What does 'energy of an object' mean? (e.g., energy of a chocolate bar)?	
(i) How can we indicate the characteristics of energy (e.g., its conservation or relativeness) if we don't know what energy is?	
(j) Why does energy, unlike other physical concepts, have forms?	**(II)** What meaning can be ascribed to energy forms (types)?
(k) What makes these forms manifest the same entity?	
(l) How do we know that one or more forms of energy can be transformed into other forms?	**(III)** What meaning can be ascribed to energy transformations/conversions/transfer?
(m) Is energy transformation a consequence of energy conservation?	
(n) How do work and heat relate to energy change?	
(o) If energy is not a material entity, how can it move from one object to another?	
(p) How do we know that energy is conserved?	**(IV)** What meaning can be ascribed to energy conservation?
(q) Is energy conservation an empirical law of nature?	
(r) Can one, in principle, refute the energy conservation law?	
(s) Is energy conservation a consequence of energy transformation?	
(t) Does energy conservation mean that energy cannot be created or destroyed?	
(u) Does energy conservation mean that energy cannot be created or destroyed?	
(v) Why does energy conservation hold only for isolated systems?	
(w) If energy is conserved, what is the meaning of energy sources?	
(x) How can energy conservation be applied?	

[a] In some cases the difficulties from one category are closely related to those belonging to another category

[b] Most of these questions were the focus of the Discussion of Strand on Energy in Lower Secondary School, held at Girep 2010, Reims

This observation enabled us to relate to energy changes in simultaneous processes. Simultaneous changes can occur solely within a system or also in the system and in its surroundings. The simultaneity of changes enabled us to generalize the concept of energy change and to apply it to cases beyond those described by temperature change.

B. Opposite Arrows of Change A further observation revealed that simultaneous changes always occur in such a way that some of them correspond to an increase in energy and others to its decrease.

C. Simultaneous Changes in Energy Can Counterbalance Each Other The previously mentioned feature of opposite arrows of changes in nature does not necessarily imply that the corresponding changes in energy are mutually counterbalanced. This remains to be determined experimentally. One has to verify that for simultaneous changes to occur, the increase in energy corresponding to some changes equals the decrease in energy corresponding to the others.

D. Isolated Versus Non-isolated Systems The concept of simultaneous changes can be used to define operationally an isolated system:

> An isolated system is one that any change within it is not coupled by changes in its surroundings and vice versa.

Note that since the borders of a system are defined arbitrarily, one can transform a non-isolated system into an isolated one by expanding its borders.

E. Energy Conservation From observations A – D one can determine empirically that in an isolated system the energy increase corresponding to some processes of change is balanced by the energy decrease corresponding to other processes. Therefore, one can regard energy conservation as an empirical law that, in principle, is refutable.

9.4.2 Didactical Decisions

Considering the four disciplines as resources for guiding our curriculum design decisions led us to agree on the following didactical principles:

Focus on Observations To encourage students: to observe various processes and draw their attention to the changes involved in them without first using the concept of energy; to look for as many processes as they can that cause a thermometer to rise or fall in temperature; to look for a common feature that enables one to compare different processes[10]; to focus on energy increase or decrease as characterizing changes (processes) in nature rather than focusing on energy as characterizing static states.

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[10] Some students say that time can be that common feature. A great idea!

Unification To unify the concept of energy change (its increase or decrease) by providing an operational definition based on Joule-like experiments, based on the change in temperature of a standard object.[11]

Reinterpretation To keep the traditional vocabulary owing to its convenience and frequent use, but suggest a new meaning to it:

- Energy transformations and transfer are presented as a convenient way to talk about energy increase and decrease in coupled processes and systems, respectively.
- Energy conservation is presented as an empirical observation of the balance between energy increase and energy decrease related to processes occurring in isolated systems.

Table 9.2 presents how our curricular decisions employed observations from Science, HS, PS, and SER:

9.4.3 Example: Different Definitions Imply Different Approaches to Teaching Energy Related to Motion

The following is an example of how one can adopt different definitions of energy change in order to arrive at the well-known expression for when an object stops:

$\Delta E_k \propto v^2 – 0$

A. A work-based definition:

   (a) $\Delta E \equiv W \equiv F.\bullet\Delta s = (ma)\bullet\Delta s = (m\frac{v^2 - 0^2}{2\Delta s})\cdot\Delta s \propto v^2 – 0$

B. An operational definition:

   (a) $\Delta E \equiv \Delta T$ (of a standard object) $\propto v^2 – 0$ (as measurements show)

Note that the first alternative requires knowledge of Newton's laws and kinematics in their mathematical formulation. Such sophistication is beyond the middle school level. The operational definition (alternative B), on the other hand, is based on knowledge of temperature measurement and the fact that a change in temperature, being a common result of different processes, can be agreed to define energy change. Such a view is well within the reach of our students, demonstrating rather well what Karplus'claim (p. 10) with regard to operational definitions.

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[11] We used a simple kitchen thermometer that has a metal "sleeve" with the sensor inserted in it. The sleeve can be regarded as a standard object.

Table 9.2 Employing science, HPS, and SER in making curricular decisions

Alternatives	Observations from science, SER, and HPS	Our decisions
1. Which concept should be emphasized: Energy (static states) or energy change (processes)?	Scientists are mostly concerned with changes in the value of energy in different kinds of processes (the 1st law of thermodynamics) rather than in its absolute value, which is more ambiguous	To emphasize changes in the value of energy and hence, on the processes by which a system's state can change
2. Provide the emphasized concept with an abstract or a concrete definition?	Scientists and PS scholars regard operational definitions to be unambiguous. SER found that students and teachers have difficulties in understanding the abstract meaning of energy	To relate energy changes (increase or decrease) to a specific measurement: Temperature change of a standard object
3. Many "energies" (types/forms) or one?	Scientists regard energy as one concept. SER found that students have difficulties in accepting the unitary nature of energy and that the community of "experts" dealing with energy (teachers, engineers, and scientists) find the terms of energy forms to be useful.	To keep the terms of energy forms or types. To unify these terms through energy change by referring to a feature common to many kinds of processes: Their ability to warm or cool (a calorimetric approach following joule and Karplus). Thus, we defined energy change as a measure of the maximal ability of a process to induce change in the temperature of a standard object
4. Energy transfer interpretation: a substance "flow" or a change in the value of energy?	Scientists regard energy transfer as a systemic feature: Its increase or decrease owing to a system's interaction with another system (the 1st law of thermodynamics). SER found that students often regard energy as a kind of substance that can move from place to place	To relate to energy transfer in terms of a simultaneous decrease and increase of energy in interacting systems
5. Energy transformations: a change between different types/forms of energy or a change in the value of energy?	Scientists did not reach a consensus regarding the scientific meaning of energy transformations. SER found that energy transformations, although useful for classroom discourse, strengthen the "many energies" concept	To relate to energy transformations in terms of a decrease and increase of energy in simultaneous processes
6. Energy conservation: a postulated character of energy or a systemic, empirically based law?	Scientists regard energy conservation either as coming from a general symmetry or as a systemic feature (through the 1st law of thermodynamics). SER found that teachers have difficulties in justifying energy conservation	To construct energy conservation as a systemic law representing the balance (supported by experiments) between the simultaneous increase and decrease of energy in certain systems

9.5 Implementation

The subject of energy is addressed directly in the Israeli middle school curriculum in grades 7 and 9. In addition, energy is addressed in grade 8 as part of a unit on electricity, and also in grade 9 as a part of a unit focusing on biology. At the middle school level the national curriculum addresses topics such as energy forms, energy transfer, energy transformations, and energy conservation and relates them to various phenomena. The main leap from the 7th grade level to the 9th grade level is that the latter requires introducing mathematical representation. Note that the Israeli national curriculum lets the textbook authors choose their own preferred didactics.

The curriculum resources that were designed according to the above approach were implemented in Israel in two phases: (a) Developing teaching materials for 7th and 9th grade science teachers[12]; (b) Developing textbooks for 7th and 9th grade levels. These phases were accompanied by special workshops for teachers.

In phase (a) the teachers were provided with a rationale explaining why energy is the “language of changes”, followed by suggestions for classroom activities, such as simple experiments and demonstrations. The teaching materials also offered the teachers specially designed questions that emphasize changes rather than static states. For example, instead of asking what is the energy of a book standing on a shelf (given the book’s mass and height above the floor), we asked what would be the change in energy when the book falls from that shelf to the floor; or, instead of asking what is the energy of a moving car (given its mass and speed relative to the road), we asked what would be the change in energy when the car stops. Similar questions were developed for other phenomena. The teaching materials that appeared during the years 2011–2012 interweaved teaching, learning, and assessment. The materials also offered a graphical representation that calls attention to processes in systems and the corresponding changes in energy (Fig. 9.1).

These materials are used by most of the science teachers in 7th to 9th grade. However, although mentioned in the rationale, these materials did not strictly follow the operational definition of energy change as mentioned above.

The materials for the 7th and 9th grades also added the operational definition of energy change by introducing the idea that many changes in nature can be quantified by measuring the change in the temperature of a standard object (a calorimetric approach).[13] Thus, these materials also offered Joule-like experiments such as those described previously (Lehavi 2014; Lehavi et al. 2014a, 2016).

In phase (b) the textbooks developed at the Weizmann Institute followed the approach described previously by referring *explicitly* to the students’ (and teachers’) attention to the following aspects of energy as a language of changes:

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[12] These materials were developed, in addition to the authors of the current paper, by Rami Arieli, Amnon Hazan, Ayelet Weizman, Yael Bamberger, Tammy Yechieli, Oren Eckstein, and Roni Mualem.

[13] These units are not the only ones used in our system, which is in the middle of shifting from the old curriculum to the new one.

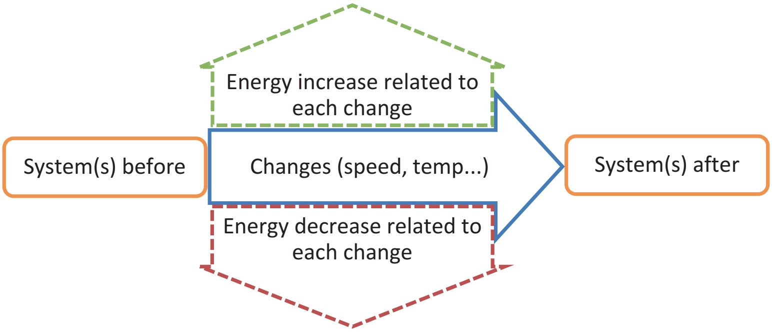

Fig. 9.1 Energy change diagram

1. *Processes:* Different processes in nature, characterized by changeable properties (parameters/indicators) such as height or speed, can be quantified by energy change.
2. *Simultaneous (or coupled) changes:* Changes in nature are always accompanied simultaneously by other changes.
3. *Unity:* Energy is considered to be a single quantity because its increase or decrease in different processes can be uniquely quantified via measurement. Different "types" or "forms" are only labels representing different processes in which energy increases or decreases (and thus they are not really different).
4. *Measurability:* Increases or decreases in energy can be verified experimentally. The results of such measurements can be generalized and used in mathematical expressions (for 9th grade level only).
5. *The meaning of "Energy transfer":* Simultaneous energy increase and decrease in interacting systems.
6. *The meaning of "Energy transformation":* An increase and decrease in energy in different kinds of simultaneous processes.
7. *Conservation:* The overall simultaneous changes in energy within certain systems (called isolated systems) are measured (or calculated, based on measurement generalizations) to mutually cancel out each other. In this respect, we wish to clarify that any classroom experiment can only support this idea as a plausible inference. We addressed it quantitatively in both grades (7th and 9th) with regard to the heat phenomenon by measuring the change in temperature of two identical objects having different temperatures. The students were able to observe that the decrease in energy of the hotter object equals the increase in energy of the colder one.

For the case of energy conservation during decreased height, we referred to it in the 9th grade as follows: First we established through Joule-like experiments that a linear relation between an energy change (measured by a change in temperature) and the height change is plausible. Then we did the same for the quadratic relations between the change in speed and in energy (again, measured by a change in temperature). We then demonstrated that for a falling body there is a linear relation between the decrease in the energy corresponding to the decrease in height and the

Table 9.3 The 7th grade unit components (14 lessons, 45 min each)

Subject	Key ideas
1. Energy – Phenomena & changes	Energy increase or decrease can describe different types of processes
	Each process can be characterized by some changeable property
	A change in temperature can indicate a change in energy
2. Energy conservation (an empirical approach)	A decrease in energy is always accompanied by its increase
	Observations and measurements show that in some systems energy increase is counterbalanced by energy decrease
3. Energy change	Energy transfer means the simultaneous energy increase/decrease in interacting systems, and energy transformation means the simultaneous energy increase/decrease in processes of different types
4. Where is the missing energy?	Changes in thermal energy cannot be fully reused
5. Energy change in warming and cooling	Heat is the gain in energy of a system due to its interaction with a warmer system
	Heat is related to radiation, convection, and conduction.
	Heat can indicate an open system

increase in energy corresponding to the increase in speed.[14] From these two experiments, together with all the qualitative examples of energy mutual increase/decrease, we were able to present the energy conservation as plausible inference.

We will describe here the structure of the 7th grade unit[15] developed at the Weizmann Institute: “A first Look at Energy”, which was intended to lay the foundation for further development in the 8th and 9th grade units. The unit comprises five themes (Table 9.3).

9.6 Conclusion

We examined the importance of considering science, HS, PS, and SER when designing a coherent science curriculum for teaching energy and discussed in detail how they were used. SER provided answers to the question, what is required in the energy language in order to address the difficulties exhibited by students and teachers. Science provided us with the principles and laws that should be addressed, together with their interpretations. PS was examined in order to determine how to make scientific concepts meaningful and relate to the scientific structure regarding energy. HS gave us the means to justify scientific claims. In addition, the philosophical discourse regarding the experiment-theory relationship and the meaning of

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[14] We analyzed a video of a falling object.

[15] Written by Amnon Hazan and Yael Bamberger, The Science Teaching Department at the Weizmann Institute of Science, Rehovot, Israel.

scientific concepts, with special attention to their definitions, provided essential and rich support in making curriculum and development decisions.

Note that each of the four PHES in our approach was employed not just for the sake of presenting them and discussing their role in understanding science, but rather, as a resource to be considered when designing a science curriculum. We regarded the PHES disciplines as important for providing guidelines for designing a curriculum rather than as bodies of knowledge from which the *content* of the curriculum should be enriched. This is especially salient with regard to the history of science. Although in our 9th grade textbook[16] we discuss the caloric theory as well as different alternatives to define weight, these are not considered by us as guidelines but rather as contents that we found important to be included in our textbook. In contrast, adopting operational definitions from PS (as well as from SER) and the Joule-Karplus thermal approach from HS, provided us with guidelines regardless of the important question of whether or not this choice should be presented explicitly to the students. Although the guidelines illustrate the approach to teaching energy, they can also be used for teaching other concepts such as electric charge or force. For example, our 8th grade unit on electricity relates the concept of electric charge to electroscope measurements and after discussing this topic, the different features of electric charge are studied.

We, as well as others (Eylon and Hofstein 2015), regard curriculum design as a discipline of its own that has undergone considerable changes in emphases and approaches. Like PS, HS the process of a curriculum design requires the examination of science in order to make it comprehensible. However, unlike those disciplines, the target population of the science curriculum designers is not the designers' community and its goal is not a scholarly investigation. Curriculum design is mainly concerned with making didactical choices with students' and teachers' communities in mind, along with practical ramifications. Therefore, it requires knowledge from the SER discipline.

It should be emphasized that we do not advocate only one way of using PHES in curriculum design. For example, one may wish to emphasize in a specific curriculum the evolution of science and hence, lean more heavily on HS or that part of PS that is devoted to the history of scientific discourse. In the case of energy, this would probably result in a curriculum much different from the one presented here – one that elaborates on how the concept of energy evolved in the course of scientific discourse. To cite another example, a curriculum that emphasizes contemporary science may highlight, as the New Framework for K-12 Science Education does, the role of fields with regard to energy. Nevertheless, we believe that in making any such curricular choices, the role of SER in the designing process should be central.

The idea that a curriculum design process should integrate multiple perspectives is not new. More than 40 years ago, Schwab (1973) argued that such a process should involve five commonplaces: subject matter, learners, milieus, teachers, and curriculum making. Our approach addresses all of these aspects, especially if one

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[16] The 9th grade textbook was developed, in addition to the authors of the current paper, by Adi Rosen, Uri Ganiel, and Amnon Hazan.

accepts Null‘s (2011) interpretation of the subject matter as involving content and methods. However, since it is not clear in Schwab’s framework whether and how considerations from PS and HS should be involved, we believe that our approach may complement this framework in curriculum design theory.

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