Energy forms or energy carriers?

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It is customary to say that energy exists in different forms which are transformed or converted into one another during physical processes. However, a careful analysis shows that thinking in and speaking of energy forms is inappropriate and conceptually even misleading. Since most textbooks use the term "energy form" without spelling out a clear procedure by which different "forms" of energy can be categorized, rigorous criteria for categorizing flowing and stored energy are discussed in this paper. These criteria show that the term "energy form" for the respective categories is unsatisfactory because it easily leads to the misinterpretation that there are different kinds of energy, rather than emphasizing the simpler and physically more correct picture of energy as an unalterable substance. Taking into account the well-known but little recognized natural law that energy always flows simultaneously with at least one other physical quantity, the concept of *energy carrier* is introduced. This concept provides a clear picture of how energy is transported, exchanged, and stored. This picture is scientifically accurate, yet simple and easy to present even at an elementary level.

I. INTRODUCTION

The purpose of this paper is to show that the concept of "energy form" is misleading. It is argued that this concept be dropped altogether and replaced by a concept more appropriate to the energy's substance-like nature: *energy carrier.*

This paper is organized as follows: In Sec. II, the idea of a substance-like quantity is presented. In Sec. III, a commonly applied but seldom recognized natural law is used to enable a strict physical definition of "energy form." In Sec. IV, arguments are advanced to suggest that, in view of this definition, the concept "energy carrier" introduced in this paper might be more appropriate than the traditional concept of energy form for a clear understanding of energy.

II. THE SUBSTANCE-LIKE NATURE OF ENERGY

There is a class of physical quantities whose characteristics are especially easy to visualize: those extensive physical quantities to which a density can be assigned. These include electric charge, mass, amount of substance (number of particles), and others. Because of the fundamental role these quantities play throughout science and because such quantities can be distributed in and flow through space, we give them a designation of their own: *substance-like.*

If a quantity is substance-like, it makes sense to say it is contained within a region of space. This means, it makes sense to ask about the amount of such a quantity within a region of space and to relate changes in this amount to the flow of this quantity to or from the considered region. Indeed it is appropriate to speak about the local conservation or nonconservation of a quantity only if this quantity is substance-like and if it obeys or violates a continuity equation. On the other hand, it is inappropriate to speak about the conservation or nonconservation of nonsubstance-Iike quantities such as, say, electric field, temperature, or velocity. Some substance-like quantities are always conserved, for example, electric charge, whereas other substance-like quantities are conserved only under special circumstances such as amount of substance (if no chemical reactions are taking place). Thus "substance-like" and "conserved" are not identical concepts: "substance-like" is more comprehensive.[1]

Both of the abovementioned quantities, electric charge and amount of substance, are traditionally recognized to be substance-like. In this paper, however, we are interested in yet another substance-like quantity: energy.

The substance-like nature of energy follows from the fact that a density and a current exist for the energy (the energy current is traditionally called "power"). It is also evident in the fact that it makes sense to ask about the local conservation of energy. Indeed, energy is a conserved, substance-like quantity.

III. ENERGY FORMS

The term "energy form" is used together with a profusion of different names such as rest or mass energy, kinetic energy, heat or thermal energy, gravitational energy, binding energy, radiant energy, elastic energy, potential energy, electrical energy, chemical energy, nuclear energy, and so on. A careful student might rightly be confused in trying to figure out, say, whether the energy contained within a battery is in the form of electrical or chemical energy. Indeed, even well-known textbooks differ amongst themselves as to their definition of the term "energy form": some[2] imply the definition has something to do with the various ways energy can be exchanged; others[3] imply the definition has something to do with the various ways energy can be stored; others[4,5] use the term in such a way that both implications seem to pertain. It might seem, therefore, that the concept of energy form has a rather ambiguous physical interpretation and, consequently, that the importance of the concept is more colloquial than scientific. The purpose of this section is to provide a rigorous definition of energy form.

Energy can be classified in two completely different ways6: first, by how energy *changes* or, what amounts to the same thing, how energy *flows* (for example, into or out of a physical system the energy of which is changing), and second, by how energy is *stored.* In the first case, one arrives at concepts like electrical energy, chemical energy, heat, work, etc. **In** the second case, one refers to concepts like internal energy, electric field energy, kinetic energy, potential energy, and so on. Unfortunately, many books speak of *energy forms* in both cases.

Consider the first classification of energy into energy changes or energy currents. *Experience shows that energy always flows simultaneously with the flow of at least one other substance-like quantity.* This statement expresses a law of nature. It can be written as[1]

$$I_E = \phi I_Q + \mu I_n + \mathbf{v}\cdot\mathbf{I}_p + TI_S + \dots \quad \text{(I)}$$

Here I_E, I_Q, I_n, I_p, and I_S stand for an energy-, charge-, molar-, momentum-,[7,8] and entropy-current, respectively, while ϕ, μ, $\mathbf{v}$, and T represent the electric potential, chemical potential, velocity, and absolute temperature. For example, energy flows (as specified by the Poynting vector field) to a toaster simultaneously with the flow of electric charge through the wires leading to the device; energy flows together with amount of substance (fuel + oxygen) into a car engine; energy flows together with momentum through a rope pulling a wagon and energy flows together with entropy through the wall of a house. **In** such cases, one speaks of the transfer or exchange of energy in one or another "form" according to the physical quantity which flows simultaneously with the energy. **In** the above examples, one speaks of electrical energy, chemical energy, work, and heat, respectively. Incidentally, the same technique can be used to classify energy forms in terms of the physical quantities which change along with the energy change of a system. Such a classification is expressed mathematically by the Gibbs Fundamental Form well known from thermodynamics.[9,10]

The breakup of *stored energy* into various parts follows from another consideration: The energy of a system can always be expressed as a function of certain other variables of the same system. For example, if we designate these variables by $x_1, x_2, x_3, \dots$ then we have $E = E(x_1, x_2, x_3, \dots)$. **If** the variables are properly chosen, the system can be completely described by such a function. **In** this case, the energy function is commonly called the "Hamiltonian" of the system (in mechanics) or a "thermodynamic potential" (in thermodynamics).[11] The energy function of many familiar physical systems can be broken up into separate terms, each of which depends upon variables common to no other term in the sum. For example, one might have $E = E'(x_1, x_2) + E''(x_3) + \dots$. If this happens to be the case, each of these terms can be baptized with a different name and one arrives at what could be called "existence forms" of energy.

An example of this procedure is given by a capacitor. The energy of this object can be written as $E(Q) = E_0 + Q^2/2C$, where Q is the charge and C the capacitance. The first term on the right-hand side of this expression is independent of Q. The second term is independent of E_0 and is called the "electric field energy." **If** one takes motion into account, the energy of the capacitor can be written as $E(Q,p) = E_0 + Q^2/2C + p^2/2m$. Here p is the momentum of the capacitor and m is its mass. The first two terms on the right-hand side of this expression are identical to those in the initial expression and have already been mentioned. The term $p^2/2m$ is independent of Q and E_0 and, therefore, can be given a name of its own: "kinetic energy" (or "energy of motion").

Generally, one is allowed to assign names to the various terms of a sum representing the energy whenever the energy of a system can be broken up into separate terms, each of which depends upon variables common to no other term in the sum. However, this is not always possible. Indeed, many important physical systems do not allow such a breakup. For example, the energy of an ideal gas is an inseparable function of the entropy S, volume V, and amount of substance n. Generally, the energy function of any energy converter is inseparable in the variables associated with the energy forms being converted. For example, the energy function of any engine which is able to transfer heat $T\,dS$ into work $-p\,dV$ (where p here stands for pressure) is inseparable in S and V.

In contrast to the naming of energy forms in terms of a breakup of the energy function, energy currents can always be classified according to Eq. (I). Thus the classification of energy in terms of energy currents is more general than the partitioning of stored energy into various terms. **It** is not advisable, however, to call these currents "energy forms." Speaking about different forms of energy is misleading from a didactic point of view. This will be discussed in the next section where we will argue in favor of a more up-to-date classification of energy in terms of the concept of *energy carriers.*

IV. ENERGY CARRIERS

If we accept the above classification of energy currents, what then is wrong with the general concept of energy form? The best way to answer this question is to consider the answer to yet another, for example: "What would be wrong with speaking about different forms of electric charge?" **In** other words, why don't we give different names to the electric charge, e.g., "electronic charge," "protonic charge," "myonic charge," "Cl-ionic charge" according to the charge carrier involved during a transfer of charge? For example, why don't we say that ionic charge is "converted" into electronic charge (or vice versa) at the electrodes of a battery or that protonic charge is converted into positronic charge in β^+-decay? Obviously, giving different names to the electric charge could lead to the mistaken impression that these designate different physical quantities when only one and the same physical quantity is involved in each case: electric charge. If the substance-like nature of energy is taken just as seriously as the substance-like nature of electric charge, then speaking about different forms of energy is just as misleading as speaking about different forms of charge would be. It is not the energy being transported through the electromagntic field, a fuel line, or a house wall which has different characteristics but, rather, the other substance-like physical quantity which flows simultaneously with the energy in each case. Consequently, energy is not actually transformed or converted within a so-called "energy transformer" or "energy converter." Rather, it is correct to say that the other substance-like physical quantity which flows along with the energy is *exchanged* within such a device. For example, energy is brought into a power plant together with coal and oxygen or, scientifically speaking, together with the amount of substance (the quantity measured in moles) of coal and of oxygen and energy always flows out of the power plant simultaneously with electric charge. Energy flows simultaneously with the flow of electric charge into a motor winding up a rope and energy flows out again through the rope along with momentum.

If it is agreed that the term "energy form" is misleading and inadequate to express the law mentioned above, what other term could be used to better replace it? Again the answer becomes obvious by asking the analogous question about electric charge. The answer is *energy carrier.* We say that the substance-like physical quantity which flows while energy is flowing, "carries" the energy. It is an "energy carrier."

It is inappropriate to speak about the forms of something which itself does not change but, rather, which only changes carriers. For example, consider some commodity, say potatoes, which changes its carrier during transport. Potatoes often have a long way to go from the field to the household: They are carried by a tractor trailer from the fields to a pickup truck which takes them to a loading station where they are loaded onto a semi, transported to another city, reloaded onto a delivery truck, and then brought to a supermarket where they finally get to the customer. Nevertheless, no one would think to label potatoes differently during each stretch of their trip, for example, "tractor potatoes," "pick-up potatoes," "semipotatoes," "delivery potatoes," and "marketing potatoes." On the other hand, it is quite natural to say that the potatoes have changed their carrier several times along their way from the fields to the household. The concept "potato carrier" is rational; the concept "potato form" is not. We can go even further with this comparison. For example, no one would think to give potatoes an *entirely* different name, say, "truck retarder" or "biostarch," during some particular part of their trip. Nevertheless, this is just what is done in the case of energy when one speaks of "heat" or "work."

This comparison of energy with potatoes to make our point is not as ridiculous as one might be inclined to think. The basis of the comparison has nothing to do with the fact that you can see potatoes but you can't see energy or that a potato is a concrete thing and energy is an abstract concept. The validity of the comparison is based solely upon the fact that one can speak of a density and current for both energy and potatoes. Of course, there are limits as to how literally the expression "energy carrier" should be understood. The word "carry" implies here only a *temporal* relationship between the flow of energy and the flow of an energy carrier. It is not meant to imply that energy and its carrier necessarily occupy the same position in space or even flow with the same velocity. The example of the energy carrier "electric charge" amply illustrates this point. The expression "energy carrier" is a didactic tool which can be used to considerable advantage if not applied too naively.

An energy carrier can be "loaded" with more or less energy in the same sense that a carrier of commodities, say a pickup truck, can be loaded with more or less of a commodity. For example, a 2-A electric current can carry a greater or lesser energy current, say 1 kW or 10 W, depending upon the value of the potential. Accordingly, the electric potential is a measure of how much energy the energy carrier "electric charge" (or "electricity") is *loaded* with. The electric potential is an *energy load factor.* Many other familiar intensive variables are also energy load factors. For example, the absolute temperature T is a measure of how much energy an entropy current is loaded with and the chemical potential μ is a measure of how much energy a molar current is loaded with. It is easy to see the importance of many intensive physical variables if their role as energy load factors is emphasized.

The picture of energy carriers and energy load factors is especially useful to describe devices which are traditionally called "energy transformers" or "converters." Traditionally speaking, energy flows into an energy transformer in one form and out in another. Unfortunately, this way of speaking suggests that one physical quantity is transformed into another within such a device. Actually, however, the energy simply changes its carrier within the device. In other words, the energy is transferred from one carrier to another within the device. Accordingly, the name *energy transceiver* is more appropriate to the actual function of such a device.

Our everyday natural and technological environment is full of examples of energy transceivers. For example, energy is transferred from the carrier "electric charge" to the carrier "entropy" within an electric oven and energy is transferred from the carrier "amount of substance" to the carrier "electric charge" within a power plant.

It is easy to graphically represent the energy transport from one device or region of space to another with the help of an *energy flow diagram.* Such diagrams provide the means for a simple, graphical calculus applicable to the solution of energy-related problems. A course[12,13] for beginners in physics (grades 5 and 6) has been developed on the basis of such diagrams and a school book[14] designed to accompany this course is available. A more detailed discussion concerning the elementary use of energy flow diagrams has already been published elsewhere.[12-14]

V. SUMMARY

Energy is a substance-like quantity: It is distributed in and can flow through space.

Since the term "energy form" leaves room for misinterpreting different energy forms as different physical quantities, it should be replaced with a more suitable concept. To this end, we rely upon the experience that energy always flows simultaneously with at least one other substance-like quantity. This shows that one must focus upon the substance-like quantities accompanying the flow of energy if one wants to get a suitable description of energy transfer.

Instead of speaking of energy forms, it is more appropriate to visualize energy as a kind of "stuff" which can flow from one place to another only when "carried" by another kind of stuff called an *energy carrier.* In this picture, energy is not transformed (or converted) from one form into another but, rather, it exchanges its carrier. In this way, one arrives at a picture of an energy transport process which is strictly valid, yet simple and easy to present even at an elementary level.

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