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A logical explanation of the concept of energy and the energy conservation principle[†]

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Abstract

The concept of energy is a longstanding enigma. An acceptable explanation is given by finding a new concept of energy: effective energy which is defined as the conserved quantity transferred between two interactions, not between two systems. The effective energy is not a property of a system, but that of a composite system. It is a kind of relation, or distance, between two systems. The conservation of effective energy is composed for reversible processes of a composite system. The conventional energy and exergy (available energy) are explained as special cases of the effective energy. Energy conservation for reversible processes can be inferred from the conservation of effective energy. In irreversible phenomena, effective energy irreversibly changes into entropy. It is revealed that the energy conservation in irreversible process is not conservation in general but just a special expression when the absolute temperature scale is adopted.

Keywords: Conserved quantity; Effective energy; Energy; Exergy; Heat; Work

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1. Introduction

In most dictionaries, energy is defined as the ability to do work, where work is again defined as the transfer of energy. This explanation of energy has been criticized for being tautological and incomplete, since energy is explained with energy transfer and it can not be applied to the cases involving heat [1]. Feynman et al. confessed that we have no knowledge of what energy is [2]. Gyftopoulos and Beretta also wrote that no easy comprehensible picture and no simple analytical expression for energy are available [3]. A reasonable explanation of energy requires a breakthrough; as Gal-Or commented that the foundations of thermodynamic theories should be re-established with an entirely new approach [4].

Energy reveals itself during transference and energy is an inferred concept from work. However, work is not an easy concept even for specialists. It is within common sense that work and heat are not freely interchangeable. Only a portion of heat can be converted into work, while work is easily changed into heat completely. This is explained as a result of the second law of thermodynamics. Then, let us consider the conversion among works. For example, the volumetric work produced by the expansion of a gas system cannot be entirely changed into shaft work. Only after a considerable portion of volumetric work is deducted to a lower pressure system can the remainder be converted into shaft work. The same logic applies to the conversion of heat into shaft work. These examples illustrate the existence of at least two different types of work. Restrictions in the energy conversion to shaft work in reversible processes cannot be accounted for by the second law of thermodynamics. Actually, they are the result of the conservation of volume and entropy. Such limitations in energy conversion are main topics in the discussion of exergy, or available energy. At least one chapter is dedicated to the explanation and application of exergy

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in most of recent thermodynamics textbooks for engineers. The concept of exergy provides a clue in understanding the real aspect of energy. In this research, the concept of exergy plays the role of connecting link in developing a new concept of energy.

The key point of this new explanation is the separation and the generalization of special works, such as the shaft work, among the conventional works. The shaft work does not transfer from one system to another; it instead transfers from one interaction to another interaction. The shaft work is not stored in the system itself but stored in the relation between systems. This is the clue to define a new kind of work. According to this generalization, exergy is a special case of the new energy, and conventional energy is again a special case of exergy. The conventional conservation of energy for reversible processes also can be explained from the conservation of the new energy. The following analysis also shows that the energy conservation in irreversible processes is not an actual conservation but just a special expression of the more general, non-conservation relation.

2. Reversible world

In conventional thermodynamics, energy conservation is formulated simultaneously for reversible and for irreversible processes. However, this is obviously unreasonable, because an irreversible phenomenon is different from a reversible process, and an independent phenomenon requires an independent principle for explanation. Therefore, the first thing to do is to distinguish the "reversible world" from the "real world." Reversible world is the space in which all processes are reversible, and all processes except for irreversible phenomena exist just as they do in the real world. When no irreversible phenomenon is present in a process, the process is easier to analyze. Therefore, it is quite reasonable to think that all definitions of physical quantities should be established in a reversible world.

The systems of interest in this study are not completely general; mass transfer, chemical reactions, mixing, gravitational and electrical remote actions etc. are excluded. These exclusions are assumed in order to reduce the complexity and ambiguity which result when the object is too far general. The whole world is assumed to consist of simple systems. The interior of a simple system is homogeneous and always in equilibrium state. Therefore, all processes in a simple system are reversible. More than two simple systems can be considered to be a composite system. The systems that comprise a composite system are referred to as subsystems. A continuous system in which the state varies continuously with position in the system is regarded as a congregation of infinitely many simple subsystems.

2.1 Interaction between simple systems - Mode-wise conserved quantities

Simple systems are the basic elements of objects in thermodynamics. The state change of a simple system occurs only through interactions with other systems and never by the system itself. Since interaction is a connection between two systems, we can assume that "there is transference of some quantity in every interaction." The mode of an interaction is determined according to the kind of transfer quantity. This proposition is straightforward yet disputable. For example, it is not easy to identify exactly what is being transferred in the interaction between two attracting or repelling systems. Hence, remote actions are excluded from this research, and are reserved for future extensions. Recently, the existence of transference quantities and of conserved quantities in a physical causation has been intensively discussed in philosophy of science, with the topics of transference theory and conserved quantity theory [5-8].

If an interaction is reversible, the transfer quantity in the interaction can be assumed to be conserved. It means that "at least one conserved transfer quantity exists for each reversible interaction." This is a super-principle on which all conservation laws are based. Since a conserved transfer quantity exists for each mode, there are as many conserved quantities as the number of modes of interactions in nature. The conserved transfer quantities in the interactions between systems are termed "the mode-wise conserved transfer quantities," because the mode of a transfer quantity does not change in an interaction. Examples of mode-wise conserved quantities are volume, entropy, electric charge, momentum and so on. If a mode-wise conserved quantity transfers into or from a system, the corresponding "mode-wise state quantity" exists in the system that it increases as the input and decreases as the output of the conserved transfer quantity, as shown below.

$$dX = \delta X_{in} - \delta X_{out} = \delta X_{netin} = -\delta X_{netout} \qquad (1)$$

This is the conservation equation for each mode-wise conserved quantity for a system. In the case of unidirectional transference from system *A* to system *B*, the following conservation equation is formulated.

$$-dX_A = \delta X_{A,out} = \delta X_{A-B} = \delta X_{B,in} = dX_B \quad (2)$$

Here, dX_A is the infinitesimal increase in mode-wise state quantity of system *A*, δX_{Aout} is the infinitesimal output from the system *A*, δX_{Bin} is the input into the system *B*, and δX_{A-B} is the transference from system *A* to system *B*.

One of the main purposes of thermodynamics is to determine the state of a system after a process takes place. The transfer quantity of a mode is independently transferred into or out of a system to change the corresponding state quantity of the system. The mode-wise state quantities compose an orthogonal set, ultimately to picture the state of a system. They become the state variables, or properties of the system. However, energy is not independent of any mode of transference, and hence energy is not included in this set of independent variables. Therefore, energy conservation is not necessary for this purpose. Thermal mode is not the mode of energy but the mode of entropy. The role of energy is independent of the mode-wise interactions between systems.

2.2 The interaction between interactions - Effective energy

In a reversible world, an interaction between two simple systems is not terminated in itself but emits or absorbs work. The work emitted from an interaction is absorbed by another interaction in the reversible world. This means that "two interactions interact with each other by exchanging work." This work is different from conventional work. A typical example is the shaft work from a heat engine between two interacting thermal systems. Let us call it "effective work" to imply that it is effective in raising an interaction between systems [9-11]. This is another class of interaction, different from the mode-wise interactions between simple systems. Because the interaction between interactions is still a type of interaction, the existence of effective work also stands on the super-principle for the existence of conserved transfer quantity in a reversible interaction. If we set up a composite system including the interacting two simple systems, effective work is the conserved transfer quantity that appears in the interaction between two composite systems. A composite system has the potential to produce effective work. This potential is termed the "effective work potential," or simply, "work potential." Both the effective work and the work potential are called "effective energy." To summarize, the effective energy is transferred between two composite systems as effective work, and is stored in a composite system as work potential. The conservation equation of effective energy is formulated as below for the reversible process of a composite system.

$$\begin{aligned} dE_{(A,B)} &= \delta W_{in} - \delta W_{out} = \delta W_{netin} \\ &= -\delta W_{netout} \end{aligned} \quad (3)$$

Here, dE is the infinitesimal increase in work potential and δW is the infinitesimal input or output of effective work. The equation indicates that work potential of a composite system increases as much as the net input of effective work, or conversely, decreases as much as the net output. In the case of unidirectional transference of effective work from a composite system *(A,B)* to another composite system *(C,D)*, the following conservation equation is formulated.

$$\begin{aligned} -dE_{(A,B)} &= \delta W_{(A,B)out} = \delta W_{(A,B)-(C,D)} \\ &= \delta W_{(C,D)in} = dE_{(C,D)} \end{aligned} \quad (4)$$

The effective work is the most primitive concept of energy, and the conservation of effective energy provides the primary formulation of energy conservation principle. The "absolute work potential" is the maximum effective work extractable from a closed system, where each amount of mode-wise quantity in the system is maintained constant. The concept of work potential can be frequently found in textbooks. One simple example is finding the maximum extractable mechanical work from two solid blocks with different temperatures [12, 13]. However, it is considered as an application of available energy and the characteristics of the mechanical work have never been discussed. The characteristic of work potential is separately discussed as adiabatic availability in the textbook by Gyftopoulos and Beretta [3].

2.3 Measurements - Effective work calculation equation

An example of the interaction between interactions is the reversible connection between a heat engine and an electric generator via a rotating shaft. Here, a thermal interaction interacts with an electrical interaction through shaft work. As illustrated in this example, an interaction can be changed reversibly into another interaction of different mode, while maintaining its amount. Therefore, effective work can be used as an intermedium to give the quantitative relation among different modes of physical quantities. A consistent rule for measurement can be given that "the amounts of physical quantities are estimated by measuring effective work only."

Let us discuss the measurements of entropy and temperature of thermal mode as an example. Entropy is defined as the conserved transfer quantity of thermal mode prior to heat. The amount of transferred entropy can be calculated using the equation below, after measuring the effective work from the process, where the entropy is reversibly transferred between two reference systems R_1 and R_2, and the temperatures of the respective reference systems are specified as T_{R1} and T_{R2}.

$$S_{R1-R2} = W_{(R1,R2)out} / (T_{R1} - T_{R2}) \tag{5}$$

The temperature of an arbitrary system can be estimated by measuring the effective work from the process in which an infinitesimal amount of entropy is reversibly transferred from the system to one of the reference systems. Infinitesimal amount is taken to give minimal effect to the system.

$$\begin{aligned} T_A &= T_{R1} + \delta W_{(A,R1)out} / \delta S_{A-R1} \\ &= T_{R1} + (\delta W_{(A,R1)out} / \delta W_{(R1,R2)out})(T_{R1} - T_{R2}) \end{aligned} \tag{6}$$

The transferred entropy in this equation can be measured by using the two reference systems as above. This is a linear interpolation or extrapolation from two reference states with the effective work. The temperature estimated by measuring the effective work only is the "thermodynamic temperature," the example of which is Celsius or Fahrenheit temperature. As shown in the equation below, the amount of effective work produced from the transference of entropy between two systems is assumed to be proportional to the temperature difference as well as the amount of transferred entropy.

$$\delta W_{(A,B)out} = (T_A - T_B)\delta S_{A-B} \tag{7}$$

If we assume a different relation, it would give rise to another definition of temperature scale. Through generalization, we can obtain similar results for other modes of interactions as well.

$$\delta W_{(A,B)out} = (Y_A - Y_B)\delta X_{A-B} \tag{8}$$

Y is the corresponding intensity in the same mode of transfer quantity X. This equation is the "effective work equation." If the composite system is composed of more than two simple systems, the amount of effective work of a mode is the summation of all the interactions. The total amount of effective work from multi-modal interactions is simply summation across all modes.

$$\delta W_{netout} = \sum\sum\sum (Y_{mi} - Y_{mj})\delta X_{m,i-j} \tag{9}$$

2.4 Modification of the conservation of effective energy

Work potential increases as much as the net input of effective work. However, work potential depends on the states and characteristics of all the simple subsystems in the composite system. If mode-wise conserved quantities were to transfer into or out of simple subsystems in a composite system, the corresponding states would be changed, and the work potential of the composite system should also be changed although no transference of effective work is involved. Therefore, if the effective work and the mode-wise quantities simultaneously enter into a composite system, the increase in work potential must be the summation of the effects of the inputs of effective work and that of mode-wise quantities.

$$\begin{aligned} dE = (dE)_W + (dE)_X = \delta W_{netin} \\ + \sum\sum (\partial E / \partial X_{mi})\delta X_{mi,netin} \end{aligned} \tag{10}$$

The calculation of the change in work potential due to a finite amount of input of mode-wise quantities is possible only when the characteristics of all the simple subsystems in the composite system are known. For this reason, the practical use of work potential will be limited. To make the calculation of work potential simple and convenient, the following operations are proposed.

Let us imagine that in the object system is a "huge system," the intensities of which are maintained constant. The work potential of the hypothetical composite system, including the imaginary huge system, is the "exergy, E_0," or the "available energy" of the system. "Exergetic work, W_0," is defined as the mode-wise conserved transfer quantity multiplied with the difference between the corresponding intensity of the system and that of the huge system.

$$\delta W_{0i} = (Y_i - Y_0)\delta X_i \tag{11}$$

This is a special case of the effective work equation. The increase in exergy due to the input of a mode-wise transfer quantity into a system is the increase in work potential of the hypothetical composite system. It is the amount of effective work extractable from the input, and can be estimated as follows. If we imagine that the input of the mode-wise conserved quantity is further transferred from the simple system to the huge system, the effective work extracted from the further transference is that from an ordinary interaction between two systems. That is the very exergetic work corresponding to the input of the mode-wise conserved quantity.

$$\begin{aligned} dE_{0i} &= dE_{(i,0)} = (Y_i - Y_0)\delta X_{i-0} \\ &+ (Y_i - Y_0)\delta X_{i,netin} = \delta W_{0i,netin} \end{aligned} \tag{12}$$

The increase in exergy by the finite input of mode-wise quantity can be estimated easily, since the final equilibrium state is fixed to be that of the auxiliary huge system. The increase in exergy due to the simultaneous inputs of effective work and of mode-wise quantity is the summation of the net inputs of effective work and exergetic work. This is the "exergy conservation equation" for reversible processes.

$$\begin{aligned} dE_0 &= (dE_0)_W + (dE_0)_X = \delta W_{netin} \\ &+ \delta W_{0,netin} \end{aligned} \tag{13}$$

This equation shows the reason why the effective work is simply added to the exergetic work in the calculation of exergy change in textbooks. Teachers have only to explain without foundation that shaft work is added as it is because it is totally available.

Let us consider a special case of exergy in which all intensities of the subsidiary huge system are maintained at zero. If we imagine again that the special huge system exists in the object system, the work potential of the hypothetical composite system including the special huge system is the "internal energy, E_{00}" of the system. Subsequently, the "half work, W_{00}" is defined as the mode-wise conserved transfer quantity multiplied by the corresponding intensity of the system.

$$\delta W_{00i} = Y_i \delta X_i \tag{14}$$

This is the conventional definition of work, but the effective work is mixed there. The increase in conventional energy due to the input of mode-wise conserved quantity into a system is the increase in work potential of the hypothetical composite system containing the special auxiliary huge system. It can be estimated as in the case of increase in exergy. The increase is the very half work of the input of the mode-wise conserved quantity into the system.

$$\begin{aligned} dE_{00i} &= dE_{(i,00)} = (Y_i - 0)\delta X_{i-00} \\ &= Y_i \delta X_{i,netin} = \delta W_{00i,netin} \end{aligned} \tag{15}$$

The increase in conventional energy due to the simultaneous inputs of both effective work and mode-wise quantity is the summation of the net inputs of effective work and half work as below. This is the conventional energy conservation equation for reversible processes.

$$\begin{aligned} dE_{00} &= (dE_{00})_W + (dE_{00})_X \\ &= \delta W_{netin} + \delta W_{00,netin} \end{aligned} \tag{16}$$

This equation shows the reason why effective work is not identified from half works in conventional thermodynamics. However, the input of half work causes the increase in mode-wise state quantity of a subsystem, while the input of effective work raises the interaction between subsystems. The thermal half work is specially treated, and the effective work and half works except thermal half work are not identified in conventional physics. Then the increase in energy is the summation of the net inputs of conventional works and thermal half work. The thermal half work here is not the conventional heat. Heat is a special case of thermal half work, which will be introduced later with the definition of absolute temperature.

The work potential of a simple system is always zero, while the exergy and internal energy of a simple system are positive values. This is the reason why we cannot extract effective work from a simple system. Internal energy is a norm, a mathematical absolute, while work potential is a metric, a mathematical distance, and exergy is an intermediation between them. Effective work is produced from an interaction between systems, while half work and exergetic work are just other names of the transference of a mode-wise conserved quantity.

3. Real world

The real world is an extension of the reversible world, allowing irreversible phenomena. The elements that compose the real world are also simple systems, and the interactions between simple systems are reversible just like in the reversible world. Irreversible phenomena additionally occur in the real world. Therefore, the only difference between the real world and reversible world is the possibility of irreversible phenomena. The key point of thermodynamics in the real world is how to describe the irreversible phenomena in addition to reversible interactions.

3.1 Irreversible phenomena

Effective work is conserved in reversible interactions between composite systems. However, in the real world, effective work may not be conserved and some portion or all of it can be vanished. The vanishing effective work does not completely disappear; strange enough, there appears entropy, the conserved quantity of thermal mode. This means that "effective work changes into entropy through an irreversible phenomenon." It is called "effective work dissipation" or "entropy generation." The entropy which is generated from the dissipation of effective work never reverts to effective work. This is the reason why we call it an irreversible process. Therefore, the amounts of dissipated effective work, W_d as well as generated entropy, S_g are always positive values. These are the fundamental expressions of the second law of thermodynamics.

$$W_d \geq 0 \ \ , \ \ S_g \geq 0 \tag{17}$$

If any small portion of effective work is changed into entropy, the process is irreversible. All the real processes in nature are somewhat irreversible because they cannot completely avoid the dissipation of effective work which is generated from all the interactions.

3.2 The characteristics of effective work

The work potential is already known and regarded as an application of the available energy in textbooks. In addition to work potential, identification of effective work among conventional works is the key point of this research. We can compose the conservation of effective energy only after finding effective work. Because the half work and the exergetic work are accompanied with mode-wise conserved quantities, they never disappear completely. However, because effective work is free from the mode-wise conserved quantities, it can be completely vanished. This is the important difference of effective work from half work or exergetic work. A simple way to be free from a mode-wise conserved quantity is a cyclic process. Rotating and oscillating motions are the examples. Another possibility is to compose a circuit in which the mode-wise conserved quantity is immediately returned to exterior of a composite system after carrying effective work. The electrical and fluid circuits are examples.

A characteristic of effective work is that it can be dissipated. The term "dissipation of energy" is commonly used in many fields of science; however, the exact meaning of is not clearly known.

3.3 The energy conservation for real word - Absolute temperature scale

The quantitative relation between dissipated effective work and generated entropy in an irreversible phenomenon can be determined experimentally. The resultant relation depends on temperature. For example, let us consider to use Celsius temperature scale, in which the freezing and boiling points of water under atmospheric pressure as two reference states are determined as 0 and 100 degrees, respectively. In this case, the experimental results are revealed as below.

$$\delta W_d = (273.15 + T_g)\delta S_g \tag{18}$$

Here, the generated entropy can be recognized as the generated thermal half work, δW_{00STg}.

$$\delta W_d = (273.15 / T_g + 1)\delta W_{00STg} \tag{19}$$

Obviously, the generated thermal half work is not equal to the dissipated effective work. However, if we adopt a new temperature scale which is defined as below,

$$K = 273.15 + T \tag{20}$$

the generated thermal half work becomes the same as the dissipated effective work.

$$\delta W_d = K\delta S_{Kg} = \delta W_{00SKg} \tag{21}$$

Here, the entropy generation is the same as it is in the case of using Celsius temperature, because the temperature differences are the same. The temperature in which the generated thermal half work is equal to the dissipated effective work is the "absolute temperature." Especially, the absolute temperature, the difference of which is the same as that of Celsius temperature, is Kelvin temperature. The thermal half work in absolute temperature is the conventional "heat." Here we can see the value of thermal half work varies according to temperature scale, and so do the internal energy and exergy. This means that half work and internal energy, as well as exergy and exergetic work are not real physical quantities but hypothetical quantities. However, the effective energy and mode-wise conserved quantities are real quantities. A hotter body does not contain more heat or more energy, but contains more entropy.

If the effective work and half works simultaneously enter into a composite system, the half works are absorbed as the input, all or some portion of the effective work is absorbed as thermal half work after being dissipated, and the remaining effective work is absorbed as itself. If we use an absolute temperature scale, the amount of generated thermal half work equals the dissipated effective work. Then, the increase in internal energy is equal to that in the case without dissipation, i.e., the summation of the inputs of conventional works and heat. This is the truth of the energy conservation in real process containing irreversible phenomena.

4. Conclusions

A reasonable explanation of energy is given by proposing a new primitive concept of energy called effective energy. Effective energy is stored as work potential and transferred as effective work. Work potential is not a property of a simple system but that of a composite system. It is a kind of relation like the distance between two systems. Exergy as well as the conventional energy can be explained as special cases of work potential. The conventional energy that we have known is not a real but a mathematically defined, hypothetical quantity. The conservations of energy and exergy for reversible processes can be explained as the modifications of the conservation of effective energy. Effective energy provides many new concepts and clear explanations for conventional concepts. The work which is not effective work is half work, which is just another name of the transference of mode-wise quantity. In an irreversible process, effective work is changed into entropy. It is revealed that the equivalence of work and heat in an irreversible phenomenon is not conservation in general, but a special expression which arises when the absolute temperature is used. A reasonable methodology can be proposed for the measurements of physical quantities with effective work. The statement that no work is extracted from a single heat source is automatically satisfied because the work potential of a simple system is identically zero. The proposal of effective energy is not simply the explanation of the concept of energy, but the discovery of a new kind of physical quantity on the point that work potential is a relation between two systems while all the conventional physical quantities are the properties of a system. To find clearer physical meanings of effective energy and to extend to general processes, additional efforts are required.

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Nomenclature

E	:	(Effective) work potential
E_0	:	Exergy
E_{00}	:	Energy of a system
K	:	Kelvin temperature scale
S	:	Entropy
T	:	Temperature or Celsius temperature scale
W	:	Effective work
W_0	:	Exergetic work
W_{00}	:	Half work
W_{00S}	:	Thermal half work or heat
X	:	Extensive quantity
Y	:	Intensity

Subscripts

A-B	:	Transfer from A to B
(A,B)	:	Composite system
d	:	Dissipation of energy
g	:	Generation of entropy or heat
i, j	:	Simple systems
m	:	Modes of processes
netin	:	Net transfer in
netout	:	Net transfer out
R	:	Reference state or system
S	:	Thermal mode or entropy

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