ENERGY SCIENCE: CONVERSION AND SYSTEMS

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1. Introduction

1.1 Definition of Energy

Any phenomenon in the world has three constituent elements, which are material, energy and information. A phenomenon is described as, "How does a body or a system of bodies appear?"—where "how," "body (bodies)," and "appear" correspond to "information," "material," and "energy" respectively. As the modern science has been developed, and as we will show hereinafter, it is clarified that these three elements are related with each other closely. The term "energy" was derived from the Greek "εργον" (ergon) meaning, "work." *Ergon* not only means work but also vigor activity, vitality, and powerfulness.

Energy is a generic term for the faculty, power or capacity for doing "work" possessed by a body or a system of bodies. The Chinese term for energy, (*Nebg Yuan*, resource of capability), expresses precisely the meaning. If the term "work" means physical work, then energy is scientifically defined. Physical work is defined by the scalar product of a force vector f and a displacement vector

$$\Delta W = (f \cdot \Delta r) \qquad (1)$$

Any form of energy can be expressed by Eq. (1), if an appropriate conversion is made. If f and Δr have the same direction, and their magnitudes are 1N and 1m, respectively, then the magnitude of the work ΔW is defined as 1J, which is SI unit system. Every derived unit of energy is compared in Table 2.

Exa	E	10^{18}
Peta	P	10^{15}
Tera	T	10^{12}
Giga	G	10^{9}
Mega	M	10^{6}
Kilo	K	10^{3}
Hecto	H	10^{2}
Deca	DA	10
Deci	D	10^{-1}
Centi	C	10^{-2}
Mili	M	10^{-3}

Micro	μ	10^{-6}
Nano	N	10^{-9}
Pico	P	10^{-12}
Femto	F	10^{-15}
Atto	A	10^{-18}

Table 1. Prefixes

1.2 History and the Fundamental Concepts of Energy Science

The founder of the modern science is Galileo Galilei (1564–1642). Modern science is defined by the “Reductionism” introduced by René Descartes (1596–1650). Galilei discovered that the speed of a falling body is proportional to the time.

Gottfried W. F. Leibniz (1646–1716) proposed the concept “vis viva,” which represents a measure of doing work, and is given by mv^2 (m: mass of the body, v: the velocity). His proposal was important, because the concept “vis mortix” (expressed by mv) by Descartes was popular in those days.

Isaac Newton (1642–1727) established modern physics, of which results are summarized in the *Philosophiae naturalis principia mathematica* (1687). One of the most fundamental ideas in Newtonian physics is the second law of motion expressed by

$$f = m\, d^2r / dt^2 \tag{2}$$

Where t is time.

If both sides of the equation are multiplied by Δr, and integrated, then we have

$$W = (1/2)\, mv^2 \tag{3}$$

Thus the Leibniz’s idea was more precise than that of Descartes.

T. Young (1773–1829) is the first scientist who defined the technical term “energy,” by which he represented the power of doing work posed by a moving body by virtue of its motion. However, his kinetic energy was expressed by $W = m\, v^2$.

J. Joule (1818–1889) is the first physicist who measured the work equivalence of heat, which is defined by

$$q = J\, W \tag{4}$$

Where q represents heat. The exact value J is

$$J = 4.1855\ [J / cal] \tag{5}$$

Joule got the value of J near Eq. (5)

If an electric current I passes in a medium with an electric resistance R, the generated thermal energy q is given by

$$q = RI^2 \tag{6}$$

Which is called the “Joulian heat” in memory of his works.

In 1853, W. Rankine (1820–1872) established the physical system of energy conversion, which is called “Energetics”—where two types of energy are specified. These are: (1) the energy of potential, static and latent type; and (2) the energy of actual, dynamic, sensible, and transitional type. He found that the summation of the potential energy and the kinetic energy of a body is constant. This is called “energy conservation law”; for example, this can be expressed in the gravity fields as

$$mgz + (1/2)\ mv^2 = mgz_0 = (1/2)\ mv_0^2 \tag{7}$$

where g is the gravitational acceleration, z is the vertical distance measured from the ground surface, and suffix 0 shows the maximum value.

Rankine’s discovery can be generalized by Newton’s mechanics, and the relationship

$$f = grad\ V(r), \tag{8}$$

where $V(r)$ is the potential energy of the field; if held, the kinetic energy added to the potential energy remains constant. Such a field is called a conservative field. Every known force except for the frictional force belongs to the conservative field. Rankine’s contribution to the heat engine is well-known by the term “Rankine cycle.”

R. Clausius (1822–1888) discovered the important concept of “entropy,” which implied that “heat is a type of energy.” It was 300 years after Galilei’s physics that the human intelligence came to be aware of “the equivalence of heat and energy.” This historical study was due to Rankine and Joule.

Increnebtal energy can be expressed generally by

$$dW = X \cdot d\ \xi \tag{9}$$

where X is the intensive variable, and ξ is the extensive variable, X and ξ are called “complementary to each other.” Examples of the complementary couples are shown in Table 3, from which one can see that thermal energy can be expressed by the multiplication of the absolute temperature with the entropy. Entropy is the “generalized displacement of the thermal energy,” and temperature is the “gernalized force of the thermal energy.”

The following relationship is confirmed:

$$dq = TdS \tag{10}$$

where dq, dS and T are the change of thermal energy, the change of entropy and the absolute temperature, respectively.

Both Rankine and N. Carnot (1796–1832) expressed their well-known ideas of thermodynamical cycles; however, they applied the caloric theory, in which heat was regarded as an invisible gaseous material called "caloric."

The discovery of entropy was greatly enhanced by L. Boltzmann (1844–1906), who in 1877 discovered the well-known formula:

$$S = k \log \Omega \tag{11}$$

where Ω is the thermodynamic probability of the system, and k is called the Boltzman's constant. Albert Einstein carved Eq. (11) on Boltzmann's tombstone, with the eulogy "Masterpiece formula of the nineteenth century." Equation (11) is an important bridge between information and energy.

Now, we must pay attention to the important work by Clausius, which is called the second law of thermodynamics. With the use of the concept of entropy, he clarified that the available energy is lost whenever energy is converted, because the entropy increases in every process of energy transition. This can be expressed by

$$W = F + FS \tag{12}$$

where F is the free energy ready to transform into work, and FS is the thermal energy. As S increases the free energy decreases, since W is constant.

W. Thomson (Lord Kelvin, 1824–1907) developed the study of energy science, and his notable achievement was the systematic study of irreversible thermodynamics.

A. Einstein (1879–1955) contributed two dramatic evolutions to energy science. One is the energy equivalence of mass, and the other is the discovery of photon (quantum) energy. Let us review briefly Einstein's theory on the energy equivalence of mass. The change of momentum is equal to the impulse (equivalent to the second law of Newton's law of motion):

$$\Delta(mv) = \Delta\left\{ m_0 v \Big/ (1 - v^2 / c^2) \right\} = f\,\Delta t \tag{13}$$

where the principle of the special relativity is applied to the mass change, and m_0 and c represent the rest mass and the light velocity, respectively. Multiplying both sides of Eq. (13) by the velocity, we have

$$\Delta\left\{ m_0 v \Big/ (1 - v^2 / c^2) \right\} = f\,\Delta x = \Delta W \tag{14}$$

Integrating Eq. (14), we have for the kinetic energy

$$T = mc^2 - m_0c^2 \qquad (15)$$

Where m_0c^2 is called the rest energy, and the total energy is expressed by

$$E = W + m_0c^2 = mc^2 \qquad (16)$$

This relationship was verified by the experiments on nuclear fission by O. Hahn and F. Strassmann in 1978. Nuclear power is based on this relationship. The energy conservation law is thus extended to include the mass equivalence. According to this extended law, we can study universal dynamics. The sum of the total energy and the total mass in the universe is constant.

Let us also briefly review quantum (photon) energy. In order to explain perfectly the radiation spectrum (energy v/s frequency) from the black body, Max Planck (1855–1947) introduced the hypothesis of light quantum, according to which the light energy is expressed by:

$$W = nh\nu \qquad (17)$$

where n (= 1,2,3….) in integers; h is Planck's constant; and ν is the frequency of light. Einstein proposed the quantum theory of light in 1905, according to which the light with the frequency ν can be regarded as a quantum (particle with no mass), of which energy is $h\nu$. This theory is analogous to the de Broglie wave, which is the wave associated with a particle with a momentum p, and the wavelength is given by $\lambda = h/p$.

We must note that the expression for photon energy W is not like Eq. (9), i.e. (intensive variable) X (extensive variable). The quantum property of light is essential in the photoelectric and photovoltaic effects.

1.3 Wattage, Units, and Threshold Ignition Energy

If Eq. (9) is differentiated with respect to t, we have the relationship

$$\frac{dW}{dt} = Xv = P \qquad (18)$$

The rate of work done per unit time (J/s) is called the wattage. The term "power" is an alias representing the wattage and the force. The term "horse-power (HP)" is a conventional term for wattage, and there are two kinds of horse-powers:

1 Hp = 0.7355 kW (French horse-power)
1 Hp = 0.7461 kW (English horse-power)

It should be noted that a very large wattage system does not always generate a large amount of energy. For example, a thunderbolt of one megavolt and hundred thousand amperes generates energy equivalent to 10^8 kJ, which is equivalent to 2.4 kl of oil. This is not so surprising, but the wattage is 10^{10} kW if the discharge is done in 10^{-2} s. This value is comparable to the energy of a typhoon. Figure 1 shows the comparison of the notable energies.

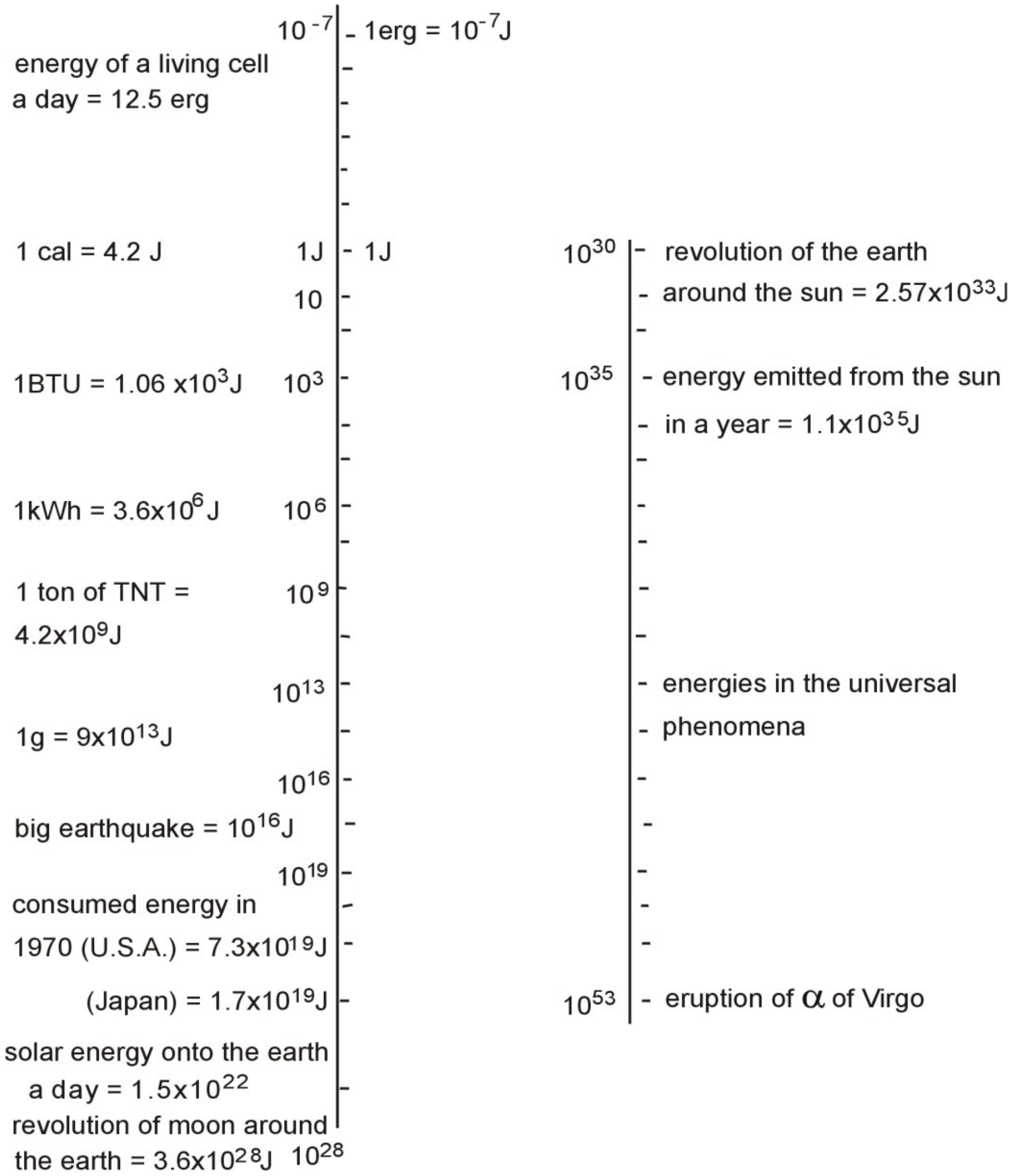

Figure 1: Comparison of the notable energies

Table 2 shows the SI and the SI-derived units for energy conversions. Parameters given in Table 2 are due to (1) 1J = 10^7 erg. (2) 1 cm^{-1} is the unit of wave number (κ), and 1 Hz is the unit of frequency (ν). (These represent the photon energy), (3) 1 J/mol, cal/mol or cal/g is the unit of chemical energy, and (4) 1 K is the unit of temperature and represents thermal energy. The conversion factors are due to the following relationships: J (mechanical and electrical); kT (k is the Boltzmann's constant, thermal); cal (thermal) eV (energy of electron under 1 V, electrical); Hz (unit of $\nu = hc/\lambda$, frequency of photon); cm^{-1} (unit of wave number, $2\pi/\lambda$, photon); J/mol (chemical potential, $\mu = dW/dM$, chemical); J, kcal; (chemical).

	EV	K	Cm^{-1}	Hz (1/s)	Erg	Cal	J/mol	Kcal/mol
1 eV	1	$1.16x10^{4}$	$0.81x10^{4}$	$2.42x10^{14}$	$1.06x10^{-12}$	$3.83x10^{-20}$	$9.65x10^{14}$	23.05
1 k	0.86×10^{-4}	1	0.695×10	2.08×10^{10}	1.38×10^{-16}	3.30×10^{-24}	8.31	1.99×10^{-3}
1 cm^{-1}	1.24×10^{-4}	1.44	1	3.00×10^{10}	1.99×10^{-16}	4.75×10^{-24}	11.96	2.86×10^{-3}
1 Hz	4.14×10^{-15}	4.80×10^{-11}	3.34×10^{-11}	1	6.63×10^{-27}	1.58×10^{-34}	4.00×10^{-10}	9.53×10^{-14}
1 erg	6.24×10^{11}	7.24×10^{15}	5.03×10^{15}	1.5×10^{26}	1	2.39×10^{-8}	6.023×10^{16}	1.44×10^{14}
1 cal	2.61×10^{19}	3.03×10^{23}	2.10×10^{23}	6.31×10^{33}	4.18×10^{7}	1	2.51×10^{24}	6.023×10^{20}
1 J/mol	1.04×10^{-5}	0.12	0.083	2.51×10^{9}	1.66×10^{-17}	3.97×10^{-25}	1	2.39×10^{-4}
1 kcal/ mol	0.043	503.4	350	1.048×10^{13}	6.95×10^{-14}	1.66×10^{-21}	4.18×10^{3}	1

Table 2: Conversion factors of the SI-derived units for energy

Wattage is a rate of generating energy or consuming energy. However, we must consider, “How does the energy generation begin?”—that is, there must be an ignition for any sensible (transitional) energy. A typical example of the ignition is the one initiated by a match. The red phosphorus match was invented in 1845. Nowadays it is very popular all over the world. Most of all the energy resources are fossil fuels coal, oil, and natural gas. The ignition temperatures of natural gas and oil are from 500–600°C and from 600– 700°C, respectively. Ignition of liquid fuel can take place only where its vapor exists. The role of a match is to provide the vaporization heat and the ignition heat.

Once the ignition reaction occurs, the continued release of the chemical binding energy becomes possible. All the fuels originating from photosynthesis have the chemical bonding energy readily released by ignition.

This process is similar to a falling domino. Falling down one after another in rapid succession in a cascading system is a model of fossil combustion.

2. Classification of Energies

2.1 General Remarks

As Eq. (9) shows, any type of incremental energy ΔW can be expressed by the product of the intensive variable (the generalized force) and the extensive variable (the generalized displacement) $\Delta\xi$. We show the conventional examples in Table 3. The explanations for the used notations are as follows: V in the I-type energy means volume, while it represents an electrical voltage in II-type energy. J and ω are the moment of inertia and the angular velocity. N and θ are the torque and the angle. K in I-type energy means the Hook’s constant, z is the vertical distance, and mgz is the potential energy. L is the self-induction (unit is 1H = 1Vs/A = 1 Wb/A). C and M are the electric capacity and the magnetization, respectively. μ In III-type energy is the chemical potential, and there is no dynamic energy in this group, G, ε^0 and μ_0 are the gravity constant, dielectric constant of the vacuum and the magnetic permeability of the vacuum, respectively. Newton’s potential and Coulomb’s potential have minus signs when they are attractive.

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Biographical Sketch

Tokio Ohta was born on 3 November 1925 in Japan. He received his education from the Department of Physics, University of Kyoto, with a Ph.D. in Solid State Physics. He has taught at the University of Kyoto, Portland State University, Oregon, USA, and the University of Tokyo, and served as the Dean of Faculty of Engineering, Yokohama National University (1985–1988), as President of Yokohama National University (1988–1994), and as the Supervisor of the International Network University of Gifu (1998–). He has been appointed to the Congress Staff (Science and Technology) of the Prime Minister (1974–1999), to the Committee Staff of the Minister of International Trade and Industry (1974–1999), and the Committee Staff of the Minister of Education and Science (1992–1995). He has published some 160 papers and 60 books on solid state physics and energy systems; has been elected to the Vice-President of International Association for Hydrogen Energy; and was the founding Past President of Hydrogen Energy sytems Society of Japan, and is a member of the general advisory board of UNESCO–EOLSS.