Work, Power, and Energy

M. KOSTIC
Northern Illinois University
DeKalb, Illinois, United States

Glossary

energy A fundamental property of a system referring to its potential to influence changes to other systems by imparting work (forced directional displacement) or heat (chaotic displacement/motion of system microstructure); energy exists in many forms—electromagnetic, electrical, nuclear, chemical, thermal, and mechanical, where electromechanical energy may be kinetic or potential—and thermal energy represents overall chaotic motion energy of molecules and related microstructure.

energy conservation May refer to the fundamental law of nature that energy and mass are conserved, that is, cannot be created or destroyed but only transferred from one form or one system to another; another meaning of energy conservation is improvement of efficiency of energy processes so that they could be accomplished with minimal use of energy sources and minimal impact on the environment.

energy conversion A process of transformation of one form of energy to another, for example, conversion of chemical to thermal energy during combustion of fuels or conversion of thermal to mechanical energy using heat engines.

energy efficiency Ratio between useful energy of a process and energy used to accomplish that process; energy, as per the conservation law, cannot be lost (destroyed), but part of energy input that is not converted into "useful energy" is customarily referred to as energy loss.

fuel cell Device undergoing electrochemical cycle where electrical work is obtained during ionization of fuel and oxidant molecules, reacting into product molecules at constant pressure and temperature, thereby avoiding heating and loss of work potential into thermal energy of the reaction products, like during combustion.

heat Inevitable (spontaneous) energy transfer due to temperature differences, to a larger or smaller degree, without control (dissipative) via chaotic displacement/motion of system molecules and related microstructure (in all directions, nonpurposeful), as opposed to controlled (purposeful and directional) energy transfer referred to as work.

heat engine Device undergoing thermomechanical cycle with mechanical expansion and compression net work obtained as difference between heat transferred to the engine from a high-temperature heat reservoir and rejected to a low-temperature reservoir, thereby converting part of thermal energy into mechanical work.

nonrenewable energy sources Energy sources created and accumulated over a very long period in the past, such as fossil and nuclear fuels, whose creation rate is many orders of magnitude smaller than the consumption rate, so that they will be depleted in a finite time period at the current rate of consumption.

power The energy rate per unit of time.

renewable energy sources The continuously or frequently available (renewed daily or at least annually) energy sources, such as solar energy, wind, water flows, ocean and tidal waves, and biomass, that are expected to be available forever for all practical purposes.

work A type of controlled energy transfer when one system is exerting force in a specific direction and, thus, is making a purposeful change (displacement) of the other systems; it is inevitably (spontaneously) accompanied, to a larger or smaller degree, by dissipative (without control) energy transfer referred to as heat.

A global overview and general concept of energy, its forms and classifications, and its manifestation as work and heat transfer is presented in this article with an objective to preserve the completeness and exactness of the fundamental concepts. The emphasis is given to work as the most useful energy transfer. However, because most work currently is obtained from fossil fuels using heat engines, and because all work is ultimately dissipated via heat to thermal

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energy, they are presented in the article, along with fuel cells, as promising devices to convert chemical fuel energy directly into electrical work without degradation of energy as in the combustion processes. The efficiencies of diverse energy-to-work conversion processes are provided. Finally, the latest developments and worldwide energy production and consumption data are effectively summarized, and diverse energy sources, reserves, and a future outlook are given.

1. BASIC CONCEPTS

Energy is the "building block" and fundamental property of matter and space and, thus, the fundamental property of existence. Energy exchanges or transfers are associated with all processes (or changes) and, thus, are indivisible from time. It is no wonder that energy is often defined as the ability to perform work, that is, as a potential for energy transfer in a specific direction (displacement in force direction) to achieve a purposeful process, as opposed to a dissipative (less purposeful) energy transfer in the form of heat. This definition of energy could be generalized as the ability to perform change.

Work is a mode of energy transfer from one acting body (or system) to another resisting body (or system), with an acting force (or its component) in the direction of motion, along a path or displacement. A body that is acting (forcing) in motion direction in time is doing work on another body that is resisting the motion (displacement rate) by an equal resistance force, including inertial force, in the opposite direction of motion. The acting body is imparting (transferring away) its energy to the resisting body, and the amount of energy transfer is the work done by the acting onto the resisting body, equal to the product of the force component in the motion direction multiplied by the corresponding displacement or vice versa (force multiplied by the displacement component in the force direction) (Fig. 1). If the force ($\vec{F}$) and displacement vectors ($\overrightarrow{ds} = \overrightarrow{dr}$) are not constant, integration of differential work transfers from initial state 1 to final state 2, defined by corresponding position vectors $\vec{r}$, will be necessary (Fig. 2).

The work is a directional energy transfer; however, it is a scalar quantity like energy, and it is distinctive from another energy transfer in the form of heat due to random motion (chaotic, in all directions) and collisions of bodies' molecules and their components.

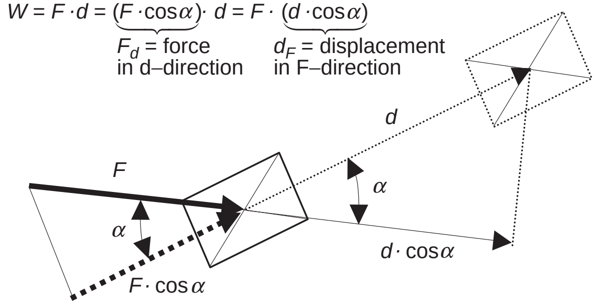

FIGURE 1 Work, force, and displacement.

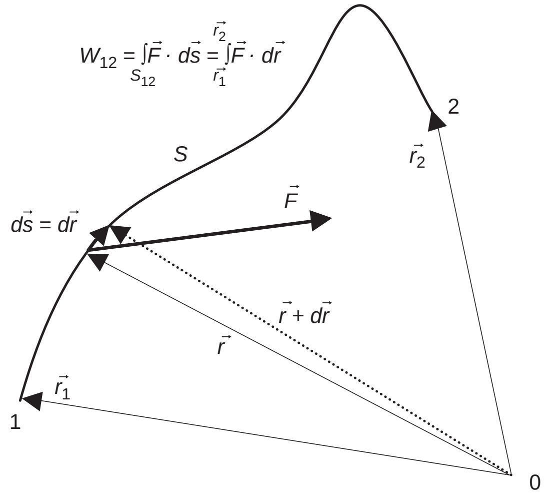

FIGURE 2 Work along arbitrary path.

1.1 Power

Energy transfer in the form of work or heat is taking place in time, at a finite rate, and cannot be instantaneous. The energy transfer per unit of time, or energy rate, is called power, usually in form of the work rate, although it may also be heating power, that is,

$$\dot{W} = \frac{dW}{dt} = \frac{\vec{F}\cdot\overrightarrow{ds}}{dt} = \vec{F}\cdot\vec{v}, \quad \text{or} \quad W_{12} = \int_{t_1}^{t_2} \dot{W}\cdot dt. \tag{1}$$

Therefore, energy (as a body or system property) and work and heat (as energy in transfer from one system to another) are interrelated. All have the same dimension (Force × Length), and related different units could be converted to each other (Table I).

Work transfer cannot occur without the existence of a resisting body or system, nor can it occur without finite displacement in the force direction. This might not always be obvious. For example, if

TABLE I

Energy Units with Conversion Factors and Energy Equivalents

Energy unit	J	kWh	Btu
1 joule (J)	1	2.78×10^{-7}	9.49×10^{-4}
1 kilowatt-hour (kWh)	3.6×10^{6}	1	3.412×10^{3}
1 kilocalorie (kcal = Cal = 1000 cal)	4187	1.19×10^{-3}	3.968
1 British thermal unit (Btu)	1055	2.93×10^{-4}	1
1 pound-force foot ($lb_f \cdot ft$)	1.36	3.78×10^{-7}	1.29×10^{-3}
1 electron volt (eV)	1.6×10^{-19}	4.45×10^{-26}	1.52×10^{-22}
1 horsepower × second (HP · sec)	745.7	2.071×10^{-4}	0.707
Energy equivalent	**J**	**kWh**	**Btu**
1 barrel (42 gallons) of crude petroleum	6.12×10^{9}	1700	5.80×10^{6}
1 ton (2000 lb) of bituminous coal	2.81×10^{10}	7800	2.66×10^{7}
1000 cubic feet of natural gas	1.09×10^{9}	303	1.035×10^{6}
1 gallon of gasoline	1.32×10^{8}	36.6	1.25×10^{5}
1 gram of uranium-235	8.28×10^{10}	2.30×10^{4}	7.84×10^{7}
1 gram of deuterium	2.38×10^{11}	6.60×10^{4}	2.25×10^{8}
2000 dietary food calories (2000 kcal)	8.374×10^{6}	2.326	7.937×10^{3}
1 solar constant × $(cm)^2$ × minute	8.374	2.326×10^{-6}	7.937×10^{-3}

one is holding a heavy weight or pushing hard against a stationary wall, there will be no work done against the weight or wall (neglecting its small deformations). However, one will be doing work internally due to contraction and expansion of one's muscles (force with displacement) and that way will be converting (spending) a lot of chemical energy via muscle work and then dissipating it into thermal energy and heat transfer (sweating and getting tired).

1.2 Energy, Power, Work and Heat Units, and Energy Equivalents

Energy is manifested via work and heat transfer, with the corresponding Force × Length dimension for work ($N \cdot m$, $kg_f \cdot m$, and $lb_f \cdot ft$ in SI, metric, and English systems of units, respectively), and the caloric units in kilocalories (kcal) or British thermal units (Btu), as heat needed to increase a unit mass of water (at a specified pressure and temperature) for 1° of temperature, so that the water-specific heat is $1\,kcal/(kg\,^\circ C) = 1\,Btu/(lb\,^\circ F)$ by definition, in the metric and English systems of units, respectively. It was demonstrated by Joule that $4187\,N \cdot m$ of work, when dissipated in heat, is equivalent to 1 kcal. In Joule's honor, $1\,N \cdot m$ of work is named after him as 1 joule or 1 J, the SI energy unit, also equal to electrical work of $1\,W \cdot s = 1\,V \cdot A \cdot s$. The SI unit for power, or the work rate, is the watt (i.e., $1\,J/s = 1\,W$) as well as corresponding units in other systems of units, for example, Btu/h. The horsepower is defined as $1\,hp = 550\,lb_f \cdot ft/s = 745.7\,W$. Other common units for energy, work, and heat, and for energy equivalents for typical fuels and processes, are given in Table I.

2. *FORMS, CLASSIFICATIONS, AND CONSERVATION OF ENERGY*

As stated in the previous section, energy is a fundamental concept indivisible from matter and space, and energy exchanges or transfers are associated with all processes (or changes) and, thus, are indivisible from time. Energy transfer is needed to produce a process to change other system properties. Among all properties, the energy is the only one that could be converted to mass and vice versa, that is, $E = mc^2$ (known in some literature as mass energy, the c is the speed of light in a vacuum); thus, the two are interrelated.

Any and all changes (happening in time) are caused by energy exchanges or transfers from one body or substance (system or subsystem) to another. A part of a system may be considered as a subsystem if energy transfer within a system is taking place; conversely, a group of interacting systems may be considered as a larger isolating system if they do not interact with the rest of the surroundings.

There are many forms and classifications of energy (Table II) all of which could be classified as microscopic (internal within a system microstructure) and/or macroscopic (external as related to the system mass as a whole with reference to other systems). Furthermore, energy may be quasi-potential (associated with a system equilibrium state and structure, i.e., system property) or quasi-kinetic (energy in transfer from one system or structure to another in the form of work or heat).

Every system in an equilibrium is defined by its state potential, where the system structure is “held” by forces (i.e., the forces “define” the system potential and state, and vice versa—action and reaction); otherwise, a system will undergo dynamic change (in time), with quasi-kinetic energy exchange toward another equilibrium. Atoms (mass) are held by atomic and gravity forces; otherwise, mass would disintegrate (“evaporate” into energy) as it does partly in nuclear reactions (nuclear energy). Molecules are held by electrochemical bonding (valence) forces (chemical reactions—chemical energy). Solids are held by “firm” intermolecular forces (melting of solids when energy is increased by heating—latent thermal energy). Liquids are also held by latent intermolecular forces (evaporation when kinetic energy of molecules is further increased by heating—latent thermal energy again). Sensible thermal energy represents energy of molecular motion and is related to temperature of a system. “Holding” potential forces may be “broken” by energy transfer (e.g., heating, high-energy particle collisions). States and potentials are often stable or “hooked’ and, thus, need to be unhooked or broken to overcome the existing “threshold” or equilibrium, as in igniting combustion or starting a nuclear reaction. Energy can be directional (purposeful or organized) or chaotic (dissipative or disorganized). For example, mass-in-motion (mechanical kinetic energy) and electricity-in-motion (electrical kinetic energy) are organized kinetic energies, whereas thermal energy is disorganized chaotic energy of motion of molecules and atoms. System energy may be defined with reference to position in a vector force field such as elastic potential (stress) energy, gravitational potential energy, or electromagnetic field energy.

Energy transfer may be in organized form (work transfer due to force action) or in chaotic disorganized form (heat transfer due to temperature difference). Energy transfer into a system builds up energy

TABLE II

Energy Forms and Classifications

Scale			Type			Transfer (release)	
				Kinetic (motion)		Quasi-kinetic (motion)	
Macro/external (mass based)	Micro/internal (structure based)	Form	Potential (state or field)	Directional[a]	Chaotic dissipative	Work directional[a]	Heat dissipative
		Mechanical					
X		• Kinetic		X		X	
X		• Gravitational[b]	X			X	
X		• Elastic	X			X	
		Thermal					
	X	• Sensible			X		X
	X	• Latent	X				X
	X	Chemical	X				X
	X	Nuclear	X				X
		Electrical					
	X	• Electrokinetic		X		X	
	X	• Electrostatic	X			X	
	X[c]	Electromagnetic	X[c]			X	

[a] Electromechanical kinetic energy type (directional/organized, the highest energy quality) is preferable because it may be converted to any other energy form/type with high efficiency.

[b] Due to mass position in a gravitational field.

[c] Electromagnetic form of energy is the smallest known scale of energy.

potential (called simply potential for short, e.g., pressure, temperature, voltage) over energy displacement (e.g., volume, entropy). Conversely, if energy is transferred from a system, its energy potential is decreased. That is why energy is transferred from higher to lower energy potential only.

All organized kinetic energy will, in part or in whole (and ultimately in whole), disorganize/dissipate within the microstructure of a system (over its mass and space and in time) into disorganized thermal energy. Entropy, as an energy displacement system property, represents the measure of energy disorganization. Contrary to energy and mass, which are conserved in the universe, the entropy is continuously generated (increased) due to continuous disorganization of energy in transfer ("spreading" of energy toward and over lower potentials in time) and, thus, degradation of quality of energy.

Often, one wants to extract energy from one system to purposefully change another system, that is, to transfer energy in organized form (as work). That is why energy is often defined as the ability to perform work, and a special quantity exergy is defined as the maximum possible work that may be obtained from a system by bringing it, in a process, to equilibrium with reference surroundings. The maximum possible work will be obtained if one prevents energy disorganization or dissipation, that is, within so-called reversible processes. Because the energy and mass are conserved during any process, only in ideal reversible processes will the entropy (measure of energy disorganization) and exergy (maximum possible work with reference to the surroundings) be conserved, whereas in the real irreversible processes, the entropy will be generated and exergy will be partly (or even fully given enough time) destroyed. Therefore, heat transfer and thermal energy are universal manifestations of all natural and artificial (manmade) processes, whereas all organized potentials and/or quasi-kinetic energies are disorganized or dissipated in the form of thermal energy in irreversible and spontaneous processes.

As stated previously, there are many different energy forms and types (Table II). One is usually not interested in (absolute) energy level; instead, one is usually interested in the change of energy (during a process) from an initial state (i) to a final state (f), so that zero reference values for different energy forms are irrelevant and are often taken arbitrarily for convenience. The following are basic correlations for energy changes of several typical energy forms often encountered in practice: motion kinetic energy (E_K) as a function of system velocity (v), spring elastic potential energy (E_{Ps}) as a function of spring deformation displacement (x), gravitational potential energy (E_{Pg}) as a function of gravitational elevation (z), and sensible thermal energy (E_U) as a function of system temperature (T):

$$\Delta E_K = \frac{1}{2} m \left(v_f^2 - v_i^2 \right); \;\; \Delta E_{Ps} = \frac{1}{2} k \left(x_f^2 - x_i^2 \right)$$
$$\Delta E_{Pg} = mg(z_f - z_i); \;\; \Delta E_U = mc_v(T_f - T_i). \qquad (2)$$

If the reference energy values are taken to be zero when the initial (i) variables are zero, these equations will represent the energy values for the final values (f) of the corresponding variables. If the corresponding parameters, spring constant k, gravity g, and constant-volume specific heat c_v, are not constant, integration of differential energy changes from initial to final states will be necessary.

Energy transfer via work W and heat transfer Q may be expressed as the product of related energy potentials (pressure P or temperature T) and corresponding energy displacements (change of volume V and entropy S, respectively), that is,

$$W_{12} = \vec{F} \cdot \vec{d} = \left[\underbrace{(P \cdot A\vec{n}) \cdot \vec{d}}_{\Delta V} \right] = P \cdot \Delta V_{12}|_{P \neq const}$$
$$= \int_{V_1}^{V_2} P \cdot dV \qquad (3)$$

$$Q_{12} = T \cdot \Delta S_{12}|_{T \neq const} = \int_{S_1}^{S_2} T \cdot dS. \qquad (4)$$

Note that in Eq. (3), force cannot act at a point but is distributed as pressure P over some area A (with orthogonal unit vector $\vec{n}$), which when displaced will cause the volume change ΔV.

In the absence of a nuclear reaction (no conversion of mass into energy, $E = mc^2$), mass and energy are conserved separately for an isolated system, a group of isolated systems, or the universe. For example, for a given process (energy exchange) between two systems, isolated from the surroundings, during time period Δt, the energy conservation law may be expressed as

$$\sum_i E_{1,i}(t + \Delta t) + \sum_j E_{2,j}(t + \Delta t)$$
$$= \sum_m E_{1,m}(t) + \sum_n E_{2,n}(t), \qquad (5)$$

where $\sum_i E_{1,i}(t)$ is the sum of all existing energy forms i of system 1 at time (t) and of system 2 and/or at time $t + \Delta t$. Then, from Eq. (5), energy transfer from system 1 to system 2 for period Δt may be in the form of work W and/or heat Q, that is,

$$
\begin{aligned}
W_{12} + Q_{12} &= W_{1\to 2} + Q_{1\to 2} \\
&= \sum_i E_{1,i}(t+\Delta t) - \sum_m E_{1,m}(t) \\
&= -\left[\sum_j E_{2,j}(t+\Delta t) - \sum_n E_{2,n}(t)\right] \\
&= -\,(W_{21} + Q_{21}) = -(W_{2\to 1} + Q_{2\to 1}).
\end{aligned} \tag{6}
$$

Note that for nonexistent terms in these equations, their values should be zero, and if the energy transfers (work and heat) are negative, they are actually in the opposite direction than was specified. Correlations are similar for mass conservations. Furthermore, the power is defined as energy transfer rate per unit of time; conversely, energy transfer is equal to the product of power and time or the integral of power over a time period, see Eq. (1).

3. WORK OF CONSERVATIVE AND NONCONSERVATIVE FORCES: WORK–ENERGY PRINCIPLE

Work against conservative (also known as internal, volumetric, or space potential field) and/or inertial forces is path independent, and the mechanical energy is conserved during such a process. However, work of nonconservative dissipative forces is path dependent, and part of the mechanical energy is converted (dissipated) to the thermal energy. The nonconservative forces are also external or surface forces.

For example, during a free gravity fall (or free bounce) without air friction, the potential energy is being converted to kinetic energy of the falling body (or vice versa for free bounce), and at any time the total mechanical energy (sum of kinetic and potential mechanical energies) is conserved, that is, stays the same (Fig. 3). The mechanical energy is also conserved if a mass freely vibrates on an ideally elastic spring or if a pendulum oscillates around its pivot, both in the absence of dissipative effects such as friction and nonelastic deformation. In general, for work of conservative forces only, the mechanical energy (E_{mech}) for N isolated systems is conserved because there is no dissipative conversion in thermal energy and, thus, no heat transfer, that is,

$$
\begin{aligned}
E_{mech} &= E_K + E_{Pg} + E_{Ps} \\
&= \sum_{j=1}^{N} \left(\frac{1}{2}mv^2 + mgz + kx\right)_j = const.
\end{aligned} \tag{7}
$$

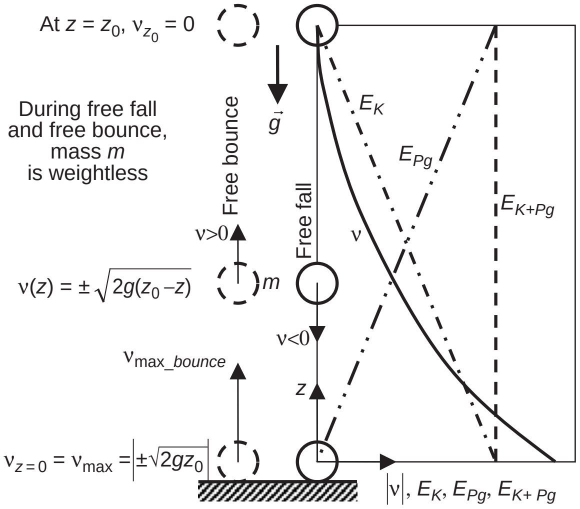

FIGURE 3 Energy and work due to conservative gravity force.

When work of nonconservative forces W_{nc} is exchanged among N isolated systems, from an initial state i to a final state f, the total mechanical energy of all systems is reduced by that work amount, that is,

$$
W_{nc,i\to f} = \left(\sum_{j=1}^{N} E_{mech,j}\right)_i - \left(\sum_{j=1}^{N} E_{mech,j}\right)_f. \tag{8}
$$

This correlation is known as the work–energy principle.

Regardless of the traveled path (or displacement), the work against conservative forces (e.g., gravity or elastic spring in the preceding cases) in the absence of any dissipative forces will depend on the final and initial positions (or states) only. However, the work of nonconservative dissipative forces W_{nc} will depend on the traveled path because the energy is dissipated during the force displacement, and mechanical energy will not be conserved but rather partly converted (via dissipation and heat transfer) into the thermal energy (see Eq. 8). This should not be confused with total energy conservation, which is always the case, and it must include both work and heat transfer (see Eqs. 5 and 6).

4. ENERGY, WORK, AND POWER OF ROTATING SYSTEMS

Motors and engines are important energy devices that convert other energy forms into their rotating shaft motion with a twisting action and, thus, into the mechanical work and kinetic energy. Also, many other devices, including parts of diverse machineries involving energy transfers in the form of work, are mounted on rotating shafts or rotating bearings or pins (e.g., disks, gears, wheels, levers). Because shafts and bearings restrict motion to rotation around their axes, any mass at distance *r* from the axis of rotation, its circumferential velocity *v*, and the related twisting circumferential force *F* are related to the corresponding angular rotational speed ω and torque *T* with the simple correlations $v = \omega r$ and $T = rF$ (written in scalar form because rotational motion and twisting force action are restricted in a single, around-the-axis direction only). Then, the kinetic energy E_K and work rate dW/dt, or the power transfer of a rotating system, can be expressed as seen in Fig. 4, where *J* is the mass moment of inertia for a rotating system. For a cylinder (or disk) of radius *R* and mass *m*, or of density ρ and thickness *b*, the mass moment of inertia around its axis is $J = mR^2/2 = (\pi/2)\rho b R^4$.

5. ENERGY SOURCES, CONVERSION TO WORK, AND EFFICIENCY

Energy sources are those systems (substances or natural phenomena) that allow for abundant, convenient, and efficient (and thus economical) conversion of their energy into useful energy forms (for consumption needs), usually thermal for heating or mechanical and electrical for work, with the latter also being very convenient for transmission and very efficient for conversion into any other useful energy form. Because energy consumption needs are time and location dependent, energy conversion rate, energy density (per unit mass, volume, area, etc.), transportation (transmission), and storage are important.

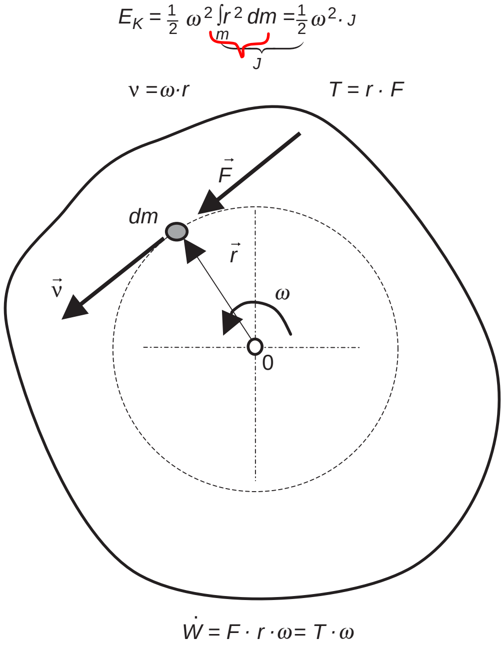

FIGURE 4 Energy and power of rotating system.

There are many sources of energy (Table III) for diverse needs of human activities and society in general. Energy consumption may be classified into four general sectors (see Table VI): (1) *residential*: for appliances and lighting, space heating, water heating, air conditioning, and so on; (2) *commercial*: for lighting, space heating, office equipment, water heating, air conditioning, ventilation, refrigeration, and so on; (3) *industrial*: for water and steam boilers, direct process energy, machine drive, and so on; and (4) *transportation*: for personal automobiles, light and heavy trucks, air transport, water transport, pipe transport, rail transport, and so on. In all four sectors, in addition to primary energy sources, electrical energy, as a secondary energy source produced from primary energy sources, is used extensively.

The primary energy sources for the world in the year 2000 and for the United States in the year 2001 are presented in Table IV. The primary energy sources for the production of electricity are presented in Table V. In addition, the U.S. energy supply by consumption sector, including electricity production, is given in Table VI. The world and U.S. populations, energy production, and energy consumption are summarized in Table IV as well. The total energy production, including losses, import, and export, is available as energy supply for consumption and storage. Also, most of the world's electricity (~64% vs ~70% in the United States) is produced from fossil fuels, with an overall conversion efficiency of only approximately 30%. The conversion efficiency is similar in nuclear power plants, which contribute approximately 17% of world electricity production and approximately 21% of U.S. electricity production. When the global energy supply is given together with fossil fuels and is expressed in British thermal units, all electrical energy (including hydro, wind, etc.) is given in equivalent British thermal units, accounting for the conversion efficiency (the U.S. Energy Information Agency uses 31%). When electrical energy is accounted for separately, the actual electrical output is given in kilowatt-hours, as seen in Tables V and VI. Because of different forms and conversion efficiencies of primary energy sources, and because of complexities of energy production and losses, transportation and storage, and import and export, it is virtually impossible to account correctly for all energy paths and forms in

TABLE III

Primary Energy Sources and Conversion to Work

Primary energy source		Conversion
Nonrenewable		
Fossil fuels	Coal	Combustion (heat and heat engine H/HE/W[a])
	Peat	
	Oil/Crude petroleum	
	Natural gas	
Nuclear	Uranium	Fission (H/HE/W)
	Thorium	
	Deuterium	Fusion[b] (H/HE/W)
Renewable[c]		
Geothermal[d]	Hot steam/water	H/HE/W
	Ground soil/rock heat	
	Volcanic, etc[b]	
Ocean–gravitational	Tidal–ocean wave	Direct to work
Solar related		
Ocean	Ocean thermal	H/HE/W
	Ocean currents	Direct to work
	Ocean wave	
Biomass	Wood	Combustion (H/HE/W)
	Vegetation, etc[e]	
Direct solar	Solar–thermal	H/HE/W
	Photoelectric	Direct to work
	Photochemical	
Electrostatic	Lightning, etc[b]	
Wind	Wind–air streams	
Hydro	River/Accumulation	
Muscular	Human and animals	

Note. Secondary energy sources (e.g., electrical, synthetic fuels, hydrogen) with energy storage and distribution completes the energy supply domain, which with energy needs, consumption, and efficiency completes the global energy realm.

Energy related processes: Electromagnetic radiation; Photosynthesis cycle in nature; Biosyntheses cycle in nature; Electrical processes: electrodynamic, electromagnetic, electrochemical; Nuclear reactions: fission, fusion, radioactive radiation; Chemical reactions: combustion, oxidation, etc.; Heat transfer and frictional dissipative processes; Thermomechanical expansion and compression; Natural air streams driven by solar dissipation, gravitation, and buoyancy (evaporation, precipitations, water streams); Natural water streams (rivers and ocean streams); Mechanical expansion and compression.

[a] H/HE/W, conversion to heat and via heat engine to work.

[b] Not commercialized yet.

[c] All renewable sources, except tidal and geothermal, are due to solar radiation.

[d] Usually renewable but may be nonrenewable.

[e] Includes many types as well as waste/garbage.

the same units; therefore, the total figures (and percentages) usually do not add up exactly.

Fossil fuels share more than 85% of the total world and U.S. energy consumption (Table IV). Nearly 40% of the total world and U.S. energy is used for electricity production (Tables IV, V, and VI), mainly in thermal and nuclear power plants ($>$80% in the world and $>$90% in the United States), using heat engines undergoing thermomechanical conversion processes with relatively low conversion efficiencies (Table VII). The overall conversion efficiencies from chemical or nuclear fuel energy to thermal energy of combustion gases or steam, and to mechanical and electrical energy, is only approximately 30 to 35%.

5.1 Heat Engines

Heat engines are devices undergoing thermomechanical cycles, similar to the one in Fig. 5, with a mechanical expansion and compression net work ($W = Q_h - Q_c$), obtained as the difference between the heat transferred to the engine from a high-temperature heat reservoir (at T_h) and rejected to a low-temperature heat reservoir (at T_c), thereby converting part of thermal energy into mechanical work. The combustion process itself is an irreversible one, where chemical energy (electrochemical energy binding reactants' molecules) is chaotically released during combustion (i.e., converted in random thermal energy of products' molecules) and cannot be fully transferred into directional work energy. The second law of thermodynamics limits the maximum amount of work that could be obtained from thermal energy between two thermal reservoirs at different temperatures, hot T_h and cold T_c, by using the ideal reversible Carnot cycle (Fig. 5) with thermal efficiency:

$$\begin{aligned}\eta_{th,C\_ad} &= \frac{W}{Q_h} = \frac{Q_h - Q_c}{Q_h} \\ &= 1 - \left.\frac{T_c}{T_h}\right|_{T_h = T_{ad} = 2273\ K,\ T_c = 293\ K} \\ &= 1 - \frac{293}{2273} = 87.1\%,\end{aligned} \tag{9}$$

where $W = W_T - W_C$ is the net work of expansion, usually turbine W_T, and compression W_C. The maximum efficiency is achieved if heat is supplied at the highest possible temperature T_h and released at the lowest possible temperature T_c. However, both temperatures are limited by the fact that a fuel combustion is performed using oxygen with ambient air, resulting in maximum so-called adiabatic, stoichiometric combustion temperature T_{ad}, which

TABLE IV

World and U.S. Total Energy Supply by Source

Source	World, 2000 Quadrillion Btu	World, 2000 Percentage	United States, 2001 Quadrillion Btu	United States, 2001 Percentage
Coal	92.51	23.3	21.93	22.6
Petroleum	155.25	39.1	38.23	39.5
Natural gas	90.83	22.9	23.22	24.0
Fossil fuels	338.59	85.3	83.38	86.0
Nuclear electric	25.51	6.4	8.03	8.3
Hydroelectric	27.46	6.9	2.38	2.5
Renewables/Others	5.36	1.4	3.11	3.2
Total	396.92	100	96.90	100

World and U.S. Population and Energy Comparisons

	World, 2000 Quadrillion Btu	World, 2000 Percentage	United States, 2000 Quadrillion Btu	United States, 2000 Percentage
Population (millions)	6080.1	100	281.4	4.6
Energy production	397	100	71.06	17.9
Energy consumption	398	100	99.32	25.0

Source. Energy Information Administration. (2001). "Annual Energy Review 2001." U.S. Department of Energy, Washington, DC.

TABLE V

World and U.S. Electric Energy Supply by Source

Source	World, 2000 Billion kWh	World, 2000 Percentage	United States, 2001 Billion kWh	United States, 2001 Percentage
Coal			1878.54	51.4
Petroleum			127.79	3.5
Natural gas			563.99	15.4
Fossil fuels	9374.6	63.8	2570.32	70.4
Nuclear electric	2434.2	16.6	758.79	20.8
Hydroelectric	2646	18.0	201.23	5.5
Renewables/Others	241.9	1.6	123.06	3.4
Total	14697	100	3653.40	100

Source. Energy Information Administration. (2001). "Annual Energy Review 2001." U.S. Department of Energy, Washington, DC.

for most fuels is approximately 2000°C or $T_{ad} = 2273\,\mathrm{K}$. A part of the heat supplied at hot temperature T_h must be released to the surroundings at a cold temperature of approximately $T_c = 20^\circ\mathrm{C} = 293\,\mathrm{K}$, resulting in a Carnot efficiency of 87.1% (see Eq. 9 and Fig. 5). However, the fuel heating value energy ($Q_{HV} = Q_{ad\_var}$) is not available entirely at the adiabatic temperature of the products but rather is distributed over their variable temperature range, from initial surrounding temperature before combustion T_c to final adiabatic temperature T_{ad} (Fig. 6). If a single Carnot cycle is used at constant temperature $T_h < T_{ad}$, only fraction $(T_{ad} - T_h)/(T_{ad} - T_c)$ of the fuel heating value will be used, resulting in a reduced Carnot efficiency:

$$\eta_{th,C} = \left(1 - \frac{T_c}{T_h}\right)\left(\frac{T_{ad} - T_h}{T_{ad} - T_c}\right)\Bigg|_{\max \text{ for } T_h = \sqrt{T_{ad}T_c}}$$

$$= \frac{\sqrt{T_{ad}/T_c} - 1}{\sqrt{T_{ad}/T_c} + 1}\Bigg|_{T_{ad} = 2273\,K,\ T_c = 293\,K} = 47.2\%. \quad (10)$$

P0140 The efficiency may be increased further by employing a large number (infinite in limit) of ideal

TABLE VI

U.S. Energy Consumption by Sector, 2001

	Primary		Electric		Total	
Sector	Quadrillion Btu	Percentage	Quadrillion Btu	Percentage	Quadrillion Btu	Percentage
Residential	6.9	7.1	13.3	35.5	20.2	20.8
Commercial	4.2	4.3	13.2	35.2	17.4	18.0
Industrial	21.6	22.3	11	29.3	32.6	33.6
Transportation	26.7	27.6	0	0.0	26.7	27.6
Electric	37.5	38.7				
Total	96.9	100.0	37.5	100	96.9	100

Source. Energy Information Administration. (2001). "Annual Energy Review 2001." U.S. Department of Energy, Washington, DC.

TABLE VII

Energy-to-Work Conversion Efficiencies

Engine/Process	Efficiency Percentage
Otto (gasoline) engine	25–30
Diesel engine	30–40
Gas turbine	30–~~35~~ 40
Steam turbine	30–40
Nuclear, steam turbine	30–35
Combined gas/steam turbines	40–~~50~~ 60+
Fuel cell (hydrogen, etc.)	40–60 +
Photovoltaic cell	10–20
Windmill	30–40 (59% limit)
Hydro turbine	80–85
Electromechanical motor/generator	80–95

Note. Thermal-to-mechanical work conversion is limited by stoichiometric combustion temperature and the Carnot cycle efficiency. Fuel cell efficiency is limited by Gibbs free energy values for process reactants and products and may be close to 100%. Because of material property limitations and process irreversibilities (dissipation of energy), practical efficiencies are much lower and there is room for substantial improvements. For example, existing hybrid cars have 80% improved efficiency (and mileage) over the same classical cars, from 25 to 45%, by using electromechanical engines/storage hybrid systems.

Carnot engines operating at various temperatures (with $dW = dQ$) or with variable hot temperature heat exchange (Fig. 6). Assuming constant specific heat of combustion products, and after integration, the variable hot temperature Carnot cycle yields the maximum possible combustion products-to-work conversion efficiency:

$$\eta_{th,C\,\mathrm{var\,max}} = \left(1 - \frac{\ln(T_{ad}/T_c)}{(T_{ad}/T_c) - 1}\right)\Bigg|_{T_{ad}=2273\ K,\ T_c=293\ K} = 69.7\%. \qquad (11)$$

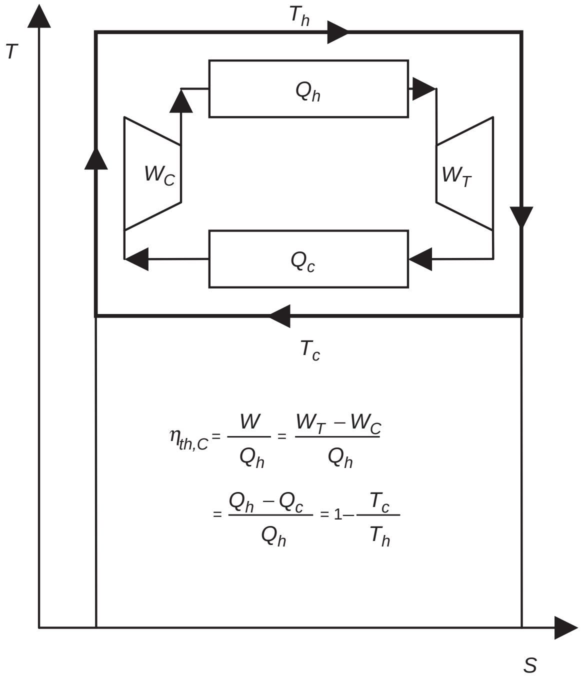

FIGURE 5 Heat engine, ideal Carnot cycle.

Because of engine material property limitations and other unavoidable irreversibilities, it is impossible to reach the ideal Carnot efficiency. Different actual heat engines undergo similar but different cycles, depending on the system design. For example, internal combustion engines undergo the Otto cycle with gasoline fuel and the Diesel cycle with diesel fuel, whereas steam and gas turbine power plants undergo the Rankine and Brayton cycles, respectively. However, with improvements in material properties, effective component cooling, and combining gas and steam turbine systems, more than 50% efficiencies are being achieved, a substantial improvement over current ones of approximately

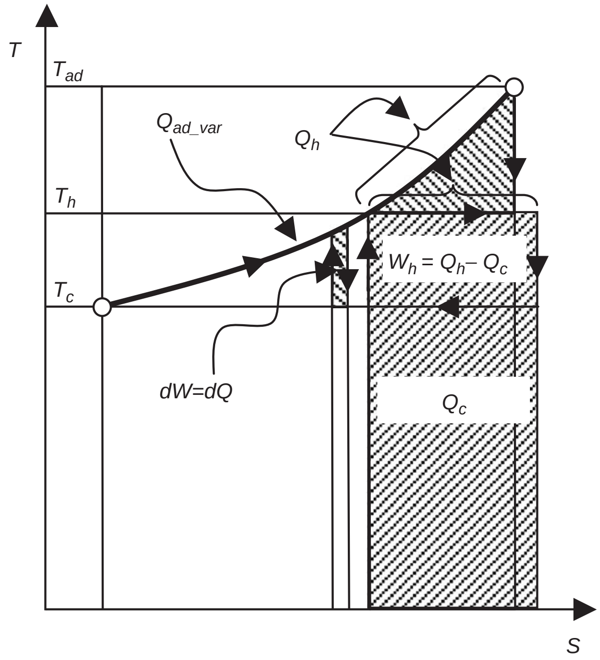

FIGURE 6 Heat engine, constant and variable temperature, ideal Carnot cycle.

35% (see Table VII). The ideal Carnot cycle is an important reference to guide researchers and engineers to better understand limits and possibilities for new concepts and performance improvements of real heat engines.

5.2 Fuel Cells

It is possible to convert fuel chemical energy to electrical work directly, without heating the reaction products as is done during combustion, by using an electrochemical cell, also known as a fuel cell. It is a very simple device, similar to a fueled-battery ~~in reverse~~. It consists of two porous metal electrodes with an electrolyte in between. The fuel (e.g., hydrogen), after diffusing through one electrode, will dissociate into positive ionic components by releasing electrons to that electrode. In the process, the positive fuel ions are transferred to another electrode that is in contact with oxygen. If an external load is connected to the electrodes, an electric current (and electrons) will be flowing and electrical work will be departed to the load, while hydrogen fuel's positive ions will be diffusing through the electrolyte and at another electrode will be reacting with oxygen, forming water as the reaction product. The high efficiency of the fuel cell results from the electrochemical process, whereby the energy of binding reactants' electrons, is converted directly into directional electrical work, departed by the electrons that move in the cell's external circuit. This is in contrast to conversion of the same energy during combustion to chaotic thermal motion (i.e., heating of combustion products' molecules), accompanied by substantial irreversibility and loss of work potential. The maximum efficiency and work from a fuel cell is limited, according to the second law of thermodynamics, to the decrease of the Gibbs free energy ($F = H - TS$) of the reactants (*re*) as they form products (*pr*) in the electrochemical reaction (i.e., $W_{max} = F_{re} - F_{pr}$), where $H = E_U + PV$ is a system and/or component enthalpy and E_U, P, V, T, and S are internal thermal energy, pressure, volume, temperature, and entropy, respectively. The difference between reactants' and products' Gibbs free energies is very close to the fuel heating value Q_{HV}, so that the fuel cell theoretical energy conversion efficiency, $\eta_{max} = W_{max}/Q_{HV}$, is close to 100% if the process is conducted at constant pressure and temperature and without dissipative heating of the products. In practice, with finite reaction rates accompanied by dissipative heating and the need for cooling to maintain reaction at as constant a temperature as possible, the efficiency is lower than the maximum possible but more than 40% or even 50%, which is still higher than the heat engine efficiencies given in Table VII along with efficiencies of other energy conversion processes to mechanical or electrical work.

6. ENERGY RESERVES AND OUTLOOK

Currently, most of the world's energy consumption is supplied by fossil fuels (~85%). However, proven fossil fuel reserves are limited, and it is estimated that if they continue to be used at the current rates (as used under current conditions), coal will be depleted in approximately 250 years, oil will be depleted in 60 years, and natural gas will be depleted in 80 years. One must keep in perspective the fact that "proven reserves" refers to the customary and economical "mining" and use of fuels, whereas new reserves and more efficient technologies are being discovered and make new fuel reserves economical. Currently, a substantial amount of the world's electricity is obtained from nuclear and hydro energy (~17 and 18%, respectively), use of other renewable energy resources is increasing (e.g., geothermal, wind, biomass, solar), and alternative synthetic fuels (e.g., hydrogen fuel cells) are being developed. It is worth noting that some countries produce most or nearly all of their electricity from hydro energy (e.g., Norway, Brazil, New Zealand, Austria, Switzerland), whereas France produces most of its electricity from nuclear fuel (76%). The nuclear fuel reserves are orders of magnitude higher than fossil fuel reserves, and nuclear fuel does not contribute to CO_2 and greenhouse gas pollution.

Furthermore, advances in energy conversion and utilization technologies as well as increases in efficiency, including computerized control and management, contribute to energy conservation, increases in safety, and reduction of related environmental pollution. Actually, per capita energy use in the United States and other developed countries has decreased during recent years. However, the increase in world population and the development of many underdeveloped and highly populated countries, such as China and India, will continue to increase the world's energy consumption.

As an ultimate energy source for virtually all natural processes, solar energy is available for direct "harvest" if needed and is absorbed by vegetation and water surfaces on Earth. Thus, it is the driving force for natural photosynthesis, and in turn for biosynthesis processes as well as natural water cycle and all atmospheric processes (see the solar-related renewable energy sources in Table III). The solar radiation power density incident to Earth's atmosphere, known as the solar constant, is 2 cal/min/(cm)^2 or 1.4 kW/m^2, which after taking into account average day/night time (50%), varying incident angle (50%), and atmospheric/cloud scatter and absorption (53%), reduces to only $0.5 \cdot 0.5 \cdot 0.47 = 11.7\%$ of the solar constant, or approximately 165 W/m^2 at the Earth's surface, as an all-time average. This solar power per square meter corresponds to human metabolic energy consumption of 3400 kcal/day. The dietary energy reference value of 2000 kcal/day is equivalent to 97 W or 331 Btu/h. Furthermore, the world's total energy consumption is approximately 7500 Btu/h per capita or 2.2 kW per capita (or 11.8 kW per capita in the United States). (The total energy rate in kilowatts needs to be scaled by 31% efficiency to be compared with the electrical energy rate in kilowatts.) The corresponding per capita electricity consumption rates are 0.275 and 1.48 kW in the world and in the United States, respectively.

Therefore, the outlook for future energy needs is encouraging. There are many diverse and abundant energy sources with promising future potentials, so that humankind should be able to enhance its activities, standard of living, and quality of living by diversifying energy sources and by improving energy conversion and utilization efficiencies while at the same time increasing safety and reducing environmental pollution.

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Further Reading

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