Principles of Energy Conversion

Part 1. Introduction to Energy Conversion

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Article 1

Introduction to Energy

One objective for this portion of the course is to understand the language of energy and energy conversion. To accomplish this we will address the following questions:

- What is energy?
- What are the units of energy?
- How do we compare forms of energies?
- How is energy converted from one form to another?
- How do we calculate efficiency of energy conversion?

1.1 What is Energy?

The modern concept of energy is only 150 to 200 years old. Yet today, energy is part of the common vernacular in nearly every language in every nation. This word is used daily when describing the energy needed to charge of a tablet or phone, energy used by refrigerators or heating and cooling a home, energy to power a vehicle, energy to run a marathon, energy efficiency, and on and on. We purchase energy bars and energy drinks to get an "energy boost". All of this describes what we use energy for, but does not define energy.

Consider this thought experiment: You are asked by a child what energy means. How would you explain energy to the child? Would you explain using the concept of work? Would you explain using electrical power from a wall receptacle? What about solar energy, wind energy, fuel cells, or biological energy conversion? Are all of these really related? Up until around 150 years ago, the answer was generally no; these things were not thought to be related by all except a few military engineers. As an engineer you will experience the legacy of this misconception when working with units and unit systems. For example, English units of heat and work are different because when heat was first being measured it was not understood that heat and work are two forms of the same thing: energy.

Energy is a universal concept that bridges all engineering and science disciplines.[1] Energy is always conserved during any process, which is a unifying concept in the physical sciences. Energy is the *"notion of invariance or constancy in the midst of change"* [1]. In other words, even though we may change the form of energy (mechanical, thermal, electrical, etc.), *total energy always remains constant*. The total energy is *conserved*. Total energy is not the same as *usable energy*, which leads to the concepts of *dissipation*, *efficiency*, and *entropy*.

[1] Mathematics is another universal concept in engineering and science.

1.2 Types of Energy

There is no agreed upon standard for energy classification, but the delineation by Culp [2] is very useful for this course. In this classification, there are two types of energy (transitional & stored) and six forms of energy (mechanical, thermal, electrical, chemical, electromagnetic, and nuclear).

Stored energy is often described as potential energy. Examples of potential energy include gravitational potential (elevation of a mass: mechanical form), inertial potential also known as kinetic energy (speed of a mass: mechanical form), chemical potential (potential for a chemical reaction to occur), electrical potential (voltage difference), electrical capacitance, and thermal capacitance.

Heat and work are examples of transitional thermal and mechanical energy, respectively. Heat and work involve interactions between the mass of interest, known as a *system*, and the surroundings. When considering energy, we distinguish between the system (mass of interest) and the surroundings with a boundary separating the two. The boundary may be physical or virtual. Transitional energies are only realized at this boundary. When considering power (energy/time) it is nearly always transitional energies being used.

2. Stored: energy which has a mass, a position in a force field, etc.

- electrical potential (voltage)
  storage mechanisms: *capacitor, inductor, superconductor, . . .*
- gravitational potential (potential energy in engineering thermodynamics)
  storage mechanisms: *water tower, hydraulic dam, raised weight, . . .*
- inertial potential (kinetic energy in engineering thermodynamics)
  storage mechanisms: *flywheel, fluid inertia, mass in motion, . . .*
- fluid compression (flow energy or boundary work in thermodynamics)
  storage mechanisms: *gas cylinder, propane tank, piston-cylinder, . . .*
- chemical potential: (internal energy, enthalpy in thermodynamics)
  storage mechanisms: *batteries, coal, petroleum, hydrogen, glucose, . . .*
- thermal: (sensible & latent heat)
  storage mechanisms: *mass, phase-change material (PCM), . . .*

1. Transitional: energy in motion, energy which crosses system boundaries.

- electrical current
- work
- heat
- electromagnetic radiation

There is often confusion between energy and devices which convert or store energy. For example, when asked to define kinetic energy many times you will hear kinetic energy defined as a flywheel. Flywheels are simply a device that store a type of mechanical energy. Similarly, batteries are a device which store a type of chemical energy. A battery thrown across the room will have stored mechanical energy (kinetic).

Each form of energy is quantified using different units. Sometimes forms of energy are described as potentials, other times as rates. The units may be of energy, or of power, or both. The difference in units arose because the concepts of work, heat, and electricity predate the concept of energy that unified these transitional forms. And the choice of units is often dictated by convenience of calculation. For example, a common unit of electromagnetic energy is electron-volt [eV]. When using silicon-based solar cells to convert light into electricity, it takes a bit more than 1 eV photon to move an electron across the band gap between the valance and conduction bands. This energy could also be expressed in Joules (unit of energy), but instead of a number close to 1 eV we would be using a number close to 2×10^{-19} J. Table 1.1 summarizes the forms, types and common units of energy.

When considering power, a subscript will be used to indicate the form of power; $\dot{W}_m$ indicates mechanical power, $\dot{W}_t$ indicates thermal power, and subscripts e and em indicate electrical power and electromagnetic power, respectively.

mechanical: [ft-lbf, J], [hp, kW$_m$] Transitional mechanical energy is **work**. Stored mechanical energy includes potential energy, which a position in a force field such as an elevated mass in a gravitational field. Other stored mechanical energies are kinetic (position in an inertial field), compressed gases, elastic strain, and magnetic potential. Mechanical energy is expressed as both energy [ft-lbf, J] and power [hp, kW$_m$].

thermal: [J, cal, Btu], [kW$_t$, Btu/hr] All forms of energy can be completely converted (100%) into thermal energy, but the reverse is not true. For example, all stored mechanical energy in a moving automobile can be converted to thermal energy by friction via the brakes. Transitional thermal energy is **heat** and is generally expressed as energy [J, cal, Btu] or power [kW$_t$, Btu/hr]. Stored thermal energy is sensible and latent heat and is expressed in units of energy per mass [Btu/lbm, kJ/kg].

electrical: [A, V], [Wh, kWh], [W$_e$, kW$_e$, MW$_e$] Transitional electrical energy occurs due to electron flow, which is expressed as current with units of Amperes. Stored electrical energy includes electrical potential in an electrostatic field and electrical potential in an inductive-field, i.e. magnetic field. Electrical energy is often expressed in terms of power [W$_e$, kW$_e$, MW$_e$] and power-time [Wh, kWh]. The latter is an expression for energy.

chemical: [Btu/lbm, Btu/lbmol, kJ/kg, kJ/kmol] There is no known transitional chemical energy. Stored energy is in the form of chemical potential and is typically expressed in units of energy per volume (molar) or energy per mass. Conversion of chemical energy is the most important to society because this includes chemical conversion to thermal energy (combustion) and chemical conversion from electromagnetic energy (photosynthesis). If energy is released during conversion of chemical energy the process is considered exothermic, while endothermic indicates energy is absorbed during the conversion process.

nuclear: [MeV/reaction] There is no known transitional nuclear energy. Stored energy is in the form of atomic mass; the relation between mass and energy is Einstein's expression $E = mc^2$. Nuclear energy is converted to other forms by particle interaction with or within an atomic nucleus. Nuclear energy is expressed a variety of units, but the most common for power generation is MeV/reaction. There are three nuclear reactions that will be discussed.

radioactive decay: an unstable nucleus decays to a more stable nucleus releasing electromagnetic energy and particles.
fission: a heavy-mass nucleus absorbs a neutron and then splits into two or more lighter-mass nuclei with a release of electromagnetic energy and particles.
fusion: two light-mass nuclei combine to form a stable, heavier-mass nuclei with a release of electromagnetic energy

electromagnetic: [J, eV, MeV] Transitional electromagnetic energy is radiation waves that travel at the speed of light. Visible, Infrared (IR) and ultraviolet (UV) light are all transitional electromagnetic energy. There is no known stored electromagnetic energy.

Electromagnetic energy is expressed in terms of electron volts [eV] or megaelectron volts [MeV]. However, the magnitude of electromagnetic energy is often expressed as frequency, ν [s^{-1}], or wavelength, λ [m], since these two are related by the speed of light, c [m/s], $c = \lambda\nu$. The energy in a particular frequency is determined using Plank's constant ($h = 6.626 \cdot 10^{-34}$ Js).

$$\text{wave energy: } E_{em} = h\nu = \frac{hc}{\lambda} \text{ [J]}$$

The most energetic wavelengths are short (high frequency).

Gamma: most energetic; emanates from atomic nuclei
X-ray: next most energetic; produced by excitation of orbital electrons
thermal (IR to UV): visible spectrum of light; produced by atomic vibrations
micro- & millimeter waves: radar and microwaves; produced by electrical discharge

The first law of thermodynamics broadly states that energy is neither destroyed or created, which implies that there are no losses when converting from one form of energy to other forms. All forms of energy, however, are not of equal worth. Electrical and chemical energy are high value commodities, while thermal energy is often of low or no value. Thermal energy associated with temperatures around 100 to 200 °C is often referred to as "low-grade heat" because this energy is difficult to convert to anything useful.

Table 1.1: Energy Form and Common Units

Energy Form	Energy Type: Transitional	Energy Type: Stored	Conversion
Electrical power: W, kW energy: kWh	electrical current	electrostatic field inductive field	• easy & efficient conversion to mechanical and thermal energy • easy, less efficient conversion to electromagnetic and chemical energy
Electromagnetic energy: eV	electromagnetic radiation	–	• easy, but inefficient conversion • photosynthesis is most common conversion process • there is no known stored form
Chemical energy/mass: kJ/kg energy/mol: kJ/kmol	–	chemical potential (+) exothermic (−) endothermic	• easily converted to thermal, electrical and mechanical energy • there is no known transitional form
Nuclear energy: MeV	–	atomic mass	• easily converted to mechanical energy, then into thermal energy • no known transitional form
Mechanical energy: ft·lbf, J power: hp, kW, Btu/hr	**work**	gravitational kinetic (inertia) elastic-strain flow potential magnetic	• easily converted to other forms of energy
Thermal energy: Btu, kJ, cal power: Btu/hr, W	**heat**	internal energy sensible heat latent heat	• inefficient conversion to mechanical and electrical energy • conversion limited by 2nd law of thermodynamics • all other forms are easily converted into thermal energy • thermal energy can be stored in everything

1.3 Measures of Energy - Units & Equivalences

There are numerous units in the field of energy and power. Below is a short list of secondary mass, energy, and power units. [3, 4]

British thermal unit [Btu]: energy required to raise the temperature of 1 lbm of water at 68 °F by 1 °F.

- 1 Btu ≡ 1055 J ≡ 778.16 ft·lbf ≡ 252 cal
- 1 Btu/s ≡ 1.055 kW
- 1 Btu/hr ≡ 0.2930711 W
- 1 therm ≡ 100,000 Btu
- 1 quad ≡ 10^{15} Btu; note this is distinct from Q sometimes used as 10^{18} Btu.

Joule [J]: equivalent of 1 N of force exerted over a distance of 1 m.

- 1 J ≡ 0.2388 cal (IT)
- 1 J = 1 N·m ≡ 6.242×10^{18} eV ≡ 0.737 ft·lbf
- 1 J/s = 1 W
- 1 kWh = 3.6×10^{6} J ≡ 3412 Btu

calorie [cal]: energy required to raise the temperature of 1 g of water by 1 °C.

- This is the International Table (IT) definition used by engineers and 1 cal = 4.1868 J which corresponds to the specific heat of water at 15°. This definition is also referred to as the steam table definition.
- Physicists use the thermochemical calorie which is equal to 4.184 J and corresponds to the specific heat of water at 20°.
- **C**alorie (capital C) is used by nutritionists and is equal to 1000 IT calories. Currently the standard is to use kilocalorie instead of Calorie, but both are equivalent to 1000 IT calories.

horsepower [hp]: power of a typical horse in England during Watt's period to raise 33 000 lbm by 1 ft in 1 minute.

- 1 hp ≡ 746 W
- 1 hp·hr ≡ 2.68×10^{6} J ≡ 0.746 kWh

mass, force, and volume: [kg, lbm, slug, mol, gallon, SCF, ton, tonne, lbf, N]

- 1 lbm ≡ 0.454 kg
- 1 slug = 32.174 lbm = 14.594 kg
- 1 lbm = 7000 grains
- 1 standard ton (short ton) = 2000 lbm = 907.2 kg = 0.9072 tonne
- 1 long ton = 2240 lbm
- 1 tonne = 1000 kg = 2204 lbf
- 1 lbf ≡ 4.448 N
- 1 imperial gallon ≡ 1.200 U.S. gallon
- 112 lbm ≡ 8 stone
- 20 hundred weight = 100 lbf

1.4 Energy Equivalences & Standard Values

Energy equivalence values for the United States Culp [2], American Physcial Society [3], Energy Information Agency [5]. The U.S. uses higher heating values (HHV) for energy content of fuels. Natural gas, for example, is sold based on a HHV energy content even though it only provides the lower heating value (LHV) since the water leaves the system as vapor. [6] Other countries may use lower heating values (LHV).

Coal: energy content varies between 10 to 30 MBtu/ton

anthracite:	HHV = 12,700 Btu/lbm = 29,540 kJ/kg = 25.4×10^6 Btu/short ton
bituminous:	HHV = 11,750 Btu/lbm = 27,330 kJ/kg = 23.5×10^6 Btu/short ton
lignite:	HHV = 11,400 Btu/lbm = 26,515 kJ/kg = 22.8×10^6 Btu/short ton
2007 average:	HHV = 20.24×10^6 Btu/short ton
1 tonne of coal	$\equiv 7 \times 10^9$ cal
	≡ 29.3 GJ ≡ 27.8 MBtu
1 ton of coal	≡ 26.6 GJ ≡ 25.2 MBtu

Crude Oil: energy content varies between 5.6 - 6.3 MBtu/bbl

nominal equivalence:	HHV = 18,100 Btu/lbm = 42,100 kJ/kg = 138,100 Btu/U.S. gal
1 bbl crude oil	≡ 5.80 MBtu ≡ 6.12 GJ
	≡ 460 lbm of coal
	≡ 5680 SCF of natural gas
	≡ 612 kWh of electricity (at $\eta_{th} = 36\%$)
1 tonne crude oil	39.68 MBtu ≡ 41.87 GJ
1 million bbl/day (Mbd)	≡ 2.12 quad/yr ≈ 2 quad/yr

Natural Gas: mostly CH_4; energy content varies between 900 - 1100 Btu/scf

nominal equivalence:	HHV = 24,700 Btu/lbm = 57,450 kJ/kg = 1,021 Btu/scf
2007 average (dry):	HHV = 1,028 Btu/scf
typical equivalence:	HHV ≈ 1,000 Btu/scf ≡ 1.055 GJ/SCF

1.5 Energy Storage

Chemical, thermal, mechanical and nuclear are the primary methods of storing large amounts of energy. Chemical energy is stored in petroleum, biomass, and chemical compounds and elements. Thermal energy is stored in all mass as sensible and latent heat. There are several important considerations when storing energy.

1. the ability to reconvert the stored energy,

2. the rate at which the stored energy may be converted, and

3. the rate at which stored energy decays.

The ability, or inability, to convert stored energy limits the forms of energy that may be utilized in each technology. For example, automobiles rely upon the chemical energy stored in gasoline or diesel fuel. Approximately 7500 gallons of gasoline are required over the lifetime of an automobile, which corresponds to $10^9\,\mathrm{kJ}_c$, or 21 142 kg of gasoline[2] (46 610 lbm = 23.5 tons). If the nuclear energy stored as mass were used instead of chemical energy, then only 0.1 μg (2.5×10^{-7} lbm) of gasoline would be required, but the stored nuclear energy in gasoline cannot be converted to other forms in any simple manner.

The rate at which energy can be converted to another form is an important consideration when coupling various technologies. For example, flywheels may be used to store mechanical energy (kinetic), but the rate at which work can be converted to kinetic energy and the subsequent discharge rate are limited by the inertia of the flywheel. Generally, a relatively long time is required to fully charge a flywheel and the rate of discharge is equally long. In contrast, capacitors can charge and discharge relatively rapidly, but the energy storage capability is significantly less than a flywheel.

Finally, energy cannot be stored indefinitely. Biomass contains substantial stored chemical energy, yet this will decompose to a less useful material with time. Similarly, flywheels will lose energy due to friction. The rate of self-discharge is an important consideration in coupling energy storage technologies with energy conversion systems.

[2] higher heating value taken as 47 300 kJ/kg

Storage Technologies	Main Advantages (relative)	Disadvantages (Relative)	Power Application	Energy Application
Pumped Storage	High Capacity, Low Cost	Special Site Requirement		●
CAES	High Capacity, Low Cost	Special Site Requirement, Need Gas Fuel		●
Flow Batteries: PSB VRB ZnBr	High Capacity, Independent Power and Energy Ratings	Low Energy Density	◐	●
Metal-Air	Very High Energy Density	Electric Charging is Difficult		●
NaS	High Power & Energy Densities, High Efficiency	Production Cost, Safety Concerns (addressed in design)	●	●
Li-ion	High Power & Energy Densities, High Efficiency	High Production Cost, Requires Special Charging Circuit	●	○
Ni-Cd	High Power & Energy Densities, Efficiency		●	◐
Other Advanced Batteries	High Power & Energy Densities, High Efficiency	High Production Cost	●	○
Lead-Acid	Low Capital Cost	Limited Cycle Life when Deeply Discharged	●	○
Flywheels	High Power	Low Energy density	●	○
SMES, DSMES	High Power	Low Energy Density, High Production Cost	●	
E.C. Capacitors	Long Cycle Life, High Efficiency	Low Energy Density	●	◐

Figure 1.1: Comparison of energy storage technologies. [7]

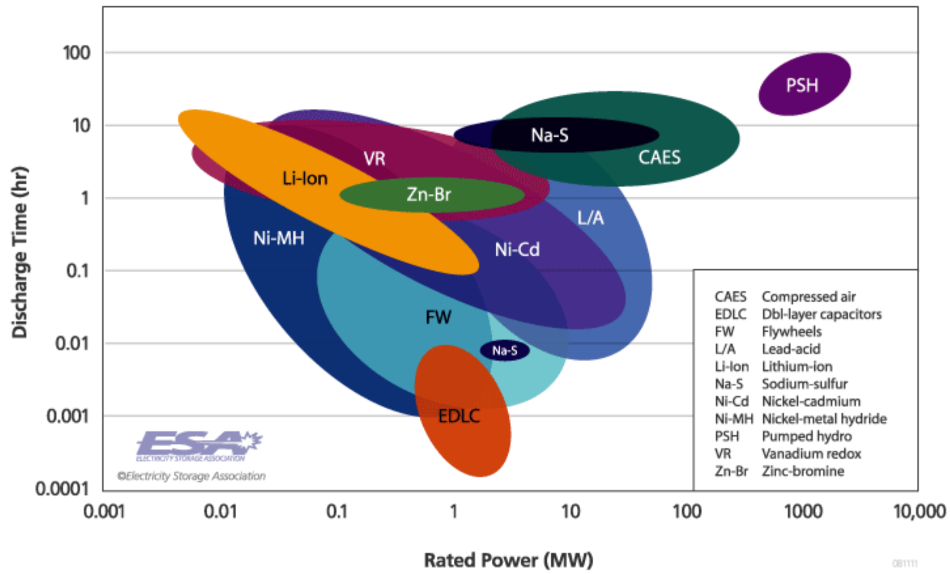


Figure 1.2: Discharge time versus power. Installed systems as of Nov. 2008. [7]

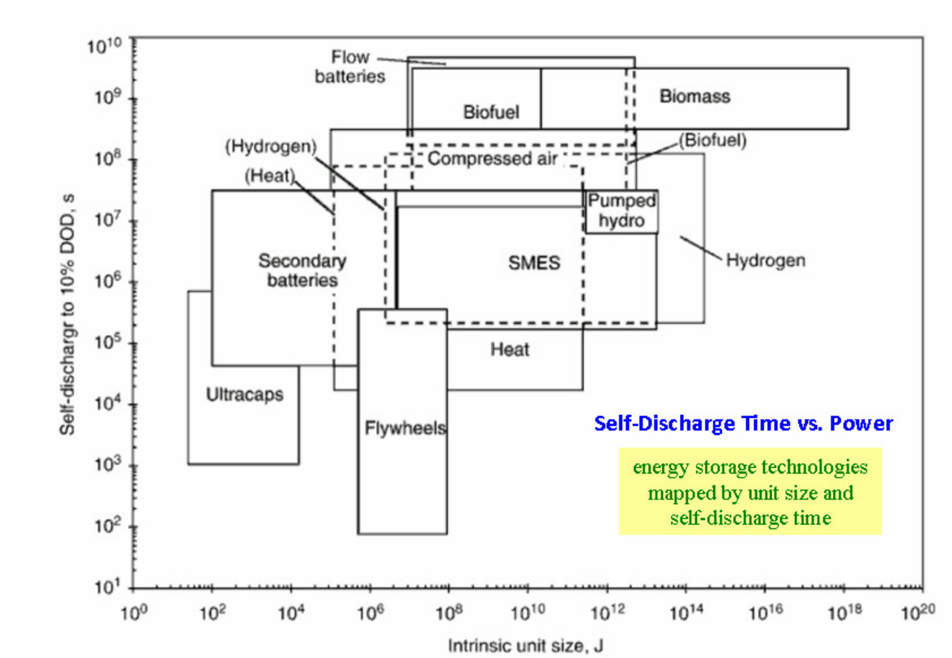


Figure 1.3: Self-discharge time of energy storage systems. [8]

1.6 Energy Conversion

The process of energy conversion can be divided into Direct and Indirect Conversion. Direct conversion is a single-step process as with photovoltaic conversion of electromagnetic energy into electrical energy. Examples of both are shown in below.

Direct: Single-step conversion process

- photovoltaics: electromagnetic $\longrightarrow$ electrical
- batteries: chemical $\longleftrightarrow$ electrical
- thermoelectric coolers (TEC): thermal $\longleftrightarrow$ electrical
- piezoelectric: mechanical $\longleftrightarrow$ electrical

Indirect: Multi-step conversion process

- Diesel cycle (gas): chemical $\longrightarrow$ thermal $\longrightarrow$ mechanical $\longrightarrow$ mechanical
- Rankine cycle (liquid-vapor), steam turbine:
  $$\left.\begin{array}{c}\text{chemical}\\ \text{nuclear}\\ \text{solar}\\ \text{geothermal}\end{array}\right\} \longrightarrow \text{thermal} \longrightarrow \text{mechanical} \longrightarrow \text{electrical}$$
- Brayton cycle (gas), gas turbine, turbojets:
  $$\left.\begin{array}{c}\text{chemical}\\ \text{nuclear}\\ \text{solar}\end{array}\right\} \longrightarrow \text{thermal} \longrightarrow \text{mechanical} \longrightarrow \text{electrical}$$
- $\left(\begin{array}{c}\text{wind turbine}\\ \text{wave energy}\\ \text{tidal energy}\end{array}\right)$ mechanical $\longrightarrow$ mechanical $\longrightarrow$ mechanical $\longrightarrow$ electrical

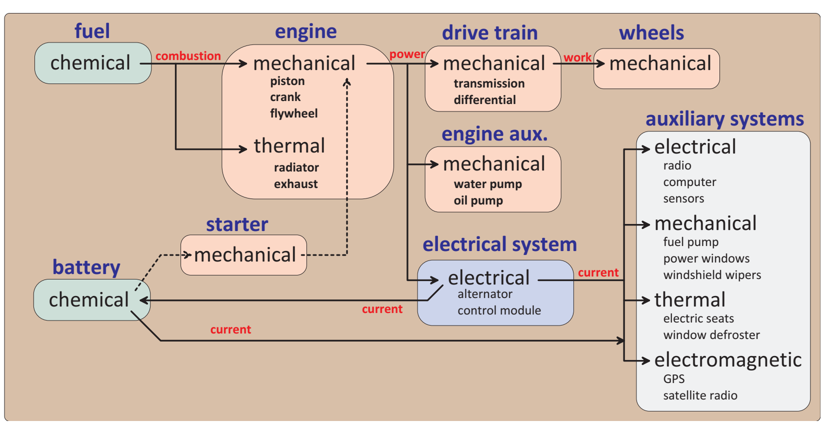


Figure 1.4: Indirect energy conversion processes in an ICE vehicle.

1.7 Efficiency of Energy Conversion

The efficiency of energy conversion is based on the notion of useful work. That is, some of the energy being converted is not converted into the desired form. Most often, the undesired conversion is to low-grade thermal energy. The general definition of efficiency can be expressed as the ratio of energy sought to energy cost.

$$\textbf{efficiency, } \eta \equiv \frac{\text{energy sought}}{\text{energy cost}}$$

1.7.1 Common Definitions of Efficiency

$$\text{combustion: } \eta = \frac{Q}{\text{HV}} \equiv \frac{\text{heat released}}{\text{heating value of fuel}}$$

$$\text{heat pump: COP} \equiv \frac{Q_H}{W_C} \equiv \frac{\text{heat into hot reservoir}}{\text{compressor work}}$$

$$\text{refrigeration: COP} \equiv \frac{Q_C}{W_C} \equiv \frac{\text{heat from cold reservoir}}{\text{compressor work}}$$

$$\text{alternator: } \eta \equiv \frac{\dot{W}_e}{\dot{W}_m} \equiv \frac{\text{electrical energy out}}{\text{mechanical energy in}}$$

$$\text{battery: } \eta = \frac{\dot{W}_e}{\dot{W}_c} \equiv \frac{\text{electrical energy out}}{\text{chemical energy in}}$$

$$\text{IC engine:`} \eta = \frac{\dot{W}_m}{\dot{W}_c} \equiv \frac{\text{mechanical energy out}}{\text{chemical energy in}}$$

$$\text{automotive transmission: } \eta = \frac{\dot{W}_m}{\dot{W}_m} \equiv \frac{\text{mechanical energy out}}{\text{mechanical energy in}}$$

$$\text{electrical transmission: } \eta = \frac{\dot{W}_e}{\dot{W}_e} \equiv \frac{\text{electrical energy out}}{\text{electrical energy in}}$$

1.7.2 Carnot Efficiency

The Carnot efficiency is the maximum efficiency of any thermodynamic power cycle. This includes gasoline engines (Otto cycle), gas turbines (Brayton cycle), steam turbine plants (Rankine cycle), and Stirling engines. The conversion efficiency of any cyclic process converting thermal energy to mechanical energy is limited by the Carnot efficiency.

$$\eta_{carnot} = 1 - \frac{T_{low}}{T_{hot}}$$

The temperatures must be in absolute units, Kelvin or Rankine. The Carnot efficiency increases as the difference increases between the hot and cold sides of the engine. Efficiencies of thermodynamic power cycles are typically around 30%.

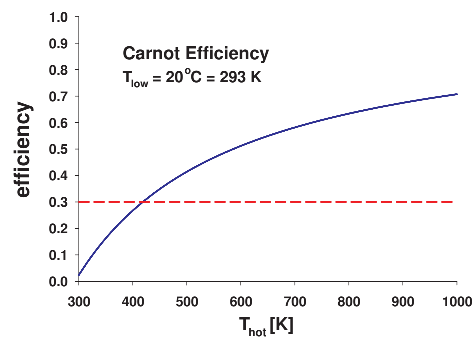


Figure 1.5: Carnot efficiency.

1.7.3 Annual Fuel Utilization Efficiency (AFUE)

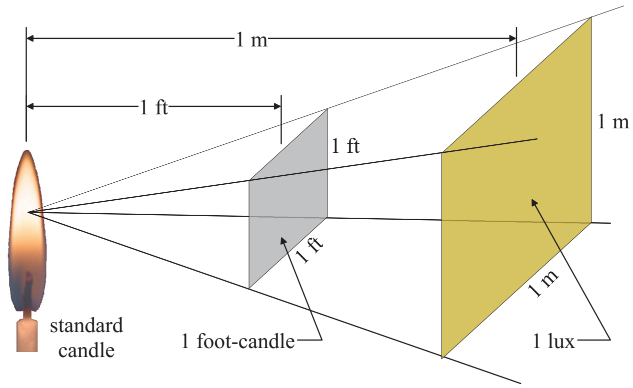
The efficiency of home heating systems are reported using Annual Fuel Utilization Efficiency (AFUE), which accounts for combustion efficiency, heat losses, and startup/shutdown losses on an annualized basis.

older heating systems: AFUE $\leq$ 60%

newer heating systems: AFUE ~ 85%

high efficiency furnaces: AFUE ~ 96%

High efficiencies are obtained using heat reclamation from the flue gas (combustion products), which results in low temperature discharge of the flue gas. The temperatures can be low enough so that there is little or no buoyancy force to push the flue gas through the exhaust ventilation. Newer systems rely on an electric fan to push the flue gas to the top of the house or the flue gas is vented horizontally out of the side of the house.



$$1 \text{ lux} = 1 \text{ lumen/m}^2 \qquad \text{and} \qquad 1 \text{ foot-candle} = 1 \text{ lumen/ft}^2$$

Figure 1.6: Definition of lux and foot-candle.

1.7.4 Lighting Efficiency

Lighting efficiency is defined as the amount of light produced per energy used to generate the light. Typically, the energy used is electrical and is measured in watts. The measure of illumination rate is the **lumen**, which is the amount of illumination passing through a 1-m^2 area located 1-m from a standard candle. Lumen is Latin for light. The definition of a standard candle has a convoluted history. The current definition of a standard candle is that is produces 4π lumens that radiate spherically in all directions.

Illumination can be divided into the total amount of light at the source, known as radiance, and the intensity of light impinging on a surface, known as illuminance. Radiance (energy released at source) is measured in candelas, or an older unit of candle-power. The illustration shows the relationship between a standard candle (radiance = 1 candela) and illuminance. At 1 foot away from the source, the intensity of 1 candela is 1 foot-candle and the illumination on a 1 square foot area is 1 lumen. Similarly, at 1 meter away from the source, the intensity of 1 candela is 1 lux and the illumination on a 1 square meter area is 1 lumen. Figure 1.6 illustrates these definitions.

The efficacy of a light source, or lighting efficiency, is defined as the light output in lumens per power input in watts. Care should be taken when reviewing published lighting efficiency. Manufacturers may report lumens per watts of visible light as efficiency instead of lumens per watts of electrical power.

$$\eta_{\text{lighting}} = \frac{\text{lumens}}{\text{watts}}$$

The theoretical limit based on an ideal light source emitting at 555 nm is 683 lumens/watt. The most efficient white light source is 275-310 lumens/watts.

Table 1.2: Typical efficiencies of several illumination sources. [9–11]

	efficiency		
light source	**lamp**	**with ballast**	**rated hours**
sunlight	92 lm/W_t		
open gas flame, candle	0.15-0.20 lm/W_t		
incandescent			
- small (flashlight, nightlight, ...)	5-6 lm/W_e		750-1000
- 40 W	12 lm/W_e		
- 100 W	18 lm/W_e		
- tungsten-halogen	18-24 lm/W_e		2000-3000
- tungsten-halogen-infrared reflector (HIR)	? lm/W_e		3000-4000
fluorescent			
- standard (tubular)			
20 W (+13 W), 24"	65 lm/W_e	39 lm/W_e	15 000-20 000
40 W (+13.5 W), 48"	79	59	
75 W (+11 W), 96"	84	73-90	
- compact fluorescence (CFl)			
11-26 W	40-70	??	6000-10 000
high-intensity discharge (HID)			
- mercury vapor	57	53.5	24 000
- metal halide 400 W (+13 W)		45-100	5000-20 000
- high pressure sodium	< 150	45-110	20 000
- low-pressure sodium (not HID)	< 200	80-160	20 000
light emitting diode (LED)			
- white, 3-10 W/unit	30	??	6000 - 50 000

1.7.5 Efficiency in Electrical Power Generation

Electrical power generation uses a unique set of performance factors related to plant efficiencies. The amount of power generated may be characterized on the rated power production of the plant or the actual power production over some period of time. A few common definitions related to electrical power production are:

Power Density: power per unit volume [kW/m^3]

Specific Power: power per unit mass [kW/kg]

Electric Power Output: Power × time [kW$_e$h]

Rated Power: power output of a plant at <u>nominal</u> operating conditions

Common terms used to describe efficiency in the U.S. electrical power generation industry:

Heat Rate (HR): thermal Btu's required to produce 1 kW$_e$h of electricity [Btu$_t$/kW$_e$h]

$$3412 \text{ Btu} \equiv 1 \text{ kW}_t\text{h}$$

$$\eta = \left.\frac{\text{electrical energy produced}}{\text{thermal energy consumed}}\right\} \text{ of the cycle } \left[\frac{\text{kW}_e}{\text{kW}_t}\right]$$

$$\text{Heat Rate} \equiv \frac{3412}{\eta}$$

Capacity Factor (CF): $\left.\dfrac{\text{average power}}{\text{rated power}}\right\}$ per a specific time period

The Capacity Factor is the ratio of "the electrical energy produced by a generating unit for a given period of time" to "the electrical energy that could have been produced at continuous rated-power operation during the same period."

Load Factor: $\equiv \left.\dfrac{\text{average power}}{\text{maximum power}}\right\}$ per a specific time period

Availability Factor: ≡ fraction of time period that power generation system is available

Unit Fuel Cost: $\equiv \dfrac{\text{(fuel cost)(heat rate of plant)}}{\text{efficiency}}$

1.7.6 Serial Efficiency

Each time energy is converted from one form to another, there is a loss of available energy; in other words, the efficiency of the energy conversion is always less than 1. In a system where there are multiple energy conversion processes occurring, the efficiencies of each subsequent conversion result in an ever decreasing net energy output. This process is shown in Figure 1.7, where

$$E_1 = \eta_1 \cdot E_0 \qquad \text{and} \qquad E_2 = \eta_2 \cdot E_1 = \eta_2 \cdot \eta_1 \cdot E_0$$

The overall efficiency is the product of all process efficiencies.

$$E_3 = \eta_3 \cdot \eta_2 \cdot \eta_1 \cdot E_0$$

Figure 1.8 illustrates the overall system efficiency for a variety of technologies.

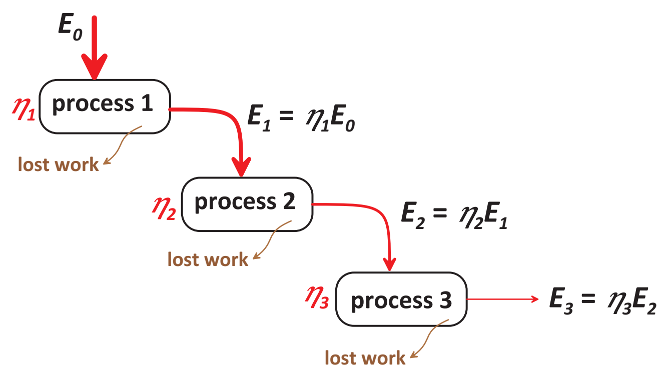


Figure 1.7: Effect of multiple conversion processes on overall conversion efficiency.

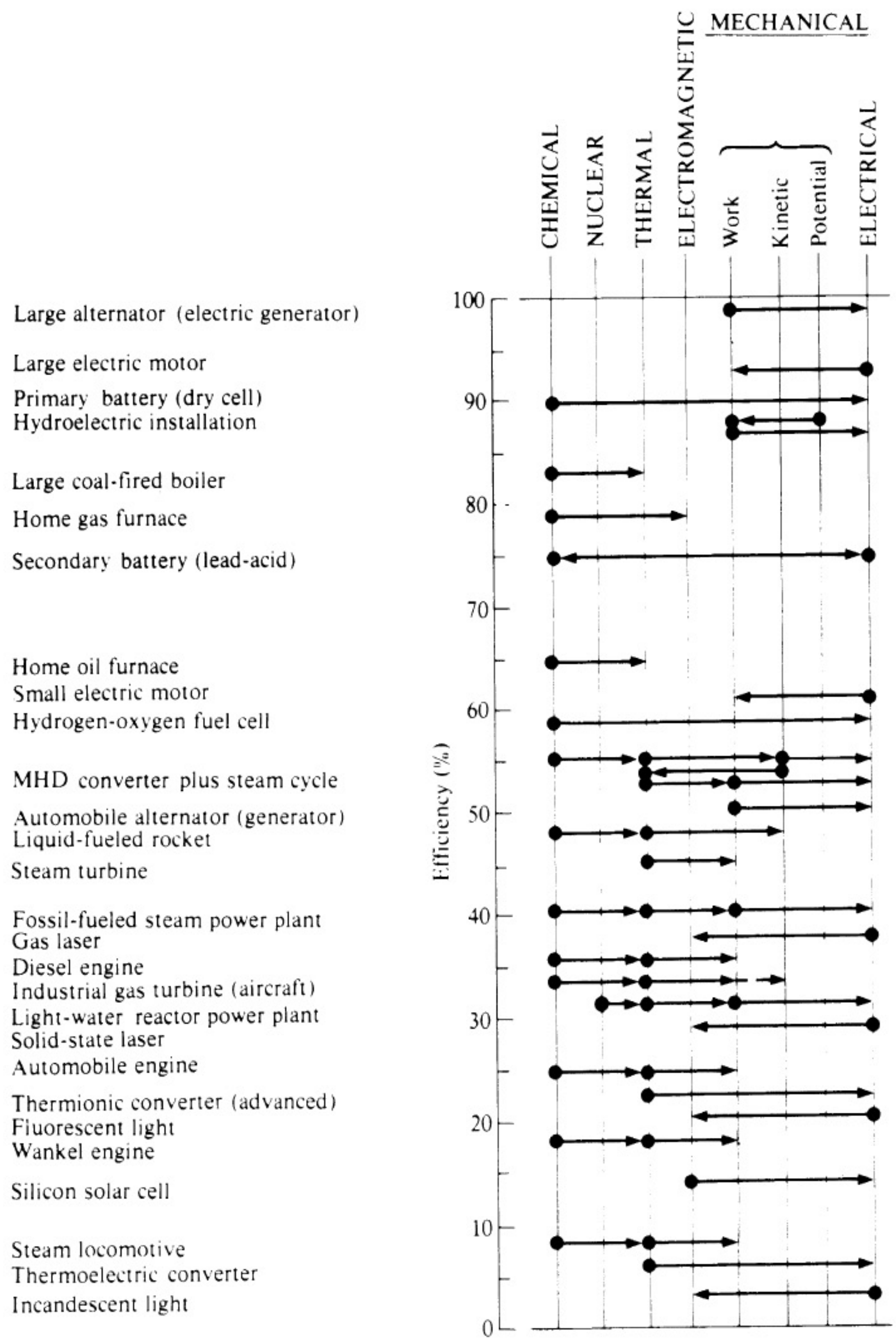


Figure 1.8: Typical conversion efficiencies. [2]

1.7.7 Examples of Energy Conversion

1.7.7.1 Example 1-1. Solar Charging of Electric Vehicle

An electric commuter vehicle uses a 24-hp electric motor and is to have a photovoltaic array on the roof to charge the batteries both while moving and parked. The average solar flux is 650 W_{em}/m^2. The commute is one hour each way and the vehicle is parked for 8 hours. Thus, for each hour of operation, you estimate that the vehicle will be parked for four hours during daylight hours. The overall electromagnetic-to-electrical-to-mechanical energy conversion is 13% and the storage efficiency of the batteries is 60%. Determine the area of the solar array required to provide sufficient energy for the commute.

The effective solar power with energy storage per hour of operation is:

$$\frac{650\,\mathrm{W_{em}}}{\mathrm{m^2}}\left[\frac{1\,\mathrm{hr} + \left(0.60\,\frac{\mathrm{W_{e,out}}}{\mathrm{W_{e,in}}}\right)\cdot 4\,\mathrm{hr}}{1\,\mathrm{hr}}\right] = 2210\,\frac{\mathrm{W_{em}}}{\mathrm{m^2}}$$

The required area of solar array required to generate 24 hp_{em}:

$$\left(24\,\mathrm{hp_{em}}\right)\left(\frac{745.7\,\mathrm{W_{em}}}{\mathrm{hp_{em}}}\right)\left(\frac{\mathrm{m^2}}{2210\,\mathrm{W_{em}}}\right) = 8.1\,\mathrm{m^2}$$

This area, 8 m^2, is required to collect 24 hp worth of electromagnetic energy during 1 hour of driving and 4 hours parked. The conversion of the electromagnetic energy to mechanical energy (motion of vehicle) is 13%a. Thus, the area required to generate 24 hp_m from 650 W_{em}/m^2 is:

$$8.1\,\mathrm{m^2}\left(\frac{\mathrm{W_{em}}}{0.13\,\mathrm{W_m}}\right) = 62.3\,\mathrm{m^2}$$

Example 1-1 in EES

```
"Example 1-1. An electric commuter vehicle uses a 24-hp electric motor and is to have
a photovoltaic array on the roof to charge the batteries both while moving and parked.
The average solar flux is 650 Wem/m^2. The commute is one hour each way and the
vehicle is parked for 8 hours.  Thus, for each hour of operation, you estimate that the
vehicle will be parked for four hours during daylight hours.   The overall
electromagnetic-to-electrical-to-mechanical energy conversion is 13% and the storage
efficiency of the batteries is 60%. Determine the area of the solar array required to
provide sufficient energy for the commute."

w''_dot_em = 650 [W/m^2]
W_dot_hp = 24 [hp]
eta_system = 0.13
eta_storage = 0.60

t_moving = 1 [hr]
t_sitting = 4 [hr]
dt = 1 [hr]

"total energy collected per area"
e''_moving = w''_dot_em *t_moving
e''_sitting =  w''_dot_em *t_sitting*eta_storage

"on a per hour basis, the solar power per area collected is"
w''_dot_em_collected = (e''_moving + e''_sitting)/dt

"The area required to collect 24 hp equivalent of electromagnetic energy is"

"convert horsepower into Watts"
c = convert(hp,W)
W_dot = c*W_dot_hp

W_dot  = w''_dot_em_collected*Area_ideal

"The conversion efficiency from electromagnetic (em) to mechanical work (m) is only 13%."
eta_system = Area_ideal/Area_actual

"eof"
```

SOLUTION

Unit Settings: SI C kPa kJ mass deg

$Area_{actual}$ = 62.29 [m^2]

$Area_{ideal}$ = 8.098 [m^2]

c = 745.7 [W/hp]

dt = 1 [hr]

e''_{moving} = 650 [W-hr/m^2]

$e''_{sitting}$ = 1560 [W-hr/m^2]

$\eta_{storage}$ = 0.6

η_{system} = 0.13

t_{moving} = 1 [hr]

$t_{sitting}$ = 4 [hr]

$\dot{w}''_{em}$ = 650 [W/m^2]

$\dot{w}''_{em,collected}$ = 2210 [W-hr/m^2]

$\dot{W}$ = 17897 [W]

$\dot{W}_{hp}$ = 24 [hp]

1.7.7.2 Example 1-2. Coal Power Plant

A coal burning power plant produces a net power of 300 MWe with a Heat Rate of 10,663. The heating value of the coal is 12,040 Btu/lbm. The gravimetric air-fuel ratio in the furnace is calculated to be 12 kg air/kg fuel.

(a) What is the thermal efficiency of the plant?
(b) How much fuel is consumed in 24 hours?
(c) What is the air flow rate?

(a) The thermal efficiency can be calculated from the definition of Heat Rate.

$$\eta_{th} = \frac{3412}{HR} = \frac{3412\,\mathrm{Btu}_{th}/\mathrm{kW}_{th}\mathrm{hr}}{10,633\,\mathrm{Btu}_{th}/\mathrm{kW}_{e}\mathrm{hr}} = 0.32\,\mathrm{kW}_{e}/\mathrm{kW}_{th}$$

(b) The amount of fuel consumed is proportional to the heat input.

$$\dot{Q}_{\mathrm{in}} = \frac{\dot{W}_{\mathrm{out}}}{\eta_{th}} = \frac{300\,\mathrm{MW}_{e}}{0.32\,\frac{\mathrm{MW}_{e}}{\mathrm{MW}_{\mathrm{th}}}} = 937.5\,\mathrm{MW}_{\mathrm{th}} = \dot{m}_{\mathrm{coal}} \cdot \mathrm{HV}$$

$$\dot{m}_{\mathrm{coal}} = \frac{937.5\,\mathrm{MW}_{\mathrm{th}}}{28,000\,\mathrm{kJ/kg}} = \frac{\left(937.5 \cdot 10^{6}\,\mathrm{W}_{\mathrm{th}}\right)\left(\mathrm{Js}^{-1}/\mathrm{W}\right)}{28 \cdot 10^{6}\,\mathrm{J/kg}} = 33.48\,\mathrm{kg/s}$$

$$\frac{m_{\mathrm{coal}}}{\mathrm{day}} = 2.86 \cdot 10^{6}\,\mathrm{kg/day}$$

(c) The air flow rate is determined from the air-fuel ratio:

$$\dot{m}_{\mathrm{air}} = \dot{m}_{\mathrm{coal}} \cdot \mathrm{AF} = (33.48\,\mathrm{kg}_{\mathrm{coal}}/\mathrm{s})\left(\frac{12\,\mathrm{kg}_{\mathrm{air}}}{\mathrm{kg}_{\mathrm{coal}}}\right) = 401.8\,\mathrm{kg}_{\mathrm{air}}/\mathrm{s}$$

Example 1-2 in EES

```
{Example 1-2. A coal burning power plant produces a net power of 300 MWe
with a Heat Rate of 10,663. The heating value of the coal is 12,040 Btu/lbm.
The gravimetric air-fuel ratio in the furnace is calculated to be 12 kg air/kg fuel.

(a) What is the thermal efficiency of the plant?
(b) How much fuel is consumed in 24 hours?
(c)  What is the air flow rate?
}

W_dot_e = 300000 [kW]
HR = 10663
HV = 12040
AF = 12

"(a) The thermal efficiency can be determined from the Heat Rate."
HR = 3412/eta_th

"The amount of fuel consumed is proportional to the heat input."
eta_th = W_dot_e/Q_dot_th
Q_dot_th = m_dot_fuel * HV

"Q_dot_th has units of kW and heating value has units of Btu/lbm.
If we don't convert one of these two, the m_dot_fuel will have units of lbm kW/Btu."

"Redefine the Heating Value as kJ/kg:  2.326 kJ/kg = 1 Btu/lbm."
HV_si = HV*2.326

"Now, the mass rate should be in kg/s."
Q_dot_th = m_dot_fuel_si*HV_si

"(b) Over a 24-hour period, the mass of fuel used is:"
m_fuel_day = m_dot_fuel_si*3600*24

"(c) The rate of air flow is determined by the air-fuel ratio."
AF = m_dot_air/m_dot_fuel_si
```

SOLUTION

Unit Settings: SI C kPa kJ mass deg

$AF = 12$ [kg_{air}/kg_{fuel}]
$\eta_{th} = 0.32$
$HR = 10663$ [Btu_{th}/kW_e]
$HV = 12040$ [Btu/lbm]
$HV_{si} = 28005$ [kJ/kg]
$\dot{m}_{air} = 401.7$ [kg/s]
$\dot{m}_{fuel} = 77.87$ [Btu/hr]
$\dot{m}_{fuel,si} = 33.48$ [kg/s]
$m_{fuel,day} = 2.892E+06$ [kg]
$\dot{Q}_{th} = 937544$ [kW]
$\dot{W}_e = 300000$ [kW]

1.7.7.3 Example 1-3. Hybrid Motorbike

You are developing a hybrid motorbike using a 2-hp, 2-stroke gasoline engine to drive a generator that powers an electric motor. There is a small lead acid battery used for storing energy. The thermal efficiency of the engine is 25%. The generator is 60% efficient. The electric drive motor is 50% efficient. The battery storage system is 75% efficient.

(a) With battery system by-passed, what is the power delivered to the wheels?

(b) Power delivered using batteries?

The motor is rated at 2-hp which is the output power. Thus, for a 25% efficient engine, 8-hp of chemical energy required to generate this 2-hp.

(a) engine ⟶ generator ⟶ motor ⟶ wheels

$$2\,\mathrm{hp}_m \longrightarrow \text{generator} \longrightarrow 2\,\mathrm{hp}_m\left(\frac{0.60\,\mathrm{hp}_e}{\mathrm{hp}_m}\right) = 1.2\,\mathrm{hp}_e$$

$$1.2\,\mathrm{hp}_e \longrightarrow \text{drive motor} \longrightarrow 1.2\,\mathrm{hp}_e\left(\frac{0.50\,\mathrm{hp}_m}{\mathrm{hp}_e}\right) = 0.6\,\mathrm{hp}_m$$

$$\text{power delivered} = 0.6\,\mathrm{hp}_m \times \left(\frac{0.7459\,\mathrm{kW}}{\mathrm{hp}}\right) = 0.45\,\mathrm{kW}_m$$

$$\begin{array}{c}\text{system efficiency when}\\ \text{starting with the fuel!}\end{array} = \left(\frac{0.25\,\mathrm{W}_m}{\mathrm{W}_c}\right)\left(\frac{0.60\,\mathrm{W}_e}{\mathrm{W}_m}\right)\left(\frac{0.50\,\mathrm{W}_m}{\mathrm{W}_e}\right) = 7.5\%\,\frac{\mathrm{W}_m}{\mathrm{W}_c}$$

(b)

$$\begin{tikzcd} \textbf{engine} \arrow[r] & \textbf{generator} \arrow[d] & \textbf{motor} \arrow[r] & \textbf{wheels} \\ & \textbf{battery} \arrow[ur] & & \end{tikzcd}$$

$$2\,\mathrm{hp}_m\left(\frac{0.60\,\mathrm{hp}_e}{\mathrm{hp}_m}\right)\left(\frac{0.75\,\mathrm{hp}_{e,b}}{\mathrm{hp}_e}\right)\left(\frac{0.50\,\mathrm{hp}_m}{\mathrm{hp}_{e,b}}\right) = 0.45\,\mathrm{hp}_m = 0.34\,\mathrm{kW}_m$$

$$\eta_{\text{system}} = 5.6\%\,\frac{\mathrm{W}_m}{\mathrm{W}_c} = 0.056\left(\frac{\text{mechanical energy out}}{\text{chemical energy in}}\right)$$

Example 1-3 in EES

"Example 1-3. You are developing a hybrid motorbike using a 2-hp, 2-stroke gasoline engine to drive a generator which powers an electric motor. There is a small lead acid battery used for storing energy. The thermal efficiency of the engine is 25%. The generator is 60% efficient. The electric drive motor is 50% efficient. The battery storage system is 75% efficient.

(a) With battery system by-passed, what is the power delivered to the wheels?
(b) Power delivered using batteries?

The motor is rated at 2-hp which is the output power. Thus, for a 25% efficient engine, 8-hp of chemical energy required to generate this 2-hp.
"

```
eta_eng = 0.25      "engine efficiency"
eta_gen = 0.60      "generator efficiency"
eta_mot = 0.50      "motor efficiency"
eta_bat = 0.75      "battery efficiency"

W_dot_mot = 2 [hp]    "output of motor"

"(a) bypassing battery system"
W_dot_wheels_a = W_dot_mot * eta_gen * eta_mot


"(b) using battery system"
W_dot_wheels_b =W_dot_mot * eta_gen * eta_bat * eta_mot


"The overall efficiency from fuel to mechanical motion is:"

eta_a = eta_eng * eta_gen * eta_mot
eta_b = eta_eng * eta_gen * eta_bat * eta_mot

"eof"
```

SOLUTION

Unit Settings: SI C kPa kJ mass deg

η_a = 0.075

η_b = 0.05625

η_{bat} = 0.75

η_{eng} = 0.25

η_{gen} = 0.6

η_{mot} = 0.5

$\dot{W}_{mot}$ = 2 [hp]

$\dot{W}_{wheels,a}$ = 0.6 [hp]

$\dot{W}_{wheels,b}$ = 0.45 [hp]

Article 2

Dimensions, Units & Unit Systems

When dealing with energy and energy conversion you will experience an incredible variety of units and unit systems. This is especially true when working with pressure and flow. Common units of pressure include psi, psig, psid, in H_2O, mm Hg, torr, millitorr, bar, atm, Pa, kPa, and MPa. While the units of pressure vary greatly, the methods for measuring pressure are most often based on two processes; converting pressure into gravitational potential or elastic-strain potential.

A wide variety of units is also used for quantifying volumetric and mass flow rates: kg/s, lbm/hr, CFM (ft^3/min), m^3/s, ft^3/hr, liters/min, gpm (gallons per minute), and so on. The choice of units used depends upon the application. Not only are a wide variety of units used in energy and energy conversion, the underlying unit systems used are fundamentally different from one another. There are two SI unit systems and three English unit systems and four of these are commonly found in industry. It is imperative that you are able to work within different unit systems with precision.

2.1 Dimensions

A dimension is a physical specification of a system – length, time, etc. There are primary dimensions and secondary dimensions. A *primary dimension* is one which is arbitrarily defined. For example, length (dimension) may be quantified using the foot (unit). The foot was defined as the physical length of a king's foot; a rather arbitrary definition. A *secondary dimension* is one which is defined in terms of primary dimensions; e.g., volume (secondary) is defined in terms of a cubic length (primary).

2.2 Units & Unit Systems

Prior to standardization efforts, most units were arbitrarily defined. There were very few secondary units. All units of length were primary; that is, an inch was arbitrarily defined as was the foot and mile. The same was true for weight (force), area, volume, and so on. There are conversions between the units, but each is arbitrarily defined. Some common primary (arbitrarily-defined) units are for weight are pound, ounce, carat, grain, and kilogram. Unit systems were developed using a minimum number of primary dimensions with all other dimensions derived. The two most common unit systems in use are SI and English Engineering.

Table 2.1: Primary dimensions and units for engineering unit systems.

	Unit System				
Dimension	SI	CGS	EE	BG	AE
mass	kg	g	lbm	–	lbm
force	–	–	lbf	lbf	–
length	m	cm	ft	ft	ft
time	s	s	s	s	s
temperature	K	°C	°R	°R	°R
primary dimensions	MLT	MLT	FMLT	FLT	MLT
magnitude of g_c	1	1	32.174	1	1

2.2.1 MLT vs FLT Unit Systems

The minimum number of primary dimensions required for a unit system that describes mechanical motion and energy can be found using Newton's Second Law.

$$F = ma \quad \longrightarrow \left(\text{force}\right) = \left(\text{mass}\right)\left(\frac{\text{length}}{\text{time}^2}\right)$$

If mass, length and time are defined as primary, then force is derived. This type of unit system is known as MLT (mass-length-time). Alternatively, force, length, and time (FLT) may be used to define the unit system and mass is derived (secondary). Table 2.1 lists six common unit systems used in engineering.

Units are often prefixed by a power of 10 for purposes of expressing values with appropriate significant digits. Examples include mm (10^{-3}m) and kPa, which is a unit of pressure equivalent to $10^3\,\text{N/m}^2$. Table 2.2 at the end of this article lists common prefixes used in engineering.

2.2.1.1 Système International d'Unités (SI) – MLT

Confusion over units prompted European scientists to convert to a base 10 system with a minimal set of primary dimensions; mass, distance, time, and temperature. A conference was held in the 1870's and countries started signing treaties to use this new unit system known as the *Système International d'Unités* (SI) system. The United States Senate ratified the treaty in 1875. SI is an MLT (mass-length-time) unit system; that is, mass, length and time are defined as primary dimensions. Force is a secondary dimension with units of newtons (N). Newtons are derived units; derived from the primary dimension units of kg, m, and s. In the SI system, the dimensional constant g_c is equal to $1\,\text{kg m/N s}^2$. As a result, the dimensional constant is commonly ignored. Conversion between force (N), energy (N m), power (N m/s), and mass (kg) always requires the use of the dimensional constant g_c even though you may not see it included in equations.

$$g_{c,\mathrm{SI}} = 1\,\frac{\mathrm{kg\,m}}{\mathrm{N\,s^2}}$$

2.2.1.2 English Engineering (EE) Unit System – FMLT

In the traditional English Engineering (EE) unit system, pound is used for both mass and force. Thus, both mass and force are primary and arbitrarily equal in magnitude; 1 lbm = 1 lbf. But weight (lbf) is related to mass (lbm) by Newton's Second Law weight = mg, where gravitational acceleration g is 32.2 ft/s^2. These two relationships cannot both be true. By definition 1 lbm weighs 1 lbf, which violates Newton's second law. A dimensional constant, or conversion factor, is required to relate these two independent primary dimensions. That conversion factor is g_c.

$$g_c F = ma \tag{2.1}$$

In the EE unit system, the dimensional constant g_c is equal to 32.174 lbm ft/lbf s^2.

The use of pound (lb) as both a unit of mass and force is a source of frustration to engineers. The pitfalls of this unit system, however, can be avoided by remembering to use the dimensional constant g_c [12]. The English Engineering (EE) system commonly used in the heating and air conditioning industry, the power and energy industry, and the aeronautics industry.

The dimensional constant g_c is used each time you relate mass, force, momentum and energy regardless of which unit system you use. g_c is always present in calculations involving energy and power even if you neglect to write it down.

$$g_{c,\mathrm{EE}} = 32.174\,\frac{\mathrm{lbm\,ft}}{\mathrm{lbf\,s^2}}$$

$$1\,\mathrm{lbf} = 4.44\,\mathrm{N}$$

$$1\,\mathrm{lbm} = 0.454\,\mathrm{kg}$$

2.2.1.3 British Gravitational (BG) Unit System – FLT

The British Gravitational (BG) Unit System is one attempt to simplify the EE system. BG is an FLT (force-length-time) system; where lbf, ft, and second are primary dimension units. Pound is not used for mass in the BG system. A new unit of mass defined as a *slug* is derived from primary dimension units of lbf, ft, and s. The dimensional constant g_c is equal to 1 slug ft/lbf s in the BG unit system and 1 slug is equivalent to 32.174 lbm. The BG unit system is not commonly found in industry, but is often used in undergraduate engineering education for problems involving English units.

$$g_{c,\mathrm{BG}} = 1\,\frac{\mathrm{slug\,ft}}{\mathrm{lbf\,s^2}}$$

$$1\,\mathrm{slug} = 32.174\,\mathrm{lbm} = 14.594\,\mathrm{kg}$$

2.2.1.4 American Engineering (AE) Unit System – MLT

The American Engineering (AE) unit system is also an attempt to simplify the EE system. AE is an MLT (mass-length-time) system; where lbm, ft, and second are primary dimension units. Pound is only used for mass in the AE system. Force is a secondary dimension with unit of poundal (pdl). The dimensional constant g_c is equal to 1 lbm ft/pdl s in the AE system and and 1 pdl is equivalent to 1/32.174 lbf. The AE system is not commonly used.

$$g_{c,\mathrm{AE}} = 1\,\frac{\mathrm{lbm\,ft}}{\mathrm{pdl\,s^2}}$$

$$1\,\mathrm{pdl} = 0.0311\,\mathrm{lbf} = 0.138\,\mathrm{N}$$

2.2.1.5 CGS Unit System – MLT

The CGS system is a variation of the SI system when working with small values of mass. The primary dimensions are mass-length-time (MLT) with units of grams (g), centimeters (cm), and seconds (s). Force is a secondary dimension with unit of *dyne*. In the CGS system, the dimensional constant g_c is equal to 1 g cm/dyne s^2. The CGS system is commonly used in chemistry and the chemical industry.

$$g_{c,\mathrm{CGS}} = 1\,\frac{\mathrm{g\,cm}}{\mathrm{dyne\,s^2}}$$

$$1\,\mathrm{dyne} = 10\,\mu\mathrm{N} = 1\cdot 10^{-5}\,\mathrm{N}$$

2.2.1.6 U.S. Customary Units

The U.S. Customary Units is a system of commonly used units, but is not a unit system per se. It is a collection of commonly used units including inch, psi, ft, lbf, and inches of water column (in w.c.). The U.S. Customary Units are widely used in the HVAC, water, and petroleum industries [6, 13]. The primary differences between U.S. Customary Units and the three other common English unit systems are the use of $\mathrm{lbf/in^2}$ (psi) and in w.c. for measures of pressure and the use of British Thermal Unit (BTU) for measures of heat and thermal energy.

2.2.1.7 Metric Gravitational Units

Like U.S. Customary Units, Metric Gravitational is not a strict unit system. Force is measured in units of kilogram-force (kgf) or kilopond (kp). The unit of mass might be kg or a metric slug (also known as a hyl or technical mass unit, TME[1]). If mass is specified in kg, then the dimensional constant g_c is not equal to 1. The use of kgf is not considered an acceptable unit of force, but remains in common use in Europe and India.

$$g_{c,MG} = 9.81\,\frac{\mathrm{kg/,m}}{\mathrm{kgf\,s^2}}$$

$$1\,\mathrm{hyl} = 9.81\,\mathrm{kg}$$

[1]from German: Technische Masseneinheit

2.2.2 Example: Mass Unit Conversion

Consider a 200 grain bullet moving at 1000 ft/s. The momentum of the bullet is mass times velocity, mV. The mass of the bullet in EE, BG, and SI unit systems is:

$$200\,\text{grains} = 0.0286\,\text{lbm} = 8.882\times10^{-4}\,\text{slug} = 0.0130\,\text{kg}$$

The momentum of the bullet is:

$$g_c \times \text{momentum} = mV \equiv [\text{with units of force}\times\text{time; lbf s \ or \ N s}]$$

where the dimensional conversion constant is:

$$g_c = 32.2\,\frac{\text{lbm ft}}{\text{lbf s}^2} = 1\,\frac{\text{slug ft}}{\text{lbf s}^2} = 1\,\frac{\text{kg m}}{\text{N s}^2} = 1\,\frac{\text{lbm ft}}{\text{pdl s}^2} = 9.81\,\frac{\text{kg m}}{\text{kgf s}^2}$$

Using BGS (mass: slugs; force: lbf)

$$\left(8.882\times10^{-4}\,\text{slug}\right)(1000\,\text{ft/s}) = 0.888\,\frac{\text{slug ft}}{\text{s}}\cdot\frac{1}{1\,\text{slug ft/lbf s}^2} = 0.888\,\text{lbf s}$$

Using EES (mass: lbm; force: lbf)

$$(0.0286\,\text{lbm})(1000\,\text{ft/s}) = 28.6\,\frac{\text{lbm ft}}{\text{s}}\cdot\frac{1}{32.2\,\text{lbm ft/lbf s}^2} = 0.888\,\text{lbf s}$$

Using SI (mass: kg; force: N)

$$(0.0130\,\text{kg})(304.8\,\text{m/s}) = 3.96\,\frac{\text{kg m}}{\text{s}}\cdot\frac{1}{1\,\text{kg m/N s}^2} = 3.96\,\text{N s}$$

Using AE (mass: lbm; force: pdl)

$$(0.0286\,\text{lbm})(1000\,\text{ft/s}) = 28.6\,\frac{\text{lbm ft}}{\text{s}}\cdot\frac{1}{1\,\text{lbm ft/pdl s}^2} = 28.6\,\text{pdl s}$$

Table 2.2: Power of ten prefixes for engineering units

factor	prefix	symbol	mass	length	time	volume	pressure
10^{18}	exa	E					
10^{15}	peta	P					
10^{12}	tera	T					
10^{9}	giga	G					GPa
10^{6}	mega	M					MPa
10^{3}	kilo	k	kg	km			kPa
10^{2}	hecto	h					
10^{1}	deka	da					
$10^{0} = 1$							
10^{-1}	deci	d				dℓ	
10^{-2}	centi	c		cm			
10^{-3}	milli	m	mg	mm	ms	mℓ	
10^{-6}	micro	μ		μm	μs	$\mu\ell$	
10^{-9}	nano	n		nm	ns	nℓ	
10^{-12}	pico	p			ps	pℓ	
10^{-15}	femto	f		fm	fs		
10^{-18}	atto	a				aℓ	
other units							
10^{-8} cm = Angstrom, Å, å							

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