1 Introduction to Energy
1.1 What is Energy? ................................................. 2
1.2 Types of Energy .............................................. 3
1.3 Forms of Energy ............................................... 3
   1.3.1 Table of Energy Forms & Units ..................... 6
1.4 Measures of Energy - Units & Equivalences ............... 7
   1.4.1 Energy Scales ......................................... 8
   1.4.2 Energy Equivalences & Standard Values .......... 9

2 Energy Storage .................................................. 10
2.1 Discharge Time versus Power ............................... 12
2.2 Self-Discharge Time versus Power ....................... 13

3 Energy Conversion .............................................. 14
3.1 Conversion Processes ......................................... 14
   3.1.1 Energy Flow in an Internal Combustion Engine Vehicle ... 15
   3.1.2 Energy Conversion Matrix ............................ 16
3.2 Energy Balance ............................................... 17
   3.2.1 Steady Energy Balance ............................... 17
   3.2.2 First Law of Thermodynamics ...................... 18

4 Efficiency of Energy Conversion .............................. 19
4.1 Efficiency Definitions ...................................... 19
   4.1.1 Example 1-1. Solar Charging of Electric Vehicle .... 20
   4.1.2 Efficiency in Electrical Power Generation ........... 22
   4.1.3 Example 1-2. Coal Power Plant ..................... 23
   4.1.4 Carnot Efficiency .................................... 25
   4.1.5 Lighting Efficiency .................................. 26
   4.1.6 Annual Fuel Utilization Efficiency (AFUE) .......... 28
4.2 Serial Efficiency ............................................ 29
   4.2.1 Typical Conversion Efficiencies ...................... 30
   4.2.2 Example 1-3. Hybrid Motorbike .................... 31

References ................................................................ 33
Introduction to Energy

The goal 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?

What is Energy?

Energy is a universal concept that bridges all engineering and science disciplines.\(^1\); a unifying concept in physical sciences:

“notion of invariance or constancy in the midst of change.”\(^1\)

We can convert energy from one form to another (e.g., mechanical-to-electrical), but the total energy is always constant. Total energy is not the same as usable energy, which leads to the concept of conversion efficiency and entropy.

\(^1\)Mathematics is another universal concept in engineering and science.
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).

Transitional and stored energy are distinguished by whether or not an energy flux crosses a real or imaginary surface. This is typically the energy we associate with work and power (transitional energy/time). For example, current flow is a form of electrical energy/time is transitional. In contrast voltage, which is electrical potential expressed in volts, is a type of stored energy.

1. **Transitional:** energy in motion, energy which crosses system boundaries.
   - electrical current
   - work
   - heat
   - electromagnetic radiation

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), . . .

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.

Forms of Energy

Each form of energy is quantified using different units. These 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 transitory forms.

The choice of units is often dictated by convenience of calculation. For example, a common unit of electromagnetic energy is electronvolt (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 $2 \times 10^{-19}$ J.

**mechanical:** [ft-lbf, J], [hp, kW] 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].

**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.

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

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

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

**chemical**: \([\text{Btu/lbm}, \text{ Btu/lbmol}, \text{ kJ/kg}, \text{ kJ/kmol}]\) 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.

**thermal**: \([J, \text{ cal}, \text{ Btu}], \ [\text{kW}_t, \text{ Btu/hr}]\) 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 \([J, \text{ cal, Btu}]\) or power \([\text{kW}_t, \text{ Btu/hr}]\).

Stored thermal energy is sensible and latent heat and is expressed in units of energy per mass \([\text{Btu/lbm, kJ/kg}]\).

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>
<thead>
<tr>
<th>Energy Form &amp; Units</th>
<th>Energy Type</th>
<th>Transitional</th>
<th>Stored</th>
<th>Conversion</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Electrical</strong></td>
<td></td>
<td>electrical current</td>
<td>electrostatic field</td>
<td>- easy &amp; efficient conversion to mechanical and thermal energy</td>
</tr>
<tr>
<td>power: W, kW, MW</td>
<td></td>
<td>units of amperes [A]</td>
<td>inductive field</td>
<td>- easy, but less efficient conversion to electromagnetic and chemical energy</td>
</tr>
<tr>
<td>power-time: Wh, kWh</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Electromagnetic</strong></td>
<td></td>
<td>electromagnetic radiation</td>
<td>–</td>
<td>- easy to convert from, but generally inefficient</td>
</tr>
<tr>
<td>energy: eV, MeV</td>
<td></td>
<td></td>
<td></td>
<td>- photosynthesis is most common conversion process</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>- no known stored form (could it be nuclear?)</td>
</tr>
<tr>
<td><strong>Chemical</strong></td>
<td></td>
<td>–</td>
<td>chemical potential</td>
<td>- easily converted to thermal, electrical and mechanical energy</td>
</tr>
<tr>
<td>energy/mass: kJ/kg</td>
<td></td>
<td></td>
<td>(+) exothermic</td>
<td>- there is no known transitional form</td>
</tr>
<tr>
<td>energy/mole: kJ/kmol</td>
<td></td>
<td></td>
<td>(−) endothermic</td>
<td></td>
</tr>
<tr>
<td><strong>Nuclear</strong></td>
<td></td>
<td>–</td>
<td>atomic mass</td>
<td>- easily converted to mechanical energy, then into thermal energy</td>
</tr>
<tr>
<td>energy: MeV</td>
<td></td>
<td></td>
<td></td>
<td>- no known transitional form (could it be electromagnetic?)</td>
</tr>
<tr>
<td><strong>Mechanical</strong></td>
<td></td>
<td>work</td>
<td>potential energy</td>
<td>- easily converted to other forms of energy</td>
</tr>
<tr>
<td>energy: ft-lbf, J</td>
<td></td>
<td></td>
<td>position in force field</td>
<td></td>
</tr>
<tr>
<td>power: hp, kW, Btu/hr</td>
<td></td>
<td></td>
<td>• gravitational</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• inertial</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• compressed fluid</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• elastic-strain</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• magnetic field</td>
<td></td>
</tr>
<tr>
<td><strong>Thermal</strong></td>
<td></td>
<td>heat</td>
<td>sensible heat</td>
<td>- inefficient conversion to mechanical and electrical energy</td>
</tr>
<tr>
<td>energy: Btu, kJ, cal</td>
<td></td>
<td></td>
<td>latent heat</td>
<td>- conversion limited by 2nd law of thermodynamics</td>
</tr>
<tr>
<td>power: Btu/hr, W</td>
<td></td>
<td></td>
<td></td>
<td>- all other forms are easily converted into thermal energy</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>- thermal energy can be stored in everything</td>
</tr>
</tbody>
</table>
Measures of Energy - Units & Equivalences

There are numerous secondary units in the field of energy and power. Some of the secondary units, particularly in the British Gravitational (BG) and English Engineering (EE) unit systems, can be confusing. Below is a short list of secondary mass, energy, and power units.

British thermal unit [Btu]: energy required to raise the temperature of 1 lbm of water at 68 °F by 1 °F.
- \(1 \text{ Btu} \equiv 1055 \text{ J} \equiv 252 \text{ cal}\)
- \(1 \text{ Btu/s} \equiv 1.055 \text{ kW}\)
- \(1 \text{ Btu/hr} \equiv 0.2930711 \text{ W}\)
- \(1 \text{ therm} \equiv 100,000 \text{ Btu}\)
- \(1 \text{ quad} \equiv 10^{15} \text{ Btu}; \text{ note this is distinct from } Q \text{ sometimes used as } 10^{18} \text{ Btu}\)

Joule [J]: equivalent of 1 N of force exerted over a distance of 1 m.
- \(1 \text{ J} \equiv 0.2388 \text{ cal (IT)}\)
- \(1 \text{ J} = 1 \text{ N \cdot m} \equiv 6.242 \times 10^{18} \text{ eV} \equiv 0.737 \text{ ft \cdot lbf}\)
- \(1 \text{ J/s} = 1 \text{ W}\)
- \(1 \text{ kWh} = 3.6 \times 10^6 \text{ J} \equiv 3412 \text{ Btu}\)

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°.
- Calorie (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 able to raise 33,000 lbm by 1 ft in 1 minute.
- \(1 \text{ hp} \equiv 746 \text{ W}\)
- \(1 \text{ hp-hr} \equiv 2.68 \times 10^6 \text{ J} \equiv 0.746 \text{ kWh}\)

Mass, force, and volume: [kg, lbm, slug, mol, gallon, SCF, ton, tonne, lbf, N]
- \(1 \text{ lbm} \equiv 0.454 \text{ kg}\)
- \(1 \text{ slug} = 32.174 \text{ lbm} = 14.594 \text{ kg}\)
- \(1 \text{ lbm} = 7000 \text{ grains}\)
- \(1 \text{ standard ton (short ton)} = 2000 \text{ lbm} = 907.2 \text{ kg} = 0.9072 \text{ tonne}\)
- \(1 \text{ long ton} = 2240 \text{ lbm}\)
- \(1 \text{ tonne} = 1000 \text{ kg} = 2204 \text{ lbf}\)
- \(1 \text{ lbf} \equiv 4.448 \text{ N}\)
- \(1 \text{ imperial gallon} \equiv 1.200 \text{ U.S. gallon}\)
- \(112 \text{ lbm} \equiv 8 \text{ stone}\)
- \(20 \text{ hundred weight} = 100 \text{ lbf}\)

Proportionality constant: \(g_c\)
- \(g_c = 1 \text{ kg} \cdot \text{m}/\text{N} \cdot \text{s}^2 \equiv 1 \text{ slug} \cdot \text{ft}/\text{lbf} \cdot \text{s}^2 \equiv 32.2 \text{ lbm} \cdot \text{ft}/\text{lbf} \cdot \text{s}^2\)
Energy Scales

- Joules
- British thermal units
- Watt hours
- Electron volts
- Mass of matter converted to energy (grams)
- Sun’s daily output of energy = $3 \times 10^{32}$ J
- Earth’s KE of translation in its orbit = $2.57 \times 10^{34}$ J
- United States energy consumption in 1970 = $7.08 \times 10^{19}$ J
- Earth’s daily receipt of solar energy = $1.49 \times 10^{22}$ J
- Moon’s KE of translation in its orbit = $3.63 \times 10^{38}$ J
- Energy equivalent of 1 ton of TNT = $4.2 \times 10^9$ J
- Energy equivalent of 1 g of matter = $9 \times 10^{12}$ J
- World use of energy in 1950 = energy of a strong earthquake = $10^{20}$ J

Energy Equivalences & Standard Values

Standard U.S. Fuel Values:
Energy equivalence values for the United States Culp [2], American Physcial Society [3], Energy Information Agency [4]. The U.S. uses higher heating values (HHV) for energy content of fuels.

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

- anthracite: \( \text{HHV} = 12,700 \text{ Btu/lbm} = 29,540 \text{ kJ/kg} = 25.4 \times 10^6 \text{ Btu/short ton} \)
- bituminous: \( \text{HHV} = 11,750 \text{ Btu/lbm} = 27,330 \text{ kJ/kg} = 23.5 \times 10^6 \text{ Btu/short ton} \)
- lignite: \( \text{HHV} = 11,400 \text{ Btu/lbm} = 26,515 \text{ kJ/kg} = 22.8 \times 10^6 \text{ Btu/short ton} \)
- 2007 average: \( \text{HHV} = 20.24 \times 10^6 \text{ Btu/short ton} \)

1 tonne of coal \( \equiv 7 \times 10^9 \text{ cal} \)
\( \equiv 29.3 \text{ GJ} \equiv 27.8 \text{ MBtu} \)
1 ton of coal \( \equiv 26.6 \text{ GJ} \equiv 25.2 \text{ MBtu} \)

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

nominal equivalence: \( \text{HHV} = 18,100 \text{ Btu/lbm} = 42,100 \text{ kJ/kg} = 138,100 \text{ Btu/U.S. gal} \)

1 bbl crude oil \( \equiv 5.80 \text{ MBtu} \equiv 6.12 \text{ GJ} \)
\( \equiv 460 \text{ lbm of coal} \)
\( \equiv 5680 \text{ SCF of natural gas} \)
\( \equiv 612 \text{ kWh of electricity (at } \eta_{th} = 36\% \) \)

1 tonne crude oil \( 39.68 \text{ MBtu} \equiv 41.87 \text{ GJ} \)

1 million bbl/day (Mbd) \( \equiv 2.12 \text{ quad/yr} \approx 2 \text{ quad/yr} \)

**Natural Gas:** mostly CH\(_4\); energy content varies between 900 - 1100 Btu/scf

nominal equivalence: \( \text{HHV} = 24,700 \text{ Btu/lbm} = 57,450 \text{ kJ/kg} = 1,021 \text{ Btu/scf} \)

2007 average (dry): \( \text{HHV} = 1,028 \text{ Btu/scf} \)

typical equivalence: \( \text{HHV} \approx 1,000 \text{ Btu/scf} \equiv 1.055 \text{ GJ/SCF} \)
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 $10^9 \text{kJ}$, or 21,142 kg of gasoline (46,610 lbm = 23.5 tons). If the nuclear energy stored as mass were used instead of chemical energy, then only 0.1 $\mu$g ($2.5 \times 10^{-7}$ 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
Comparison of energy storage technologies. Electricity Storage Association [5]

<table>
<thead>
<tr>
<th>Storage Technologies</th>
<th>Main Advantages (Relative)</th>
<th>Disadvantages (Relative)</th>
<th>Power Application</th>
<th>Energy Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pumped Storage</td>
<td>High Capacity, Low Cost</td>
<td>Special Site Requirement</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CAES</td>
<td>High Capacity, Low Cost</td>
<td>Special Site Requirement, Need Gas Fuel</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flow Batteries: PSB, URB, ZnBr</td>
<td>High Capacity, Independent Power and Energy Ratings</td>
<td>Low Energy Density</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Metal-Air</td>
<td>Very High Energy Density</td>
<td>Electric Charging is Difficult</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NaS</td>
<td>High Power &amp; Energy Density, High Efficiency</td>
<td>Production Cost, Safety Concerns (addressed in design)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Li-ion</td>
<td>High Power &amp; Energy Density, High Efficiency</td>
<td>High Production Cost, Requires Special Charging Circuit</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NiCd</td>
<td>High Power &amp; Energy Density, Efficiency</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other Advanced Batteries</td>
<td>High Power &amp; Energy Density, High Efficiency</td>
<td>High Production Cost</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lead-Acid</td>
<td>Low Capital Cost</td>
<td>Limited Cycle Life when Deeply Discharged</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flywheels</td>
<td>High Power</td>
<td>Low Energy Density</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SMES, DSMES</td>
<td>High Power</td>
<td>Low Energy Density, High Production Cost</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E.C. Capacitors</td>
<td>Long Cycle Life, High Efficiency</td>
<td>Low Energy Density</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Discharge Time versus Power

Self-Discharge Time versus Power

Self-discharge time of energy storage systems. Goswami and Kreith [6]

energy storage technologies mapped by unit size and self-discharge time
Energy Conversion

Conversion Processes

**Direct**: Single-step conversion process

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

**Indirect**: Multi-step conversion process

- Diesel cycle (gas): chemical $\rightarrow$ thermal $\rightarrow$ mechanical $\rightarrow$ mechanical
- Rankine cycle (liquid-vapor), steam turbine:
  - chemical nuclear solar geothermal $\rightarrow$ thermal $\rightarrow$ mechanical $\rightarrow$ electrical
- Brayton cycle (gas), gas turbine, turbojets:
  - chemical nuclear solar $\rightarrow$ thermal $\rightarrow$ mechanical $\rightarrow$ electrical
- (wind turbine wave energy tidal energy) mechanical $\rightarrow$ mechanical $\rightarrow$ mechanical $\rightarrow$ electrical
Energy Flow in an Internal Combustion Engine Vehicle

- **Fuel**: Chemical
  - **Combustion**: Mechanical
    - **Piston**, **Crank**, **Flywheel**
  - **Thermal**
    - **Radiator**, **Exhaust**
- **Battery**: Chemical
  - **Current**
- **Engine**: Mechanical
  - **Combustion**
  - **Thermal**
    - **Radiator**, **Exhaust**
- **Drive Train**: Mechanical
  - **Transmission**, **Differential**
- **Wheels**: Mechanical
- **Engine Aux.**: Mechanical
  - **Water Pump**, **Oil Pump**
- **Electrical System**: Electrical
  - **Alternator**, **Control Module**
- **Auxiliary Systems**
  - **Electrical**
    - **Radio**, **Computer**, **Sensors**
  - **Mechanical**
    - **Fuel Pump**, **Power Windows**, **Windshield Wipers**
  - **Thermal**
    - **Electric Seats**, **Window Defroster**
  - **Electromagnetic**
    - **GPS**, **Satellite Radio**
## Energy Conversion Matrix

<table>
<thead>
<tr>
<th>FROM</th>
<th>Mechanical energy</th>
<th>Potential energy</th>
<th>Thermal energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Work</td>
<td>—</td>
<td>Impulse and momentum changes (turbine blades?)</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>Inertial field (kinetic) energy</td>
<td>Falling weight hydraulic turbine(s)</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>Gravitational field energy</td>
<td>Springs</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>Elastic strain energy</td>
<td>Bellows</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>Compressed fluid energy</td>
<td>Air motors</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>Flywheel</td>
<td>Linear acceleration</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>Dropping weight</td>
<td>Catapult</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>Nozzle</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Mechanical energy</td>
<td>Raise weight</td>
<td>Rocket</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>Spring-weight systems</td>
<td>Upward nozzle</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>Hydraulic lift &amp; jack</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>Board-on-tube gauge Strain gauge</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>Diffuser</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>Piston in cylinder</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>Magnetic field energy</td>
<td>Pull ferromagnetic materials from magnetic poles</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>Fluid heating</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>Electron flow through an inductor</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>Use of magnets in small motors and generators</td>
<td>Photovoltaic</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>Solar cell</td>
<td>Battery</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>Nuclear battery</td>
<td>Thermoelectricity</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>Thermodynamic energy</td>
<td>Waste</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>Waste</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>Nuclear energy</td>
<td>Radioactivity</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>Heat</td>
<td>Radiation damage</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>Friction</td>
<td>Sensible heat</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>Frictional impact</td>
<td>Latent heat</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>Friction</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>Plastic flow</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>Unrestricted expansion</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>Internal energy</td>
<td>Conduction</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>Compression Friction</td>
<td>Convection</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>Diffuser</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>Friction</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>Friction</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>Plastic flow</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>Friction</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

---

**Energy Balance**

*Closed System* – no mass flow in or out of system

*Open System* – mass flow in and/or out of system

**Steady Energy Balance**

For a steady-state, open system:

\[ \Delta Q - \Delta W = \Delta E = (E_p + E_k + E_i + E_f)_{\text{out}} - (E_p + E_k + E_i + E_f)_{\text{in}} \]

- \( \Delta Q \): heat into system
- \( \Delta W \): work produced by system
- \( \Delta E \): change in system energy
- \( E_p \): potential energy = \( mzg/g_c \)
- \( E_k \): kinetic energy = \( mV^2/2g_c \)
- \( E_i \): internal energy = \( mu \)
- \( E_f \): flow energy = \( P\dot{V} = mP/\rho \)

This is the first law of thermodynamics, which is really:

change in transitional energy \( \iff \) change in stored energy

**Steady** implies that there is no energy or mass accumulation within the system. That is different than the exchange of energy in the mass which passes through the system. The mass which passes through may accumulate energy.

*The 1st Law of Thermodynamics applies to the fluid!*
First Law of Thermodynamics

Steady, rate form of the 1st Law:

\[ \sum Q - \sum W = \sum_{\text{out}} m - \sum_{\text{in}} m \]  

(1)

Heat (\(\dot{Q}\)) & Work (\(\dot{W}\))

Not the same as useful heat and work

Heat and work are balanced by changes in stored energy in the fluid.

The sign convention on heat (\(Q\)) and work (\(W\)) may change. For example, some thermodynamic textbooks will write the first law of thermodynamics (equation 1) as \(\Delta Q + \Delta W\), in which case \(\Delta W\) is the work into the system. The choice of sign convention will vary between engineering disciplines as well. It is not important which sign convention you use as long as you are consistent. The meaning of a positive or negative work can always be ascertained by examining how the stored energy term (\(\Delta E\)) changes.
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.

\[
\text{efficiency, } \eta \equiv \frac{\text{energy sought}}{\text{energy cost}}
\]

Efficiency Definitions

- **combustion**:  
  \[
  \eta = \frac{Q}{HV} \equiv \frac{\text{heat released}}{\text{heating value of fuel}}
  \]

- **heat pump**:  
  \[
  \text{COP} \equiv \frac{Q_H}{W_C} \equiv \frac{\text{heat into hot reservoir}}{\text{compressor work}}
  \]

- **refrigeration**:  
  \[
  \text{COP} \equiv \frac{Q_C}{W_C} \equiv \frac{\text{heat from cold reservoir}}{\text{compressor work}}
  \]

- **alternator**:  
  \[
  \eta = \frac{\dot{W}_e}{\dot{W}_m} \equiv \frac{\text{electrical energy out}}{\text{mechanical energy in}}
  \]

- **battery**:  
  \[
  \eta = \frac{\dot{W}_e}{\dot{W}_c} \equiv \frac{\text{electrical energy out}}{\text{chemical energy in}}
  \]

- **IC engine**:  
  \[
  \eta = \frac{\dot{W}_m}{\dot{W}_c} \equiv \frac{\text{mechanical energy out}}{\text{chemical energy in}}
  \]

- **automotive transmission**:  
  \[
  \eta = \frac{\dot{W}_m}{\dot{W}_m} \equiv \frac{\text{mechanical energy out}}{\text{mechanical energy in}}
  \]

- **electrical transmission**:  
  \[
  \eta = \frac{\dot{W}_e}{\dot{W}_c} \equiv \frac{\text{electrical energy out}}{\text{electrical energy in}}
  \]
**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}/m². 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:

$$\frac{650 \text{ W}_{em}}{\text{m}^2} \left[ 1 + \frac{0.60 \frac{\text{W}_{out}}{\text{W}_{in}}}{1} \cdot 4 \right] = \frac{2210 \text{ W}_{em}}{\text{m}^2}$$

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

$$\left( 24 \text{ hp}_{em} \right) \left( \frac{745.7 \text{ W}_{em}}{\text{hp}_{em}} \right) \left( \frac{\text{m}^2}{2210 \text{ W}_{em}} \right) = 8.1 \text{ m}^2$$

This area, 8 m², 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%. Thus, the area required to generate 24 hp_{m} from 650 W_{em}/m² is:

$$8.1 \text{ m}^2 \left( \frac{\text{W}_{em}}{0.13 \text{ W}_{m}} \right) = 62.3 \text{ m}^2$$
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."

\[ w_{\text{dot\_em}} = 650 \text{ [W/m}^2\text{]} \]
\[ W_{\text{dot\_hp}} = 24 \text{ [hp]} \]
\[ \eta_{\text{system}} = 0.13 \]
\[ \eta_{\text{storage}} = 0.60 \]
\[ t_{\text{moving}} = 1 \text{ [hr]} \]
\[ t_{\text{sitting}} = 4 \text{ [hr]} \]
\[ dt = 1 \text{ [hr]} \]

"total energy collected per area"
\[ e_{\text{moving}} = w_{\text{dot\_em}} \cdot t_{\text{moving}} \]
\[ e_{\text{sitting}} = w_{\text{dot\_em}} \cdot t_{\text{sitting}} \cdot \eta_{\text{storage}} \]

"on a per hour basis, the solar power per area collected is"
\[ w_{\text{dot\_em\_collected}} = \frac{e_{\text{moving}} + e_{\text{sitting}}}{dt} \]

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

"convert horsepower into Watts"
\[ c = \text{convert(hp,W)} \]
\[ W_{\text{dot}} = c \cdot W_{\text{dot\_hp}} \]
\[ W_{\text{dot}} = w_{\text{dot\_em\_collected}} \cdot \text{Area\_ideal} \]

"The conversion efficiency from electromagnetic (em) to mechanical work (m) is only 13%." 
\[ \eta_{\text{system}} = \frac{\text{Area\_ideal}}{\text{Area\_actual}} \]

"eof"

**SOLUTION**

**Unit Settings**: SI C kPa kJ mass deg 
\[ A_{\text{Actual}} = 62.29 \text{ [m}^2\text{]} \]
\[ A_{\text{Ideal}} = 8.098 \text{ [m}^2\text{]} \]
\[ c = 745.7 \text{ [W/hp]} \]
\[ dt = 1 \text{ [hr]} \]
\[ e_{\text{moving}} = 650 \text{ [W-hr/m}^2\text{]} \]
\[ e_{\text{sitting}} = 1560 \text{ [W-hr/m}^2\text{]} \]
\[ \eta_{\text{storage}} = 0.6 \]
\[ \eta_{\text{system}} = 0.13 \]
\[ t_{\text{moving}} = 1 \text{ [hr]} \]
\[ t_{\text{sitting}} = 4 \text{ [hr]} \]
\[ w_{\text{em}} = 650 \text{ [W/m}^2\text{]} \]
\[ w_{\text{em\_collected}} = 2210 \text{ [W-hr/m}^2\text{]} \]
\[ W = 17897 \text{ [W]} \]
\[ Whp = 24 \text{ [hp]} \]
Efficiency in Electrical Power Generation

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

- **Power Density**: power per unit volume \([\text{kW/m}^3]\)
- **Specific Power**: power per unit mass \([\text{kW/kg}]\)
- **Electric Power Output**: \(\text{Power} \times \text{time} \ [\text{kW} \cdot \text{h}]\)
- **Rated Power**: power output of a plant at nominal operating conditions

**Performance Factors:**

- **Heat Rate (HR)**: thermal Btu’s required to produce 1 kW\(_t\)h of electricity \([\text{Btu}_t/\text{kW}_e \cdot \text{h}]\)
  \[
  3412 \text{ Btu} = 1 \text{kW}_t \cdot \text{h}
  \]
  \[
  \eta = \frac{\text{electrical energy produced}}{\text{thermal energy consumed}} \text{ of the cycle} \left[\frac{\text{kW}_e}{\text{kW}_t}\right]
  \]
  \[
  \text{Heat Rate} = \frac{3412}{\eta}
  \]

- **Capacity Factor (CF)**: \(\frac{\text{average power}}{\text{rated power}}\) 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** = \(\frac{\text{average power}}{\text{maximum power}}\) per a specific time period

- **Availability Factor** = fraction of time period that power generation system is available

- **Unit Fuel Cost** = \(\frac{(\text{fuel cost})(\text{heat rate of plant})}{\text{efficiency}}\)
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.

\[ \eta_{th} = \frac{3412}{10,663} \text{Btu/kWh} = 0.32 \text{kWe/kWth} \]

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

\[ Q_{in} = \frac{W_{out}}{\eta_{th}} = \frac{300 \text{MW_e}}{0.32 \text{MW_e/MW_th}} = 937.5 \text{MW_th} = m_{coal} \cdot \text{HV} \]

\[ m_{coal} = \frac{937.5 \text{MW_th}}{28,000 \text{kJ/kg}} = \frac{(937.5 \cdot 10^6 \text{W_th}) (\text{J/s/W})}{28 \cdot 10^6 \text{J/kg}} = 33.48 \text{kg/s} \]

\[ m_{coal} \text{ day} = 2.86 \cdot 10^6 \text{kg/day} \]

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

\[ m_{air} = m_{coal} \cdot \text{AF} = (33.48 \text{kg_coal/s}) \left( \frac{12 \text{kg_air}}{1 \text{kg_coal}} \right) = 401.8 \text{kg_air/s} \]
Example 1-2 in EES

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?

\[ W_{\text{dot, e}} = 300000 \text{ [kW]} \]
\[ \text{HR} = 10663 \]
\[ \text{HV} = 12040 \]
\[ \text{AF} = 12 \]

"(a) The thermal efficiency can be determined from the Heat Rate."
\[ \text{HR} = \frac{3412}{\eta_{\text{th}}} \]

"The amount of fuel consumed is proportional to the heat input."
\[ \eta_{\text{th}} = \frac{W_{\text{dot, e}}}{Q_{\text{dot, th}}} \]
\[ Q_{\text{dot, th}} = m_{\text{dot, fuel}} \times \text{HV} \]

"\( Q_{\text{dot, th}} \) has units of kW and heating value has units of Btu/lbm. If we don’t convert one of these two, the \( m_{\text{dot, fuel}} \) will have units of lbm kW/Btu."

"Redefine the Heating Value as kJ/kg: 2.326 kJ/kg = 1 Btu/lbm."
\[ \text{HV}_{\text{si}} = \text{HV} \times 2.326 \]

"Now, the mass rate should be in kg/s."
\[ Q_{\text{dot, th}} = m_{\text{dot, fuel, si}} \times \text{HV}_{\text{si}} \]

"(b) Over a 24-hour period, the mass of fuel used is:"
\[ m_{\text{fuel, day}} = m_{\text{dot, fuel, si}} \times 3600 \times 24 \]

"(c) The rate of air flow is determined by the air-fuel ratio."
\[ \text{AF} = \frac{m_{\text{dot, air}}}{m_{\text{dot, fuel, si}}} \]

SOLUTION

Unit Settings: SI C kPa kJ mass deg
\[ \text{AF} = 12 \text{ [kg} \text{air/kgfuel]} \]
\[ \eta_{\text{th}} = 0.32 \]
\[ \text{HR} = 10663 \text{ [Btu/hr/kWe]} \]
\[ \text{HV} = 12040 \text{ [Btu/lbm]} \]
\[ \text{HV}_{\text{si}} = 28005 \text{ [kJ/kg]} \]
\[ m_{\text{air}} = 77.87 \text{ [Btu/hr]} \]
\[ m_{\text{fuel, si}} = 33.48 \text{ [kg/s]} \]
\[ m_{\text{fuel}} = 2.892 \times 10^6 \text{ [kg]} \]
\[ W_{\text{e}} = 300000 \text{ [kW]} \]
\[ \dot{Q}_{\text{th}} = 937544 \text{ [kW]} \]
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.

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

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%.
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 it produces \(4\pi\) 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.

\[
1 \text{ lux} = 1 \text{ lumen/m}^2 \\
1 \text{ foot-candle} = 1 \text{ lumen/ft}^2
\]
The efficacy of a light source, or lighting efficiency, is defined as the light output in lumens per power input in watts.\textsuperscript{3}  

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

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.

Typical efficiencies of several illumination sources \[7, 8, 9\]:

<table>
<thead>
<tr>
<th>light source</th>
<th>efficiency</th>
<th>lamp with ballast</th>
<th>rated hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>sunlight</td>
<td>92 lm/Wt</td>
<td></td>
<td></td>
</tr>
<tr>
<td>open gas flame, candle</td>
<td>0.15-0.20 lm/Wt</td>
<td></td>
<td></td>
</tr>
<tr>
<td>incandescent</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- small (flashlight, nightlight, . . . )</td>
<td>5-6 lm/Wt</td>
<td></td>
<td></td>
</tr>
<tr>
<td>40 W</td>
<td>12 lm/Wt</td>
<td></td>
<td>750-1000</td>
</tr>
<tr>
<td>100 W</td>
<td>18 lm/Wt</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- tungsten-halogen</td>
<td>18-24 lm/Wt</td>
<td></td>
<td>2000-3000</td>
</tr>
<tr>
<td>- tungsten-halogen-infrared reflector (HIR)</td>
<td>7 lm/Wt</td>
<td></td>
<td>3000-4000</td>
</tr>
<tr>
<td>fluorescent</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- standard (tubular)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20 W (+13 W), 24&quot;</td>
<td>65 lm/Wt</td>
<td>39 lm/Wt</td>
<td>15 000-20 000</td>
</tr>
<tr>
<td>40 W (+13.5 W), 48&quot;</td>
<td>79</td>
<td>59</td>
<td></td>
</tr>
<tr>
<td>75 W (+11 W), 96&quot;</td>
<td>84</td>
<td>73-90</td>
<td></td>
</tr>
<tr>
<td>- compact fluorescence (CFI)</td>
<td>40-70</td>
<td>??</td>
<td>6000-10 000</td>
</tr>
<tr>
<td>high-intensity discharge (HID)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- mercury vapor</td>
<td>57</td>
<td>53.5</td>
<td>24 000</td>
</tr>
<tr>
<td>- metal halide 400 W (+13 W)</td>
<td></td>
<td></td>
<td>45-100</td>
</tr>
<tr>
<td>- high pressure sodium</td>
<td></td>
<td></td>
<td>45-110</td>
</tr>
<tr>
<td>- low-pressure sodium (not HID)</td>
<td></td>
<td></td>
<td>80-160</td>
</tr>
<tr>
<td>light emitting diode (LED)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- white, 3-10 W/unit</td>
<td>30</td>
<td>??</td>
<td>6000 - 50 000</td>
</tr>
</tbody>
</table>

\textsuperscript{3} 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.
Annual Fuel Utilization Efficiency (AFUE)

Annual Fuel Utilization Efficiency (AFUE): accounts for combustion efficiency, heat losses, and startup/shutdown losses on an annualized basis.

- older heating systems $\leq 60\%$
- newer heating systems $\sim 85\%$
- high efficiency furnaces $\sim 96\%$

The very high efficiency is due to 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.
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.

\[
\eta_1 = \frac{\text{energy out}}{\text{energy in}} = \frac{E_1}{E_0} \quad \text{Thus, } E_1 = \eta_1 \cdot E_0
\]

and \( E_2 = \eta_2 \cdot E_1 = \eta_2 \cdot \eta_1 \cdot E_0 \)

Finally, \( E_3 = \eta_3 \cdot \eta_2 \cdot \eta_1 \cdot E_0 = E_0 \cdot \Pi \eta_n \)
Typical Conversion Efficiencies

from *Principles of Energy Conversion, 2nd ed.* [2]
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 \rightarrow generator \rightarrow motor \rightarrow wheels

2 \text{hp}_m \rightarrow \text{generator} \rightarrow 2 \text{hp}_m \left(\frac{0.60 \text{hp}_e}{\text{hp}_m}\right) = 1.2 \text{hp}_e

1.2 \text{hp}_e \rightarrow \text{drive motor} \rightarrow 1.2 \text{hp}_e \left(\frac{0.50 \text{hp}_m}{\text{hp}_e}\right) = 0.6 \text{hp}_m

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

\text{system efficiency when starting with the fuel!} = \left(\frac{0.25 W_m}{W_c}\right) \left(\frac{0.60 W_e}{W_m}\right) \left(\frac{0.50 W_m}{W_e}\right) = 7.5\% \frac{W_m}{W_c}

(b) engine \rightarrow generator \rightarrow \text{motor} \rightarrow \text{wheels}

\rightarrow \text{battery}

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

\eta_{\text{system}} = 5.6\% \frac{W_m}{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.

\[
\eta_{\text{eng}} = 0.25 \quad \text{"engine efficiency"}
\]
\[
\eta_{\text{gen}} = 0.60 \quad \text{"generator efficiency"}
\]
\[
\eta_{\text{mot}} = 0.50 \quad \text{"motor efficiency"}
\]
\[
\eta_{\text{bat}} = 0.75 \quad \text{"battery efficiency"}
\]

\[
W_{\text{dot,mot}} = 2 \; [\text{hp}] \quad \text{"output of motor"}
\]

"(a) bypassing battery system"

\[
W_{\text{dot,\;wheels\;a}} = W_{\text{dot,mot}} \times \eta_{\text{gen}} \times \eta_{\text{mot}}
\]

"(b) using battery system"

\[
W_{\text{dot,\;wheels\;b}} = W_{\text{dot,mot}} \times \eta_{\text{gen}} \times \eta_{\text{bat}} \times \eta_{\text{mot}}
\]

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

\[
\eta_a = \eta_{\text{eng}} \times \eta_{\text{gen}} \times \eta_{\text{mot}}
\]
\[
\eta_b = \eta_{\text{eng}} \times \eta_{\text{gen}} \times \eta_{\text{bat}} \times \eta_{\text{mot}}
\]

"eof"

SOLUTION

Unit Settings: SI C kPa kJ mass deg

\[
\eta_a = 0.075 \quad \eta_b = 0.05625
\]
\[
\eta_{\text{bat}} = 0.75 \quad \eta_{\text{eng}} = 0.25
\]
\[
\eta_{\text{mot}} = 0.5
\]
\[
W_{\text{mot}} = 2 \; [\text{hp}]
\]
\[
W_{\text{wheels,a}} = 0.6 \; [\text{hp}]
\]
\[
W_{\text{wheels,b}} = 0.45 \; [\text{hp}]
\]
References


