Chapter 1 Energy and Power, and the Physics of Explosions

Energy is the ability to do work.

(Work is defined numerically as the magnitude of a force multiplied by the amount the force moves in the direction of the force.)

Alternative definition for Energy: anything that can be turned into heat. Heat is something that raises the temperature of a material, as measured by a thermometer.
Kinds of energy

Kinetic Energy or energy of motion –

$$K = \frac{1}{2} mv^2 \quad 1 \text{ Joule} = 1 \text{ kg-m}^2/\text{s}^2$$

Potential Energy - invisible energy stored in the force fields between interacting particles. Example: lifting a mass off the ground requires work and creates potential energy. Releasing object permits the stored energy to appear as visible kinetic energy.

Radiation – freely moving wave light force fields such as electromagnetic infrared, light, UV and gravitational waves

Heat – a mixture of microscopic incoherent kinetic and potential and radiation fields at the atomic scale
Calorie, Joule, and kilowatt-hour

International energy unit – 1 joule = 1 kg m²/s²

Unit of food equivalent energy -1 (kg) Calorie = 1000 (gm) calorie = 1 kcal (sometimes Calorie is called calorie not Calorie, this is quite confusing)

1 kcal = energy to raise the temperature of 1 kg of water by 1 degree C
1 (gm) cal = energy to raise the temperature of 1 kg of water by 1 degree C

Conversion factor
1 (gm) cal = 4.18 joules , 1 (kg) cal = 1 kcal = 4.18 kJ

Electrical unit -1 kilowatt-hour= 1 kJoule per s times 3600 s = 3600 kJoules
1 (gm) cal = 1.163 x 10⁻⁶ kW-h
Conversion of units

A package of cookies says it contains 20 servings and each serving is two cookies and each serving contains 400 (food) Calories. How many kilojoules does each cookies supply?

\[
\frac{400 \text{ Cal}}{\text{serving}} \times \frac{1 \text{ serving}}{2 \text{ cookies}} \times \frac{4.2 \text{ kJ}}{1 \text{ Cal}} = 840 \frac{\text{kJ}}{\text{cookie}}
\]

\[
1 \text{ W} = 1 \frac{j}{s} \times \frac{1 \text{ (gm)cal}}{4.18 j} \times \frac{1 \text{ kcal}}{1000 \text{(gm)cal}} \times \frac{3600 \text{ s}}{1 \text{ hour}} = 0.86 \frac{\text{kcal}}{\text{hour}}
\]
Accuracy

In this text and in our work, we are interested in the magnitude of quantities and important factors, not accuracy.

So we use approximations like

3.1459 = 3

1 m = 39.27 in = 36 in = 3 ft
Energy use example

Humans “consume” energy. More accurately, we transform it. At the most basic level, we eat food to power our bodies into motion and make up for heat loss to radiation from our bodies.

1 gm of a chocolate chip cookie = 21,000 joules = 5 kcal

40 gm cookie = 200 kcal = 840 kJ
= energy of 1,680,000 kg moving at 1 m/s
= potential energy of 100 kg at height of 840 m = 2500 ft

Efficiency of converting combustible food energy to mechanical energy via muscles is about 20%. One cookie can in fact only power yourself up a 2,500/5 = 500 ft hill.


A typical adult at rest burns 50 kcal/hr or 500 Watts or 1200 kcal/day. This is the energy radiated as body heat. Activity adds to the requirements.

1 W mechanical work at 20% efficiency requires 5 W food energy or 4.3 kcal/hr
## Energy density in various substances

### Energy per gram

<table>
<thead>
<tr>
<th>object</th>
<th>Calories (or Watt-hours)</th>
<th>joules</th>
<th>compared to TNT</th>
</tr>
</thead>
<tbody>
<tr>
<td>bullet (at sound speed, 1000 ft per sec)</td>
<td>0.01</td>
<td>40</td>
<td>0.015</td>
</tr>
<tr>
<td>battery (auto)</td>
<td>.03</td>
<td>125</td>
<td>0.05</td>
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<td>battery (rechargeable computer)</td>
<td>0.1</td>
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<td>0.15</td>
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<tr>
<td>battery (alkaline flashlight)</td>
<td>0.15</td>
<td>600</td>
<td>0.23</td>
</tr>
<tr>
<td>TNT (the explosive trinitrotoluene)</td>
<td>0.65</td>
<td>2,723</td>
<td>1</td>
</tr>
<tr>
<td>modern High Explosive (PETN)</td>
<td>1</td>
<td>4200</td>
<td>1.6</td>
</tr>
<tr>
<td>chocolate chip cookies</td>
<td>5</td>
<td>21,000</td>
<td>8</td>
</tr>
<tr>
<td>coal</td>
<td>6</td>
<td>27,000</td>
<td>10</td>
</tr>
<tr>
<td>butter</td>
<td>7</td>
<td>29,000</td>
<td>11</td>
</tr>
<tr>
<td>alcohol (ethanol)</td>
<td>6</td>
<td>27,000</td>
<td>10</td>
</tr>
<tr>
<td>gasoline</td>
<td>10</td>
<td>42,000</td>
<td>15</td>
</tr>
<tr>
<td>natural gas (methane, CH₄)</td>
<td>13</td>
<td>54,000</td>
<td>20</td>
</tr>
<tr>
<td>hydrogen gas or liquid (H₂)</td>
<td>26</td>
<td>110,000</td>
<td>40</td>
</tr>
<tr>
<td>asteroid or meteor (30 km/sec)</td>
<td>100</td>
<td>450,000</td>
<td>165</td>
</tr>
<tr>
<td>uranium-235</td>
<td>20 million</td>
<td>82 billion</td>
<td>30 million</td>
</tr>
</tbody>
</table>

Note: nuclear energy density = 1 million times chemical energy density
Power

Power = rate of change of energy
1 Watt = 1 Joule/s

Examples:
Toaster – 1 kW = 1000 Joules/s of electrical energy converted to thermal radiant energy

Laser pointer – 1 mW = 1/1000 Joules/s of electrical energy converted to single color light plus heat

Human metabolic heat = roughly 50-100 W like a 50-100 W light bulb
Surprises

TNT has 8 times less energy per gm than a cookies but releases its energy quickly (explosively)
Cookies have 4 times the energy density of gasoline (YUM!)
Batteries have a very low energy storage capacity (yuck)
Explosive energy release

Explosion = rapid uncontrolled energy release. TNT (trinitrotoluene) = 0.65 Cal/gm in ms

Nuclear energy is roughly 1,000,000 times as energetic per particle as chemical energy. Ur (235) = 20,000,000 Cal/gm in a “flash”
Energy in a meteor

Let a 30 m (98 ft) diameter iron body weighing about 200,000 metric tons (around 440 million pounds) strike Earth at a typical, in-space velocity of 30 km (19 mi/s) per s. This impact would generate about 20 megatons (TNT-equivalent) of energy (about $10^{17}$ joules) that would cut out a crater about a kilometer and a half (almost a mile) wide and 185 m (607 ft) deep. This is the size of Meteor (Barringer) Crater.

That is about the size of the largest nuclear weapon ever tested.

The US has 530 ICBMs with 335 kT yield of 177 MT, about 8 Barringer Craters worth, and a similar number of SLBMs.
Meteors vs nuclear weapons

All nuclear weapons detonated in one place would make one Zhamanshin crater.
Russia plans space project to prevent asteroid collision

Russia is considering a project to launch a spaceship to try to divert a large asteroid from hitting Earth after 2030, the head of the country's space program said today.

Anatoly Perminov, head of Roscosmos, tells Voice of Russia radio that Moscow may invite experts from Europe, the United States and China to join the project aimed at thwarting the menacing asteroid Apophis.

"People's lives are at stake. We should pay several hundred million dollars and design a system that would prevent a collision, rather than sit and wait for it to happen and kill hundreds of thousands of people," Perminov says, according to RIA Novosti news agency.
Importance of energy

Energy flow drives life.

Energy can destroy life too.

Kinetic energy in coherent motion of a macroscopic object KE = (1/2) m v^2 is tangible. Energy has also invisible forms.

The good news: Energy is all around us and is conserved. The bad news: Not all energy is available to be used/transformed.

How can we understand it and use it wisely?
An energy technology

When hydrogen and oxygen combine to form H₂O (Water), energy is released.

We have seen an explosive energy release when we ignited a mixture of hydrogen and oxygen gas in a balloon.

The reverse process is possible.

Electrolysis is used to crack water into hydrogen gas +oxygen gas.

Electrical energy is transformed into chemical energy – energy is “stored.”
Fuel cells

A fuel cell combine hydrogen and oxygen to form water releasing energy in a **controlled** manner.
Hydrogen as a means of transporting energy

Hydrogen and oxygen can be manufactured, stored, and combined to release energy. Research topic: what kinds of fuel cells might be used to power vehicles?

Uranium, gasoline, and TNT

The amount of energy in U-235 is 30 million times that of the energy found in TNT.

Think of nuclear reactions as ultra-strong chemical reactions.

In chemical reactions, electrons bound in atoms by electric forces are rearranged.

In nuclear reactions, nucleons (protons and neutrons) bound by ultra-strong nuclear forces are rearranged.
Energy costs

<table>
<thead>
<tr>
<th>fuel</th>
<th>market cost</th>
<th>cost per kWh (1000 Cal)</th>
<th>cost if converted to electricity</th>
</tr>
</thead>
<tbody>
<tr>
<td>coal</td>
<td>$40 per ton</td>
<td>0.4¢</td>
<td>1.2¢</td>
</tr>
<tr>
<td>natural gas</td>
<td>$10 per million cubic feet</td>
<td>3¢</td>
<td>9¢</td>
</tr>
<tr>
<td>gasoline</td>
<td>$3 per gallon</td>
<td>9¢</td>
<td>27¢</td>
</tr>
<tr>
<td>electricity</td>
<td>$0.10 per kWh</td>
<td>10¢</td>
<td>10¢</td>
</tr>
<tr>
<td>car battery</td>
<td>$50 to buy battery</td>
<td>21¢</td>
<td>21¢</td>
</tr>
<tr>
<td>computer battery</td>
<td>$100 to buy battery</td>
<td>$4.00</td>
<td>$4.00</td>
</tr>
<tr>
<td>AAA battery</td>
<td>$1.50 per battery</td>
<td>$1000.00</td>
<td>$1000.00</td>
</tr>
</tbody>
</table>

The commercial cost of energy is an important consideration. The world has vast supplies of cheap (but dirty) coal.
Energy conservation

Should you turn the lights of when you leave your house?
Energy conservation

Should you turn the lights off when you leave your house?

Depends on the season and how you heat and cool your home what your concern might be.

The energy of the lights ALL goes to heat your home – directly as heat and indirectly as light that converts to heat. So you save on your heating requirements in the winter but lose in the summer if you use air conditioning.

But, if you use gas to heat (it’s cheaper), you pay (three times) more for the electrical component of the heat.

From a climate point of view, the impact depends on the source of the electricity, in balance with the impact of burning gas to heat your home!
Your electrical bill

What does it cost to leave a light on all day?

\[ 100 \, W \times 24 \, hours = 2400 \, W - hours = 2.4 \, kWh \]

\[ 2.4 \, kWh \times \frac{0.1\$}{kWh} = 24 \, cents \]

Dirt cheap, literally. We just find and dig up energy resources. We don’t “pay” to lug or pump water uphill so we can operate a hydroelectric plant. We take advantage of the Sun – evaporation and rain.

Energy is free. Making it available costs money.
Forms of energy

Solar radiation
Kinetic energy of gas in wind
Gravitational potential energy of water
Chemical energy of controlled recombination in batteries
Chemical energy of explosive combination in gasoline engines
Nuclear fusion energy (and fission energy!)
Power is a measure of energy flow

Power = energy/time

1 Watt = 1 W = 1 watt = 1 joule per second, 1 kW = 1 kilowatt = 1000 joules per second
Other units: megawatt (1 MW = 1 million watts), and gigawatt (1 GW = 1 billion watts = 1E9 watts = 109 watts = 1000 MW)

A 100 W bulb converts 100 joules of electrical energy each second into heat and light.
A 1000 W = 1kW toaster does the same thing.

Energy = power x time

A 1 kW toaster operated for 100 seconds transforms 100 kJ of energy.
A 1kW toaster operated for (1 hour = 3600 s) transforms 3600 kJ = 1 kWh
Conservation of energy

One of the most basic principles of physics is that energy is conserved. (Another is momentum conservation)

Example: Stirring water requires energy and work to move the spoon. That energy flows into the water and heats it. Just as rubbing your hands together requires work and heats your hands.
Conservation of energy

Another example:
Gunpowder ignites converting some chemical energy into kinetic energy of gaseous molecules. Chemical energy is converted to thermal energy.
These push on the back side of a bullet causing it to accelerate. The thermal energy is converted into visible kinetic energy of the bullet, coherent motion of the molecules in the bullet.
Horsepower

A canonical horse can continuously (for hours on end) do work equivalent to a mechanical power of one horsepower.

1 hp = 0.18 Cal/s = 746 W (like a toaster)

One horse is roughly 7 canonical men/women. A 200 hp engine is roughly 1400 men, and does not tire.
Power plants

Typical toaster 1 kW
Typical house 10 kW
Typical electric power plant 100 MW = 100,000 kW
(almost big enough for Madison)
Large power plant is 10 times the capacity or 1000 MW = 1 GW
US power consumption = 400 GW = 1/5th of all
World power consumption=2000 GW =1 terawatts
Solar power

The Sun shines day and day out on the Earth. The power received is 1kW per square meter, enough in 1 square meter to power a toaster.
Solar power

How much land is required to intercept enough sunlight to power the US?
Solar power

How much land is required to intercept enough sunlight to power the US?

Assume P=1 kW/square m and efficiency of 50%.
To intercept 1 GW = 1000,000 kW requires 1000,000 square meters or 1 km x 1 km.
To intercept 1 tW =1000 GW requires 1000 square km (a square 30 km on a side)
Solar power

The square is about 300 km on a side
Exercise and diet

Humans “consume” energy. More accurately, we transform it. At the most basic level, we eat food to power our bodies into motion and make up for heat loss to radiation from our bodies.

Compute the number of food calories (kcal) you need as follows:

\[
P = \left( \frac{13.7516m}{1 \text{ kg}} + \frac{5.0033h}{1 \text{ cm}} - \frac{6.7550a}{1 \text{ year}} + 66.4730 \right) \frac{\text{kcal}}{\text{day}}
\]

\[
P = \left( \frac{9.5634m}{1 \text{ kg}} + \frac{1.8496h}{1 \text{ cm}} - \frac{4.6756a}{1 \text{ year}} + 655.0955 \right) \frac{\text{kcal}}{\text{day}}
\]

where \( P \) is total heat production at complete rest, \( m \) is the weight, \( h \) is the stature (height), and \( a \) is the age
Exercise and diet

At least, that is the standard formula...

What about the temperature of the environment?

It takes more energy to stay warm (via muscle tension and shivering) in Wisconsin than in Florida.

Research question: How much more or less food energy does a person living in the US require than a person living in Africa?

Exercise versus diet

In principle if you cut your food consumption by about 500 Cal/day you will lose 1 pound each week.

Alternative is running hard for an hour on Monday, on Tuesday, on Wednesday, or Thursday, or Friday, and also on Saturday and Sunday.

I tried essentially both together. My weight hardly changed. Perhaps my muscle mass increased?

BTW: Scale accuracy is only ± 5 pounds so be careful.

My weight fluctuates several pounds each day.
Wind power

<table>
<thead>
<tr>
<th>#</th>
<th>County</th>
<th>Owner/Project Name</th>
<th>Utility Purchaser</th>
<th>Start Date</th>
<th>No. of Turbines</th>
<th>MW</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>Dodge</td>
<td>Babcock &amp; Brown &quot;Butter Ridge&quot;</td>
<td>WPPI</td>
<td>01/09</td>
<td>36</td>
<td>54</td>
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<tr>
<td>2</td>
<td>Fond du Lac</td>
<td>WI Power &amp; Light &quot;Cedar Ridge&quot;</td>
<td>WP&amp;L</td>
<td>12/08</td>
<td>41</td>
<td>68</td>
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<td>3</td>
<td>Fond du Lac</td>
<td>We Energies &quot;Blue Sky Green Field&quot;</td>
<td>We Energies</td>
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<td>145</td>
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<td>4</td>
<td>Dodge/Fond du Lac</td>
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<td>MGE, WPPI, WPL, WPS</td>
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<td>5</td>
<td>Iowa</td>
<td>Next Era Resources &quot;Mantorp&quot;</td>
<td>WE, WPL</td>
<td>2001</td>
<td>20</td>
<td>30</td>
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<td>6</td>
<td>Kewaunee</td>
<td>Madison Gas &amp; Electric &quot;Rosiere&quot;</td>
<td>MGE</td>
<td>1999</td>
<td>17</td>
<td>11.2</td>
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</table>

http://www.renewwisconsin.org/windfarm/windwisconsin.htm

Total 2009 commercial wind power 449 MW
Kinetic energy/potential energy

Remember, \( KE = \frac{1}{2} mv^2 \)

From this formula you may find the motional energy in joules of an object of mass in kg and speed in m/s.

Another handy formula. The energy (joules) to lift mass \( m \) (kg) a height \( h \) (m) is \( U = mgh \) where \( g=10 \) is called the acceleration of gravity. (The gravitational force is \( mg \).)
Kinetic energy

Example: Estimate the kinetic energy of the air in a cubic meter of wind of speed 8 m/s. The mass of air is about 1 kg. (dry air has a density of 1.2041 kg/m$^3$)

\[
KE = \frac{1}{2}mv^2 = \frac{1}{2} \times 1 \text{ kg} \times (8 \text{ m/s})^2 = 32 \text{ joules}
\]
Wind power estimate

Example: A windmill intercepts an area of 10x10=100 square meters of wind at 8 m/s.

Eight cubic meters of wind are intercepted by each square meter of windmill each second. What total wind power is intercepted?

\[ P = \frac{32}{m^3/s} \frac{8 m^3}{s-m^2} 100 m^2 = 25,600 \frac{j}{s} = 25 kW \]
Wind in Wisconsin

Where to site wind power in Wisconsin

Pink area has mean annual wind speed of 8 m/s

http://www.focusonenergy.com/Information-Center/Renewables/Wind-Maps-Data/
Wind in Texas

Roscoe wind farm (RWF) is the largest onshore wind farm in the world. It is situated 45 miles south-west of Abilene in Texas, USA. RWF is owned and operated by Germany-based E.ON Climate and Renewables (EC&R).

With an installed capacity of 781.5MW, RWF exceeds the capacity of the previously largest Horse Hollow Wind Energy Center (735.5MW) located in Taylor and Nolan counties southwest of Abilene.