Lecture 2 – Energy Basics

Dr. Yu Zhang

ECE Department, UC Santa Cruz

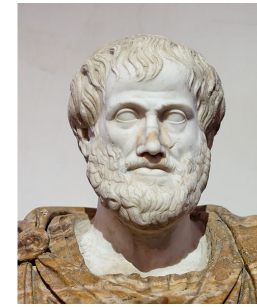
ECE180J

Outline

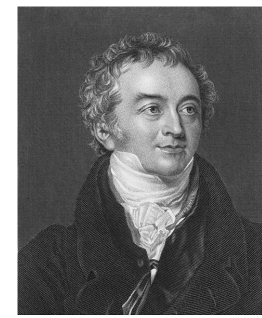
- Energy and Power
- Units and Scientific Notation
- Law of Conservation of Energy
- Efficiency and Capacity Factor
- Capital Recovery Factor & Levelized Cost of Energy

B1: *Renewable and Efficient Electric Power Systems (2nd ed):* Chap 1 & 2, Appendix A
B3: *Renewable Energy Power for a Sustainable Future (4th ed):* Chap 1, Appendix A

Energy



- The word energy derives from the Greek *en* (in) and *ergon* (work) *[wiki: Ancient Greek: ἐνέργεια, energeia, meaning 'activity, operation', appeared for the 1st time in Aristotle's work in the 4th century BC]*



Thomas Young, British polymath and physician

- In 1807, Thomas Young was possibly the first to use the term "energy" in its modern sense.

- Broad definition: **the capacity doing work**
  How much potential a physical system has to change

energy noun

en·er·gy | \ ˈe-nər-jē \

plural **energies**

Definition of *energy*

1 a : dynamic quality
// narrative *energy*

b : the capacity of acting or being active
// intellectual *energy*

c : a usually positive spiritual force
// the *energy* flowing through all people

2 : vigorous exertion of power : EFFORT
// investing time and *energy*

3 : a fundamental entity of nature that is transferred between parts of a system in the production of physical change within the system and usually regarded as the capacity for doing work

4 : usable power (such as heat or electricity)

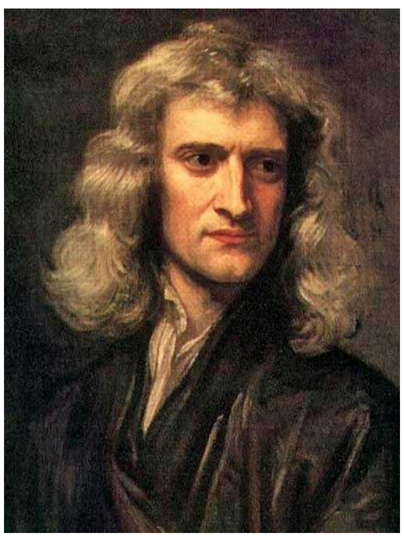
also : the resources for producing such power

Unit of Energy

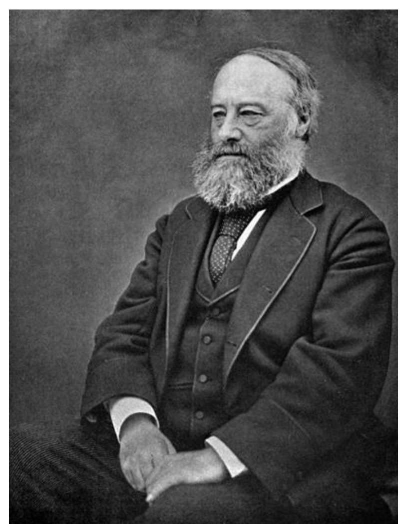
The energy supplied by force of 1 Newton in causing movement through 1 meter.

- Energy (J) = Force (N) x Distance (m)

- Joule (J) - the unit of energy



Isaac Newton (1642-1727)
English physicist



James Joule (1818-1889)
English physicist

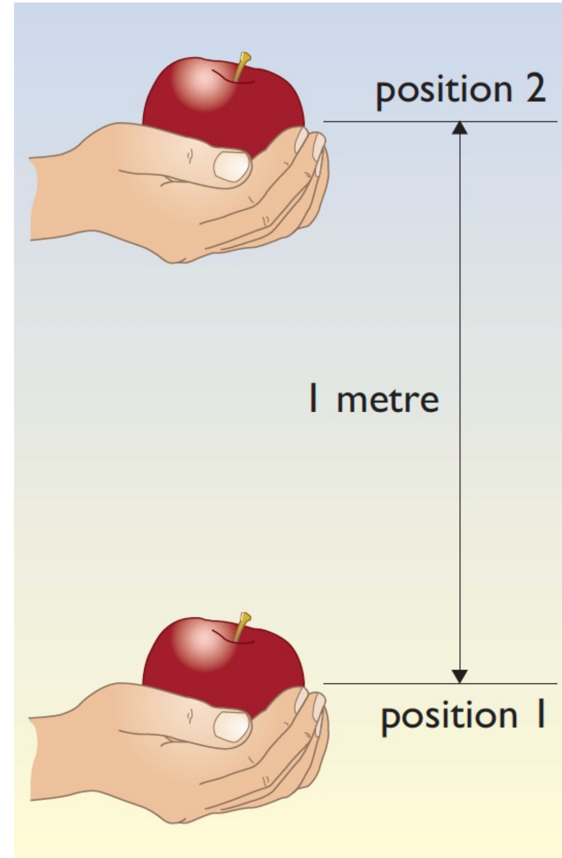
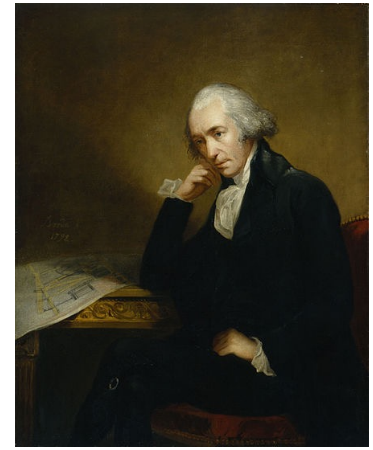


Figure 1.1 The amount of energy required to raise a 100 g apple vertically through 1 m is approximately one joule (1 J)

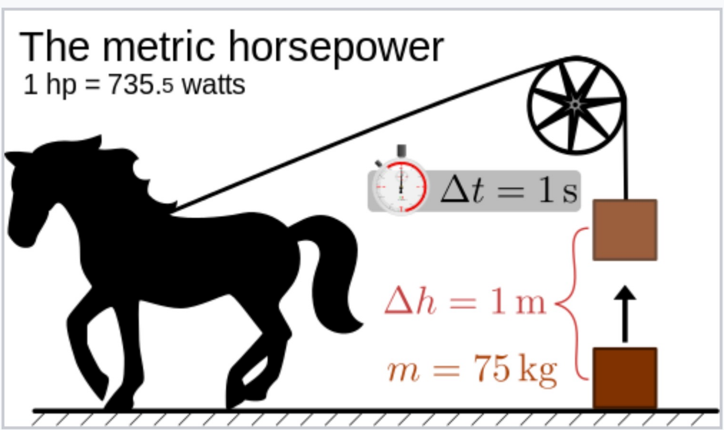
Power

➢ Power is the amount of energy transferred or converted per unit time (rate of doing work)

- Power (W) = Energy (J) / Time (sec)
- Watt (W) - the unit of energy



James Watt (1736-1819)
Scottish inventor



One *metric horsepower* is needed to lift 75 kilograms by 1 meter in 1 second.

$$1\mathrm{hp} = \frac{mg \times d}{t} = \frac{75 \times 9.8 \times 1}{1s} = 735W$$

Toyota Camry SE: 203 hp

Porsche 911 GT2: 700 hp

Mechanical Power

Power in mechanical systems is the combination of forces and movement.

- The product of a force on an object and the object's velocity $P = \mathbf{F} \cdot \mathbf{v}$
- The product of a torque on a shaft and the shaft's angular velocity $P = \boldsymbol{\tau} \cdot \boldsymbol{\omega}$

Assume a constant force **F** throughout a distance **x**, then

$$P = \frac{dW}{dt} = \frac{d}{dt}\left(\mathbf{F} \cdot \mathbf{x}\right) = \mathbf{F} \cdot \frac{d\mathbf{x}}{dt} = \mathbf{F} \cdot \mathbf{v}.$$

If we have a variable force **F** over a curve C: then

$$W = \int_C \mathbf{F} \cdot d\mathbf{r} = \int_{\Delta t} \mathbf{F} \cdot \frac{d\mathbf{r}}{dt}\, dt = \int_{\Delta t} \mathbf{F} \cdot \mathbf{v}\, dt.$$

$\Downarrow$ Fundamental theorem of calculus

$$\boxed{P = \frac{dW}{dt} = \frac{d}{dt} \int_{\Delta t} \mathbf{F} \cdot \mathbf{v}\, dt = \mathbf{F} \cdot \mathbf{v}.}$$

Electric Power

Electric power is the rate at which electrical energy is transferred by an electric circuit.

Consider an DC (direct-current) circuit, we have $P = VI = I^2R = \frac{V^2}{R}$

Question: How about AC (alternating-current) circuit?
Answer: Use phasor representations

- **The phasor associated with signal $v(t) = V_0 \cos(\omega t + \phi)$ is the complex number $\mathbf{V} = V_0 e^{j\phi}$, we have the one-to-one mapping**

$$v(t) = V_0 \cos(\omega t + \phi) \longleftrightarrow \mathbf{V} = V_0 e^{j\phi}$$

- **If $\mathbf{X} = |\mathbf{X}| e^{j\phi}$ then $\mathfrak{Re}[|\mathbf{X}| e^{j\phi} e^{j\omega t}] = |\mathbf{X}| \cos(\omega t + \phi)$**
- **Essentially, we decompose a sinusoid into the product (a.k.a. analytic representation) of a complex constant and a factor depending on time and frequency.**
- **The complex constant is called a phasor, which depends on amplitude and phase angle.**

Electric Power (cont'd)

Complex power (units: volt-ampere (VA)) is defined as

$$S = VI^* = |S|e^{j\varphi} = |S|\angle\varphi$$

Phase angle difference

Voltage phasor

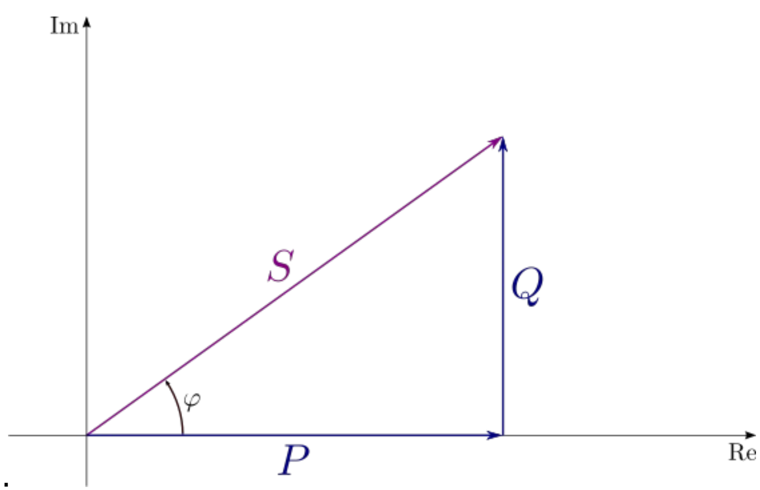
Complex conjugate of current phasor

Apparent power is the magnitude of complex power (units in VA)

$$S = P + jQ \Rightarrow \begin{cases} P = |S|\cos\varphi \\ Q = |S|\sin\varphi \end{cases}$$

Real/active power (units in watt)

Reactive power (units in volt-ampere reactive (VAR))



The Power Triangle

The complex power is the vector sum of active and reactive power. The apparent power is the magnitude of the complex power.

Active power, P

Reactive power, Q

Complex power, S

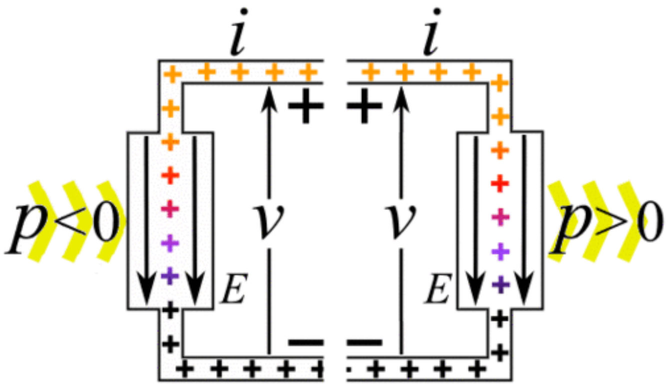
Apparent power, $|S|$

Phase of voltage relative to current, φ

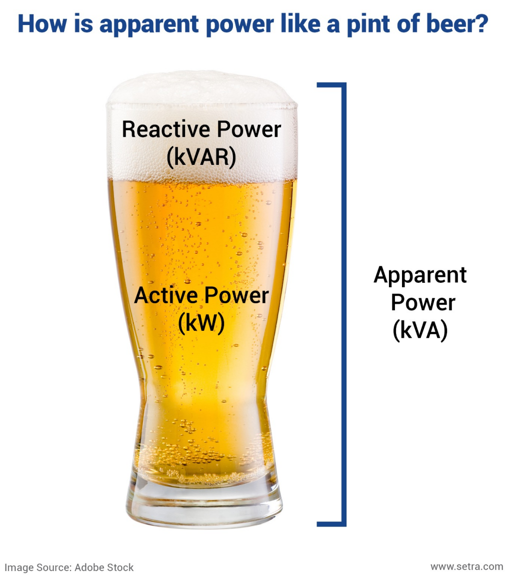
Source: Wiki

Active vs Reactive Power

In AC circuits, energy storage elements such as inductor and capacitor may result in periodic reversals of the direction of energy flow.



- Active power P is useful power that does some meaningful work.
- Reactive power Q flows back and forth (in both directions from source to load) and produces electric or magnetic flux.
- Q is the power that will help to do that meaningful work. E.g., all the mechanical output of the motor is due to P but the conversion of electrical to mechanical power is done by the help of magnetic field created by Q.
- Q is often used to support the voltage level in power systems.



Active vs Reactive Power (cont'd)

	Motor	Airplane
Useful work	To rotate motor	To transport passengers
Active power	Power used to rotate motor	Fuel spent to carry total weight of all passengers combined
Reactive power	Power used to create magnetic field between stator and rotor	Fuel spent to lift the weight of airplane itself

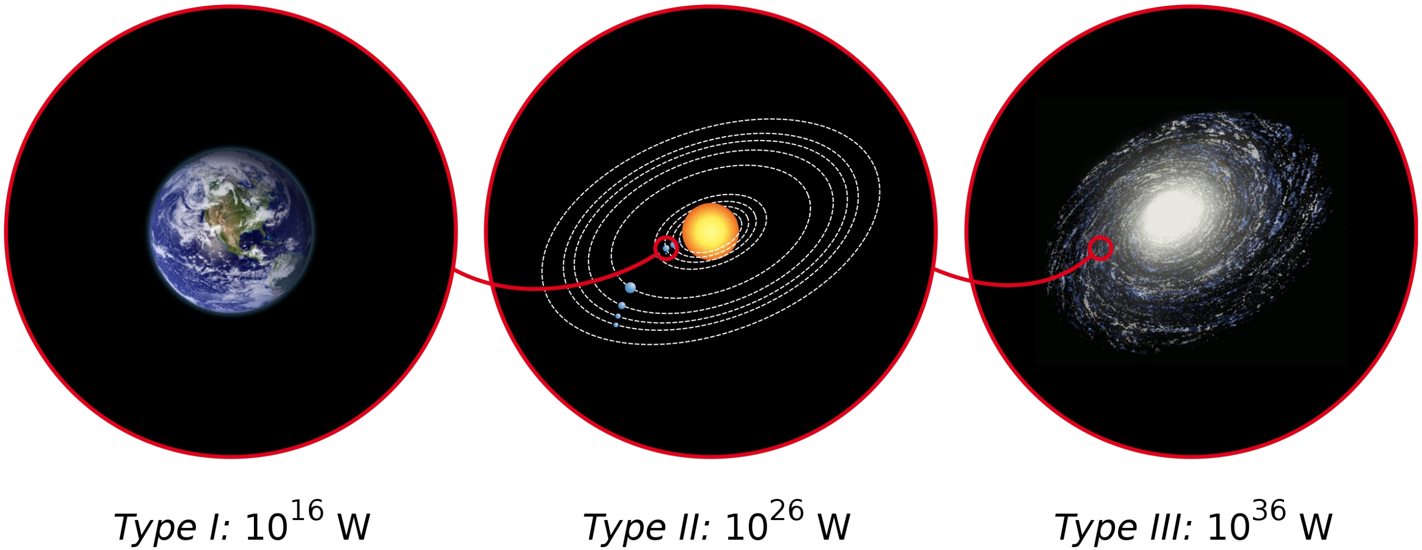
Producing reactive power in power systems:

- Mainly produced by synchronous generators through rotor field current (generator excitation).
- However, there is a limit to the magnitude of field current that can be given to rotor windings of a generator in order to produce reactive power.
- This issue can be solved by installing compensator devices (capacitor banks) at the receiving end of a power transmission system.

Source: Quora

Civilization’s Level

In 1964, Soviet astronomer Nikolai Kardashev defined **three levels of civilization**, based on the order of magnitude of power available to each:



- Type I (planetary civilization): can use and store all of the energy available on its planet.
- Type II (stellar civilization): can use and control energy at the scale of its planetary system.
- Type III (galactic civilization): can control energy at the scale of its entire host galaxy.

International System of Units (SI)

Base quantity	SI base unit Name	SI base unit Symbol
length	meter	m
mass	kilogram	kg
time	second	s
electric current	ampere	A
thermodynamic temp	kelvin	K
amount of substance	mole	mol
luminous intensity	candela	cd

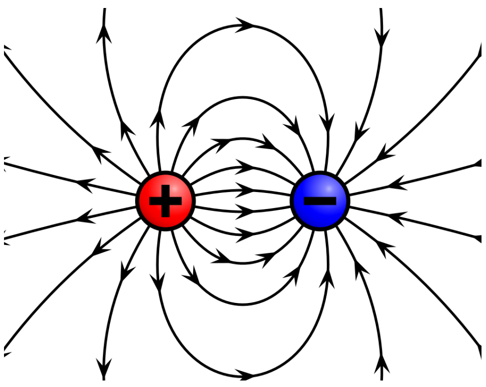
SI derived units are formed by powers, products or quotients of the base units

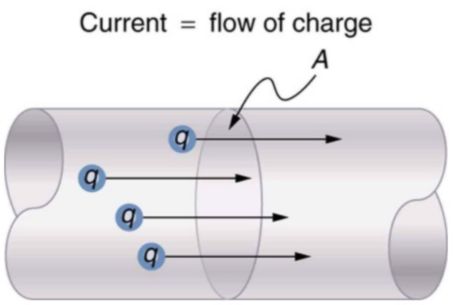
Name[note 1]	Symbol	Quantity	In other SI units	In SI base units
radian[note 2]	rad	angle		$(\mathrm{m \cdot m^{-1}})$
steradian[note 2]	sr	solid angle		$(\mathrm{m^2 \cdot m^{-2}})$
hertz	Hz	frequency		$\mathrm{s^{-1}}$
newton	N	force, weight		$\mathrm{kg \cdot m \cdot s^{-2}}$
pascal	Pa	pressure, stress	$\mathrm{N/m^2}$	$\mathrm{kg \cdot m^{-1} \cdot s^{-2}}$
joule	J	energy, work, heat	$\mathrm{N \cdot m}$	$\mathrm{kg \cdot m^2 \cdot s^{-2}}$
watt	W	power, radiant flux	J/s	$\mathrm{kg \cdot m^2 \cdot s^{-3}}$
coulomb	C	electric charge or quantity of electricity		$\mathrm{s \cdot A}$
volt	V	voltage (electrical potential), emf	W/A	$\mathrm{kg \cdot m^2 \cdot s^{-3} \cdot A^{-1}}$

Example (change of units): $$\mathrm{J} = \frac{\mathrm{kg \cdot m^2}}{\mathrm{s^2}} = \mathrm{N \cdot m} = \mathrm{Pa \cdot m^3} = \mathrm{W \cdot s} = \mathrm{C \cdot V}.$$

Key Quantities in Power Systems

Charge (q): the physical property of matter that causes it to experience a force when placed in an electromagnetic field (emf). An atom consists of a positively charged nucleus surrounded by some negatively charged electrons. The charge associated with one electron is 1.602 x 10^{-19} C.



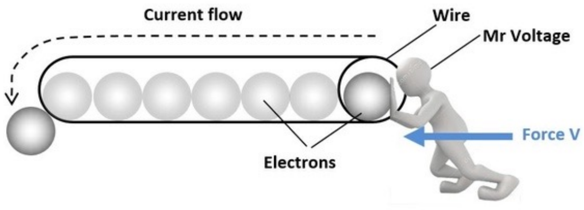


Current (i): Movement of free electrons. Defined as the net rate of flow of charge past a point or through an area.

$$\boxed{i := \frac{dq}{dt}}$$

Voltage (v): Electric potential difference between two points, which is defined as the amount of energy (w) in moving a unit of charge (q) from one point to another.

$$\boxed{v := \frac{dw}{dq}}$$



Quiz

By the definitions of power, voltage and current, derive their relationship: P=VI

$$p = \frac{dw}{dt} = \frac{dw}{dq} \times \frac{dq}{dt} = v \times i$$

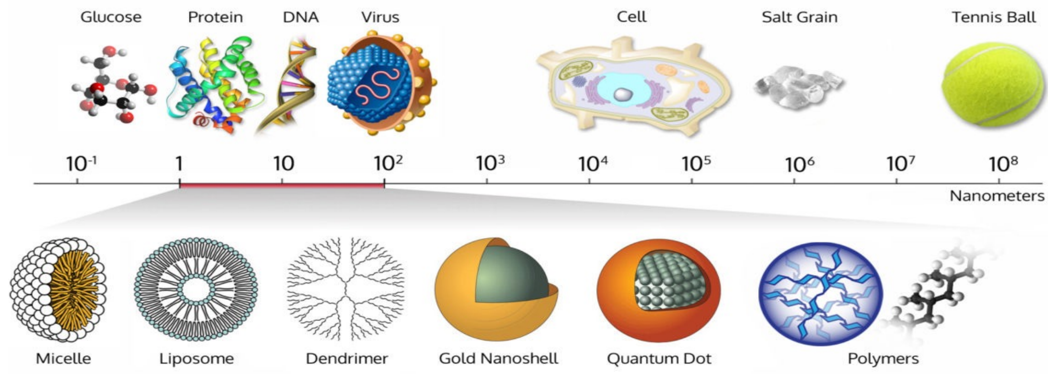
Relationships of Key Quantities

Electrical Quantity	Symbol	Unit	Abbreviation	Relationship
Charge	q	coulomb	C	$q = \int i\, dt$
Current	i	ampere	A	$i = dq/dt$
Voltage	v	volt	V	$v = dw/dq$
Power	p	joule/second	J/s	$p = dw/dt$
		or watt	W	
Energy	w	joule	J	$w = \int p\, dt$
		or watt-hour	Wh	

Scientific Notation

Small Quantities			Large Quantities		
Quantity	Prefix	Symbol	Quantity	Prefix	Symbol
10^{-3}	milli	m	10^{3}	kilo	k
10^{-6}	micro	μ	10^{6}	mega	M
10^{-9}	nano	n	10^{9}	giga	G
10^{-12}	pico	p	10^{12}	tera	T

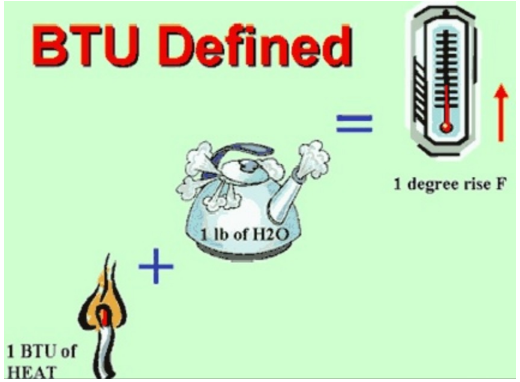
The IBM Model 350 disk file with a storage space of 5MB from 1956 and a Micro SD Card



See more: [The Smallest to the Biggest Thing in the Universe!]()

Popular Units for Comparing Energy

- **British thermal units (Btu) =** the amount of heat to raise the temperature of one pound of water by one degree Fahrenheit.
- barrels of oil equivalent
- metric tons of oil (coal) equivalent



- 1 barrel (42 gallons) of crude oil = 5,800,000 Btu
- 1 gallon of gasoline = 114,100 Btu
- 1 gallon of diesel fuel = 137,452 Btu
- 1 gallon of heating oil = 138,500 Btu
- 1 cubic foot of natural gas = 1,037 Btu
- 1 gallon of propane = 91,333 Btu
- 1 short ton (2,000 pounds) of coal = 19,489,000 Btu
- 1 kWh of electricity = 3,412 Btu

The unit of million Btu (mmBtu) is more commonly used

* See B3-Appx A for some other units

Converting to Btu

Example 1:

- Your home has a natural gas furnace that used 81,300 cubic feet of natural gas for heating last winter.
- Your neighbor has a furnace that burns heating oil, which used 584 gallons of heating oil last winter.

Q: Which home used more energy for heating?

Natural gas: 81,300 cubic feet (your home)	×	1,037 Btu/cubic foot	= 84,308,100 Btu
Heating oil: 584 gallons (neighbor's home)	×	138,500 Btu/gallon	= 80,884,000 Btu

A: You used more energy to heat your home!

Converting to Btu (cont'd)

Example 2:

You need a new furnace. You consider heating systems that use natural gas or heating oil. The costs of the fuels: $10.40 per thousand cubic feet (natural gas), and $2.70 per gallon (heating oil).

Q: Which one to buy?

Solution: Compare the price of the fuels on an equal basis

Natural gas	$10.40 per thousand cubic feet	÷	1.037 million Btu per thousand cubic feet	= $10.03 per million Btu
Heating oil	$2.70 per gallon	÷	0.1385 million Btu per gallon	= $19.49 per million Btu

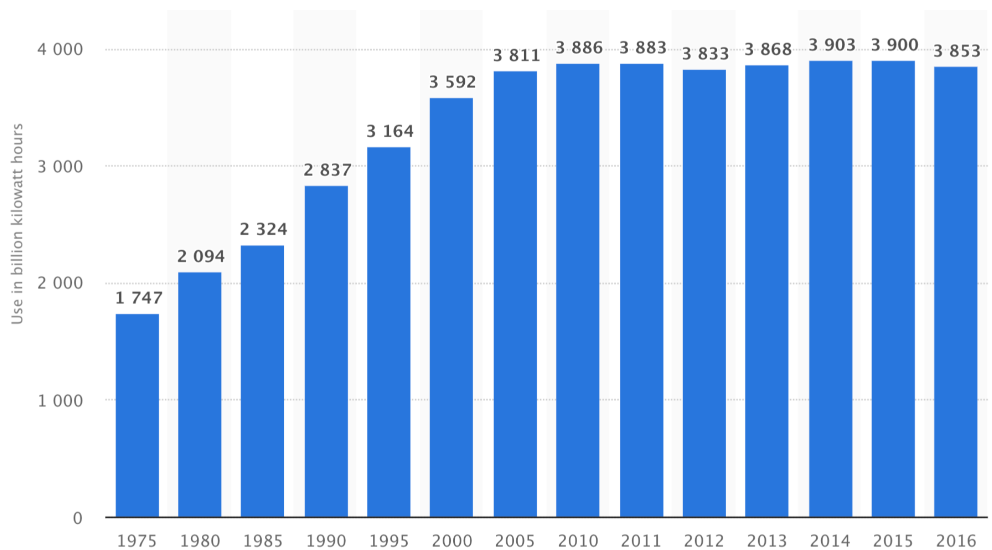
A: Go for natural gas one

Energy Consumption

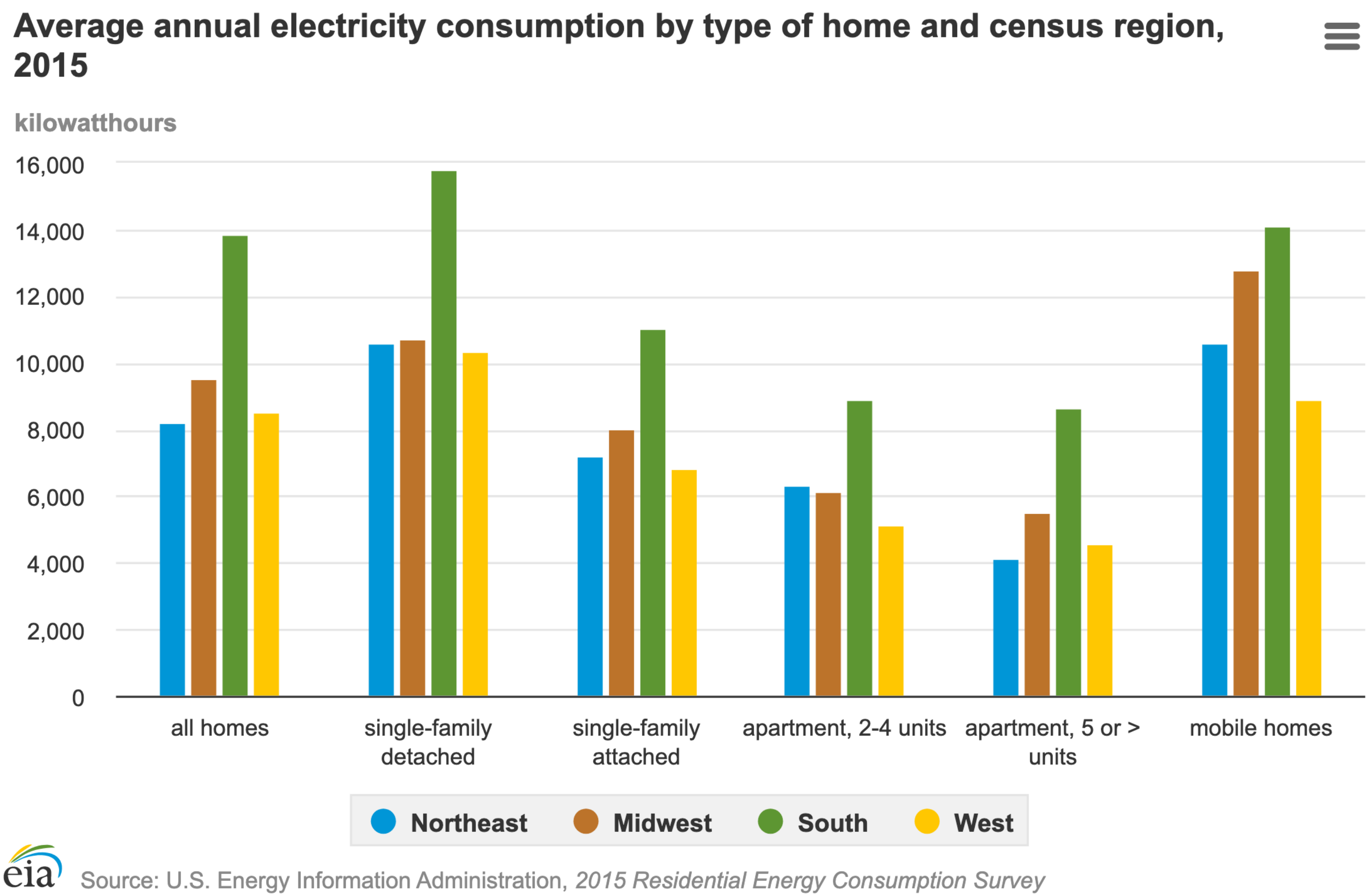
Example 1: A cell phone camera consumes 10^{-8} Joules/pixel for analog-digital conversion

1080x1920 pixels/frame = 2.1million pixels/frame = 0.021 J/frame
30 frames/second for video = 0.62 J/sec = 0.62 watts.

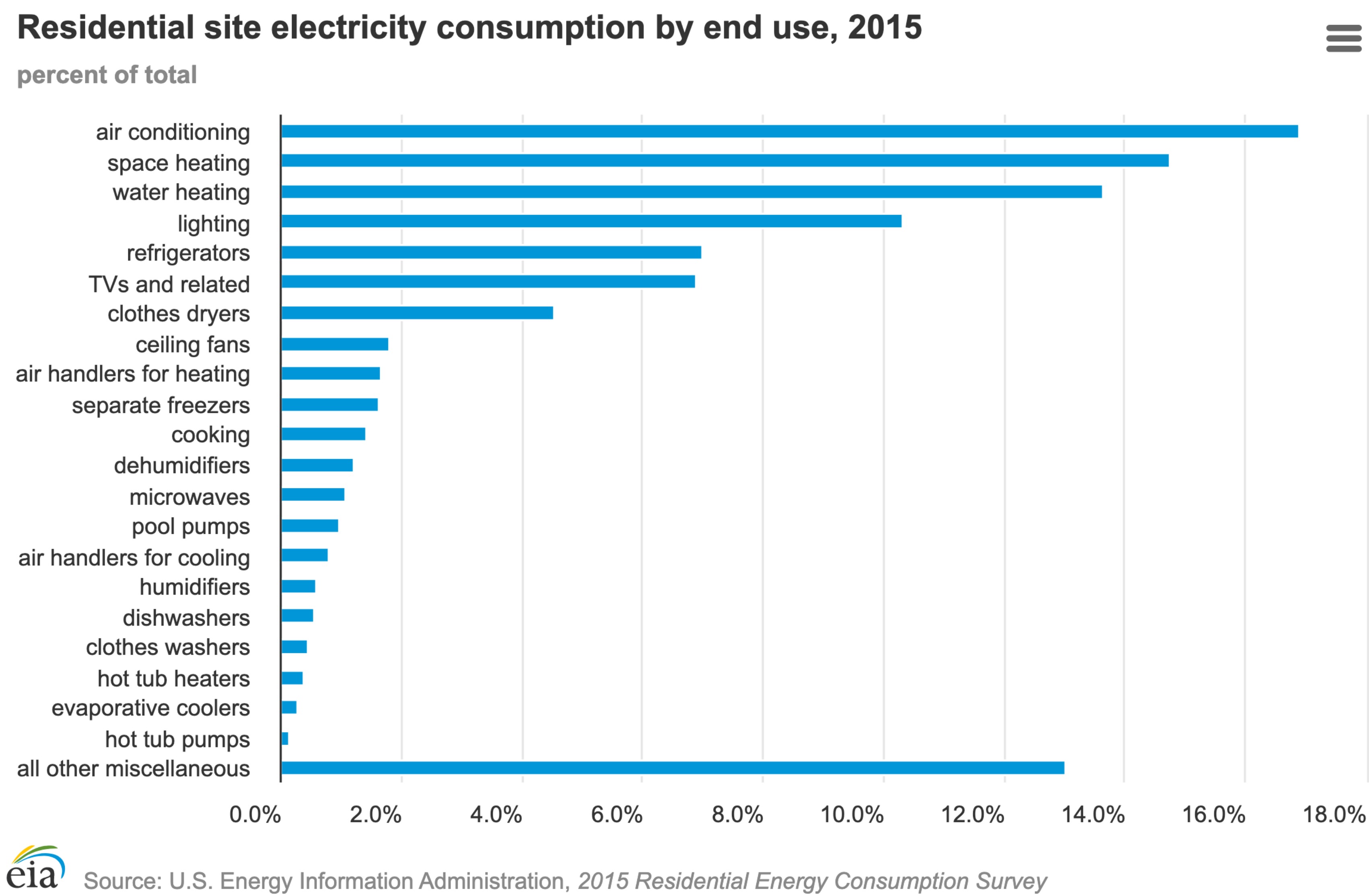
Example 2: U.S. annual electric energy consumption is about 3900 billion kWh (about 11,974 kWh per person, which means on average we each use 1.37 kW of power continuously).



Household Annual Energy Consumption



Energy Consumption Percentage of End Use



Typical Power Ratings of Appliances

ESSENTIAL APPLIANCES

ESTIMATED WATTAGE

Household Appliances	Rated (Running) Watts	Additional Surge Watts
Ceiling Fan	60 W	70 W
Central AC (10,000 BTU)	1,500 W	4,500 W
Central AC (24,000 BTU)	3,800 W	11,400 W
Central AC (40,000 BTU)	6,000 W	6,700 W
Dehumidifier	240 W	0 W
Electric Heater (Fan)	2,000 W	1,000 W
Electric Thermal Radiator	500 W	0 W
Electric Water Heater	4,000 W	0 W
Electric Water Heater (Immersion)	3,000 W	0 W
Electric Water Heater (Tankless)	6,600 W	2,200 W

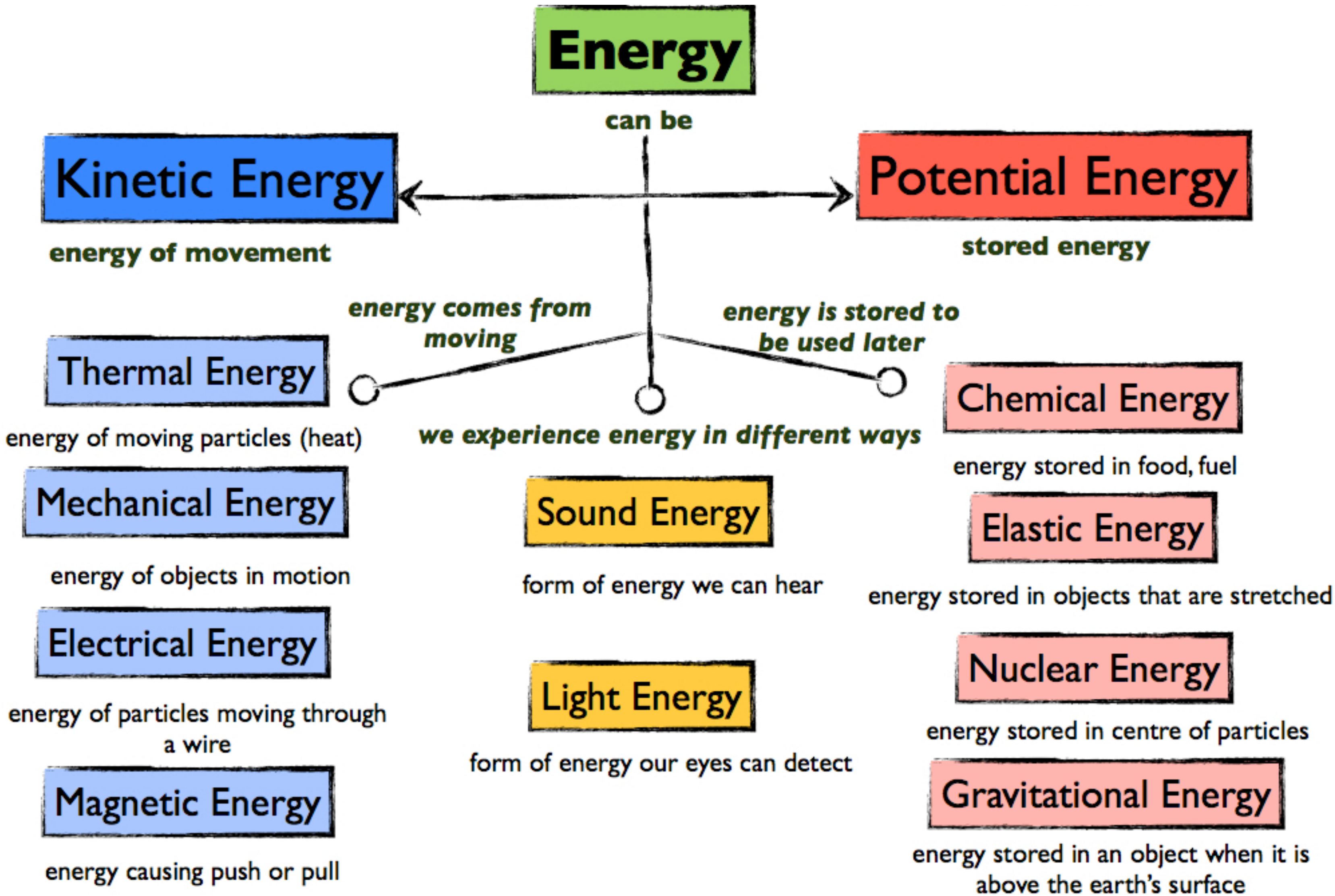
KITCHEN APPLIANCES

ESTIMATED WATTAGE

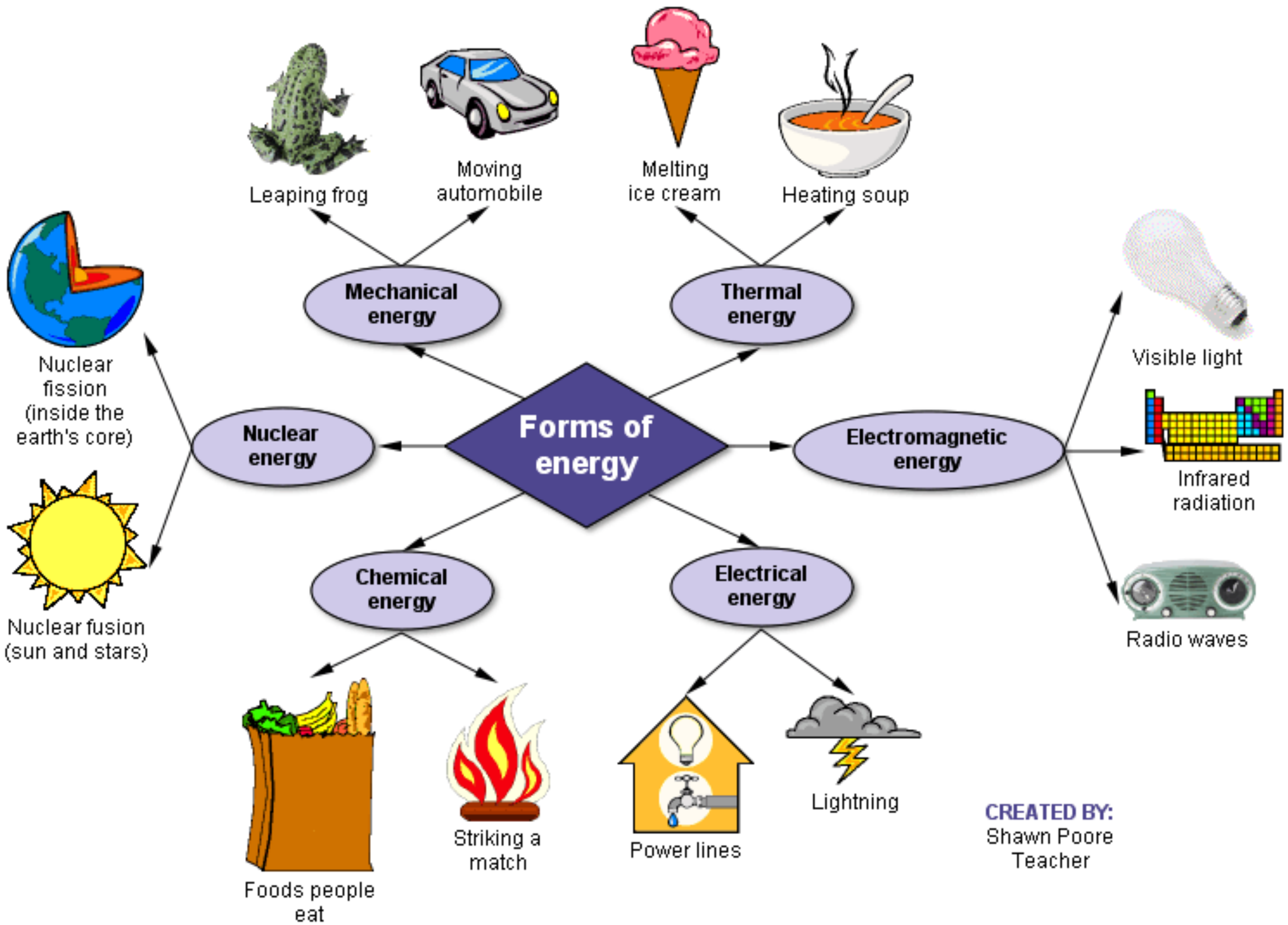
Household Appliances	Rated (Running) Watts	Additional Surge Watts
Air Fryer	1,500 W	0 W
Coffee Maker	1,000 W	0 W
Cooker Hood	20 W	10 W
Deep Freezer	500 W	1,500 W
Dishwasher	1,500 W	1,500 W
Electric Can Opener	170 W	0 W
Electric Kettle	1,200 W	3,000 W
Electric Oven	2,150 W	0 W
Electric Stove (8" Element)	2,100 W	0 W
Espresso Coffee Machine	1,300 W	200 W

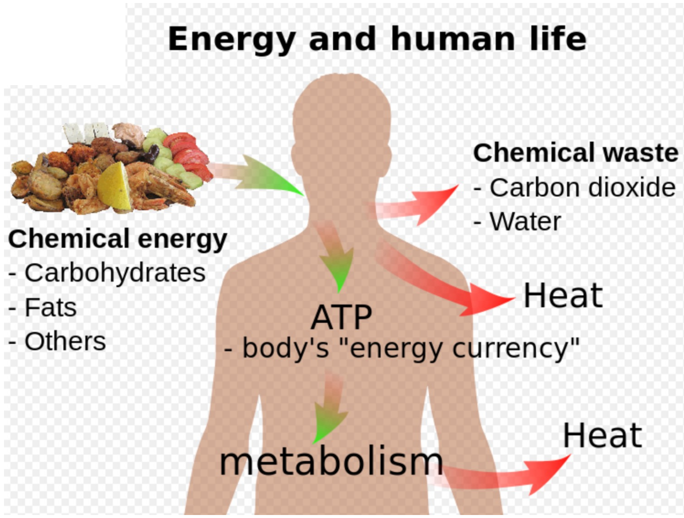
See details https://generatorist.com/power-consumption-of-household-appliances

Forms of Energy



Picture source: mskuksclass.weebly.com/lesson-2-forms-of-energy.html


Leaping frog
Moving automobile
Melting ice cream
Heating soup
Mechanical energy
Thermal energy
Nuclear fission (inside the earth's core)
Nuclear energy
Forms of energy
Electromagnetic energy
Visible light
Infrared radiation
Radio waves
Nuclear fusion (sun and stars)
Chemical energy
Electrical energy
Foods people eat
Striking a match
Power lines
Lightning
CREATED BY:
Shawn Poore
Teacher


Energy and human life
Chemical energy
- Carbohydrates
- Fats
- Others
Chemical waste
- Carbon dioxide
- Water
Heat
ATP
- body's "energy currency"
metabolism
Heat

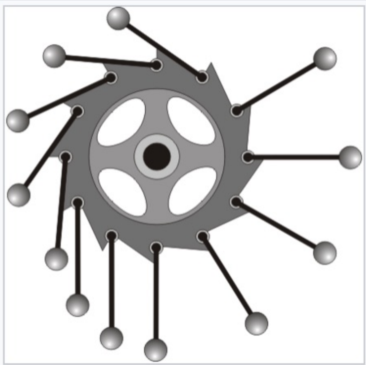
Comics Energy ...

Conservation of Energy

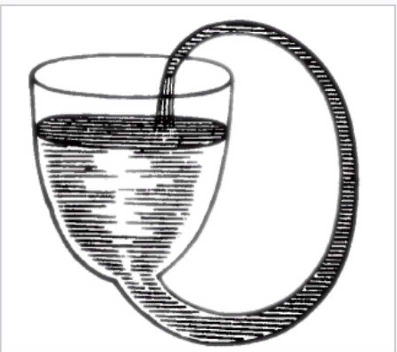
Law of Conservation of Energy:

Energy is a property that is not created/destroyed, although energy can change in form.

- The total energy of an isolated system remains constant (be conserved over time) – **First law of thermodynamics**
- A perpetual motion machine of the first kind cannot exist: no system without an external energy supply can deliver an unlimited amount of energy to its surroundings.

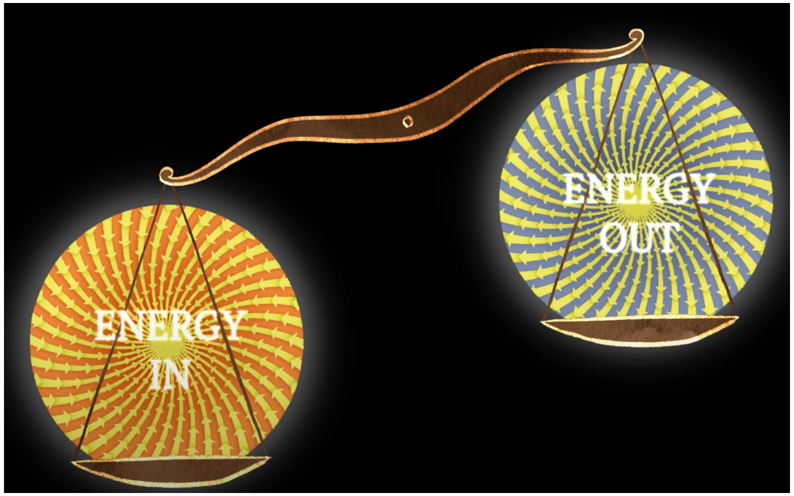


The "Overbalanced Wheel".



The "Capillary Bowl"

Perpetual Motion Machine!?



Three Laws of Thermodynamics:

- The 1st law: Energy can neither be created nor destroyed.
- The 2nd law: The entropy of any isolated system always increases.
- The 3rd law: The entropy of a system approaches a constant value as the temperature approaches absolute zero.

Conservation of energy can arguably be violated by general relativity on the cosmological scale.
Einstein tells us that space and time are dynamical, and in particular that they can evolve with time. When the space through which particles move is changing, the total energy of those particles is not conserved.

https://www.discovermagazine.com/the-sciences/energy-is-not-conserved

Noether's Theorem

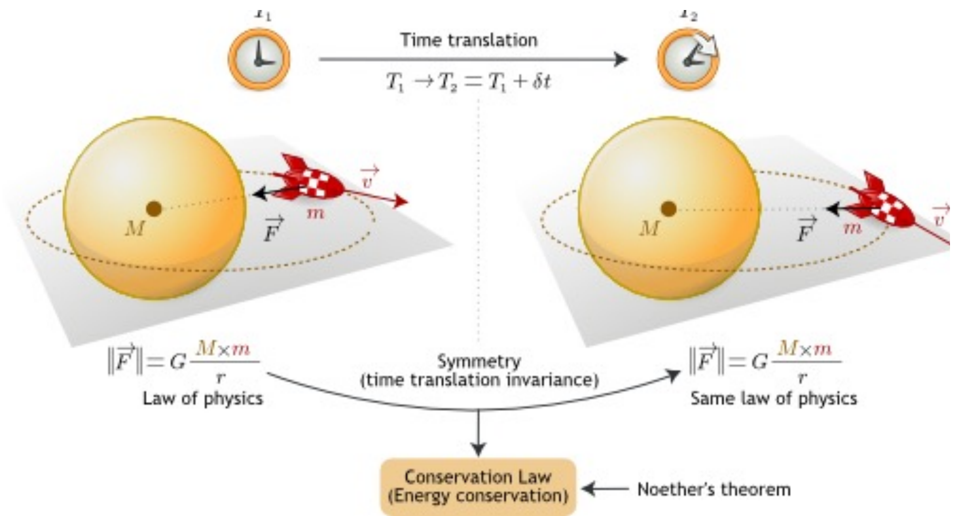
Noether's Theorem: For every continuous global symmetry, there exists a conserved quantity.

- Global means that the symmetry must uniformly apply to the entire system and not vary spatially across the system.
- Continuous means the symmetry can be applied for a continuous range of some parameter, such as a shift or a rotation.

Emmy Noether (1882-1935)
German mathematician

Symmetry	Conservation law
Time-translation	Energy
Space-translation	Momentum
Rotation	Angular momentum

Time Symmetry and Energy Conservation



Time-translation symmetry: the laws of physics do not change over time (time invariance).
Fig source: quantum-bits

If physics really does change over time; e.g., gravitation constant *G*.

- Then, we can always raise the weight when gravity is weak and lower it when gravity is strong.
- The key: the energy we get back out is greater than what we originally put in. Each time, we make a profit in energy.
- We keep running the cycle and become richer and richer.

Hence, conservation in energy implies time symmetry.
Noether's Theorem asserts that it works the other way around as well, which requires in-depth mathematical derivations with Lagrangian function and principle of least action.

https://en.wikipedia.org/wiki/Noether%27s_theorem

FINANCIAL ASPECTS OF POWER PLANTS

Efficiency & Capacity Factor

Efficiency $= \dfrac{\textit{actual energy output}}{\textit{energy input}} \times 100\%$

Capacity Factor (CF) $= \dfrac{\textit{actual energy output}}{\textit{maximum possible energy output}} \times 100\%$

Clearly, both quantities can be calculated by using “power” instead of “energy”.

Examples:

- A solar panel creates 300 kW of electricity from 900 kW of sunlight. Its efficiency is $\dfrac{300\text{ kW}}{900\text{ kW}} \times 100\% = 33.3\%$.
- A power plant uses 3,412 MMBtu of fuels to generate 5×10^5 kWh energy in a week. Its efficiency is $\dfrac{5 \times 10^5\text{ kWh}}{10^6\text{ kWh}} \times 100\% = 50\%$ (1 kWh = 3,412 Btu).
- A 1MW wind turbine produces 3000MWh electricity in a year. Its capacity factor is $\dfrac{3000\text{ MWh}}{1 \times 365 \times 24\text{ MWh}} \times 100\% = 34.2\%$.

Capital Recovery Factor (CRF)

A loan of P
with interest rate i

	A	A		A	
0	1	2	$\cdots$	n-1	n

A: annual payment

Task: Find the equal annual payment A for a n-year fixed-rate i loan P.

$$\sum_{s=0}^{n-1} A(i+1)^s = A\frac{(i+1)^0-(i+1)^n}{1-(i+1)} = A\frac{(i+1)^n-1}{i} = P(i+1)^n \Rightarrow$$

$$A(\$/\mathrm{yr}) = P(\$)\cdot \mathrm{CRF}(\%/\mathrm{yr}) \quad \text{where } CRF = \frac{i(1+i)^n}{[(1+i)^n-1]}$$

The formula can be easily adjusted to find monthly payments

$$\mathrm{CRF}(i,n) = \frac{(i/12)[1+(i/12)]^{12n}}{[1+(i/12)]^{12n}-1}\text{per month}$$

Discount Factor and Present Value Function

- Alternative approach: Compute the net present value (NPV) of those equal cash flows A

$$\frac{A}{1+i} + \frac{A}{(1+i)^2} + \cdots + \frac{A}{(1+i)^n} = P$$

When converting a future value F into a present worth P,

- Interest term i is often referred to as a discount rate d.
- The discount rate can be thought of as the interest rate that could have been earned if the money had been put into the best alternative investment.

We introduce a conversion factor called the present value function (PVF):

$$\mathrm{PVF} = \frac{P}{A} = \sum_{s=1}^{n} \frac{1}{(1+d)^s} = \frac{(1+d)^n - 1}{d(1+d)^n}$$

Equivalent Discount Rate with Fuel Escalation

The fuel cost in the future may be higher than it is today, which means that the annual amount of money saved by an efficiency measure could increase with time. To account for that, let e denote the fuel escalation rate, we have

$$\mathrm{PVF}(d, e, n) = \frac{1+e}{1+d} + \frac{(1+e)^2}{(1+d)^2} + \ldots + \left(\frac{1+e}{1+d}\right)^n$$

We can define the equivalent discount rate with fuel escalation as d'

$$\frac{1+e}{1+d} = \frac{1}{1+d'} \Rightarrow d' = \frac{d-e}{1+e}$$

Example of PV Electricity Cost

A 3-kW photovoltaic system, which operates with a capacity factor (CF) of 0.25, costs $10,000 to install. There are no annual costs associated with the system other than the payments on a 6%, 20-year loan. Find the cost of electricity generated by the system (¢/kWh).

Solution:

$$A = P \times \text{CRF}(0.06, 20) = \$10{,}000 \times 0.0872/\text{yr} = \$872/\text{yr}$$

$$\text{Annual energy (kWh/yr)} = \text{Rated power (kW)} \times 8760 \text{ hr/yr} \times \text{CF}$$

In this case

$$\text{kWh/yr} = 3 \text{ kW} \times 8760 \text{ h/yr} \times 0.25 = 6570 \text{ kWh/yr}$$

The cost of electricity from the PV system is therefore

$$\text{Cost of PV electricity} = \frac{\$872/\text{yr}}{6570 \text{ kWh/yr}} = \$0.133/\text{kWh} = 13.3¢/\text{kWh}$$

Levelized Cost of Energy (LCOE)

$$\text{LCOE (\$/kWh)} = \frac{\text{[Annual fixed cost + Annual variable cost] (\$/yr)}}{\text{Annual output (kWh/yr)}}$$

- LCOE is used for investment planning and to compare different methods of electricity generation on a consistent basis.
- LCOE is an estimation of the cost of production of energy, thus it tells nothing about the price for consumers and is most meaningful from the investor's point of view.
- Inputs to LCOE are chosen by the estimator. They can include the cost of capital, decommissioning, fuel costs, fixed and variable operations and maintenance costs, financing costs, and an assumed utilization rate.

LCOE Concept

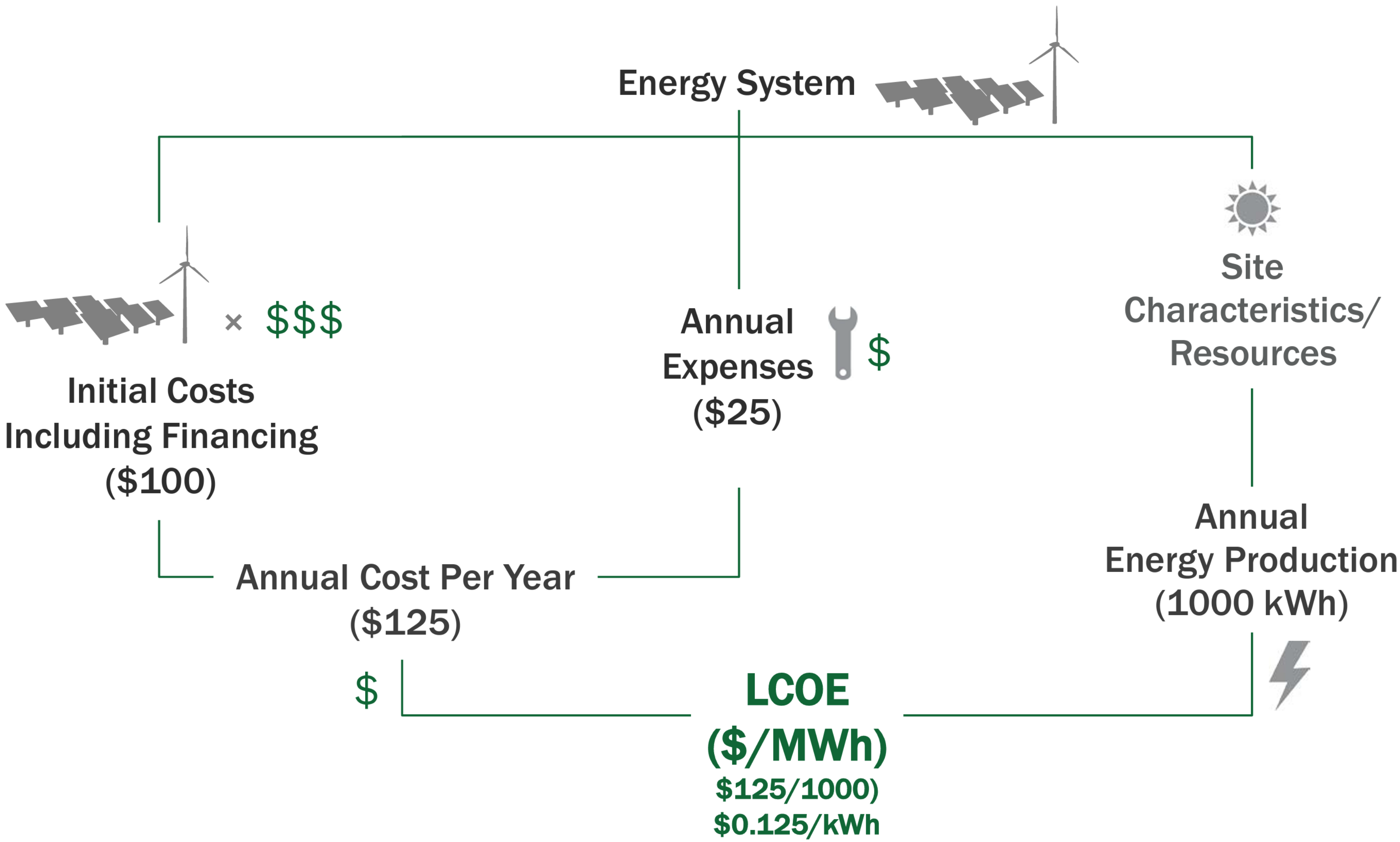


Fig source: www.energy.gov/sites/prod/files/2015/08/f25/LCOE.pdf

Fixed and Variable Costs

- Fixed costs include capital costs, taxes, insurance, and any fixed O&M costs that will be incurred even when the plant isn't operated.

$$\text{Fixed (\$/yr-kW)} = \text{Capital cost (\$/kW)} \times \text{Fixed charge rate (yr}^{-1}\text{)}$$

where the fixed charge rate (FCR) accounts for interest on loans, acceptable returns for investors, fixed O&M, charges, taxes, etc.

- Variable costs are the added costs associated with actually running the plant. These are mostly fuel plus variable O&M costs.

$$\begin{aligned}\text{Variable (\$/yr-kW)} &= [\text{Fuel (\$/Btu)} \times \text{Heat rate (Btu/kWh)} \\ &\quad + \text{O\&M (\$/kWh)}] \times \text{h/yr}\end{aligned}$$

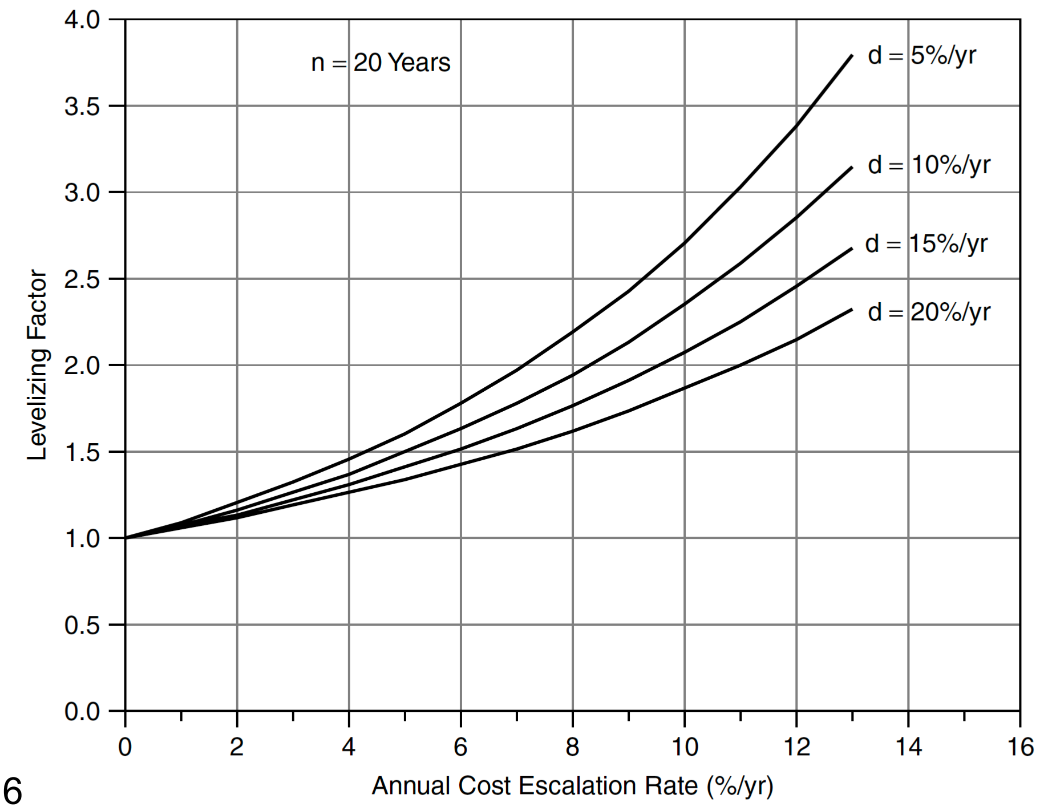
Here, we assume a constant rated power and no adjustment for cost escalation.

- Heat rate is the amount of energy used by a power plant to generate 1 kWh of electricity. Hence, it measures the efficiency of electrical power plants that convert a fuel into heat & electricity.

Levelizing Factor

- To account for the cost escalation, inflation (fuel price, variable O&M etc), we need to multiply the variable costs with the levelizing factor.

$$\text{Levelizing factor (LF)} = \underbrace{\left[\frac{(1+d')^n - 1}{d'(1+d')^n}\right]}_{\mathrm{PVF}(d',n)} \cdot \underbrace{\left[\frac{d(1+d)^n}{(1+d)^n - 1}\right]}_{\mathrm{CRF}(d,n)}$$

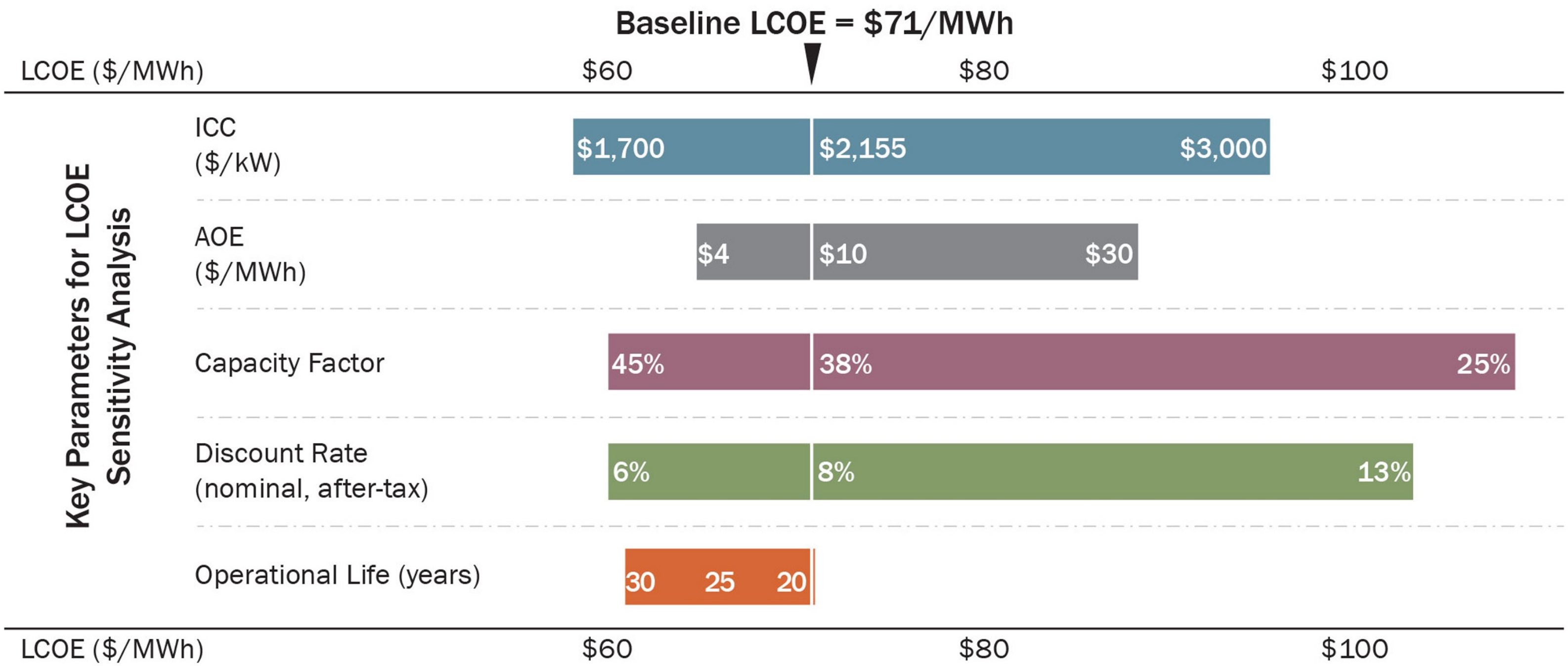


$$d' = \frac{d - e}{1 + e}$$

d'= d & LF=1 if e = 0

B1: page 42, 6

Big Driving Factors of Wind LCOE



Source: Tegen et al. 2012

Initial capital cost (ICC) and capacity factor are two critical drivers. But, discount rate (financing costs) and annual operating expenses (AOE) are non-trivial.

Find Annual Fixed Cost

Example 1. Consider a natural-gas fired combined cycle (NGCC) power plant with a total installed cost of \$1300/kW. Assume this is an investor-owned utility (IOU) with 52% equity financing at 11.85% and 48% debt at 5.40% with investments "booked" on a 20-year term. Add 2% of the capital cost per year to account for insurance, property taxes, fixed O&M, and another 4% for corporate taxes. Find the annual fixed cost of this plant (\$/yr-kW).

Solution.

Step 1) find the weighted average cost of capital:

Average cost of capital = 0.52 × 11.85% + 0.48 × 5.40% = 8.754%

Step 2) compute the CRF: $$\mathrm{CRF} = \frac{0.08754\,(1+0.08754)^{20}}{\left[(1+0.08754)^{20}-1\right]} = 0.10763/\mathrm{yr} = 10.763\%/\mathrm{yr}$$

Step 3) compute the FCR:

FCR = 10.763% (finance) + 2% (fixed O&M, etc.) + 4% (taxes) = 16.763%

Step 4) compute the annual fixed cost:

Annual fixed cost = \$1300/kW × 0.16763/yr = \$218/yr-KW

B1: page 38-40

Find LCOE

Example 2. Consider the NGCC plant in Example 1. Suppose natural gas now costs \$6/MMBtu and it is projected to rise at 5%/yr in the future. The owners have a 10% discount factor. Annual O&M adds another 0.4 ¢/kWh. If its heat rate is 6900 Btu/kWh and the plant has a 70% CF, find its LCOE.

Solution. Using Equation 1.9 with an assumed 1 kW of rated power, the annual energy delivered per kW of rated power is

$$\text{Annual energy} = 1\ \text{kW} \times 8760\ \text{h/yr} \times 0.70 = 6132\ \text{kWh/yr}$$

From Figure 1.28 the levelizing factor for fuel is 1.5. From Equation 1.10, the annualized fuel cost per kW is

$$\begin{aligned}\text{Annual fuel cost (per kW)} &= 6132\ \text{kWh/yr} \times 6900\ \text{Btu/kWh} \times \$6/10^6\ \text{Btu} \times 1.5 \\ &= \$381/\text{yr}\end{aligned}$$

LCOE (cont'd)

$$\text{Annual energy} = 1\ \text{kW} \times 8760\ \text{h/yr} \times 0.70 = 6132\ \text{kWh/yr}$$

Annual O&M adds another \$0.004/kWh × 6132 kWh/yr = \$25/yr

$$\text{Total variable costs (per kW)} = \$381 + \$25 = \$406/\text{yr}$$

Adding the \$218/yr-kW for annualized fixed costs gives a total

$$\text{Total annualized costs} = (\$218 + \$406)\ \$/\text{yr-kW}$$

Using Equation 1.12, the total levelized cost is therefore

$$\text{LCOE} = \frac{\$218/\text{yr-kW} + \$406/\text{yr-kW}}{8760\ \text{h/yr} \times 0.70} = \$0.1017/\text{kWh} = 10.17¢/\text{kWh}$$

B1: page 42

Alternative Formula for LCOE

- LCOE as a measure of the average net present cost of electricity generation for a generator over its lifetime.

$$\mathrm{LCOE} = \frac{\text{sum of costs over lifetime}}{\text{sum of electrical energy produced over lifetime}} = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}}$$

I_t : investment expenditures in the year *t*

M_t : operations and maintenance expenditures in the year *t*

F_t : fuel expenditures in the year *t*

E_t : electrical energy generated in the year *t*

r : discount rate

n : expected lifetime of system or power station

Source: wiki

Electricity Rates

Credit to Sifat Chowdhury (UCSC-ECE)

Energy Statement

ENERGY STATEMENT
www.pge.com/MyEnergy

1 Account No: 1023456789-0
Statement Date: 02/19/2019
Due Date: 03/12/2019

Service For:

[redacted]

Questions about your bill?

24 hours per day, 7 days per week
Phone: 1-866-743-0335
www.pge.com/MyEnergy

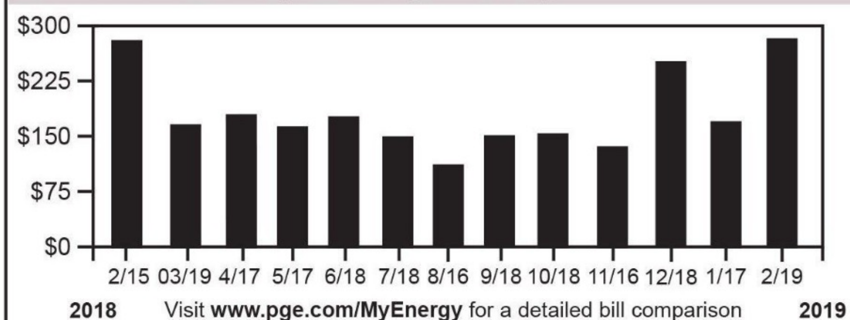
Local Office Address

100 N. MAIN ST
FORT BRAGG, CA 95437

Your Account Summary

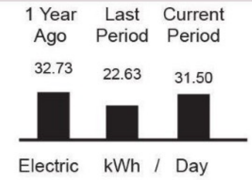
Credit Balance on Previous Statement	$179.42
Payment(s) Received Since Last Statement	-179.42
Previous Unpaid Balance	0.00
2 Current PG&E Electric Delivery Charges	$185.01
3 Sonoma Clean Power Electric Generation Charges	90.54
Total Amount Due by 03/12/2019	**$275.55**

Electric Monthly Billing History



Visit **www.pge.com/MyEnergy** for a detailed bill comparison

Daily Usage Comparison



Energy Statement (Cont'd)

ENERGY STATEMENT
www.pge.com/MyEnergy

Account No: 1023456789-0
Statement Date: 02/19/2019
Due Date: 03/12/2019

Details of PG&E Electric Delivery Charges

01/11/2019 - 02/21/2019 (32 billing days)

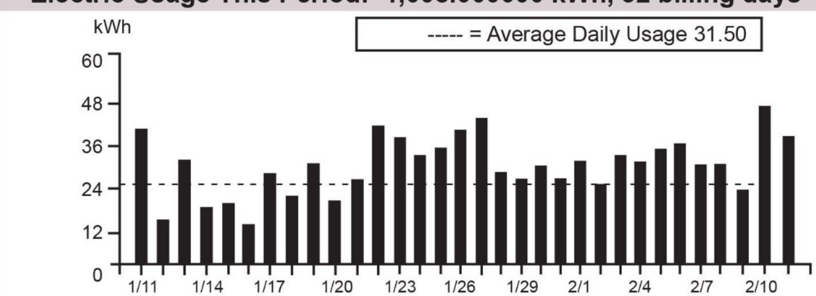
Service For: 281 TALON DR
Service Agreement ID: 2416854841
Rate Schedule: E1 X Residential Service

01/11/2019 - 02/11/2019 **Your Tier Usage** 1 2

Tier 1 Allowance	342.40	kWh	(32 days x 10.7 kWh/day)		
Tier 1 Usage	342.400000	kWh	@ $0.21183	$72.53	
Tier 2 Usage	665.600000	kWh	@ $0.28011	186.44	
Generation Credit				-108.66	4
Power Charge Indifference Adjustment				34.15	5
Franchise Fee Surcharge				0.55	6
Total PG&E Electric Delivery Charges				**$185.01**	7

2013 Vintaged Power Charge Indifference Adjustment

Electric Usage This Period: 1,008.000000 kWh, 32 billing days



Service Information

Meter #	1005868421
Current Meter Reading	30,877
Prior Meter Reading	29,869
Total Usage	1,008.000000 kWh
Baseline Territory	X
Heat Source	B - Not Electric
Serial	Q
Rotating Outage Block	12P

Different Charges

Most common components in utility bills

1) **Energy charges**
- Based on the amount of electricity (kWh) consumed.
- Cost can vary by time of use and by season.

2) **Demand charges**
- Based on maximum demand (kW) in each month.
- Shifting usage from high to low demand period lowers this charge.

3) **Fixed charges**
- Includes maintenance, generation, T&D, public programs like California Alternate Rates for Energy (CARE) and wildfire mitigation.
- Billed monthly and determined by rate schedule, not consumption.

https://www.energy.gov/eere/femp/evaluating-your-utility-rate-options

Energy Charge

- You pay for the total amount of electrical energy that is used, typically measured in kilowatt-hours (kWh).

Example: At a rate of 10 cents per kWh, how much does it cost to keep a 100 W light bulb on for one day?

Solution: 100 W = 0.1 kW, 1day = 24 hours, so

cost = 0.1 kW x 24 hours x \$0.10/kWh = \$0.24 = 24 ¢

→ for one month (30days) that amounts to \$7.20

Load Factor

$$\text{Load factor (\%)} = \frac{\text{Average power}}{\text{Peak power}} \times 100\%$$

For example, a customer with a peak demand of 100 kW that uses 876,000 kWh/yr (8760 h/yr × 100 kW) would have an annual load factor of 100%. Another customer using the same 876,000 kWh/yr with a peak demand of 200 kW would have a load factor of 50%. For this example, the utility would need twice as much generation capacity and twice as much transmission and distribution capacity to serve the customer with the lower load factor, which means that the rate structure must be designed to help recover those extra costs. Since they use the same amount of energy, the $/kWh charge won't differentiate between the two, but the demand charges $/kW-mo will. A stiff demand charge will encourage customers to shed some of their peak power, perhaps by shifting it to other times of day to even out their demand.

Example of Demand Charge

Example: Two customers each use 100,000 kWh/mo. Customer A has a load factor of 15% and Customer B has a 60% load factor. Using a rate structure with energy charges of \$0.06/kWh and demand charges of \$10/kW-mo, compare their monthly utility bills.

Solution. They both have the same energy costs: $100{,}000\ \text{kWh/mo} \times \$0.06/\text{kWh} = \$6000/\text{mo}$

the peak demand for A is

$$\text{Peak(A)} = \frac{100{,}000\ \text{kWh/mo}}{15\% \times 24\ \text{h/day} \times 30\ \text{day/mo}} \times 100\% = 925.9\ \text{kW}$$

which, at \$10/kW-mo, will incur demand charges of \$9259/mo.

The peak demand for B is

$$\text{Peak(B)} = \frac{100{,}000\ \text{kWh/mo}}{60\% \times 24\ \text{h/day} \times 30\ \text{day/mo}} \times 100\%$$

$$= 231.5\ \text{kW} \qquad \text{costing } \$2315/\text{mo}$$

The total monthly bill for A with the poor load factor is nearly twice as high as for B (\$15,259 for A and \$8315 for B).

How Electricity Rate is Decided

The factors deciding the electricity rate

- electric distribution and transmission
- costs of procuring power
- revenues needed for public programs (e.g., low-income and energy-efficiency programs).
- an approved rate of return for shareholder investments

Rates are the same across PG&E's entire service area. However, the amount of electricity allotted at the lowest available price (baseline) is different for each customer.

https://www.pge.com/en_US/residential/rate-plans/how-rates-work/learn-how-rates-are-set/learn-how-rates-are-set.page

Formulas for Calculating Electricity Rate

$$TRR = OE + r \times (RB)$$

Where:

$$TRR = \text{total revenue requirement } (\$)$$
$$OE = \text{operating expenses } (\$)$$
$$r = \text{rate of return on rate base } (\%)$$
$$RB = \text{rate base } (\$)$$

- FERC has jurisdiction over electric transmission rate base and rates.
- CPUC has jurisdiction over generation and distribution grid.

$$\frac{TRR_e \times p}{S \times s} = ARR_e$$

Where: TRR_e = total electric revenue requirement ($) for a given year

p = residential revenues as % of total revenue (%) calculated using historic data

S = total sales (kWh) forecasted for that same year

s = residential sales as % of total sales (%)

ARR_e = average residential electric rate ($/kWh) for that year

Hay, C., & Chhabra, M. (2020). The impact of wildfires and beneficial electrification on electricity rates in PG&E's service territory. *The Electricity Journal*, *33*(3), 106710.

Regulation of Electricity Rate

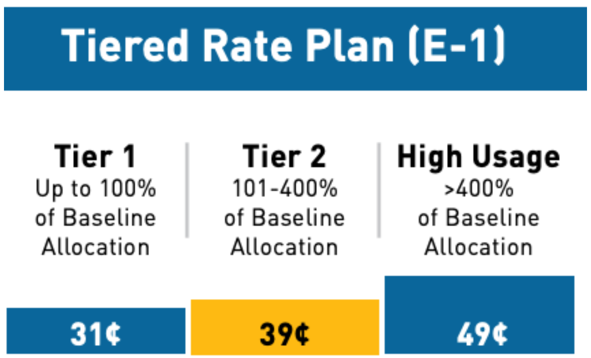
- When PG&E makes any rate change, they need to submit an application to the California Public Utilities Commission (CPUC).
- The application is reviewed in a public hearing and by stakeholders (such as groups representing residential and business consumers, low-income and community advocates, environmental groups, agricultural interests and others).
- After this lengthy process, the CPUC issues a decision. PG&E then incorporates the approved changes into rates.

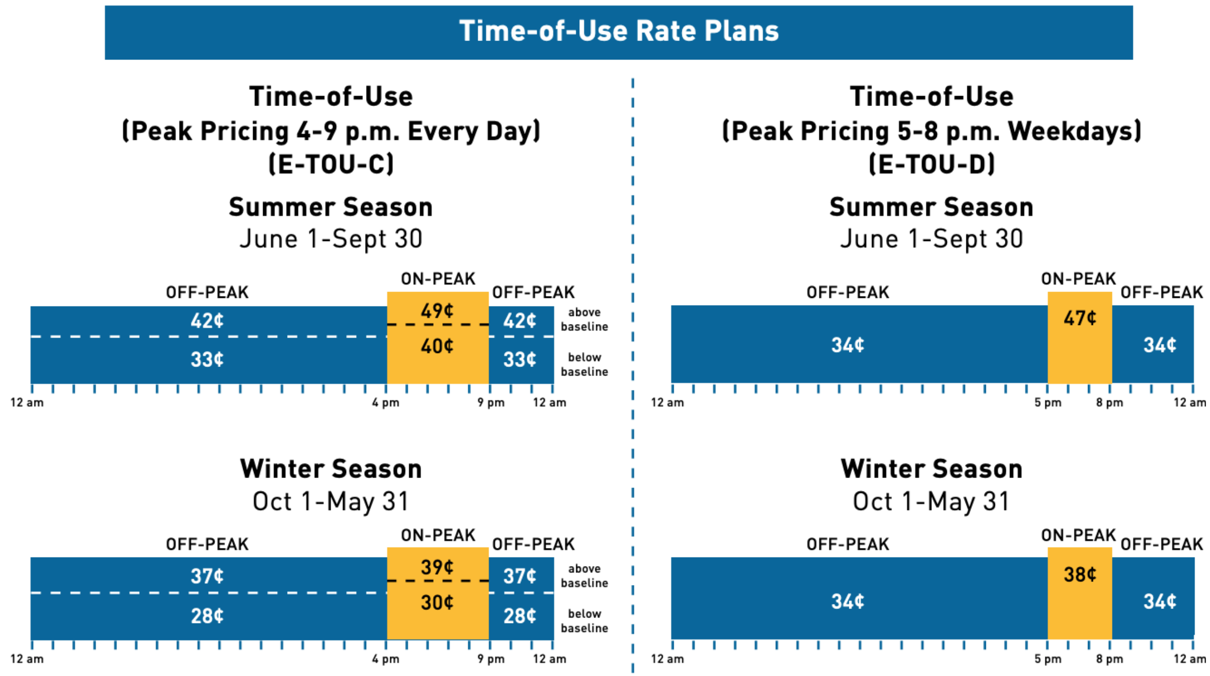
PG&E changes its electricity rates only 2-3 times a year.
Their natural gas supply rates change every month.

https://www.cpuc.ca.gov/-/media/cpuc-website/about-cpuc/documents/transparency-and-reporting/fact_sheets/californiapublicutilitiescommissionelectricity713.pdf

Types of Rate Plans

Three main rate plans by PG&E: 1) Tiered rate plan; 2) Time-of-use rate plan; 3) Plug-in Electric Vehicles rate plan





E-TOU-D may be more attractive for higher energy users

https://www.pge.com/pge_global/common/pdfs/rate-plans/how-rates-work/Residential-Rates-Plan-Pricing.pdf

Baseline Allowance and Add-on

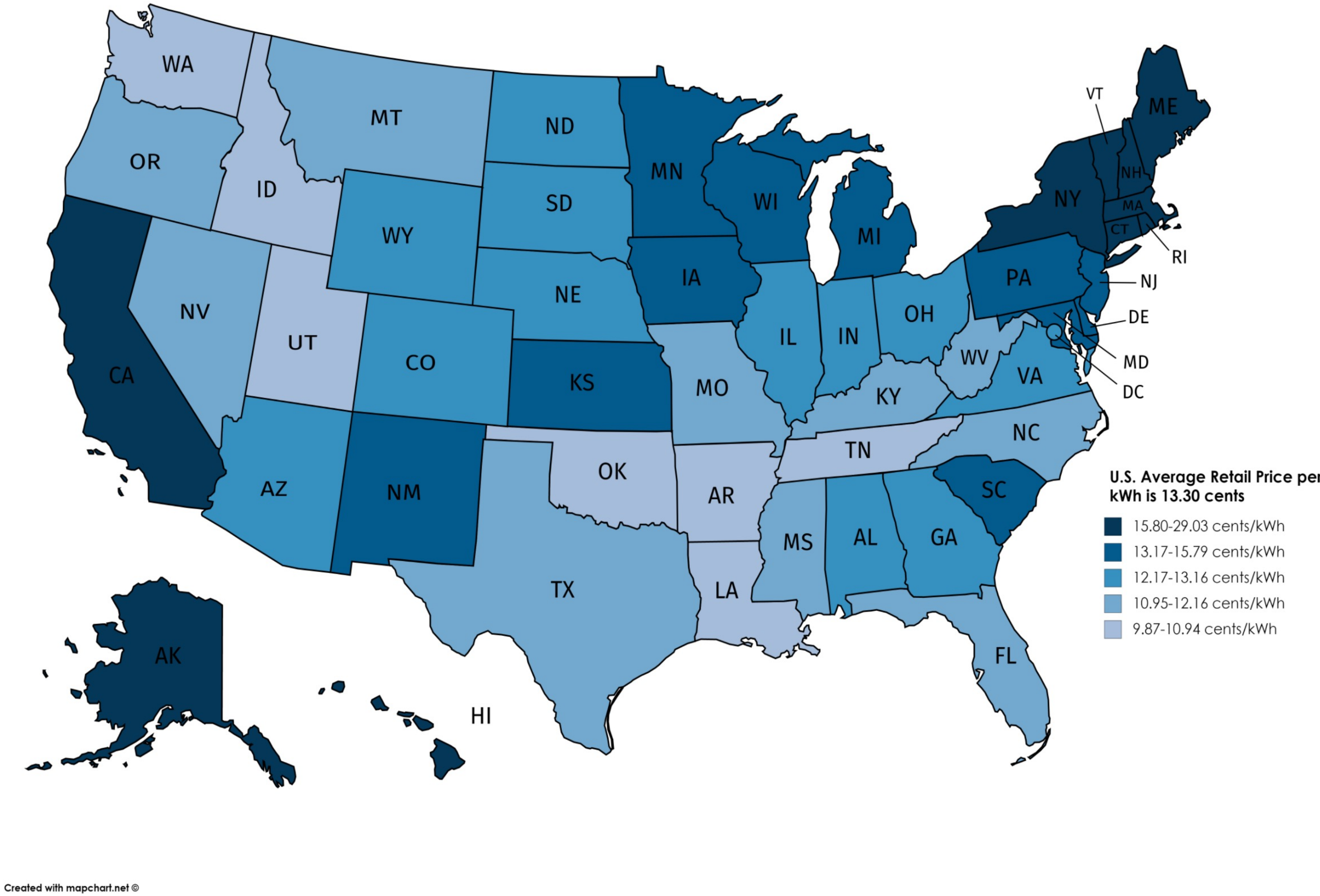
Baseline Allowance consists of an allotment of energy available at the lowest price

- It is the minimum level of usage needed to satisfy a substantial portion of the electricity needs of the average customer in a specific geographic region called a Climate Zone.
- Zones don't follow county/city boundaries, but are based on areas with similar geography and climate, the season, and the household heating source.
- Customers in hotter Climate Zones have higher.
- PG&E has 16 different Climate Zones.

There are several **add-ons** added to the base plan, e.g., SmartRate Add-on, Net-energy metering Add-on, and Solar Choice plans

1. https://www.pge.com/en_US/residential/rate-plans/how-rates-work/learn-how-rates-are-set/learn-how-rates-are-set.page
2. https://www.pge.com/en_US/residential/rate-plans/rate-plan-options/understanding-rate-plans/understanding-rate-plans.page

Residential Electric Supply Rates in 2018



10 Most Expensive States to Live In

Rank	State	January 2018 Rate (cents per kWh)
1	Hawaii	31.14
2	Rhode Island	22.24
3	Alaska	21.67
4	Massachusetts	20.60
5	Connecticut	20.00
6	New Hampshire	19.23
7	**California**	**18.81**
8	New York	17.74
9	Vermont	17.36
10	Maine	16.02

10 Most Cheapest States to Live In

Rank	State	January 2018 Rate (cents per kWh)
1	Louisiana	8.72
2	Oklahoma	8.79
3	North Dakota	9.00
4	Missouri	9.19
5	Nebraska	9.29
6	Arkansas	9.36
7	Washington	9.51
8	Kentucky	9.78
9	Tennessee	10.02
10	North Carolina	10.27