Thursdays 3:30-6:00 PM
133 Reynolds Hall
Fall 2023 Semester

STIA 4102

CLEAN ENERGY INNOVATION

Lecture 1:

Introduction to Energy

SFS
GEORGETOWN UNIVERSITY

pre-course intro survey
(MANDATORY)

August 24th, 2023
Prof. Jonathan “Jo” Melville

Lecture Overview

1. Intro questionnaire
2. Lecture overview *(you are here)*
3. Course expectations
4. About me
5. Physics 101
6. What is energy?
7. What is money?
8. A little soapboxing
9. Semester overview

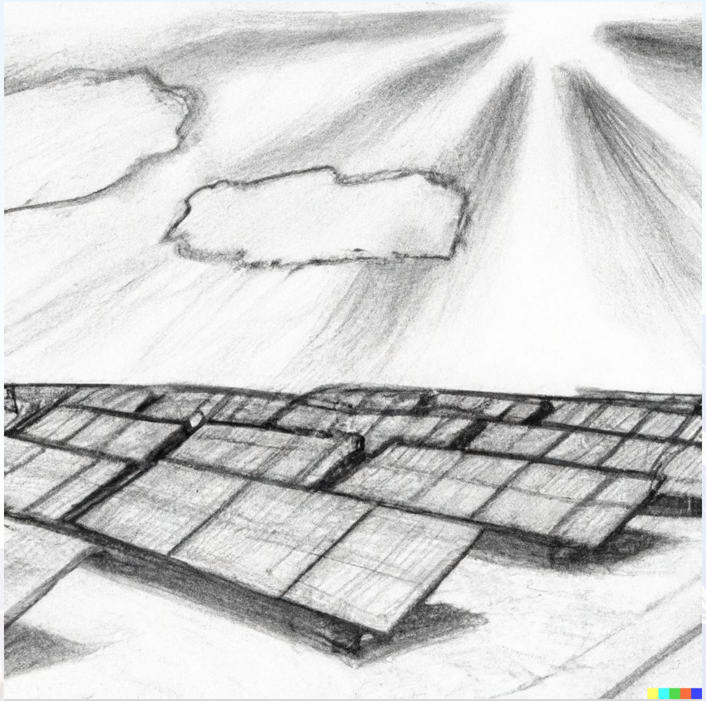


Image by DALL·E 2
PROMPT: "a hand-drawn pencil sketch of a field of solar panels on a sunny day with a few clouds"

Course Expectations

(learners)

(teachers)

<u>I expect from you:</u>

- be curious!
  - (ask questions!)
- be respectful!
  - (to me and to each other)
- be honest!
  - (i promise i will not get mad)

(ethics)

(grading)

Course Expectations

(learners)

Expect from me:

(teachers)

- bad humor
- different outfits
- unrelated tangents
- my best
- emails
- belief in you

(ethics)

(grading)

Course Expectations

(learners)

I expect from you:

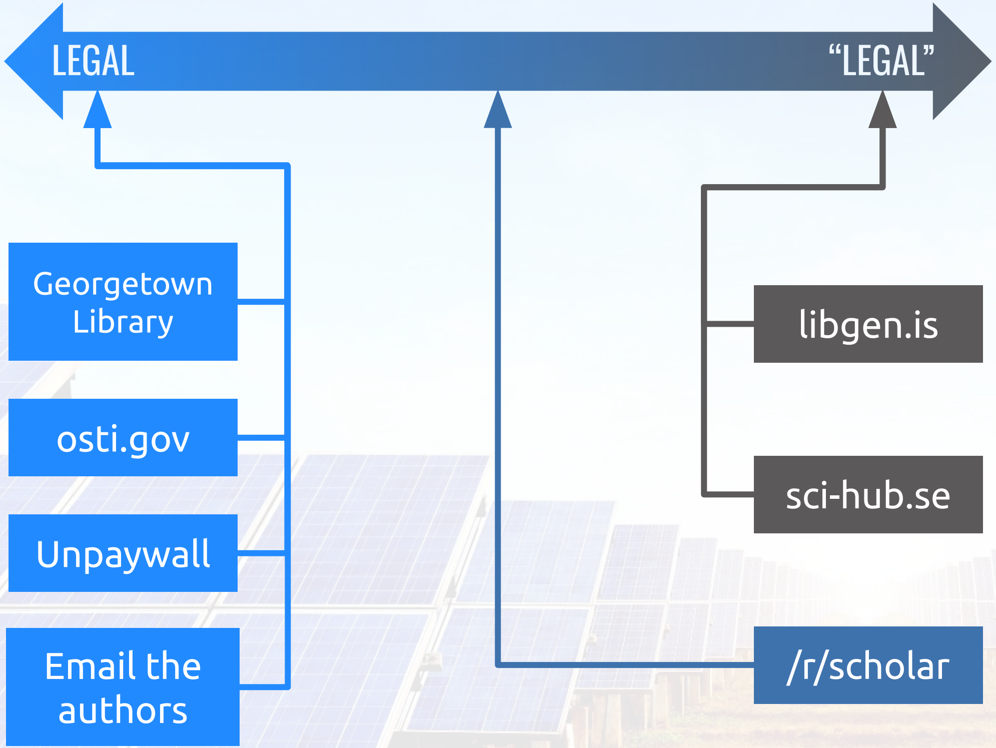
- proper citations
- clever use of tools
- communication
- collaboration

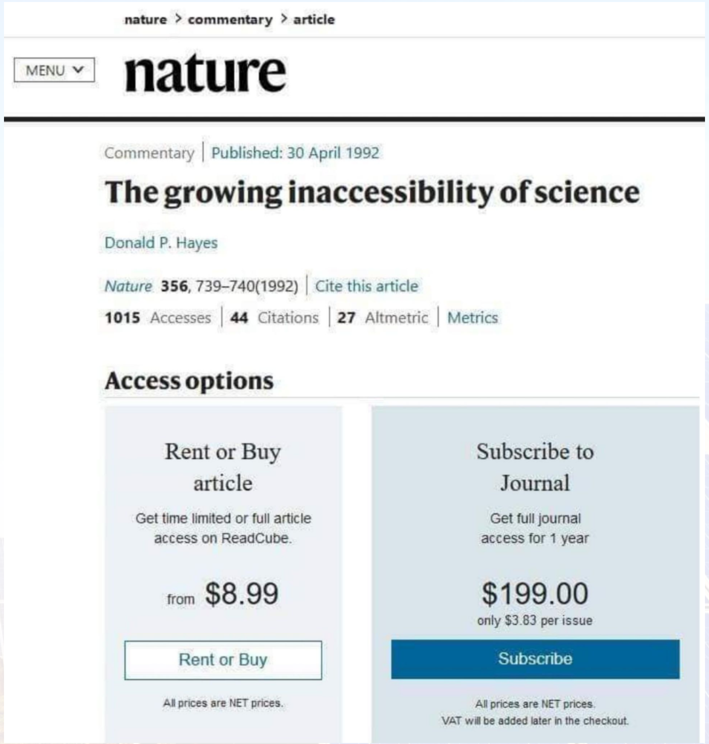
Image by DALL·E 2
PROMPT: "an oil painting in the style of Matisse of a college student using ChatGPT for help on a homework assignment"

(ethics)

(grading)

Aside: Journal Access for Dummies





Course Expectations

(learners)

Expect from me:

(teachers)

- generous scoring
- reasonable leniency
- please just give me an excuse to give you all A's, this really doesn't have to be difficult, as long as you show up and make a cursory effort at participation no one is going to question whether you earned a good grade

(ethics)

(grading)

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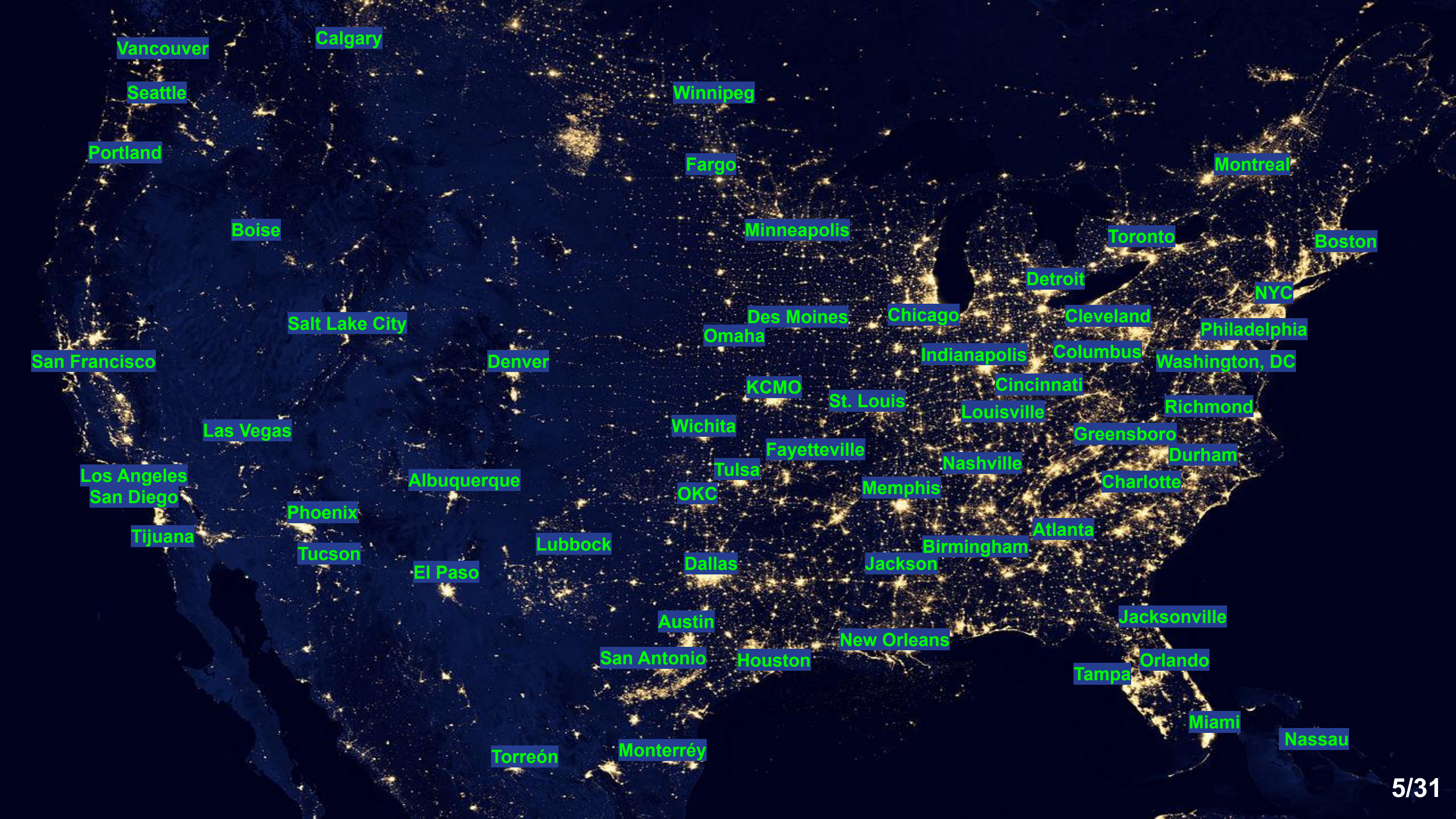
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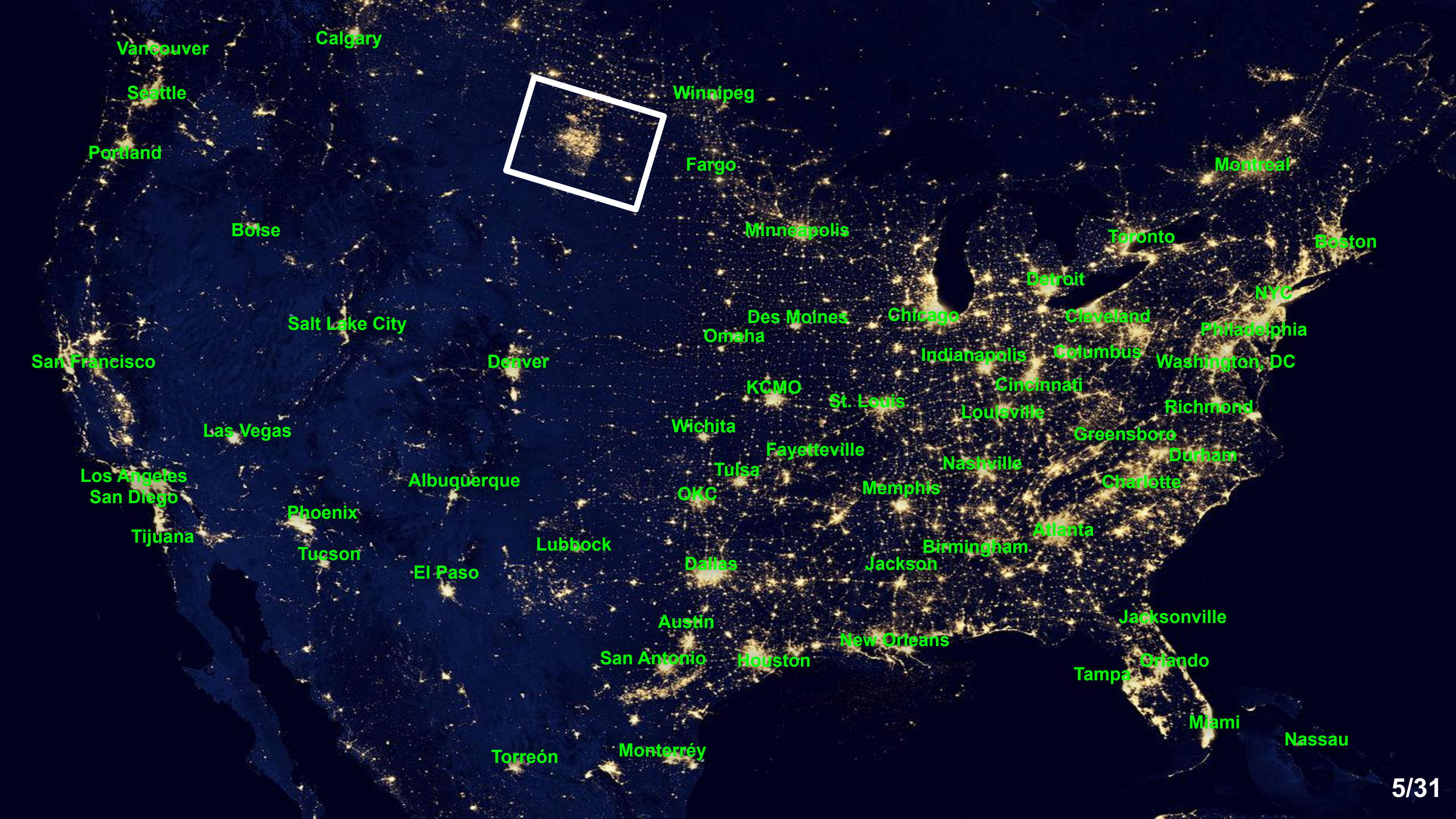
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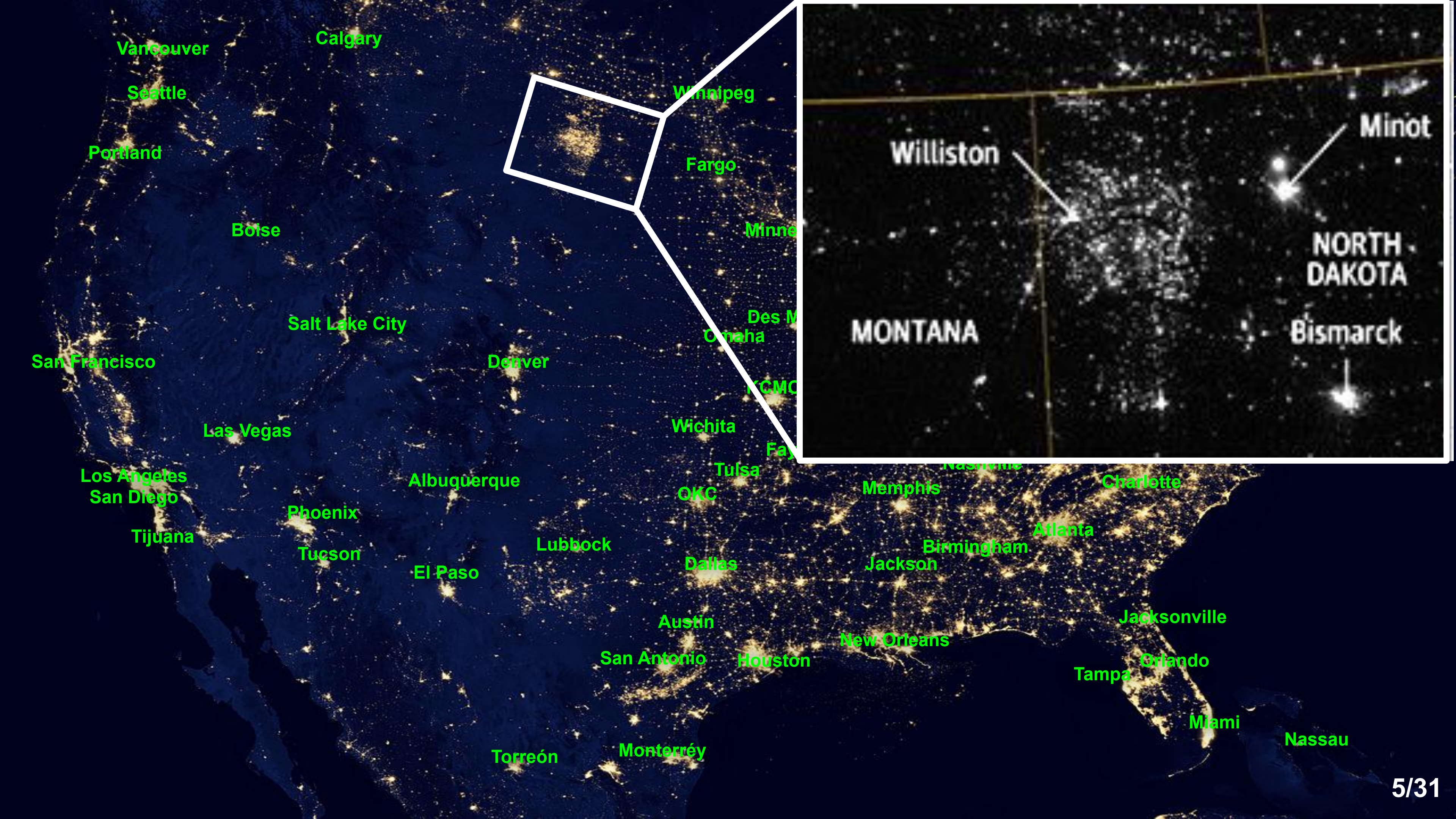
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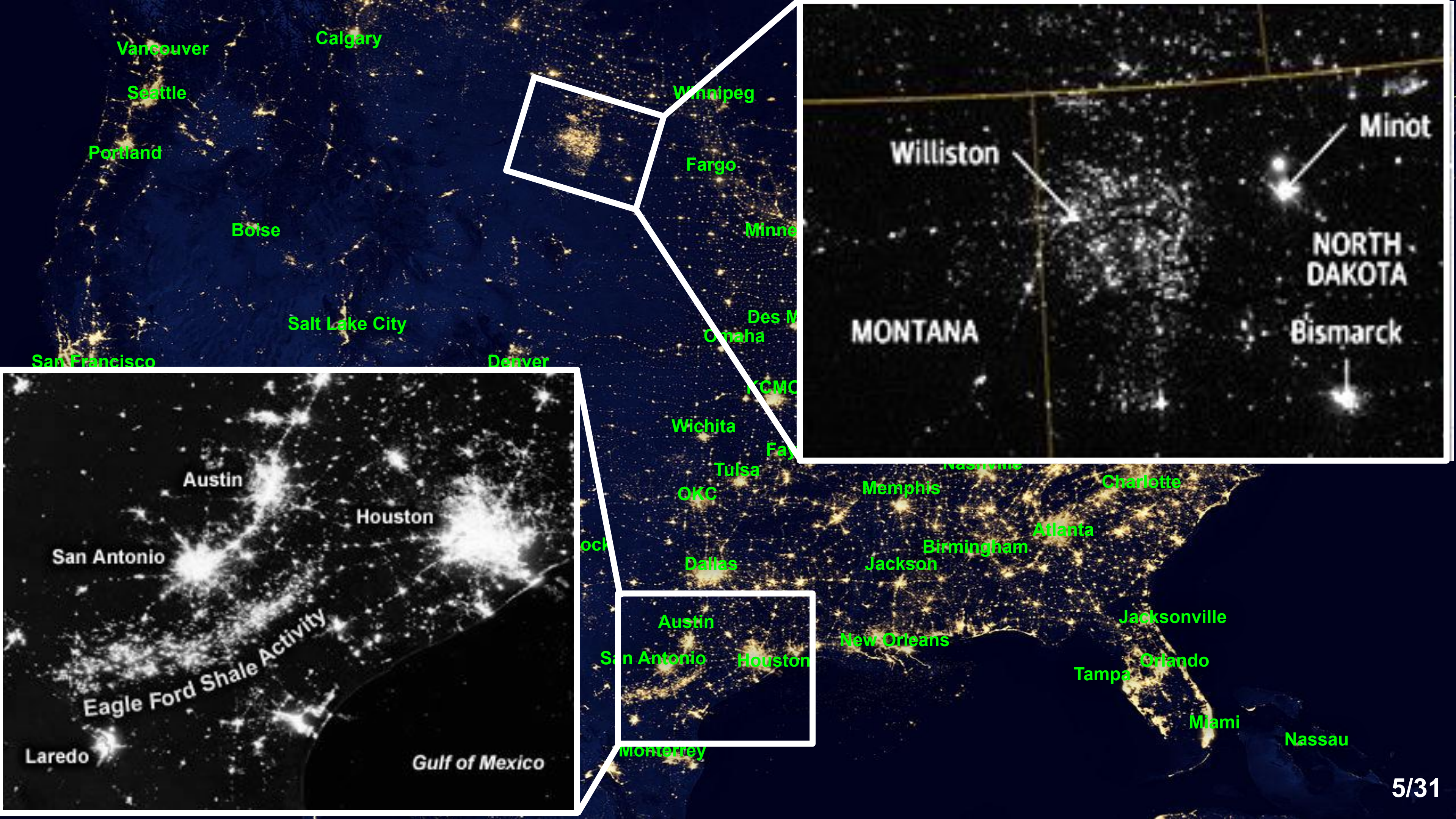
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Williston
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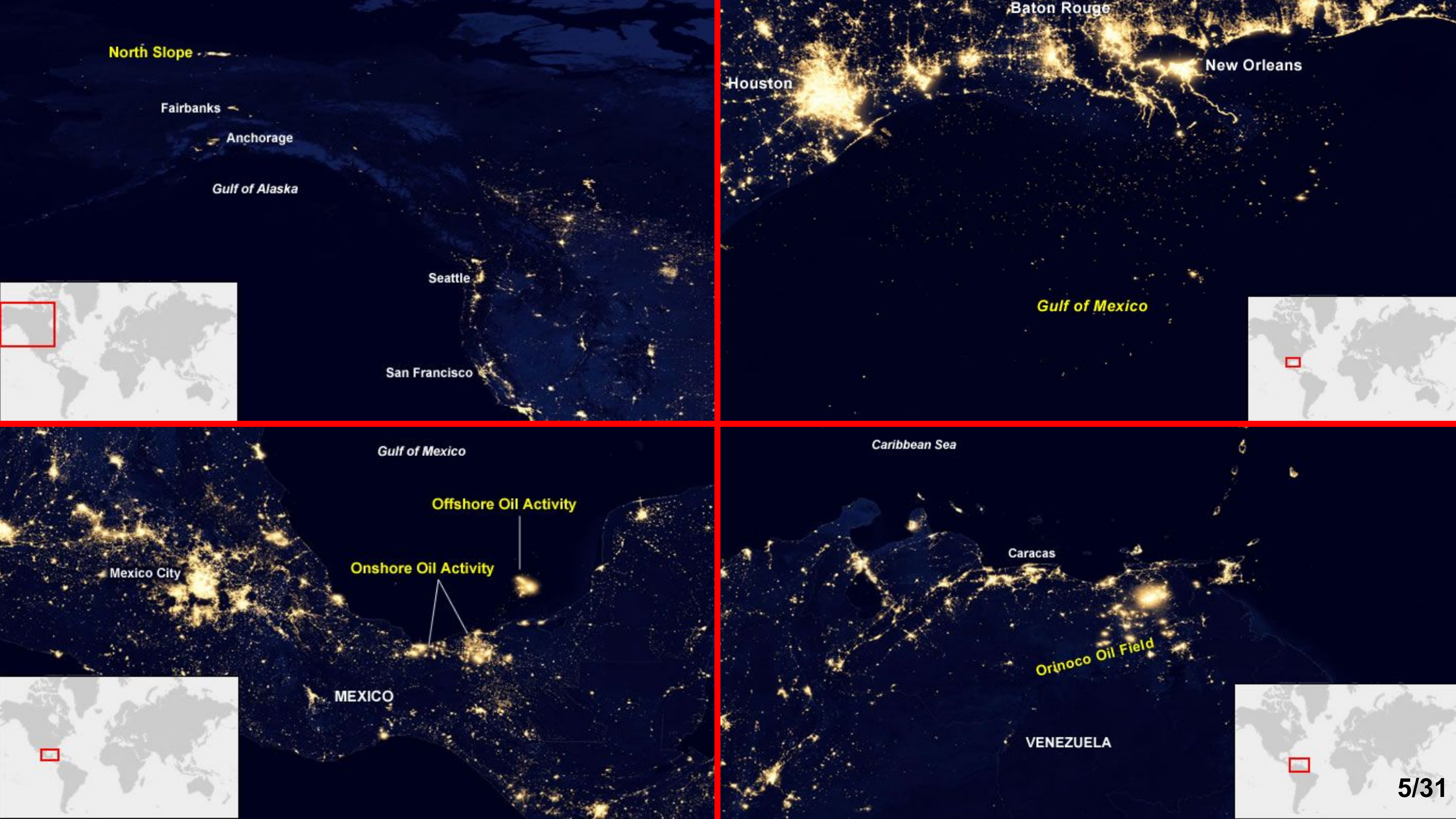
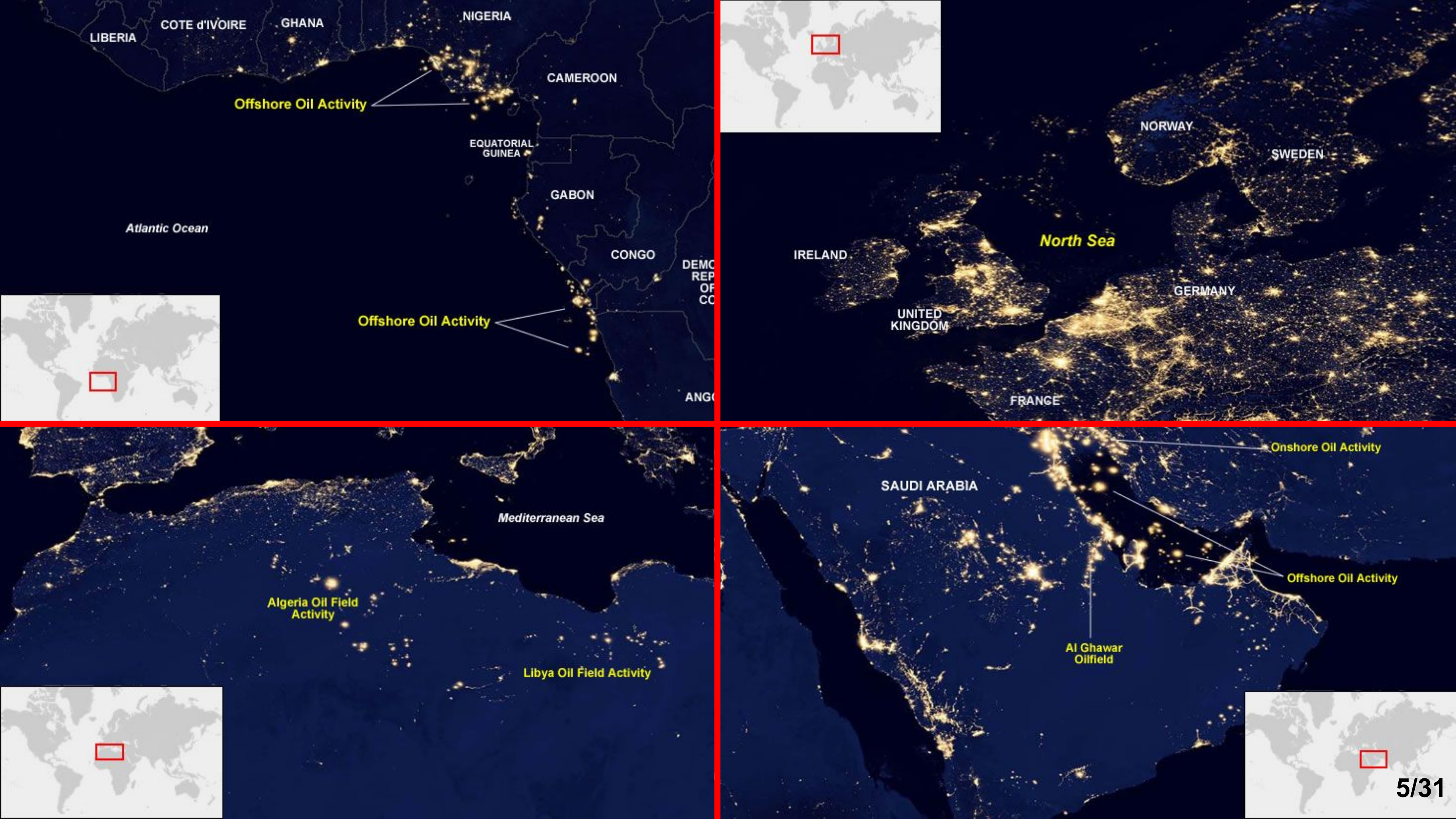
NORTH DAKOTA
MONTANA
Bismarck
Austin
Houston
San Antonio
Eagle Ford Shale Activity
Laredo
Gulf of Mexico

How much methane do we flare?

- 143,000,000,000 m^3/y CH_4
- $29,800,000,000/yr
- 500 Mt/y CO_2^e (2022)
  - *c.f.* total fossil CO_2 emissions: 37.9 Gt/y (2021, global)
  - about as much CO_2 as Brazil
- 3.5% of global supply
  - enough to heat every home in America

https://www.iea.org/energy-system/fossil-fuels/gas-flaring
Energies **2016**, *9*, 14.


North Slope
Fairbanks
Anchorage
Gulf of Alaska
Seattle
San Francisco
Baton Rouge
Houston
New Orleans
Gulf of Mexico
Gulf of Mexico
Offshore Oil Activity
Onshore Oil Activity
Mexico City
MEXICO
Caribbean Sea
Caracas
Orinoco Oil Field
VENEZUELA


LIBERIA
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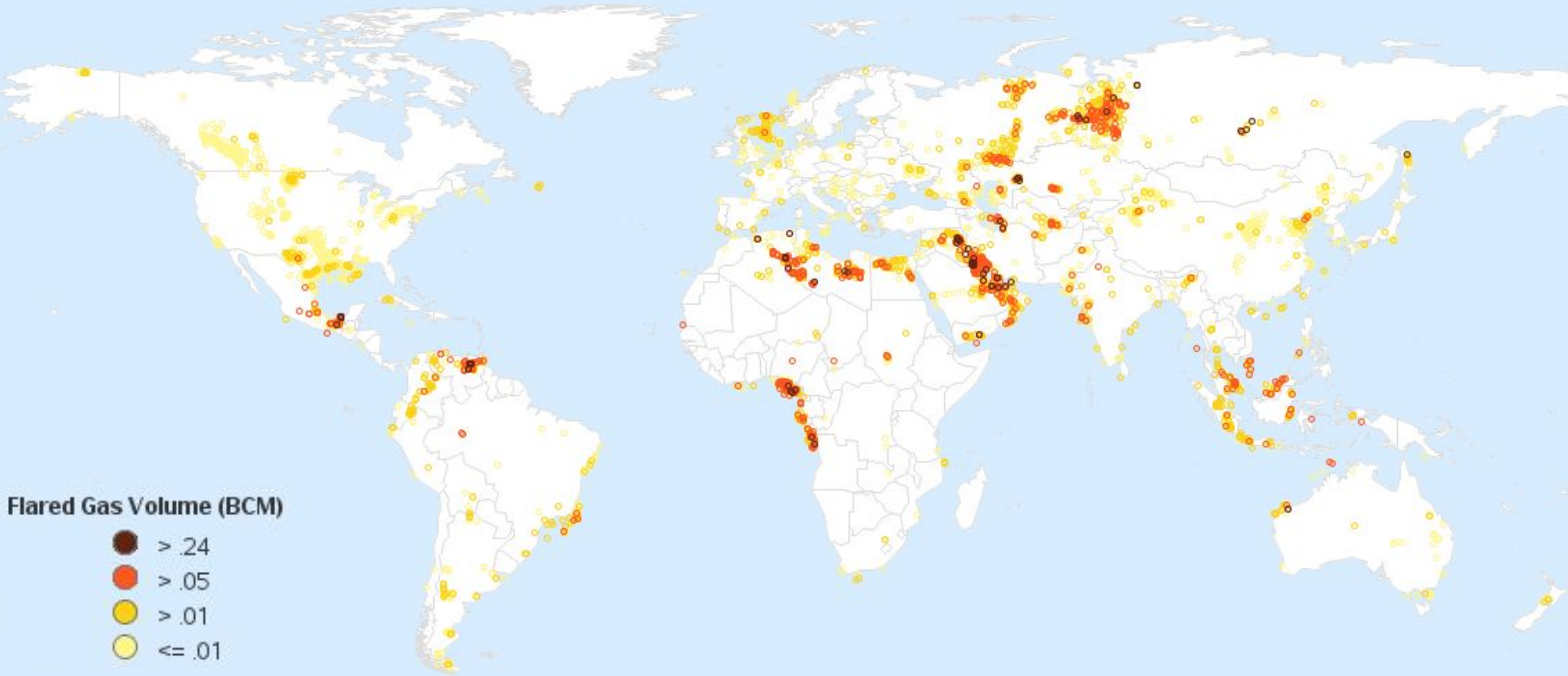
GHANA
NIGERIA
CAMEROON
Offshore Oil Activity
EQUATORIAL GUINEA
GABON
Atlantic Ocean
CONGO
Offshore Oil Activity
NORWAY
SWEDEN
North Sea
IRELAND
GERMANY
UNITED KINGDOM
FRANCE
Mediterranean Sea
Algeria Oil Field Activity
Libya Oil Field Activity
Onshore Oil Activity
SAUDI ARABIA
Offshore Oil Activity
Al Ghawar Oilfield

Where is Methane Flared?

LNG terminals:	2%
Gas refineries:	8%
Production areas:	90%

Elvidge, C. D. *et al Energies* **9**, 14 (2016).

Locations Flaring Natural Gas in 2012



Data source: Christopher Elvidge study 'Methods for Global Survey of Natural Gas Flaring from Visible Infrared Imaging Radiometer Suite Data'

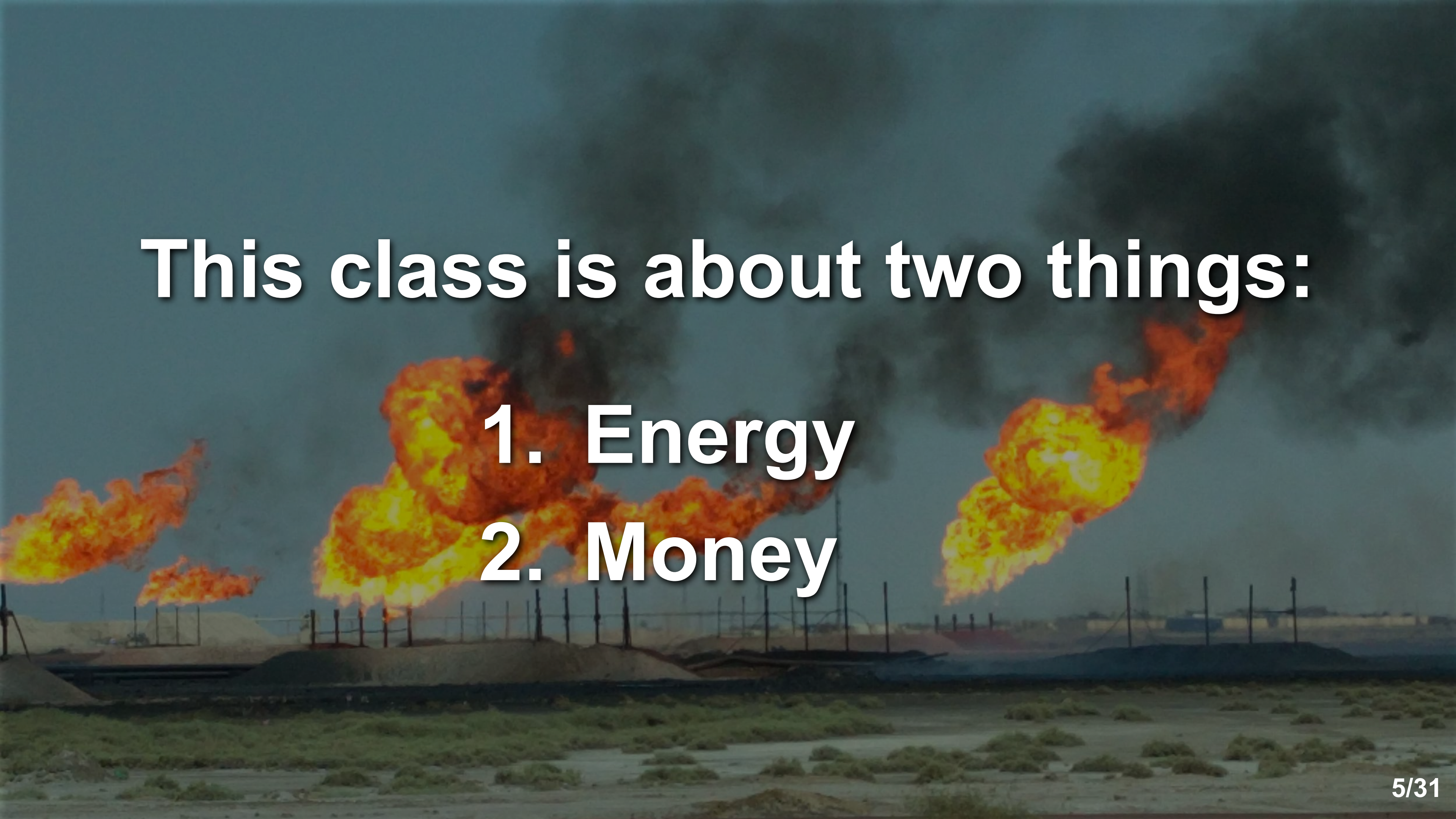
Why do we this?

1. Natural gas is mostly methane (CH_4)
   - Methane is a greenhouse gas 30-200× worse than CO_2

2. Natural gas is a gas*[citation needed]*
   - Extracting natural gas to bring to market requires capture, compression, liquefaction, transport…

3. Natural gas is cheap
   - Gas produced in remote (“stranded”) locations is not profitable to sell

→ **might as well just burn it to CO_2, which is less harmful than CH_4**


This class is about two things:
1. Energy
2. Money

WE INTERRUPT THE
REGULARLY SCHEDULED
PROGRAM TO BRING YOU THIS
IMPORTANT MESSAGE

Newton's Three Laws of Motion

- **1st law: inertia**
  - an object at rest tends to remain at rest
  - an object in motion tends to remain in motion
- **2nd law: force**
  - moving an object with mass requires force
  - force = mass × acceleration
- **3rd law: reaction**
  - every action has an equal and opposite reaction

The Three Laws of Thermodynamics

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The Three Laws of Thermodynamics

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        - ↪ (you can't quit)

Intro to SI units (the metric system)

unit	symbol	*measures*
second	s	*time*

time

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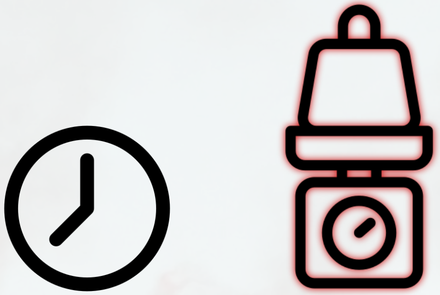
kilogram	kg	*mass*



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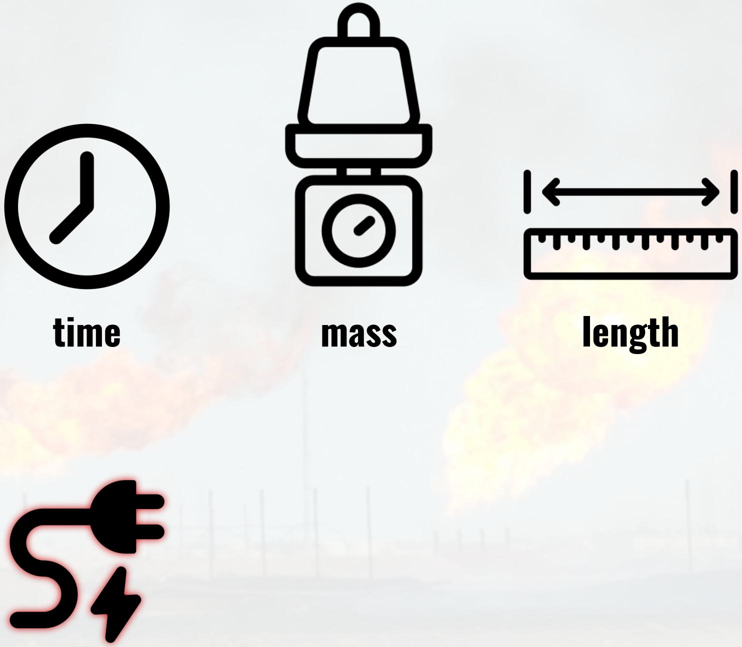

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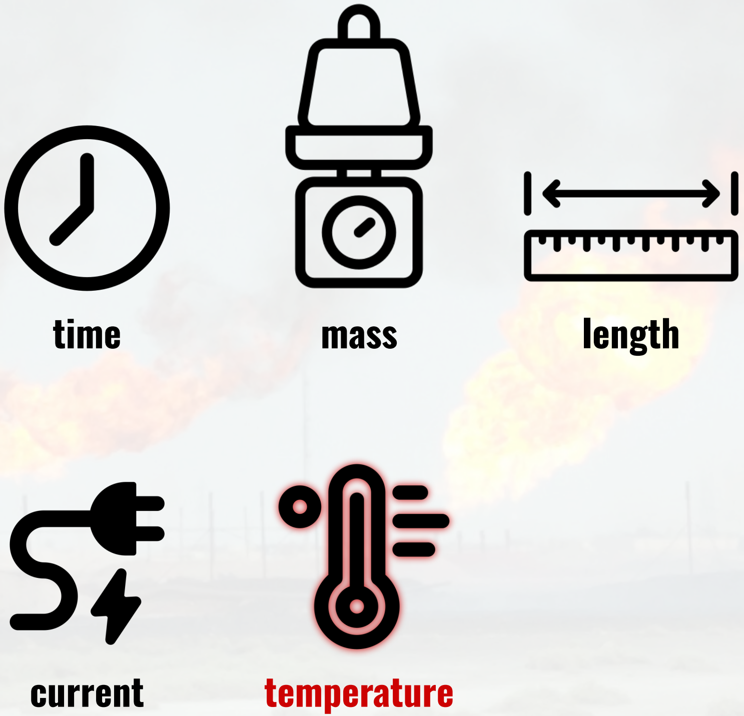

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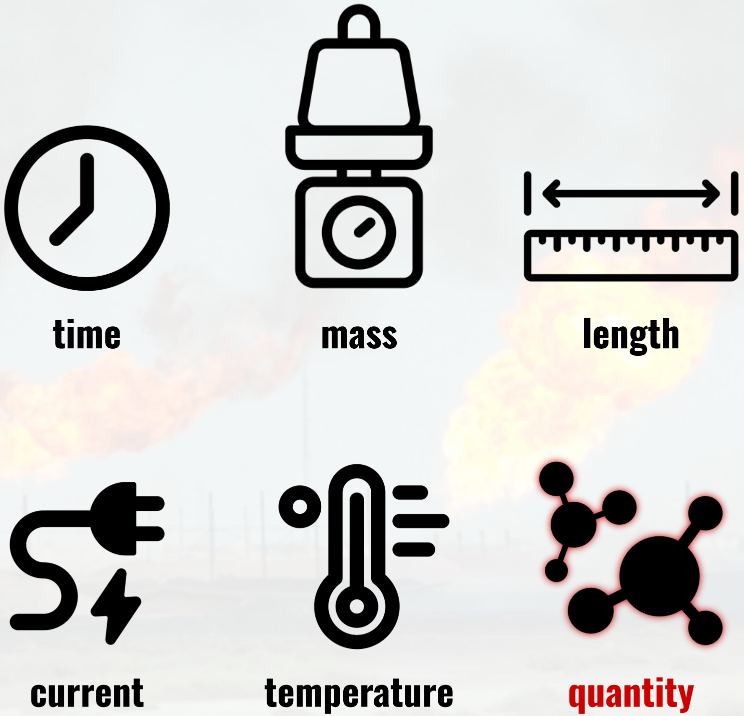

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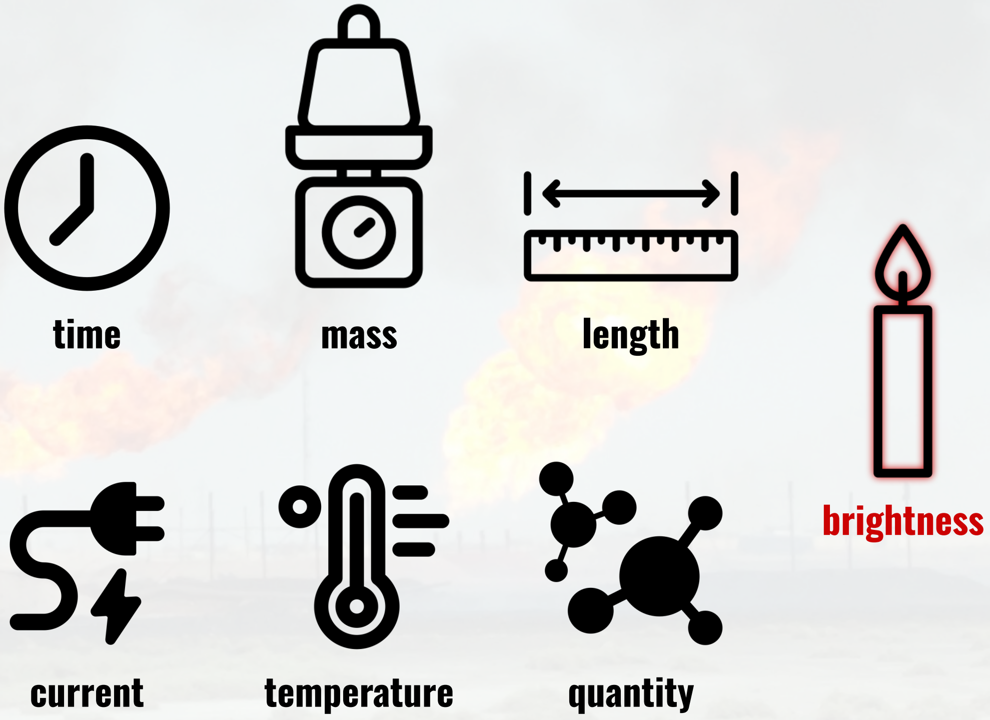

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prefix	symbol	power	order	decimal
atto-	a	10^{-18}	quintillionth	0.000000000000000001
femto-	f	10^{-15}	quadrillionth	0.000000000000001
pico-	p	10^{-12}	trillionth	0.000000000001
nano-	n	10^{-9}	billionth	0.000000001
micro-	µ	10^{-6}	millionth	0.000001
milli-	m	10^{-3}	thousandth	0.001
centi-	c	10^{-2}	hundredth	0.01
deci-	d	10^{-1}	tenth	0.1
--		10^{0}	--	1
deka-	da	10^{1}	ten	10
hecto-	h	10^{2}	hundred	100
kilo-	k	10^{3}	thousand	1000
mega-	M	10^{6}	million	1000000
giga-	G	10^{9}	billion	1000000000
tera-	T	10^{12}	trillion	1000000000000
peta-	P	10^{15}	quadrillion	1000000000000000
exa-	E	10^{18}	quintillion	1000000000000000000

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centi-	***c***	10^{-2}	***hundredth***	***0.01***
deci-	d	10^{-1}	tenth	0.1
--		10^{0}	--	1
deka-	da	10^{1}	ten	10
hecto-	h	10^{2}	hundred	100
kilo-	***k***	10^{3}	***thousand***	***1000***
mega-	***M***	10^{6}	***million***	***1000000***
giga-	***G***	10^{9}	***billion***	***1000000000***
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exa-	***E***	10^{18}	***quintillion***	***1000000000000000000***

SI Units are all interconnected!

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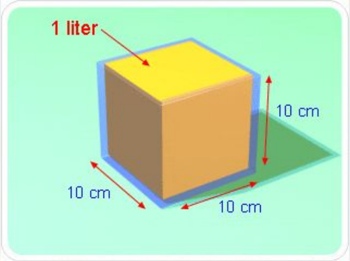

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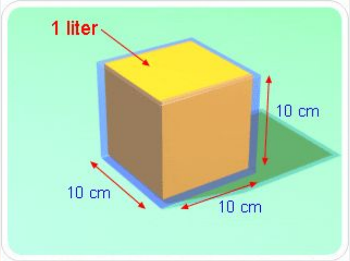

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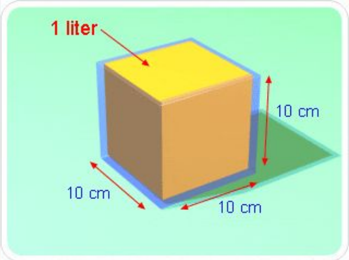

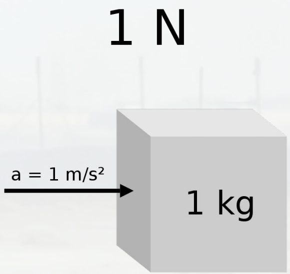

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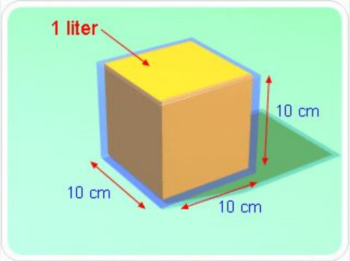

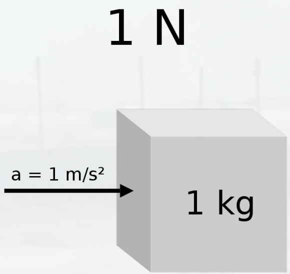

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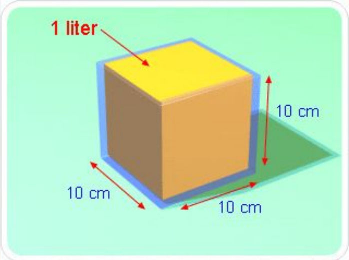

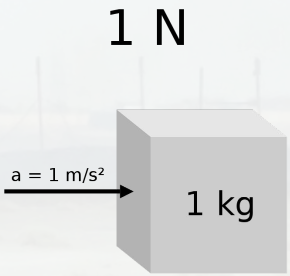

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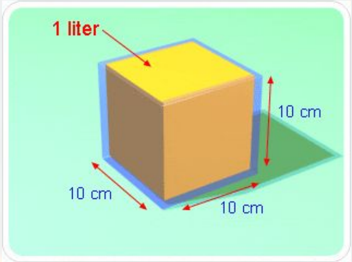

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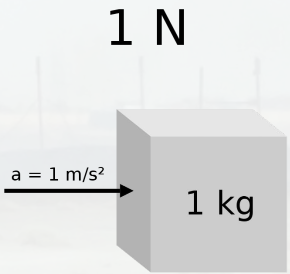
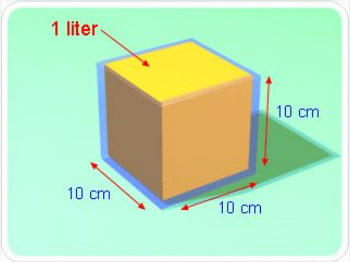
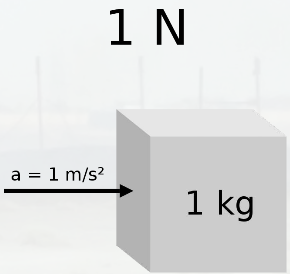
  - 1 N = 1 kg·m/s^2
- 1 joule (J) = work done by 1 N over 1 m
  - 1 J = 1 N·m



SI Units are all interconnected!

- 1 cubic centimeter (cm^3) = 1 milliliter (mL)
  - 1 mL of water: 1 gram (g)
- 1000 mL = 1 liter (L)
  - 1 L of water: 1 kilogram (kg)
- 1 newton (N) = force to accelerate 1 kg by 1 m/s^2
  - 1 N = 1 $kg \cdot m/s^2$
- 1 joule (J) = work done by 1 N over 1 m
  - 1 J = 1 N·m
- 1 watt (W) = power of 1 Joule over 1 sec





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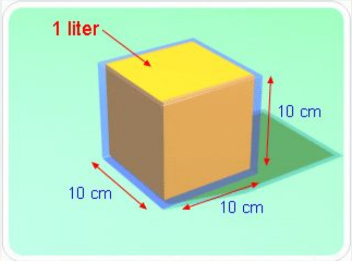
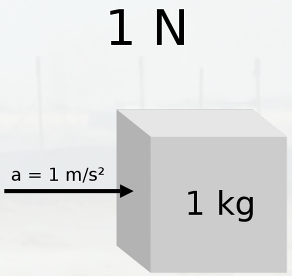
  - 1 W = 1 J/s





INTERNATIONAL SYSTEM OF UNITS (SI)

SI Base Units

Base Quantity	Name	Symbol
Length	meter	m
Mass	kilogram	kg
Time	second	s
Electric current	ampere	A
Thermodynamic temperature	kelvin	K
Amount of substance	mole	mol
Luminous intensity	candela	cd

SI Derived Units

Derived Quantity	Name	Symbol	Equivalent SI Units
Frequency	hertz	Hz	s^{-1}
Force	newton	N	$m \cdot kg \cdot s^{-2}$
Pressure	pascal	Pa	N/m^2
Energy	joule	J	N•m
Power	watt	W	J/s
Electric charge	coulomb	C	s•A
Electric potential	volt	V	W/A
Electric resistance	ohm	Ω	V/A
Celsius temperature	degree Celsius	°C	K*

*Unit degree Celsius is equal in magnitude to unit kelvin

SI Prefixes

Factor	Name	Symbol	Numerical Value
10^{12}	tera	T	1 000 000 000 000
10^{9}	giga	G	1 000 000 000
10^{6}	mega	M	1 000 000
10^{3}	kilo	k	1 000
10^{2}	hecto	h	100
10^{1}	deka	da	10
10^{-1}	deci	d	0.1
10^{-2}	centi	c	0.01
10^{-3}	milli	m	0.001
10^{-6}	micro	μ	0.000 001
10^{-9}	nano	n	0.000 000 001
10^{-12}	pico	p	0.000 000 000 001

Adapted from NIST Special Publication 811.
SI rules and style conventions recommend using spaces rather than commas to separate groups of three digits.

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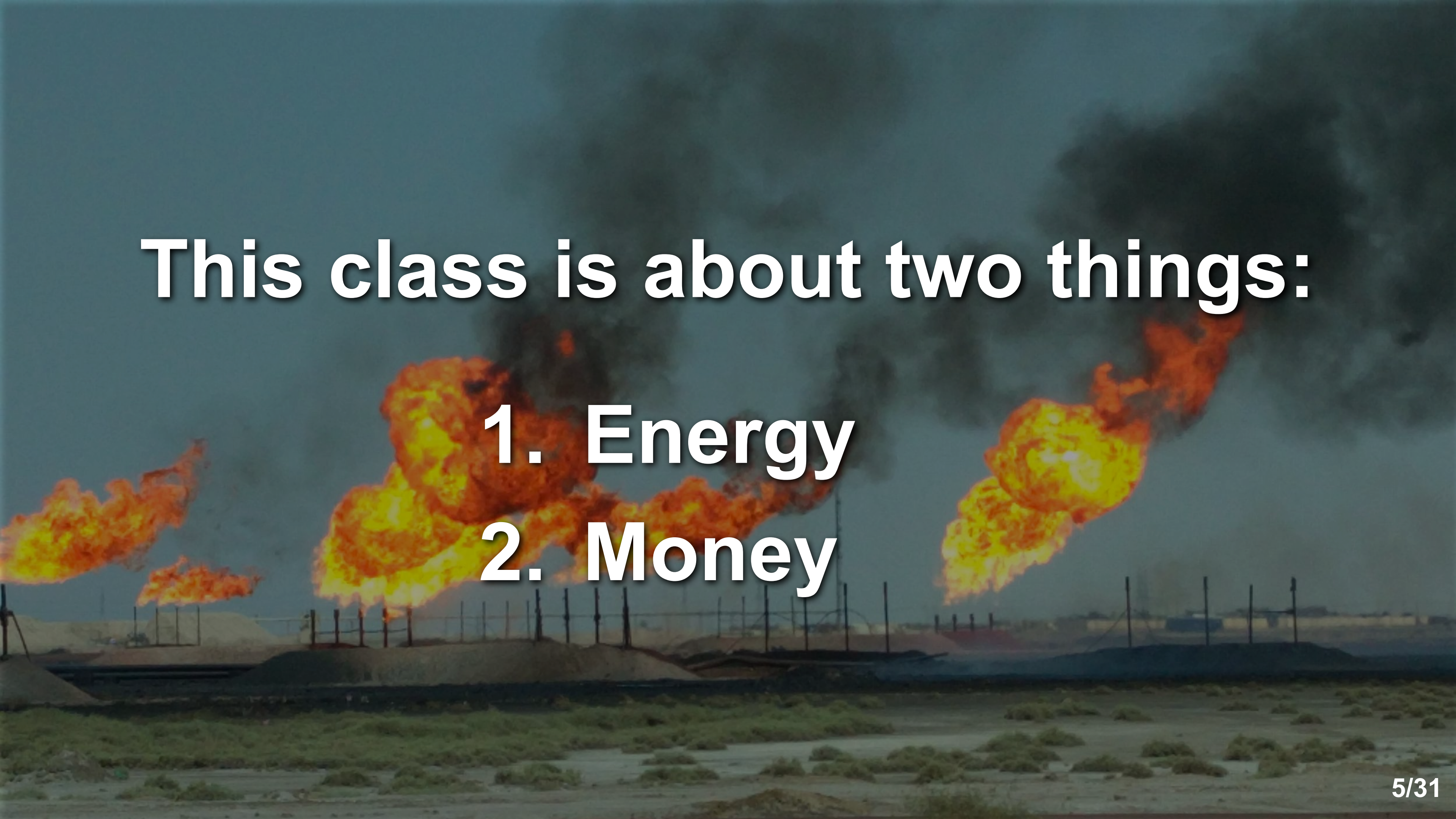
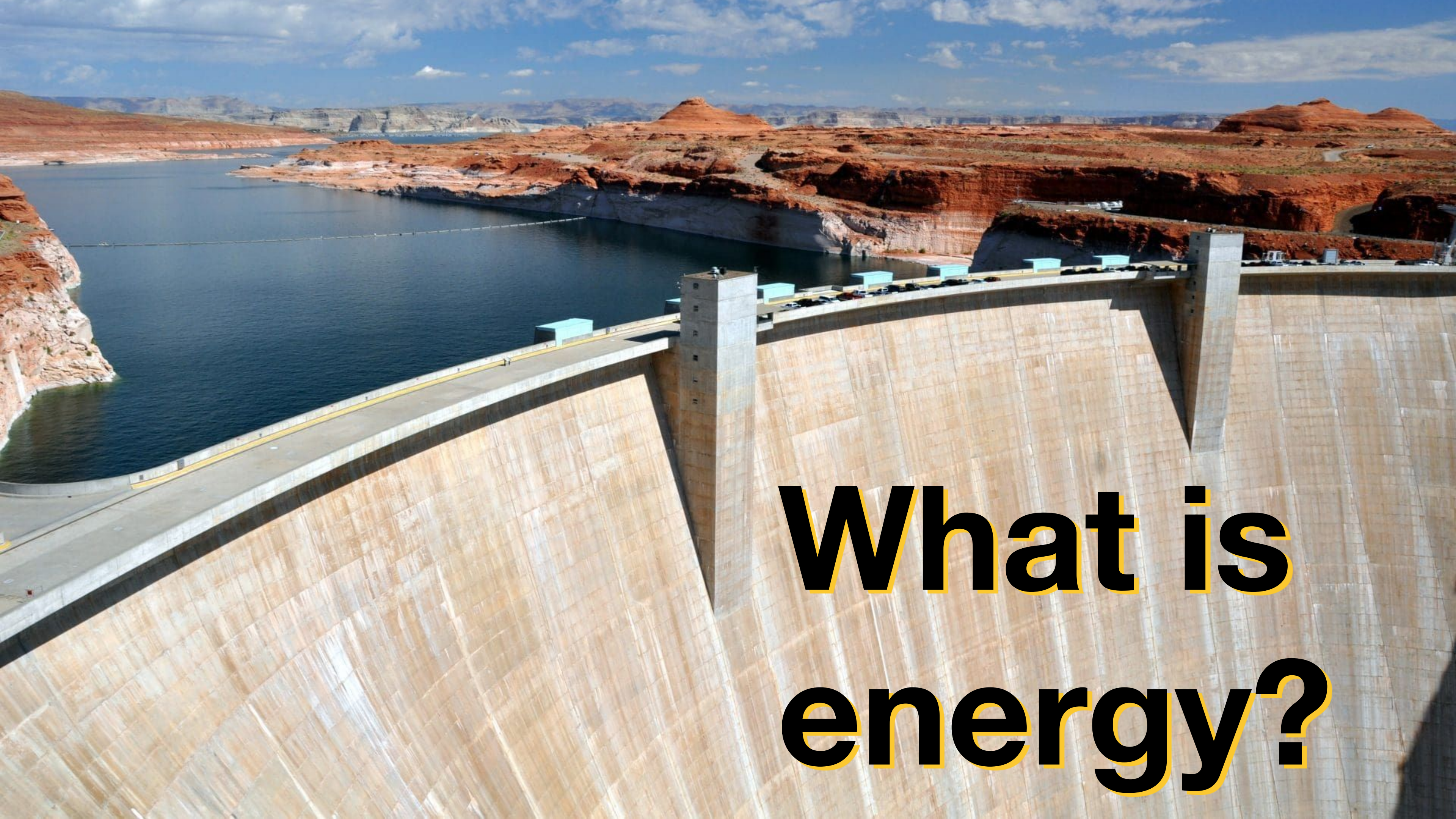
AP6899


AND NOW BACK TO
OUR REGULARLY
SCHEDULED
PROGRAMMING



This class is about two things:

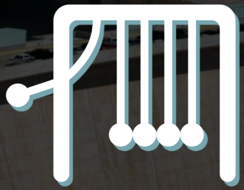
1. Energy
2. Money


What is
energy?

Types of Energy

thermal

elastic



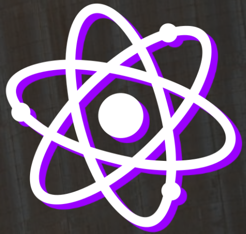
mechanical

gravitational

chemical

magnetic

electrical

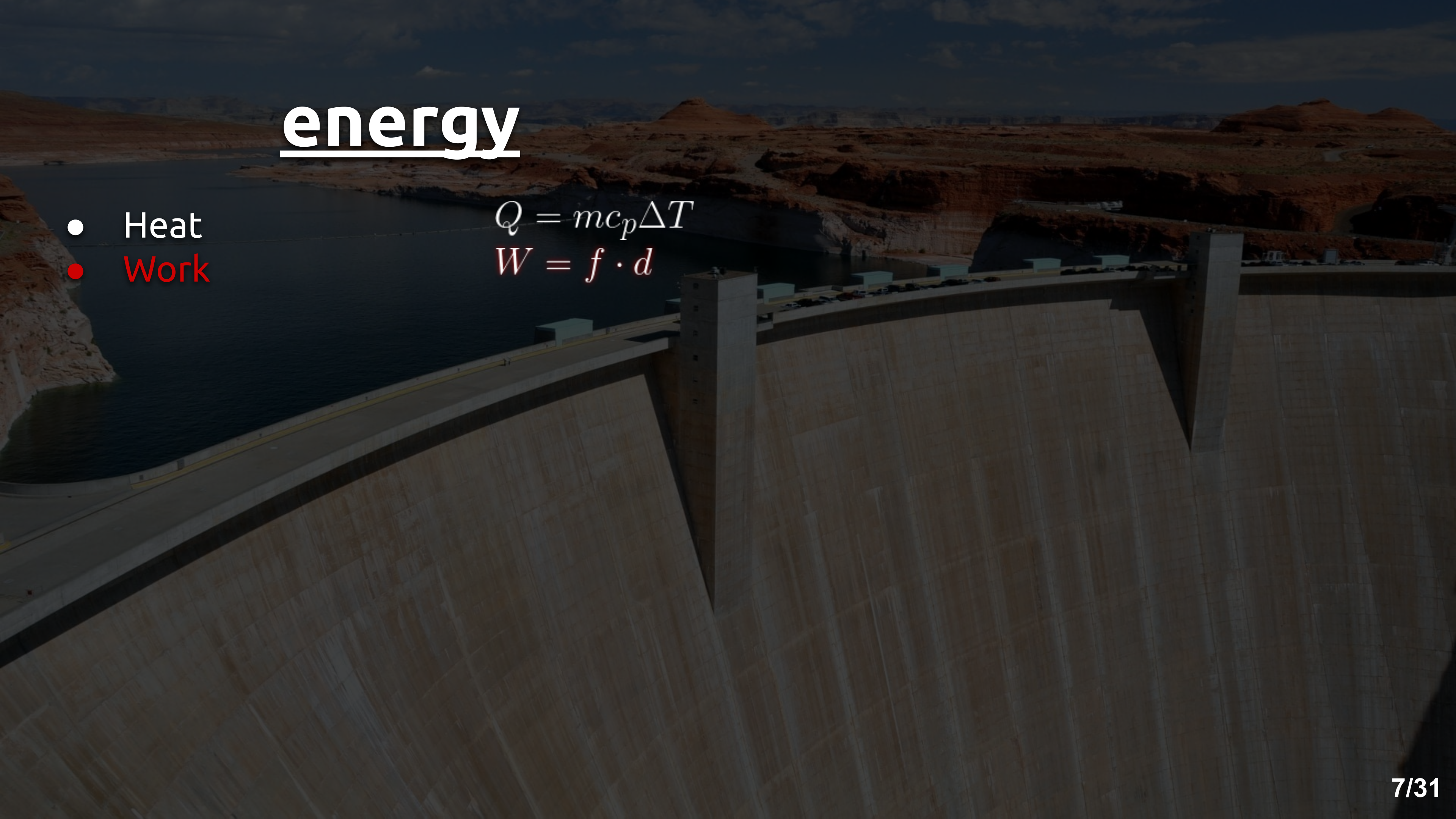


nuclear

energy

energy

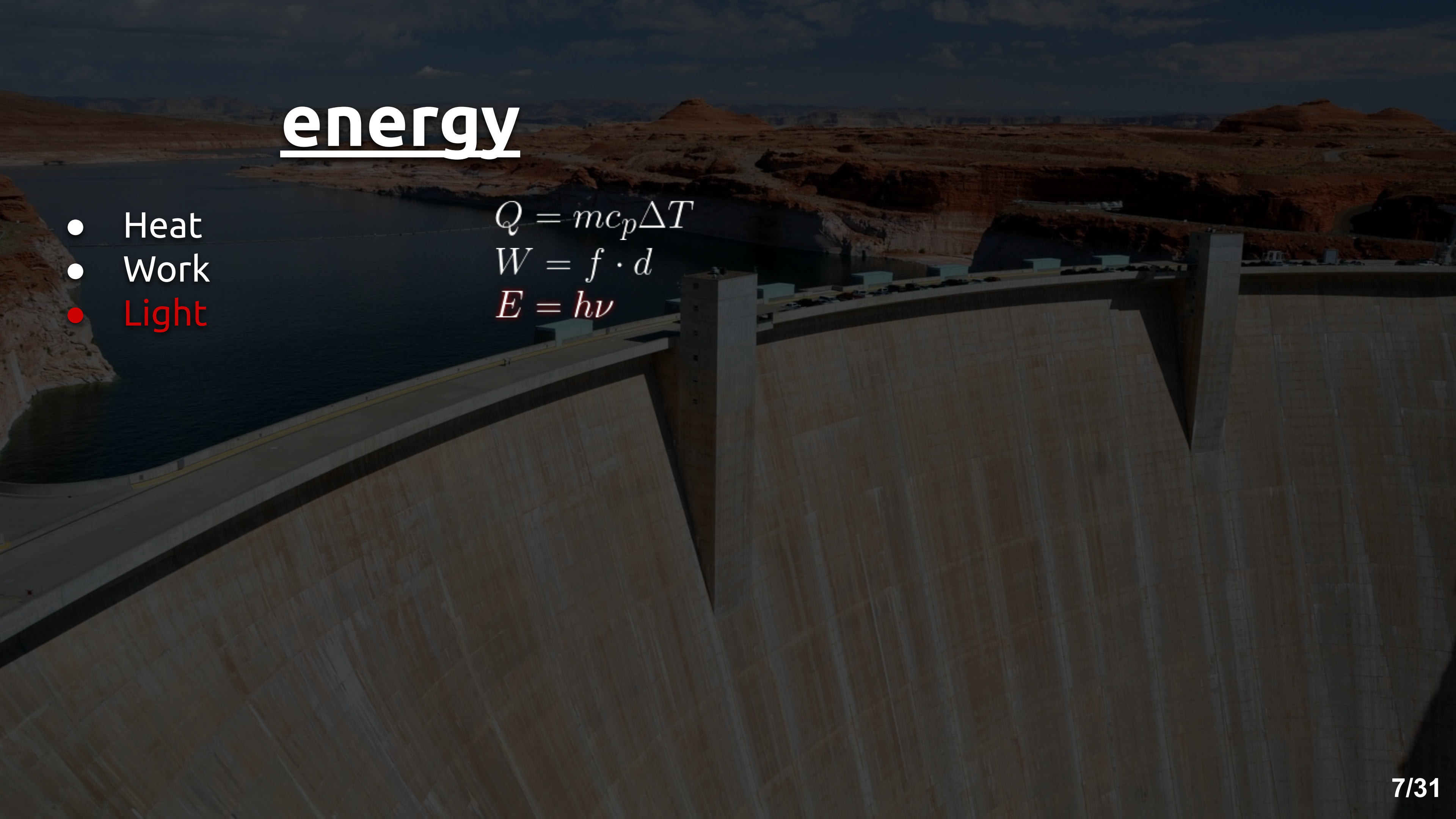
- Heat $Q = mc_p\Delta T$



energy

- Heat
- Work

$$Q = mc_p\Delta T$$
$$W = f \cdot d$$



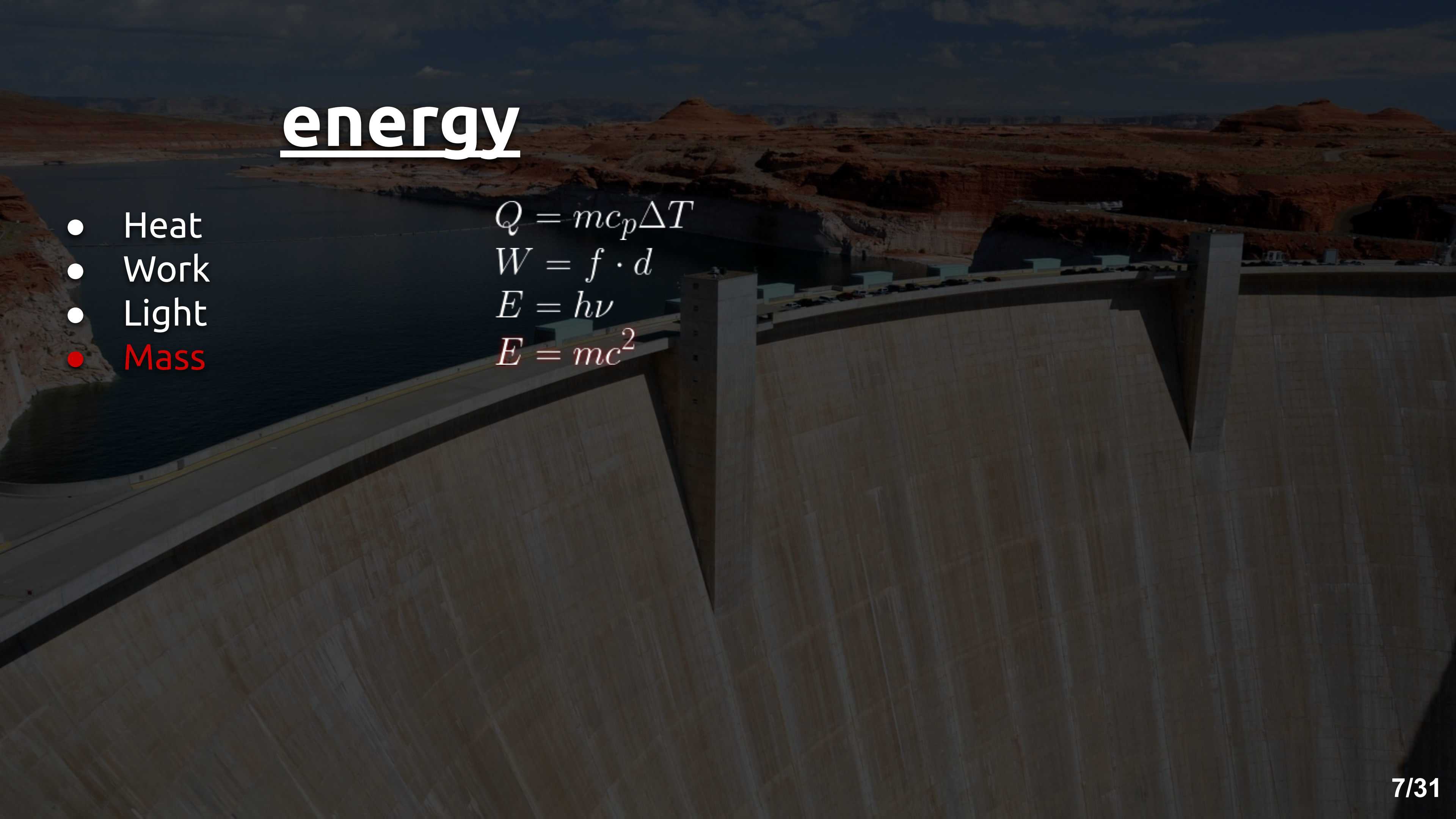
energy

- Heat
- Work
- Light

$$Q = mc_p\Delta T$$

$$W = f \cdot d$$

$$E = h\nu$$


energy
Heat
Work
Light
Mass
$Q = mc_p\Delta T$
$W = f \cdot d$
$E = h\nu$
$E = mc^2$

energy

- Heat
- Work
- Light
- Mass
- Motion (kinetic)

$$Q = mc_p\Delta T$$
$$W = f \cdot d$$
$$E = h\nu$$
$$E = mc^2$$

energy

- Heat
- Work
- Light
- Mass
- Motion (kinetic)
  - Linear

$$Q = mc_p\Delta T$$

$$W = f \cdot d$$

$$E = h\nu$$

$$E = mc^2$$

$$E_{\text{lin}} = \frac{1}{2}mv^2$$

energy

- Heat
- Work
- Light
- Mass
- Motion (kinetic)
  - Linear
  - Rotational

$$Q = mc_p\Delta T$$

$$W = f \cdot d$$

$$E = h\nu$$

$$E = mc^2$$

$$E_{\text{lin}} = \frac{1}{2}mv^2$$

$$E_{\text{rot}} = \frac{1}{2}I\omega^2$$

energy

- Heat
- Work
- Light
- Mass
- Motion (kinetic)
  - Linear
  - Rotational
- Position (potential)

$$Q = mc_p\Delta T$$

$$W = f \cdot d$$

$$E = h\nu$$

$$E = mc^2$$

$$E_{\text{lin}} = \frac{1}{2}mv^2$$

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energy

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- Position (potential)
  - Gravitational $U_{\text{grav}} = mgh$

energy

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  - Spring / Elastic — $U_{\text{spring}} = \frac{1}{2}kx^2$

energy

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  - Chemical $\Delta H^{\ominus}_{\text{rxn}} = \sum_i a_i \Delta_{\text{f}} H^{\ominus}_{\text{products}} - \sum_j b_j \Delta_{\text{f}} H^{\ominus}_{\text{reactants}}$

energy

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    $$\Delta H^\circ_{\text{rxn}} = \sum_i a_i \Delta H^\circ_{\text{f products}} - \sum_j b_j \Delta_{\text{f}} H^\circ_{\text{reactants}}$$

don't worry about it

energy

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  - Chemical $\Delta H^\circ_{\text{rxn}} = \sum_i a_i \Delta H^\circ_{\text{f, products}} - \sum_j b_j \Delta H^\circ_{\text{f, reactants}}$

don't worry about it

units: all joules (J)

energy

NOT energy

- Heat $Q = mc_p \Delta T$
- Work $W = f \cdot d$
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don't worry about it

units: all joules (J)

NOT energy

- Power:

energy

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don't worry about it

units: all joules (J)

NOT energy

- Power:
  - rate of energy per time

energy

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don't worry about it

units: all joules (J)

NOT energy

- Power:
  - rate of energy per time
  - **unit:** watt (W) = 1 J/sec

energy

- Heat $Q = mc_p\Delta T$
- Work $W = f \cdot d$
- Light $E = h\nu$
- Mass $E = mc^2$
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don't worry about it

units: all joules (J)

NOT energy

- Power:
  - rate of energy per time
  - **unit:** watt (W) = 1 J/sec
- Force:

energy

- Heat — $Q = mc_p\Delta T$
- Work — $W = f \cdot d$
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don't worry about it

units: all joules (J)

NOT energy

- Power:
  - rate of energy per time
  - **unit:** watt (W) = 1 J/sec
- Force:
  - rate of energy per distance

energy

- Heat $Q = mc_p\Delta T$
- Work $W = f \cdot d$
- Light $E = h\nu$
- Mass $E = mc^2$
- Motion (kinetic)
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don't worry about it

units: all joules (J)

NOT energy

- Power:
  - rate of energy per time
  - **unit:** watt (W) = 1 J/sec
- Force:
  - rate of energy per distance
  - **unit:** newton (N) = 1 J/m

energy

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don't worry about it

units: all joules (J)

NOT energy

- Power:
  - rate of energy per time
  - **unit:** watt (W) = 1 J/sec
- Force:
  - rate of energy per distance
  - **unit:** newton (N) = 1 J/m
- Voltage:

energy

- Heat $Q = mc_p\Delta T$
- Work $W = f \cdot d$
- Light $E = h\nu$
- Mass $E = mc^2$
- Motion (kinetic)
  - Linear $E_{\text{lin}} = \frac{1}{2}mv^2$
  - Rotational $E_{\text{rot}} = \frac{1}{2}I\omega^2$
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don't worry about it

units: all joules (J)

NOT energy

- Power:
  - rate of energy per time
  - **unit:** watt (W) = 1 J/sec
- Force:
  - rate of energy per distance
  - **unit:** newton (N) = 1 J/m
- Voltage:
  - rate of energy per charge

energy

NOT energy

- Heat $Q = mc_p\Delta T$
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don't worry about it

units: all joules (J)

- Power:
  - rate of energy per time
  - **unit:** watt (W) = 1 J/sec
- Force:
  - rate of energy per distance
  - **unit:** newton (N) = 1 J/m
- Voltage:
  - rate of energy per charge
  - **unit:** volt (V) = 1 J/C

energy

- Heat $Q = mc_p\Delta T$
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don't worry about it

units: all joules (J)

NOT energy

- Power:
  - rate of energy per time
  - **unit:** watt (W) = 1 J/sec
- Force:
  - rate of energy per distance
  - **unit:** newton (N) = 1 J/m
- Voltage:
  - rate of energy per charge
  - **unit:** volt (V) = 1 J/C
- Pressure:

energy

- Heat $Q = mc_p\Delta T$
- Work $W = f \cdot d$
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- Mass $E = mc^2$
- Motion (kinetic)
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- Position (potential)
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  - Chemical ~~$\Delta H^\circ_{\text{rxn}} = \sum_i a_i \Delta H^\circ_{\text{f products}} - \sum_j b_j \Delta H^\circ_{\text{f reactants}}$~~ *don't worry about it*

units: all joules (J)

NOT energy

- Power:
  - rate of energy per time
  - **unit:** watt (W) = 1 J/sec
- Force:
  - rate of energy per distance
  - **unit:** newton (N) = 1 J/m
- Voltage:
  - rate of energy per charge
  - **unit:** volt (V) = 1 J/C
- Pressure:
  - rate of energy per volume

energy

- Heat — $Q = mc_p\Delta T$
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don't worry about it

units: all joules (J)

NOT energy

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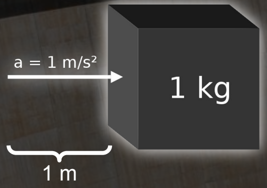
  - **unit:** watt (W) = 1 J/sec
- Force:
  - rate of energy per distance
  - **unit:** newton (N) = 1 J/m
- Voltage:
  - rate of energy per charge
  - **unit:** volt (V) = 1 J/C
- Pressure:
  - rate of energy per volume
  - **unit:** pascal (Pa) = J/m^3

Joules (J)

- joule (J)



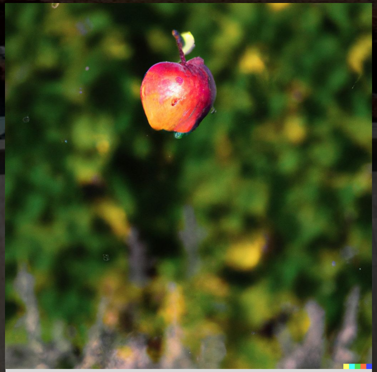


Image by DALL·E 2
PROMPT: "a high-resolution photograph of an apple in midair falling from a tree"

one joule: energy of a small (~100 g) apple falling ~1 meter

Joules (J)

- joule (J)
- kilojoule (kJ): 10^3 J

one kilojoule: energy in a typical watch battery (button cell)

Joules (J)

- joule (J)
- kilojoule (kJ): 10^3 J
- megajoule (MJ): 10^6 J

one megajoule: energy in a fully charged car battery

Joules (J)

- joule (J)
- kilojoule (kJ): 10^3 J
- megajoule (MJ): 10^6 J
- gigajoule (GJ): 10^9 J

one gigajoule: total energy of an average lightning bolt

-OR-

two propane tanks

Joules (J)

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- kilojoule (kJ): 10^3 J
- megajoule (MJ): 10^6 J
- gigajoule (GJ): 10^9 J
- terajoule (TJ): 10^{12} J

one terajoule: average annual electricity use of a American neighborhood (~25 homes)

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- terajoule (TJ): 10^{12} J
- exajoule (EJ): 10^{18} J

one exajoule: 1% of total annual American energy usage

calories and Calories (cal_{th} / kcal)

"thermal calorie"

(cal_{th}, cal, calorie)

- energy to heat 1 gram of water by 1 °C
- 1 cal = 4.184 J

"food calorie"

(kcal, kilocalorie, Cal, Calorie)

- energy to heat 1 *kilo*gram of water by 1 °C
- 1 kcal = 4.184 kJ = 4,184 J
- the one what's on the back of the box
- i am aware this is dumb and confusing

British Thermal Units (BTU)

- 1 British thermal unit (BTU or Btu):

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- "quad": quadrillion (10^{15}) BTU
  - ≈ 1.055 EJ (~1% of annual US energy demand)

watt-hours (Wh, W·h, W·hr)

power = energy ÷ time

power × time = energy

1 Wh = 3600 J

1 kWh = 3600 kJ

1 MWh = 3600 MJ ...

$$1\ \mathrm{W} = 1\ \frac{\mathrm{J}}{\mathrm{sec}}$$

$$1\ \mathrm{W}\cdot\mathrm{h} = (1\ \mathrm{W}) \times (1\ \mathrm{hr})$$

$$(1\ \mathrm{W}) \times (1\ \mathrm{hr}) = (1\ \frac{\mathrm{J}}{\mathrm{sec}}) \times (1\ \mathrm{hr} \times \frac{3600\ \mathrm{sec}}{1\ \mathrm{hr}})$$

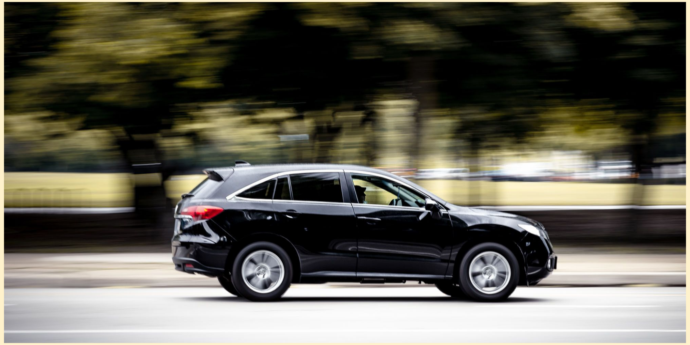
$$= (1\ \frac{\mathrm{J}}{\cancel{\mathrm{sec}}}) \times (1\ \cancel{\mathrm{hr}} \times \frac{3600\ \cancel{\mathrm{sec}}}{1\ \cancel{\mathrm{hr}}})$$

$$= 3600\ \mathrm{J}$$

- same logic for watt-days, watt-years
- global annual power use: ~20 TW·y


Which
has
more
energy?

Which has more energy?

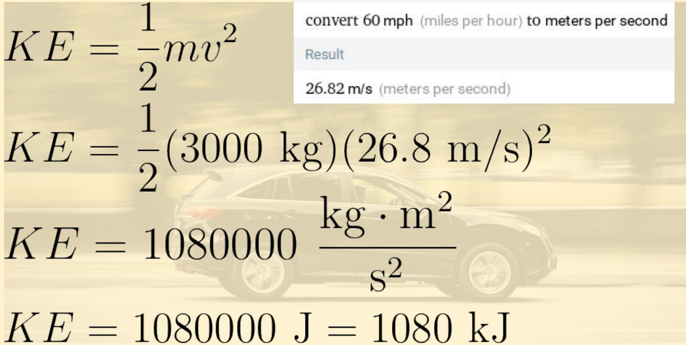


a 3-ton SUV driving down the freeway at 60 mph

?

a regular-sized Snickers bar

Which has more energy?



Input interpretation

convert 60 mph (miles per hour) to meters per second

Result

26.82 m/s (meters per second)

$$KE = \frac{1}{2}mv^2$$

$$KE = \frac{1}{2}(3000\ \text{kg})(26.8\ \text{m/s})^2$$

$$KE = 1080000\ \frac{\text{kg}\cdot\text{m}^2}{\text{s}^2}$$

$$KE = 1080000\ \text{J} = 1080\ \text{kJ}$$

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Nutrition Facts

Serving Size 2.07 oz (58.7g)
Servings Per Container 1 package

Amount Per Serving	
Calories 280	Calories from Fat 130
	% Daily Value*
Total Fat 14g	22%
Saturated Fat 5g	25%
Trans Fat 0g	0%
Cholesterol 5mg	2%
Sodium 140mg	6%
Total Carbohydrate 35g	12%
Fiber 1g	4%
Sugars 30g	
Protein 4g	
Vitamin A 0% • Vitamin C	0%
Calcium 4% • Iron	2%

* Percent Daily Values are based on a 2,000 calorie diet. Your daily values may be higher or lower depending on your caloric needs.

	Calories:	2,000	2,500
Total Fat	Less Than	65g	80g
Sat Fat	Less Than	20g	25g
Cholesterol	Less Than	300mg	300mg
Sodium	Less Than	2,400mg	2,400mg
Total Carbohydrate		300g	375g
Dietary Fiber		25g	30g

Snickers Bar

INGREDIENTS: MILK CHOCOLATE (SUGAR, COCOA BUTTER, CHOCOLATE, LACTOSE, SKIM MILK, MILK FAT, SOY LECITHIN, ARTIFICIAL FLAVOR), PEANUTS, CORN SYRUP, SUGAR, SKIM MILK, BUTTER, MILK FAT, PARTIALLY HYDROGENATED SOYBEAN OIL, LACTOSE, SALT, EGG WHITES, ARTIFICAL FLAVOR

a regular-sized Snickers bar

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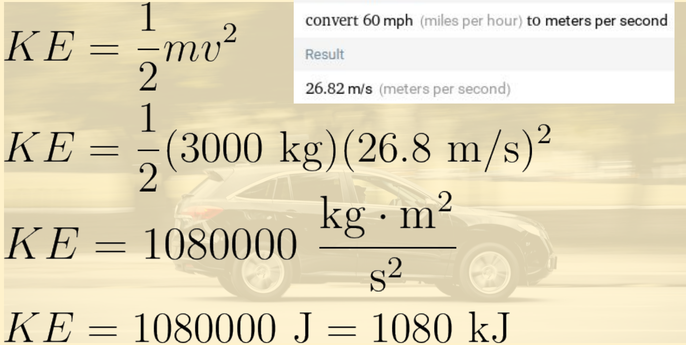

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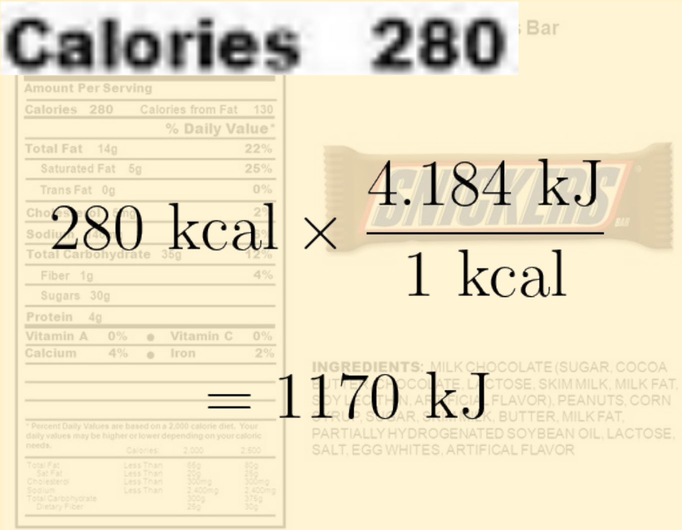

$$280\ \text{kcal} \times \frac{4.184\ \text{kJ}}{1\ \text{kcal}}$$

$$= 1170\ \text{kJ}$$

a regular-sized Snickers bar

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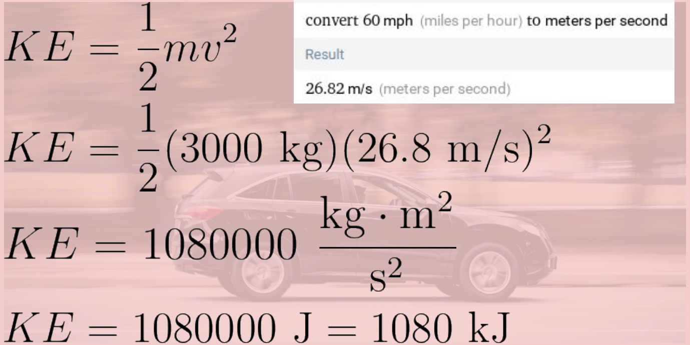

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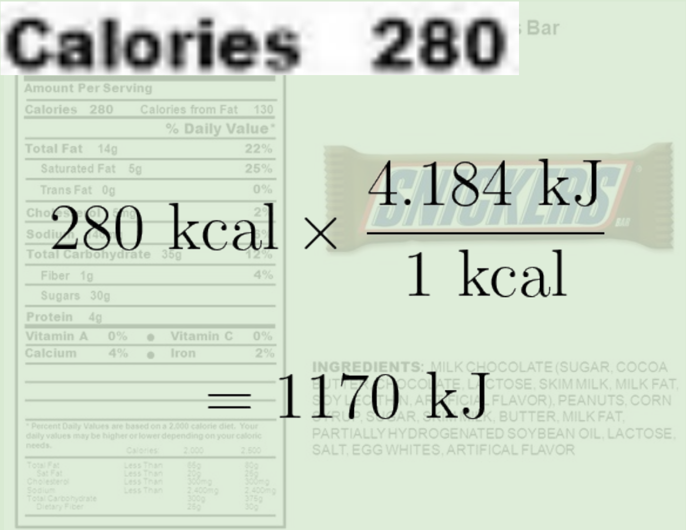

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Which is more energy?

one ton of TNT

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typical fridge annual energy use

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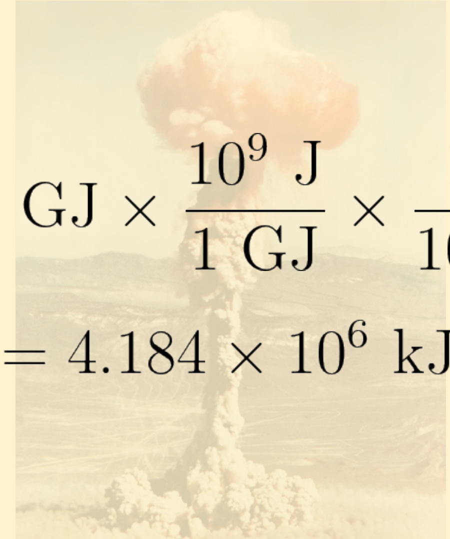

$$4.184\ \text{GJ} \times \frac{10^9\ \text{J}}{1\ \text{GJ}} \times \frac{1\ \text{kJ}}{1000\ \text{J}}$$

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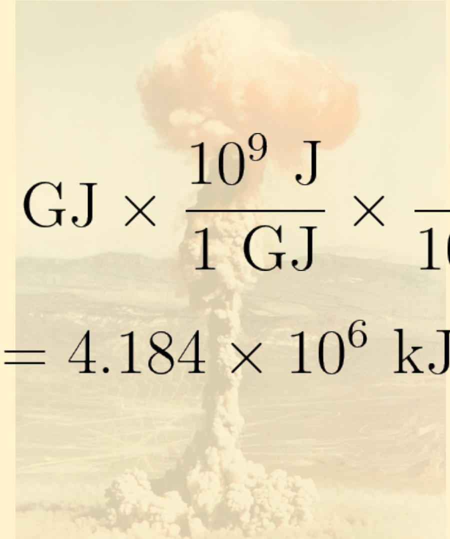

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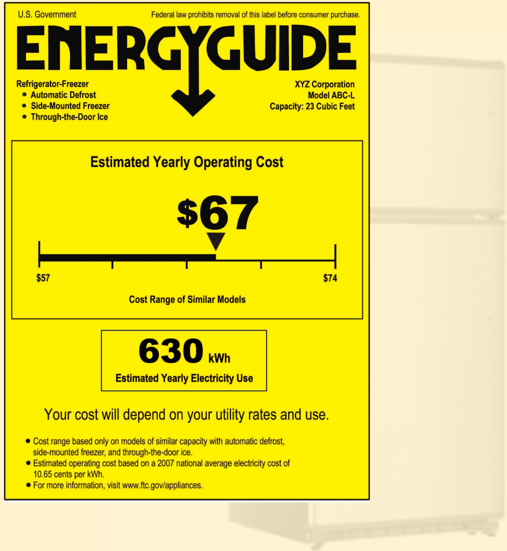

typical fridge annual energy use

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one ton of TNT

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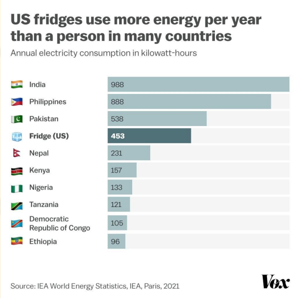
$$630\ \text{kWh}$$

$$630\ \text{kW} \cdot \text{h}$$

$$630\ \frac{\text{kJ}}{\text{s}} \cdot \text{h} \times 3600\ \frac{\text{s}}{\text{h}}$$

$$= 2.27 \times 10^6\ \text{kJ}$$



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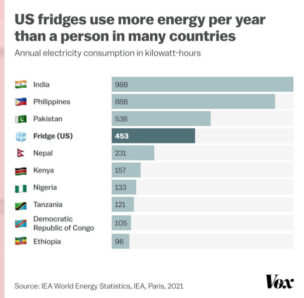

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Ford F-150 gas tank

?

melt and boil a 1-tonne iceberg

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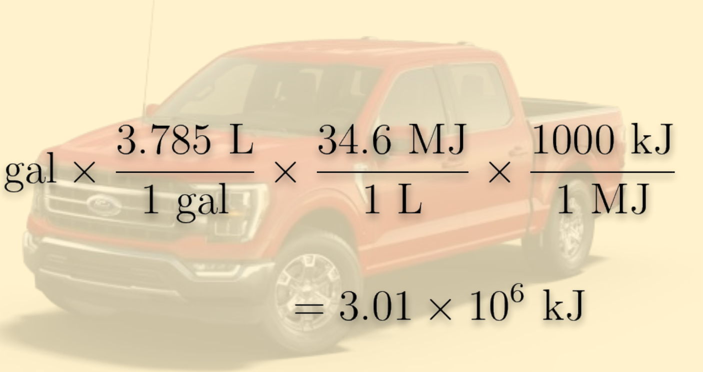

$$23 \text{ gal} \times \frac{3.785 \text{ L}}{1 \text{ gal}} \times \frac{34.6 \text{ MJ}}{1 \text{ L}} \times \frac{1000 \text{ kJ}}{1 \text{ MJ}}$$

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$$\Delta H^{\text{water}}_{\text{fusion}} = 79.7\ \frac{\text{kcal}}{\text{kg}} \qquad \Delta H^{\text{water}}_{\text{vaporization}} = 533\ \frac{\text{kcal}}{\text{kg}}$$

$$c^{\text{water}} = 1\ \frac{\text{kcal}}{\text{kg}\cdot{}^{\circ}\text{C}} \qquad Q = mc\Delta T$$

$$1000\ \text{kg} \times \left[\frac{79.7\ \text{kcal}}{\text{kg}} + \left(\frac{1\ \text{kcal}}{\text{kg}\cdot{}^{\circ}\text{C}} \times 100\ {}^{\circ}\text{C}\right) + \frac{533\ \text{kcal}}{\text{kg}}\right]$$

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$$= 7.12 \times 10^{5}\ \text{kcal} \times \frac{4.184\ \text{kJ}}{1\ \text{kcal}} = 2.98 \times 10^{6}\ \text{kJ}$$

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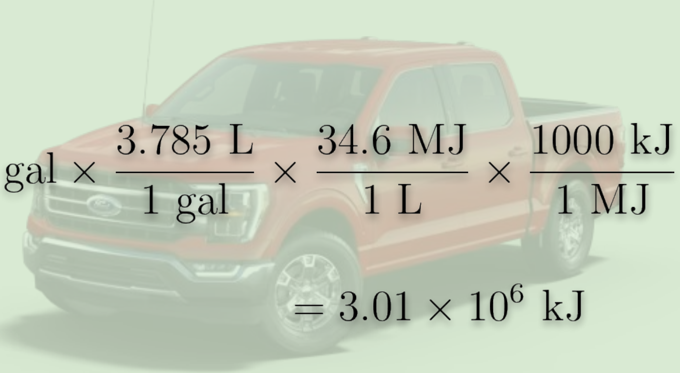

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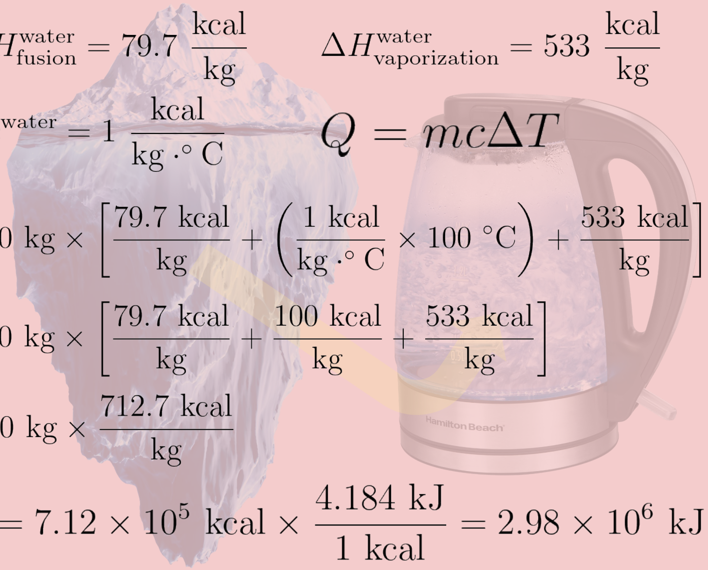

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Which is more energy?

total caloric content of food eaten over an 80-year lifespan

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one gram of fissile uranium

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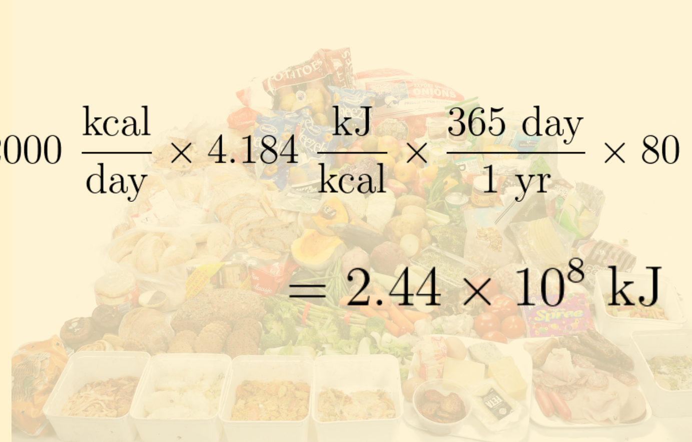

$$2000\ \frac{\text{kcal}}{\text{day}} \times 4.184\ \frac{\text{kJ}}{\text{kcal}} \times \frac{365\ \text{day}}{1\ \text{yr}} \times 80\ \text{yr}$$

$$= 2.44 \times 10^8\ \text{kJ}$$

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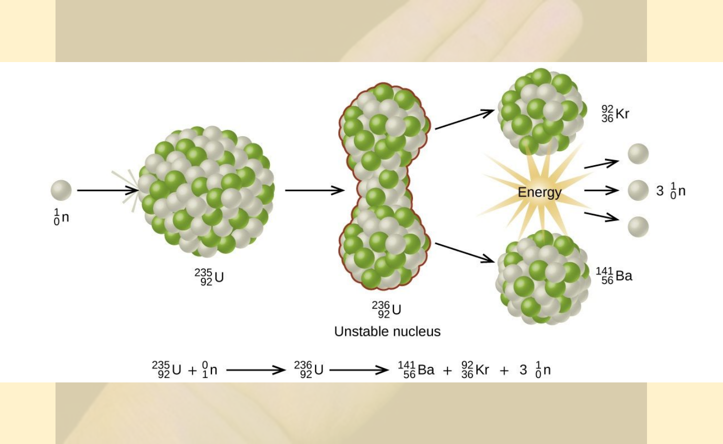

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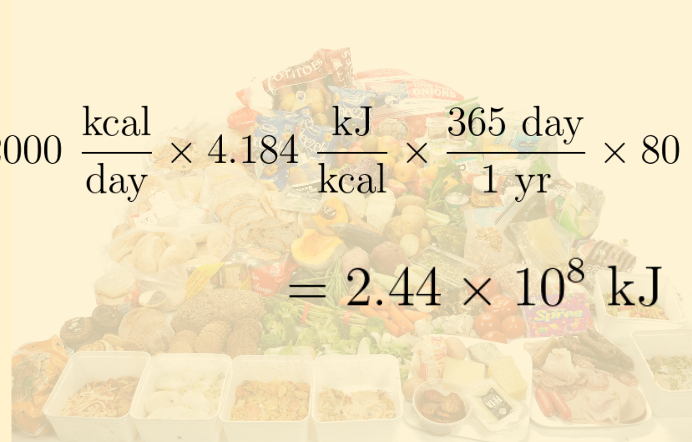

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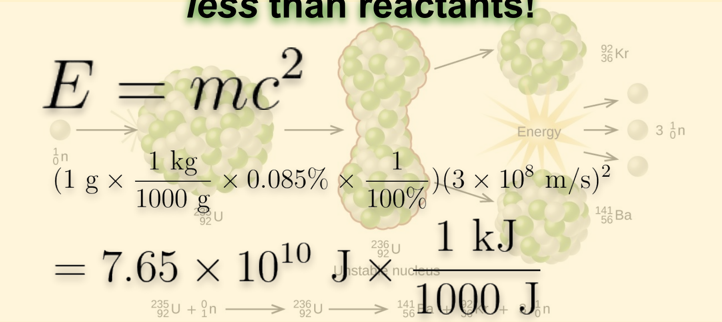

$$E = mc^2$$

$$(1\ \text{g} \times \frac{1\ \text{kg}}{1000\ \text{g}} \times 0.085\% \times \frac{1}{100\%})(3 \times 10^{8}\ \text{m/s})^2$$

$$= 7.65 \times 10^{10}\ \text{J} \times \frac{1\ \text{kJ}}{1000\ \text{J}}$$

$$= 7.65 \times 10^{7}\ \text{kJ}$$

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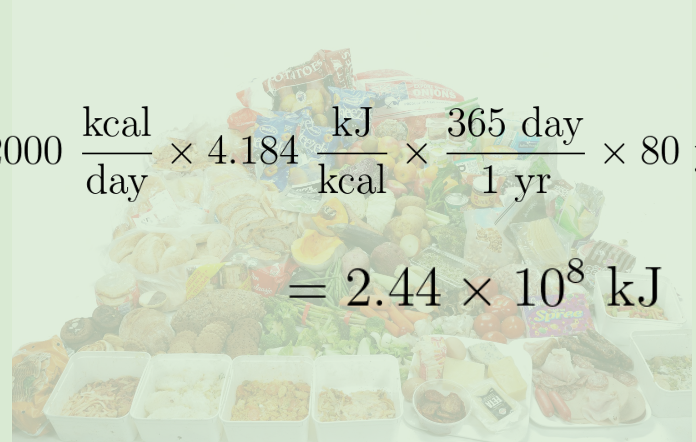

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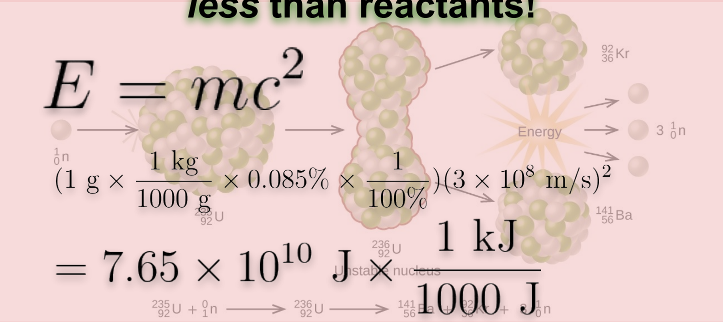

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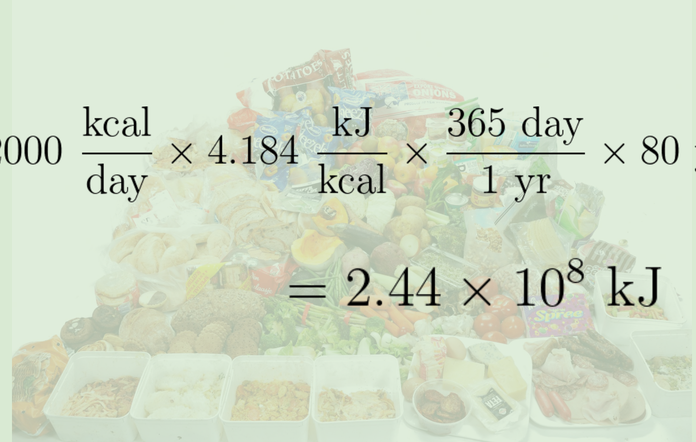

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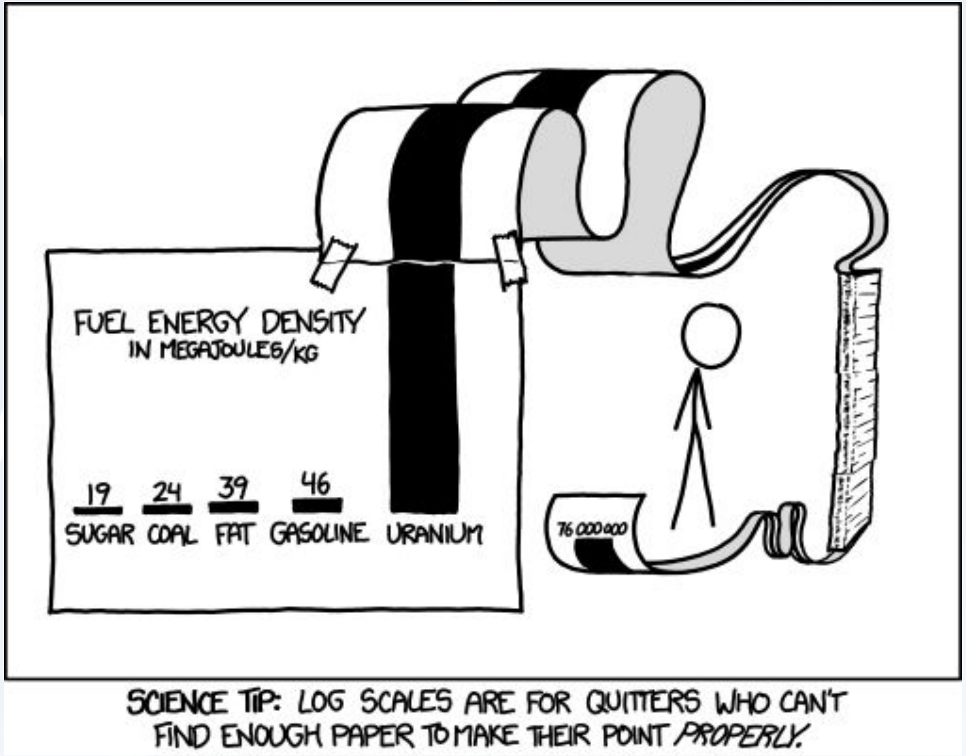

https://xkcd.com/1162/

Which is more energy?

global annual energy use
(2022)

?

1 hour of sunlight

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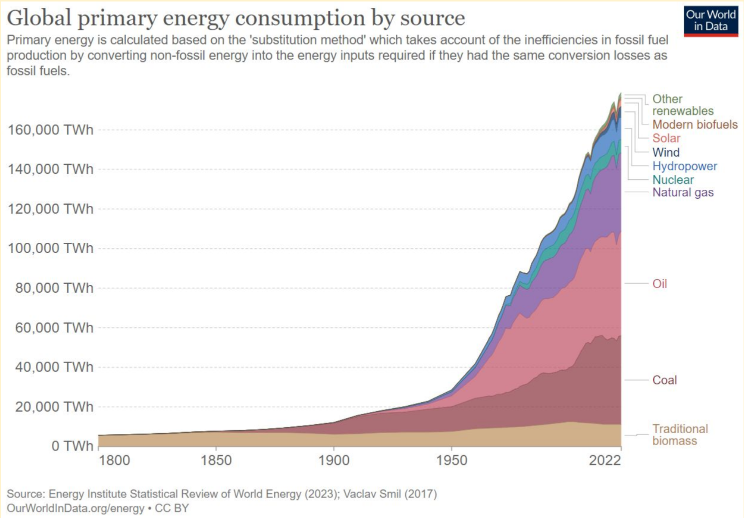

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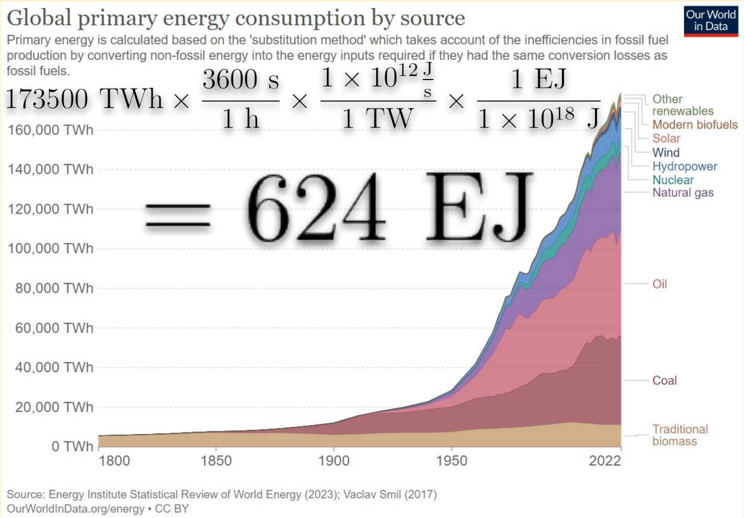

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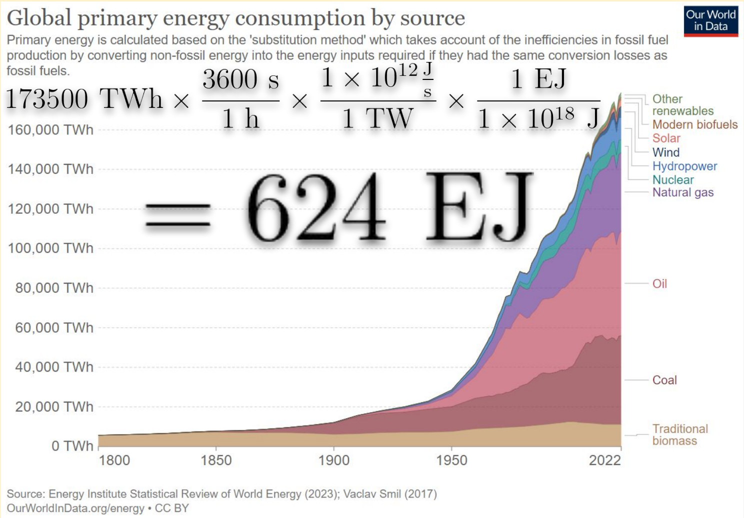
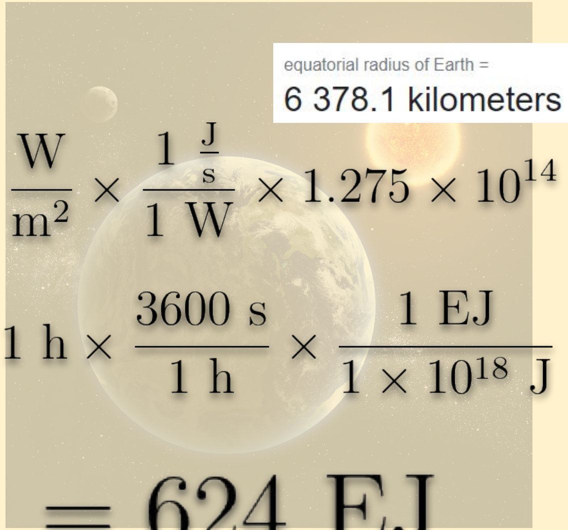


$$173500\ \mathrm{TWh} \times \frac{3600\ \mathrm{s}}{1\ \mathrm{h}} \times \frac{1 \times 10^{12}\ \frac{\mathrm{J}}{\mathrm{s}}}{1\ \mathrm{TW}} \times \frac{1\ \mathrm{EJ}}{1 \times 10^{18}\ \mathrm{J}}$$

$$= 624\ \mathrm{EJ}$$

global annual energy use (2022)

?



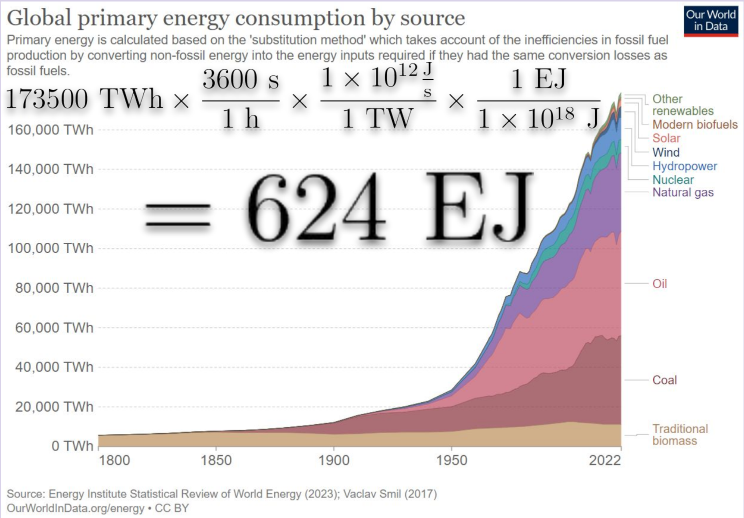
$$1361\ \frac{\mathrm{W}}{\mathrm{m}^2} \times \frac{1\ \frac{\mathrm{J}}{\mathrm{s}}}{1\ \mathrm{W}} \times 1.275 \times 10^{14}\ \mathrm{m}^2$$

$$\times 1\ \mathrm{h} \times \frac{3600\ \mathrm{s}}{1\ \mathrm{h}} \times \frac{1\ \mathrm{EJ}}{1 \times 10^{18}\ \mathrm{J}}$$

$$= 624\ \mathrm{EJ}$$

1 hour of sunlight

Which is more energy?

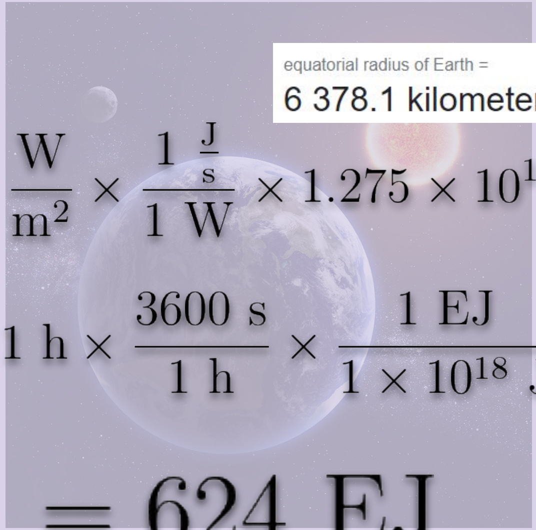


$$173500\ \text{TWh} \times \frac{3600\ \text{s}}{1\ \text{h}} \times \frac{1 \times 10^{12}\ \frac{\text{J}}{\text{s}}}{1\ \text{TW}} \times \frac{1\ \text{EJ}}{1 \times 10^{18}\ \text{J}}$$

$$= 624\ \text{EJ}$$

global annual energy use (2022)

$\approx$



equatorial radius of Earth =
6 378.1 kilometers

$$1361\ \frac{\text{W}}{\text{m}^2} \times \frac{1\ \frac{\text{J}}{\text{s}}}{1\ \text{W}} \times 1.275 \times 10^{14}\ \text{m}^2$$

$$\times\, 1\ \text{h} \times \frac{3600\ \text{s}}{1\ \text{h}} \times \frac{1\ \text{EJ}}{1 \times 10^{18}\ \text{J}}$$

$$= 624\ \text{EJ}$$

1 hour of sunlight

What is money?

How much does energy cost?

How much does energy cost?

Depends on how you:

How much does energy cost?

Depends on how you:

- make it

How much does energy cost?

Depends on how you:

- make it
- store it

How much does energy cost?

Depends on how you:

- make it
- store it
- ship it

How much does energy cost?

Depends on how you:

- make it
- store it
- ship it

How can you make it?

How much does energy cost?

Depends on how you:

- make it
- store it
- ship it

How can you make it?

- burn fossil fuels

How much does energy cost?

Depends on how you:

- make it
- store it
- ship it

How can you make it?

- burn fossil fuels
- burn biomass

How much does energy cost?

Depends on how you:

- make it
- store it
- ship it

How can you make it?

- burn fossil fuels
- burn biomass
- solar photovoltaics

How much does energy cost?

Depends on how you:

- make it
- store it
- ship it

How can you make it?

- burn fossil fuels
- burn biomass
- solar photovoltaics
- wind turbines

How much does energy cost?

Depends on how you:

- make it
- store it
- ship it

How can you make it?

- burn fossil fuels
- burn biomass
- solar photovoltaics
- wind turbines
- hydroelectric dam

Three Gorges Dam

Hubei, China

30°49′23″N 111°00′12″E

Location in Hubei Province

Three Gorges Dam (China)

Installed capacity:	22500 MW
Capacity factor:	45%
Annual generation:	103.6 TWh *(2021)*
Construction began:	December 1994
Opening date:	July 2003
Construction cost:	¥203 bn (US$31.8 bn)
Owner(s):	China Yangtze Power *(subsidiary of China Three Gorges Corp.)*

中国长江三峡集团公司
China Three Gorges Corporation

How much does energy cost?

Depends on how you:

- make it
- store it
- ship it

How can you make it?

- burn fossil fuels
- burn biomass
- solar photovoltaics
- wind turbines
- hydroelectric dam
- nuclear reactor

How much does energy cost?

Depends on how you:

- make it
- store it
- ship it

How can you make it?

- burn fossil fuels
- burn biomass
- solar photovoltaics
- wind turbines
- hydroelectric dam
- nuclear reactor
- geothermal plant

How much does energy cost?

Depends on how you:

- make it
- store it
- ship it

How can you make it?

- burn fossil fuels
- burn biomass
- solar photovoltaics
- wind turbines
- hydroelectric dam
- nuclear reactor
- geothermal plant
- solar concentrator

How much does energy cost?

Depends on how you:

- make it
- store it
- ship it

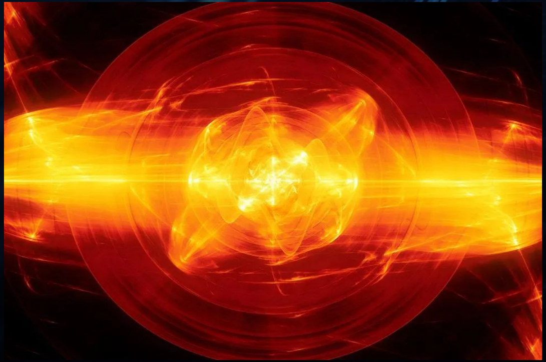
How can you make it?

- burn fossil fuels
- burn biomass
- solar photovoltaics
- wind turbines
- hydroelectric dam
- nuclear reactor
- geothermal plant
- solar concentrator
- tidal energy station

How much does energy cost?

Depends on how you:

- make it
- store it
- ship it



How can you make it?

- burn fossil fuels
- burn biomass
- solar photovoltaics
- wind turbines
- hydroelectric dam
- nuclear reactor
- geothermal plant
- solar concentrator
- tidal energy station
- nuclear fusion

How much does energy cost?

Depends on how you:

- make it
- store it
- ship it

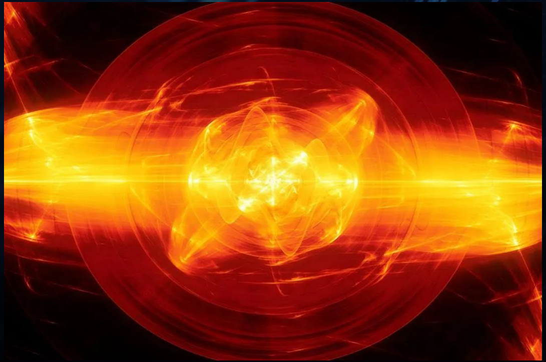
How can you make it?

- burn fossil fuels
- burn biomass
- solar photovoltaics
- wind turbines
- hydroelectric dam
- nuclear reactor
- geothermal plant
- solar concentrator
- tidal energy station
- nuclear fusion (you wish)

How much does energy cost?

Depends on how you:

- make it
- store it
- ship it



How can you make it?

- burn fossil fuels
- burn biomass
- solar photovoltaics
- wind turbines
- hydroelectric dam
- nuclear reactor
- geothermal plant
- solar concentrator
- tidal energy station
- nuclear fusion (you wish)
- ... (and more)

How much does energy cost?

Depends on how you:

- make it
- store it
- ship it

How can you store it?

How much does energy cost?

Depends on how you:

- make it
- store it
- ship it

How can you store it?

- Chemical fuels

How much does energy cost?

Depends on how you:

- make it
- store it
- ship it

How can you store it?

- Chemical fuels
  - Fossil fuels

How much does energy cost?

Depends on how you:

- make it
- store it
- ship it

How can you store it?

- Chemical fuels
  - Fossil fuels
  - Biofuels

How much does energy cost?

Depends on how you:

- make it
- store it
- ship it

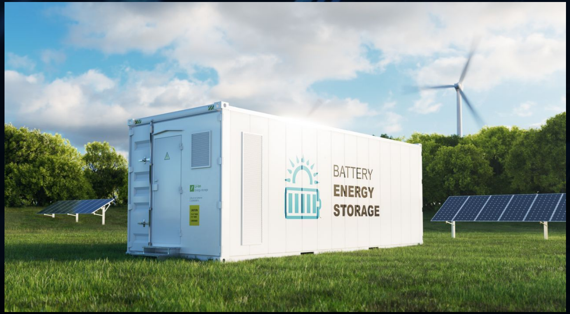
How can you store it?

- Chemical fuels
  - Fossil fuels
  - Biofuels
  - Non-fossil hydrocarbons

How much does energy cost?

Depends on how you:

- make it
- store it
- ship it



How can you store it?

- Chemical fuels
  - Fossil fuels
  - Biofuels
  - Non-fossil hydrocarbons
- Batteries (all sorts)

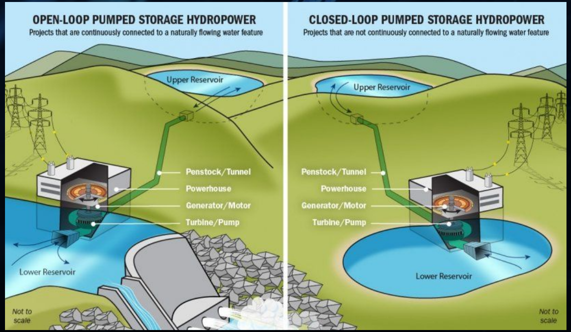
How much does energy cost?

Depends on how you:

- make it
- store it
- ship it

How can you store it?

- Chemical fuels
  - Fossil fuels
  - Biofuels
  - Non-fossil hydrocarbons
- Batteries (all sorts)
- Pumped hydroelectric storage



How much does energy cost?

Depends on how you:

- make it
- store it
- ship it

How can you store it?

- Chemical fuels
  - Fossil fuels
  - Biofuels
  - Non-fossil hydrocarbons
- Batteries (all sorts)
- Pumped hydroelectric storage
- Thermal energy storage
  - Sensible (molten-salt)

How much does energy cost?

Depends on how you:

- make it
- store it
- ship it

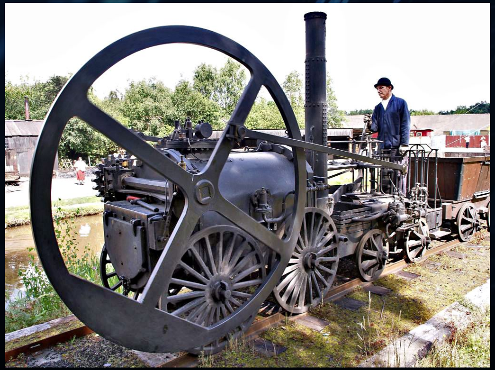
How can you store it?

- Chemical fuels
  - Fossil fuels
  - Biofuels
  - Non-fossil hydrocarbons
- Batteries (all sorts)
- Pumped hydroelectric storage
- Thermal energy storage
  - Sensible (molten-salt)
  - Non-sensible (phase-change)

How much does energy cost?

Depends on how you:

- make it
- store it
- ship it



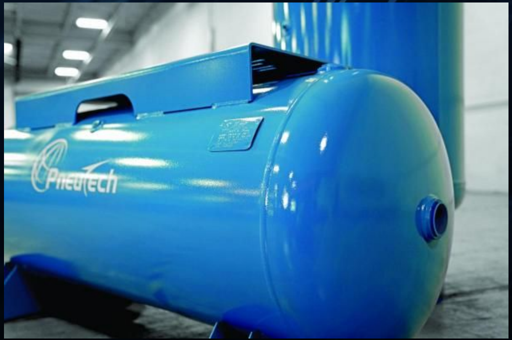
How can you store it?

- Chemical fuels
  - Fossil fuels
  - Biofuels
  - Non-fossil hydrocarbons
- Batteries (all sorts)
- Pumped hydroelectric storage
- Thermal energy storage
  - Sensible (molten-salt)
  - Non-sensible (phase-change)
- Flywheels

How much does energy cost?

Depends on how you:

- make it
- store it
- ship it



How can you store it?

- Chemical fuels
  - Fossil fuels
  - Biofuels
  - Non-fossil hydrocarbons
- Batteries (all sorts)
- Pumped hydroelectric storage
- Thermal energy storage
  - Sensible (molten-salt)
  - Non-sensible (phase-change)
- Flywheels
- Compressed air

How much does energy cost?

Depends on how you:

- make it
- store it
- ship it

How can you store it?

- Chemical fuels
  - Fossil fuels
  - Biofuels
  - Non-fossil hydrocarbons
- Batteries (all sorts)
- Pumped hydroelectric storage
- Thermal energy storage
  - Sensible (molten-salt)
  - Non-sensible (phase-change)
- Flywheels
- Compressed air
- Springs

How much does energy cost?

Depends on how you:

- make it
- store it
- ship it

How can you store it?

- Chemical fuels
  - Fossil fuels
  - Biofuels
  - Non-fossil hydrocarbons
- Batteries (all sorts)
- Pumped hydroelectric storage
- Thermal energy storage
  - Sensible (molten-salt)
  - Non-sensible (phase-change)
- Flywheels
- Compressed air
- Springs

(and so on and so forth)

How much does energy cost?

Depends on how you:

- make it
- store it
- ship it

How can you ship it?

- By grid

How much does energy cost?

Depends on how you:

- make it
- store it
- ship it

How can you ship it?

- By grid
- By pipeline

How much does energy cost?

Depends on how you:

- make it
- store it
- ship it

How can you ship it?

- By grid
- By pipeline
- By train

How much does energy cost?

Depends on how you:

- make it
- store it
- ship it

How can you ship it?

- By grid
- By pipeline
- By train
- By ship

How much does energy cost?

Depends on how you:

- make it
- store it
- ship it

How can you ship it?

- By grid
- By pipeline
- By train
- By ship
- By truck

How much does energy cost?

Depends on how you:

- make it
- store it
- ship it

How can you ship it?

- By grid
- By pipeline
- By train
- By ship
- By truck
- By plane

How much does energy cost?

Depends on how you:

- make it
- store it
- ship it

How can you ship it?

- By grid
- By pipeline
- By train
- By ship
- By truck
- By plane
- Wirelessly?

How much does energy cost?

Depends on how you:

- make it
- store it
- ship it

How can you ship it?

- By grid
- By pipeline
- By train
- By ship
- By truck
- By plane
- Wirelessly? *(not yet)*

How much does energy cost?

Depends on how you:

- make it
- store it
- ship it

How can you ship it?

- By grid
- By pipeline
- By train
- By ship
- By truck
- By plane
- Wirelessly? *(not yet)*

less $$$

more $$$

How much does energy cost?

Depends on how you:

- make it
- store it
- ship it

How can you ship it?

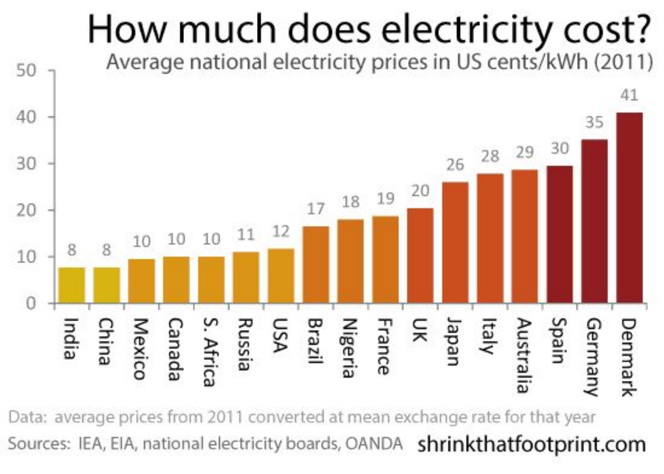
- By grid
- By pipeline
- By train
- By ship
- By truck
- By plane
- Wirelessly? *(not yet)*

less $$$

more $$$

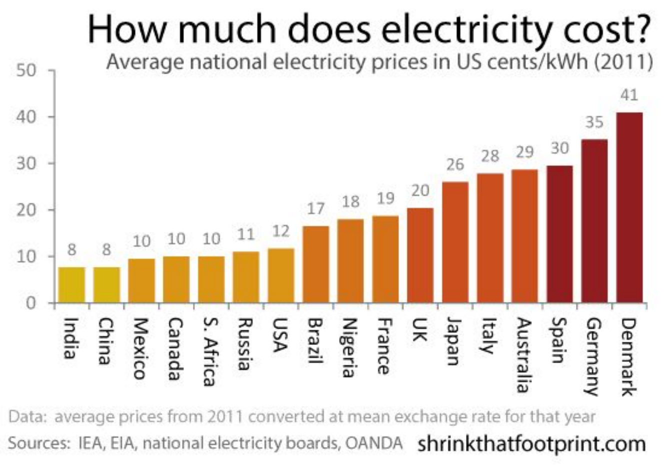
(It depends on how you store it.)

How much does energy cost?

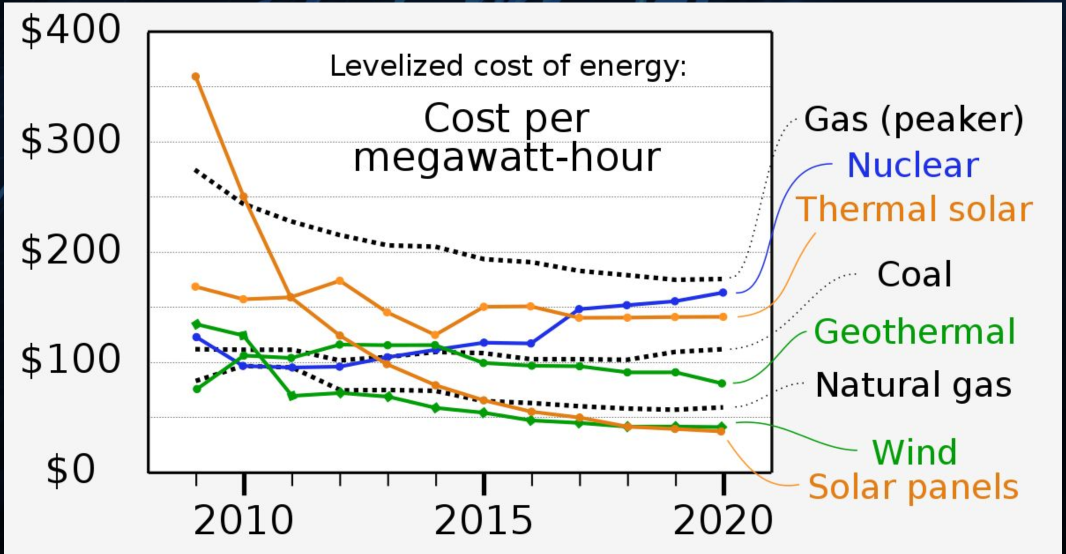


typically between
5 ~ 50 ¢/kWh

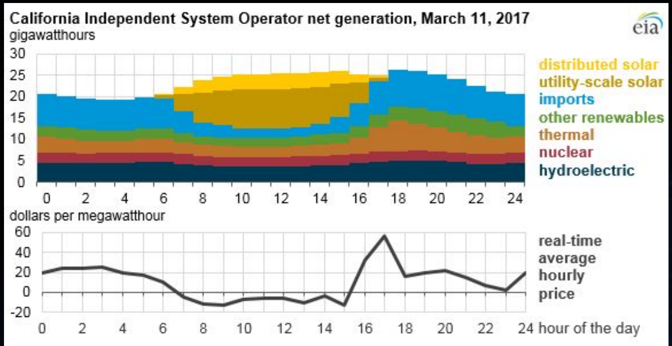
How much does energy cost?



typically between 5 ~ 50 ¢/kWh

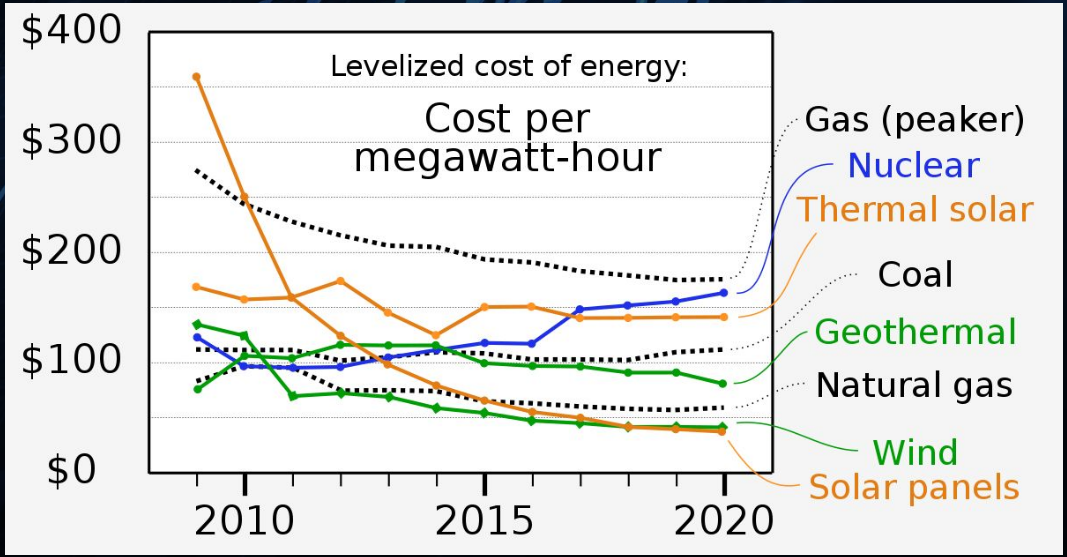


How much does energy cost?

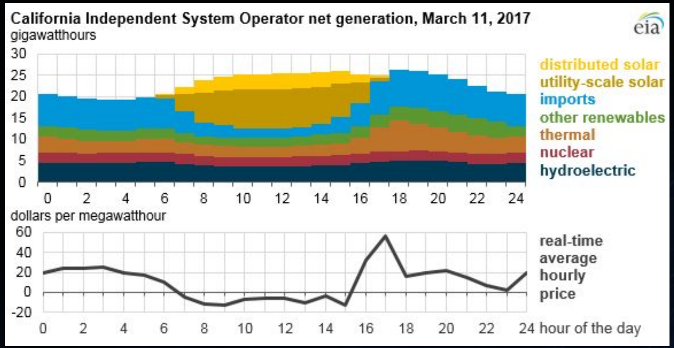


typically between
5 ~ 50 ¢/kWh

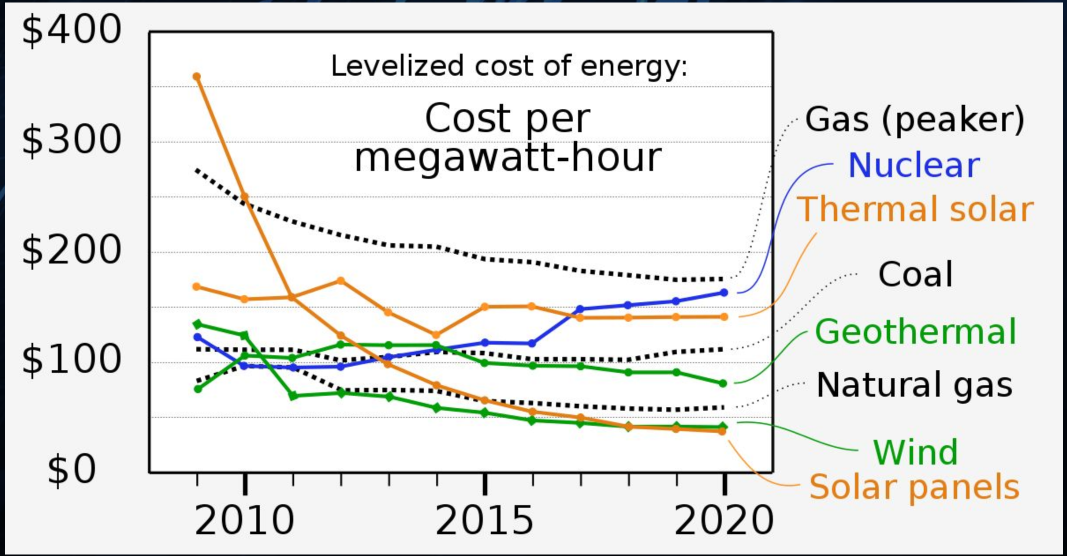
sometimes even (briefly) negative!



How much does energy cost?



typically between 5 ~ 50 ¢/kWh



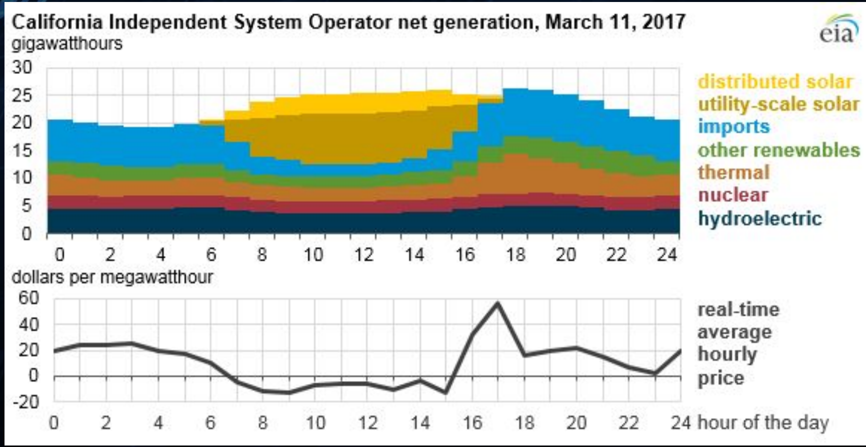
sometimes even (briefly) negative!

(timing is important!)

Price isn't the only factor!

Also need to consider:

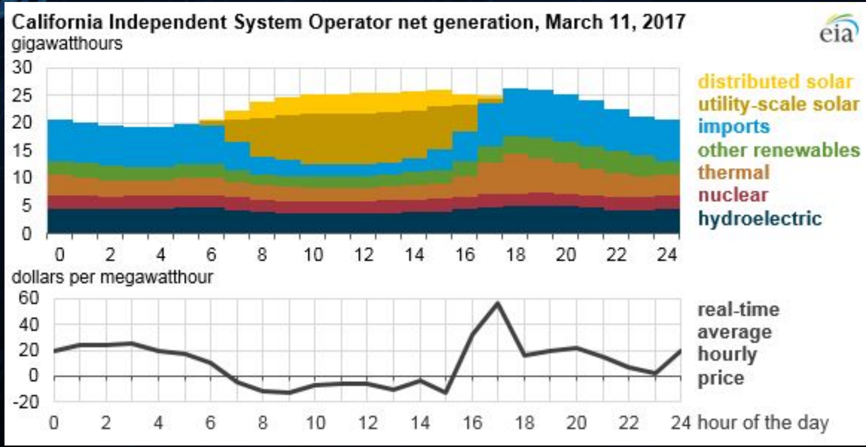
- Reliability
  - timing is important!



Price isn't the only factor!

Also need to consider:

- Reliability / intermittency
  - timing is important!
  - capacity factor



Price isn't the only factor!

Also need to consider:

- Reliability / intermittency
  - timing is important!
  - capacity factor
- Carbon footprint!

Image by DALL·E 2
PROMPT: "an abstract painting of an avatar of rampant unchecked capitalism destroying global human society as we know it"

Price isn't the only factor!

Also need to consider:

- Reliability / intermittency
  - timing is important!
  - capacity factor
- Carbon footprint!
  - direct and indirect

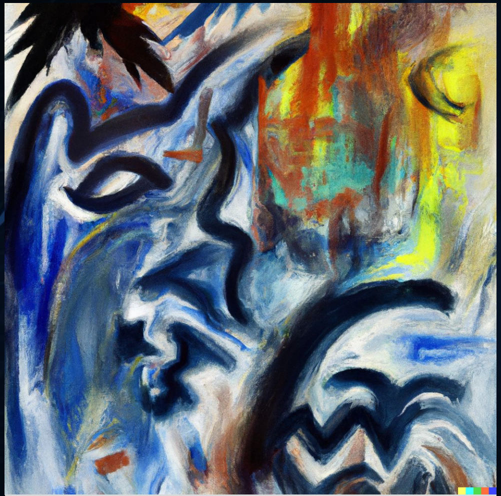


Image by DALL·E 2
PROMPT: "an abstract painting of an avatar of rampant unchecked capitalism destroying global human society as we know it"

Price isn't the only factor!

Also need to consider:

- Reliability / intermittency
  - timing is important!
  - capacity factor
- Carbon footprint!
  - direct and indirect
  - probably the reason you are all here

Image by DALL·E 2
PROMPT: "an abstract painting of an avatar of rampant unchecked capitalism destroying global human society as we know it"

Price isn't the only factor!

Also need to consider:

- Reliability / intermittency
  - timing is important!
  - capacity factor
- Carbon footprint!
  - direct and indirect
  - probably the reason you are all here
  - capitalism is good at maximizing capital

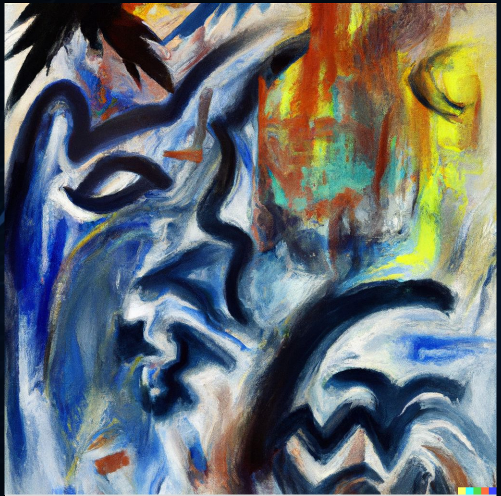
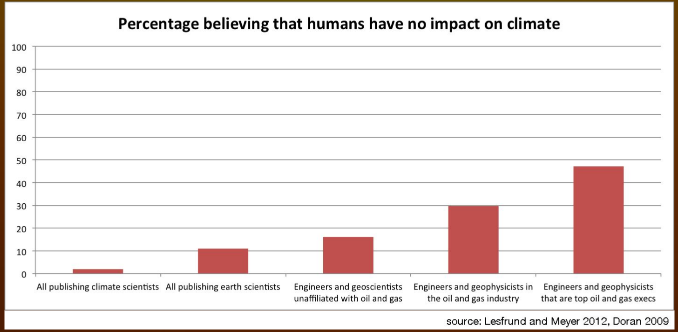
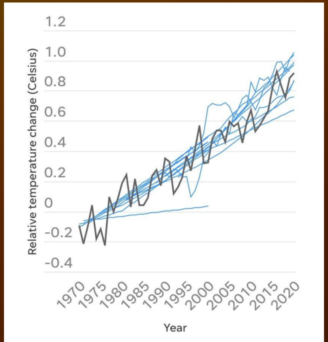


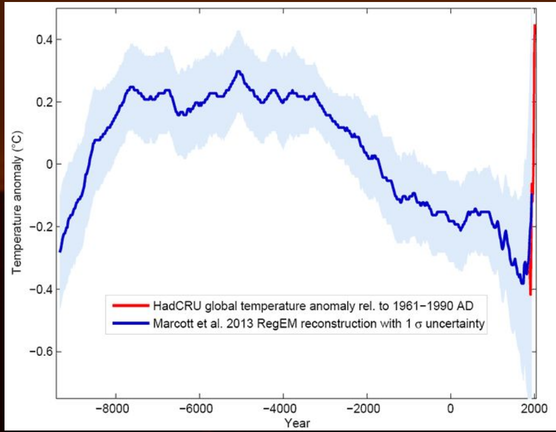
Image by DALL·E 2
PROMPT: "an abstract painting of an avatar of rampant unchecked capitalism destroying global human society as we know it"

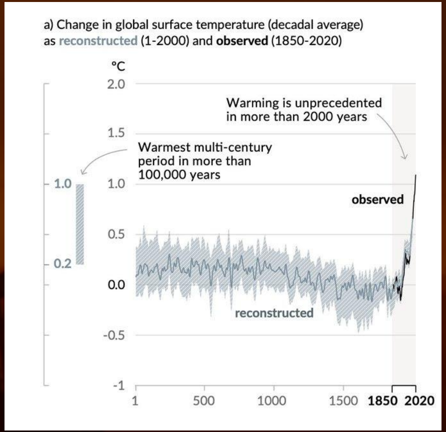

how bad is it, doc?
(we do a little editorializing)

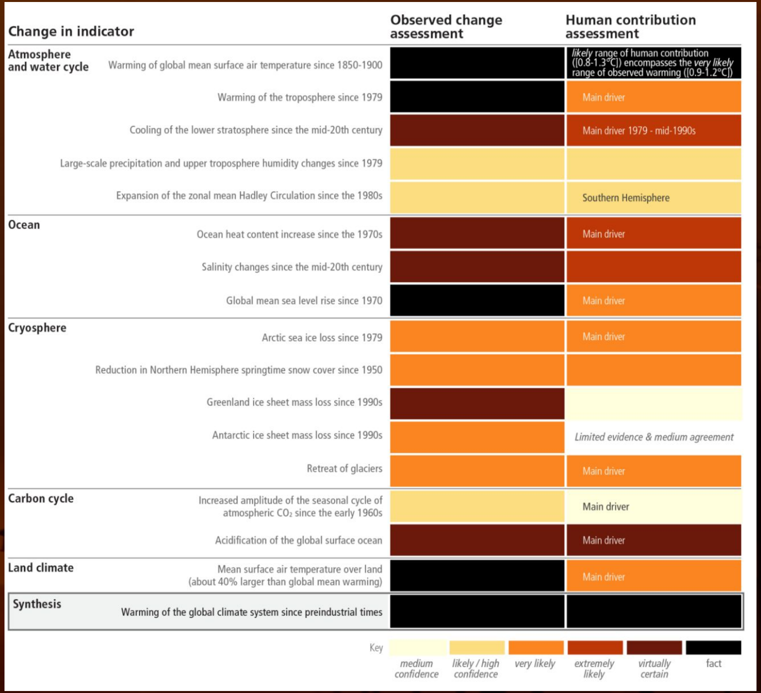
Anthropogenic global warming is real





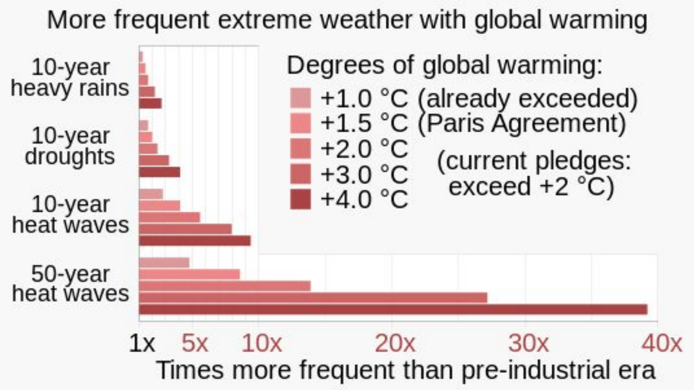


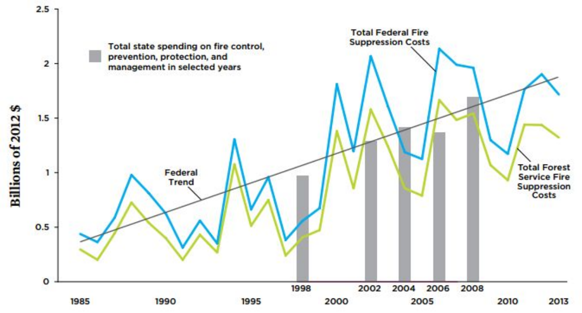


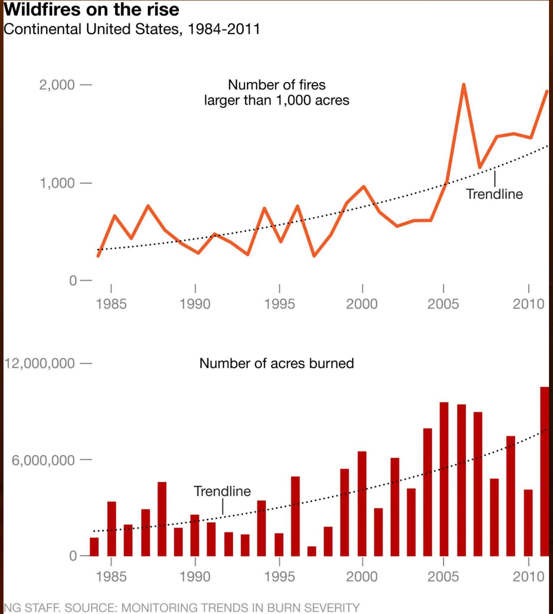


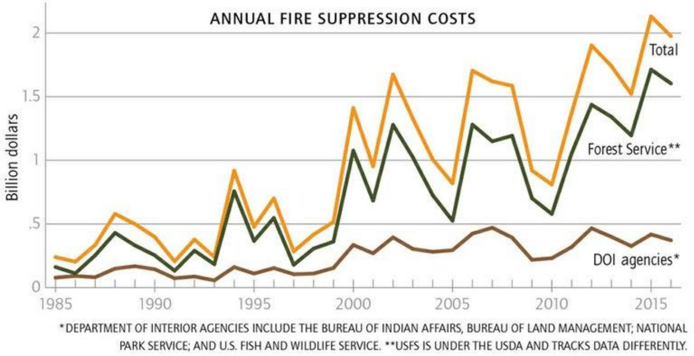
Lee, Hoesung, et al. "AR6 Synthesis Report: Climate Change 2023." *Summary for Policymakers* (2023).

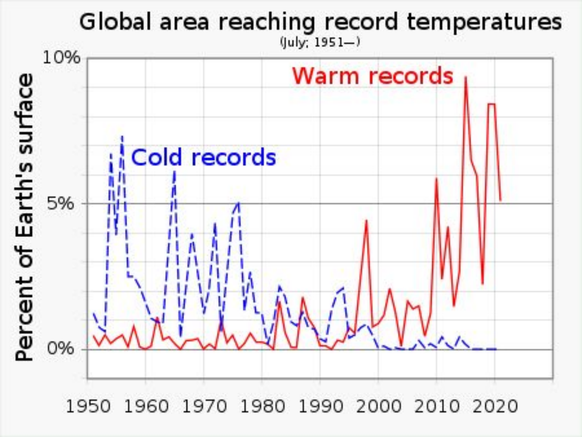
Anthropogenic global warming is bad





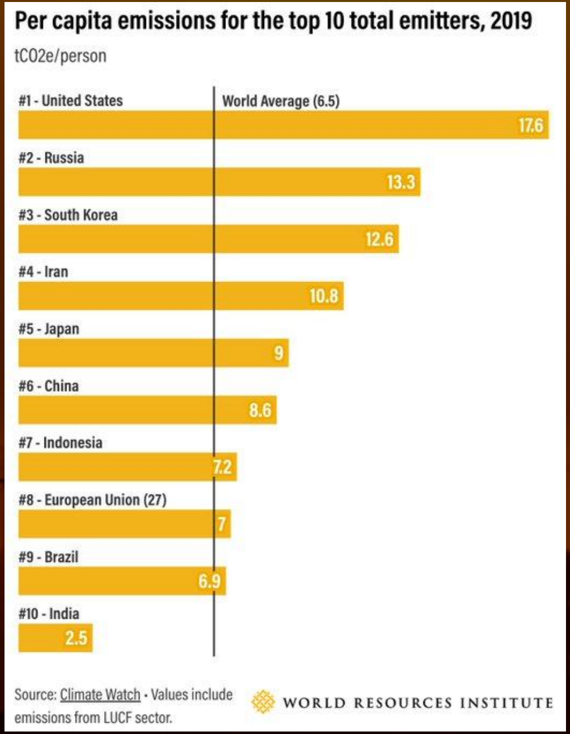


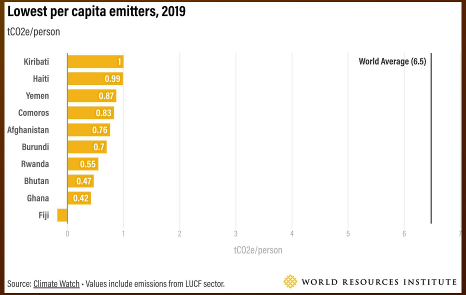


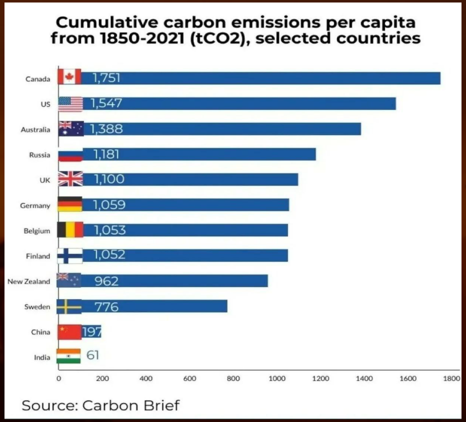


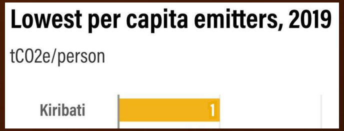
Lee, Hoesung, et al. "AR6 Synthesis Report: Climate Change 2023." *Summary for Policymakers* (2023).

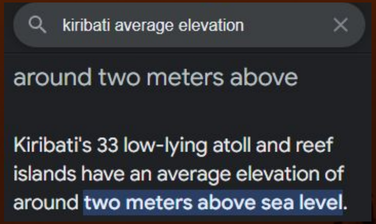
Most vulnerable global populations are broadly least responsible

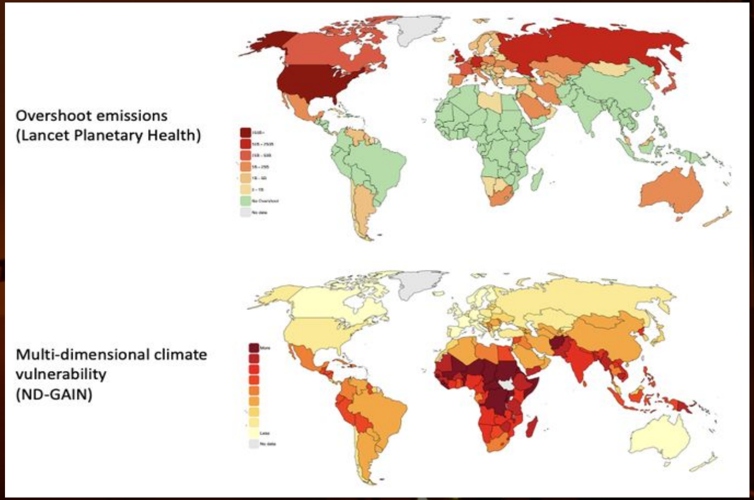




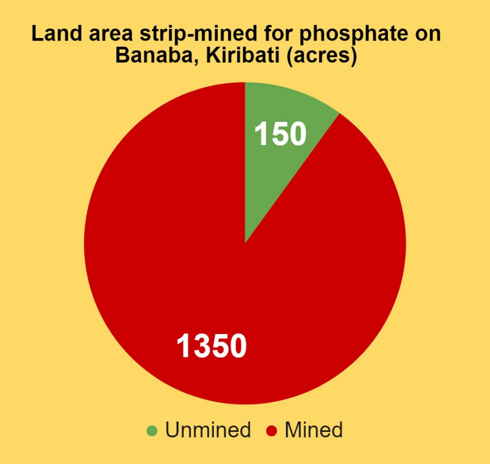








Banaba, Kiribati



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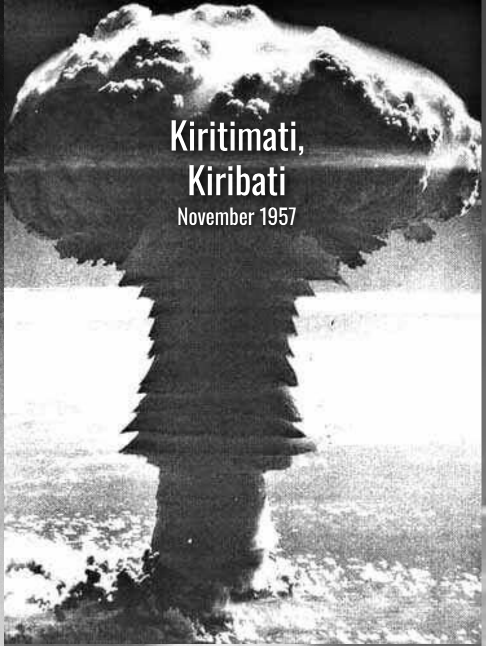

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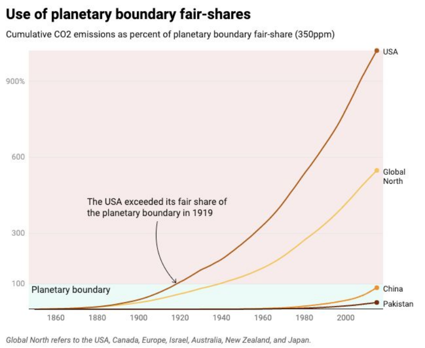
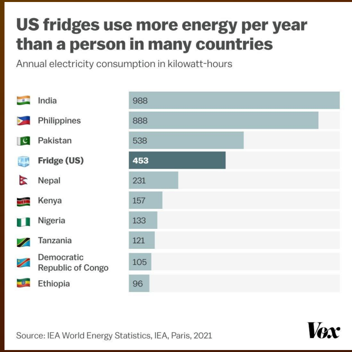
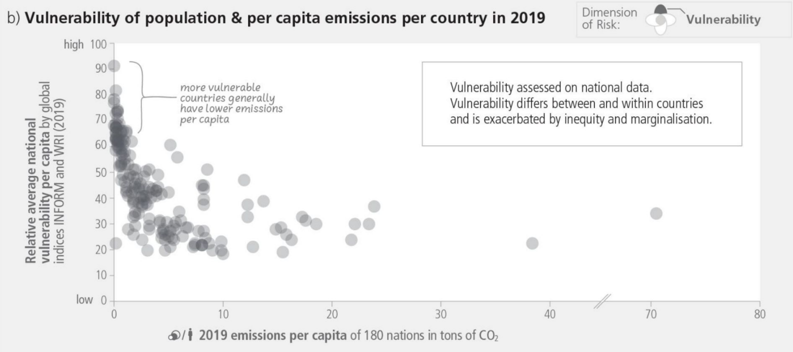
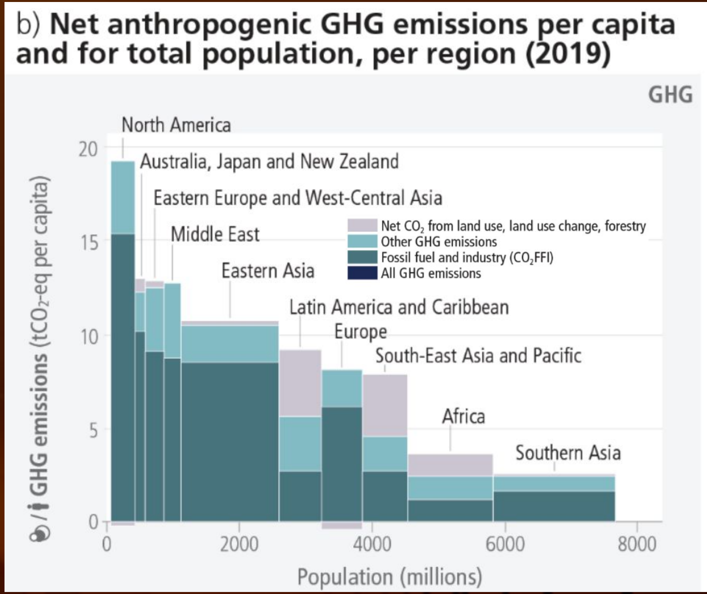
Most vulnerable global populations are broadly least responsible









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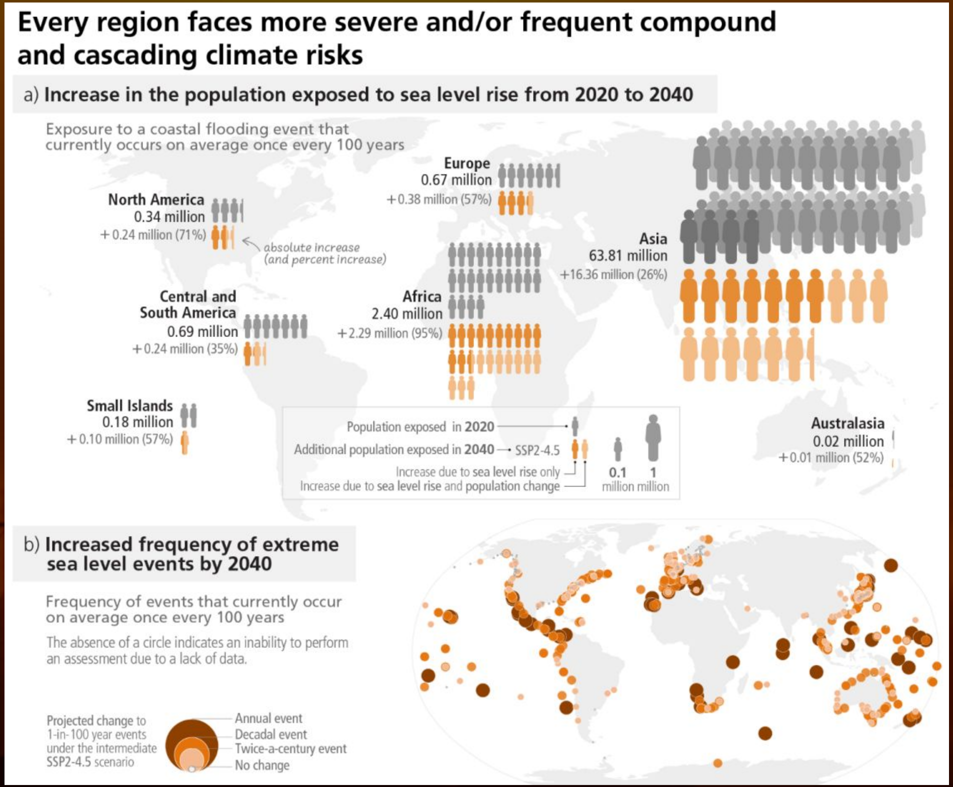
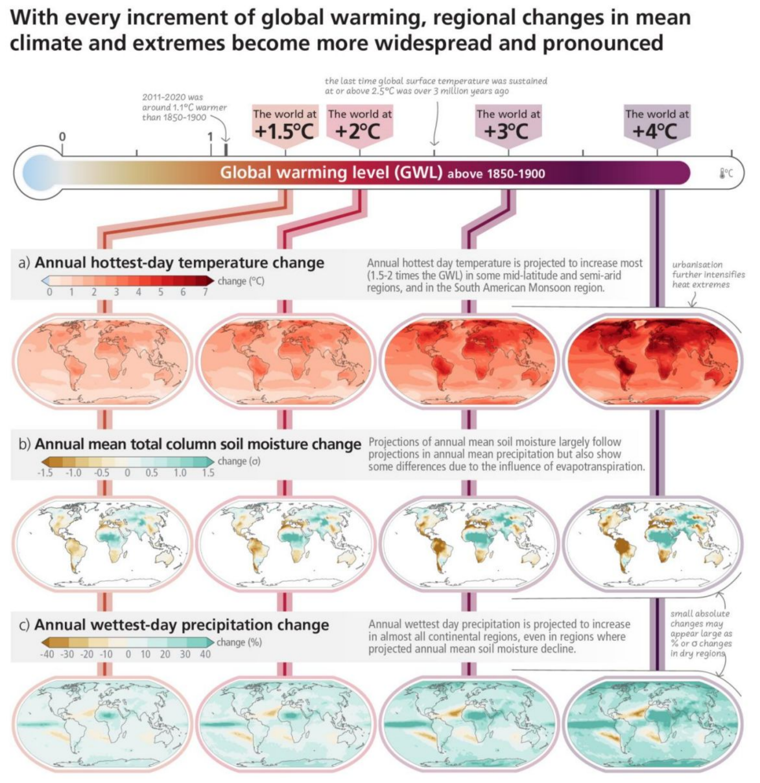
...but everyone will be affected





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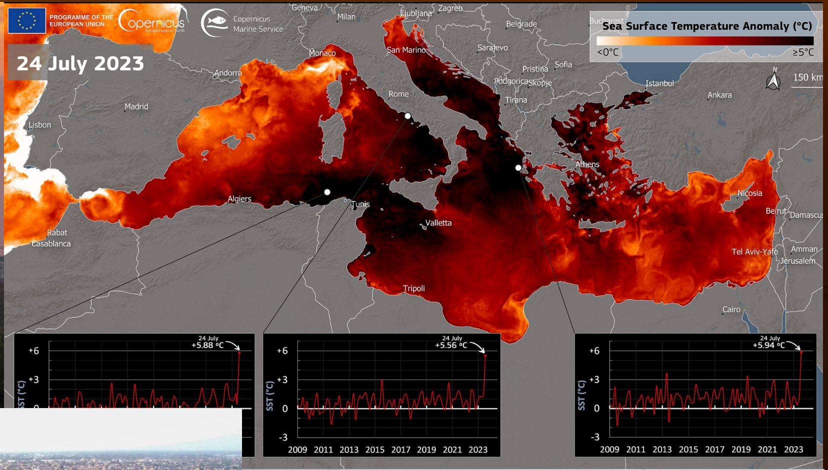

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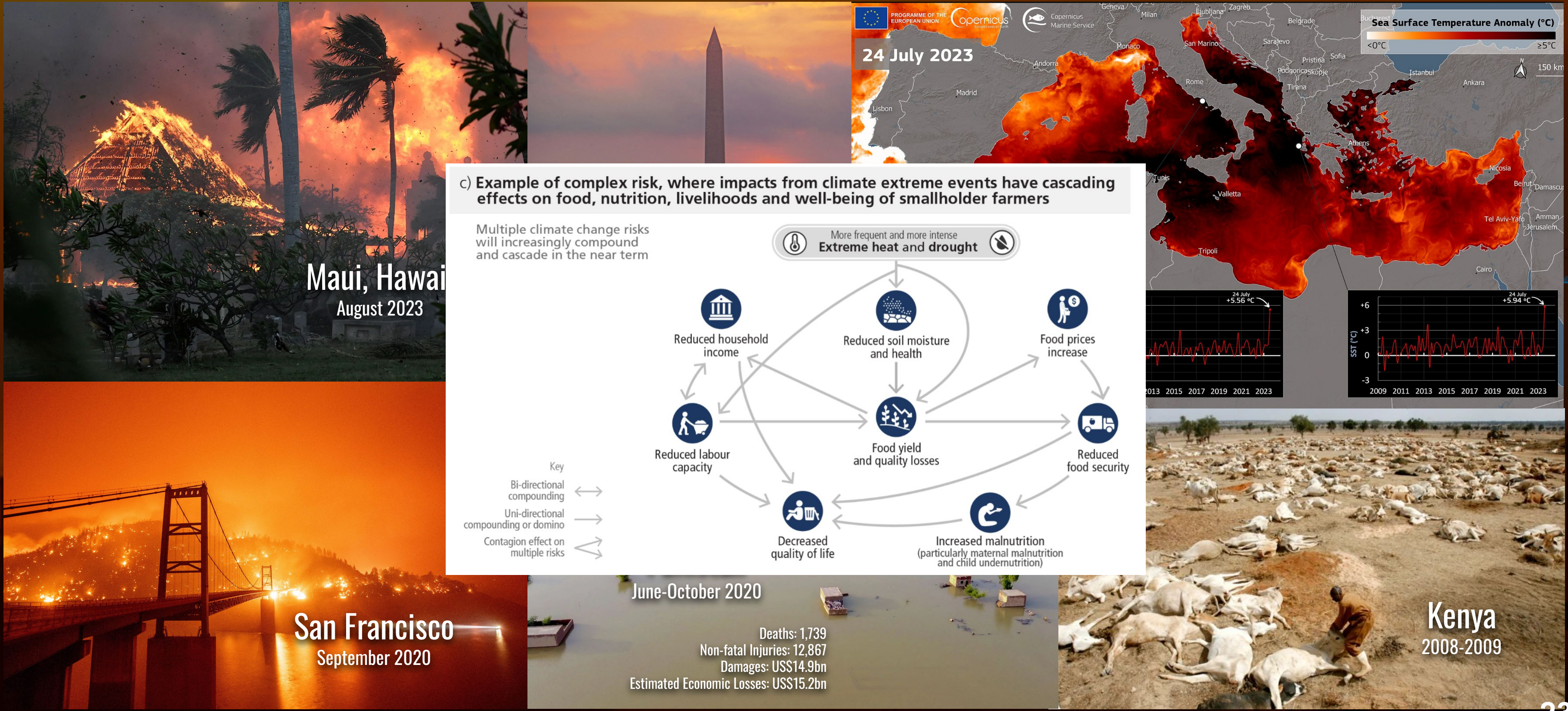

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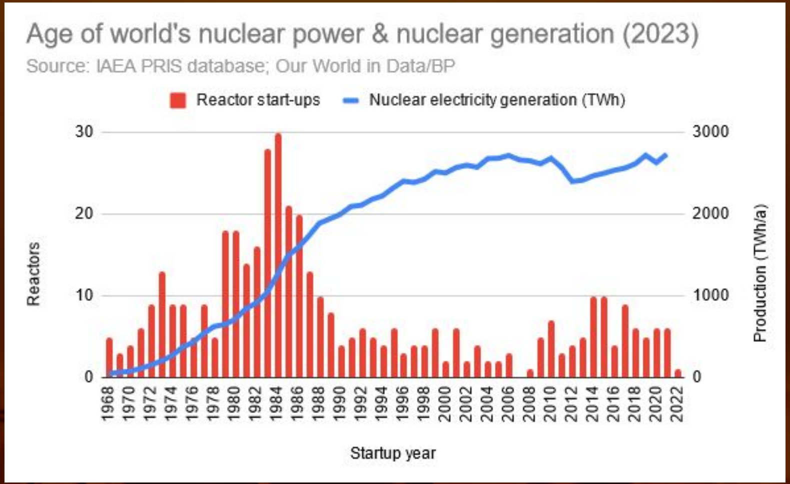
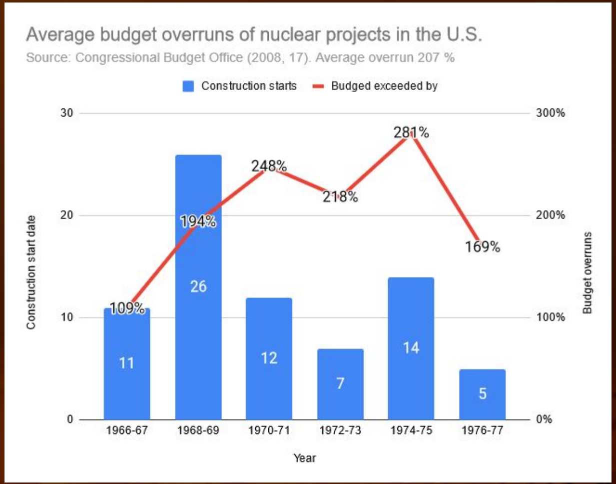
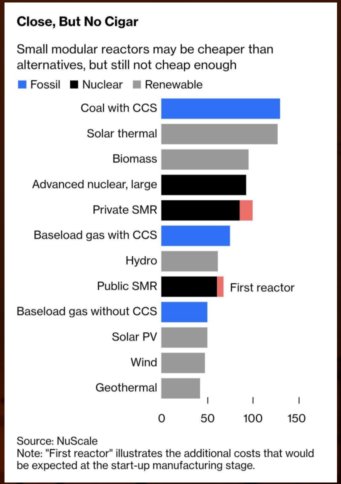
Technical merit is meaningless without deployability







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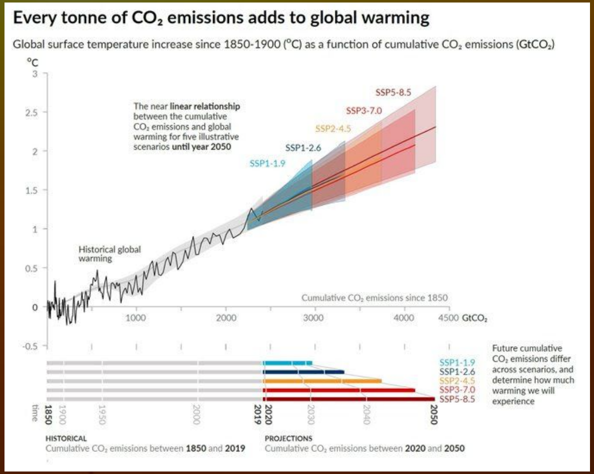
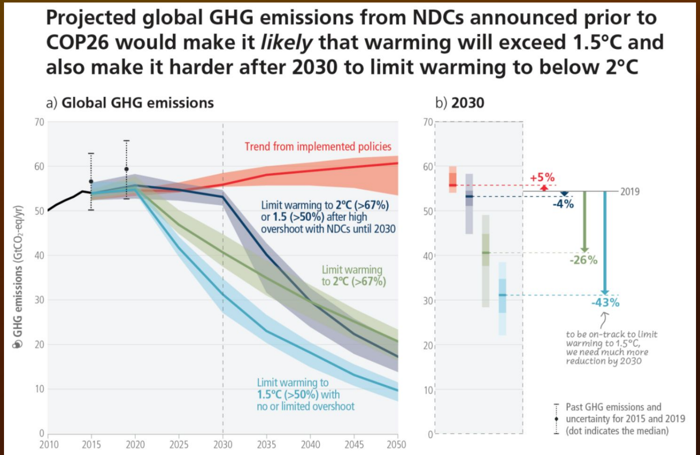
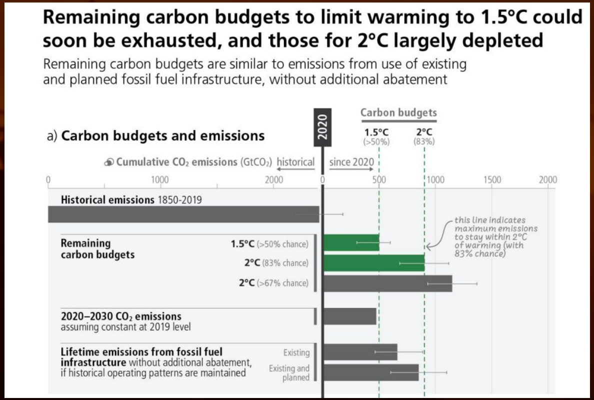
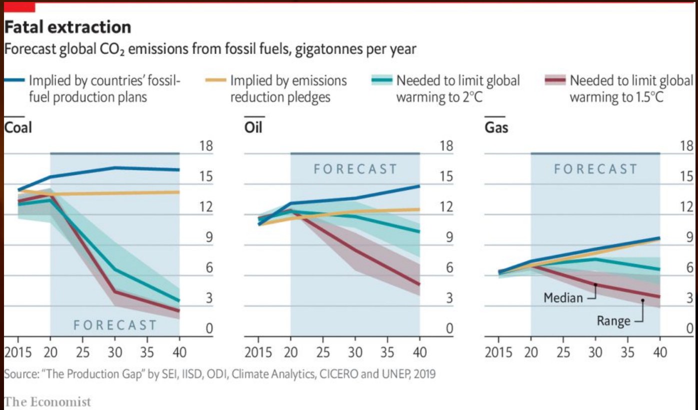
Many trends are pessimistic









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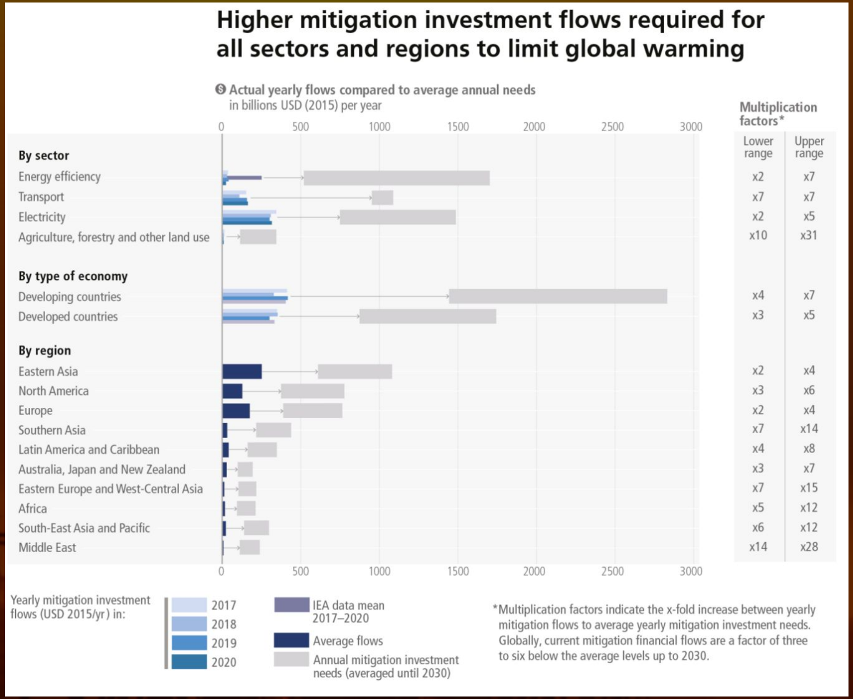

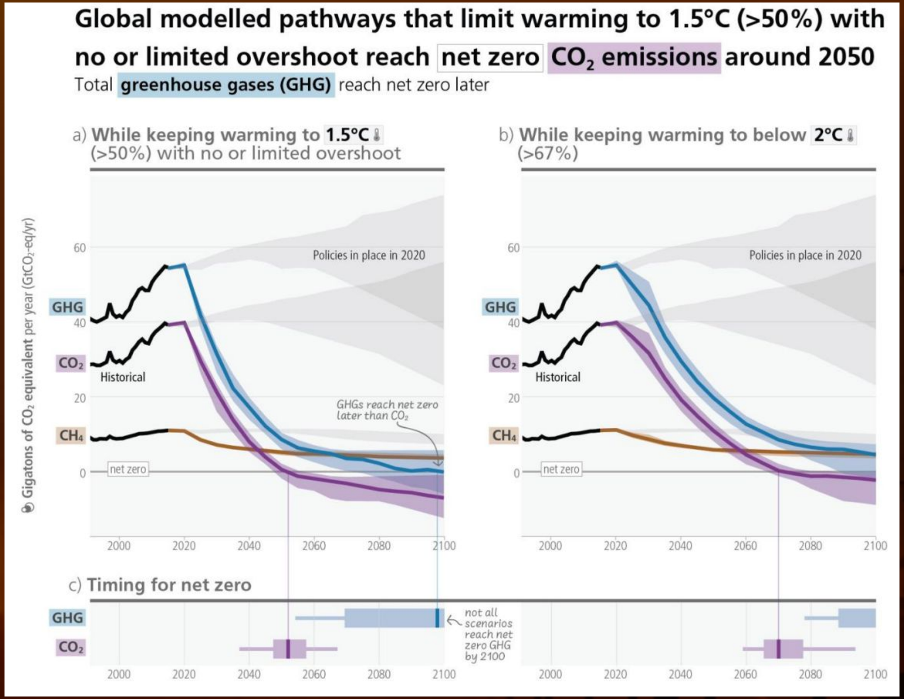

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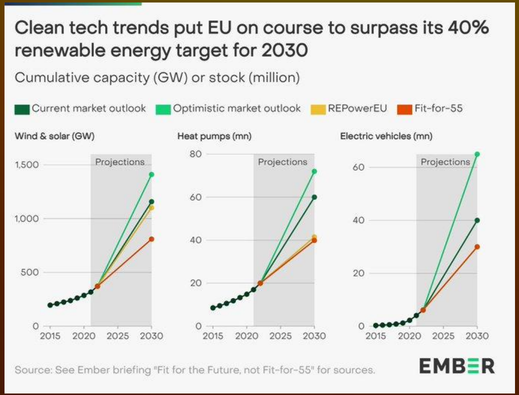
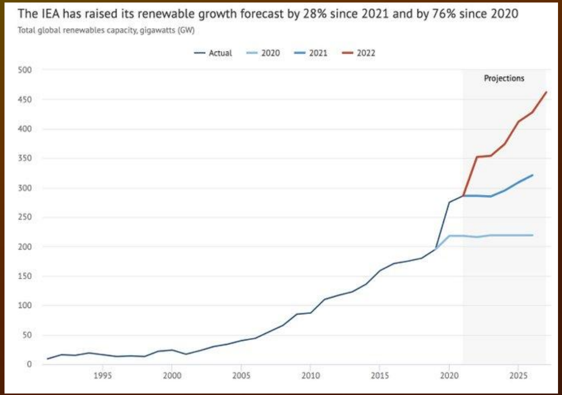
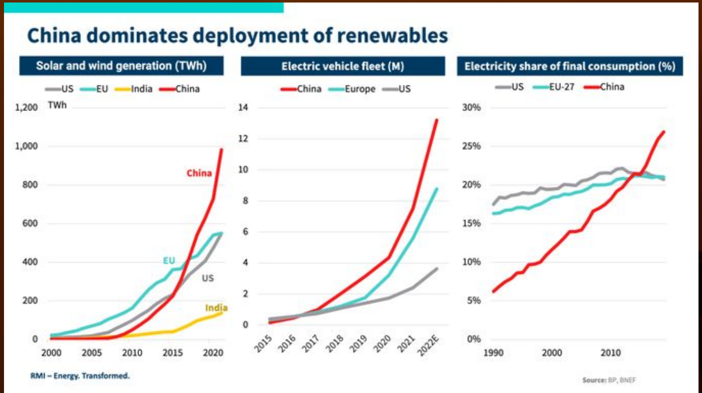
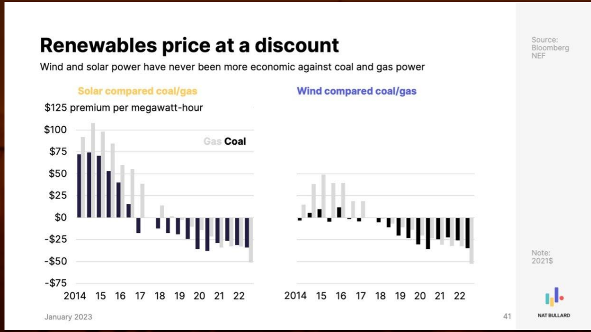
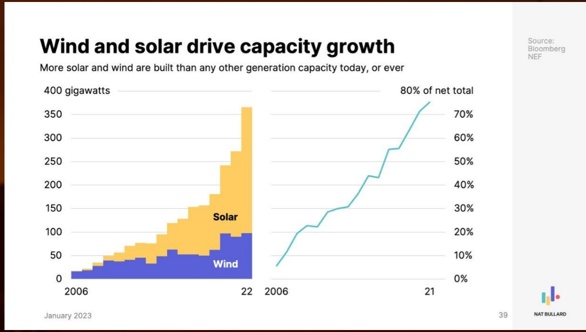
Cheap renewables are a rare bright spot

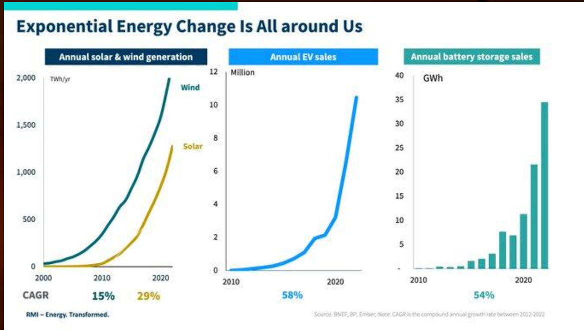












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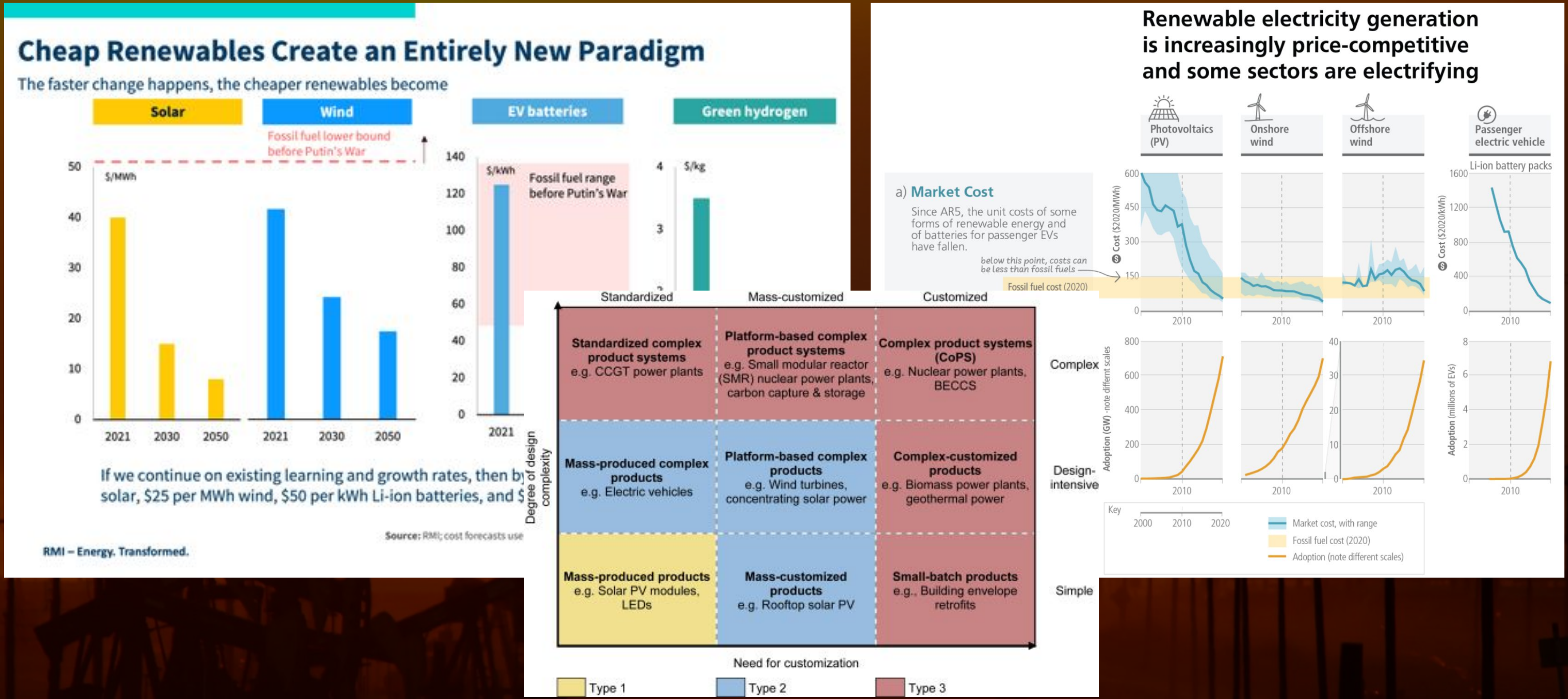

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Techno-optimism is not enough.

there is no silver bullet solution:

- not nuclear power
- not mass solar + wind
- not carbon capture
- not fusion energy
- not geoengineering

Policy is necessary!

There is a moral imperative to act.

realism is not nihilism:

- things will never get so bad that they can't get worse
- every thousandth of a degree of warming prevented means millions of lives saved
- it is our responsibility to fight!

DOOMERS GET OUT


Semester
Overview
a preview of coming
attractions

Course Outline

- Planned class structure:

Course Outline

- Planned class structure:
  - 1 hr lecture

Course Outline

- Planned class structure:
  - 1 hr lecture
  - ½ hr break

Course Outline

- Planned class structure:
    - 1 hr lecture
    - ½ hr break
    - 1 hr discussion

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  - Unit 1: clean energy fundamentals

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  - Unit 2: clean energy challenges

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  - Unit 1: clean energy fundamentals
  - Unit 2: clean energy challenges
  - Unit 3: clean energy innovation

Unit 1: Energy Fundamentals

2. Hydrogen

Unit 1: Energy Fundamentals

2. Hydrogen
3. Renewable Energy

Unit 1: Energy Fundamentals

2. Hydrogen
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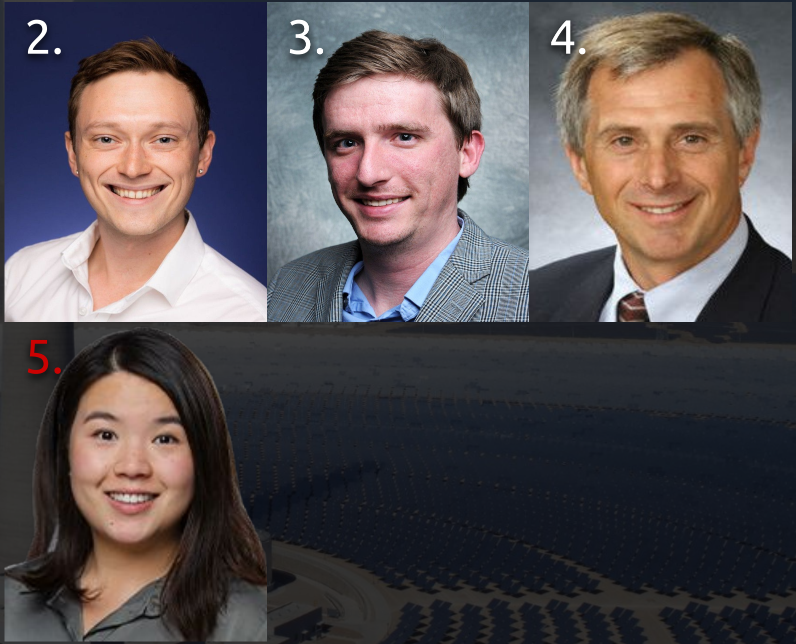
4. Fossil Energy

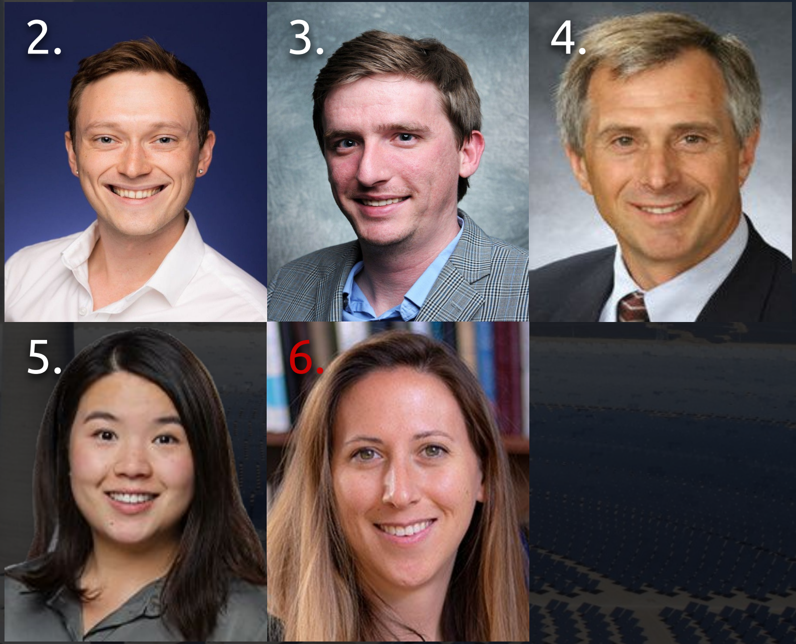
Unit 1: Energy Fundamentals

2. Hydrogen
3. Renewable Energy
4. Fossil Energy
5. Bioenergy



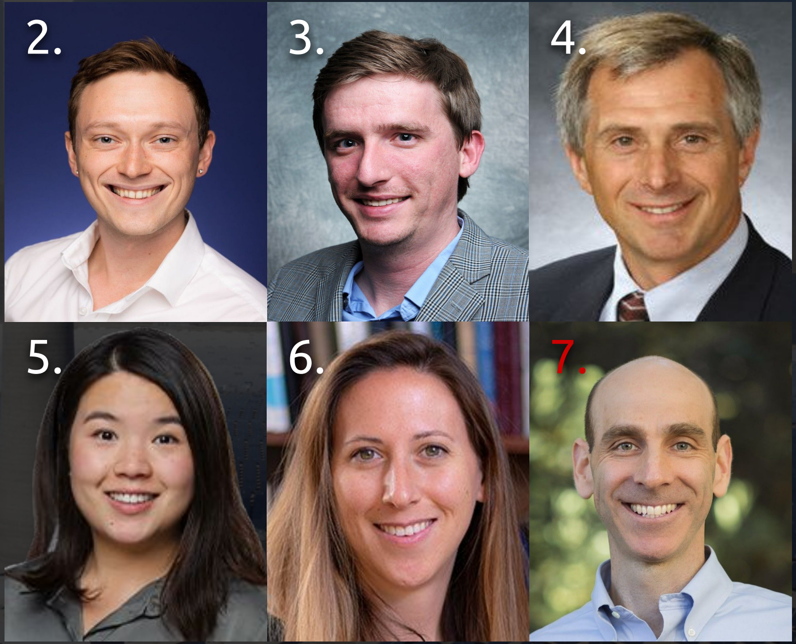
Unit 1: Energy Fundamentals

2. Hydrogen
3. Renewable Energy
4. Fossil Energy
5. Bioenergy
6. Nuclear Energy



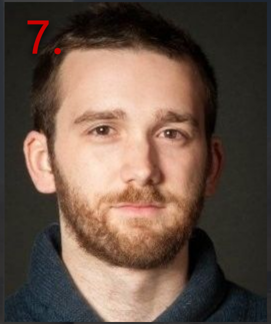
Unit 1: Energy Fundamentals

2. Hydrogen
3. Renewable Energy
4. Fossil Energy
5. Bioenergy
6. Nuclear Energy
7. The Grid



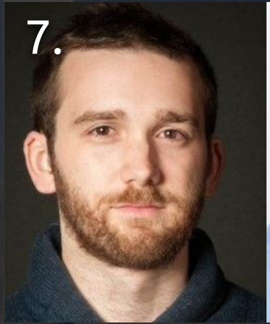
Unit 2: Energy Challenges

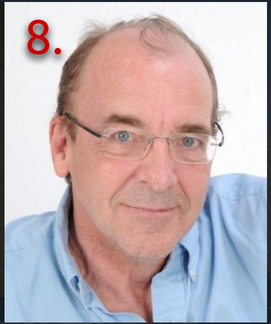
7. Transportation



Unit 2: Energy Challenges

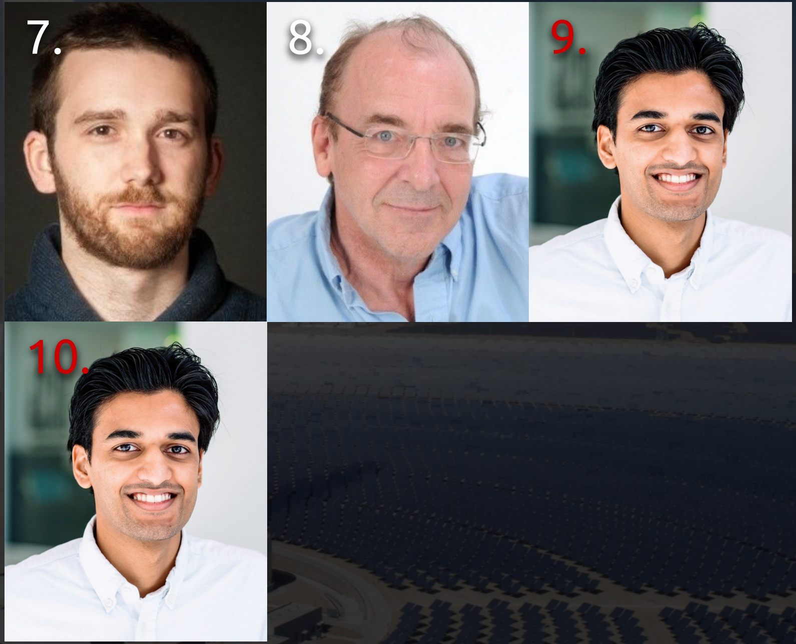
7. Transportation
8. Critical Minerals





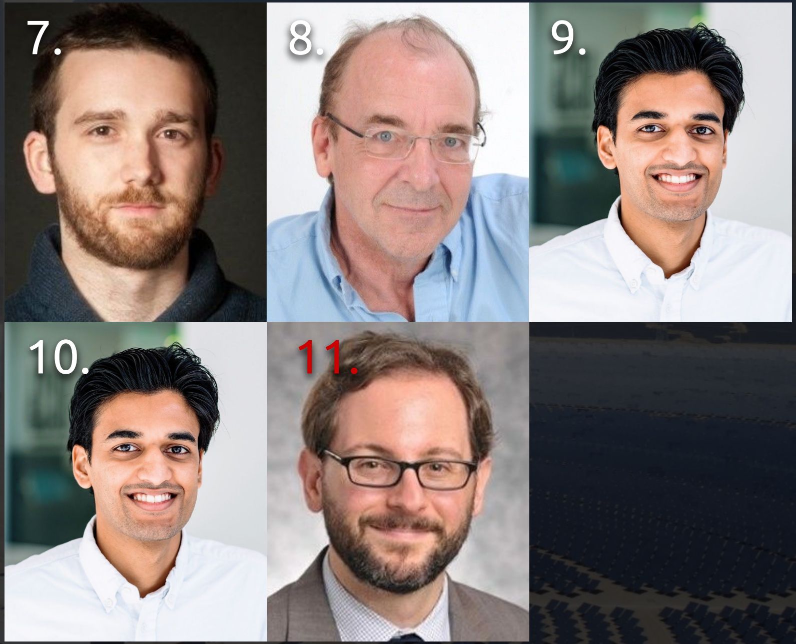
Unit 2: Energy Challenges

7. Transportation
8. Critical Minerals
9. Carbon Capture
10. Energy Storage



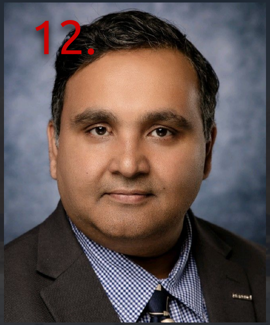
Unit 2: Energy Challenges

7. Transportation
8. Critical Minerals
9. Carbon Capture
10. Energy Storage
11. Industrial Decarb



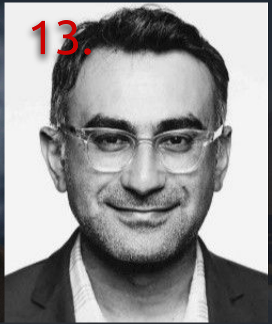
Unit 3: Energy Innovation

12. Cleantech 1.0



Unit 3: Energy Innovation

12. Cleantech 1.0
13. Cleantech Investing



Questions?

pre-course intro survey
(MANDATORY)

Crescent Dunes Solar Energy Project
Nevada, United States of America
38°14'00"N 117°22'01"W

Nameplate capacity:	110 MW
Capacity factor:	51.9% *(planned)*
	20.3% *(2018)*
Annual generation:	196 GWh *(2018)*
Construction began:	September 2011
Opening date:	September 2015
Construction cost:	US$975 million
Owner(s):	Tonopah Solar Energy, LLC

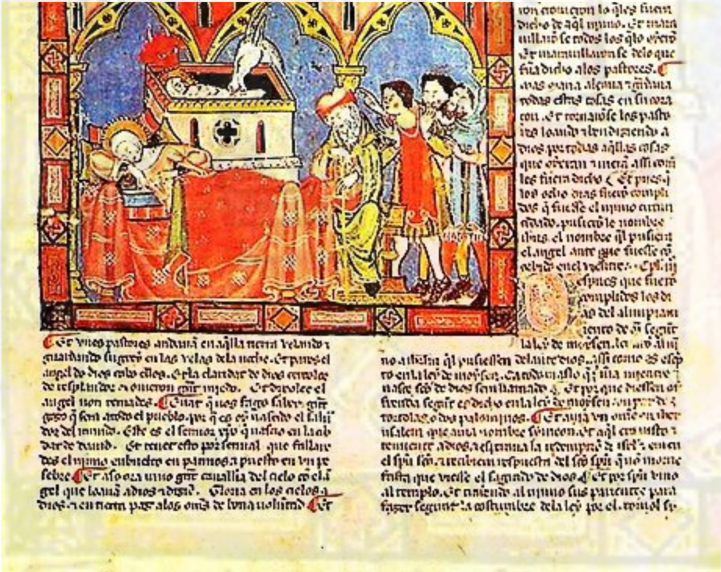
The More You Know:
my favorite word etymology

Minium

Minium druse on cerussite from the Old Yuma Mine, Tucson Mountains, Arizona

General	
Category	Oxide mineral
Formula	$Pb^{2+}{}_2Pb^{4+}O_4$

The color was used in particular for the paragraph signs, versals, capitals, and headings which were colored red in medieval manuscripts.[2] The Latin verb for this kind of work was *miniare*, to apply minium, and a person who did this was known as a *miniator*. These medieval artists also made small illustrations and decorative drawings in the manuscripts, which became known as *miniatures*, the source of the English word for small works of art.[4]



minho (river) →

minium (mineral) →

miniare (pigment) →

miniature (art) →

miniature (size)