

# 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

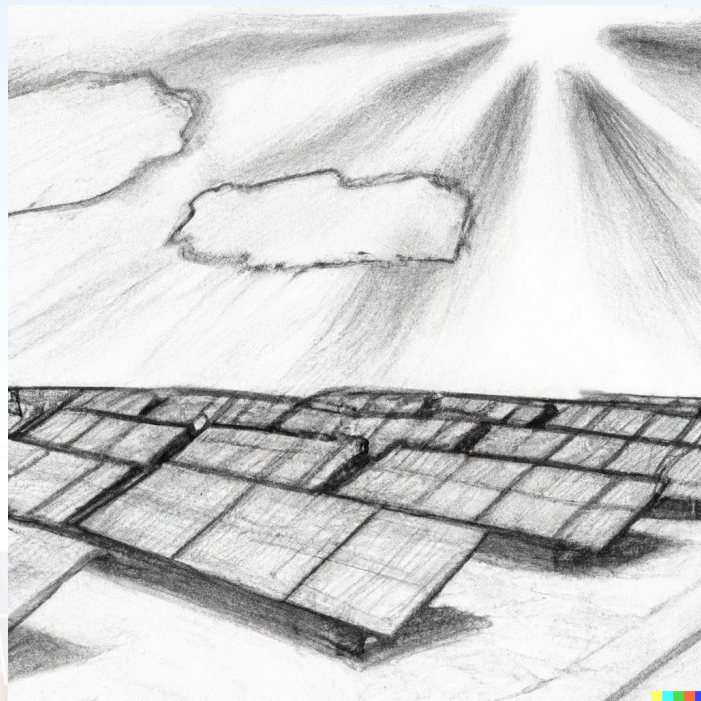


Image by DALL·E 2

PROMPT: "a hand-drawn pencil sketch of a field of solar panels on a sunny day with a few clouds"

# Course Expectations

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(learners)

(teachers)

## I expect from you:

- 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

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(learners)

## I expect from you:

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

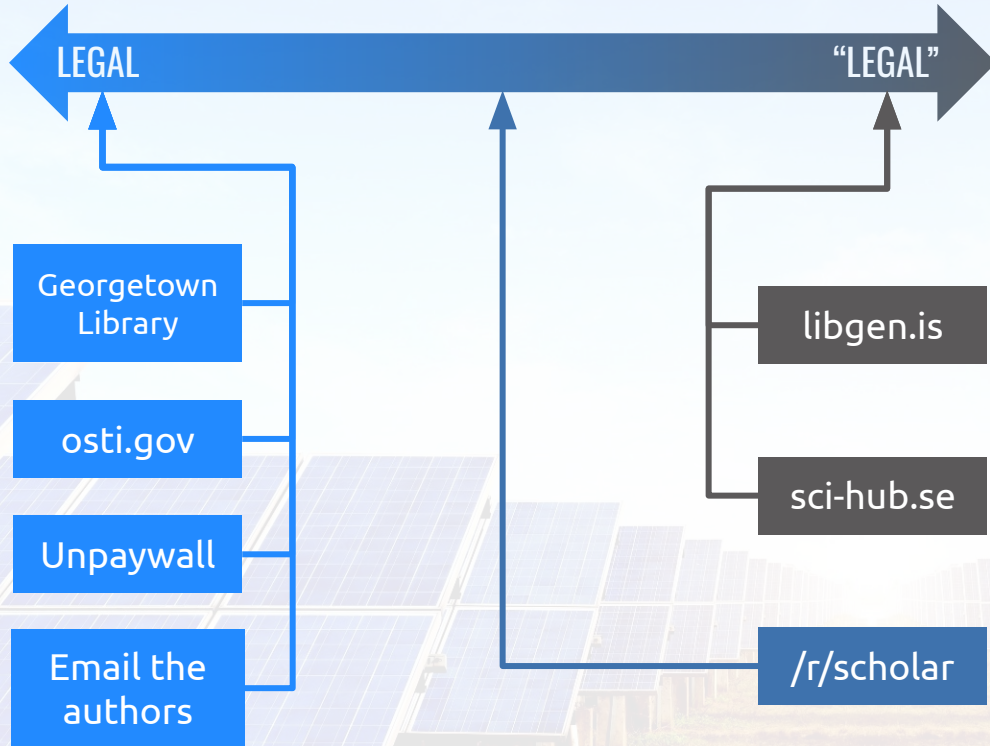
(ethics)



*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"

(grading)

# Aside: Journal Access for Dummies



nature > commentary > article

MENU ▾ **nature**

Commentary | Published: 30 April 1992

## The growing inaccessibility of science

Donald P. Hayes

Nature 356, 739–740(1992) | Cite this article

1015 Accesses | 44 Citations | 27 Altmetric | Metrics

### Access options

<p>Rent or Buy article</p> <p>Get time limited or full article access on ReadCube.</p> <p>from <b>\$8.99</b></p> <p>Rent or Buy</p> <p>All prices are NET prices.</p>	<p>Subscribe to Journal</p> <p>Get full journal access for 1 year</p> <p><b>\$199.00</b> only \$3.83 per issue</p> <p>Subscribe</p> <p>All prices are NET prices. VAT will be added later in the checkout.</p>
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# Course Expectations

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(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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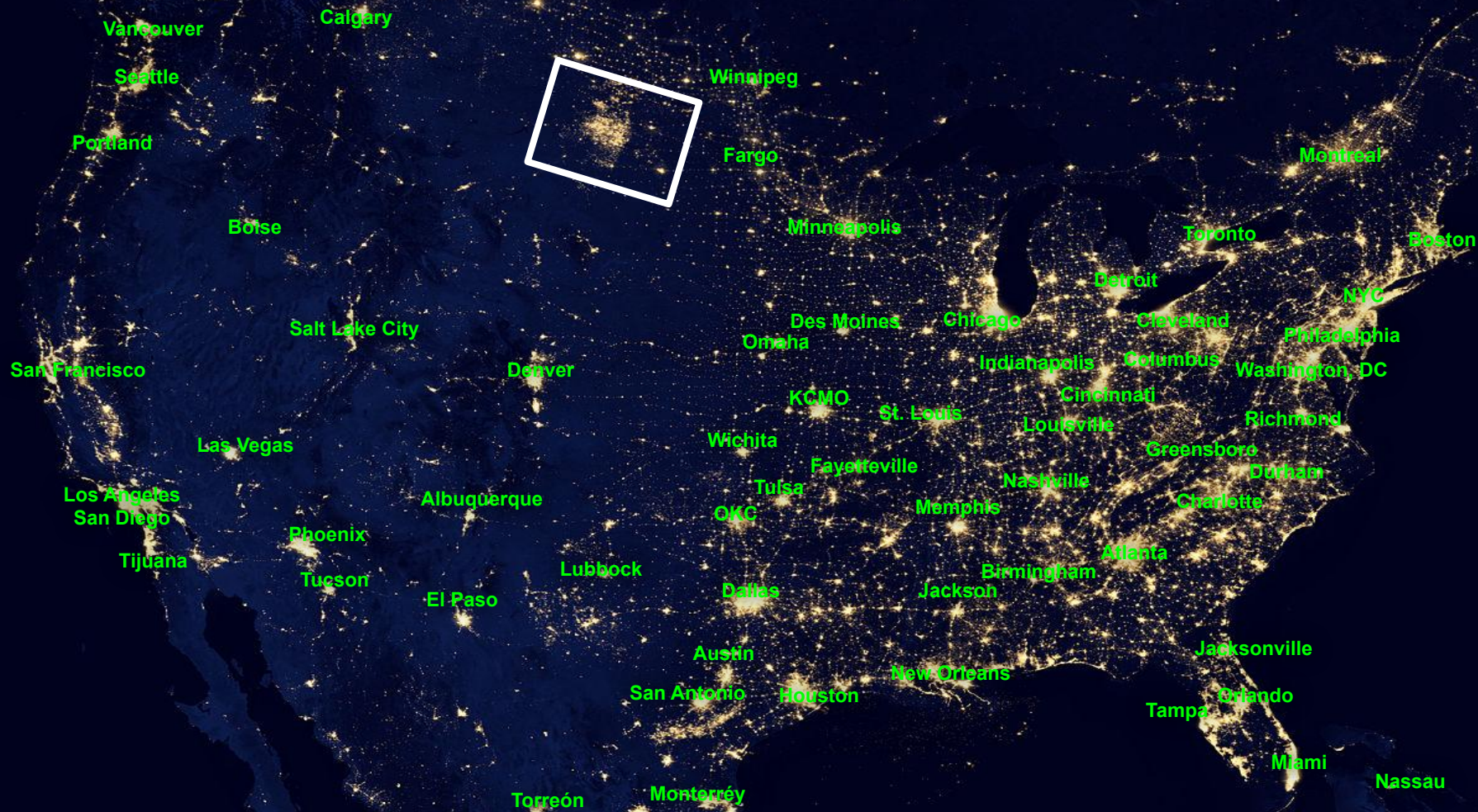
Any views expressed by the Professor throughout the Course are solely those of the Professor and do not reflect the official policy or position of the Advanced Research Projects Agency - Energy (ARPA-E), DOE, or the U.S. Government.

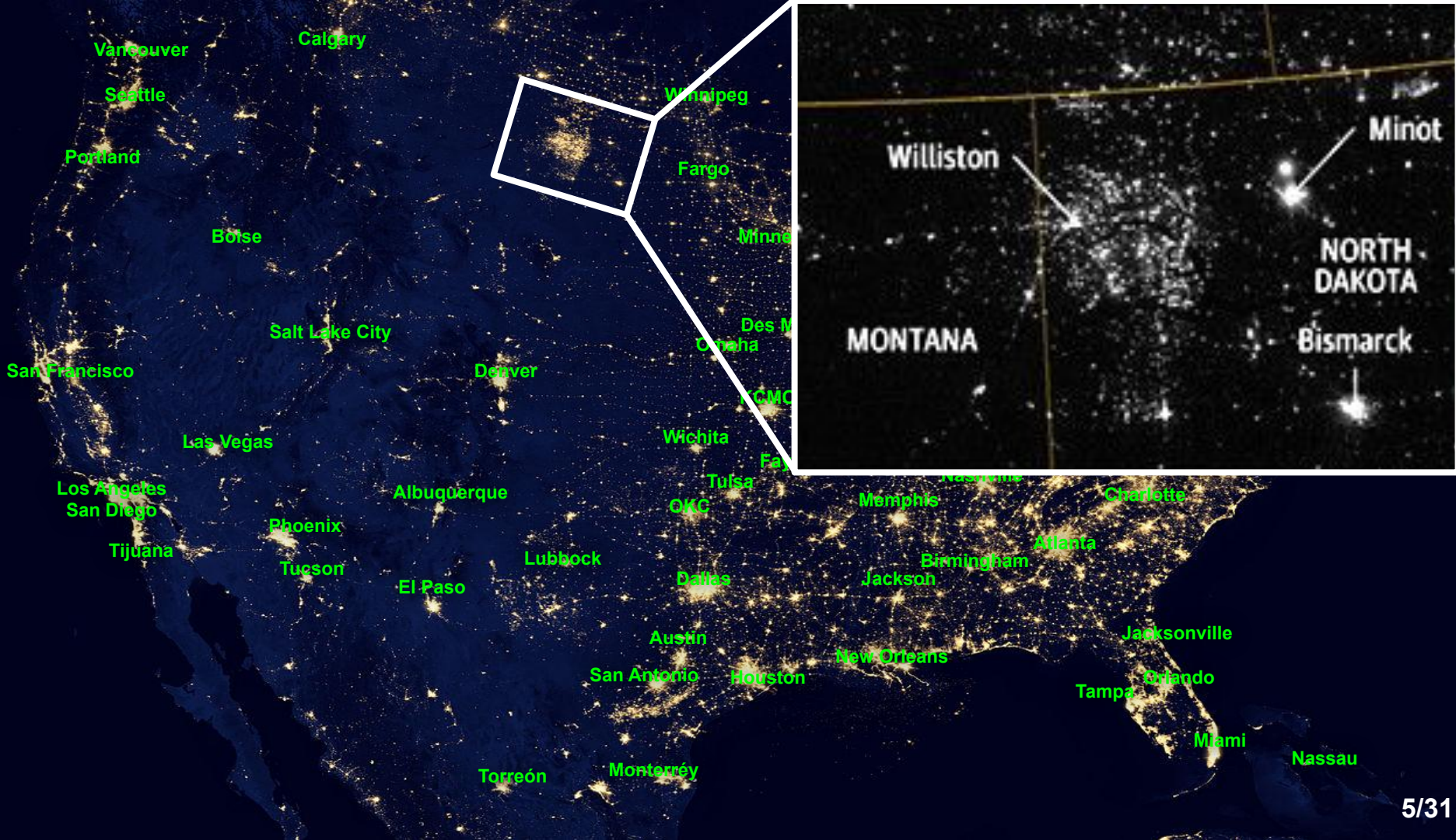
Reference to any specific commercial product, process, or service by trade name, trademark, manufacture, or otherwise does not constitute an endorsement, a recommendation, or a favoring by ARPA-E, the DOE, or the U.S. government. The DOE does not endorse or sponsor any commercial product, service, or activity.

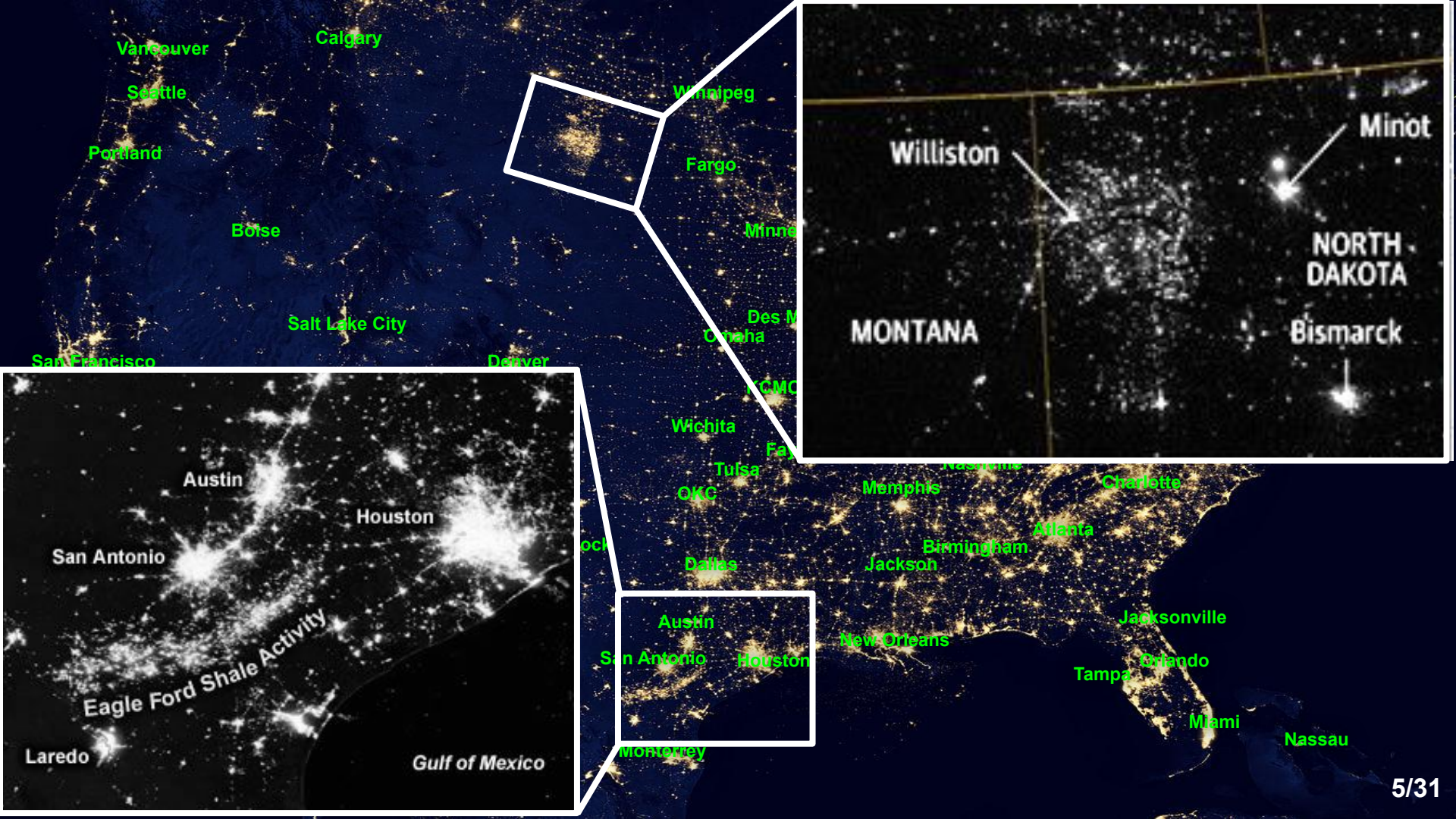












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Bismarck

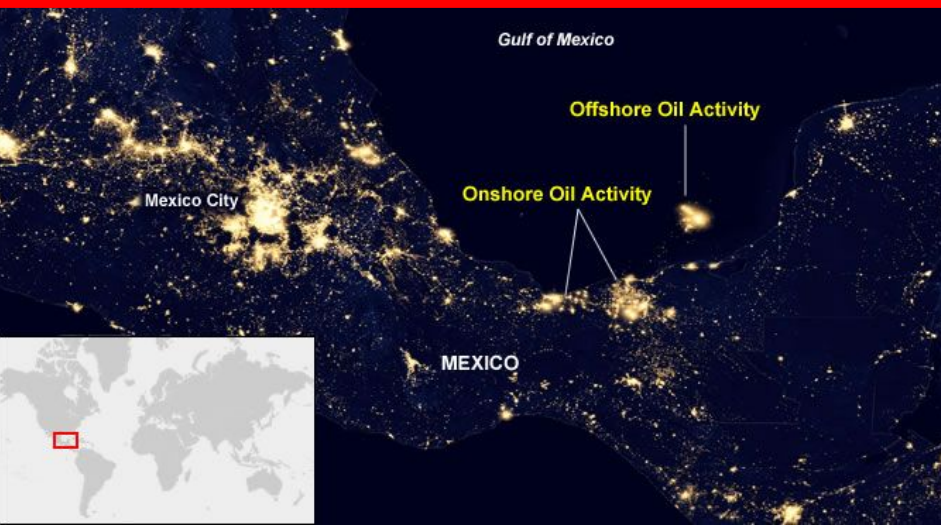
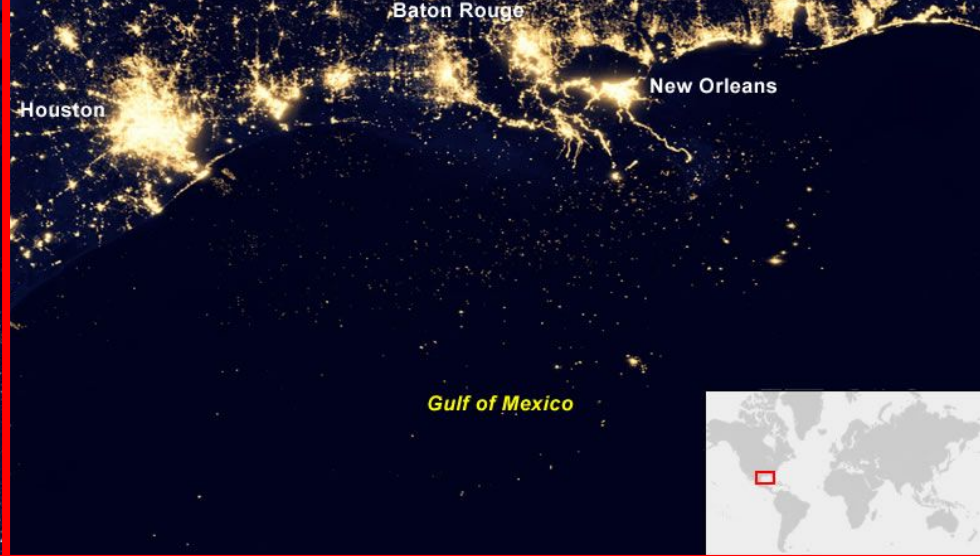
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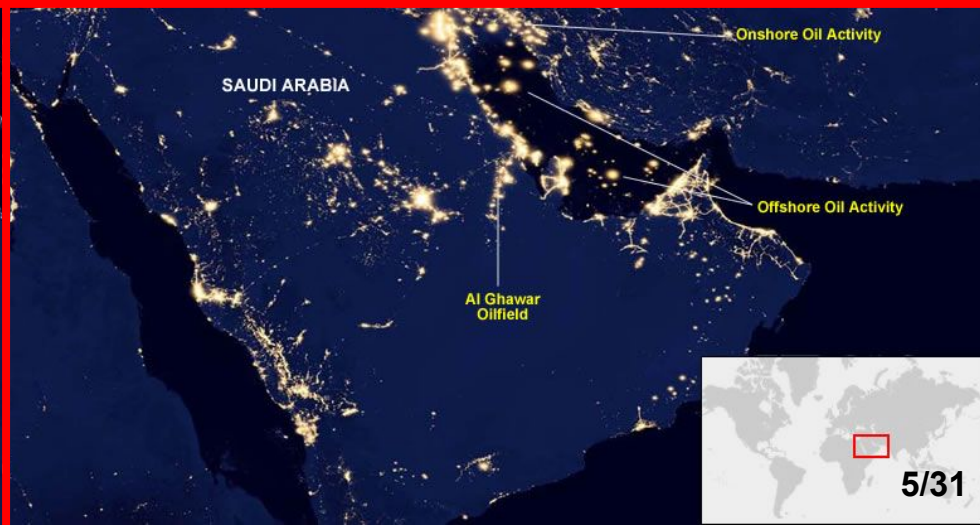
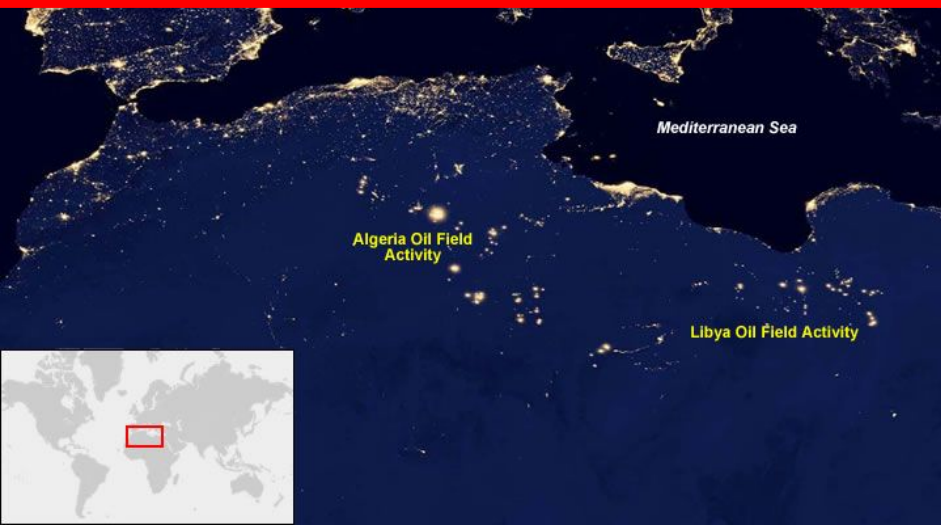
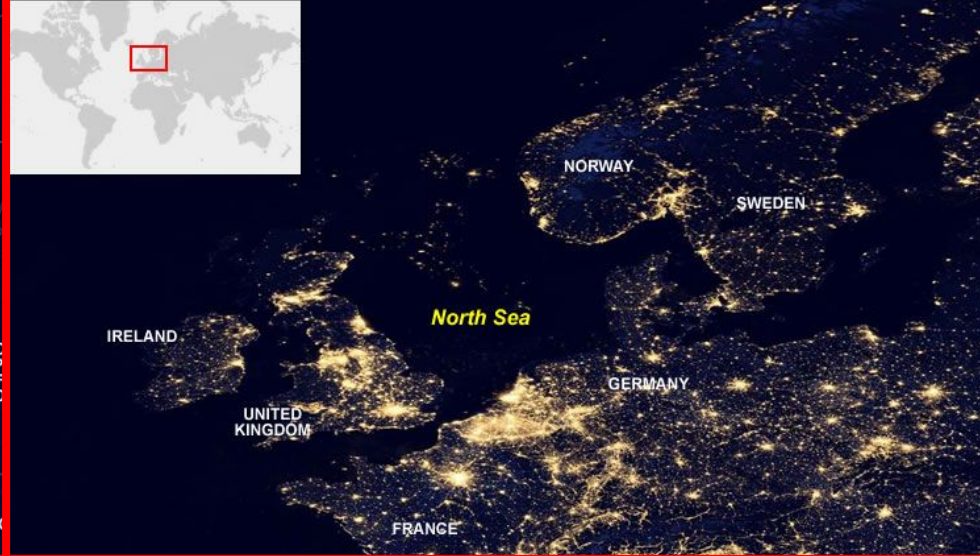
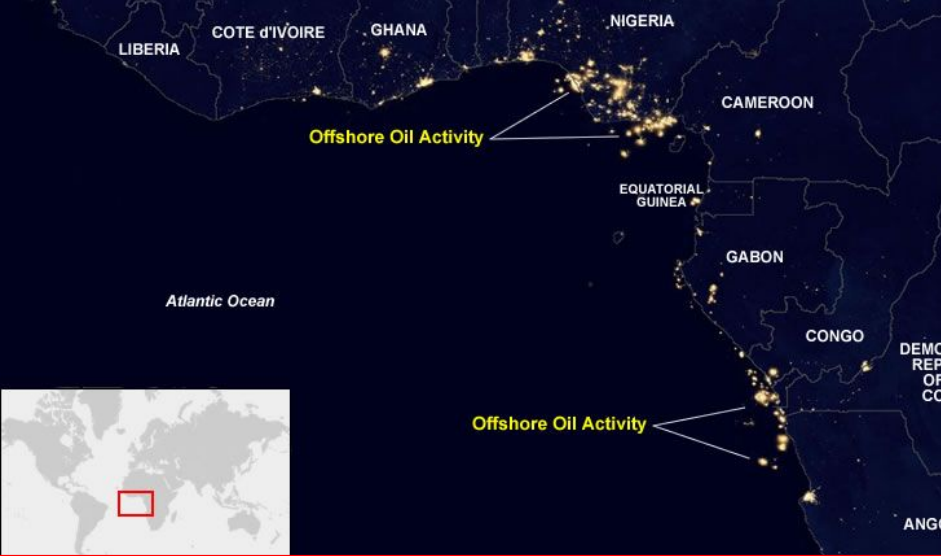
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Orlando  
Miami  
Nassau

Austin  
San Antonio  
Houston  
Monterrey

# How much methane do we flare?

- 143,000,000,000 m<sup>3</sup>/y CH<sub>4</sub>
- \$29,800,000,000/yr
- 500 Mt/y CO<sub>2</sub><sup>e</sup> (2022)
  - *c.f.* total fossil CO<sub>2</sub> emissions: 37.9 Gt/y (2021, global)
  - about as much CO<sub>2</sub> as Brazil
- 3.5% of global supply
  - enough to heat every home in America





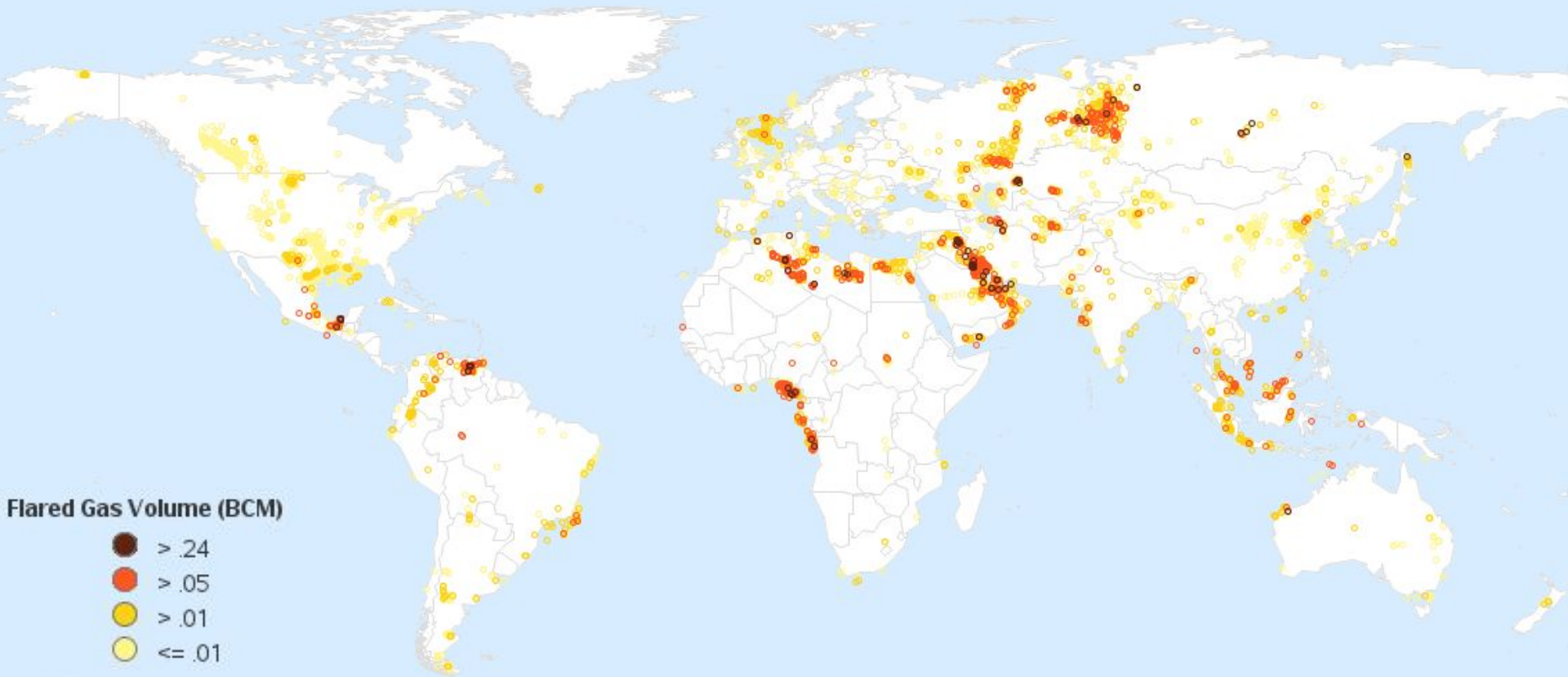


# Where is Methane Flared?

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<b>LNG terminals:</b>	<b>2%</b>
<b>Gas refineries:</b>	<b>8%</b>
<b>Production areas:</b>	<b>90%</b>

# Locations Flaring Natural Gas in 2012



# Why do we this?

1. Natural gas is mostly methane ( $\text{CH}_4$ )
  - Methane is a greenhouse gas 30-200× worse than  $\text{CO}_2$
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  $\text{CO}_2$ , which is less harmful than  $\text{CH}_4$



**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

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- **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
- $\text{force} = \text{mass} \times \text{acceleration}$

- **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

---

**1. Energy cannot be created or destroyed**





# The Three Laws of Thermodynamics

---

## 1. Energy cannot be created or destroyed

↳ *you can never get more energy out of a system than you put in*



# The Three Laws of Thermodynamics

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## 1. Energy cannot be created or destroyed

↳ *you can never get more energy out of a system than you put in*

## 2. Entropy of the universe always increases

# The Three Laws of Thermodynamics

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## 1. Energy cannot be created or destroyed

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↳ *real-world systems are always less than 100% efficient*

# The Three Laws of Thermodynamics

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↳ *you can never get more energy out of a system than you put in*

## 2. Entropy of the universe always increases

↳ *real-world systems are always less than 100% efficient*

## 3. Absolute zero can't be reached

# The Three Laws of Thermodynamics

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↳ *atomic motion stops at  $T = -273.15\text{ }^{\circ}\text{C}$  (zero Kelvin)*

# The Three Laws of Thermodynamics

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## 1. Energy cannot be created or destroyed

- ↳ *you can never get more energy out of a system than you put in*
  - ↳ (you can't win)

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- ↳ *real-world systems are always less than 100% efficient*

## 3. Absolute zero can't be reached

- ↳ *atomic motion stops at  $T = -273.15 \text{ }^\circ\text{C}$  (zero Kelvin)*

# The Three Laws of Thermodynamics

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## 1. Energy cannot be created or destroyed

- ↳ *you can never get more energy out of a system than you put in*
  - ↳ (you can't win)

## 2. Entropy of the universe always increases

- ↳ *real-world systems are always less than 100% efficient*
  - ↳ (you always lose)

## 3. Absolute zero can't be reached

- ↳ *atomic motion stops at  $T = -273.15 \text{ }^\circ\text{C}$  (zero Kelvin)*

# The Three Laws of Thermodynamics

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## 1. Energy cannot be created or destroyed

- ➔ *you can never get more energy out of a system than you put in*
  - ↪ (you can't win)

## 2. Entropy of the universe always increases

- ➔ *real-world systems are always less than 100% efficient*
  - ↪ (you always lose)

## 3. Absolute zero can't be reached

- ➔ *atomic motion stops at  $T = -273.15\text{ }^{\circ}\text{C}$  (zero Kelvin)*
  - ↪ (you can't quit)



# Intro to SI units (the metric system)

unit	symbol	measures
------	--------	----------

second	s	<i>time</i>
--------	---	-------------



**time**

# Intro to SI units (the metric system)

unit	symbol	measures
second	s	<i>time</i>
kilogram	kg	<i>mass</i>



**time**



**mass**

# Intro to SI units (the metric system)

unit	symbol	measures
second	s	<i>time</i>
kilogram	kg	<i>mass</i>
metre	m	<i>length</i>



time



mass



length

# Intro to SI units (the metric system)

unit	symbol	measures
second	s	<i>time</i>
kilogram	kg	<i>mass</i>
metre	m	<i>length</i>
ampere	A	<i>electric current</i>



**time**



**mass**



**length**



**current**

# Intro to SI units (the metric system)

unit	symbol	measures
second	s	<i>time</i>
kilogram	kg	<i>mass</i>
metre	m	<i>length</i>
ampere	A	<i>electric current</i>
kelvin	K	<i>[absolute] temperature</i>



**time**



**mass**



**length**



**current**



**temperature**

# Intro to SI units (the metric system)

unit	symbol	measures
second	s	<i>time</i>
kilogram	kg	<i>mass</i>
metre	m	<i>length</i>
ampere	A	<i>electric current</i>
kelvin	K	<i>[absolute] temperature</i>
mole	mol	<i>"amount of substance"</i>



**time**



**mass**



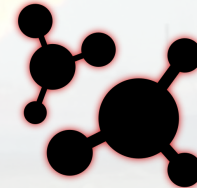
**length**



**current**



**temperature**



**quantity**

# Intro to SI units (the metric system)

unit	symbol	measures
second	s	<i>time</i>
kilogram	kg	<i>mass</i>
metre	m	<i>length</i>
ampere	A	<i>electric current</i>
kelvin	K	<i>[absolute] temperature</i>
mole	mol	<i>"amount of substance"</i>
candela	cd	<i>luminous intensity</i>



**time**



**mass**



**length**



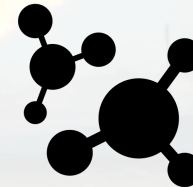
**brightness**



**current**



**temperature**



**quantity**

# Intro to SI units (the metric system)

unit	symbol	measures	prefix	symbol	power	order	decimal
second	s	<i>time</i>	atto-	a	$10^{-18}$	quintillionth	0.000000000000000001
			femto-	f	$10^{-15}$	quadrillionth	0.0000000000000001
			pico-	p	$10^{-12}$	trillionth	0.000000000001
kilogram	kg	<i>mass</i>	nano-	n	$10^{-9}$	billionth	0.00000001
			micro-	μ	$10^{-6}$	millionth	0.000001
			milli-	m	$10^{-3}$	thousandth	0.001
metre	m	<i>length</i>	centi-	c	$10^{-2}$	hundredth	0.01
			deci-	d	$10^{-1}$	tenth	0.1
			--	--	$10^0$	--	1
ampere	A	<i>electric current</i>	deka-	da	$10^1$	ten	10
kelvin	K	<i>[absolute] temperature</i>	hecto-	h	$10^2$	hundred	100
			kilo-	k	$10^3$	thousand	1000
			mega-	M	$10^6$	million	1000000
mole	mol	<i>"amount of substance"</i>	giga-	G	$10^9$	billion	1000000000
			tera-	T	$10^{12}$	trillion	1000000000000
			peta-	P	$10^{15}$	quadrillion	1000000000000000
candela	cd	<i>luminous intensity</i>	exa-	E	$10^{18}$	quintillion	1000000000000000000



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unit	symbol	measures	prefix	symbol	power	order	decimal
second	s	<i>time</i>	atto-	a	$10^{-18}$	quintillionth	0.000000000000000001
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			pico-	p	$10^{-12}$	trillionth	0.000000000001
kilogram	kg	<i>mass</i>	<b>nano-</b>	<b><i>n</i></b>	<b><math>10^{-9}</math></b>	<b><i>billionth</i></b>	<b><i>0.00000001</i></b>
			<b>micro-</b>	<b><math>\mu</math></b>	<b><math>10^{-6}</math></b>	<b><i>millionth</i></b>	<b><i>0.000001</i></b>
			<b>milli-</b>	<b><i>m</i></b>	<b><math>10^{-3}</math></b>	<b><i>thousandth</i></b>	<b><i>0.001</i></b>
metre	m	<i>length</i>	<b>centi-</b>	<b><i>c</i></b>	<b><math>10^{-2}</math></b>	<b><i>hundredth</i></b>	<b><i>0.01</i></b>
			deci-	d	$10^{-1}$	tenth	0.1
ampere	A	<i>electric current</i>	--	--	$10^0$	--	1
			deka-	da	$10^1$	ten	10
kelvin	K	<i>[absolute] temperature</i>	hecto-	h	$10^2$	hundred	100
			<b>kilo-</b>	<b><i>k</i></b>	<b><math>10^3</math></b>	<b><i>thousand</i></b>	<b><i>1000</i></b>
mole	mol	<i>"amount of substance"</i>	<b>mega-</b>	<b><i>M</i></b>	<b><math>10^6</math></b>	<b><i>million</i></b>	<b><i>1000000</i></b>
			<b>giga-</b>	<b><i>G</i></b>	<b><math>10^9</math></b>	<b><i>billion</i></b>	<b><i>1000000000</i></b>
candela	cd	<i>luminous intensity</i>	<b>tera-</b>	<b><i>T</i></b>	<b><math>10^{12}</math></b>	<b><i>trillion</i></b>	<b><i>1000000000000</i></b>
			peta-	P	$10^{15}$	quadrillion	1000000000000000
			<b>exa-</b>	<b><i>E</i></b>	<b><math>10^{18}</math></b>	<b><i>quintillion</i></b>	<b><i>1000000000000000000</i></b>

# SI Units are all interconnected!

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- 1 cubic centimeter ( $\text{cm}^3$ ) = 1 milliliter (mL)



# SI Units are all interconnected!

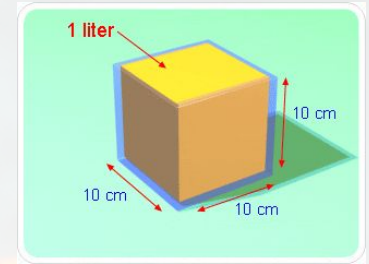
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- 1 cubic centimeter ( $\text{cm}^3$ ) = 1 milliliter (mL)
  - 1 mL of water: 1 gram (g)

# SI Units are all interconnected!

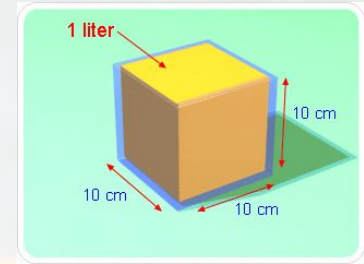
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- 1 cubic centimeter ( $\text{cm}^3$ ) = 1 milliliter (mL)
  - 1 mL of water: 1 gram (g)
- 1000 mL = 1 liter (L)



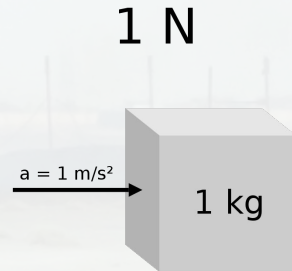
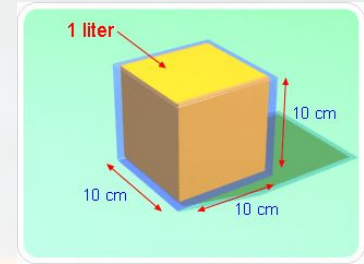
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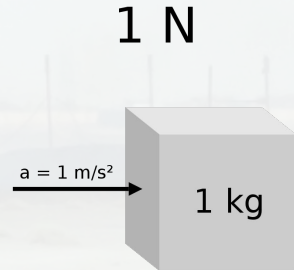
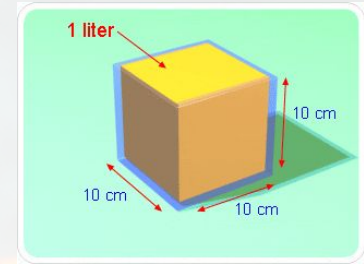
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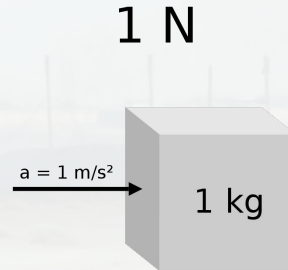
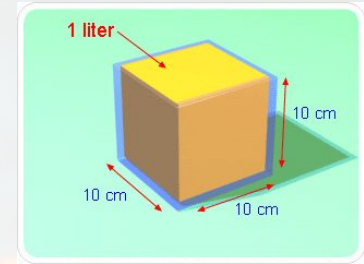
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  - $1 \text{ N} = 1 \text{ kg} \cdot \text{m/s}^2$



# SI Units are all interconnected!

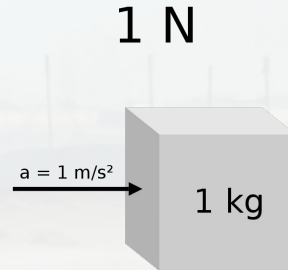
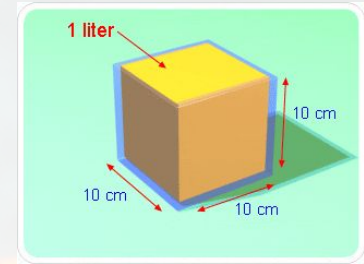
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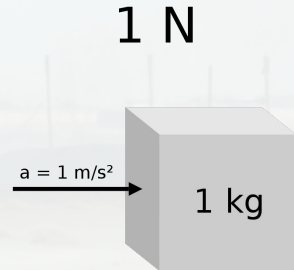
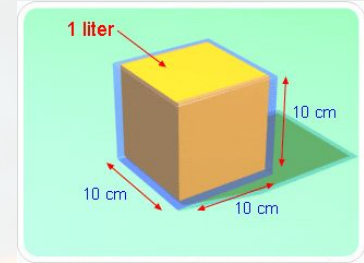
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  - $1 \text{ J} = 1 \text{ N} \cdot \text{m}$



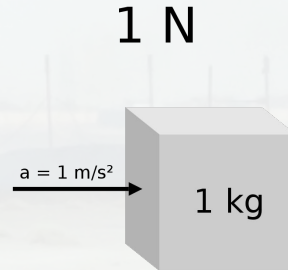
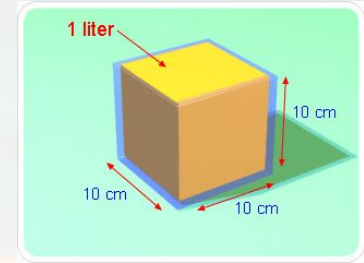
# SI Units are all interconnected!

- 1 cubic centimeter ( $\text{cm}^3$ ) = 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  $1 \text{ m/s}^2$ 
  - $1 \text{ N} = 1 \text{ kg} \cdot \text{m/s}^2$
- 1 joule (J) = work done by 1 N over 1 m
  - $1 \text{ J} = 1 \text{ N} \cdot \text{m}$
- 1 watt (W) = power of 1 Joule over 1 sec



# SI Units are all interconnected!

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- 1 watt (W) = power of 1 Joule over 1 sec
  - $1 \text{ W} = 1 \text{ J/s}$



# 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 <sup>-1</sup>
Force	<b>newton</b>	N	m•kg•s <sup>-2</sup>
Pressure	pascal	Pa	N/m <sup>2</sup>
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 <sup>12</sup>	tera	T	1 000 000 000 000
10 <sup>9</sup>	giga	G	1 000 000 000
10 <sup>6</sup>	mega	M	1 000 000
10 <sup>3</sup>	kilo	k	1 000
10 <sup>2</sup>	hecto	h	100
10 <sup>1</sup>	deka	da	10
10 <sup>-1</sup>	deci	d	0.1
10 <sup>-2</sup>	centi	c	0.01
10 <sup>-3</sup>	milli	m	0.001
10 <sup>-6</sup>	micro	μ	0.000 001
10 <sup>-9</sup>	nano	n	0.000 000 001
10 <sup>-12</sup>	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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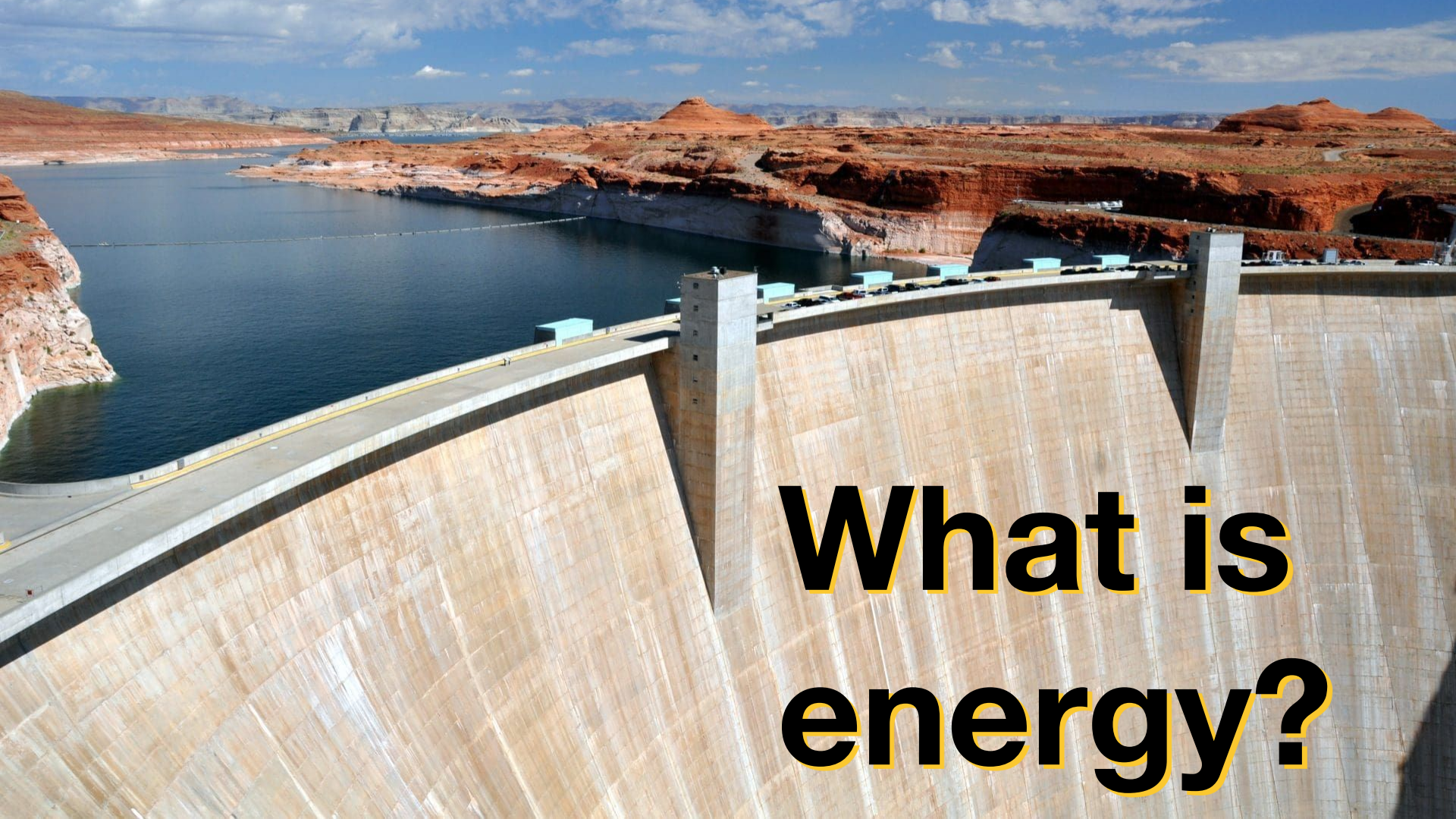
AND NOW BACK TO  
OUR REGULARLY  
SCHEDULED  
PROGRAMMING



**This class is about two things:**

**1. Energy**

**2. Money**



**What is  
energy?**

# Types of Energy



thermal



elastic



mechanical



gravitational



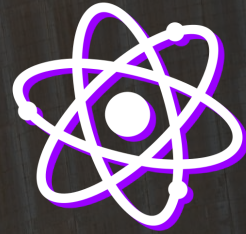
chemical



magnetic



electrical



nuclear



energy

A large concrete dam with water behind it, set against a dark, rocky landscape. The dam is made of large, rectangular concrete panels. The water is dark and calm. The background shows a rugged, rocky terrain under a dark sky.

# 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)

$$Q = mc_p \Delta T$$

$$W = f \cdot d$$

$$E = h\nu$$

$$E = mc^2$$

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

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

# energy

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

$$Q = mc_p \Delta T$$

$$W = f \cdot d$$

$$E = h\nu$$

$$E = mc^2$$

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

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

$$U_{\text{grav}} = mgh$$

# energy

- Heat
- Work
- Light
- Mass
- Motion (kinetic)
  - Linear
  - Rotational
- Position (potential)
  - Gravitational
  - Spring / Elastic

$$Q = mc_p \Delta T$$

$$W = f \cdot d$$

$$E = h\nu$$

$$E = mc^2$$

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

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$$U_{\text{grav}} = mgh$$

$$U_{\text{spring}} = \frac{1}{2}kx^2$$

# energy

- Heat
- Work
- Light
- Mass

$$Q = mc_p\Delta T$$

$$W = f \cdot d$$

$$E = h\nu$$

$$E = mc^2$$

- Motion (kinetic)

- Linear

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

- Rotational

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

- Position (potential)

- Gravitational

$$U_{\text{grav}} = mgh$$

- Spring / Elastic

$$U_{\text{spring}} = \frac{1}{2}kx^2$$

- Chemical

$$\Delta H_{\text{rxn}}^{\ominus} = \sum_i a_i \Delta_f H_{\text{products}}^{\ominus} - \sum_j b_j \Delta_f H_{\text{reactants}}^{\ominus}$$

# energy

- Heat
- Work
- Light
- Mass

$$Q = mc_p \Delta T$$

$$W = f \cdot d$$

$$E = h\nu$$

$$E = mc^2$$

- Motion (kinetic)

- Linear

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

- Rotational

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- Position (potential)

- Gravitational

$$U_{\text{grav}} = mgh$$

- Spring / Elastic

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- Chemical

$$\Delta H_{\text{rxn}}^{\circ} = \sum_i a_i \Delta_f H_{\text{products}}^{\circ} - \sum_j b_j \Delta_f H_{\text{reactants}}^{\circ}$$

*don't worry about it*

# energy

- Heat
- Work
- Light
- Mass

$$Q = mc_p \Delta T$$

$$W = f \cdot d$$

$$E = h\nu$$

$$E = mc^2$$

- Motion (kinetic)

- Linear

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

- Rotational

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

- Position (potential)

- Gravitational

$$U_{\text{grav}} = mgh$$

- Spring / Elastic

$$U_{\text{spring}} = \frac{1}{2}kx^2$$

- Chemical

$$\Delta H_{\text{rxn}}^\circ = \sum_i \nu_i \Delta H_f^\circ(\text{products}) - \sum_j \nu_j \Delta H_f^\circ(\text{reactants})$$

*don't worry about it*

**units:** all joules (J)

# energy

- Heat
- Work
- Light
- Mass
- Motion (kinetic)
  - Linear
  - Rotational
- Position (potential)
  - Gravitational
  - Spring / Elastic
  - Chemical

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$$\Delta H_{\text{rxn}}^\circ = \sum_i \nu_i \Delta H_f^\circ(\text{products}) - \sum_j \nu_j \Delta H_f^\circ(\text{reactants})$$

*don't worry about it*

# NOT energy

**units:** all joules (J)

# energy

- Heat
- Work
- Light
- Mass
- Motion (kinetic)
  - Linear
  - Rotational
- Position (potential)
  - Gravitational
  - Spring / Elastic
  - Chemical

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*don't worry about it*

**units:** all joules (J)

# NOT energy

- Power:



# energy

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

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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
- Work
- Light
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- Motion (kinetic)
  - Linear
  - Rotational
- Position (potential)
  - Gravitational
  - Spring / Elastic
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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
- Work
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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

- Heat
- Work
- Light
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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
- Work
- Light
- Mass
- Motion (kinetic)
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$$Q = mc_p \Delta T$$

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$$\Delta H_{\text{rxn}}^\circ = \sum_i \nu_i \Delta H_f^\circ(\text{products}) - \sum_j \nu_j \Delta H_f^\circ(\text{reactants})$$

*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

# energy

- Heat
- Work
- Light
- Mass
- Motion (kinetic)
  - Linear
  - Rotational
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$$\Delta H_{\text{rxn}}^\circ = \sum_i \nu_i \Delta H_f^\circ(\text{products}) - \sum_j \nu_j \Delta H_f^\circ(\text{reactants})$$

*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



# energy

- Heat
- Work
- Light
- Mass
- Motion (kinetic)
  - Linear
  - Rotational
- Position (potential)
  - Gravitational
  - Spring / Elastic
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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
- Work
- Light
- Mass
- Motion (kinetic)
  - Linear
  - Rotational
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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:
  - rate of energy per volume

# energy

- Heat
- Work
- Light
- Mass
- Motion (kinetic)
  - Linear
  - Rotational
- Position (potential)
  - Gravitational
  - Spring / Elastic
  - Chemical

$$Q = mc_p\Delta T$$

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$$\Delta H_{\text{rxn}}^\circ = \sum_i \nu_i \Delta H_f^\circ(\text{products}) - \sum_j \nu_j \Delta H_f^\circ(\text{reactants})$$

*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
  - **unit:** pascal (Pa) = J/m<sup>3</sup>

# Joules (J)

- joule (J)

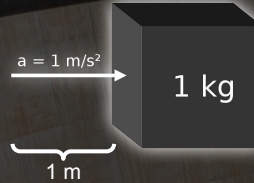


Image by DALL·E 2  
PROMPT: "a high-resolution photograph of an apple in midair falling from a tree"

**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)

- joule (J)
- 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)



# Joules (J)

- joule (J)
- kilojoule (kJ):  $10^3$  J
- megajoule (MJ):  $10^6$  J
- gigajoule (GJ):  $10^9$  J
- terajoule (TJ):  $10^{12}$  J
- exajoule (EJ):  $10^{18}$  J



**one exajoule:** 1% of total  
annual American energy  
usage

# calories and Calories ( $\text{cal}_{\text{th}}$ / kcal)

## “thermal calorie” ( $\text{cal}_{\text{th}}$ , cal, calorie)

- energy to heat 1 gram of water by  $1\text{ }^{\circ}\text{C}$
- $1\text{ cal} = 4.184\text{ J}$

## “food calorie” (kcal, kilocalorie, Cal, Calorie)

- energy to heat 1 *kilogram* of water by  $1\text{ }^{\circ}\text{C}$
- $1\text{ kcal} = 4.184\text{ kJ} = 4,184\text{ J}$
- the one what’s on the back of the box
- i am aware this is dumb and confusing

<b>Nutrition Facts</b>	
8 servings per container	
<b>Serving size</b>	<b>2/3 cup (55g)</b>
<b>Amount per serving</b>	
<b>Calories</b>	<b>230</b>

# British Thermal Units (BTU)

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- “MMBTU”: one million BTU
  - common price unit for natural gas (1~10 \$/MMBTU)
- “quad”: quadrillion ( $10^{15}$ ) BTU
  - $\approx$  1.055 EJ (~1% of annual US energy demand)

# watt-hours (Wh, W·h, W·hr)

power = energy ÷ time

power × time = energy

$$1 \text{ Wh} = 3600 \text{ J}$$

$$1 \text{ kWh} = 3600 \text{ kJ}$$

$$1 \text{ MWh} = 3600 \text{ MJ} \dots$$

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

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

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

$$(1 \text{ W}) \times (1 \text{ hr}) = \left(1 \frac{\text{J}}{\text{sec}}\right) \times \left(1 \text{ hr} \times \frac{3600 \text{ sec}}{1 \text{ hr}}\right)$$

$$= \left(1 \frac{\text{J}}{\text{sec}}\right) \times \left(1 \cancel{\text{hr}} \times \frac{3600 \text{ sec}}{1 \cancel{\text{hr}}}\right)$$

$$= 3600 \text{ J}$$

**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?

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

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

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

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

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

Input interpretation

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

Result

26.82 m/s (meters per second)

?



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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%

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, ARTIFICIAL FLAVOR

\*Percent Daily Values are based on a 2,500 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 15g	20g
Cholesterol	Less Than 300mg	300mg
Sodium	Less Than 2,400mg	2,400mg
Total Carbohydrate	300g	375g
Dietary Fiber	25g	30g

a regular-sized Snickers bar

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**Calories 280** Bar

Amount Per Serving	
Calories	280
Calories from Fat	130
% Daily Value*	
Total Fat	14g
Saturated Fat	5g
Trans Fat	0g
Cholesterol	20mg
Sodium	10mg
Total Carbohydrate	35g
Fiber	1g
Sugars	30g
Protein	4g
Vitamin A	0%
Calcium	4%
Vitamin C	0%
Iron	2%

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

$$= 1170 \text{ kJ}$$

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

a regular-sized Snickers bar



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Result

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Amount Per Serving	
Calories	280
Calories from Fat 130	
% Daily Value*	
Total Fat	14g 22%
Saturated Fat	5g 25%
Trans Fat	0g 0%
Cholesterol	20mg 4%
Sodium	10mg 2%
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a regular-sized Snickers bar

# Which is more energy?



one ton of TNT

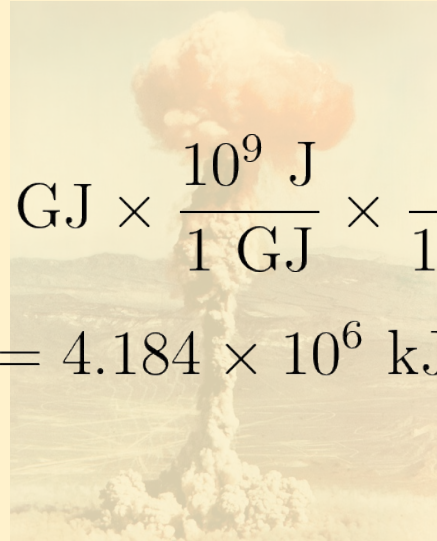
?



typical fridge annual energy use

# Which is more energy?

$$4.184 \text{ GJ} \times \frac{10^9 \text{ J}}{1 \text{ GJ}} \times \frac{1 \text{ kJ}}{1000 \text{ J}} \\ = 4.184 \times 10^6 \text{ kJ}$$



one ton of TNT

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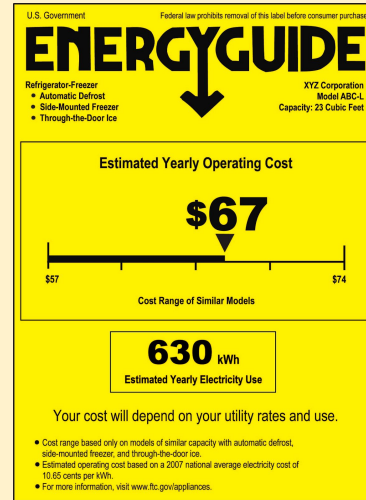
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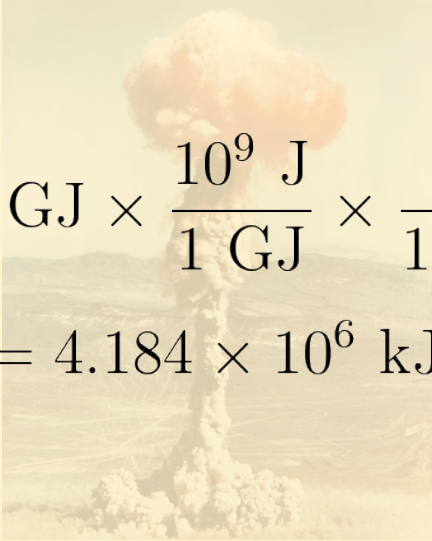
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one ton of TNT

?

**630 kWh**

Estimated Yearly Electricity Use

630 kWh

630 kW · h

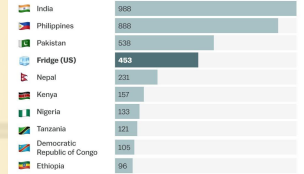
$$630 \frac{\text{kJ}}{\text{s}} \cdot \text{h} \times 3600 \frac{\text{s}}{\text{h}}$$

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

typical fridge annual energy use

US fridges use more energy per year than a person in many countries

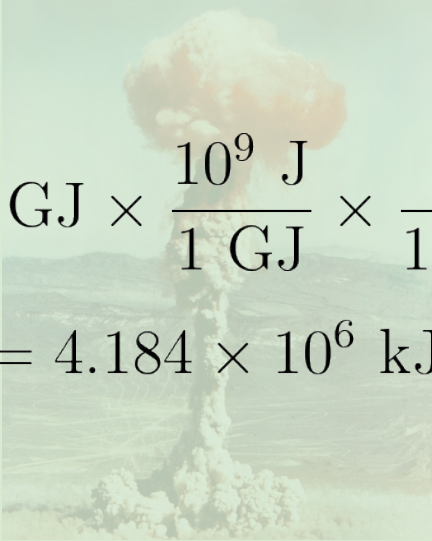
Annual electricity consumption in kilowatt-hours



Source: IEA World Energy Statistics, IEA, Paris, 2021

Vox

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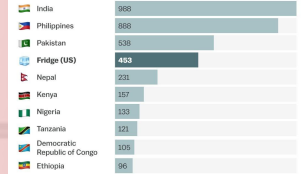
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Ford F-150 gas tank

?



melt and boil a 1-tonne iceberg

# Which is more energy?

$$23 \text{ gal} \times \frac{3.785 \text{ L}}{1 \text{ gal}} \times \frac{34.6 \text{ MJ}}{1 \text{ L}} \times \frac{1000 \text{ kJ}}{1 \text{ MJ}} = 3.01 \times 10^6 \text{ kJ}$$

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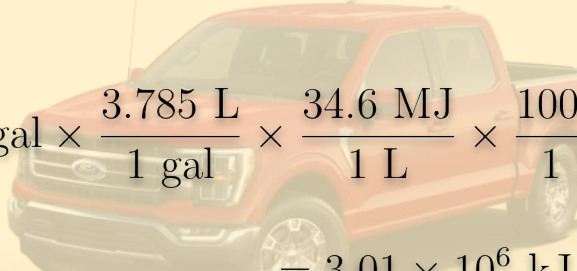
?



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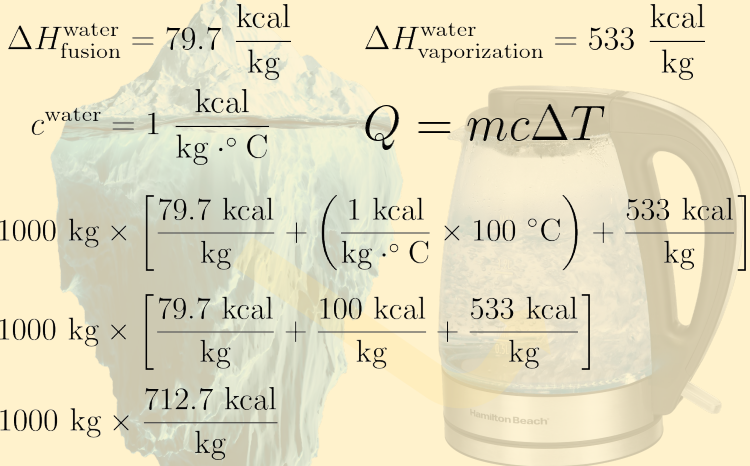


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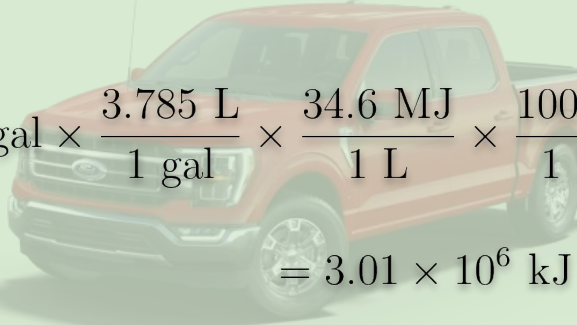
Ford F-150 gas tank

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$$\Delta H_{\text{fusion}}^{\text{water}} = 79.7 \frac{\text{kcal}}{\text{kg}} \quad \Delta H_{\text{vaporization}}^{\text{water}} = 533 \frac{\text{kcal}}{\text{kg}}$$
$$c_{\text{water}} = 1 \frac{\text{kcal}}{\text{kg} \cdot ^\circ\text{C}} \quad Q = mc\Delta T$$
$$1000 \text{ kg} \times \left[ \frac{79.7 \text{ kcal}}{\text{kg}} + \left( \frac{1 \text{ kcal}}{\text{kg} \cdot ^\circ\text{C}} \times 100 \text{ }^\circ\text{C} \right) + \frac{533 \text{ kcal}}{\text{kg}} \right]$$
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$$= 7.12 \times 10^5 \text{ kcal} \times \frac{4.184 \text{ kJ}}{1 \text{ kcal}} = 2.98 \times 10^6 \text{ kJ}$$

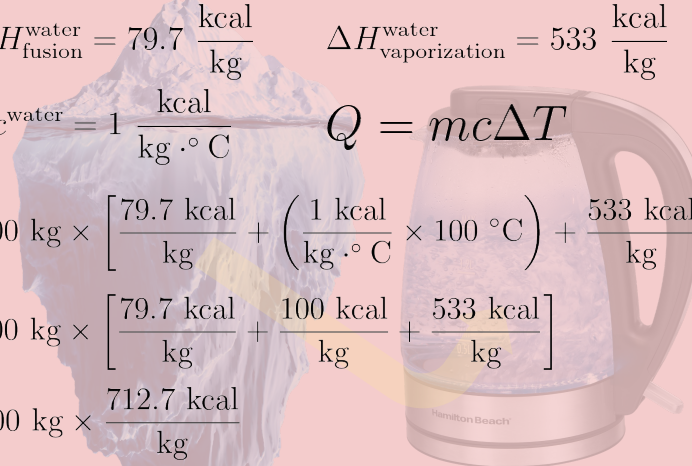
melt and boil a 1-tonne iceberg

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# Which is more energy?



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

?



one gram of fissile uranium

# Which is more energy?

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

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

total caloric content of food  
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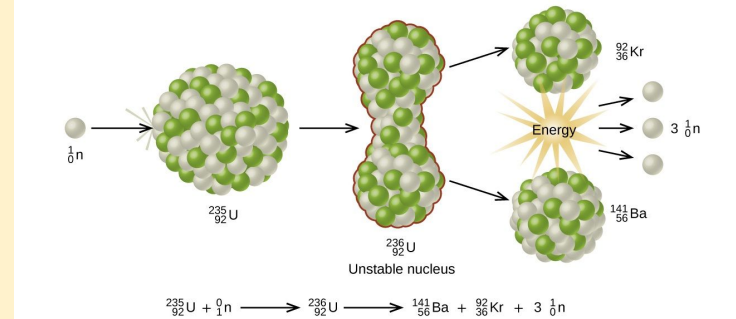
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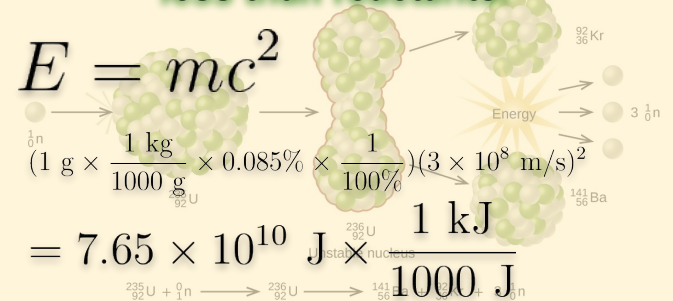
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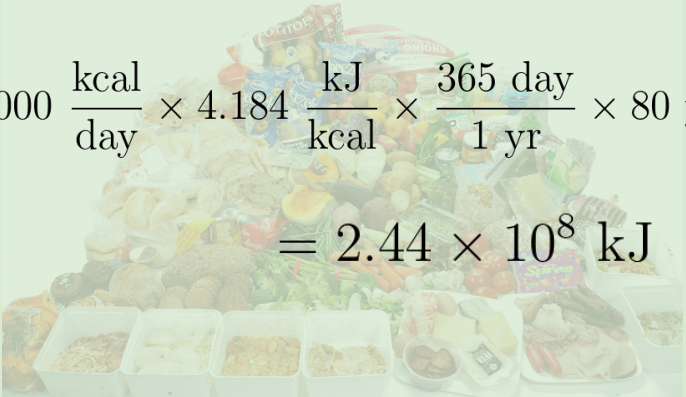
**<sup>235</sup>U fission products weigh 0.085% less than reactants!**



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# Which is more energy?



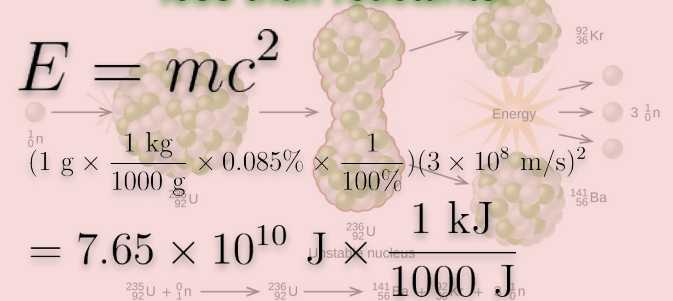
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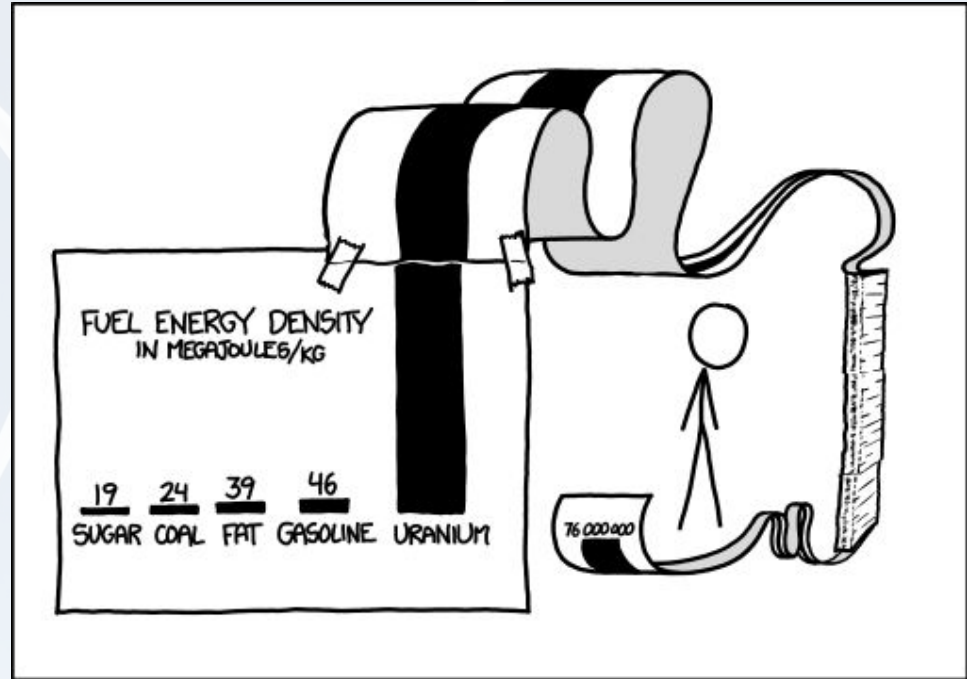
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SCIENCE TIP: LOG SCALES ARE FOR QUITTERS WHO CAN'T FIND ENOUGH PAPER TO MAKE THEIR POINT *PROPERLY*.



# Which is more energy?



global annual energy use  
(2022)

?



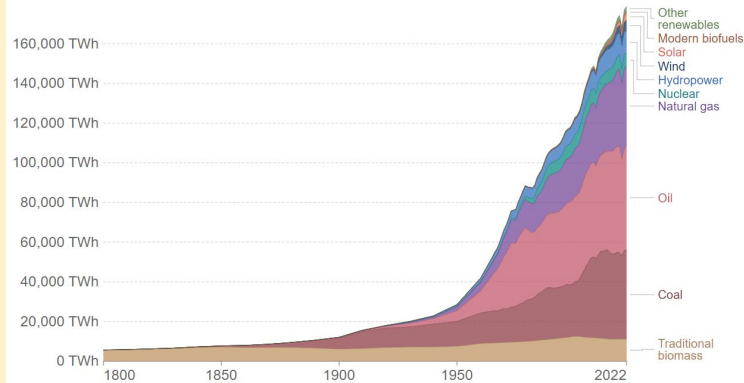
1 hour of sunlight

# Which is more energy?

## Global primary energy consumption by source

Primary energy is calculated based on the 'substitution method' which takes account of the inefficiencies in fossil fuel production by converting non-fossil energy into the energy inputs required if they had the same conversion losses as fossil fuels.

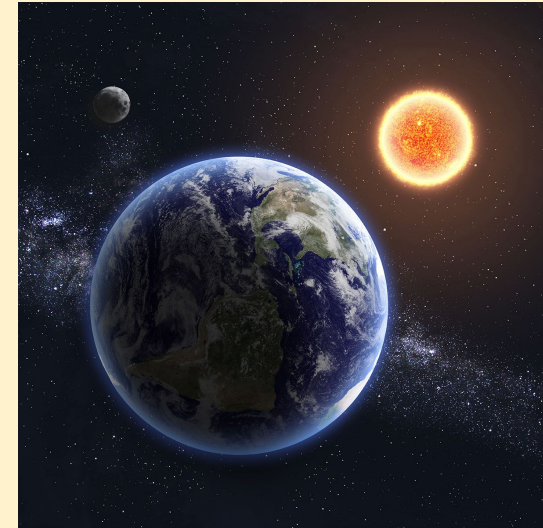
Our World  
in Data



Source: Energy Institute Statistical Review of World Energy (2023); Vaclav Smil (2017)  
OurWorldinData.org/energy • CC BY

global annual energy use  
(2022)

?



1 hour of sunlight

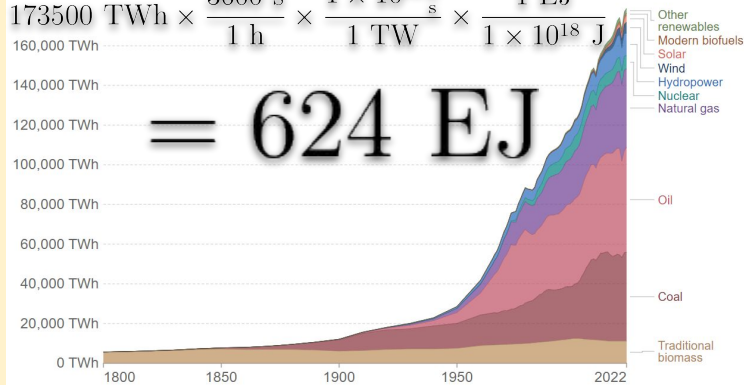
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$$173500 \text{ TWh} \times \frac{3600 \text{ s}}{1 \text{ h}} \times \frac{1 \times 10^{12} \text{ J}}{1 \text{ TW}} \times \frac{1 \text{ EJ}}{1 \times 10^{18} \text{ J}}$$

= 624 EJ



global annual energy use  
(2022)

?

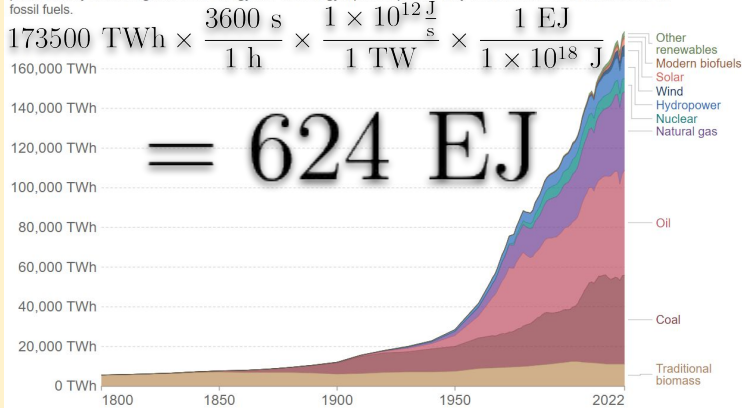


1 hour of sunlight

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Source: Energy Institute Statistical Review of World Energy (2023); Vaclav Smil (2017)  
OurWorldInData.org/energy • CC BY

global annual energy use  
(2022)

?

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

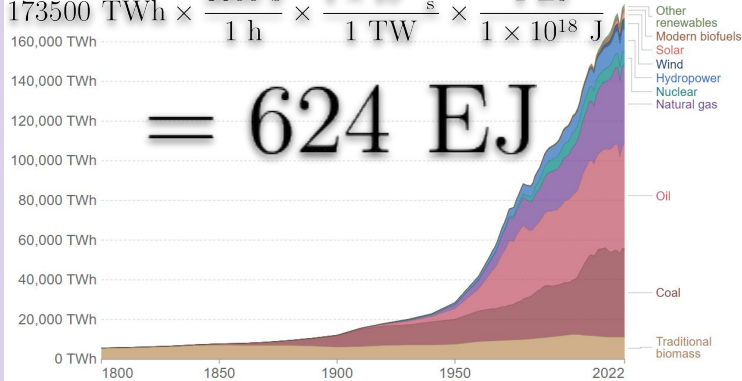
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1 hour of sunlight

# What is money?



# How much does energy cost?

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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:      How can you **make it**?

- **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**?

- **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)

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



# 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



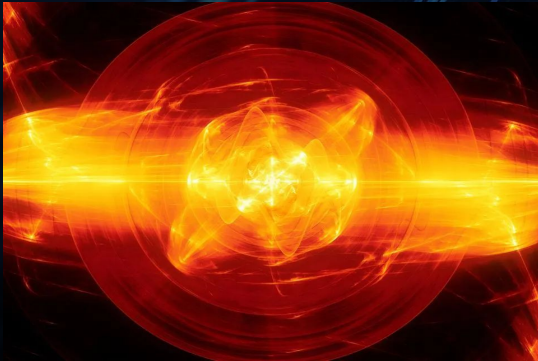
How can you **make it**?

- 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:      How can you **store it**?

- make it
- **store it**
- ship 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



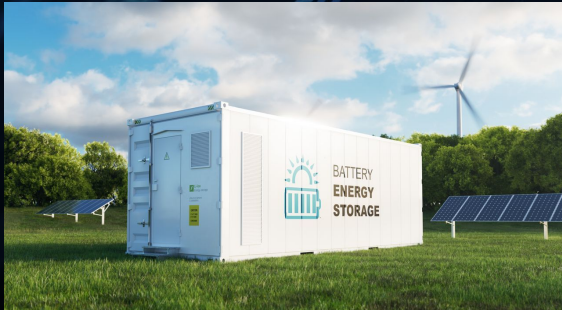
# How much does energy cost?

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)**





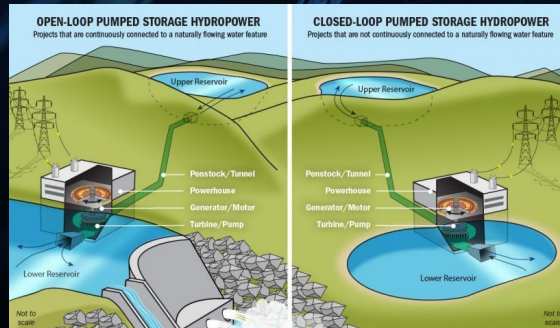
# How much does energy cost?

Depends on how you:

- make it
- **store it**
- ship it

How can you **store it**?

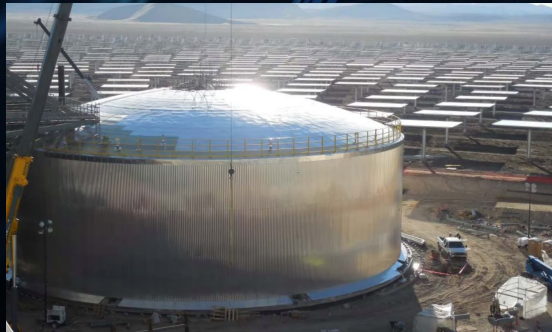
- Chemical fuels
  - Fossil fuels
  - Biofuels
  - Non-fossil hydrocarbons
- Batteries (all sorts)
- **Pumped hydroelectric storage**



# 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**?

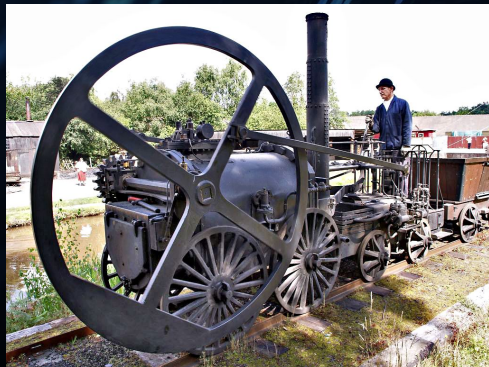
- Chemical fuels
  - Fossil fuels
  - Biofuels
  - Non-fossil hydrocarbons
- Batteries (all sorts)
- Pumped hydroelectric storage
- **Thermal energy storage**
  - Sensible (molten-salt)
  - **Non-sensible (phase-change)**



# How much does energy cost?

Depends on how you:

- make it
- **store it**
- ship it



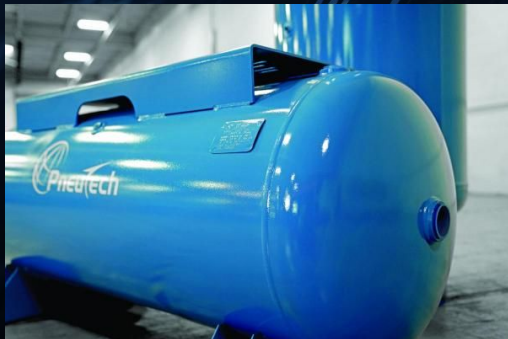
How can you **store it**?

- 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)*

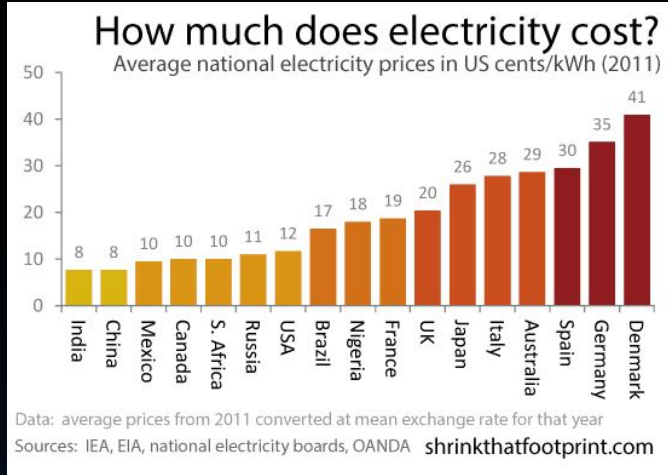
*less \$\$\$*

*more \$\$\$*

**(It depends on how you store it.)**

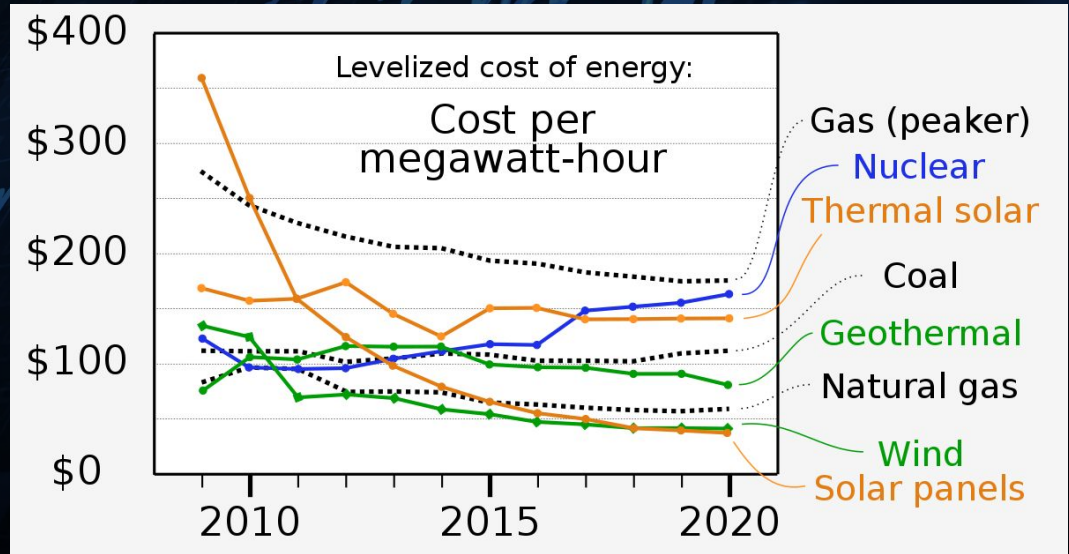
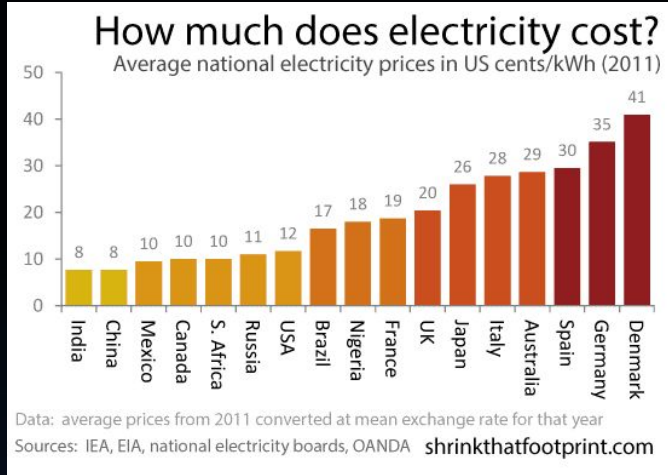
# How much does energy cost?

typically between  
5 ~ 50 ¢/kWh



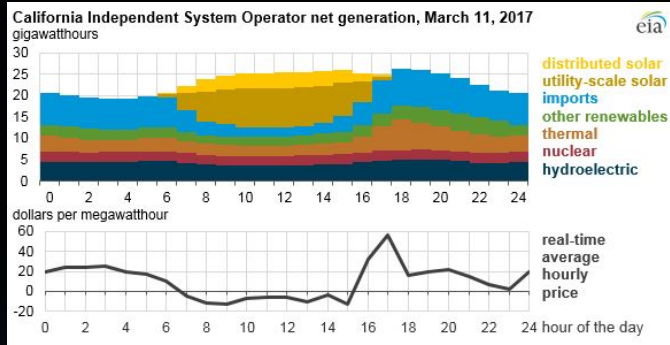
# How much does energy cost?

typically between  
5 ~ 50 ¢/kWh

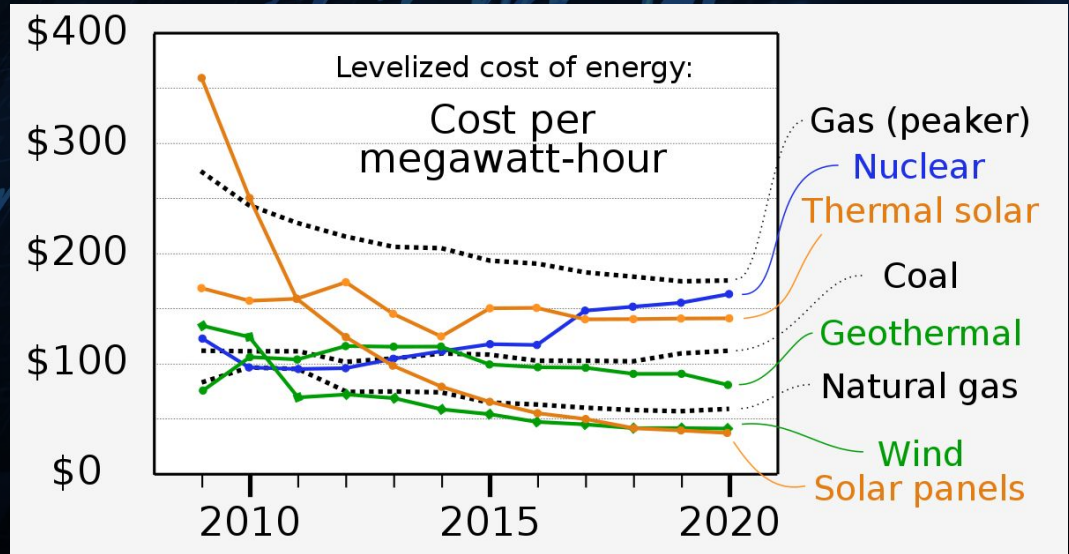


# How much does energy cost?

typically between  
5 ~ 50 ¢/kWh

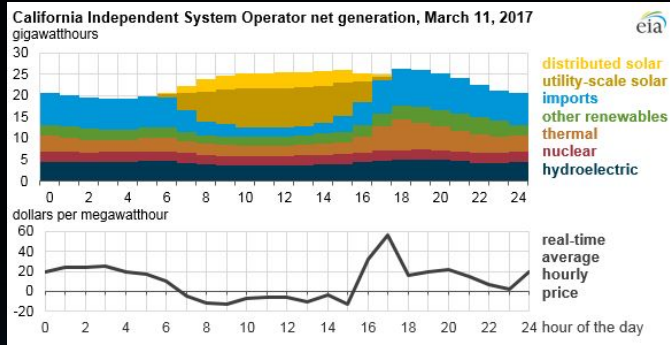


sometimes even  
(briefly) negative!



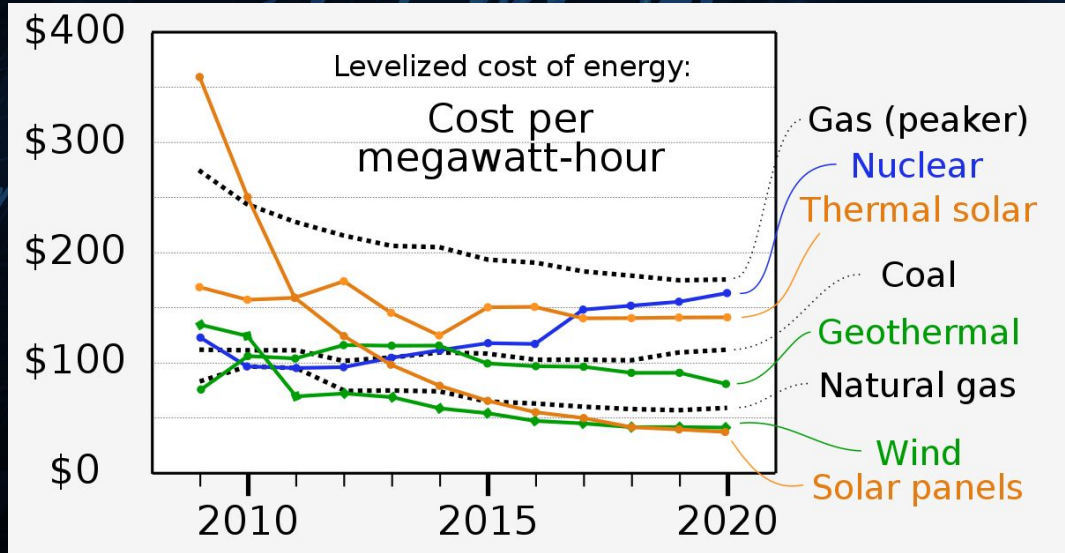
# How much does energy cost?

typically between  
5 ~ 50 ¢/kWh



sometimes even  
(briefly) negative!

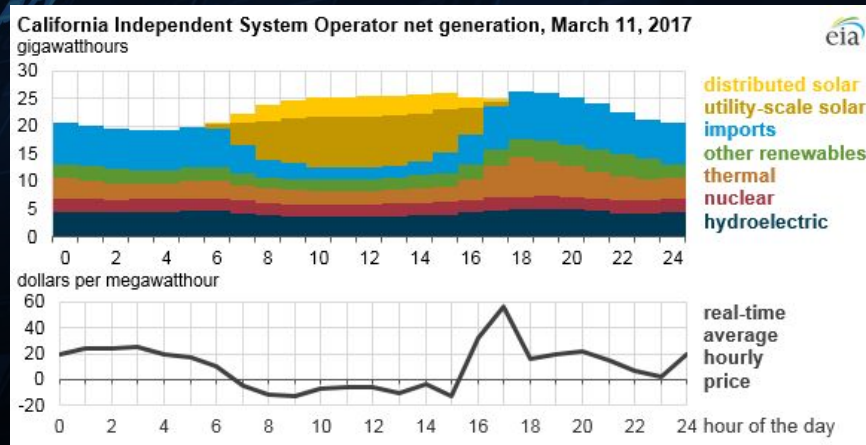
*(timing is important!)*



# Price isn't the only factor!

Also need to consider:

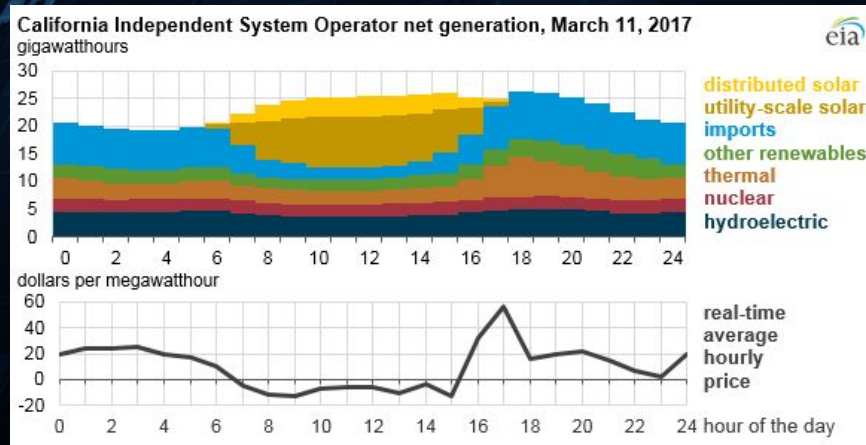
- Reliability
  - timing is important!



# 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



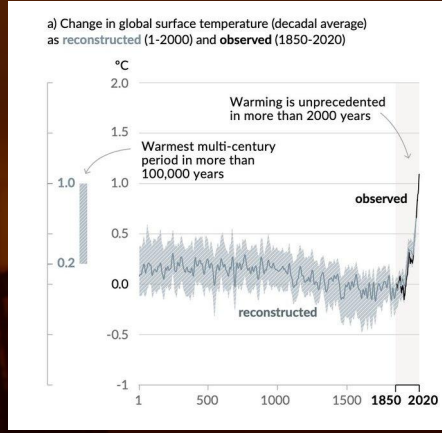
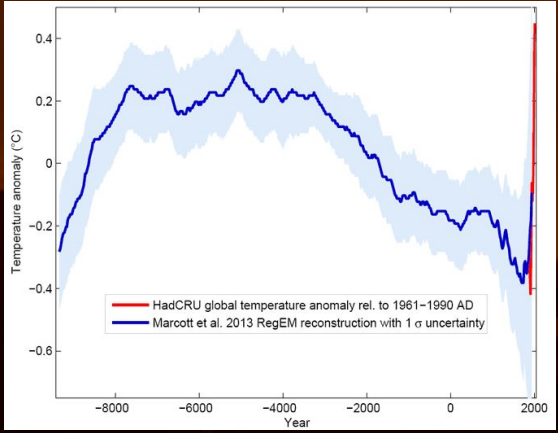
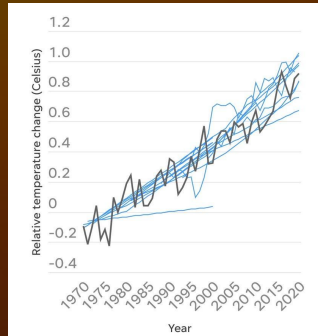
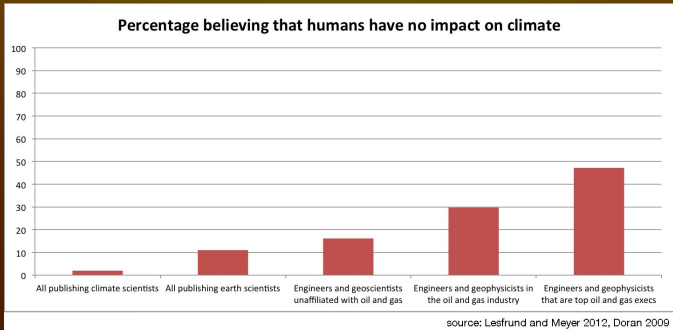
*Image by DALL-E 2*

PROMPT: "an abstract painting of an avatar of rampant unchecked capitalism destroying global human society as we know it"

A sunset over a marina. The sky is a deep orange and yellow, with a large, bright sun in the upper left corner. In the foreground, the silhouettes of numerous boat masts and rigging are visible against the bright sky. A single bird is seen in flight in the center of the image. The overall scene is hazy and atmospheric.

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

# Anthropogenic global warming is real

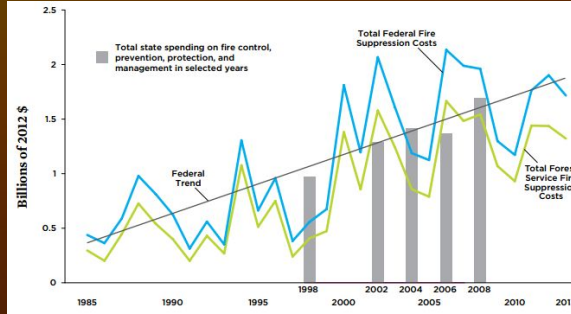
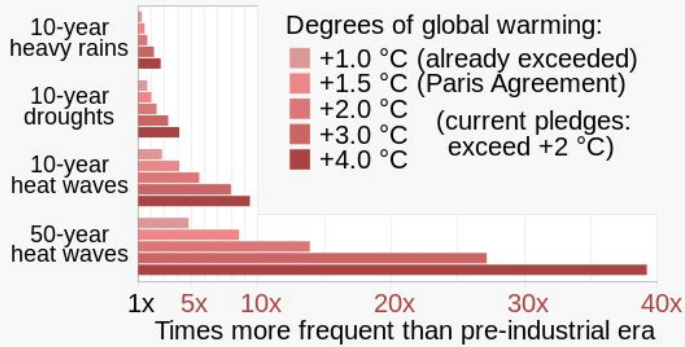


Change in indicator	Observed change assessment	Human contribution assessment
<b>Atmosphere and water cycle</b>	Warming of global mean surface air temperature since 1850-1900	likely range of human contribution (0.8-1.3 °C) encompasses the very likely range of observed warming (0.8-1.2 °C)
	Warming of the troposphere since 1979	Main driver
	Cooling of the lower stratosphere since the mid-20th century	Main driver 1979 - mid-1990s
	Large-scale precipitation and upper troposphere humidity changes since 1979	
	Expansion of the zonal mean Hadley Circulation since the 1980s	Southern Hemisphere
<b>Ocean</b>	Ocean heat content increase since the 1970s	Main driver
	Salinity changes since the mid-20th century	
	Global mean sea level rise since 1970	Main driver
<b>Cryosphere</b>	Arctic sea ice loss since 1979	Main driver
	Reduction in Northern Hemisphere springtime snow cover since 1950	
	Greenland ice sheet mass loss since 1990s	
	Antarctic ice sheet mass loss since 1990s	Limited evidence & medium agreement
	Retreat of glaciers	Main driver
<b>Carbon cycle</b>	Increased amplitude of the seasonal cycle of atmospheric CO <sub>2</sub> since the early 1960s	Main driver
	Acidification of the global surface ocean	Main driver
<b>Land climate</b>	Mean surface air temperature over land (about 40% larger than global mean warming)	Main driver
<b>Synthesis</b>	Warming of the global climate system since preindustrial times	

Key: medium confidence, likely/high confidence, very likely, extremely likely, virtually certain, fact

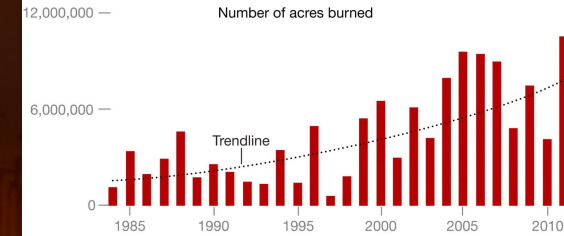
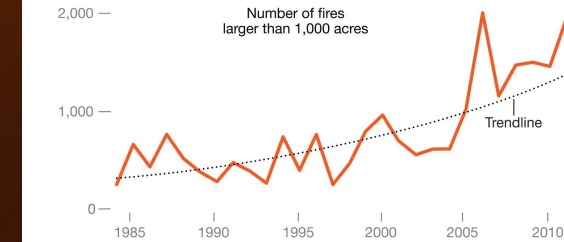
# Anthropogenic global warming is bad

## More frequent extreme weather with global warming



## Wildfires on the rise

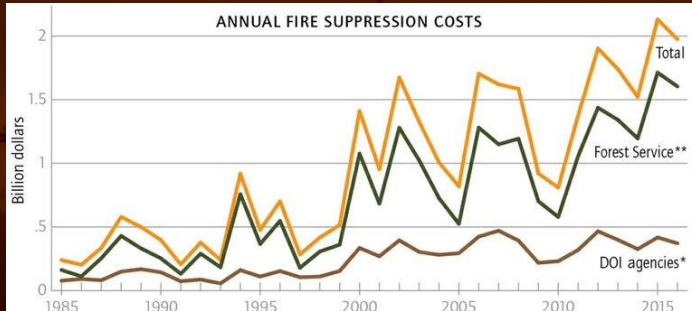
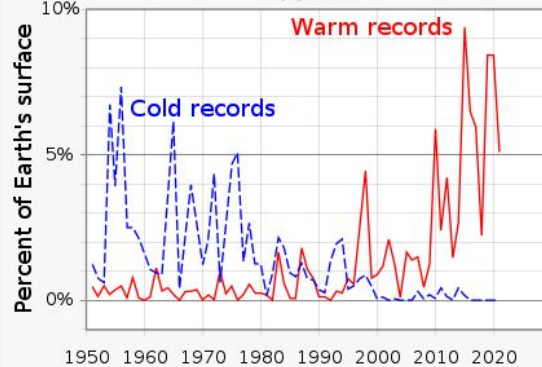
Continental United States, 1984-2011



NG STAFF. SOURCE: MONITORING TRENDS IN BURN SEVERITY

## Global area reaching record temperatures

(July, 1951-)

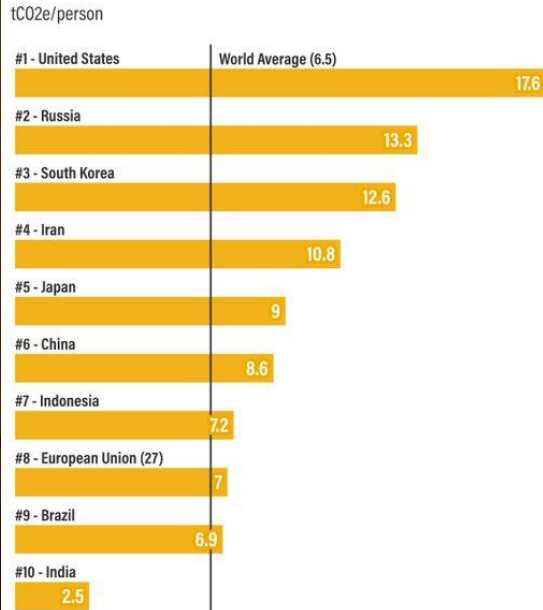


\*DEPARTMENT OF INTERIOR AGENCIES INCLUDE THE BUREAU OF INDIAN AFFAIRS, BUREAU OF LAND MANAGEMENT, NATIONAL PARK SERVICE, AND U.S. FISH AND WILDLIFE SERVICE. \*\*USFS IS UNDER THE USDA AND TRACKS DATA DIFFERENTLY.

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

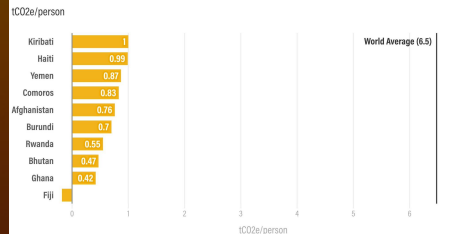
# Most vulnerable global populations are broadly least responsible

## Per capita emissions for the top 10 total emitters, 2019



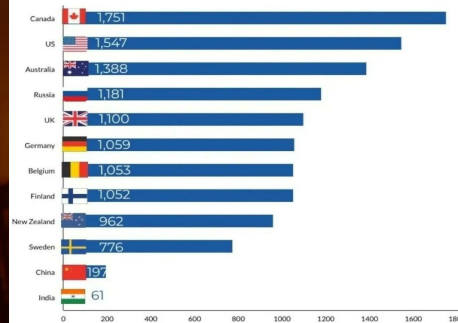
Source: [Climate Watch](#) - Values include emissions from LUCF sector. WORLD RESOURCES INSTITUTE

## Lowest per capita emitters, 2019



Source: [Climate Watch](#) - Values include emissions from LUCF sector. WORLD RESOURCES INSTITUTE

## Cumulative carbon emissions per capita from 1850-2021 (tCO2), selected countries



Source: Carbon Brief

## Lowest per capita emitters, 2019

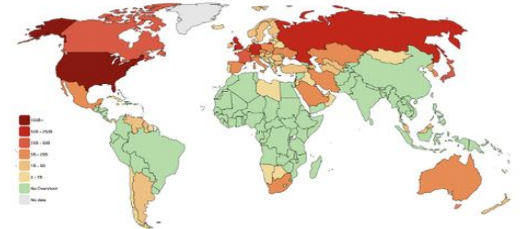


kiribati average elevation

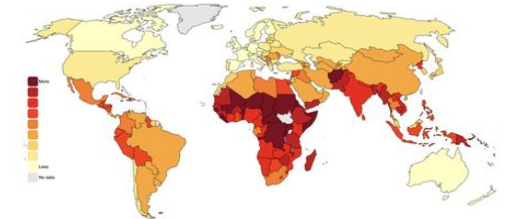
around two meters above

Kiribati's 33 low-lying atoll and reef islands have an average elevation of around **two meters above sea level**.

## Overshoot emissions (Lancet Planetary Health)



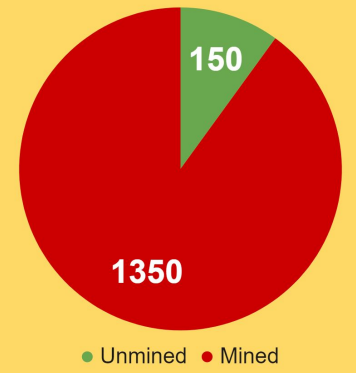
## Multi-dimensional climate vulnerability (ND-GAIN)



# Banaba, Kiribati



Land area strip-mined for phosphate on Banaba, Kiribati (acres)

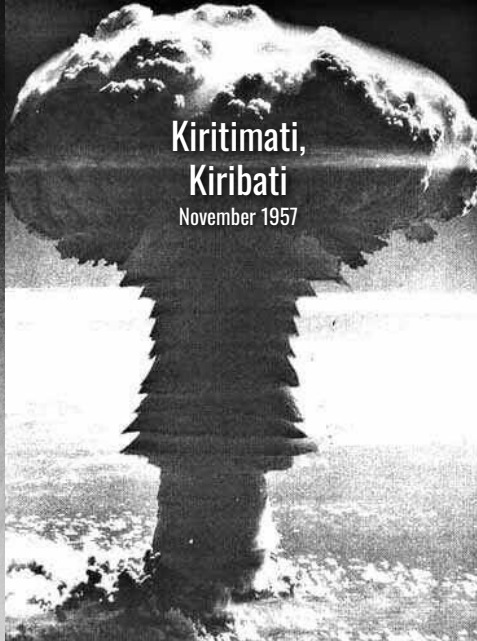


Cushman, G. T. *Guano and the Opening of the Pacific World: A Global Ecological History*; Cambridge University Press, 2013.  
Greenhill, R. G.; Miller, R. M. *J. Lat. Am. Stud.* **1973**, *5*, 107–131.  
Szpak, P.; Millaire, J.-F.; White, C. D.; Longstaffe, F. J. *J. Archaeol. Sci.* **2012**, *39*, 3721–3740.  
Manner, H. I.; Thaman, R. R.; Hassall, D. C. *Aust. Geogr.* **1985**, *16*, 185–195.  
James, J. C. *Am. Lit. Hist.* **2012**, *24*, 115–142.  
<https://www.theguardian.com/world/2021/jun/09/the-island-with-no-water-how-foreign-mining-destroyed-banaba>  
<https://www.banaban.com/destruction-caused-phosphate-mining>





Malden Island,  
Kiribati  
May 1957



Kiritimati,  
Kiribati  
November 1957



Kiritimati,  
Kiribati  
September 1958



Kiritimati,  
Kiribati  
April 1958

Cushman, G. T. *Guano and the Opening of the Pacific World: A Global Ecological History*; Cambridge University Press, 2013.

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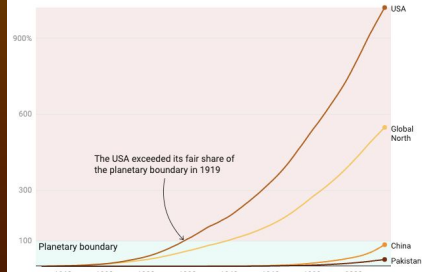
<https://www.theguardian.com/world/2021/jun/09/the-island-with-no-water-how-foreign-mining-destroyed-banaba>

<https://www.banaban.com/destruction-caused-phosphate-mining>

# Most vulnerable global populations are broadly least responsible

## Use of planetary boundary fair-shares

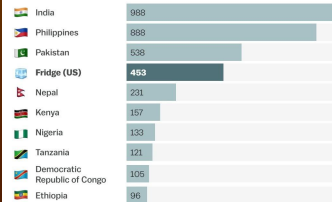
Cumulative CO2 emissions as percent of planetary boundary fair-share (350ppm)



Global North refers to the USA, Canada, Europe, Israel, Australia, New Zealand, and Japan.

## US fridges use more energy per year than a person in many countries

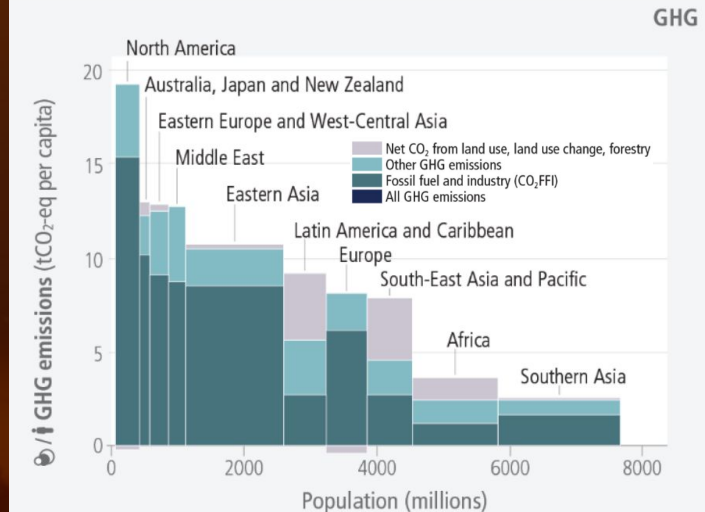
Annual electricity consumption in kilowatt-hours



Source: IEA World Energy Statistics, IEA, Paris, 2021

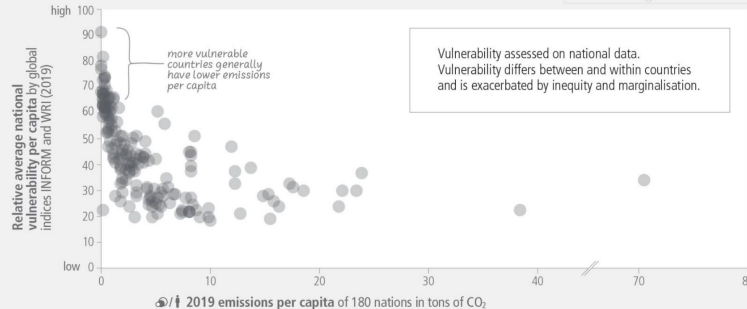
Vox

## b) Net anthropogenic GHG emissions per capita and for total population, per region (2019)



## b) Vulnerability of population & per capita emissions per country in 2019

Dimension of Risk: Vulnerability



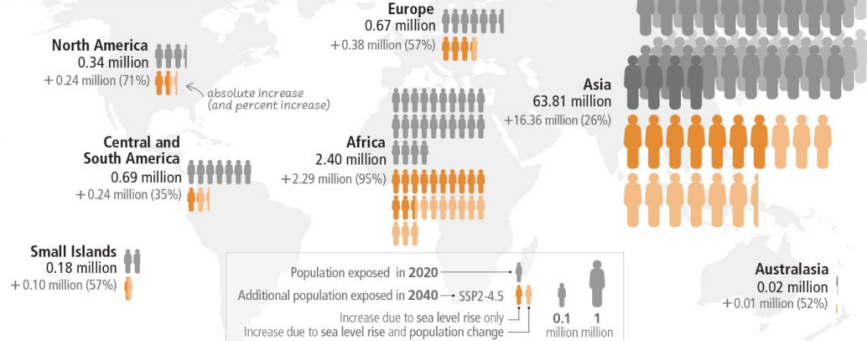
Lee, Hoesung, et al. "AR6 Synthesis Report: Climate Change 2023." *Summary for Policymakers* (2023).

# ...but everyone will be affected

## Every region faces more severe and/or frequent compound and cascading climate risks

### a) Increase in the population exposed to sea level rise from 2020 to 2040

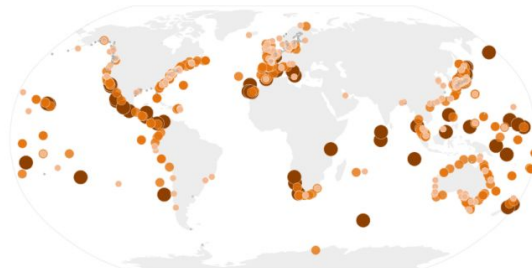
Exposure to a coastal flooding event that currently occurs on average once every 100 years



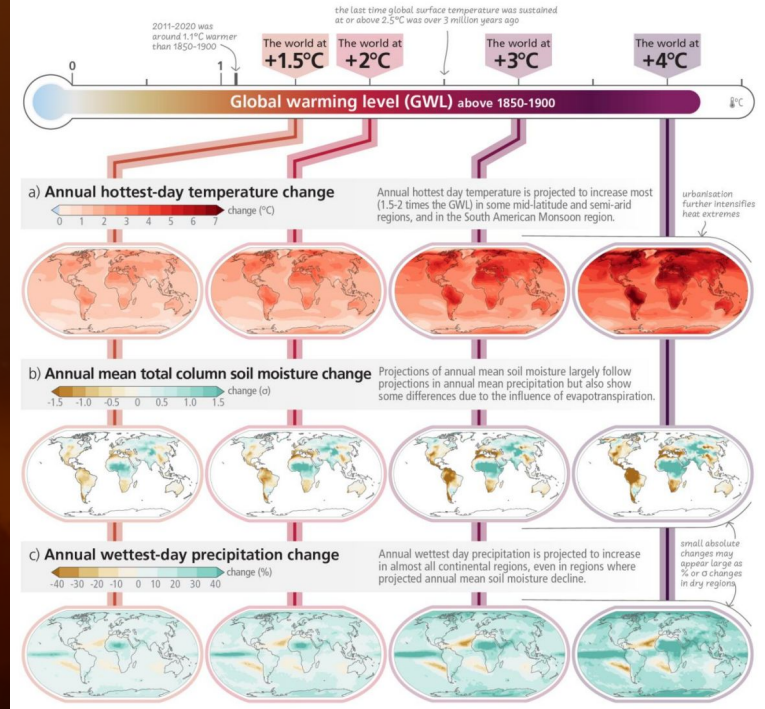
### b) Increased frequency of extreme sea level events by 2040

Frequency of events that currently occur on average once every 100 years

The absence of a circle indicates an inability to perform an assessment due to a lack of data.



## With every increment of global warming, regional changes in mean climate and extremes become more widespread and pronounced



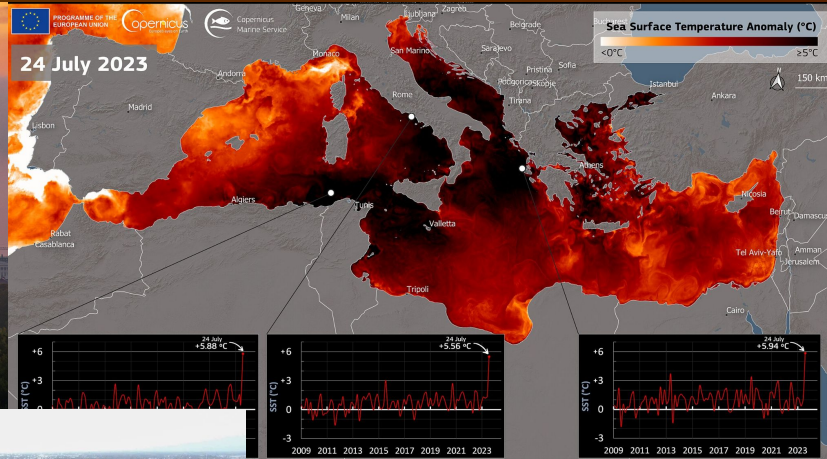
# ...but everyone will be affected



Maui, Hawaii  
August 2023



Washington, DC  
July 2023



San Francisco  
September 2020



Pakistan  
June-October 2020

Deaths: 1,739  
Non-fatal Injuries: 12,867  
Damages: US\$14.9bn  
Estimated Economic Losses: US\$15.2bn



Kenya  
2008-2009

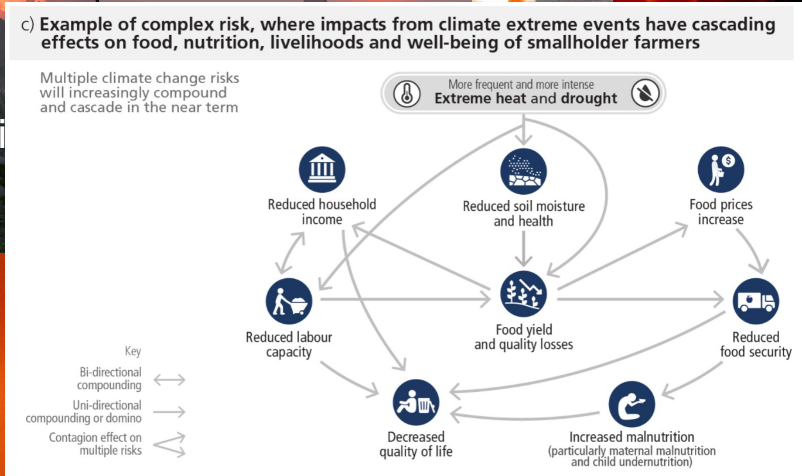
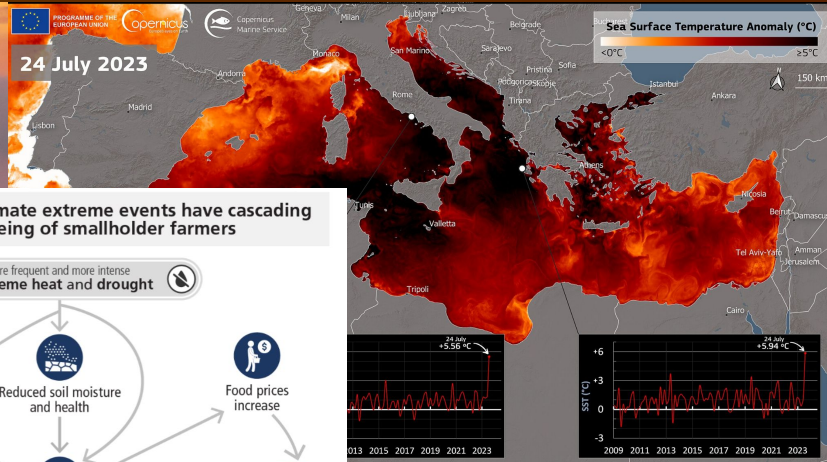
# ...but everyone will be affected



Maui, Hawaii  
August 2023



San Francisco  
September 2020

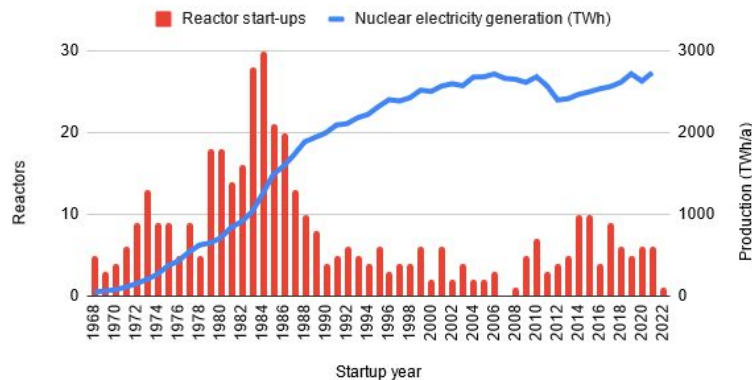


Kenya  
2008-2009

# Technical merit is meaningless without deployability

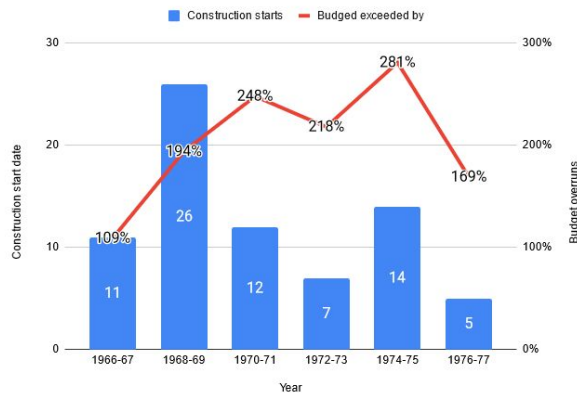
## Age of world's nuclear power & nuclear generation (2023)

Source: IAEA PRIS database; Our World in Data/BP



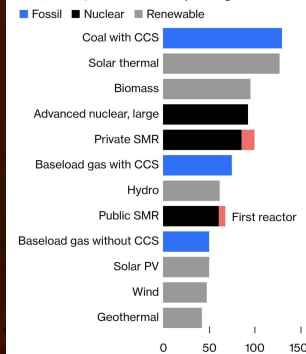
## Average budget overruns of nuclear projects in the U.S.

Source: Congressional Budget Office (2008, 17). Average overrun 207 %



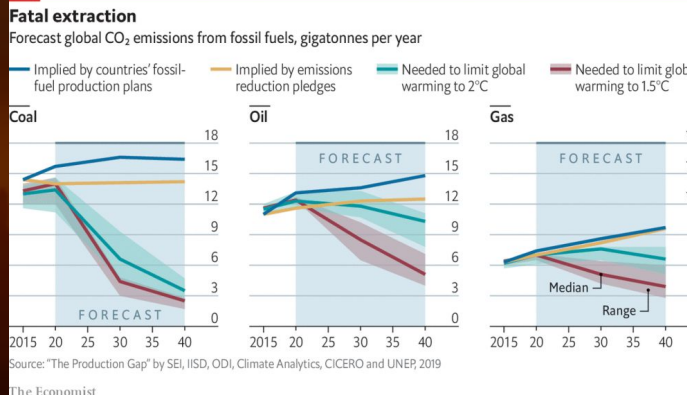
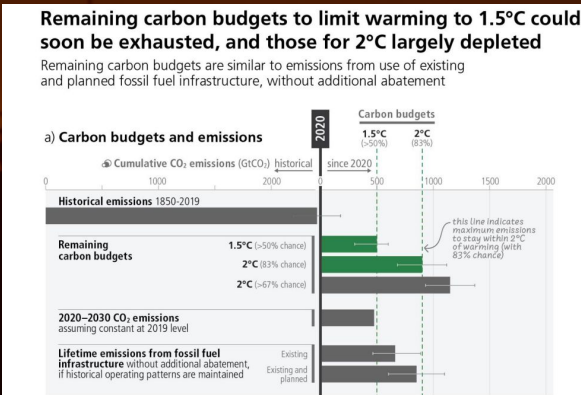
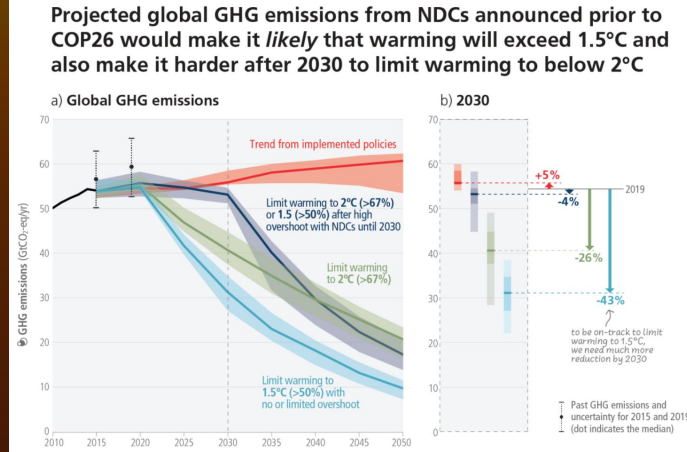
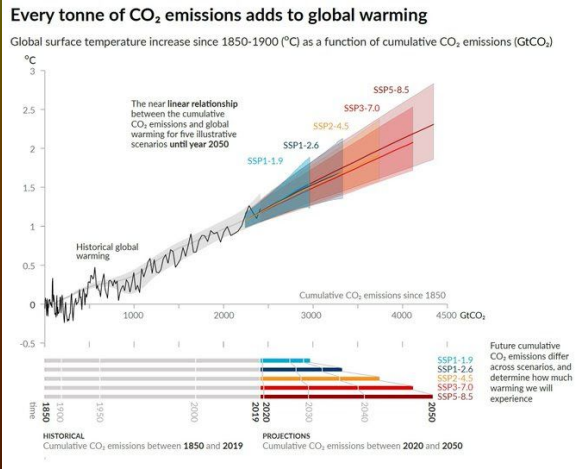
## Close, But No Cigar

Small modular reactors may be cheaper than alternatives, but still not cheap enough



Source: NuScale  
Note: "First reactor" illustrates the additional costs that would be expected at the start-up manufacturing stage.

# Many trends are pessimistic



# Many trends are pessimistic

## Higher mitigation investment flows required for all sectors and regions to limit global warming

Actual yearly flows compared to average annual needs in billions USD (2015) per year

Multiplication factors\*

Lower range Upper range

x2 x7

x7 x7

x2 x5

x10 x31

x4 x7

x3 x5

x2 x4

x3 x6

x2 x4

x7 x14

x4 x8

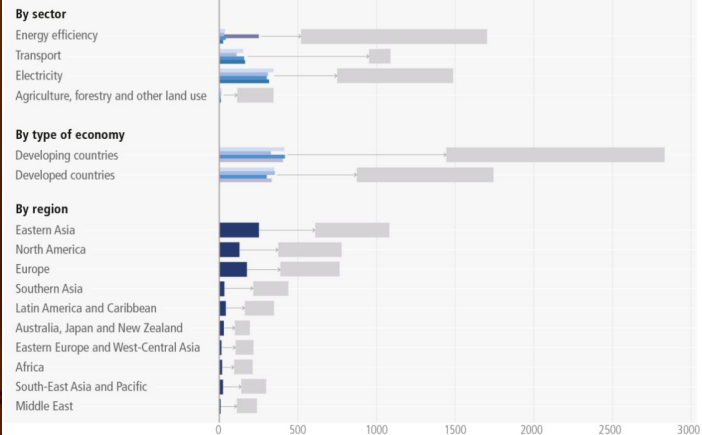
x3 x7

x7 x15

x5 x12

x6 x12

x14 x28



Yearly mitigation investment flows (USD 2015/yr) in:



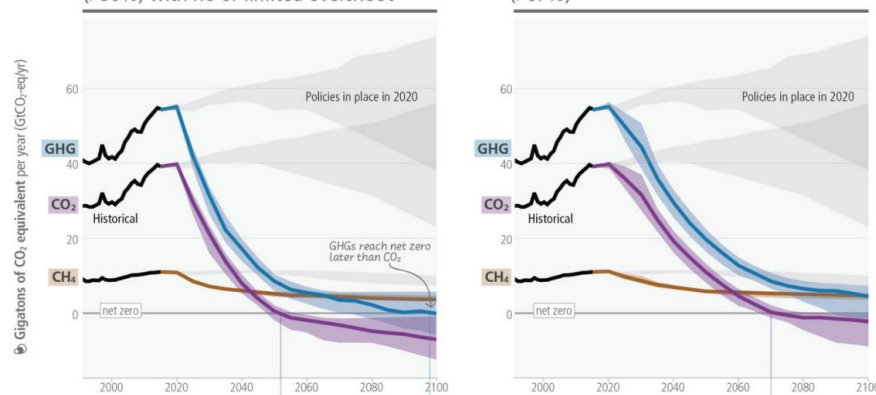
\*Multiplication factors indicate the x-fold increase between yearly mitigation flows to average yearly mitigation investment needs. Globally, current mitigation financial flows are a factor of three to six below the average levels up to 2030.

## Global modelled pathways that limit warming to 1.5°C (>50%) with no or limited overshoot reach net zero CO<sub>2</sub> emissions around 2050

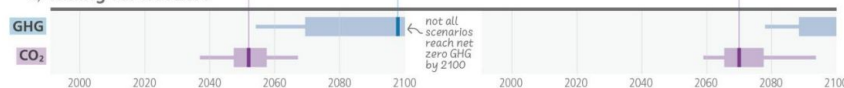
Total greenhouse gases (GHG) reach net zero later

a) While keeping warming to 1.5°C (>50%) with no or limited overshoot

b) While keeping warming to below 2°C (>67%)



c) Timing for net zero

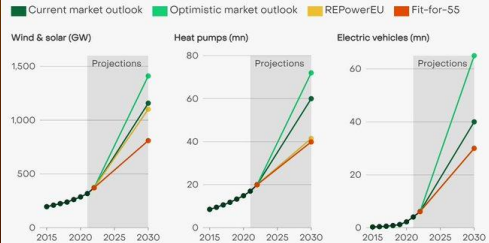




# Cheap renewables are a rare bright spot

## Clean tech trends put EU on course to surpass its 40% renewable energy target for 2030

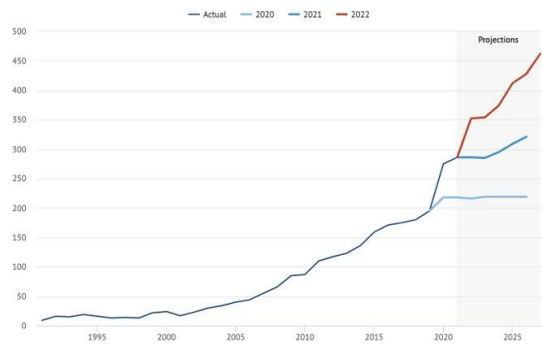
Cumulative capacity (GW) or stock (million)



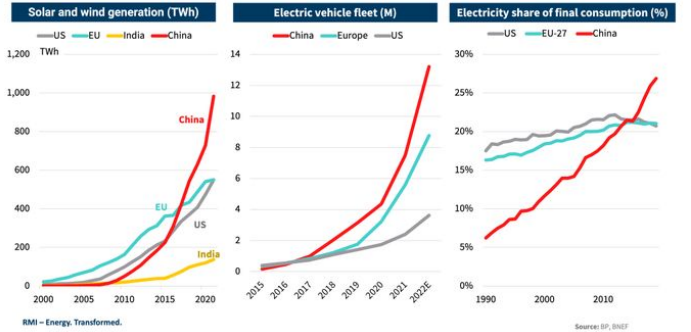
Source: See Ember briefing "Fit for the Future, not Fit-for-55" for sources.

EMBER

The IEA has raised its renewable growth forecast by 28% since 2021 and by 76% since 2020



## China dominates deployment of renewables

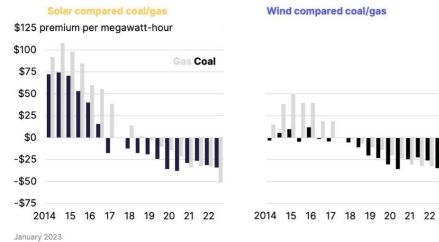


RMI - Energy Transformed.

Source: BP, ENEC

## Renewables price at a discount

Wind and solar power have never been more economic against coal and gas power



January 2023

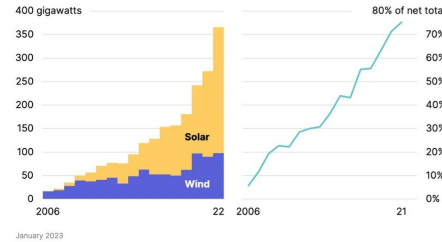
41

Source: Bloomberg NEF

Note: 2021S  
MPT BILBAO

## Wind and solar drive capacity growth

More solar and wind are built than any other generation capacity today, or ever



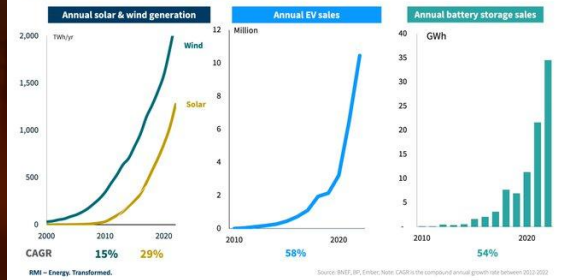
January 2023

39

Source: Bloomberg NEF

Note: 2021S  
MPT BILBAO

## Exponential Energy Change Is All around Us



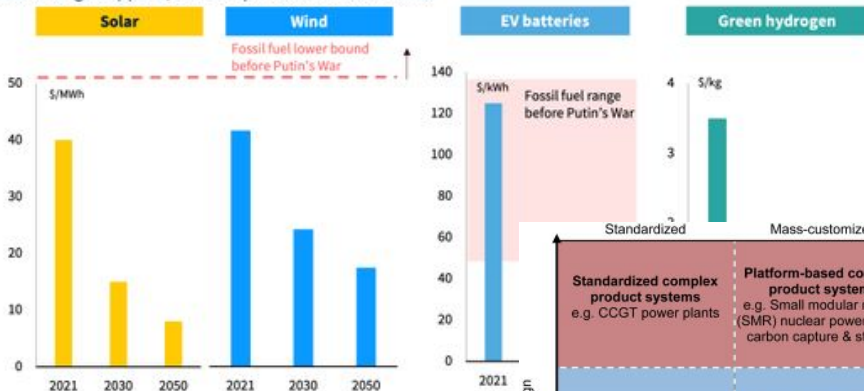
RMI - Energy Transformed.

Source: BNEF, BP, ENEC. Note: CAGR is the compound annual growth rate between 2010-2020

# Cheap renewables are a rare bright spot

## Cheap Renewables Create an Entirely New Paradigm

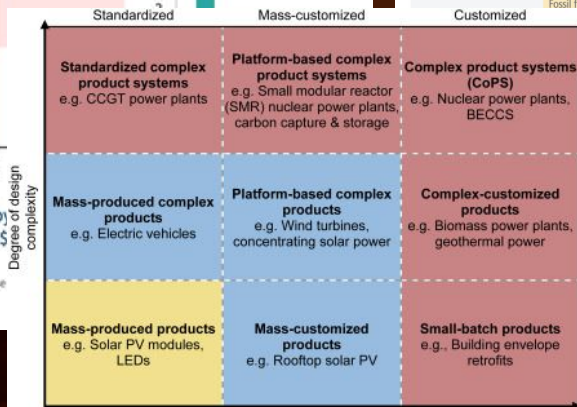
The faster change happens, the cheaper renewables become



If we continue on existing learning and growth rates, then by 2050, \$25 per MWh wind, \$50 per kWh Li-ion batteries, and \$1.50 per kg green hydrogen.

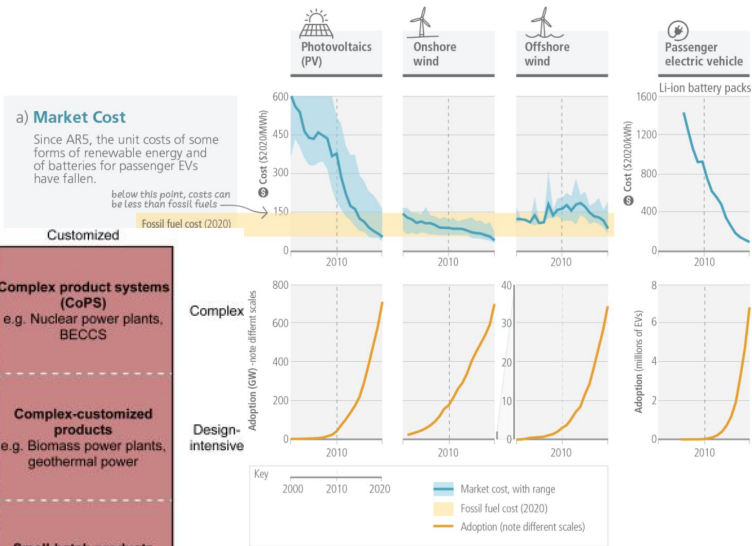
RMI - Energy. Transformed.

Source: RMI; cost forecasts use



Type 1 (Yellow), Type 2 (Blue), Type 3 (Red)

## Renewable electricity generation is increasingly price-competitive and some sectors are electrifying



# 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*

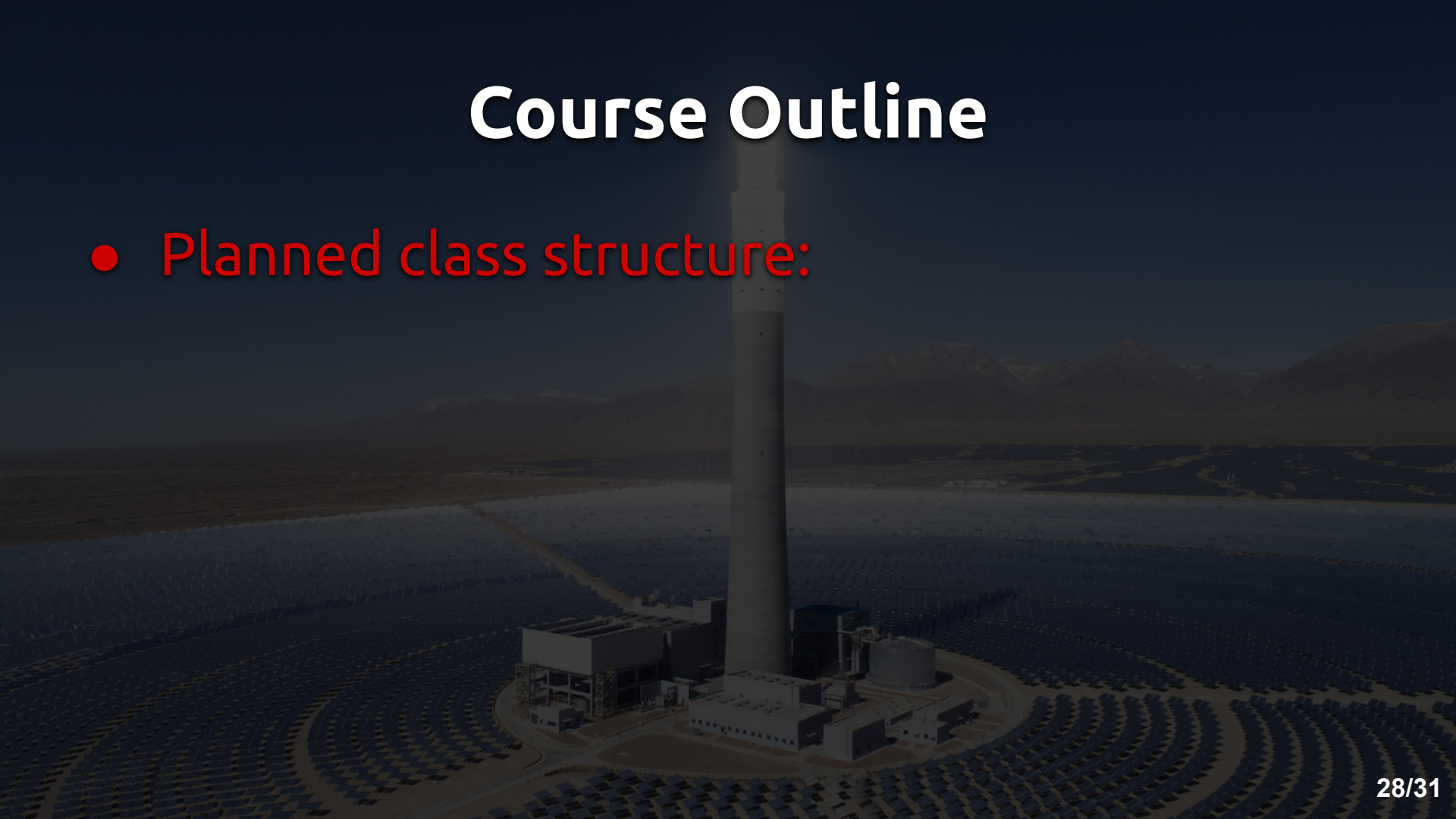
# Semester Overview

An aerial photograph of a solar tower power plant. A tall, cylindrical receiver tower stands in the center, emitting a bright white glow from its top. The tower is surrounded by a circular arrangement of heliostats (mirrors) that reflect sunlight onto it. In the background, there are snow-capped mountains under a clear blue sky. The foreground shows the dense field of heliostats and some industrial buildings at the base of the tower.

*a preview of coming  
attractions*

# Course Outline

- Planned class structure:



# Course Outline

- Planned class structure:
  - 1 hr lecture

# Course Outline

An aerial view of a large stadium with a tall, cylindrical tower in the center. The stadium is filled with rows of seats, and the tower is illuminated from below. The background shows a landscape with mountains and a river.

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

# Course Outline

The background of the slide is a dark, atmospheric photograph of a large lecture hall. In the center of the hall, a tall, white, cylindrical structure, possibly a chimney or a decorative element, stands prominently. The seating is arranged in a semi-circular pattern, and the overall lighting is very low, creating a sense of depth and focus on the central structure. In the distance, a body of water and mountains are visible under a dark sky.

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



# Course Outline

- Planned class structure:
  - 1 hr lecture
  - ½ hr break
  - 1 hr discussion
- This is a technical survey course!

# Course Outline

An aerial photograph of a solar power plant, also known as a solar tower or CSP (Concentrated Solar Power) plant. The central feature is a tall, cylindrical receiver tower. Surrounding the tower is a vast field of solar collectors, which are heliostats that reflect sunlight onto the tower. The plant is situated in a desert-like environment with mountains in the background under a clear sky.

- Planned class structure:
  - 1 hr lecture
  - ½ hr break
  - 1 hr discussion
- This is a technical survey course!
  - Unit 1: clean energy fundamentals

# Course Outline

- Planned class structure:
  - 1 hr lecture
  - ½ hr break
  - 1 hr discussion
- This is a technical survey course!
  - Unit 1: clean energy fundamentals
  - Unit 2: clean energy challenges

# Course Outline

- Planned class structure:
  - 1 hr lecture
  - ½ hr break
  - 1 hr discussion
- This is a technical survey course!
  - 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
3. Renewable Energy
4. Fossil Energy



# Unit 1: Energy Fundamentals

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





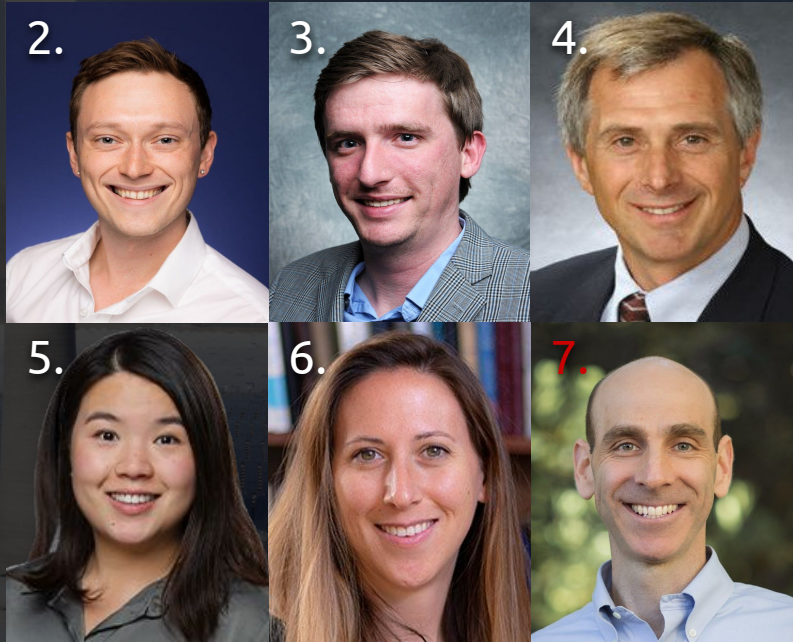
# Unit 1: Energy Fundamentals

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

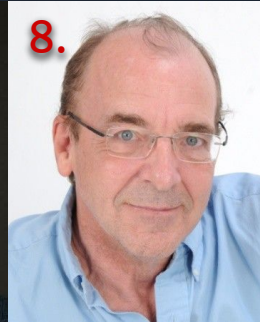
## 7. Transportation



# 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

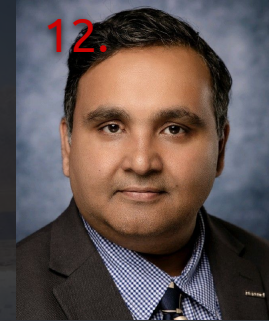
10. Energy Storage

11. Industrial Decarb



# Unit 3: Energy Innovation

## 12. Cleantech 1.0



# Unit 3: Energy Innovation

12. Cleantech 1.0

13. Cleantech Investing

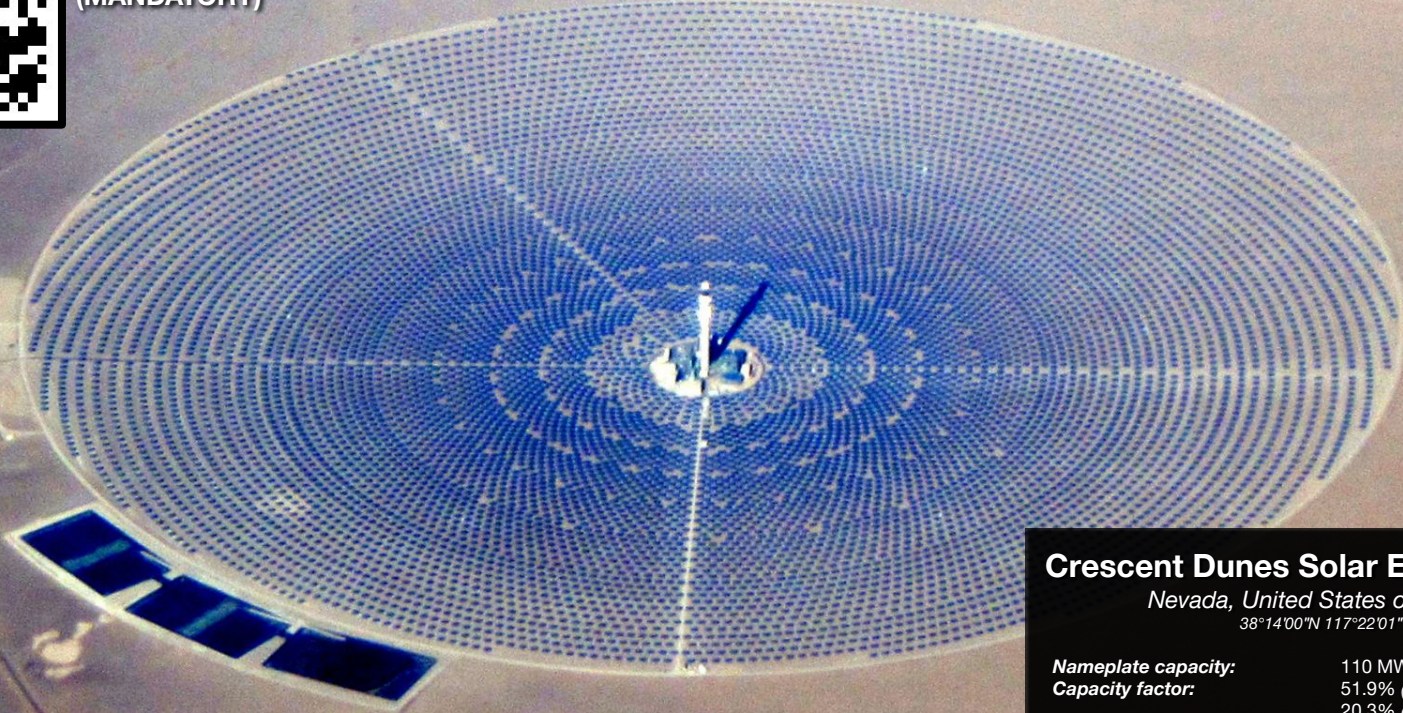




# Questions?



pre-course intro survey  
(MANDATORY)



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

<b>Nameplate capacity:</b>	110 MW
<b>Capacity factor:</b>	51.9% (planned) 20.3% (2018)
<b>Annual generation:</b>	196 GWh (2018)
<b>Construction began:</b>	September 2011
<b>Opening date:</b>	September 2015
<b>Construction cost:</b>	US\$975 million
<b>Owner(s):</b>	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

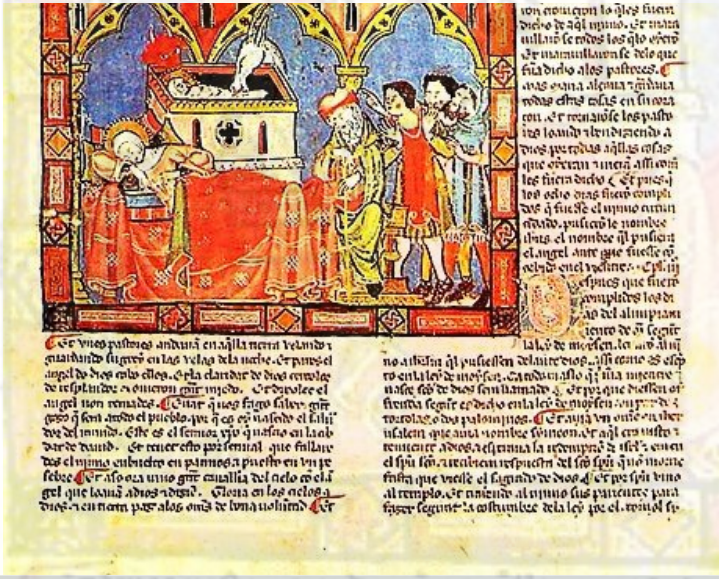
**Category** Oxide mineral

**Formula**  $\text{Pb}^{2+}_2\text{Pb}^{4+}\text{O}_4$





The color was used in particular for the paragraph signs, versals, capitals, and headings which were colored red in medieval manuscripts.<sup>[2]</sup> 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.<sup>[4]</sup>



- minho (river) →
- minium (mineral) →
- miniare (pigment) →
- miniature (art) →
- miniature (size)