Demystifying Climate Change

Session 8

Amelioration Strategies:

Mitigation, Adaptation, Intervention and Policy

This Session truncated by Internet failure

OLLI at Illinois
Spring 2021

D. H. Tracy
DavidHTracy@gmail.com

OSHER LIFELONG LEARNING INSTITUTE

March 23, 2021

To OLLI attendees:

My apologies for the internet failure this morning which prevented this session from happening.

This is a static PDF version of the presentation.

If you own Powerpoint and would like to see the actual Powerpoint presentation, contact me by email and I'll send you a link for your private use.

Regards,
Dave Tracy

OLLI at Illinois
Spring 2021

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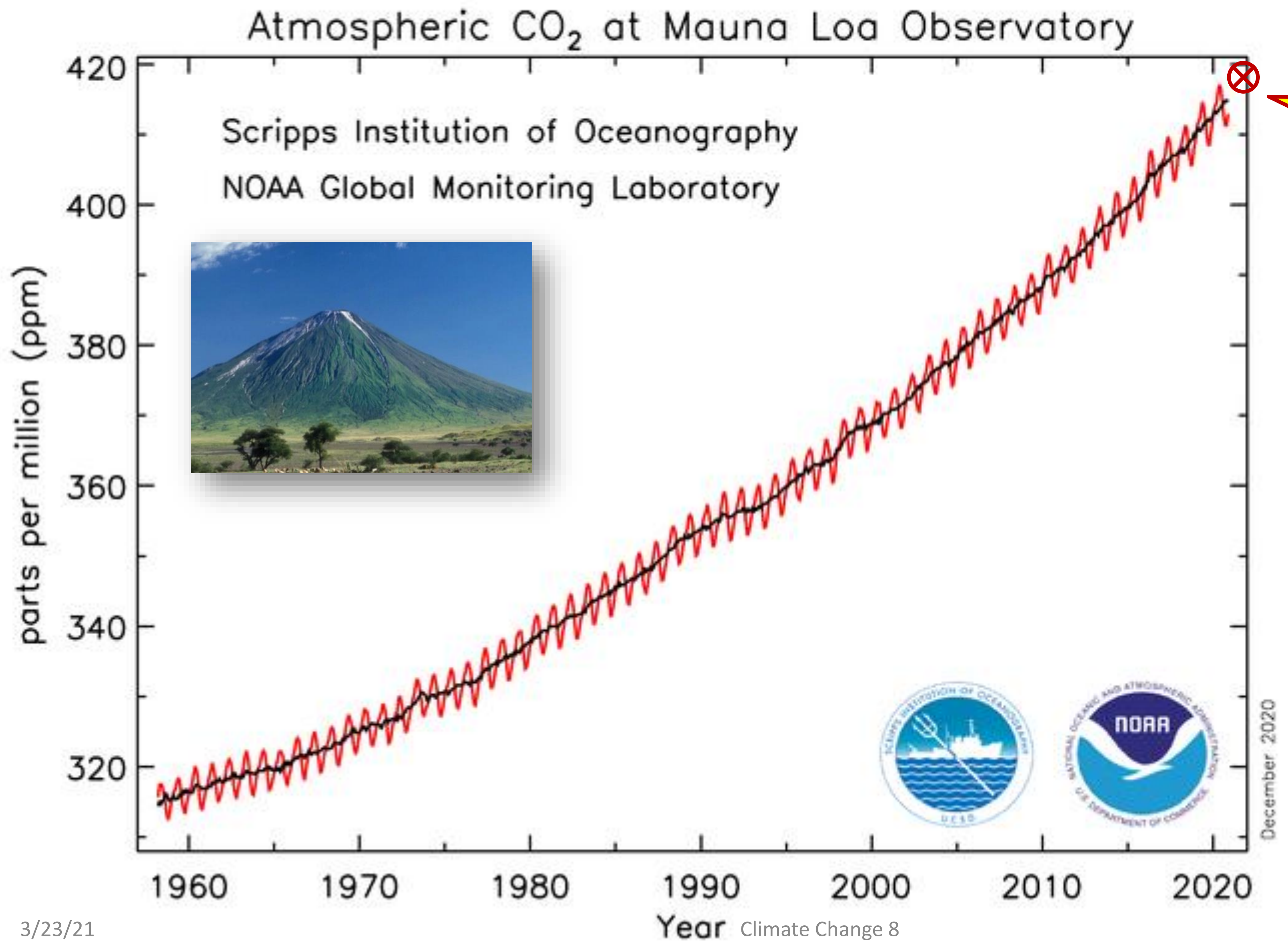

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Mar 21, 2021

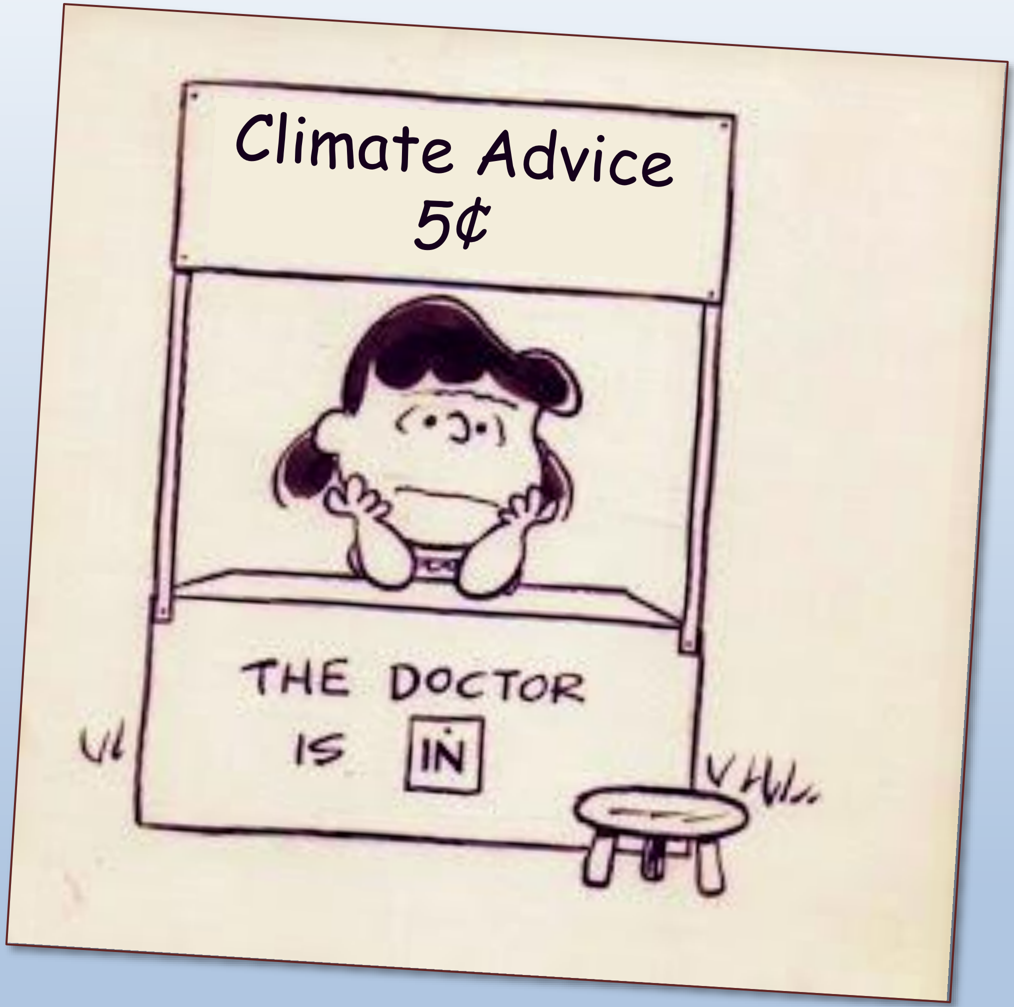
Course Outline

1. Building Blocks: Some important concepts
2. Our Goldilocks Earth: a Radiative Balancing Act
3. The Role of the Atmosphere: Greenhouse Gases & Clouds
4. Global Circulation and Dynamics of the Earth System:
   Oceans, Atmosphere, Biosphere, Cryosphere, People, Lithosphere
5. Natural Variability of the Climate, short and long term. Ice Ages
6. Carbon Dioxide and other Greenhouse Gases:
   Where do they come from, where do they go, how are they regulated?
7. Impacts and Future Projections for Global Warming -- Uncertainties
8. **Amelioration Strategies. The Climate Debate. Policy Options.**

When you see this symbol, I am offering my opinions. Feel free to ignore the associated comments or conclusions. ☺

IMHO

In My Humble Opinion

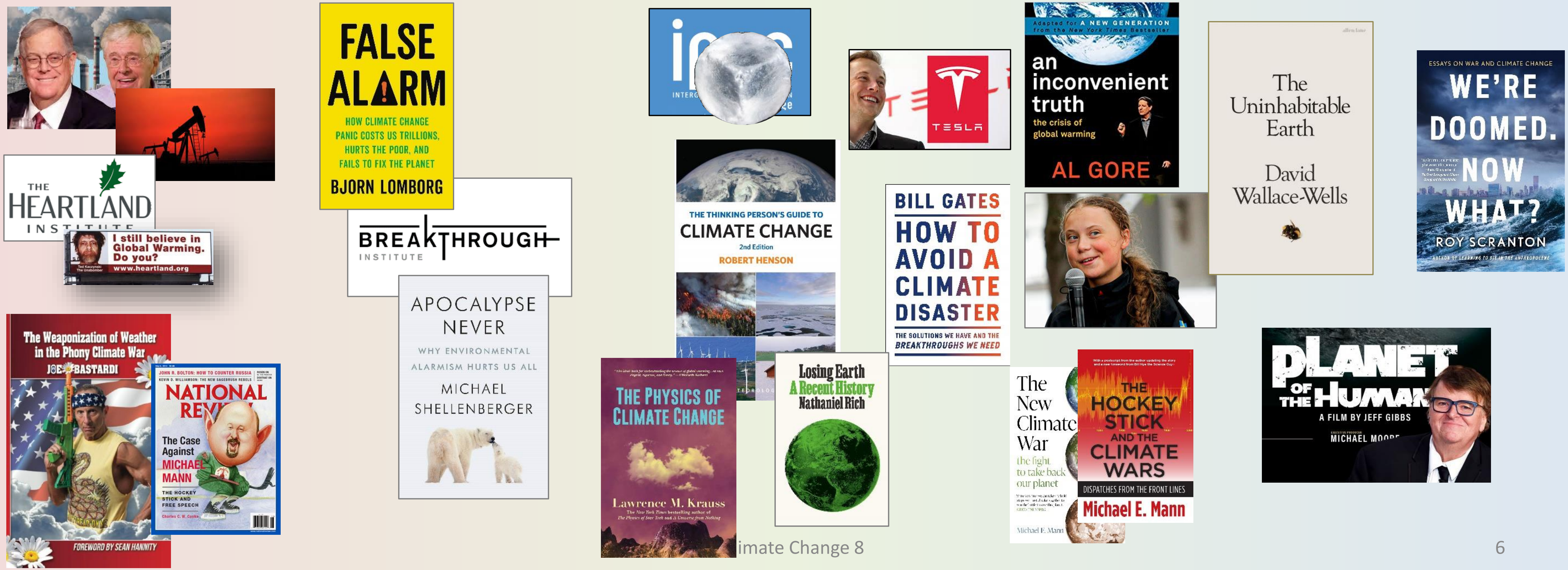


Climate Wars

Deniers	Soft Deniers	Deflectors [Inactivists]	Scientists & Experts	Doers	Activists	Soft Doomsayers	Doomsayers

Skepticism — **Belief**

Advocacy *(Disinformation/ Cherry Picking)* — neutrality — Advocacy *(Disinformation/Cherry Picking)*



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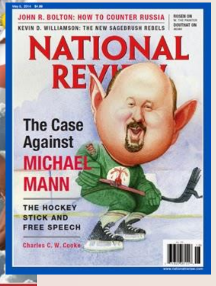
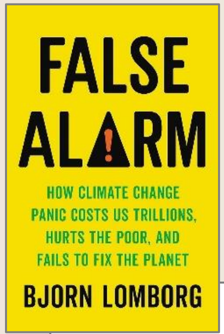
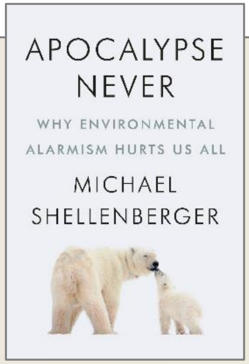
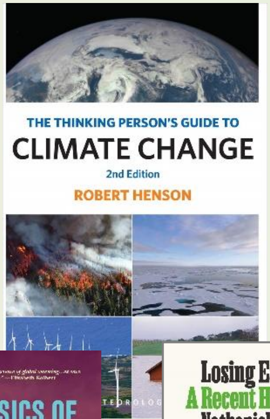
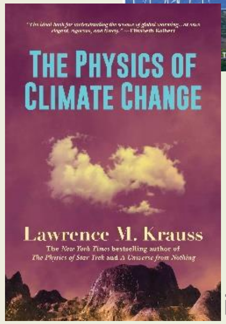
THE HEARTLAND INSTITUTE

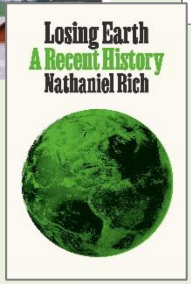



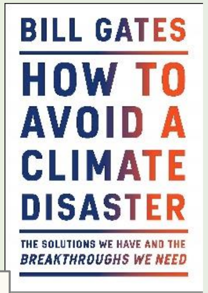


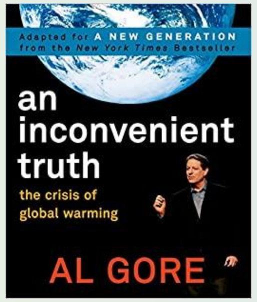
BREAKTHROUGH INSTITUTE


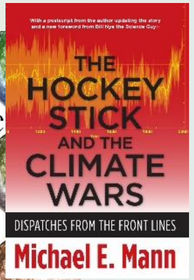
ipcc INTERGOVERNMENTAL PANEL ON climate change


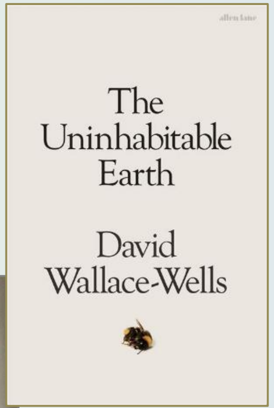


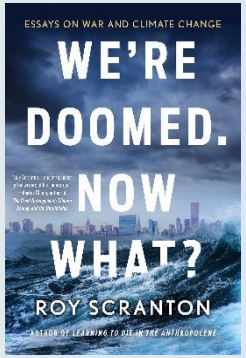










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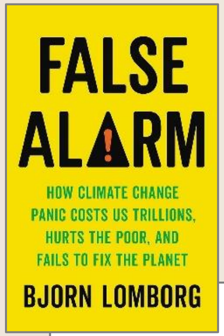

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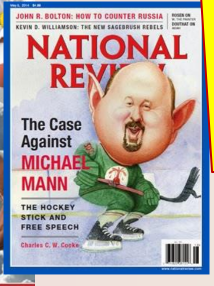
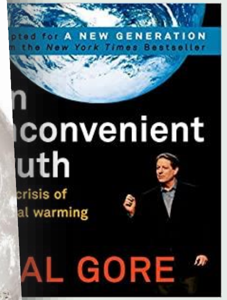
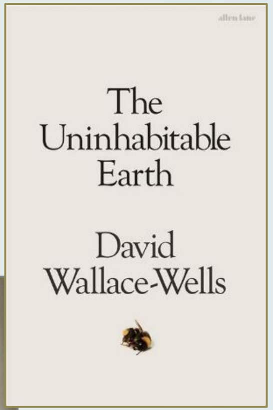
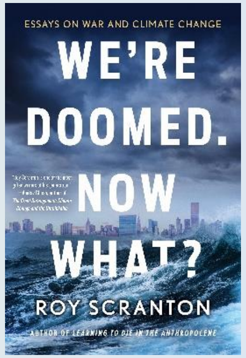
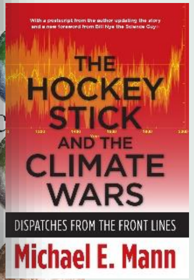


Useful perspective on the debate. Fairly balanced, albeit from an avowed advocate.









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For your intellectual health:

IMHO

Do **NOT** read just <u>*one*</u> of these books!

Amelioration: What Can Be Done?

- Mitigation

Reducing or Eliminating the GH Gas Drivers

Global Effect

- Adaptation

Learning to Live with Climate Change

Local to Regional

- Intervention

Active Measures to Counteract Ongoing Climate Change

Regional to Global

Amelioration: What Can Be Done?

- Mitigation

Reducing or

- Adaptati

- Intervention

Underlying all of these: **Policy Issues**

- Regulations and Laws
- R & D Funding
- Economic Incentive structures
- International Relations

Global Effect

Local to Regional

Active Measures to Counteract Ongoing Climate Change

Regional to Global

Routes toward NetZero

Regulation and Mandates

- Renewable Portfolio Standards
  (for electric power)
  - Varies State by State
- CAFE Standards
  - Corporate Average Fuel Economy for cars
- State Clean Air Standards
  - CA + 13 other states
- Environmental Reviews for Project Licences

Subsidies and Incentives

- Renewable Tax Credits
  - Production Tax Credit (Wind)
  - Investment Tax Credit (Wind and Solar)
- AcceleratedDepreciation
- Rural Energy for America Program
- Carbon Capture Tax Credit

Market Based Mechanisms

“Price on Carbon”

- Carbon (Dioxide) Tax
  - Direct tax on emissions
  - Unpopular, rare
- Cap and Trade System
  - Emission Allowances are auctioned off each year
  - Allowances may be traded (bought & sold)

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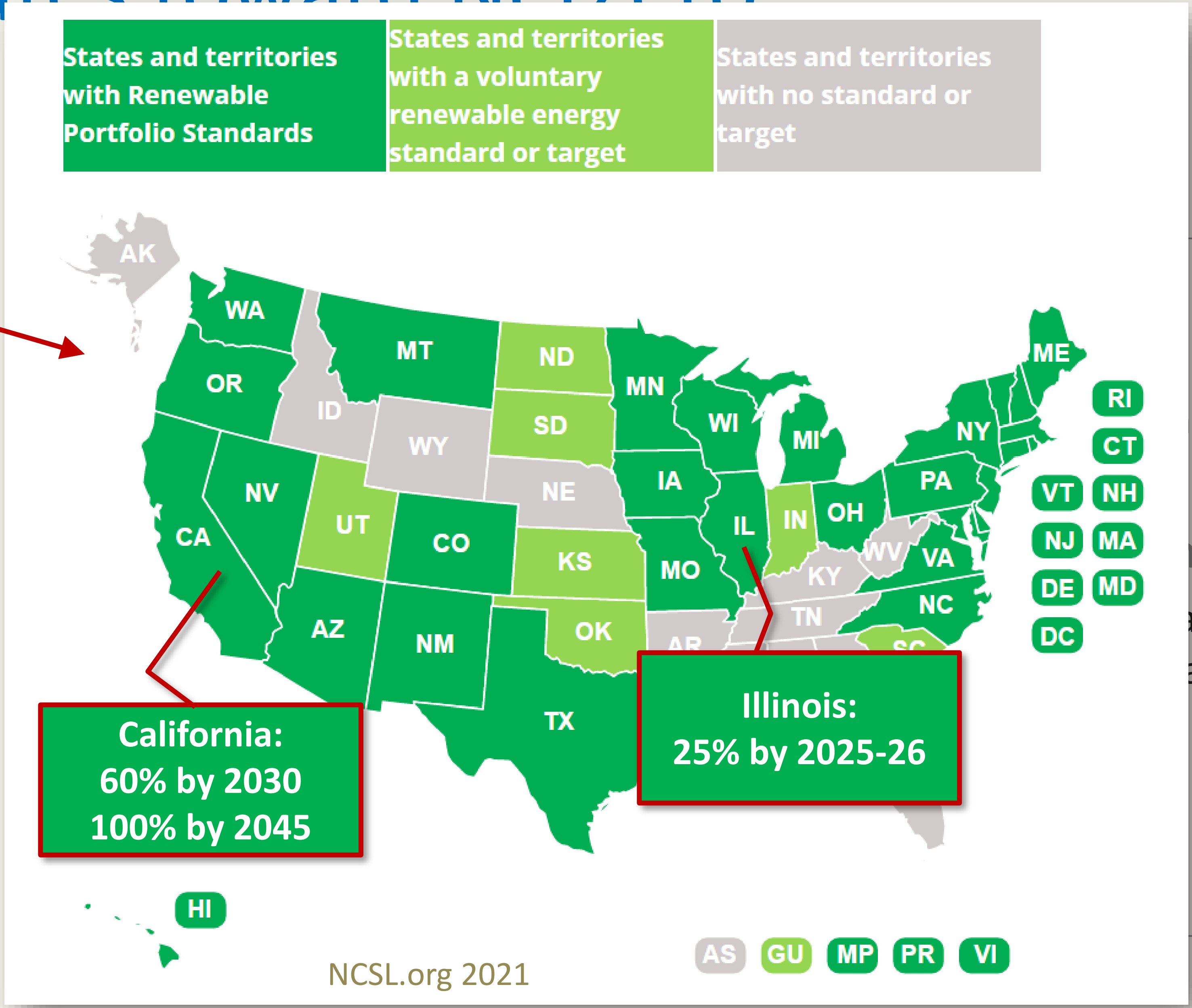

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These have jump-started wind and solar power projects, but are now phasing out.

Market Based Mechanisms

"Price on Carbon"

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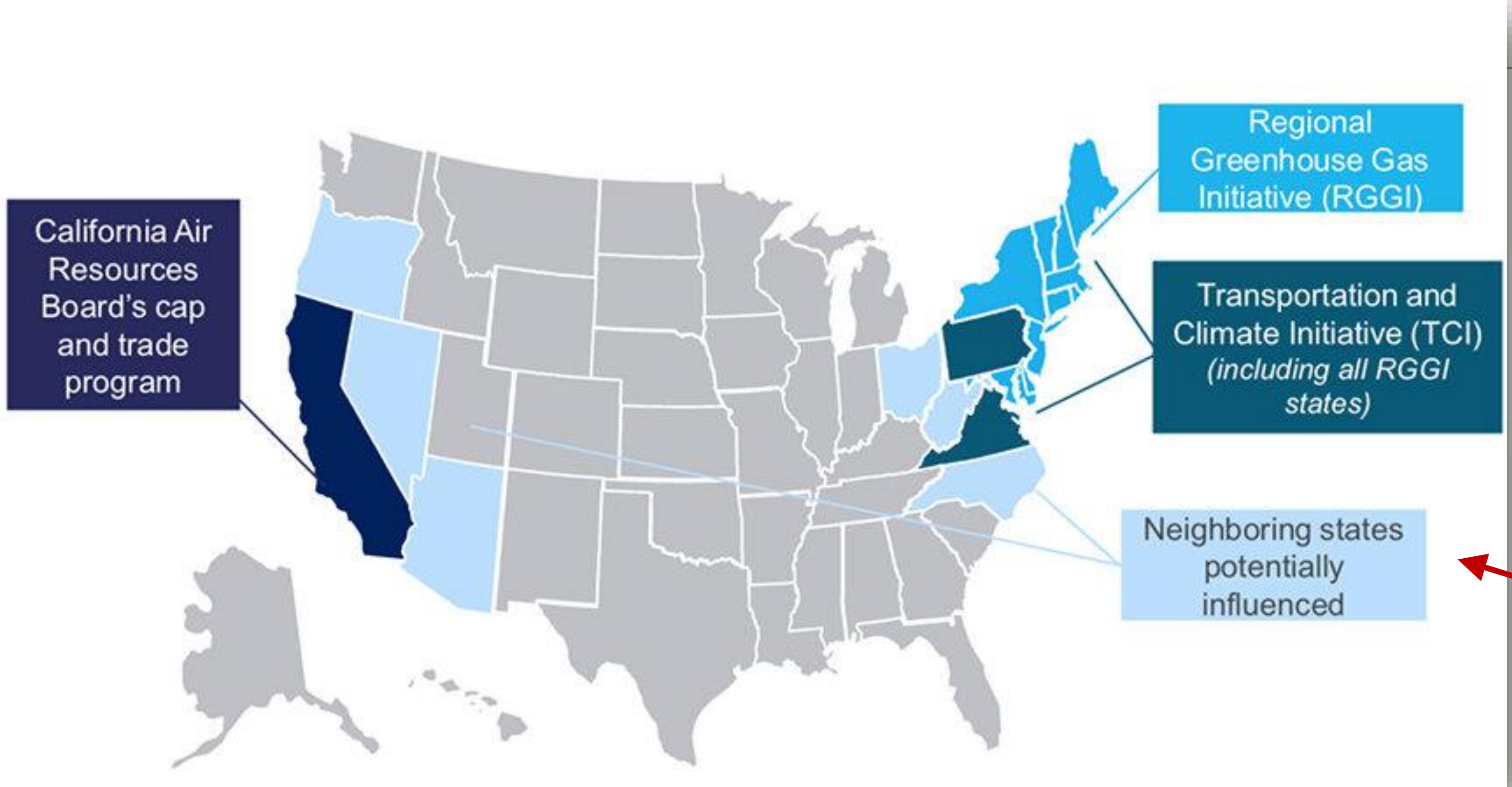
Routes toward NetZero

Regulation and Mandates

Subsidies and Incentives



Environmental Reviews for Project Licences

Market Based Mechanisms

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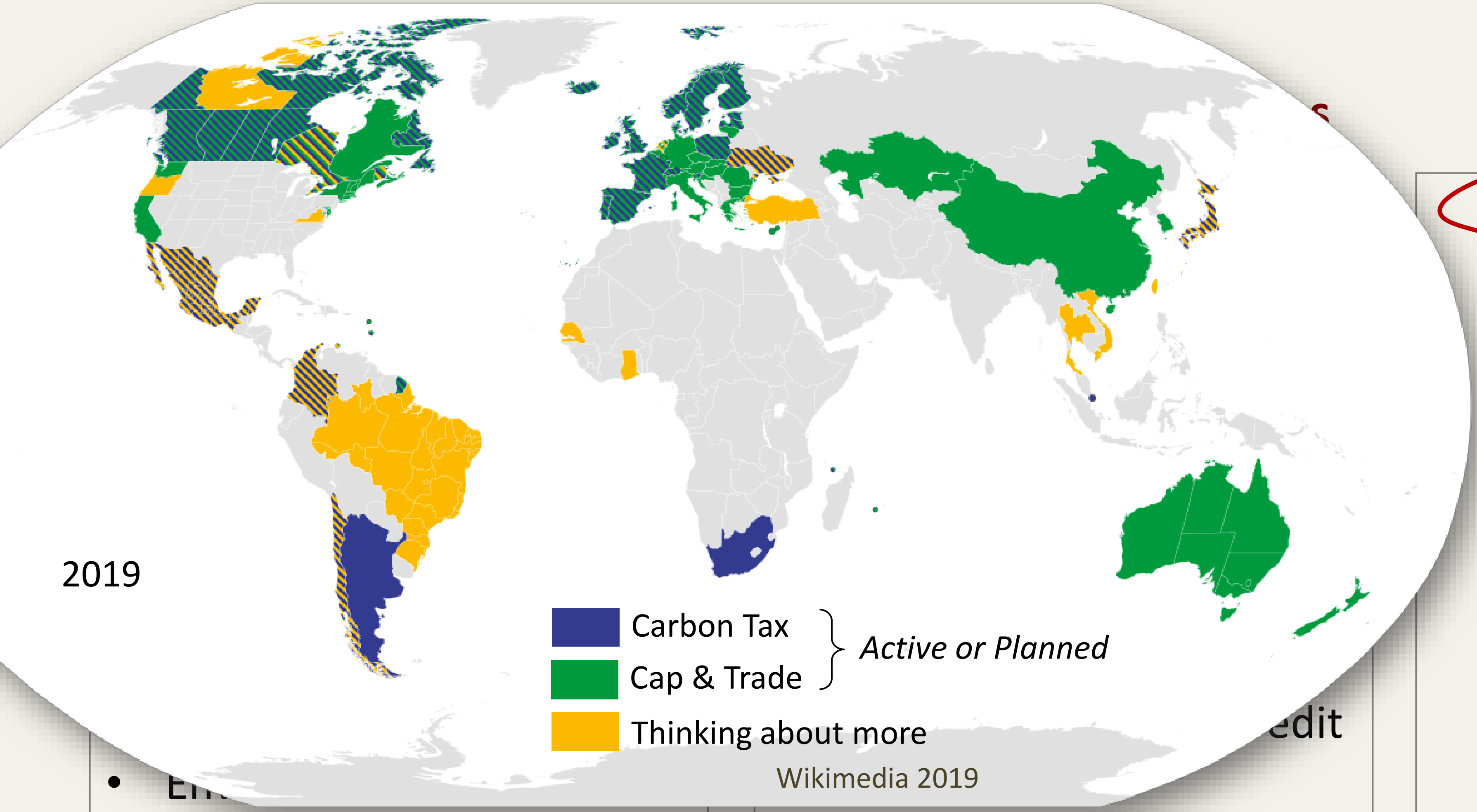

Project Licences

edit

Market Based Mechanisms

"Price on Carbon"

Carbon (Dioxide) Tax

- Direct tax on emissions
- Unpopular, rare

Cap and Trade System

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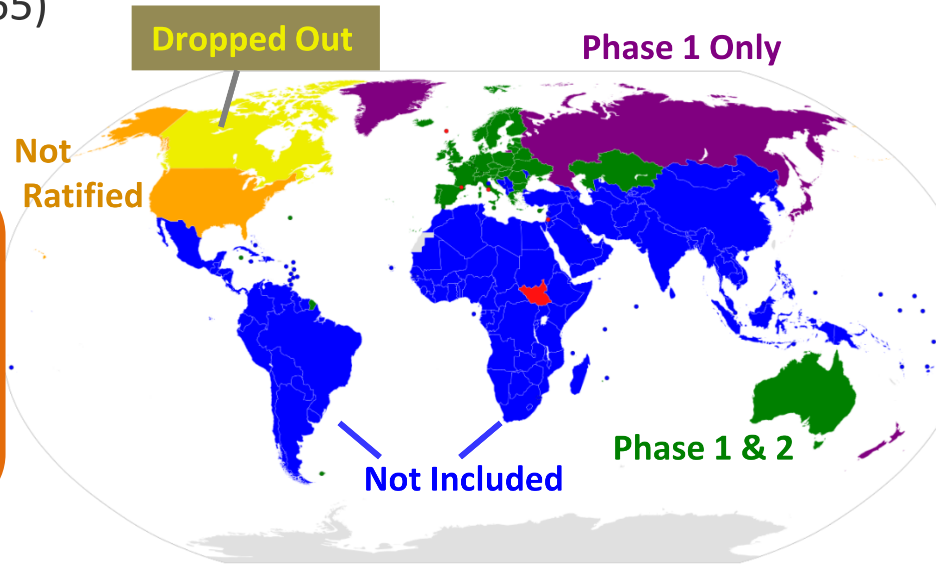
United Nations Framework Convention on Climate Change (UNFCCC)

Established by Treaty of **Rio** de Janeiro **1992**.   154 nations (now 165)



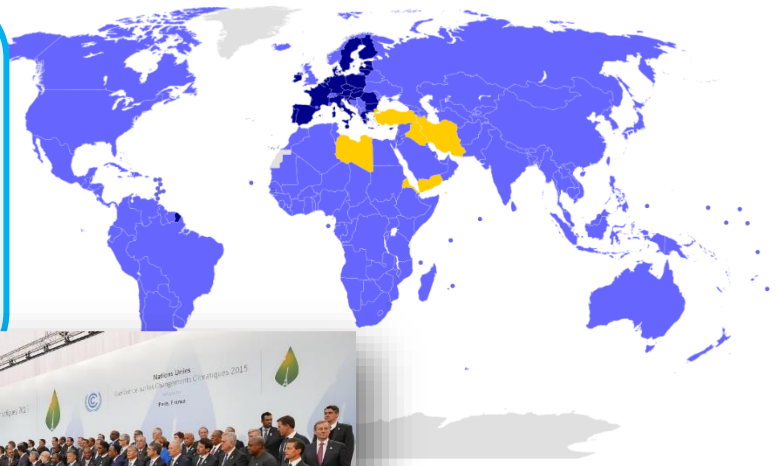
COP = **C**onference **o**f the **P**arties, meets annually.

1995 COP 1 Berlin
1996 COP 2 Geneva
1997 COP 3 **Kyoto**
1998 COP 4 Buenos Aires
....

Kyoto Protocols:
<u>Enforceable</u> emission reductions
for some Developed Countries only.
- Phase 1 *2008-2012* 5% GHG⇩ 1990
- Phase 2 *2012-2020* Flop

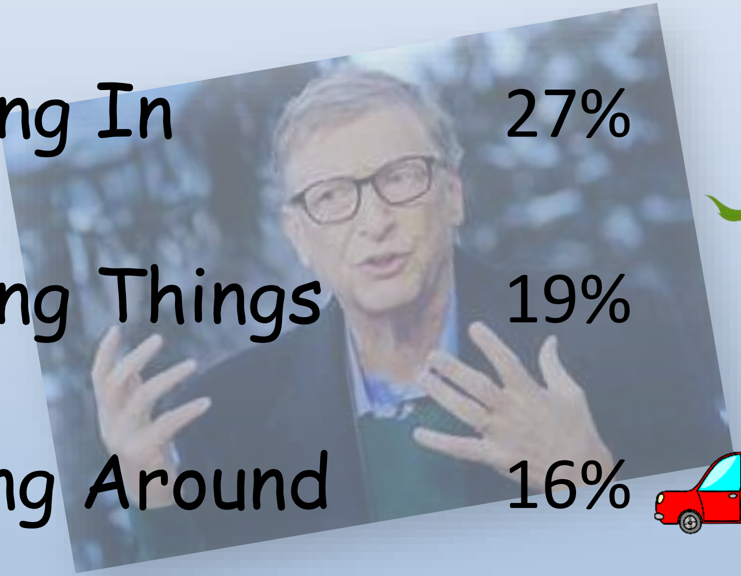
2014 COP 20 Lima
2015 COP 21 **Paris**
2016 COP 22 Marrakech
....

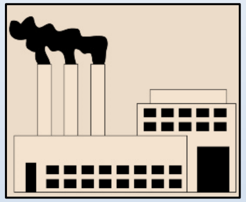
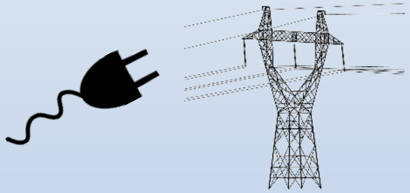
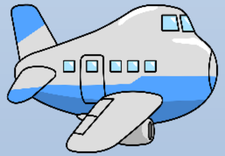
Paris Agreement:
Nearly all countries sign on.
Explicit Goal of "well below 2° C warming"
Countries set own plans ….
No real enforcement.
US dropped out briefly in 2020



2019 COP 25 Madrid
2020 [*Canceled due to COVID*]
2021 COP 26 Glasgow (November)

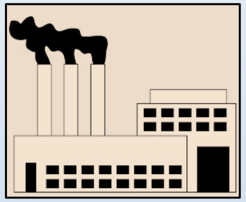
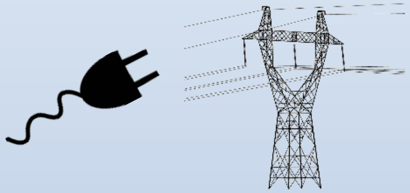
Mitigation: What Activities Emit Greenhouse Gases?



- Making Things 31%  Manufacturing
- Plugging In 27%  Electricity
- Growing Things 19%   Agriculture
- Getting Around 16%    Transportation
- Keeping Warm 7%   Space Heating

Bill Gates: *How to Avoid a Climate Catastrophe*

Mitigation: Low Hanging Fruit

- Making Things 31%  Manufacturing
- Plugging In 27%  Electricity
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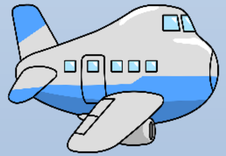
- Getting Around 16%    Transportation
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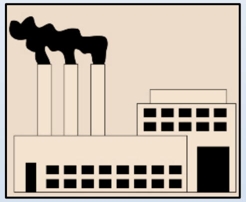
- Making Things 31%  Manufacturing
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Energy Efficiency Improvements

- Immediate economic payback
- Reduce GHG emissions
- Reduce amount of "dirty" infrastructure to be replaced.

Zero/Low Carbon Replacements May Come at a Price
…but not always

Bill Gates: *How to Avoid a Climate Catastrophe*

Green Premium can be Positive (costs more) or Negative (cheaper)

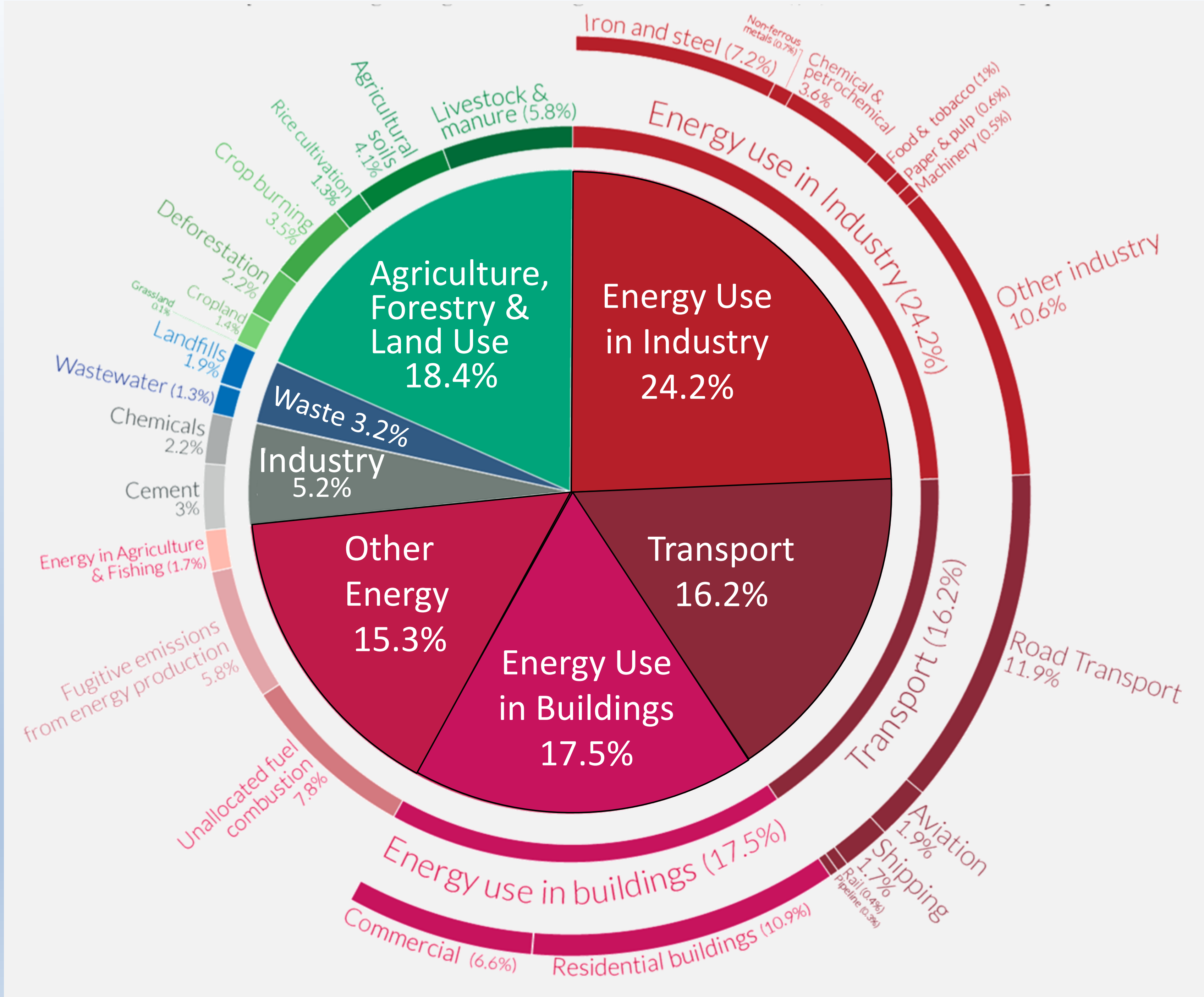
*A Current Example**

Diesel Fuel (Petroleum)	$ **2.40** /Gal
BioDiesel Fuel (B100)	$ **3.33** /Gal
Green Premium:	**$ 0.93** /Gal

* https://AFDC.energy.gov/fuels/prices.html [Oct 1-15 2020]

Greenhouse Gas Emissions Globally by Sector

Data for 2016
Total 49.4 GigaTons
CO_2equiv



Modified from OurWorldInData.org (2020)
Source: Climate Watch, World Resources Institute

Zooming in on Sectors

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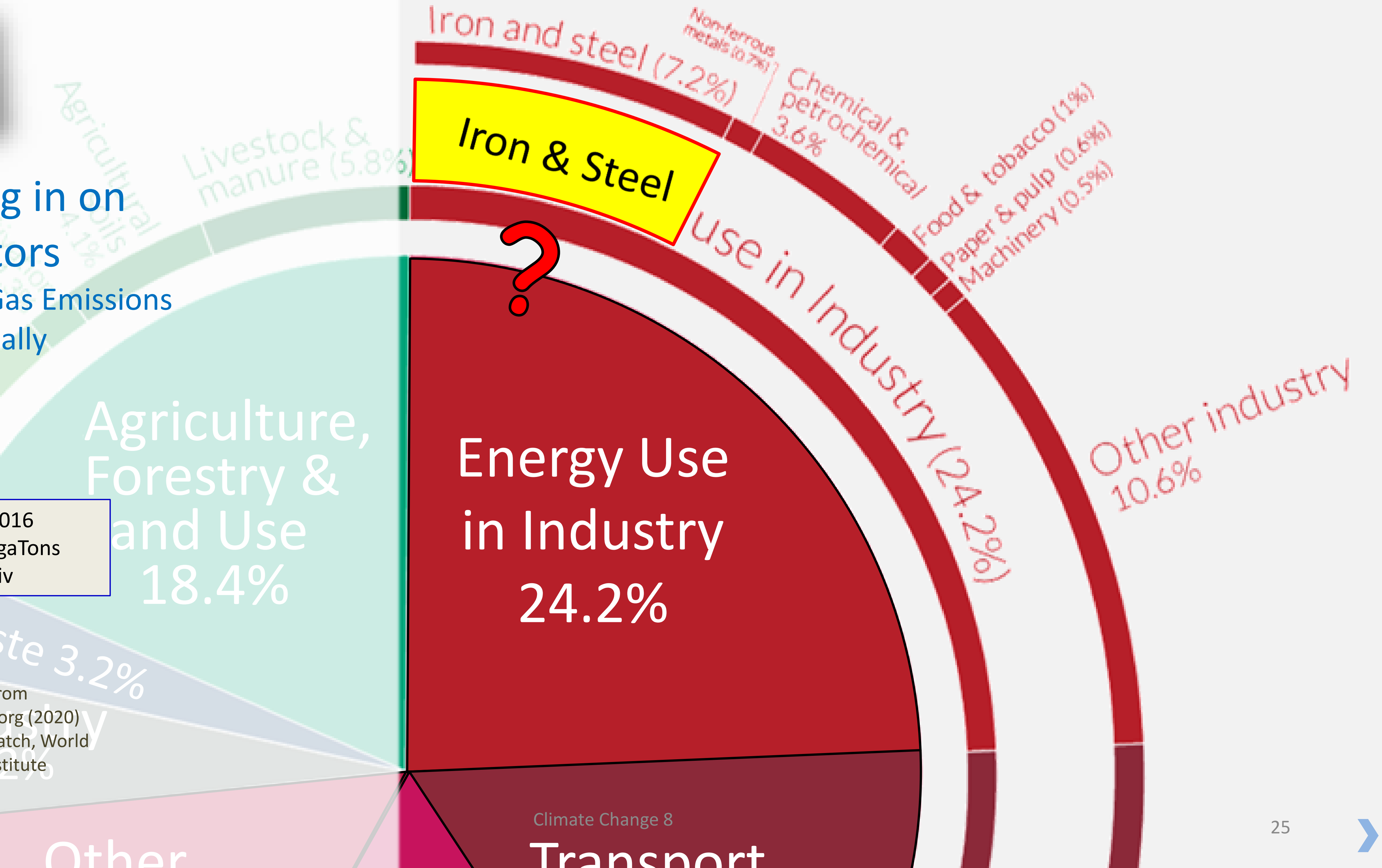

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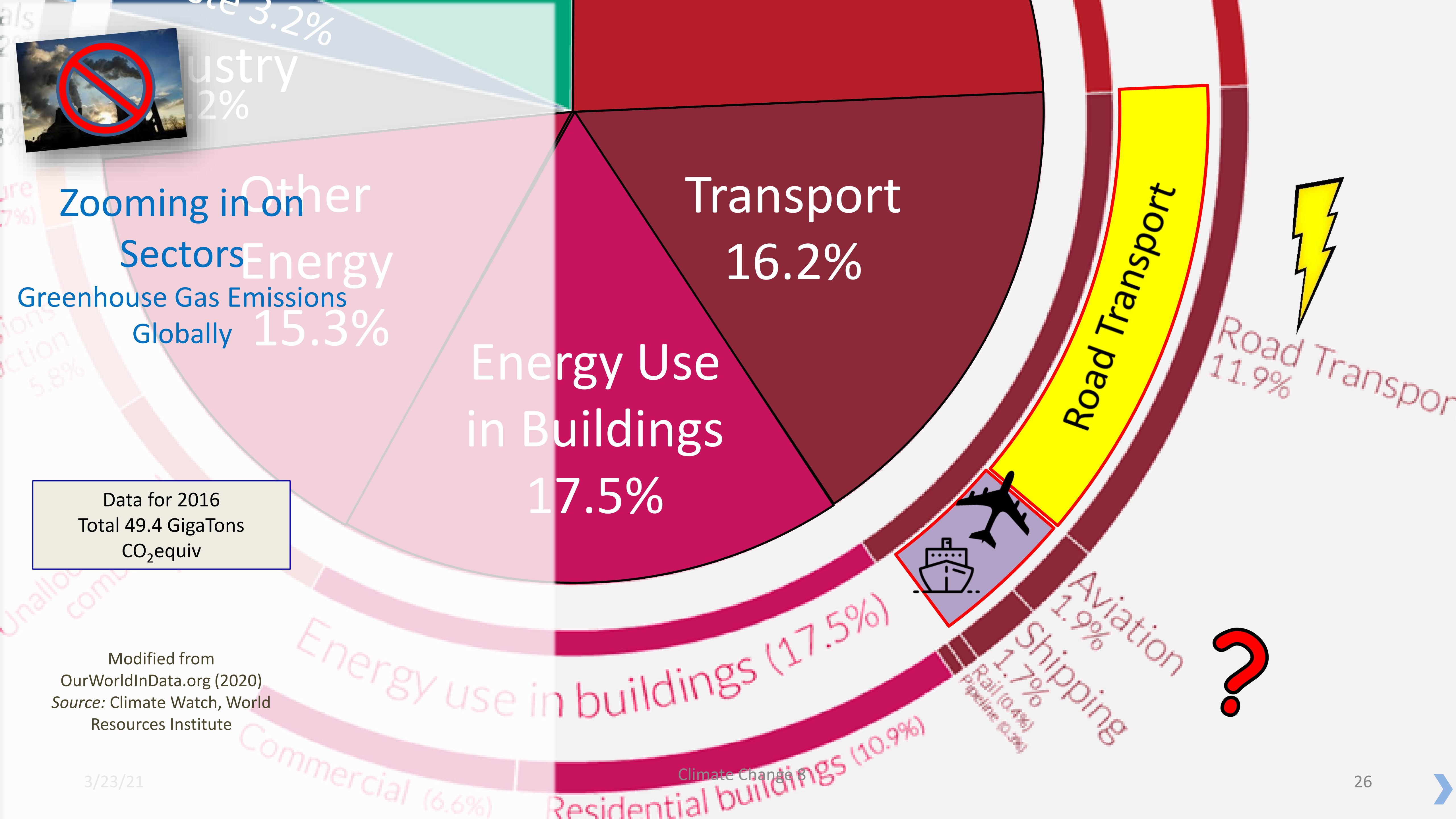

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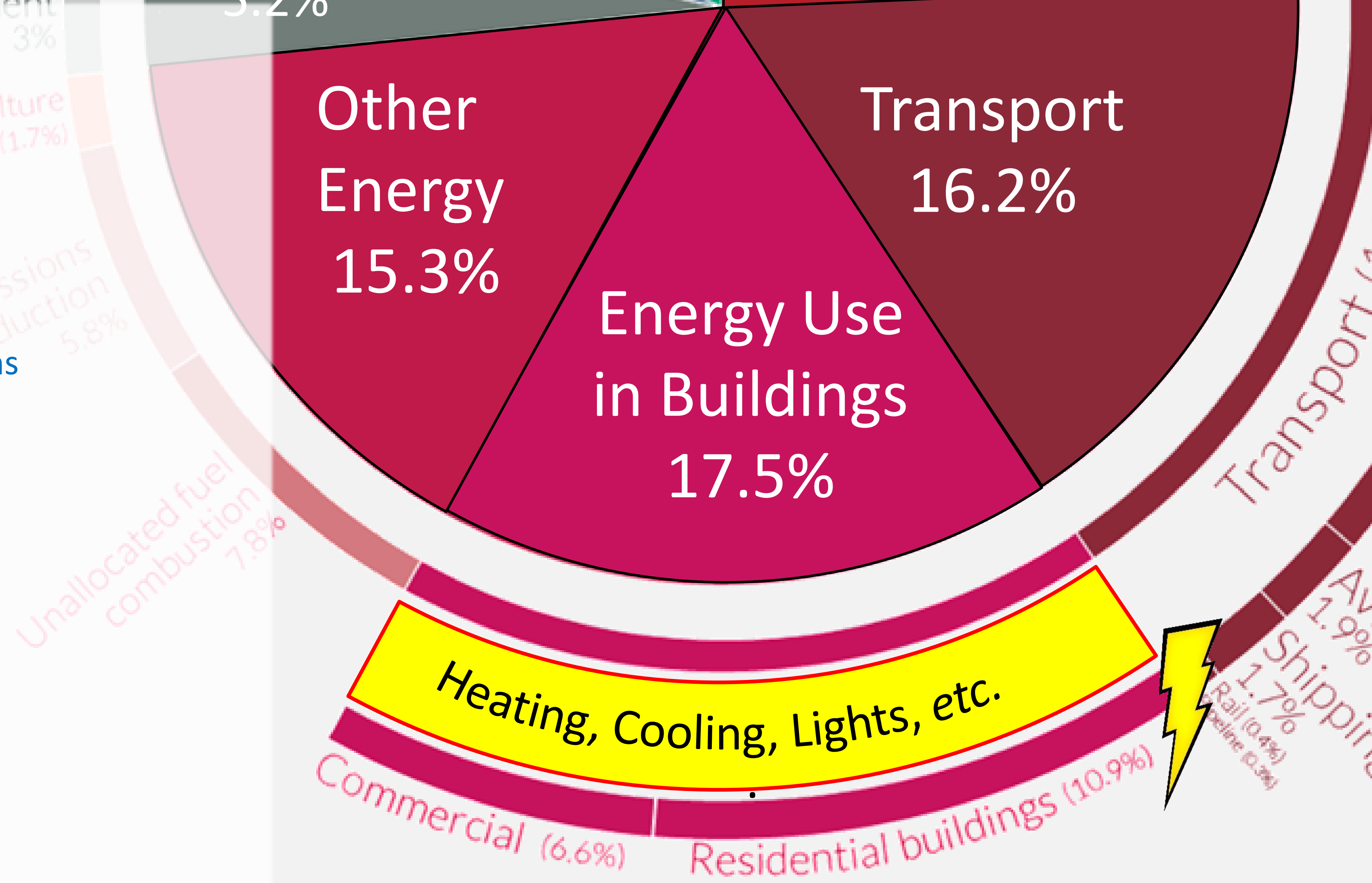

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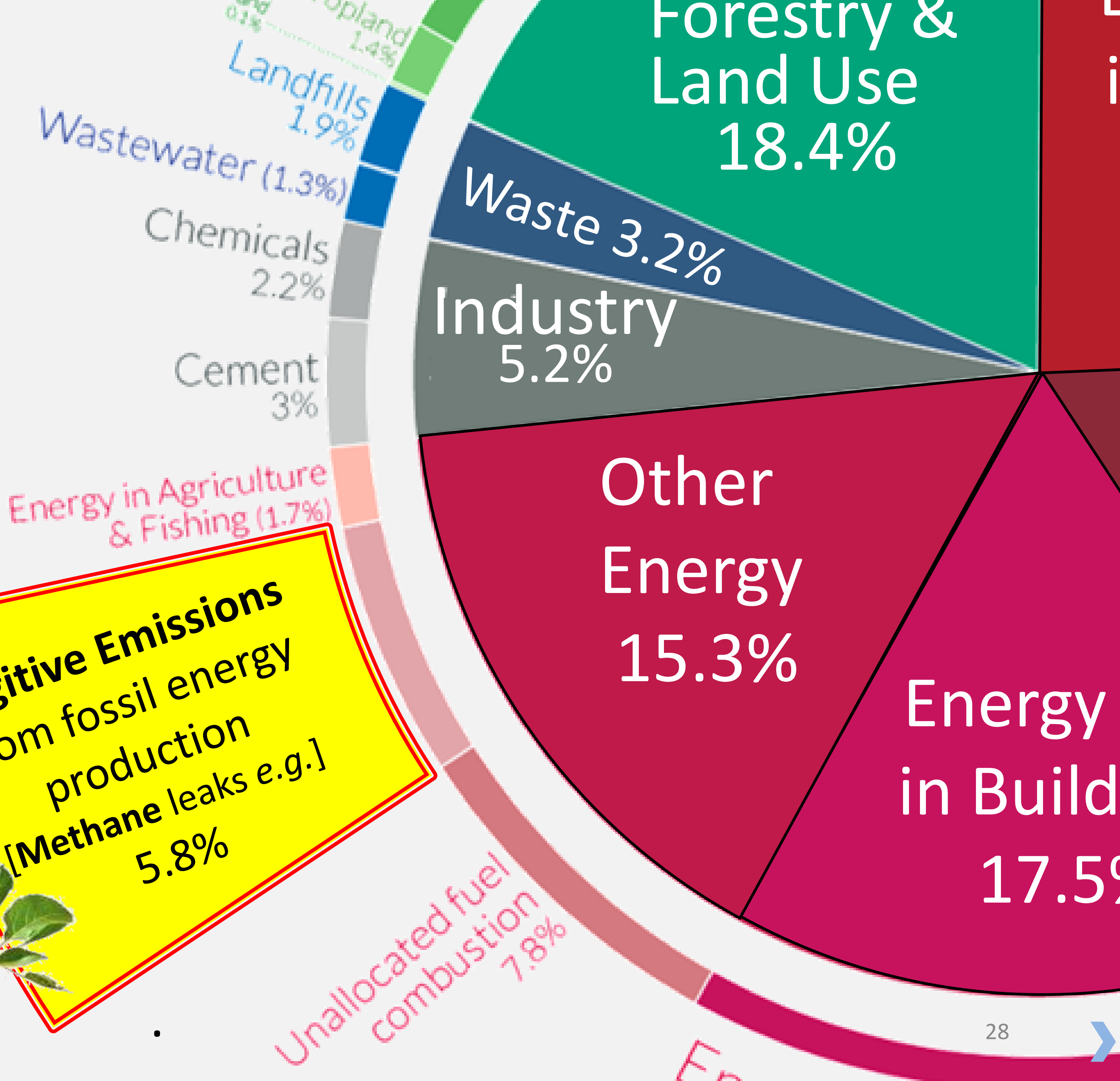

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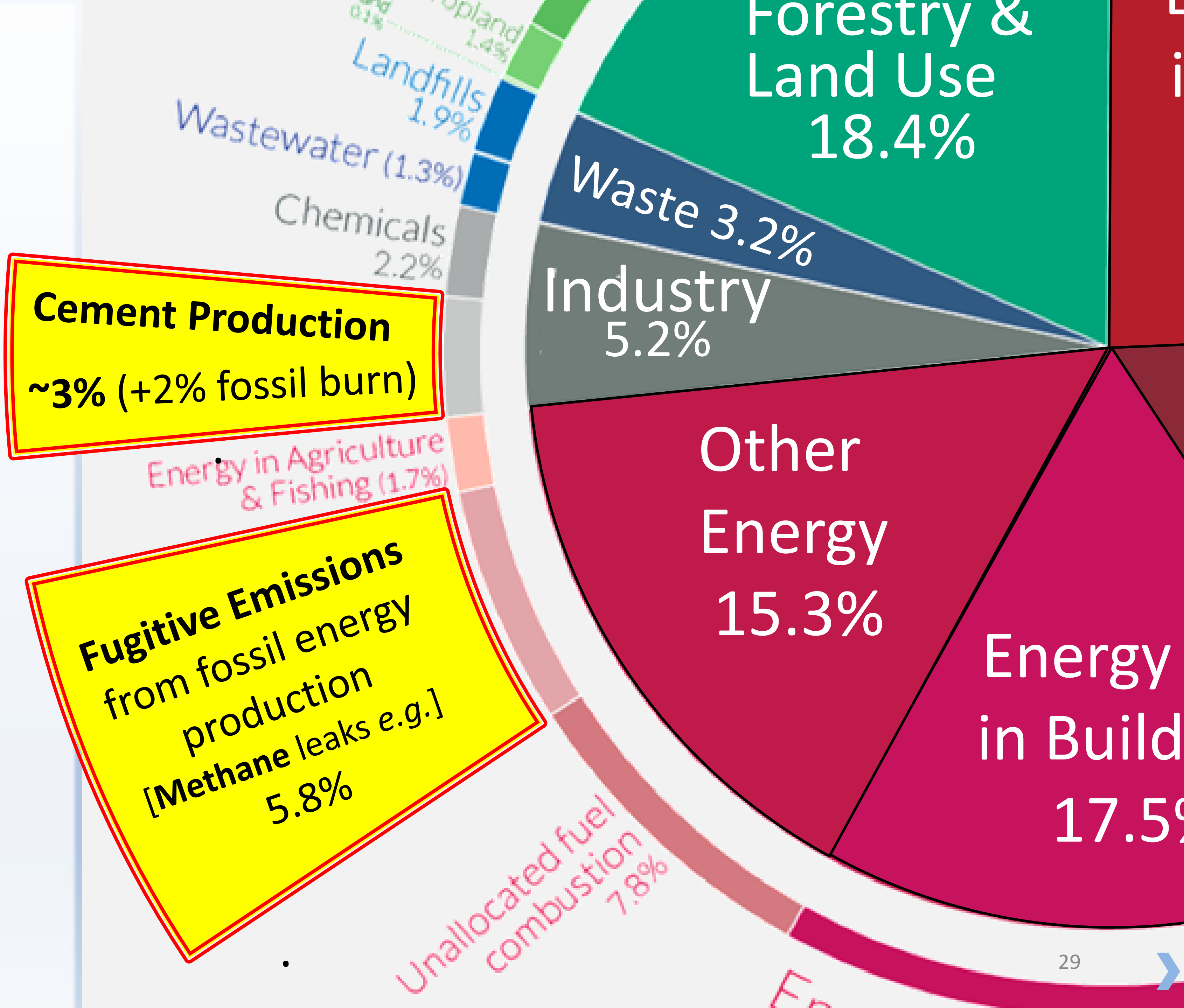

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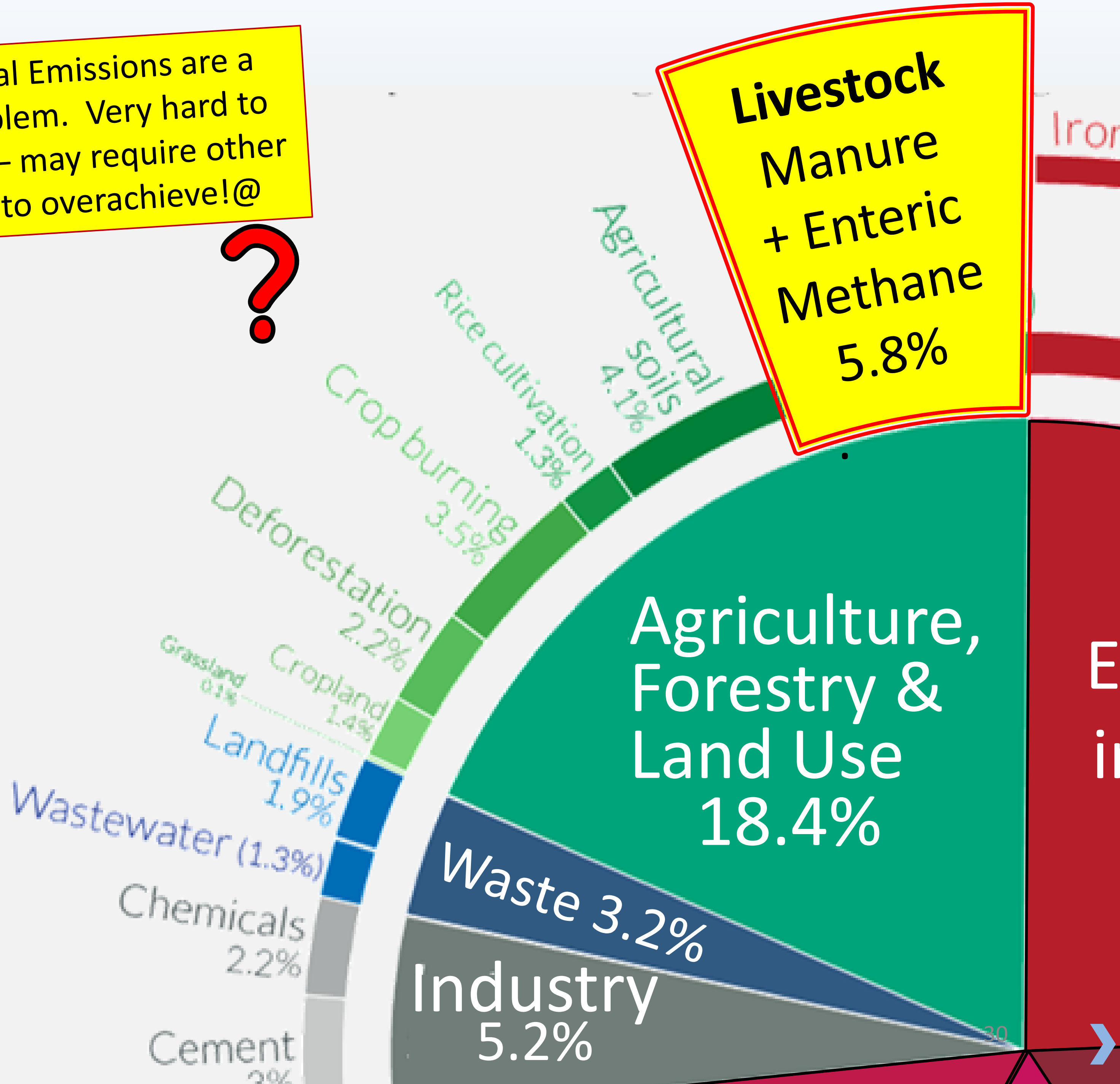
Agricultural Emissions are a tough problem. Very hard to get to zero – may require other elements to overachieve!@



Global Greenhouse Gas Emissions

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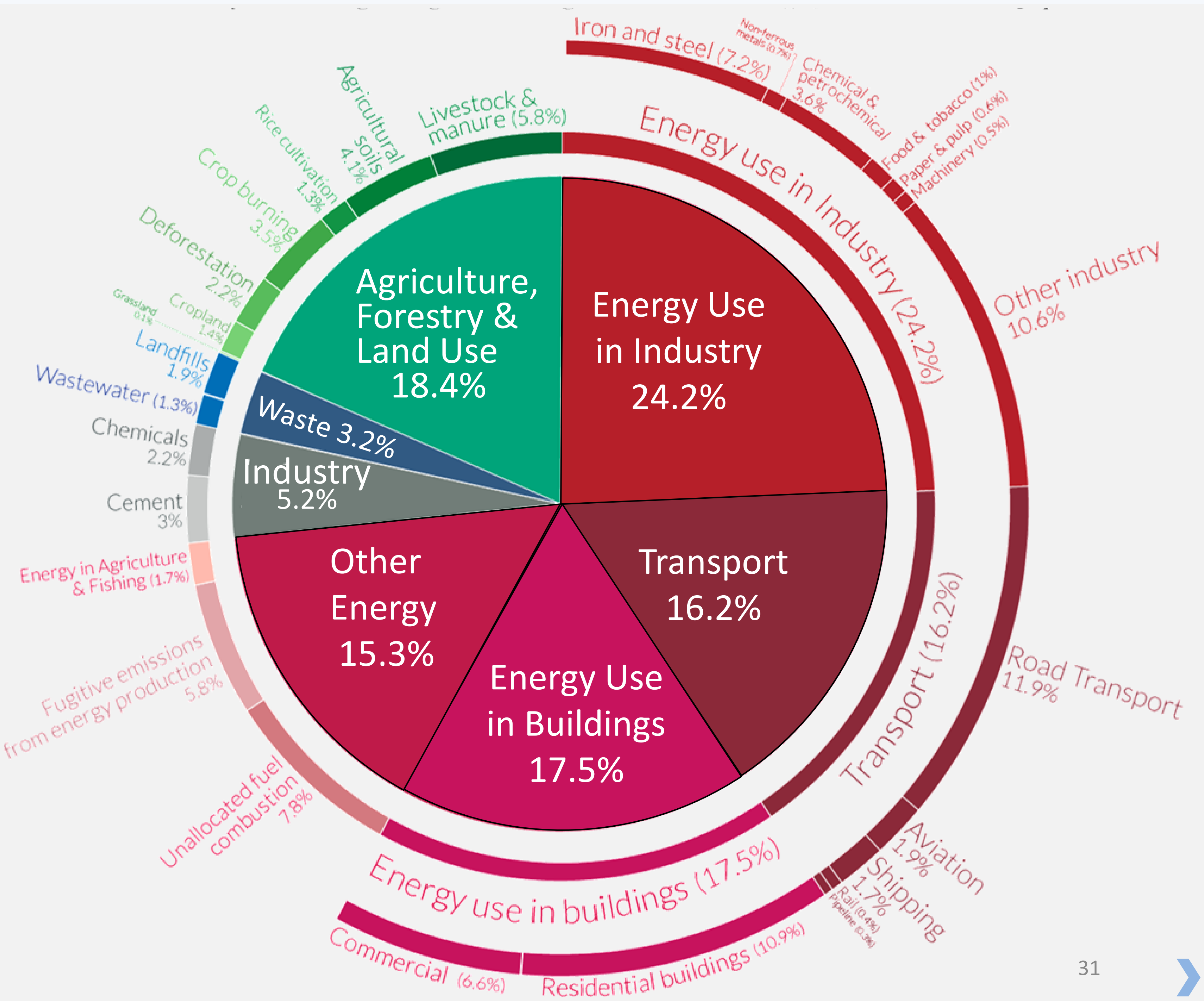

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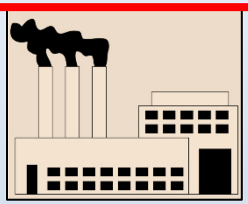
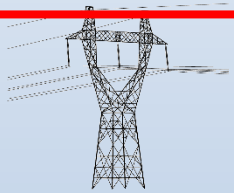
Mitigation

- Making Things 31%  Manufacturing
- Plugging In 27%   Electricity
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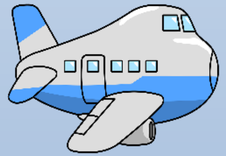
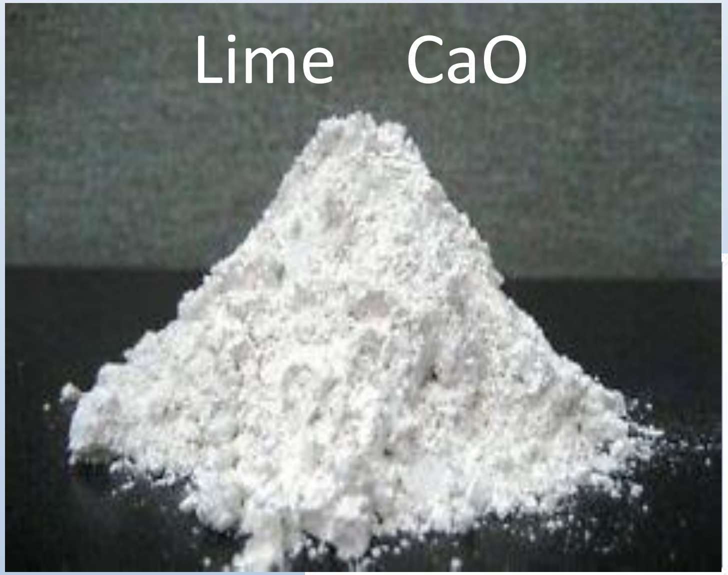
- Getting Around 16%    Transportation
- Keeping Warm 7%   Space Heating

Portland Cement

Cement made on huge scale mixing these or similar ingredients in a kiln.
All but Lime can be mined directly.



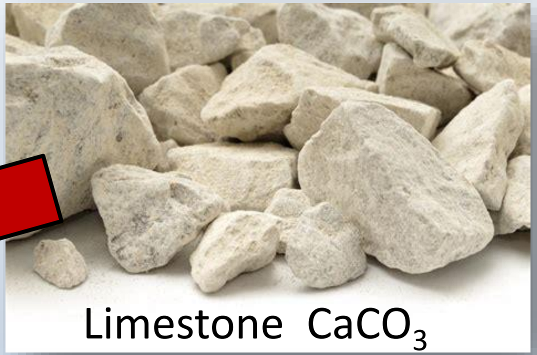
Portland Cement

3%!

of CO_2 equiv

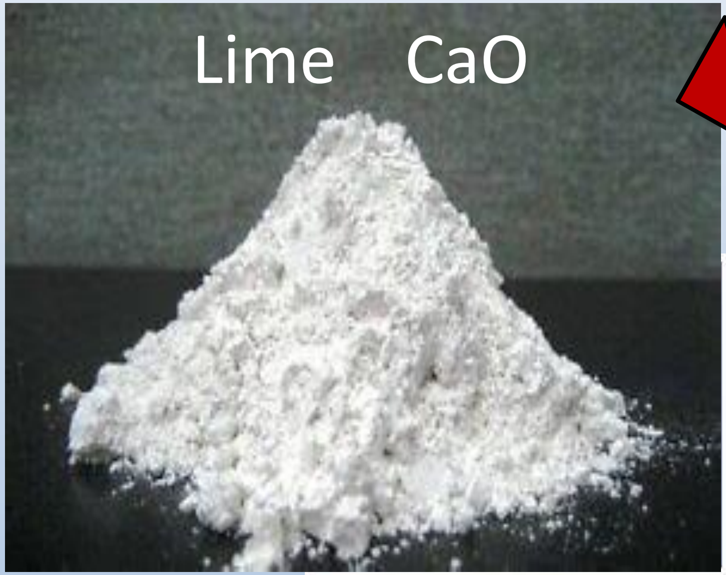
CO_2

The Lime comes from heating Limestone.



HEAT

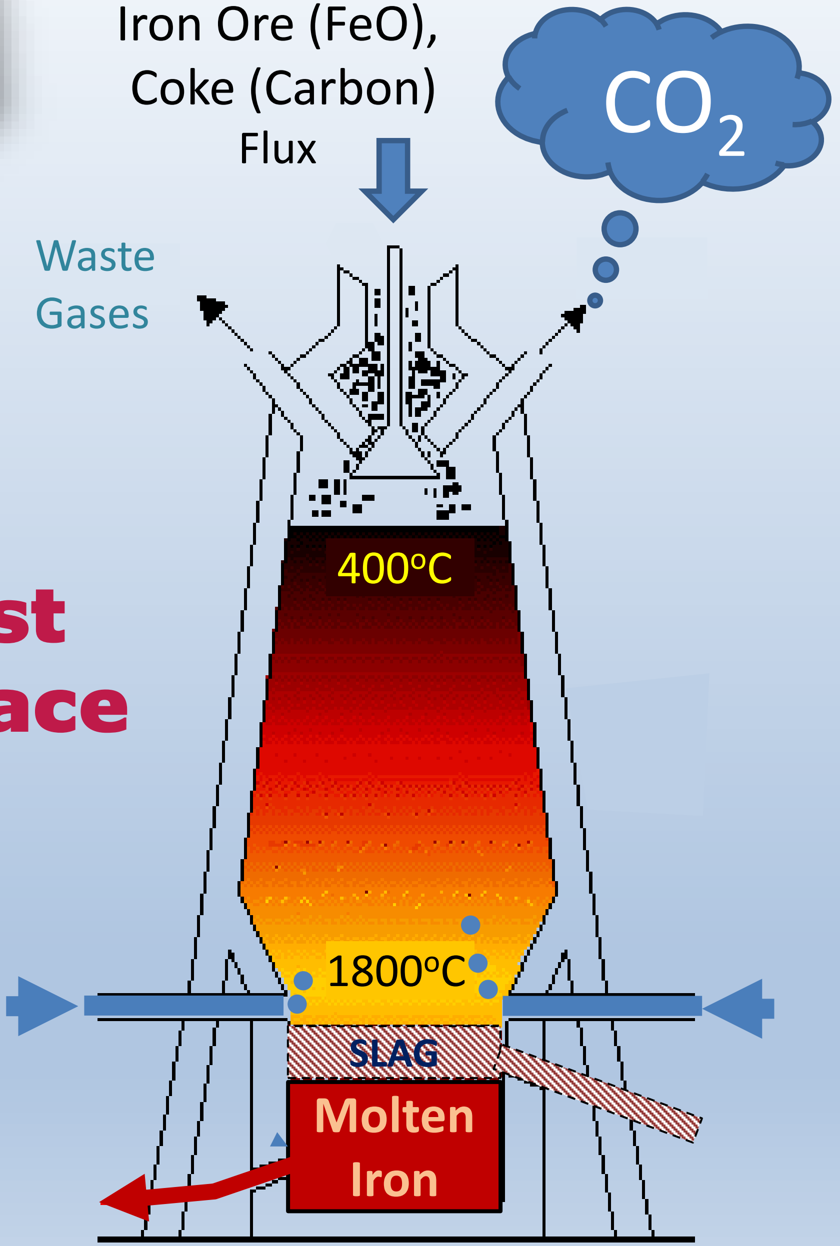
$$CaCO_3 + \text{heat} \rightarrow CaO + CO_2\uparrow$$



Partial solutions exist, but come at a price…

75-140%

Iron and Steel



Blast Furnace

7%!

of CO_2 equiv

How to clean this up?

1. Capture the CO_2 and Sequester It *or*
2. Avoid using Carbon to reduce the ore.

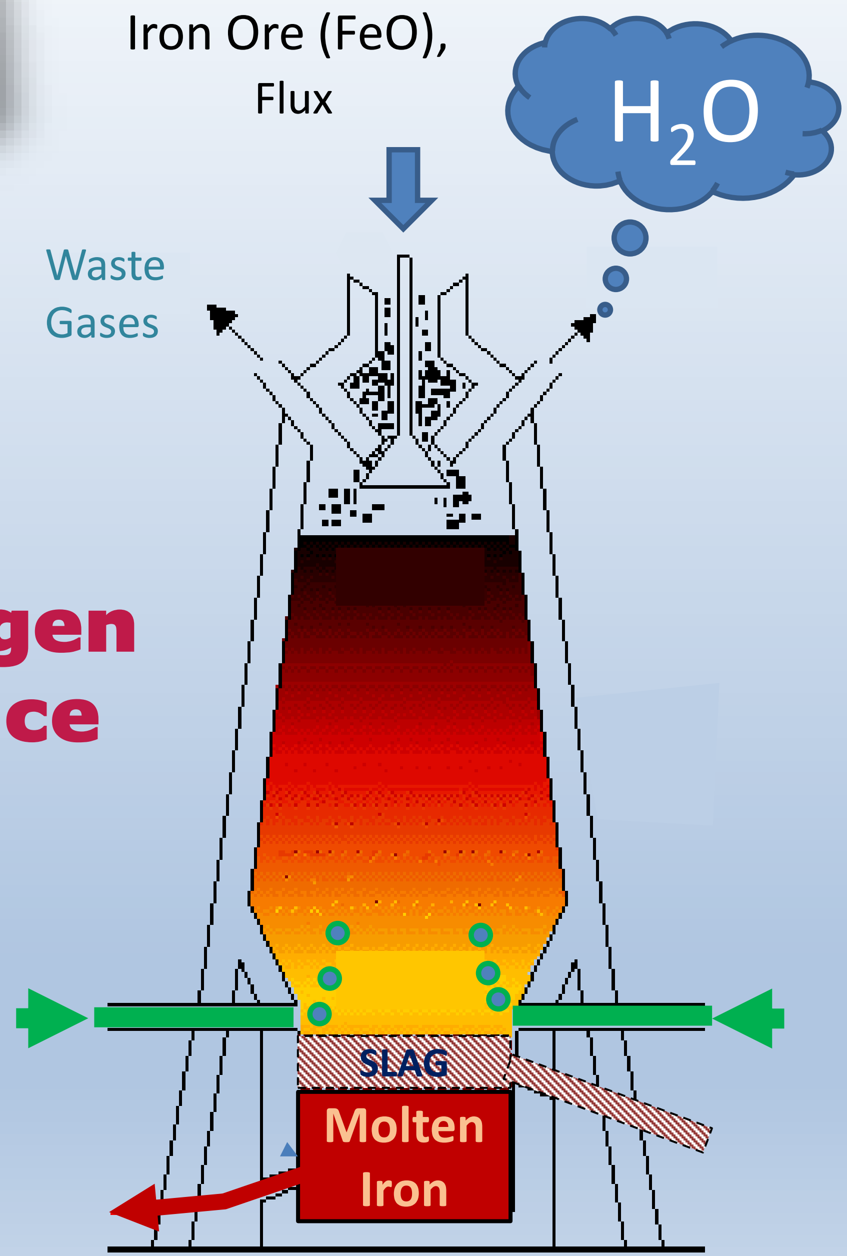
$$2\,FeO + C \rightarrow 2\,Fe + CO_2\uparrow$$

Greatly oversimplified!!

Each ton of Iron produced generates 1.8 tons of CO_2

Hydrogen Metallurgy

Smelting Iron ore using Hydrogen is a proven approach, now being developed.



Hydrogen Furnace

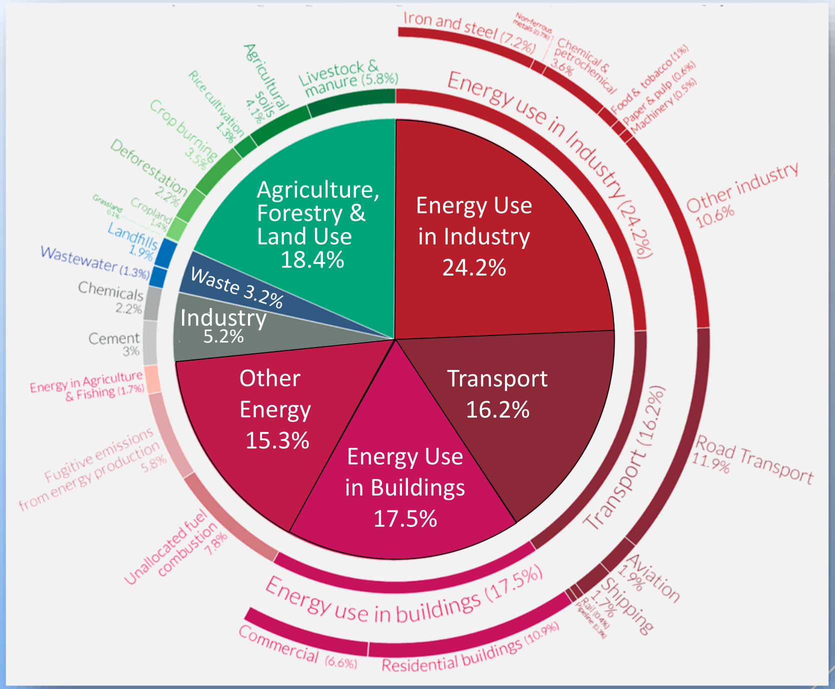
Green **Hydrogen** (H_2)

15-30%

$$FeO + H_2 \rightarrow Fe + H_2O\uparrow$$

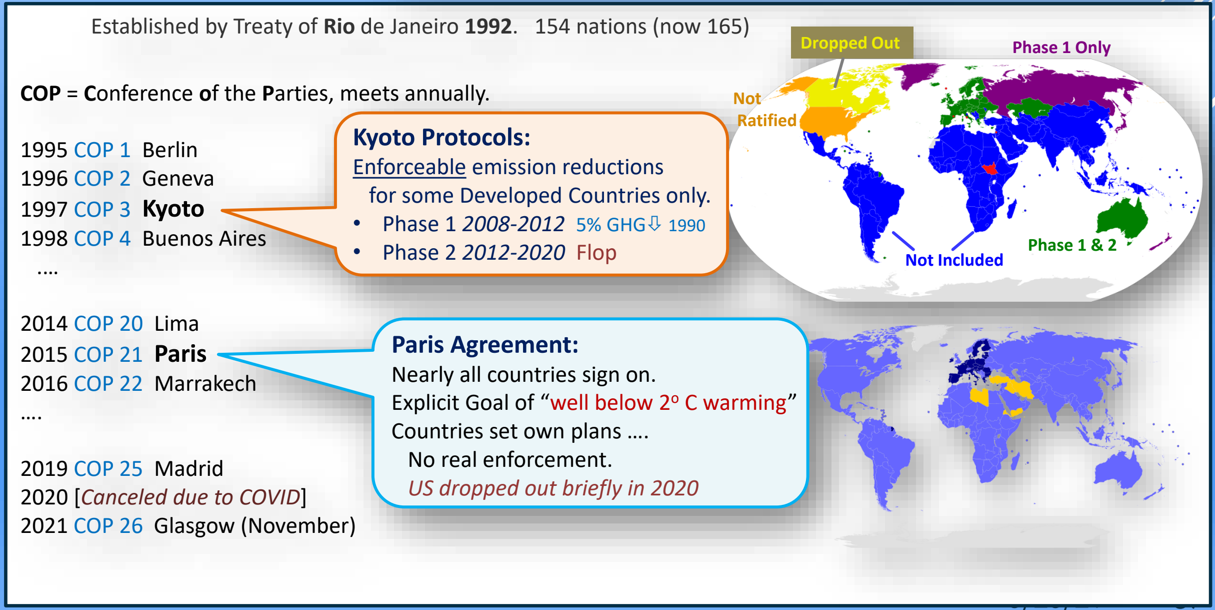
Again, Greatly oversimplified!!

Questions?



Agriculture, Forestry & Land Use 18.4%
Energy Use in Industry 24.2%
Waste 3.2%
Industry 5.2%
Other Energy 15.3%
Transport 16.2%
Energy Use in Buildings 17.5%
Iron and steel (7.2%)
Chemical & petrochemical 3.6%
Food & tobacco (1%)
Paper & pulp (0.6%)
Machinery (0.5%)
Energy use in Industry (24.2%)
Other industry 10.6%
Livestock & manure (5.8%)
Agricultural soils 4.1%
Rice cultivation 1.3%
Crop burning 3.5%
Deforestation 2.2%
Cropland 1.4%
Landfills 1.9%
Wastewater (1.3%)
Chemicals 2.2%
Cement 3%
Energy in Agriculture & Fishing (1.7%)
Fugitive emissions from energy production 5.8%
Unallocated fuel combustion 7.8%
Transport (16.2%)
Road Transport 11.9%
Aviation 1.9%
Shipping 1.7%
Energy use in buildings (17.5%)
Commercial (6.6%)
Residential buildings (10.9%)

Deniers
Soft Deniers
Deflectors [Inactivists]
Scientists & Experts
Doers
Activists
Soft Doomsayers
Doomsayers
Skepticism
Belief
Advocacy (Disinformation/ Cherry Picking)
neutrality
Advocacy (Disinformation/Cherry Picking)
FALSE ALARM
BJORN LOMBORG
THE HEARTLAND INSTITUTE
BREAKTHROUGH INSTITUTE
APOCALYPSE NEVER
MICHAEL SHELLENBERGER
CLIMATE CHANGE
BILL GATES
HOW TO AVOID A CLIMATE DISASTER
an inconvenient truth
AL GORE
The Uninhabitable Earth
David Wallace-Wells
WE'RE DOOMED. NOW WHAT?
ROY SCRANTON
The Physics of Climate Change
Lawrence M. Krauss
Losing Earth
Nathaniel Rich
The New Climate War
The Hockey Stick and the Climate Wars
Michael E. Mann
PLANET OF THE HUMANS
NATIONAL REVIEW

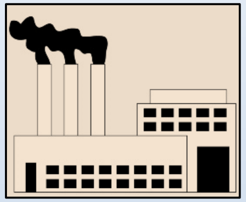


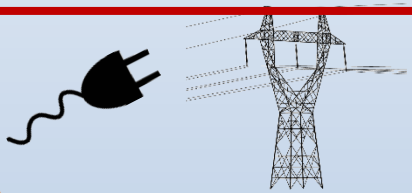
Established by Treaty of Rio de Janeiro 1992. 154 nations (now 165)
COP = Conference of the Parties, meets annually.
1995 COP 1 Berlin
1996 COP 2 Geneva
1997 COP 3 Kyoto
1998 COP 4 Buenos Aires
....
2014 COP 20 Lima
2015 COP 21 Paris
2016 COP 22 Marrakech
....
2019 COP 25 Madrid
2020 [Canceled due to COVID]
2021 COP 26 Glasgow (November)
Kyoto Protocols:
Enforceable emission reductions
for some Developed Countries only.
Phase 1 2008-2012 5% GHG⇩ 1990
Phase 2 2012-2020 Flop
Dropped Out
Phase 1 Only
Not Ratified
Not Included
Phase 1 & 2
Paris Agreement:
Nearly all countries sign on.
Explicit Goal of "well below 2° C warming"
Countries set own plans ....
No real enforcement.
US dropped out briefly in 2020

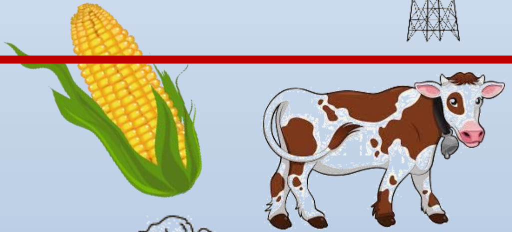
Green Electrification of Energy is a Promising Approach

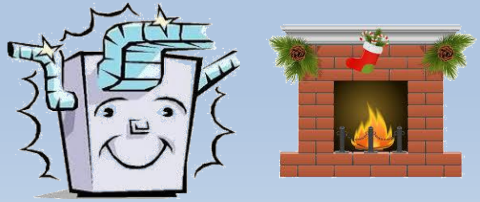
Electric sector will grow to help provide solutions in other sectors!

• Making Things	31%	acturing
• Plugging In	27% ↑	Electricity
• Growing Things	19%	Agriculture
• Getting Around	16%	Transportation
• Keeping Warm	7%	Space Heating







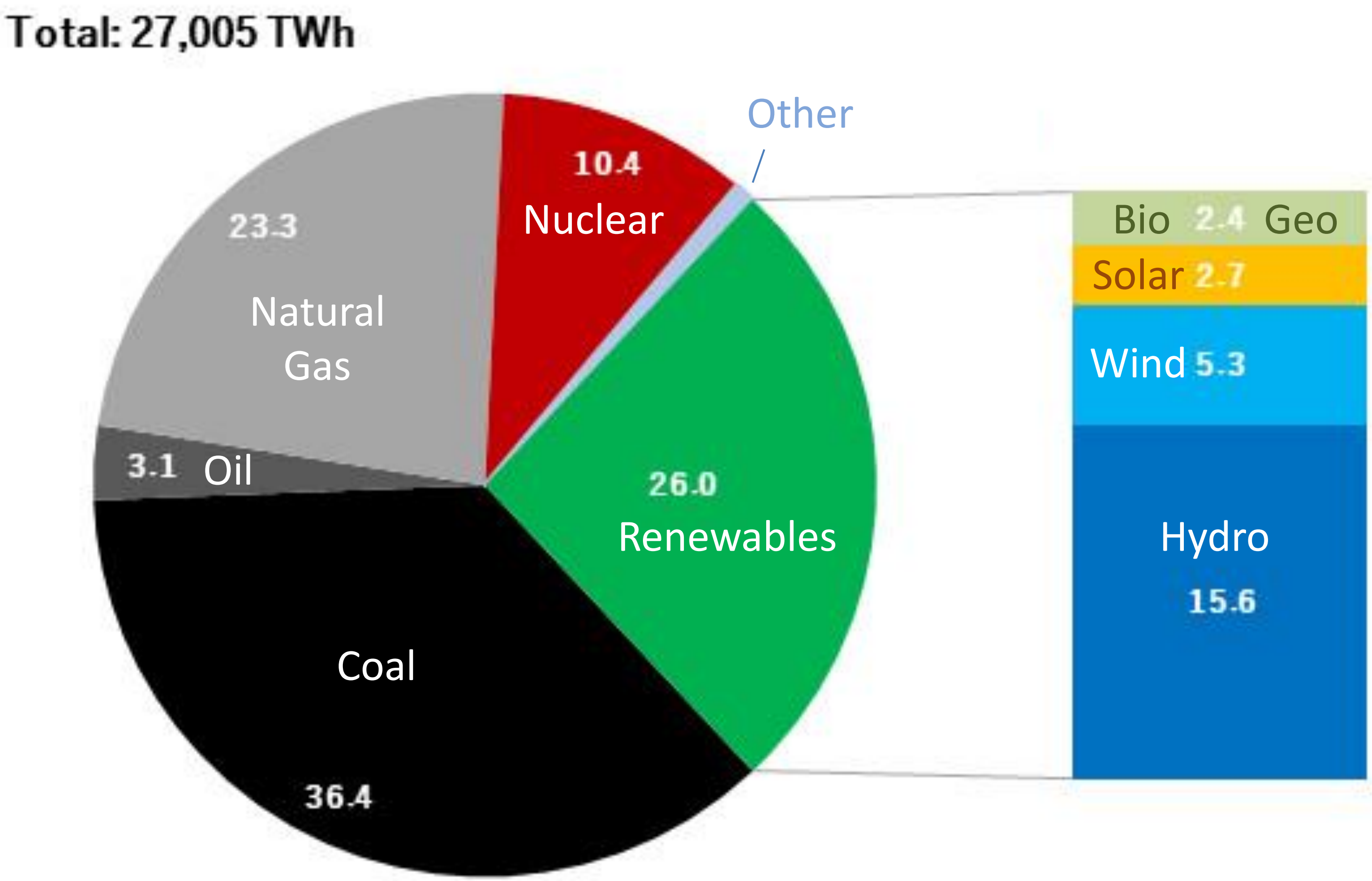


World Electricity Generation 2019

CO_2 *
- Coal
- Oil
- Gas

No GH Gases*
- Nuclear
- Hydroelectric
- Wind
- Solar
- Boutique
  - Geothermal
  - Biomass
  - Tidal/Wave

** During operation*



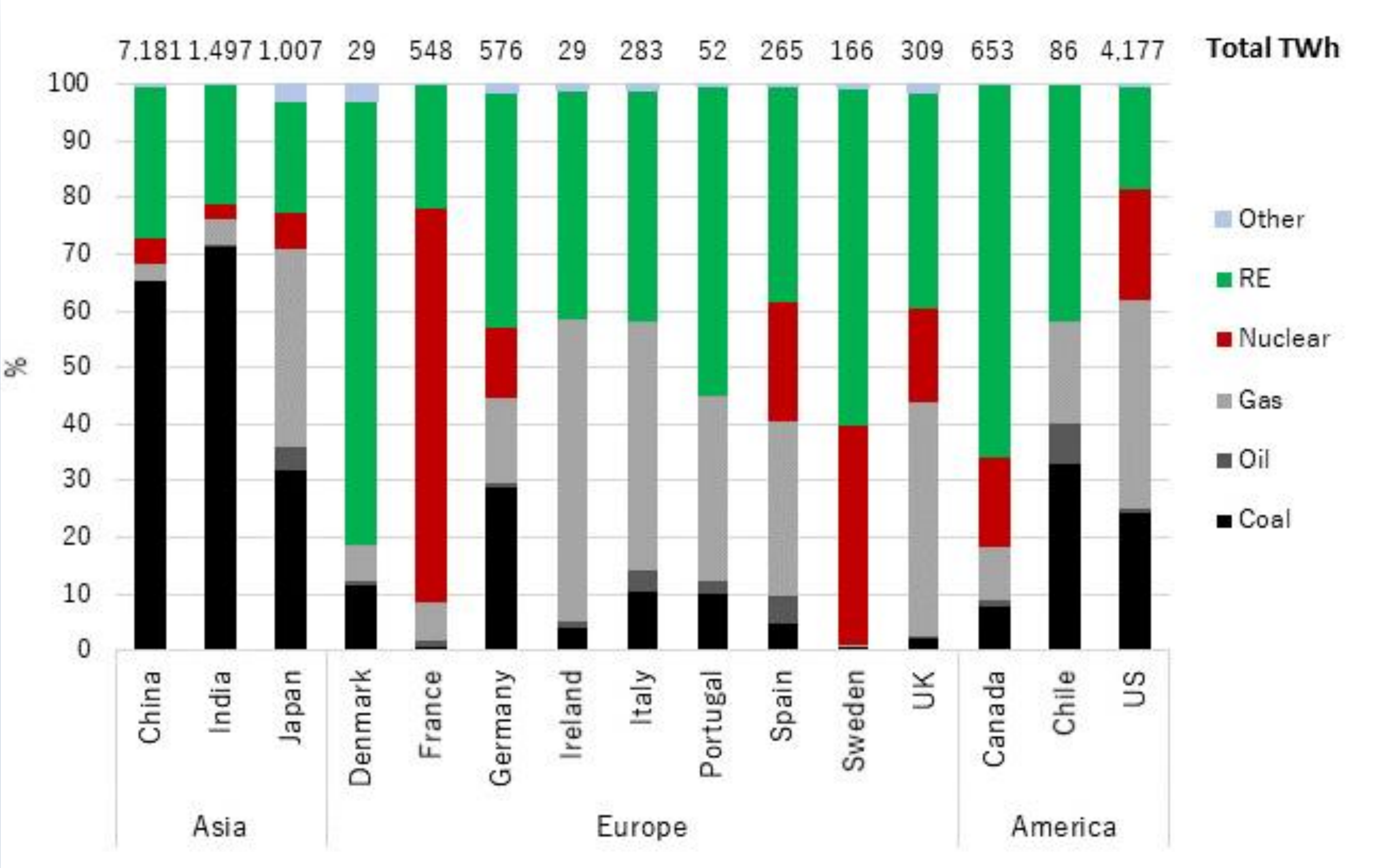
BP, Statistical Review of World Energy 2020

World Electricity Generation 2019

CO_2 *
- Coal
- Oil
- Gas

No GH Gases*
- Nuclear
- Hydroelectric
- Wind
- Solar
- Boutique
  - Geothermal
  - Biomass
  - Tidal/Wave

Wide variety of generation mixes by country.



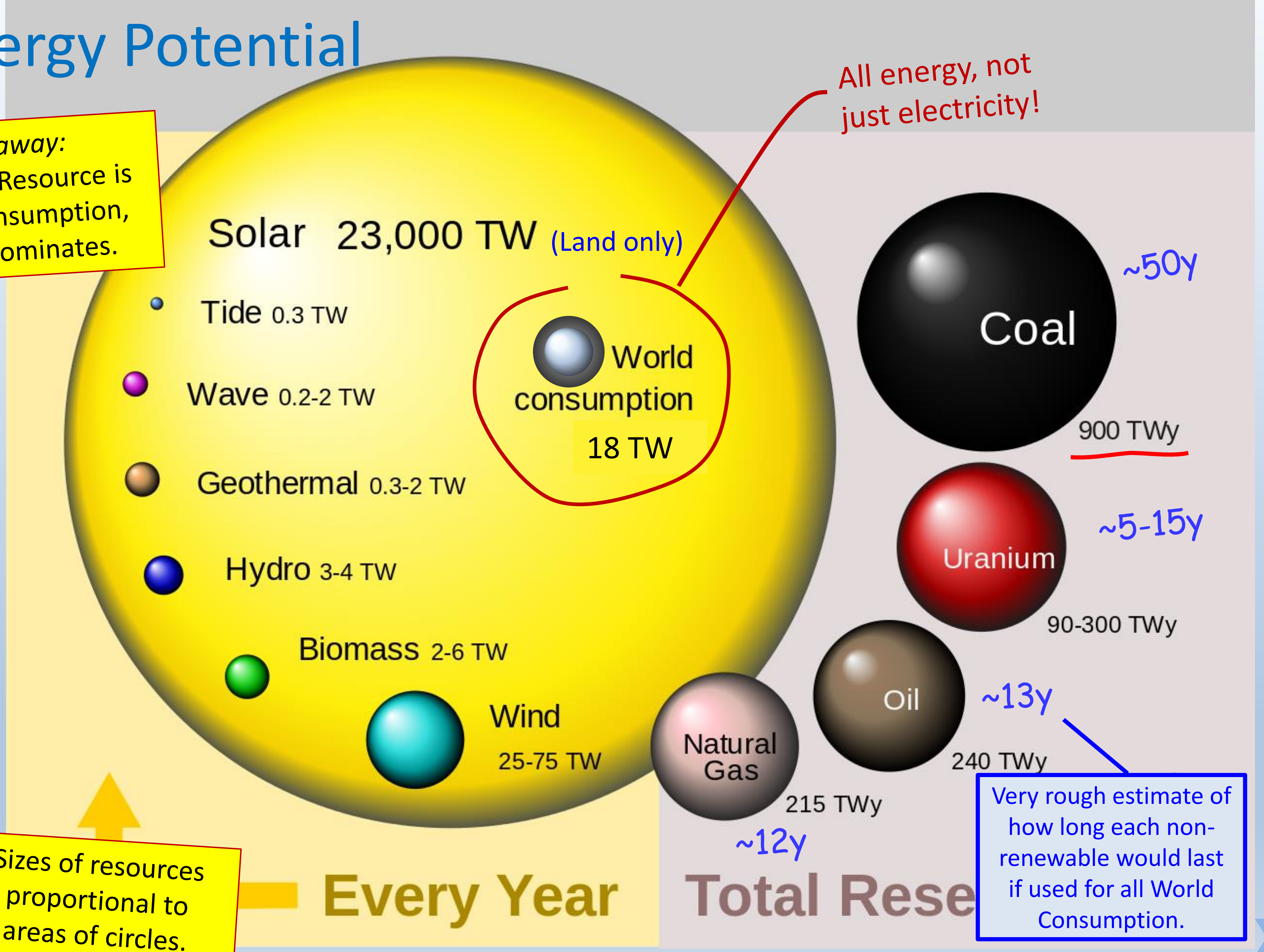
BP, Statistical Review of World Energy 2020

Global Energy Potential

Takeaway:
The Solar Resource is 1000x consumption, totally dominates.

Non-Renewable
- Coal
- Oil
- Gas
- Nuclear

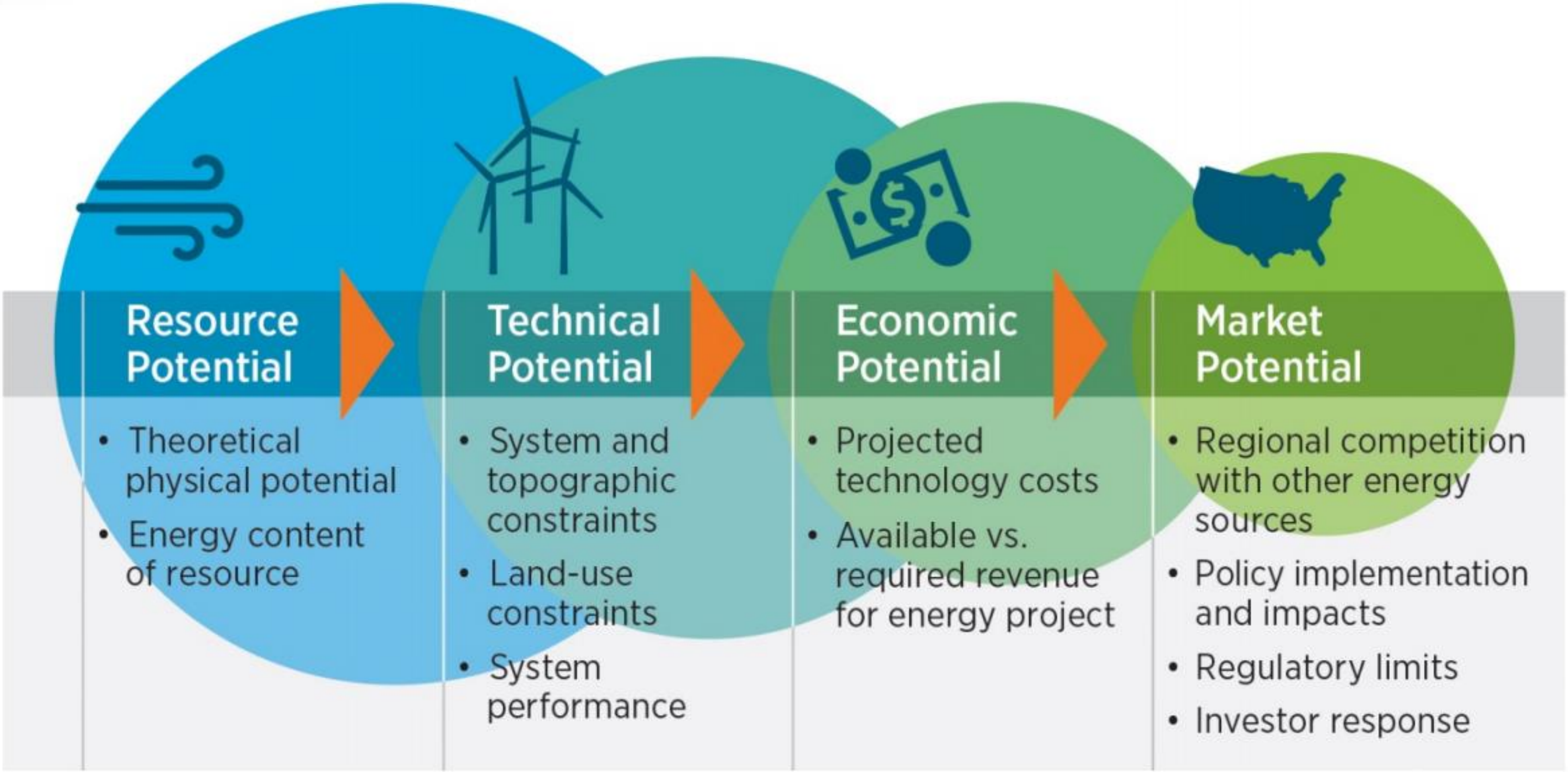
Renewable
- Hydroelectric
- Wind
- Solar
- Boutique
  - Geothermal
  - Biomass
  - Tidal/Wave



Sizes of resources proportional to areas of circles.

Rfassbind Wikimedia 2014

Hurdles to Successful Decarbonization

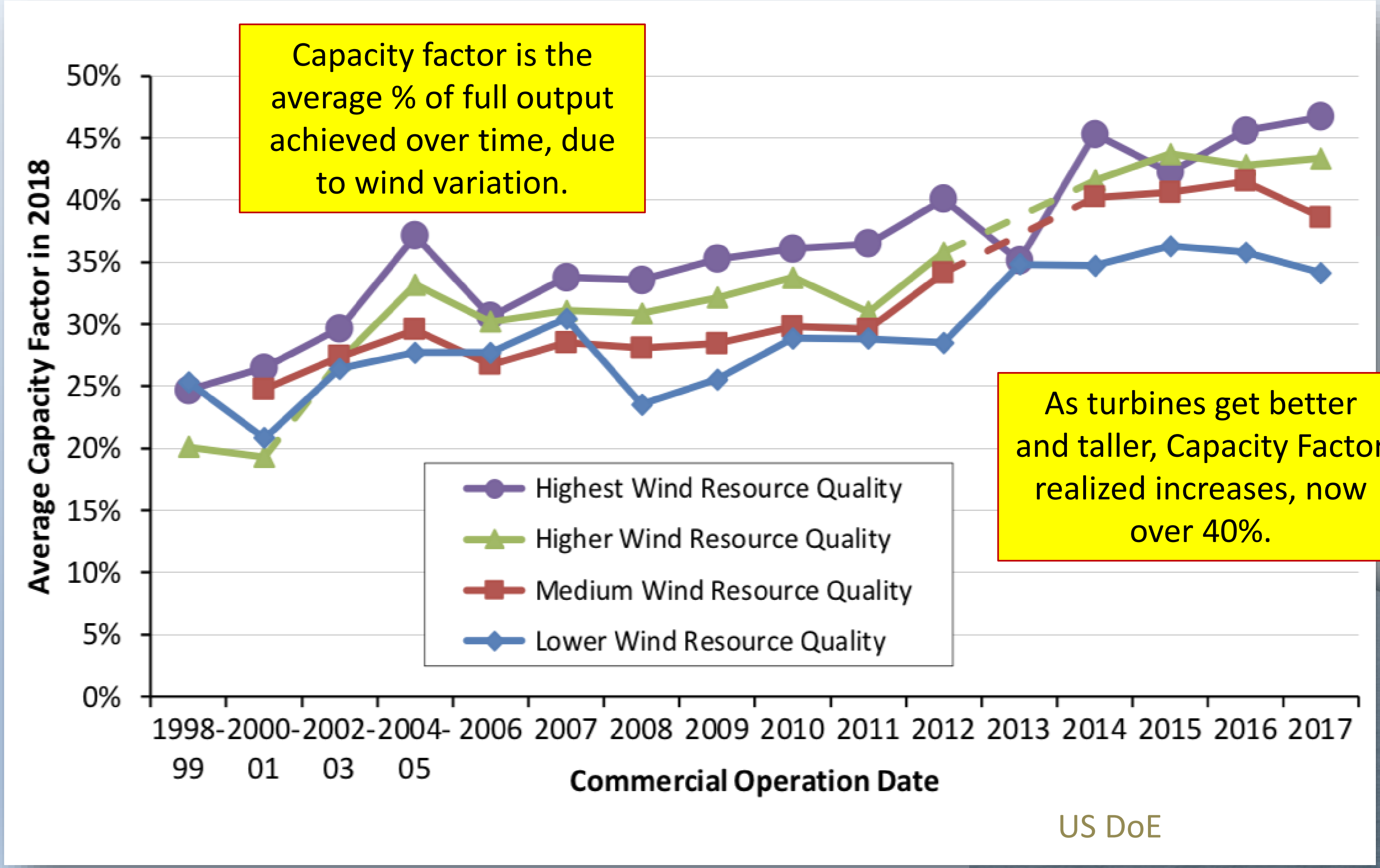


NREL Report: *Estimating Renewable Energy Economic Potential…* Brown et al. (2016)

Wind Turbines: Ashore and Offshore

Now ~ 700 GigaWatt
Installed Capacity
(5% Offshore)

Wind Turbines: Capacity Factor Increasing



15 Megawatt Turbines coming soon

Solar Comes in Two Flavors

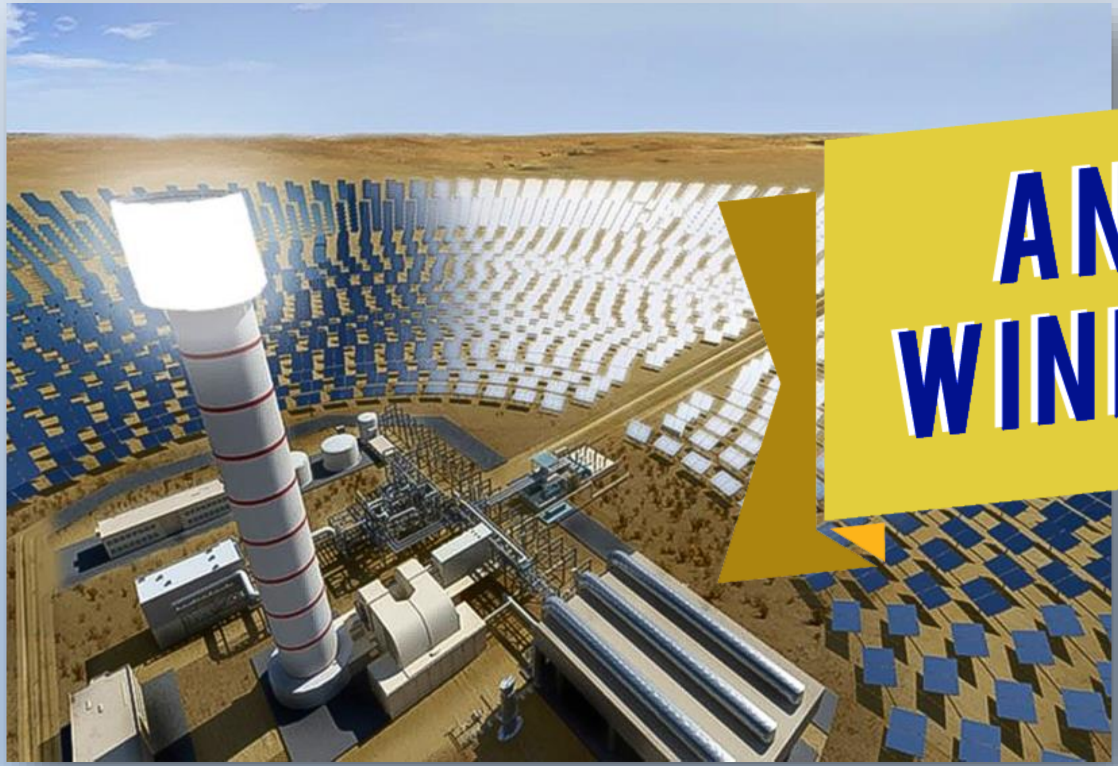
Concentrated Solar Power – **CSP**
(Thermal)

PhotoVoltaic Solar Power **PV**
(Photons $\rightarrow$ Electrons)

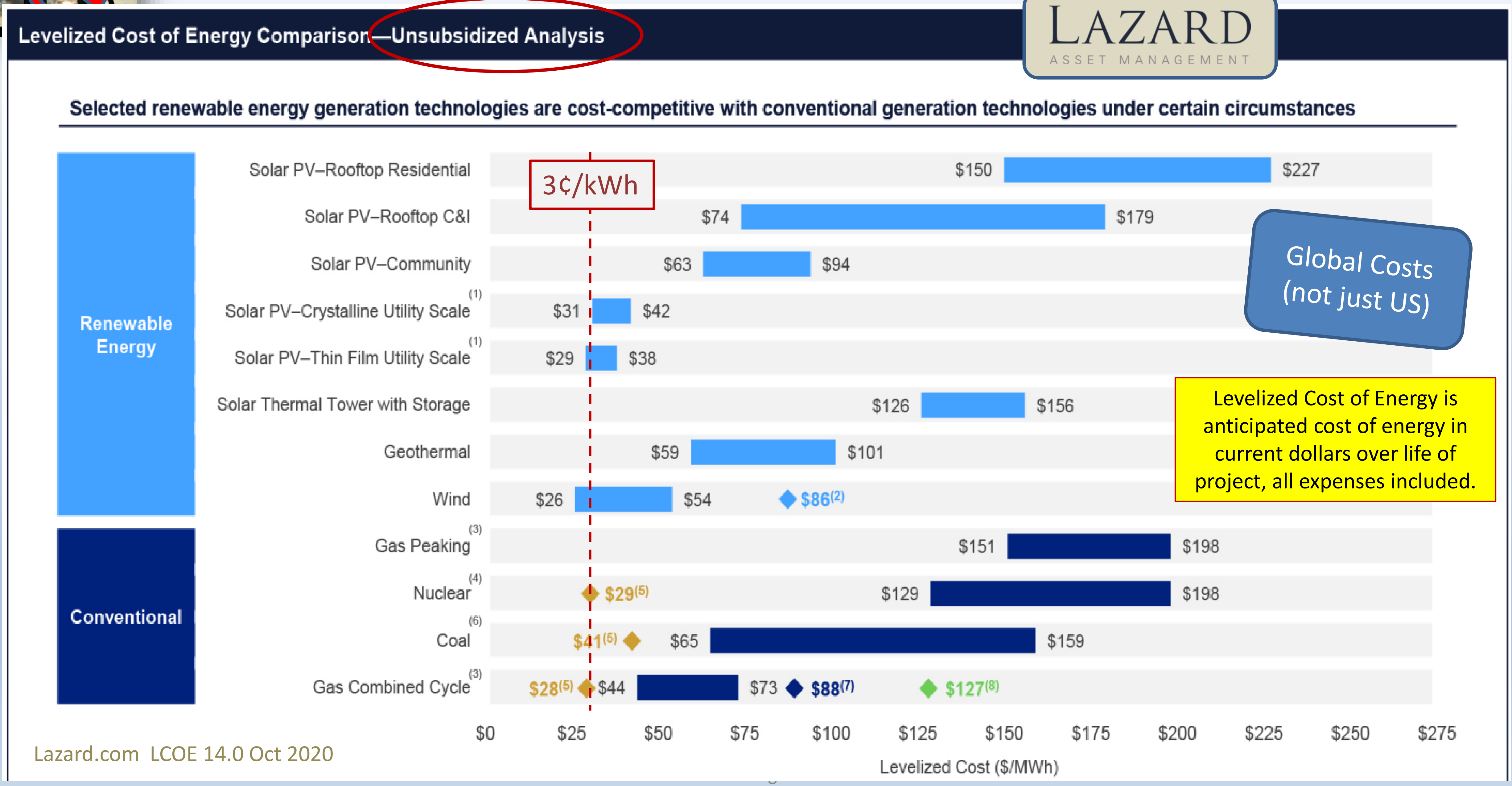
Solar Comes in Two Flavors

Concentrated Solar Power – **CSP**
(Thermal)

PhotoVoltaic Solar Power **PV**
(Photons → Electrons)



Levelized Costs of New Generation Facilities 2020

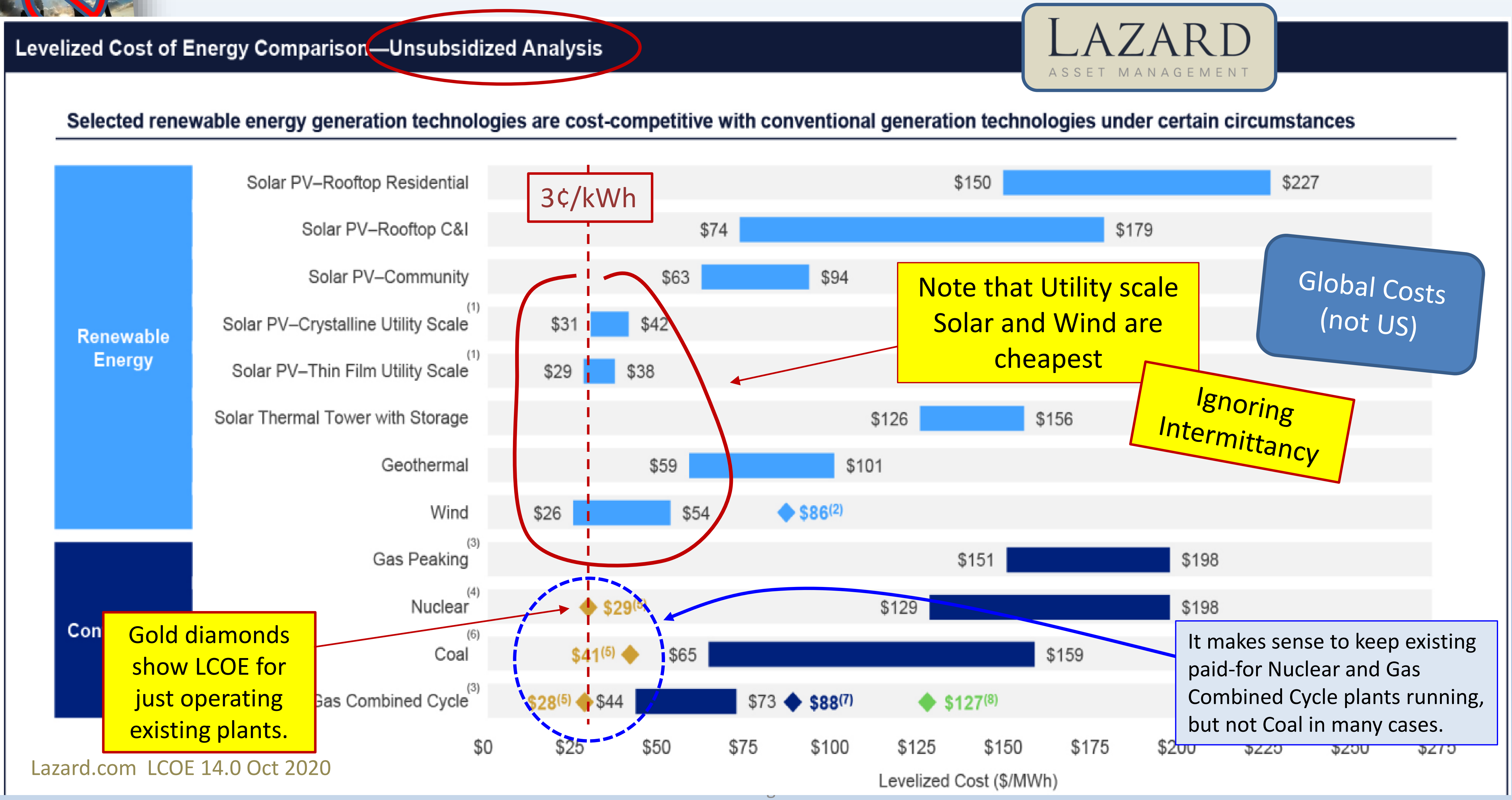


Global Costs (not just US)

Levelized Cost of Energy is anticipated cost of energy in current dollars over life of project, all expenses included.

Lazard.com LCOE 14.0 Oct 2020

Levelized Costs of New Generation Facilities 2020



Lazard.com LCOE 14.0 Oct 2020

Levelized Cost History of Renewables 2009-2020

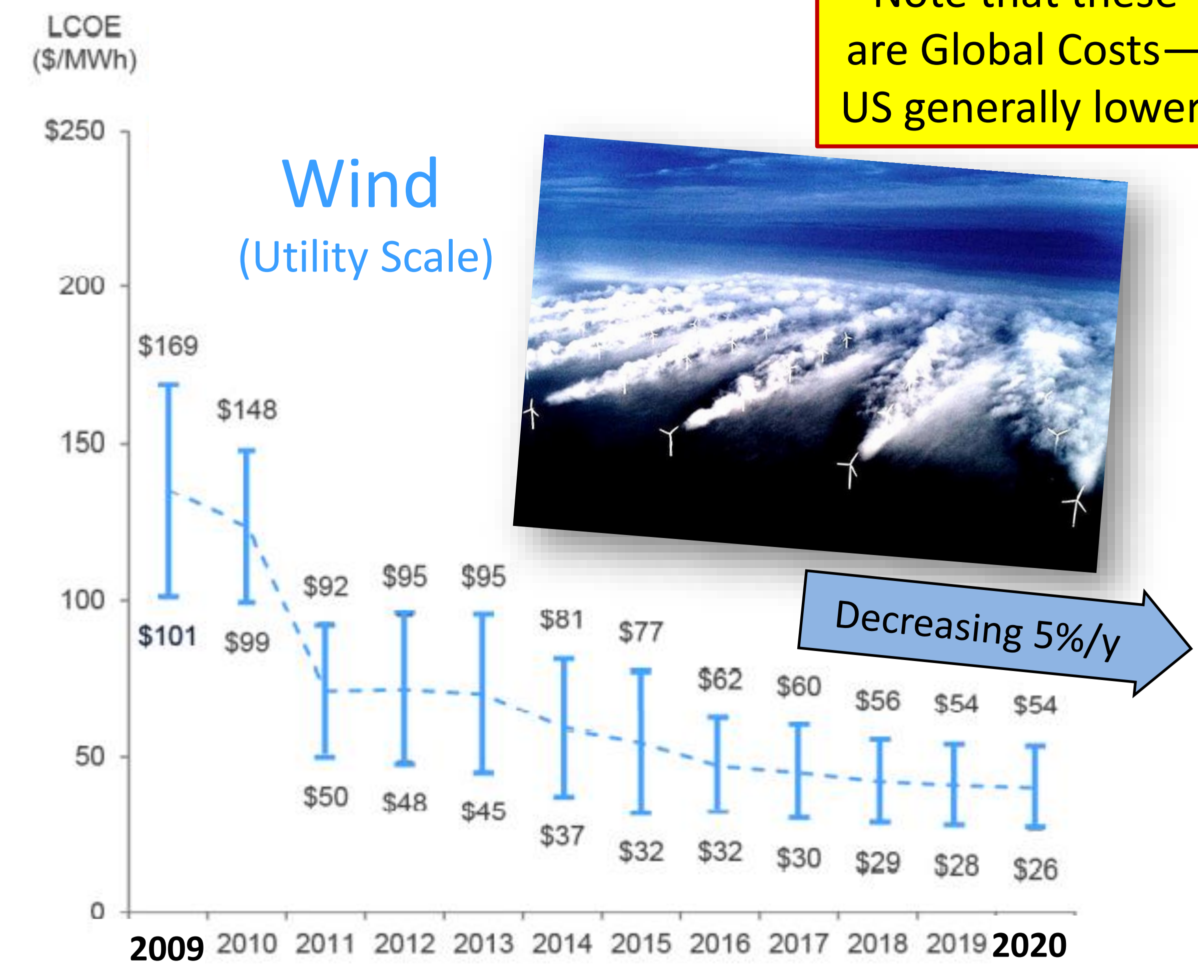
Historical Renewable Energy LCOE Declines

Global Costs
(US Lower)

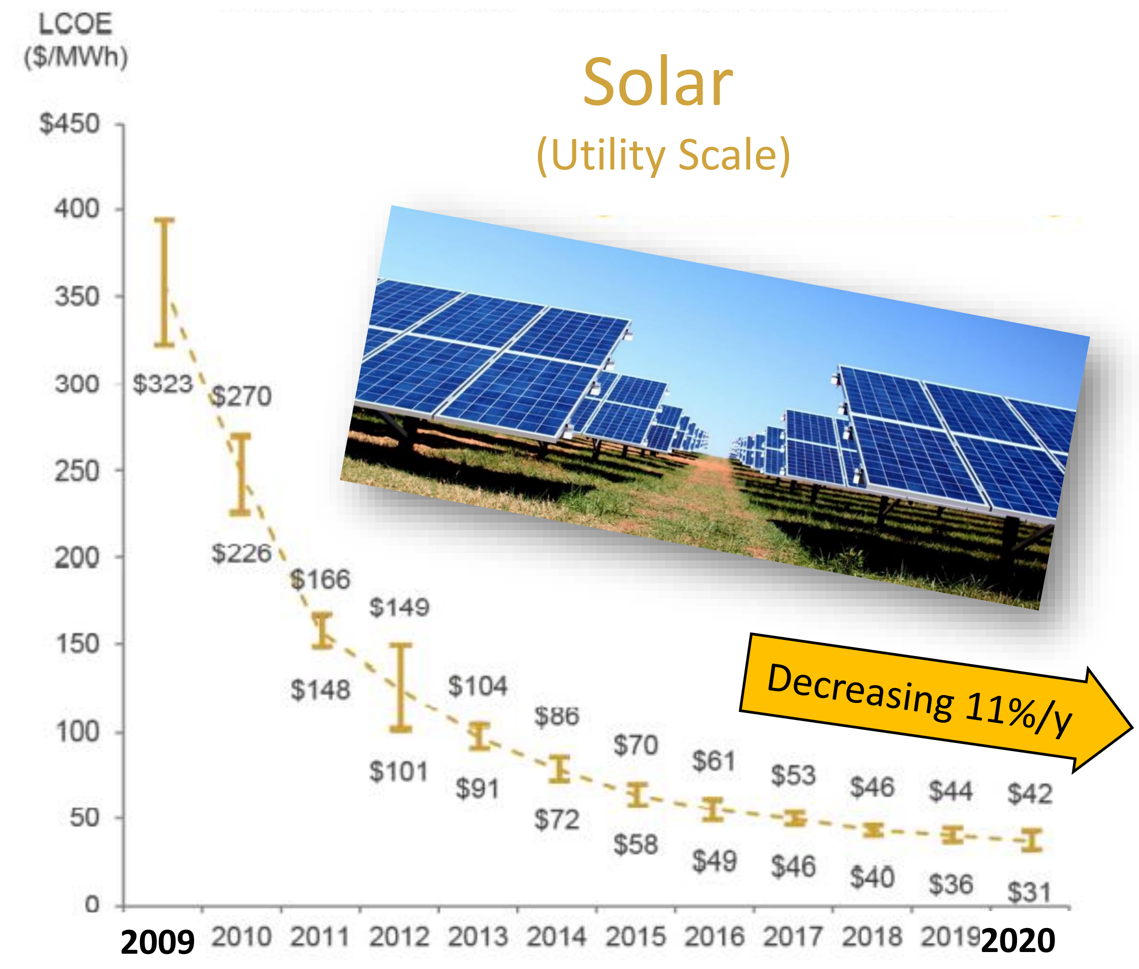
LAZARD
ASSET MANAGEMENT

Note that these are Global Costs—US generally lower.

Unsubsidized Wind LCOE

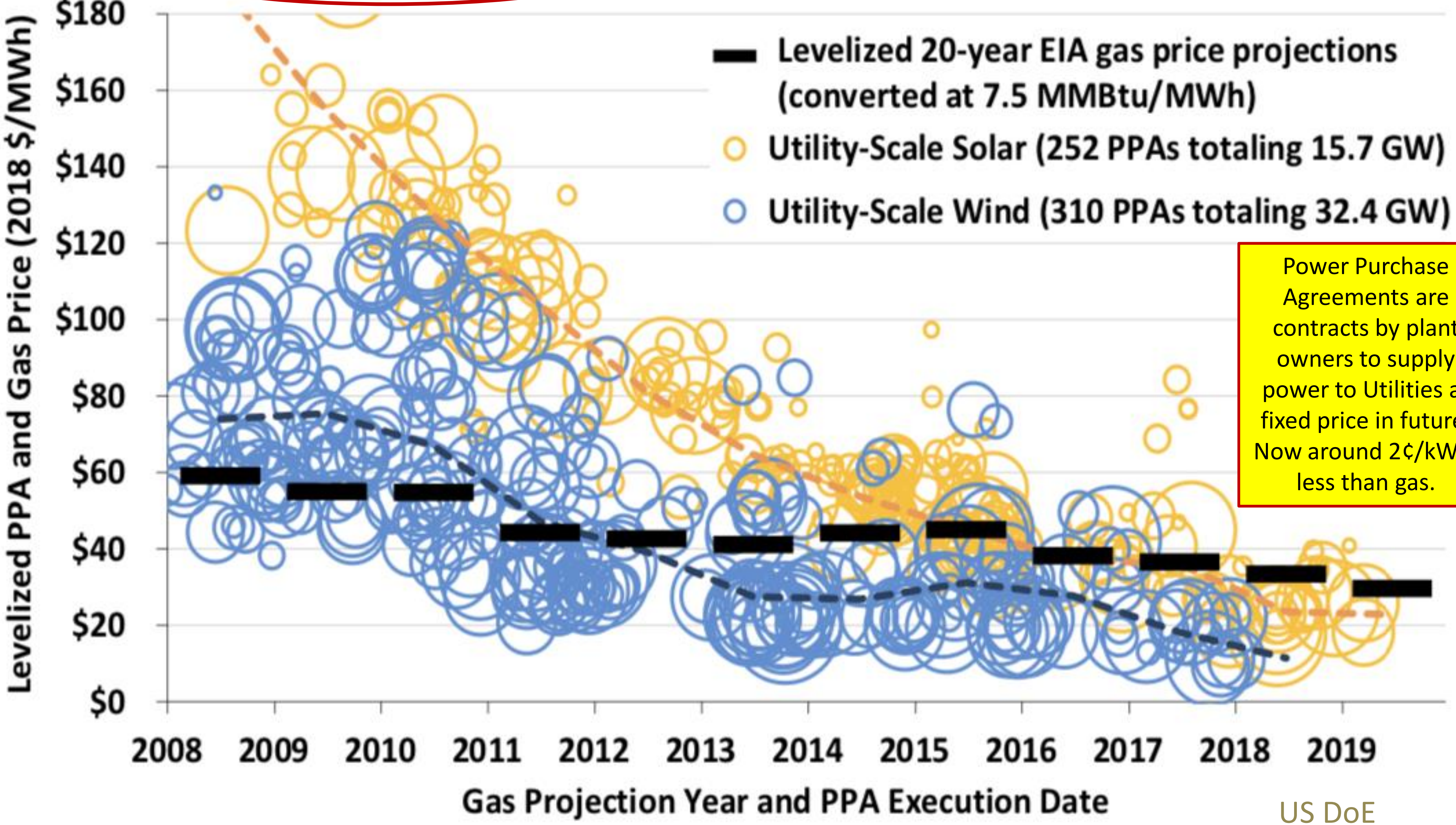


Unsubsidized Solar PV LCOE



Lazard.com LCOE 14.0 Oct 2020

Power Purchase Agreement Prices for Wind and Solar as Compared to Gas Costs



Power Purchase Agreements are contracts by plant owners to supply power to Utilities at fixed price in future. Now around 2¢/kWh, less than gas.

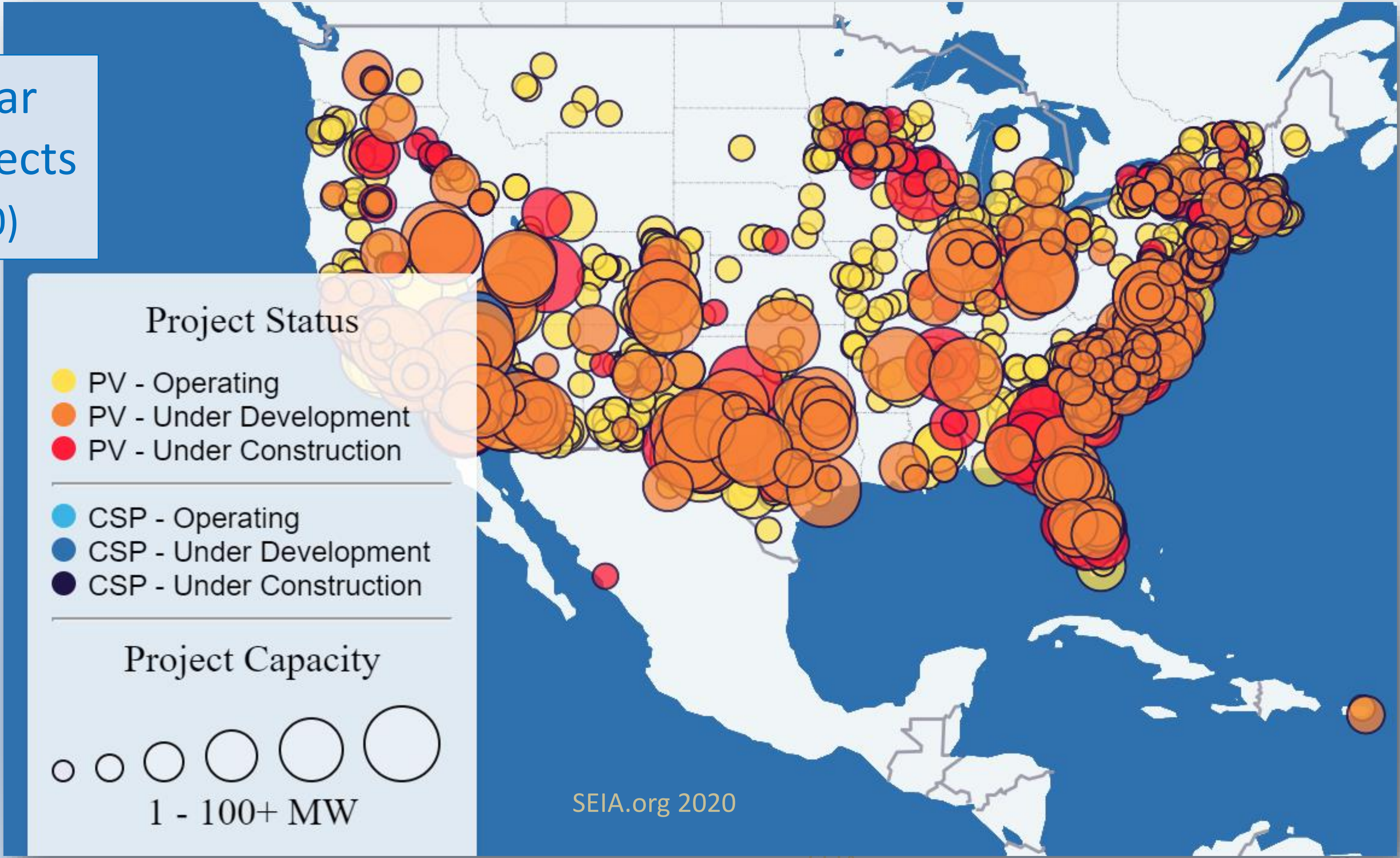
US DoE

So What is the Green Premium for Wind and Solar Now?

- Typically, close to zero
- Already *Negative* in most cases*
  - ➢ That trend will continue IMHO
- Main caveat is intermittency

* "…solar PV is consistently cheaper than new coal- or gas fired power plants in most countries, and solar projects now offer some of the lowest cost electricity ever seen."
World Energy Outlook 2020, International Energy Agency
(Emphasis added)

Major Solar Power Projects (mid 2020)



A Short Diversion

Op Ed

UI Solar Farms 1 and 2

- > 48,000 Modules (310-400 w each)
- ~ 70 acres
- ~18 MW DC nominal

Annual Production (Both Farms)
~ 20 million kWh [Predicted]

6% of UI Consumption!

http://icap.sustainability.illinois.edu/project/solar-farm

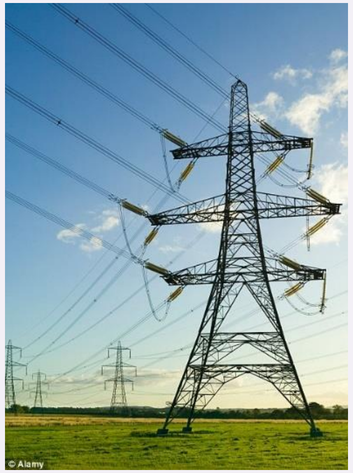
Sunlight on Champaign County

Noonish on a nice June day...

$P_{SOLAR} \approx 2.7$ Terawatts

(photons)

Global Electricity Consumption



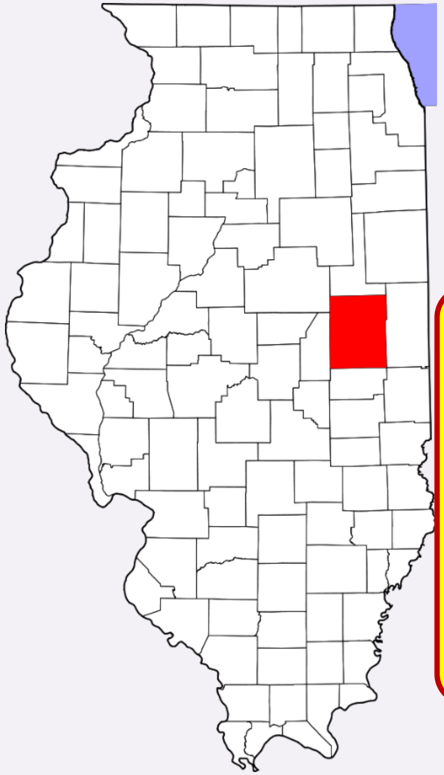
≈ Two
1 Megaton
H-Bombs
per hour

$P_{WORLD} \approx 2.4$ Terawatts

(electric, 2019)

Op Ed

Sunlight on Champaign County



Noonish on a nice

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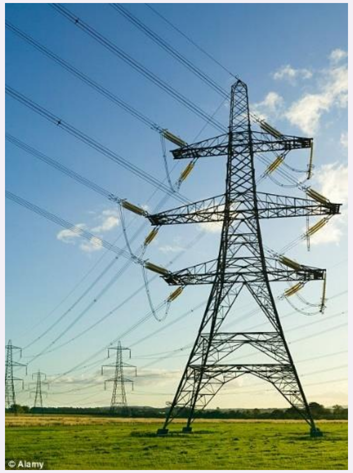
Global Electricity Consumption

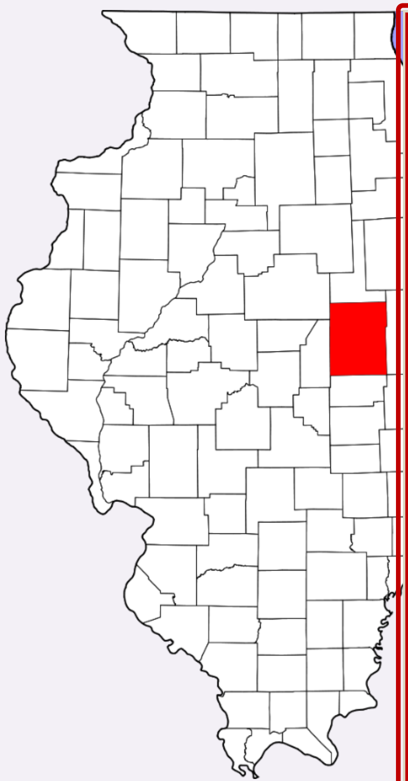


$P_{WORLD} \approx 2.4$ Terawatts
(electric, 2019)

So *could* we run the world on Champaign County Sunlight?

Op Ed

Sunlight on Champaign County



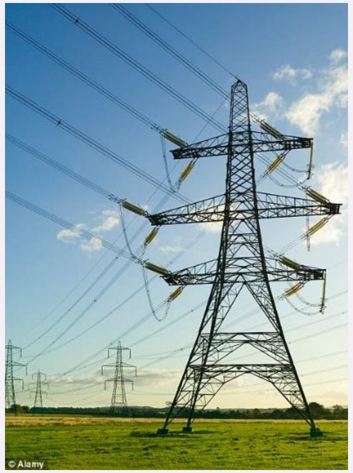
Issues:

- Cell Efficiency ≈ 20%
- Sun Availability ≈ 20%
- Long Distance Transmission?
- High Capacity Storage?
- Overall, down ~50x
  - i.e., **all the Illinois Farmland**

$P_{SOLAR} \approx 2.7$ Terawatts

(photons)

Global Electricity Consumption



The point is, that is not much land use to power entire world…

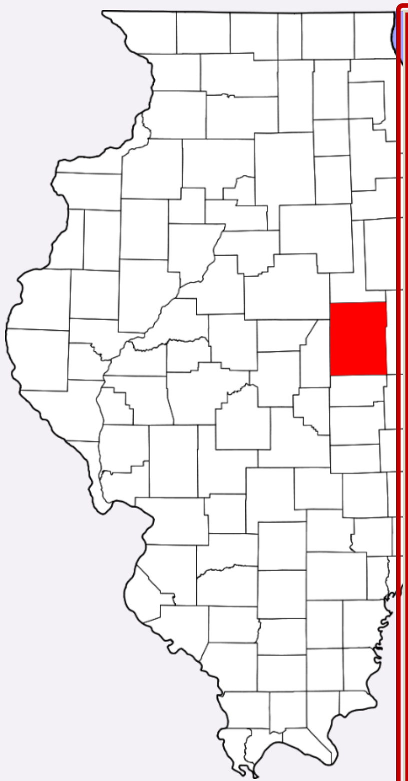
$P_{WORLD} \approx 2.4$ Terawatts

(electric, 2019)

Op Ed

Sunlight on Champaign County

Global Electricity Consumption



Issues:

- Cell Efficiency ≈ 20%
- Sun Availability ≈ 20%
- Long Distance Transmis
- High Capacity Storage?
- Overall, down ~50x
  - i.e., **all the Illinois Farm**

United States only:
18 % of World Consumption

Elko County, Nevada

to power US

$P_{SOLAR} \approx 2.7$ Terawatts
(photons)

$P_{WORLD} \approx 2.4$ Terawatts
(electric, 2019)

Op Ed

Could We Turn Farmland into Solar Farms?

Revenue Per Acre for Central Illinois

Operating costs:
~ 1 worker per
100 acres.

$648 Annual Gross Revenue per Acre

Net, less operating costs:
$218/acre

Fair Rental

Schnitkey, G. "Continued Downward Pressure on 2017 Cash Rent." *farmdoc daily* (6):155, Department of Agricultural and Consumer Economics, University of Illinois at Urbana-Champaign, August 16, 2016.

~$15,000*

Est. Wholesale Annual Electricity Revenue per Acre

So if you owned land, who do you think could pay a higher rent?

UI Solar Farm #1:
* ~7.5 million kWh for
~15 acres @ ~ **3¢**/kWh

Could We Turn Farmland into Solar Farms?

Revenue Per Acre for Central Illinois

Op Ed

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~$15,000*

Est. Wholesale Annual Electricity Revenue per Acre

Operating costs:
~ 1 worker per
100 acres.

- Very Large Capital Cost for Solar
- *But*
  Land Rental cost would be insignificant

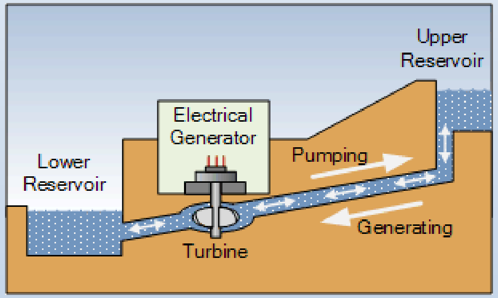
UI Solar Farm #1:
* ~7.5 million kWh for
~15 acres @ ~ **3¢**/kWh

Intermittency of Solar and Wind

Appropriate Mix of Generation Modes

Short to Medium Term Storage

Pumped Hydro (>90%)



Thermal Storage

Long Distance Transmission Grids

Very High Voltage DC Transmission Lines can be continental in scale with very low loss.

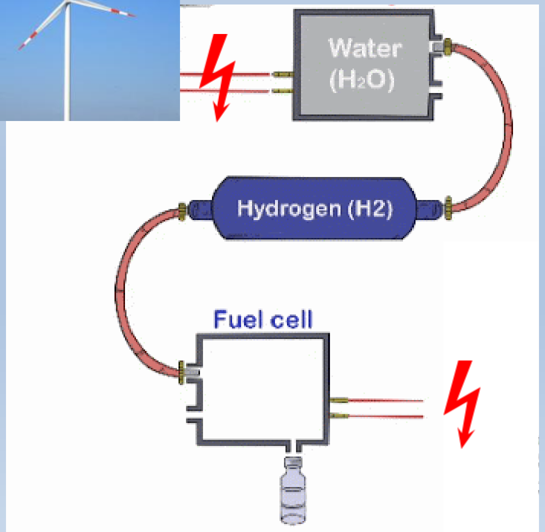
China: 3,324 km, 1.1 MV DC

Long Term Storage via Electrofuels

Green Hydrogen H_2 from Water:

$$2\,H_2O + e \rightarrow 2\,H_2 + O_2$$

Electrolysis



Intermittency of Solar and Wind

Appr

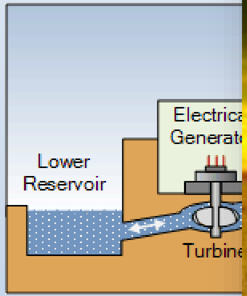
Gene

Load Shifting/Load Management:

- Turning things on/off smartly
  - EV car charging at best times
  - Hot water heating
- Home Battery packs
  - Avoid outages
  - Store cheap power for use when price spikes

Short to Medium Term Storage

Pumped H



Thermal Storage

ies

Long Distanc

Transmission G

Very High Voltage D
Transmission Lines
can be continental i
scale with very low lo

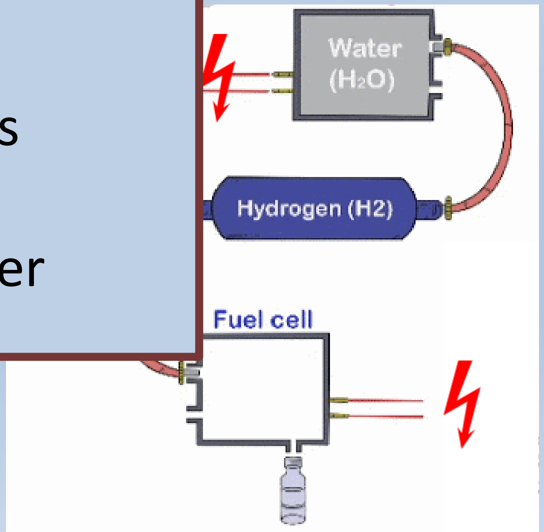
China: 3,324 km, 1.1 MV DC

Making Hay While the Sun Shines

- Making Green Hydrogen or other Electro-Fuels
- Smelting Aluminum
- Desalinization of ocean water

$2 H_2O + e \rightarrow 2 H_2 + O_2$

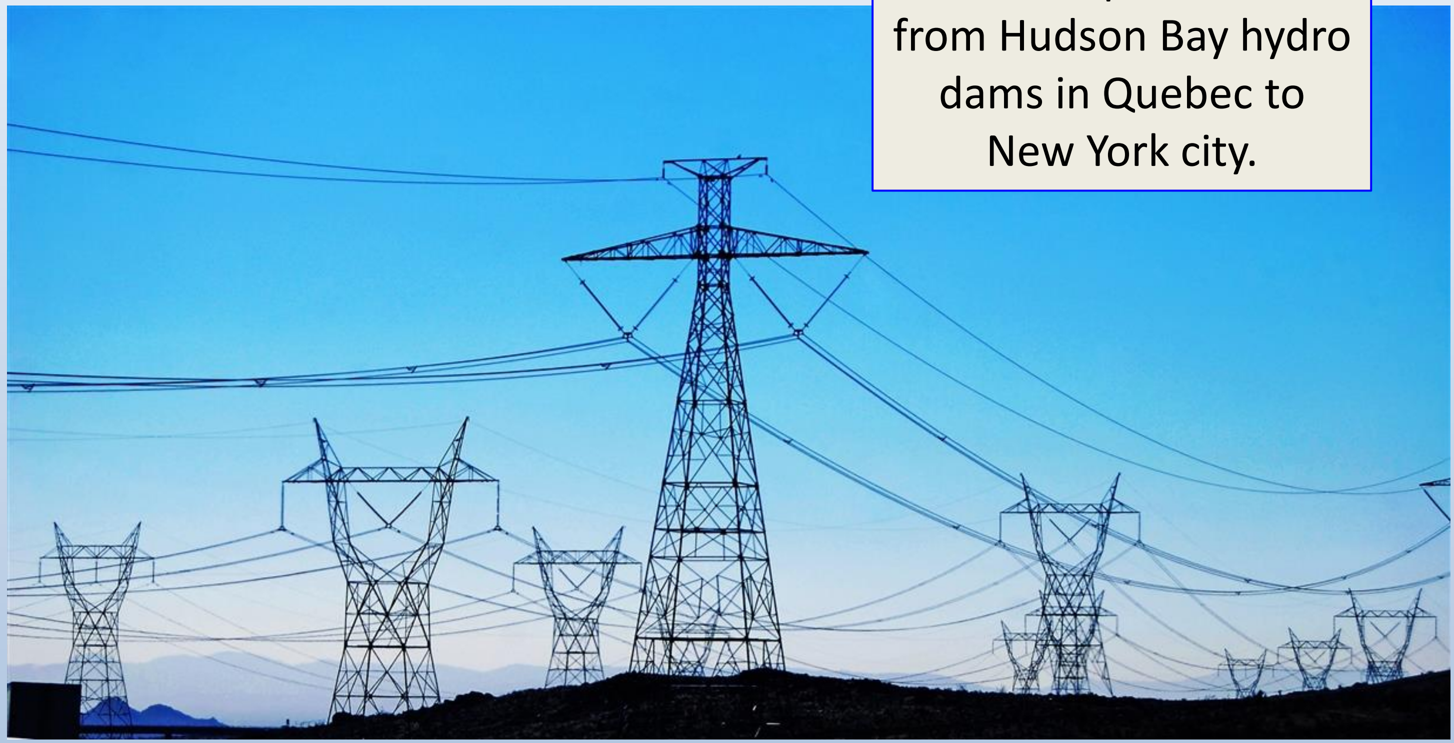
Electrolysis



Long Distance Electric Transmission

- High Voltage DC Lines
  - < 3% loss per 1000 km
  - Much lower than AC
  - 2000 mile DC line in operation in China

    (ABB, 12 GW, 1100 kV)
- No practical limits to continental scale transmission



An example: HVDC from Hudson Bay hydro dams in Quebec to New York city.

There are many HVDC power lines in the world already. Cheaper per mile (fewer wires, etc.), but need expensive end-terminals AC-DC, so best for long distance.

Australia-ASEAN Power Link

Proposed 2300 mile underwater HVDC transmission line from Australia to Singapore

Australia-ASEAN Power Link

Li Ion Battery

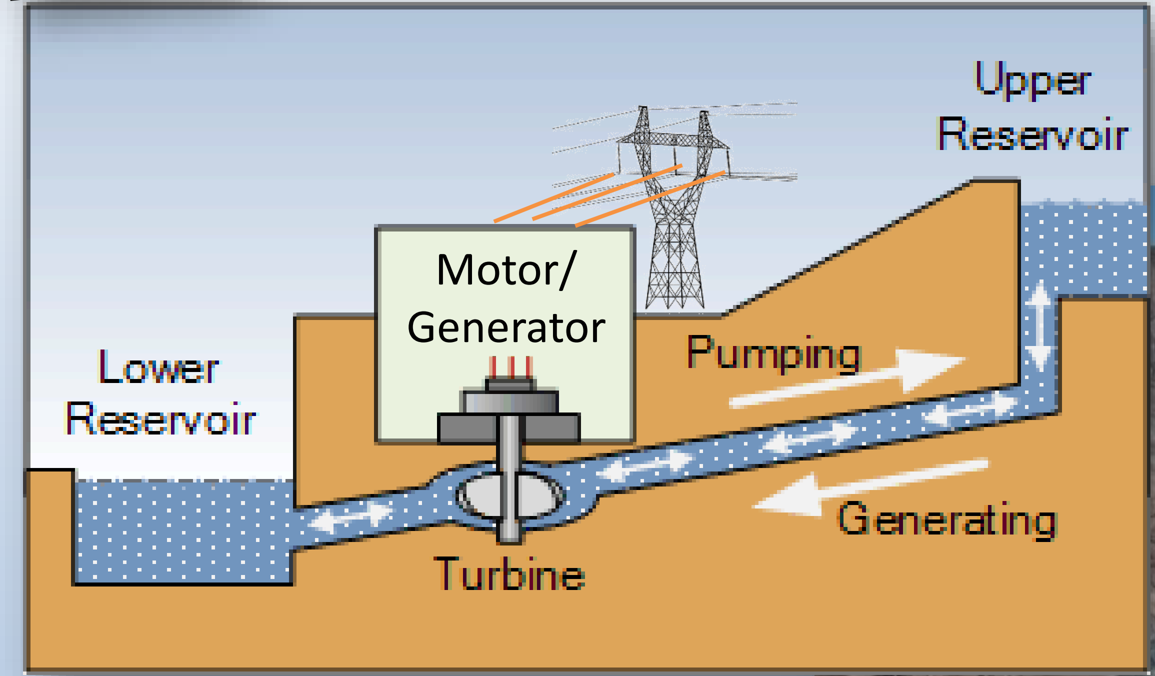
3 GW
~ 20% of Power Requirement

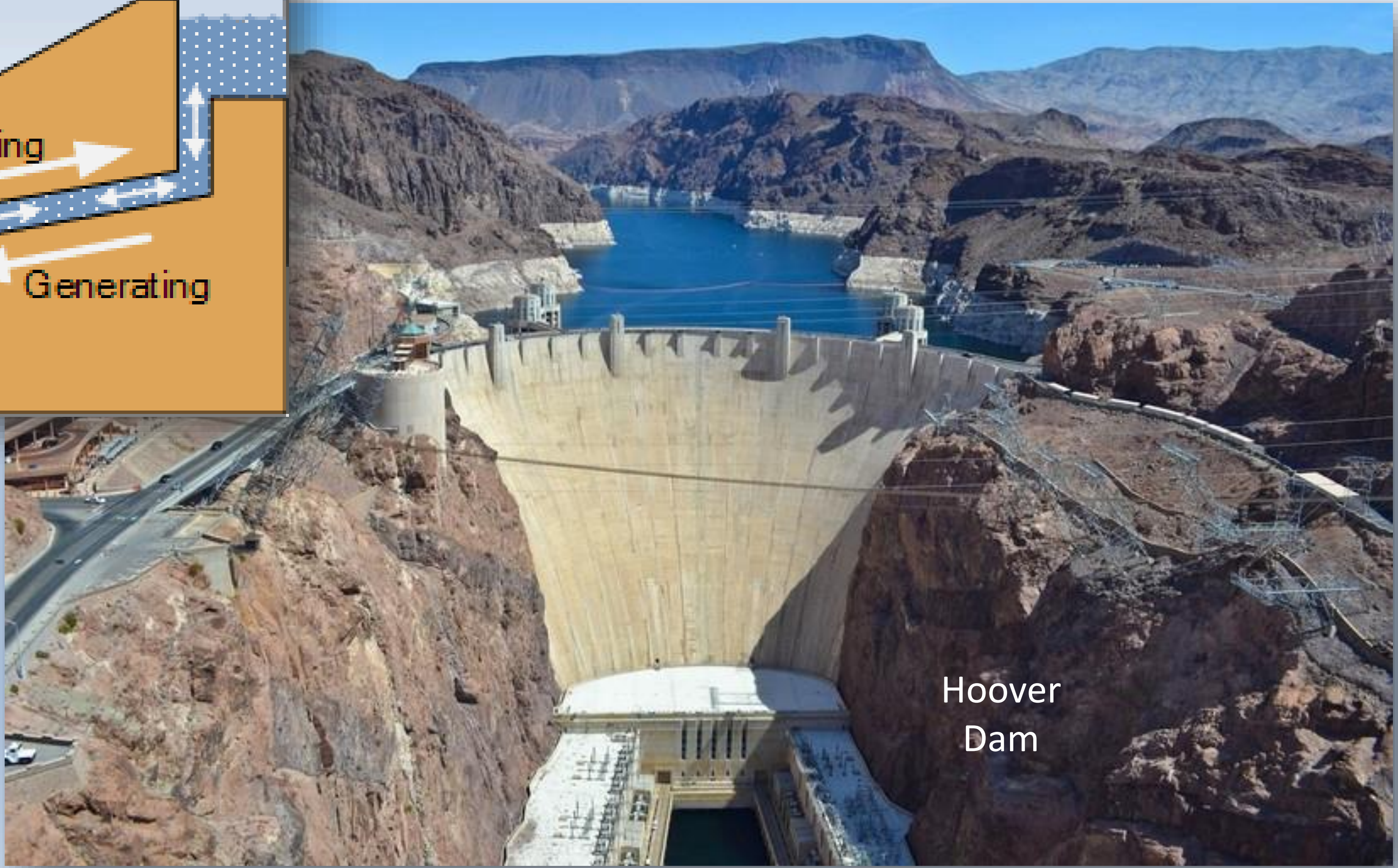
14 GW Solar Farm
+ Li Ion Battery

If Approved, online 2027

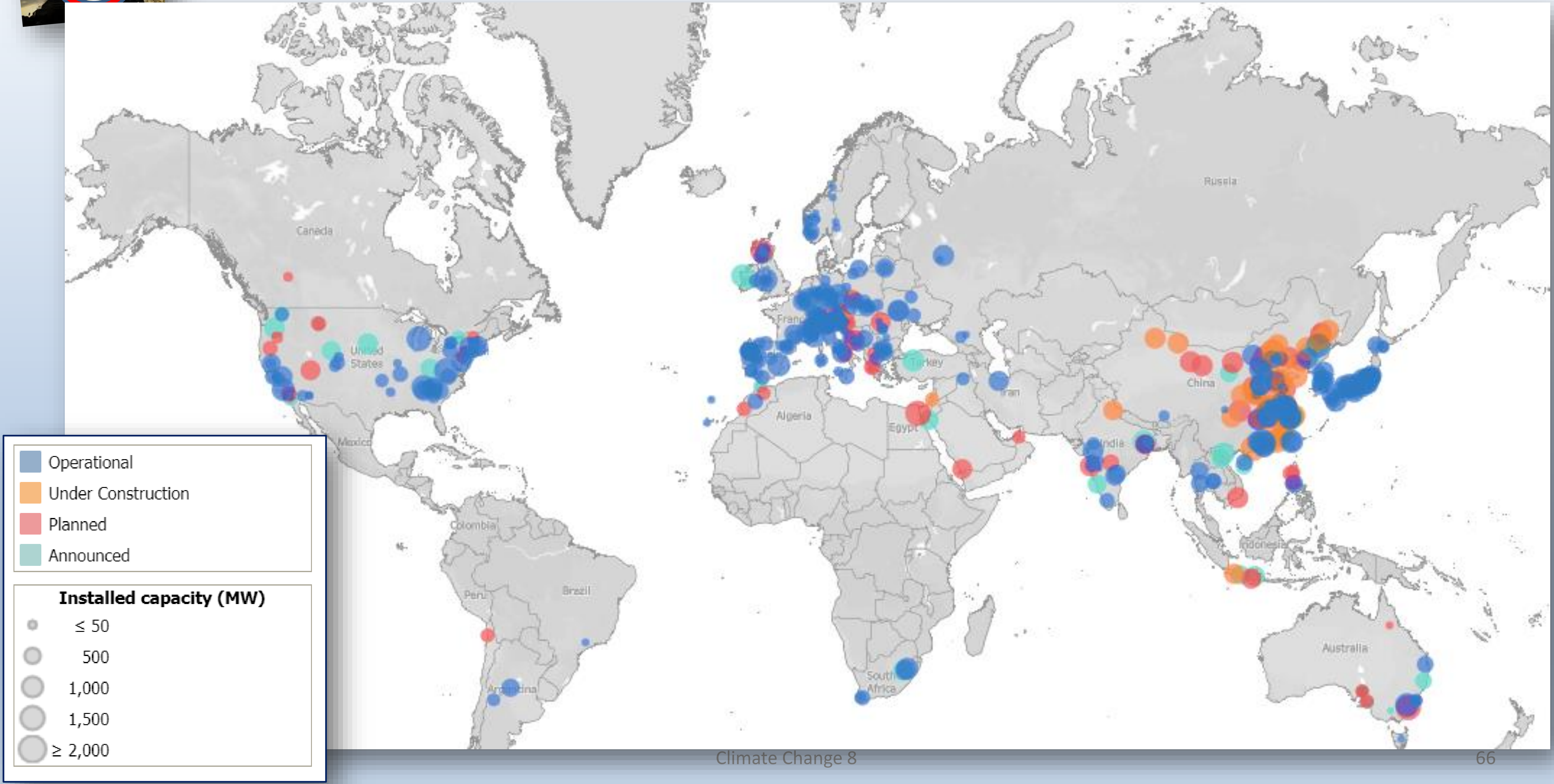
Pumped Storage

94% of All Existing Power Storage

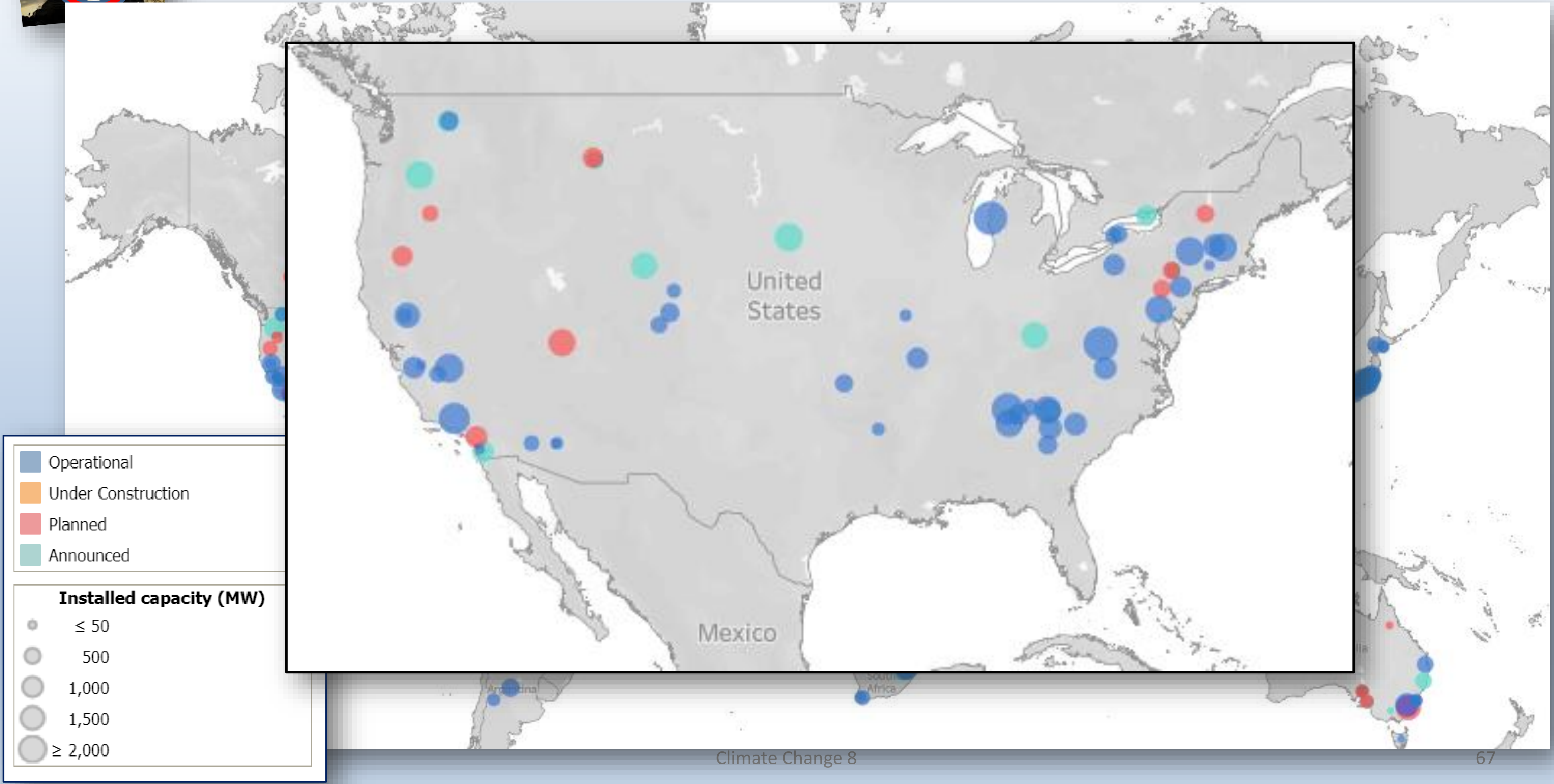




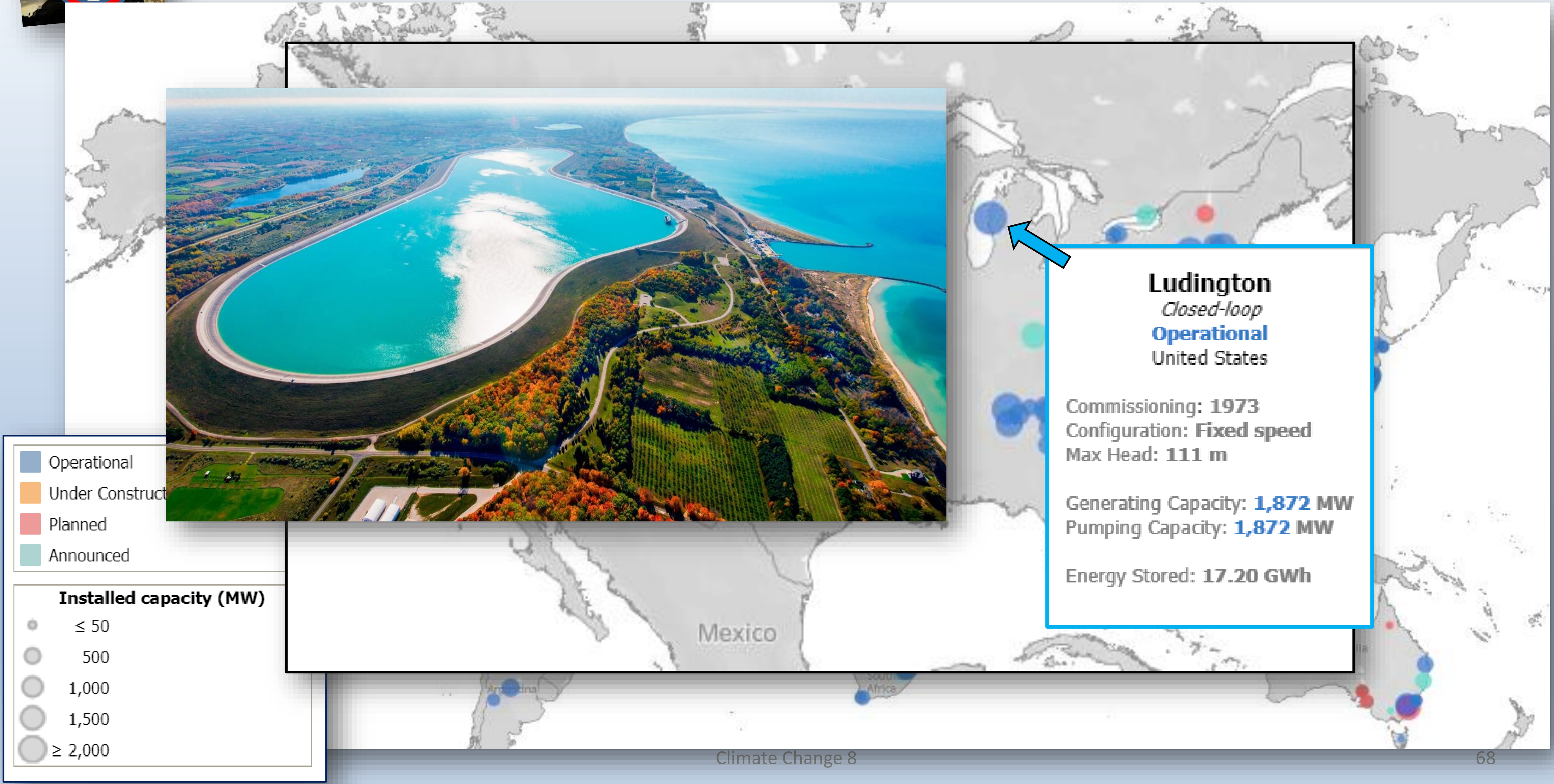
Pumped Storage Installations



Pumped Storage Installations

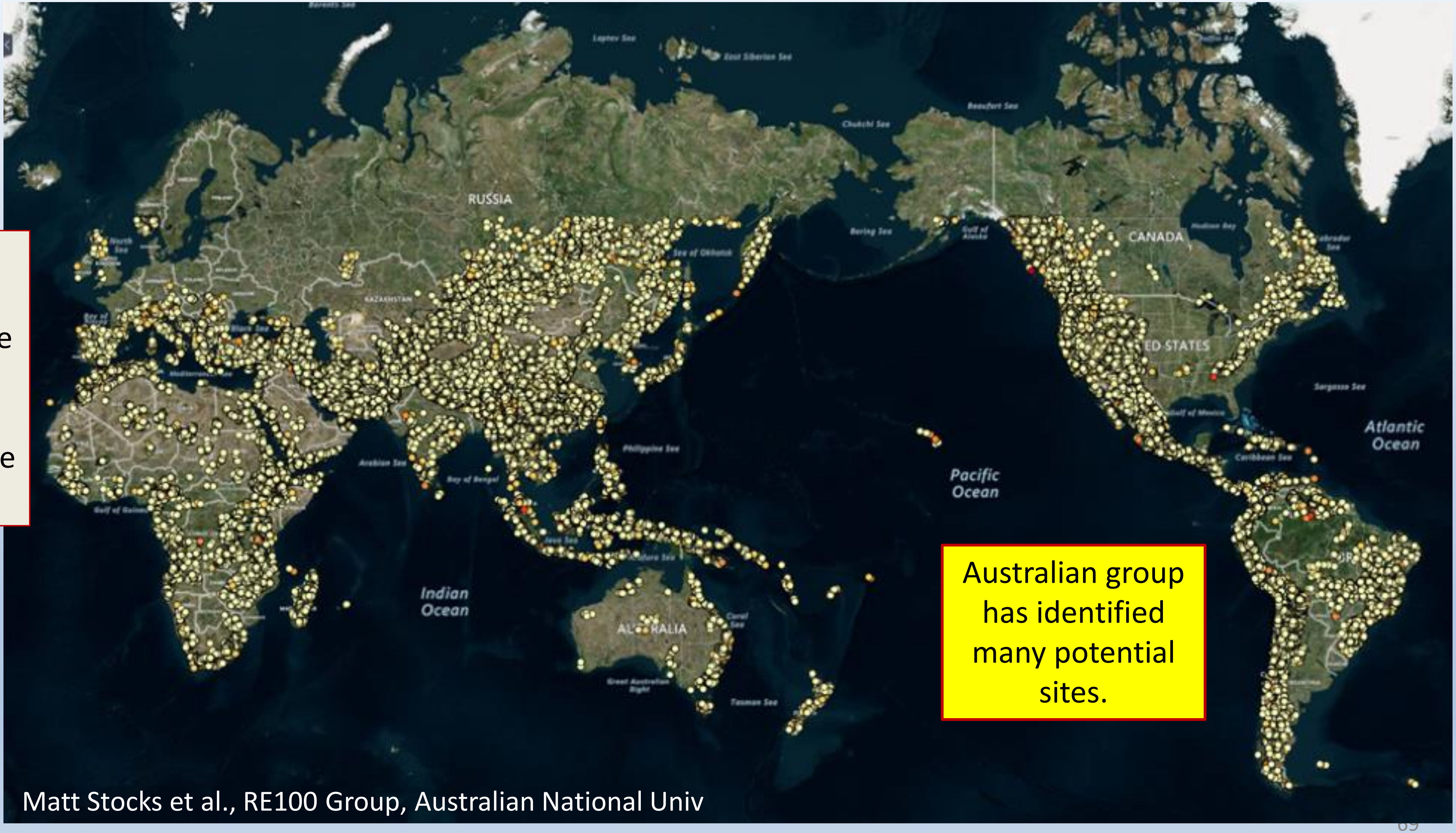


Pumped Storage Installations



660,000 Candidate Locations for Pumped Hydro Storage

Claim:
100x more potential Storage Sites than needed for a 100% Renewable electric system



Australian group has identified many potential sites.

Matt Stocks et al., RE100 Group, Australian National Univ

Clai
100x n
potential
Sites t
needed
100% Ren
electric s

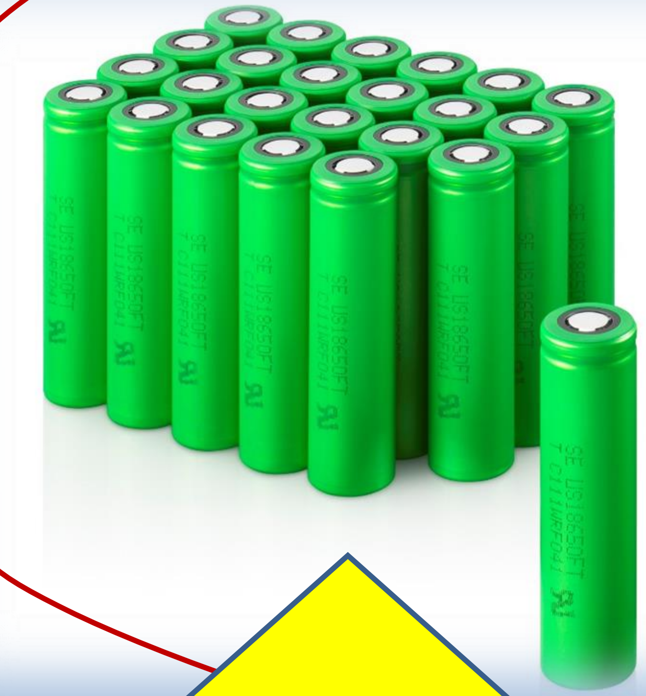
Unfortunately, Midwest is too flat….

[Global PHES Atlas - RE100 - ANU]

Battery Storage

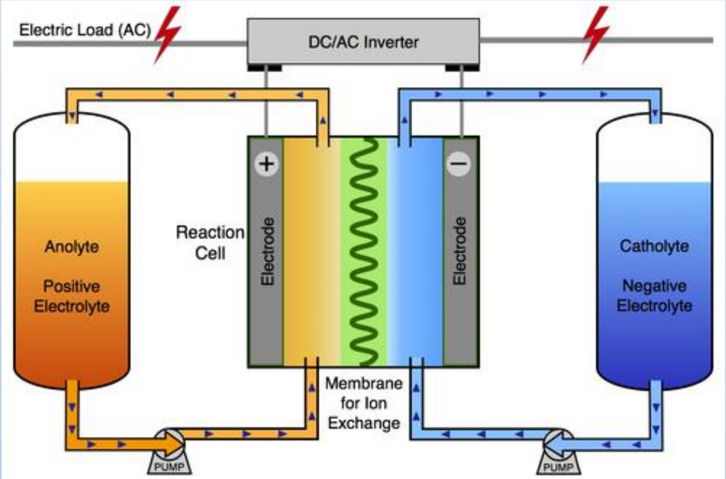
Lead-Acid

Lithium-Ion



Growing Fast

Redox Flow Batteries
Vanadium Flow Battery, e.g.



Losing out, but may yet have a role in *long-term* power storage

Utility Scale Battery Storage facility under construction at Moss Landing in Monterey CA .

Later this year, there will be a total of 600 MW/2300 MWh of Battery Storage at two facilities in this area to supply San Francisco homes.

October 2020
Moss Landing CA

Battery Costs Coming Down Rapidly

- Lithium Ion now dominant (leveraging EV car development)
  - Vanadium flow batteries are an alternative for long term storage
- Li-Ion now ~ 10 ¢/kWh (LCOS)
- Solar power + 4 hour Battery storage combination recently being offered at 4 ¢/kWh (PPA Power Purchase Agreement)
- Cost of fully battery stabilized solar or wind expected to cost only an extra 0.5 to 0.7 ¢/kWh in a decade.
- Tesla plans/hopes to be producing 3 TeraWatt-hours/year of Li-Ion batteries by 2030

Enough to supply Earth for 1 hour…

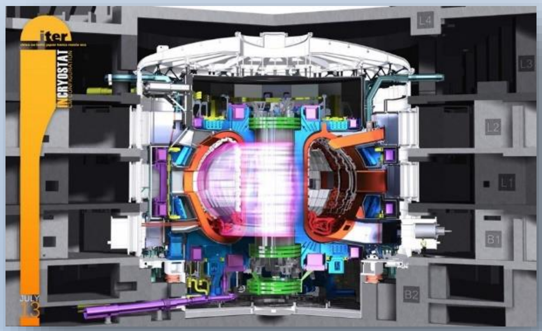
Other Paths to Decarbonization of Electric Power

- Nuclear Fission
  - Already 10% of the mix
  - Existing plants can be competitive
  - New capacity very expensive
    - New proposals for lower cost/ intrinsically safe designs

- Nuclear Fusion
  - Too late
  - Too expensive

IMHO

Great if it happens...



ITER Tokomak

- Started 1988
- Testing to begin 2025
- ~ $30 billion

$${}^{2}_{1}D + {}^{3}_{1}T \rightarrow {}^{4}_{2}He + {}^{1}_{0}n + 17.59\ \text{MeV}$$

- Fossil Fuels with Carbon Sequestration

Potentially a clean solution ...

CO_2

Retrofitting Fossil Fuel Plants to Capture CO_2

Carbon Capture and Storage (**CCS**)

FutureGen Project ~ 2007

Mattoon Illinois

- \$1.6 Billion CCS Demonstration
- 230 MW Coal Fired Power Plant
- CO_2 *was* to be pumped into underground saline formations for permanent storage

---

Illinois Industrial Carbon Capture and Storage Project

Decatur

ADM + UI Geological Survey

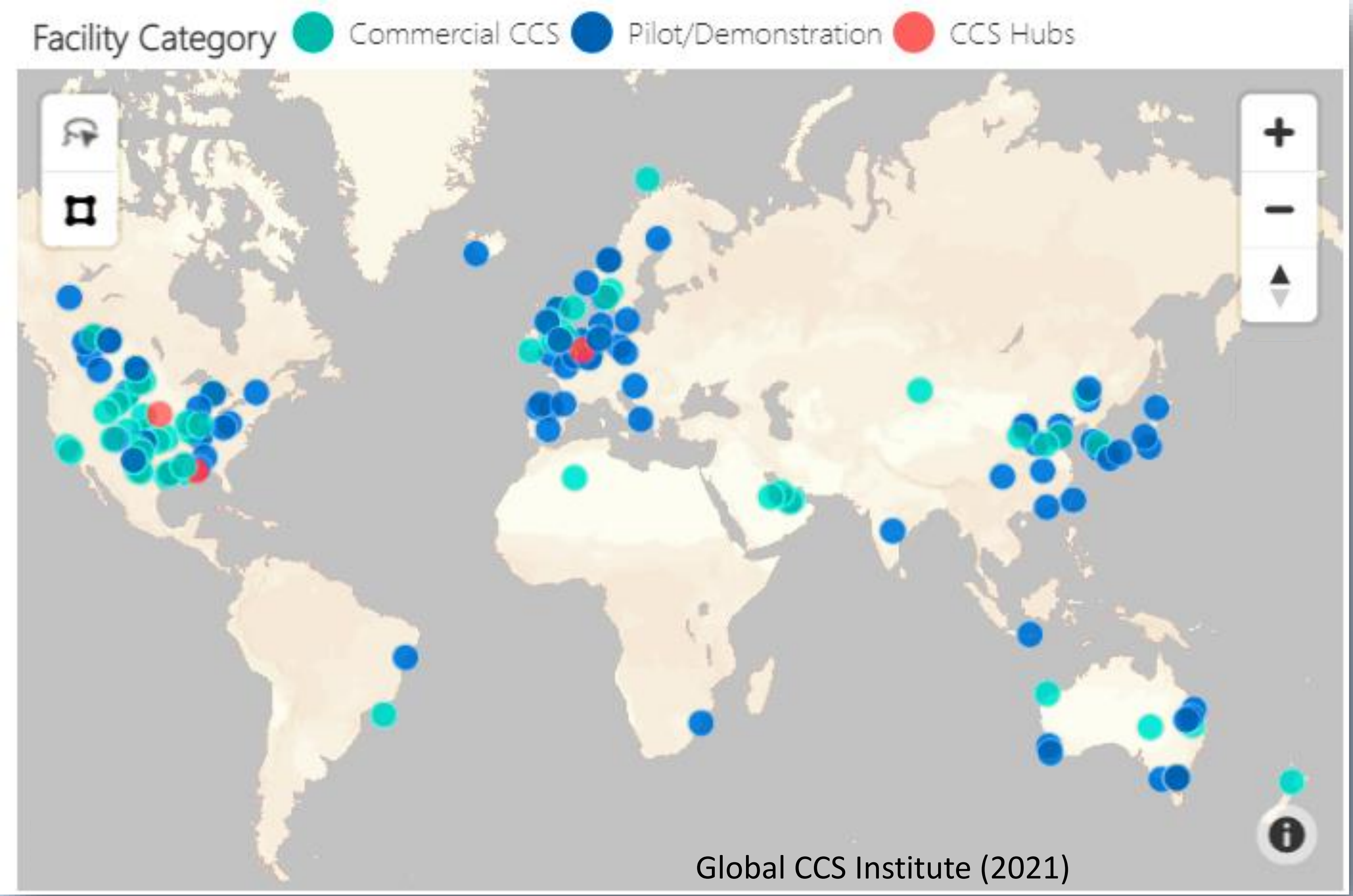
- Ethanol Plant produces CO_2 as byproduct
- CO_2 injection into Mount Simon Sandstone started April 2017
- ~700,000 tons/year projected
- ***Now seems to have gone silent…..***


Johnathan Hettinger,
Midwest Center for Investigative Reporting
November 19, 2020
Despite hundreds of millions in tax dollars, ADM's carbon capture program still hasn't met promised goals

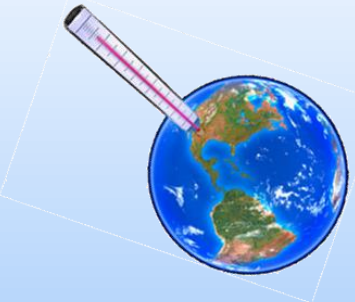

Kemper Mississippi $7.5B Carbon Capture Project Suspended in 2017

But there are still many **CCS** Projects Planned, Operational, or Completed.

In the US, most operational CCS projects sell the CO_2 for **Enhanced Oilfield Recovery** rather than inject it for permanent Geologic Storage.



Global CCS Institute (2021)

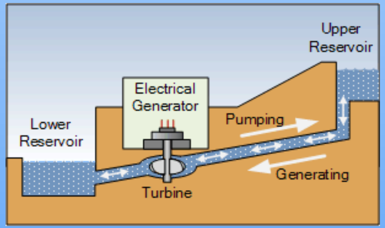


Questions on Electrification?

Appropriate Mix of Generation Modes

Short to Medium Term Storage

Pumped Hydro (>90%)



Thermal Storage

Long Distance Transmission Grids

Very High Voltage DC Transmission Lines can be continental in scale with very low loss.

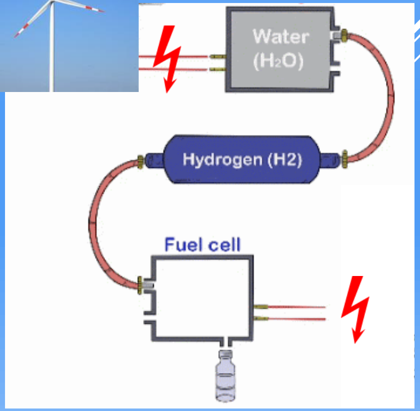
China: 3,324 km, 1.1 MV DC

Long Term Storage via Electrofuels

Green Hydrogen H_2 from Water:

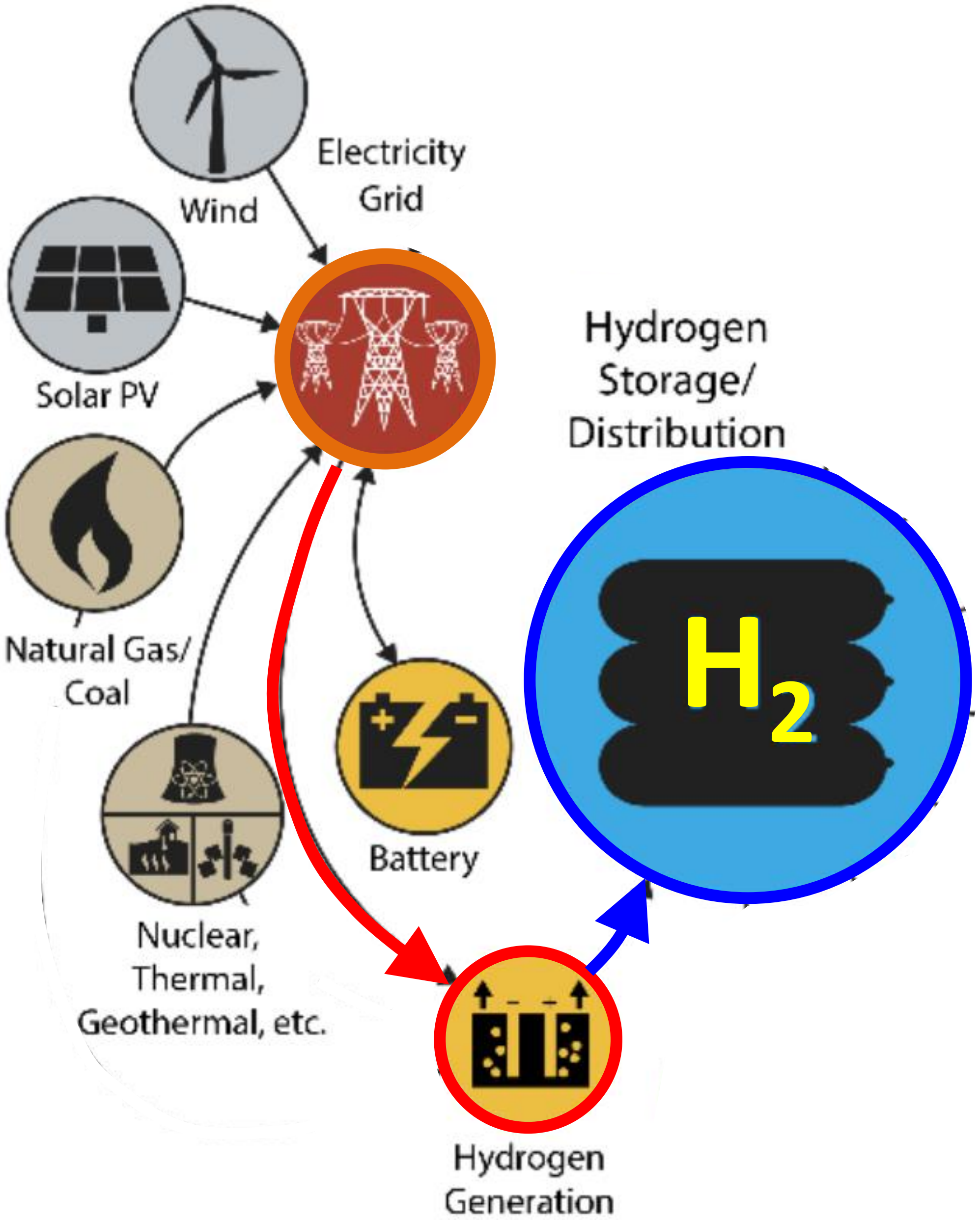
$$2\,H_2O + e \rightarrow 2\,H_2 + O_2$$

Electrolysis



The Hydrogen Economy:

Using H_2 as an Energy Intermediate



- **H_2** from excess electricity
- **H_2** stored or transported
- **H_2** Later used for
  - end uses
  - making electricity

Ruth et al, NREL/PR-6A20-70456 (2017) *H2@Scale: Technical & Economic Potential of Hydrogen as an Energy Intermediate*

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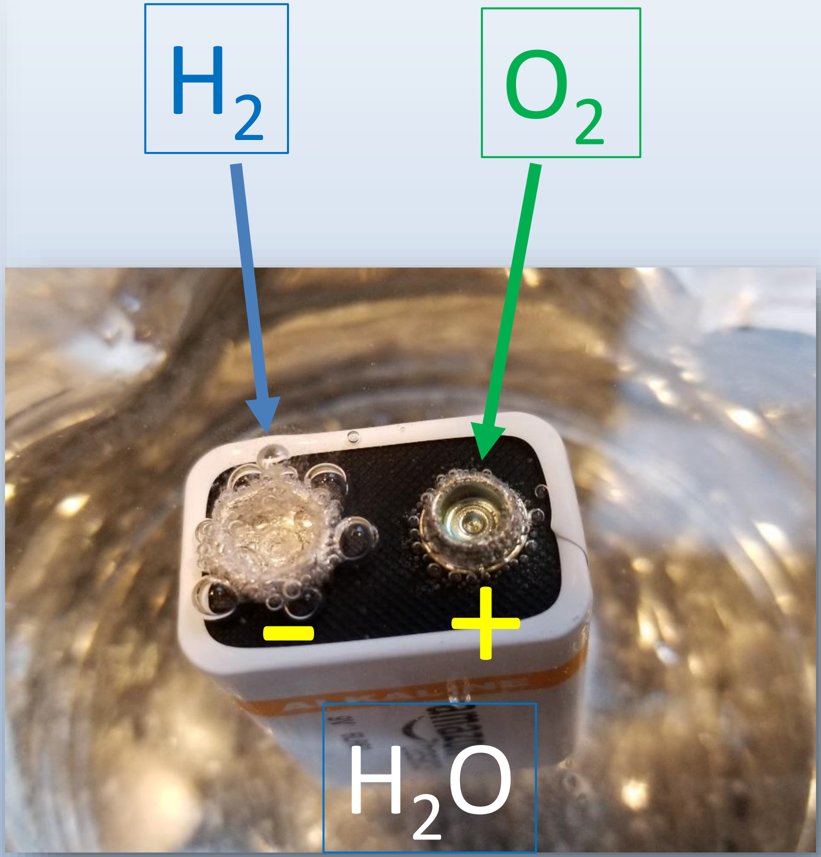

Hint:
If you try this at home, add a little vinegar, citric acid, or salt to the water to make it conductive.

4 Kinds

Hydrogen is Made, not Mined

...it takes energy!

The Hydrogen Economy:

Using H_2 as an Energy Intermediate

- **H_2** from excess electricity
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  - making electricity

Black/Brown H_2

from Coal

$C + 2\,H_2O$
$\rightarrow 2\,\mathbf{H_2} + \mathbf{CO_2}$

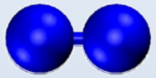
"Steam Reformation"

Grey H_2

from Methane

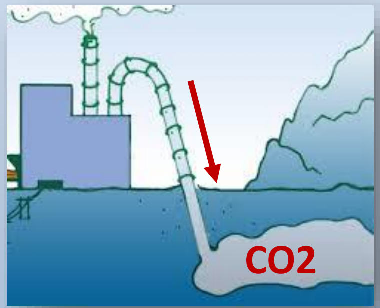
$CH_4 + 2\,H_2O$
$\rightarrow 4\,\mathbf{H_2} + \mathbf{CO_2}$

"Steam Reformation"



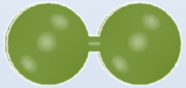
Blue H_2

Fossil+CCS



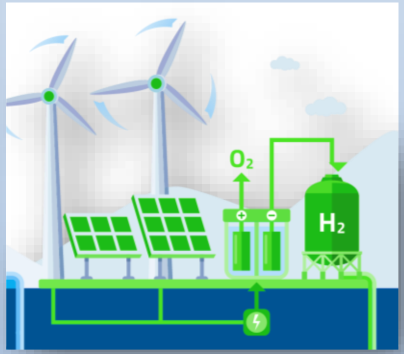
CCS=

"**C**arbon **C**apture and **S**equestration"



Green H_2

from Renewable Electricity



$2\,H_2O$ + electricity
$\rightarrow 2\,\mathbf{H_2} + \mathbf{O_2}$

(~ 80% Efficient)

4 Kinds

Hydrogen is Made, not Mined

...it takes energy!

Actually, there *are* places where H2 is found underground and might be drilled for!

The Hydrogen Economy:

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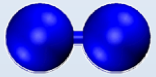

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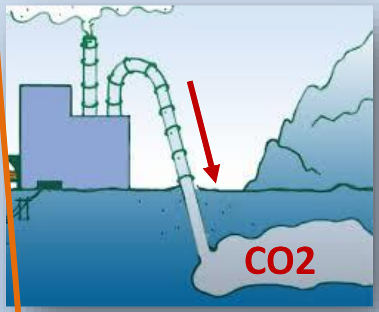
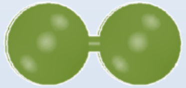


CCS=

"Carbon Capture and Sequestration"



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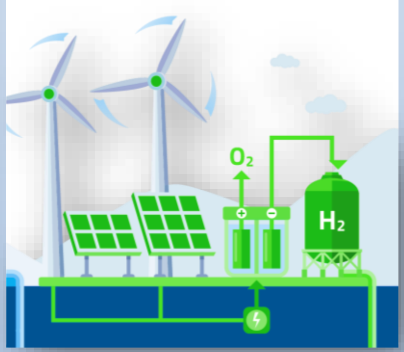

$2\,H_2O$ + electricity

$\rightarrow 2\,\mathbf{H_2} + O_2$

(~ 80% Efficient)

By far the main source now is Grey

Storing and Moving Hydrogen

The Hydrogen Economy:

Using H_2 as an Energy Intermediate

- **H_2** from excess electricity
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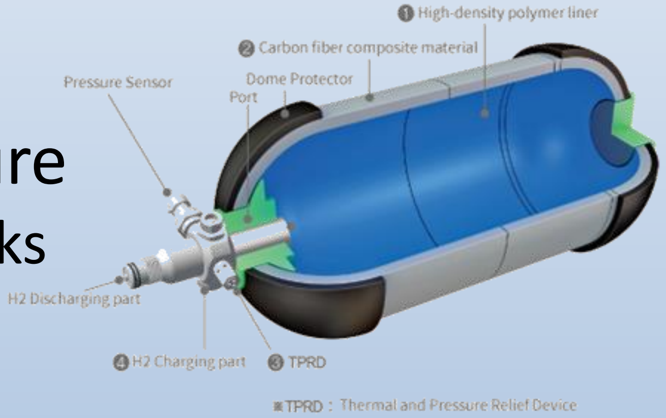
- **H_2** Later used for
  - end uses
  - making electricity

Hydrogen embrittlement is the issue in high pressure pipelines.

- Pumped through pipelines
  - Special steels required
  - Already done on a wide scale

- Stored under high pressure
  - Typically carbon fiber tanks
  - Tanks heavier than contents



- Stored as a cryogenic liquid
  - 20 ^{o}K (-253 ^{o}C)
  - Lots of energy used to liquify

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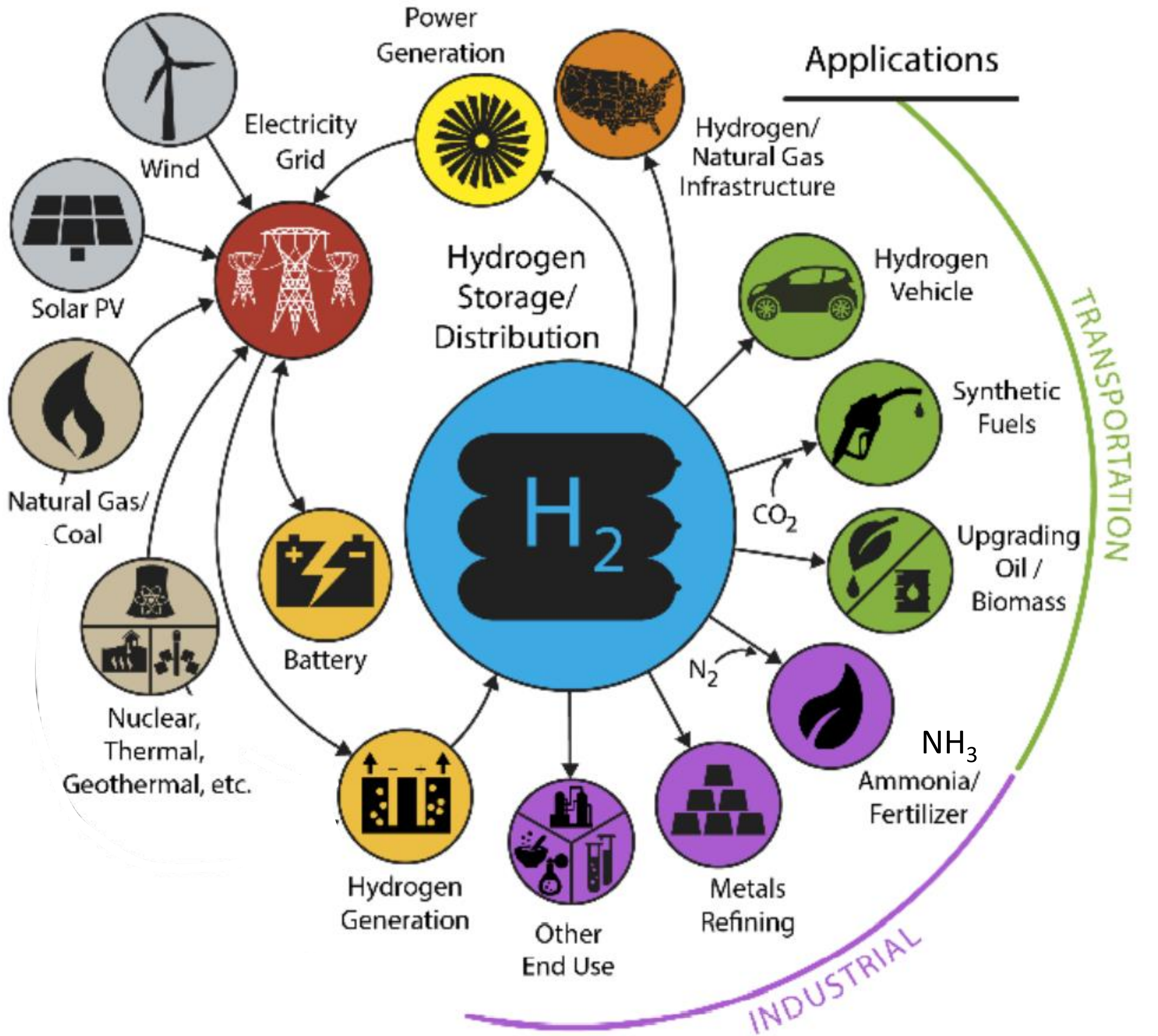

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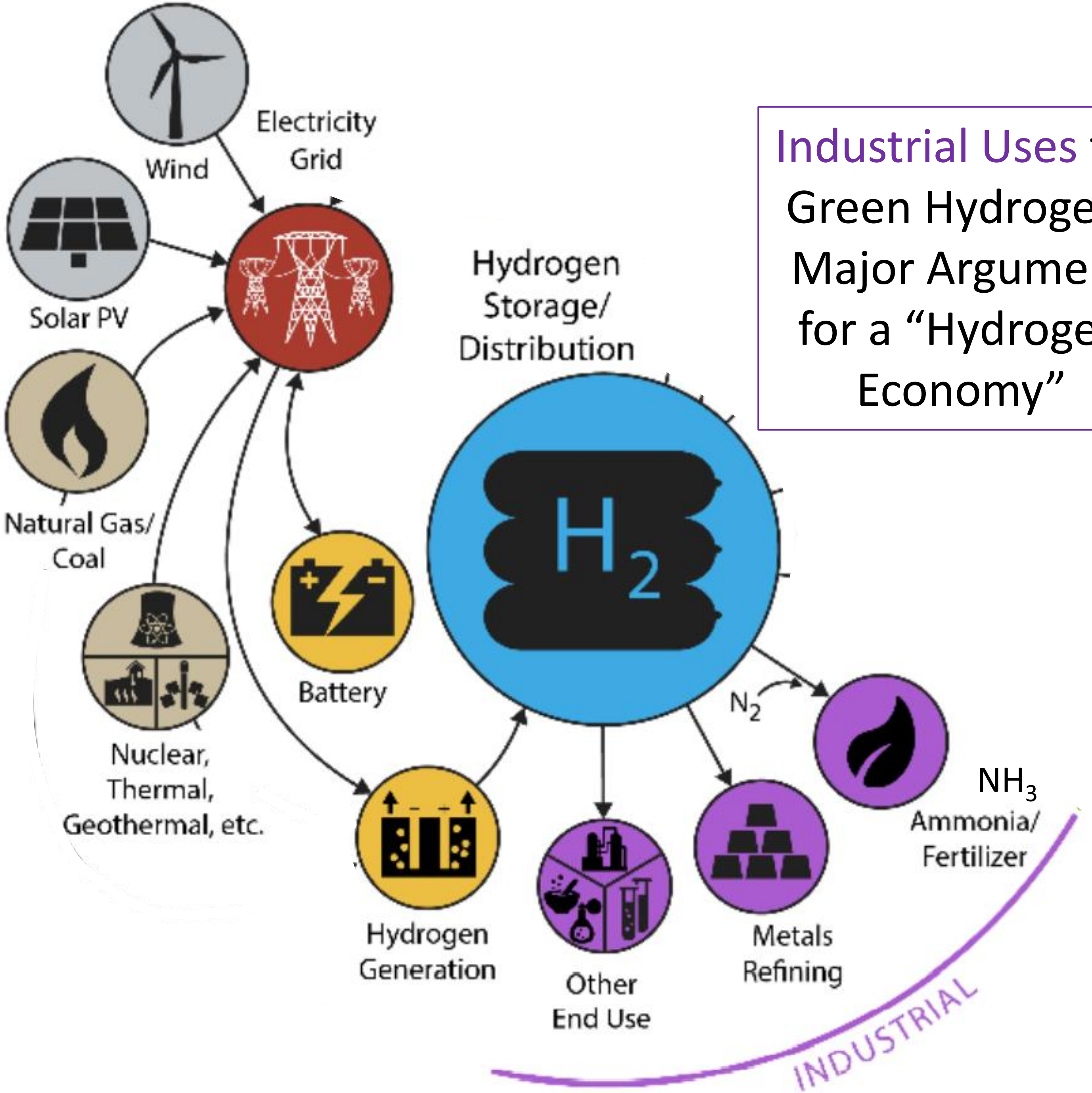

Industrial Uses for Green Hydrogen: Major Argument for a "Hydrogen Economy"

The Hydrogen Economy:

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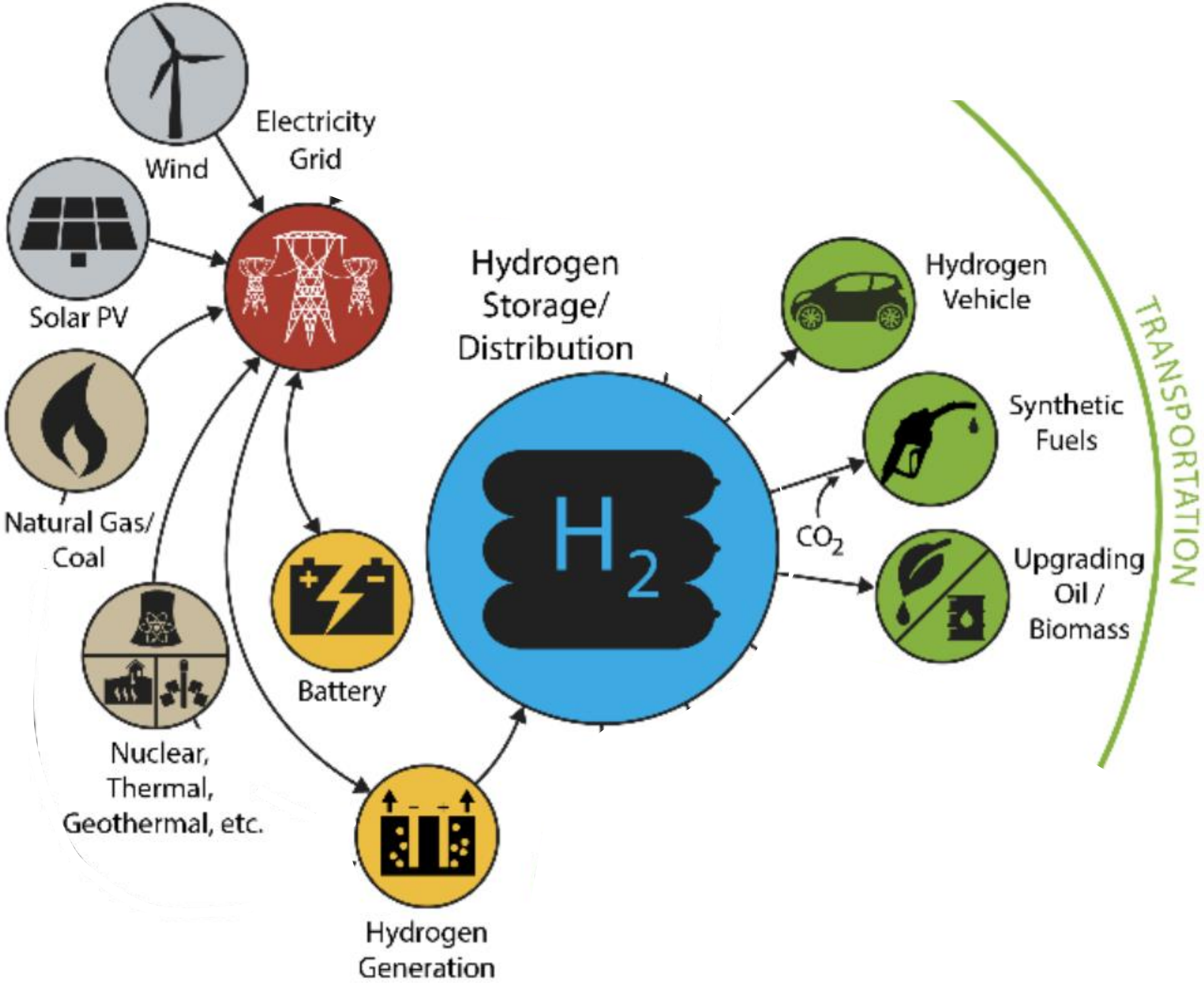

Ruth et al, NREL/PR-6A20-70456 (2017) *H2@Scale: Technical & Economic Potential of Hydrogen as an Energy Intermediate*

H_2 in Transportation?

The Hydrogen Economy:

Using H_2 as an Energy Intermediate

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Hydrogen Fuel cell vehicles being pushed by Toyota, but they are said to lose $70K on each one.

Right here in CU:

H_2 in Transportation?

MTD

The Hydrogen Economy:

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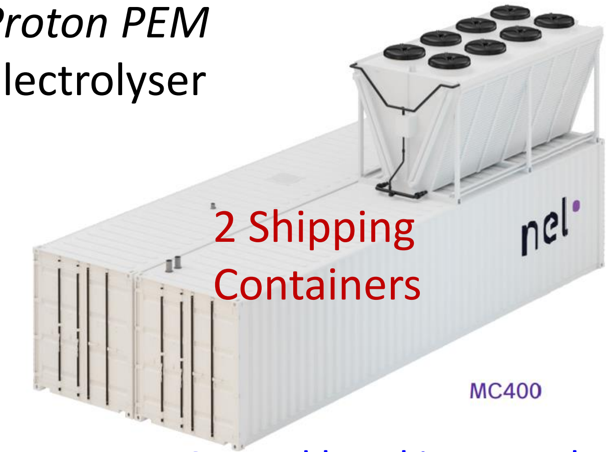
Ruth et al, NREL/PR-6A20-70456 (2017) *H2@Scale: Technical & Economic Potential of Hydrogen as an Energy Intermediate*

2 New Flyer *Xcelsior H2* 60' Buses

Begins Sept 2021

Long shot

Nel Hydrogen
Proton PEM
Electrolyser



2 Shipping Containers

Ground breaking March 4

H_2 in Transportation?

IMHO

The Hydrogen Economy:

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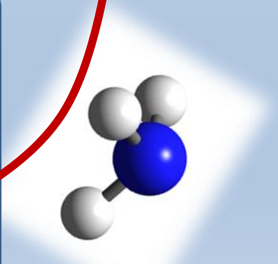
Possible Roles for Hydrogen in:

- Long haul trucks
- Heavy Equipment
- Large ships
- Trains
- Long range aircraft

An Indirect way to use H_2 in transport:

Make Liquid Ammonia

$$N_2 + 3\,H_2 \rightarrow 2\,NH_3$$



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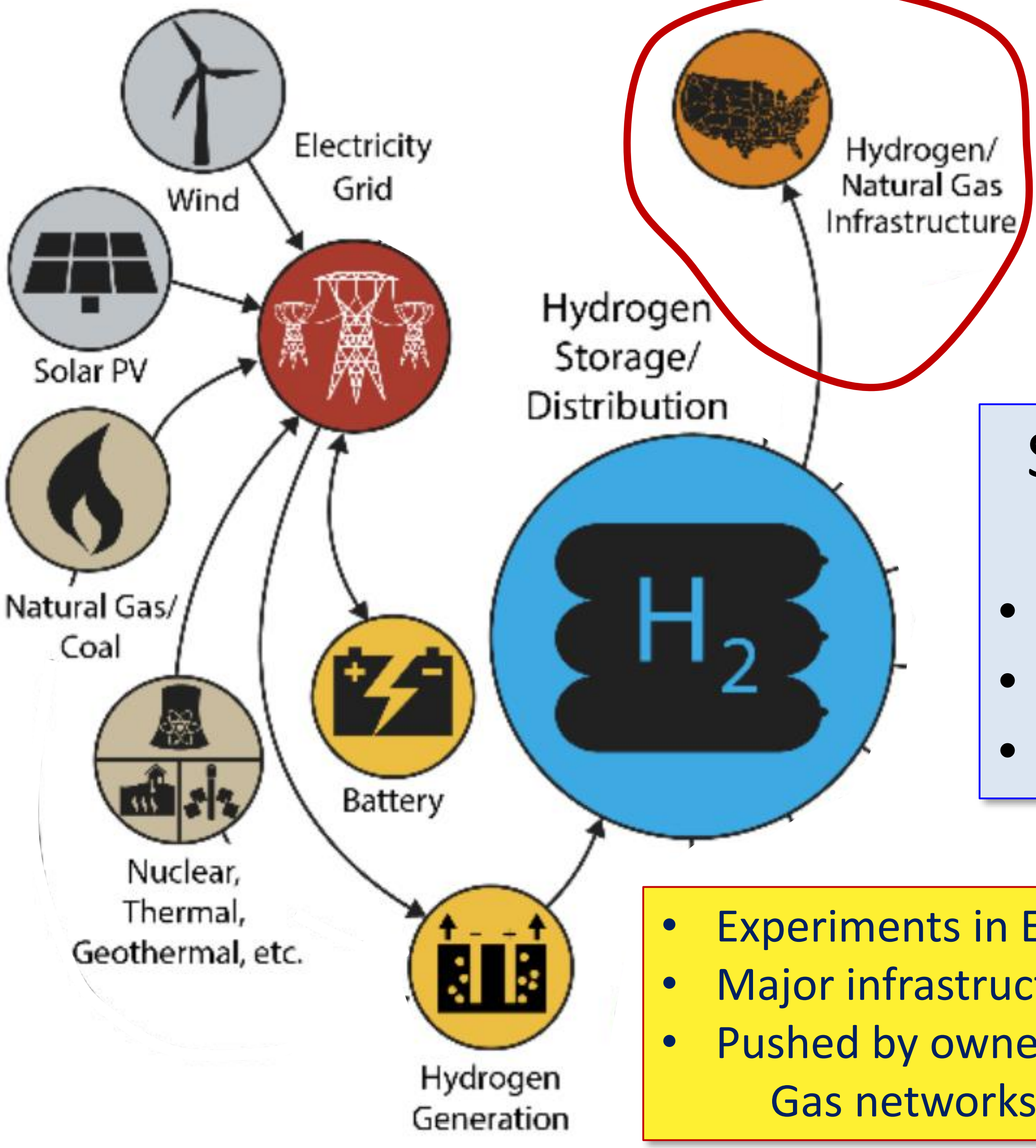

Substitute for Methane
- Industrial Heat
- Space Heating
- Cooking

- Experiments in Europe under way
- Major infrastructure changes
- Pushed by owners of existing Natural Gas networks

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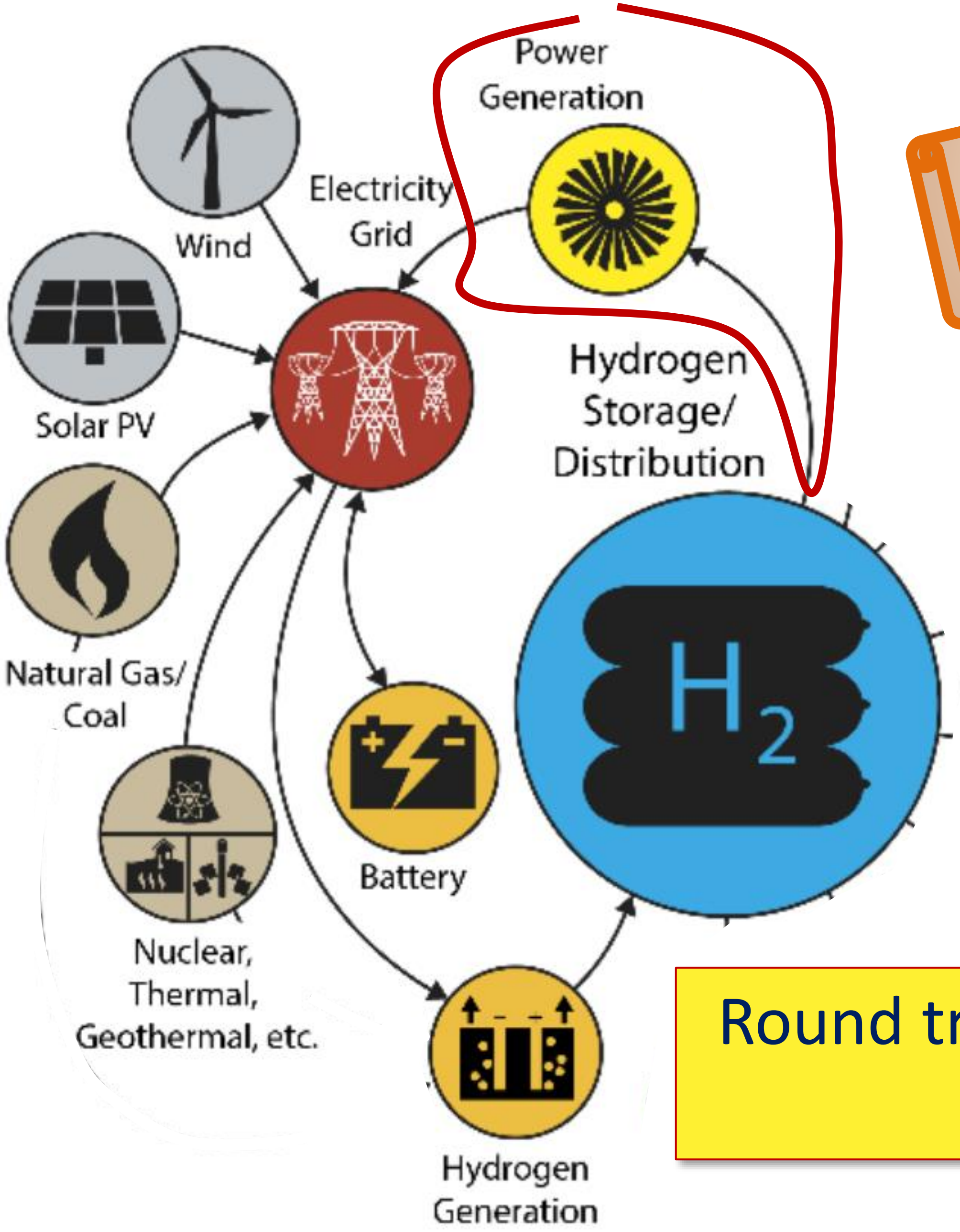

Not likely

In Power Generation, **H_2** acts as a distribution and storage medium

Round trip efficiency is low ~ 30-50%

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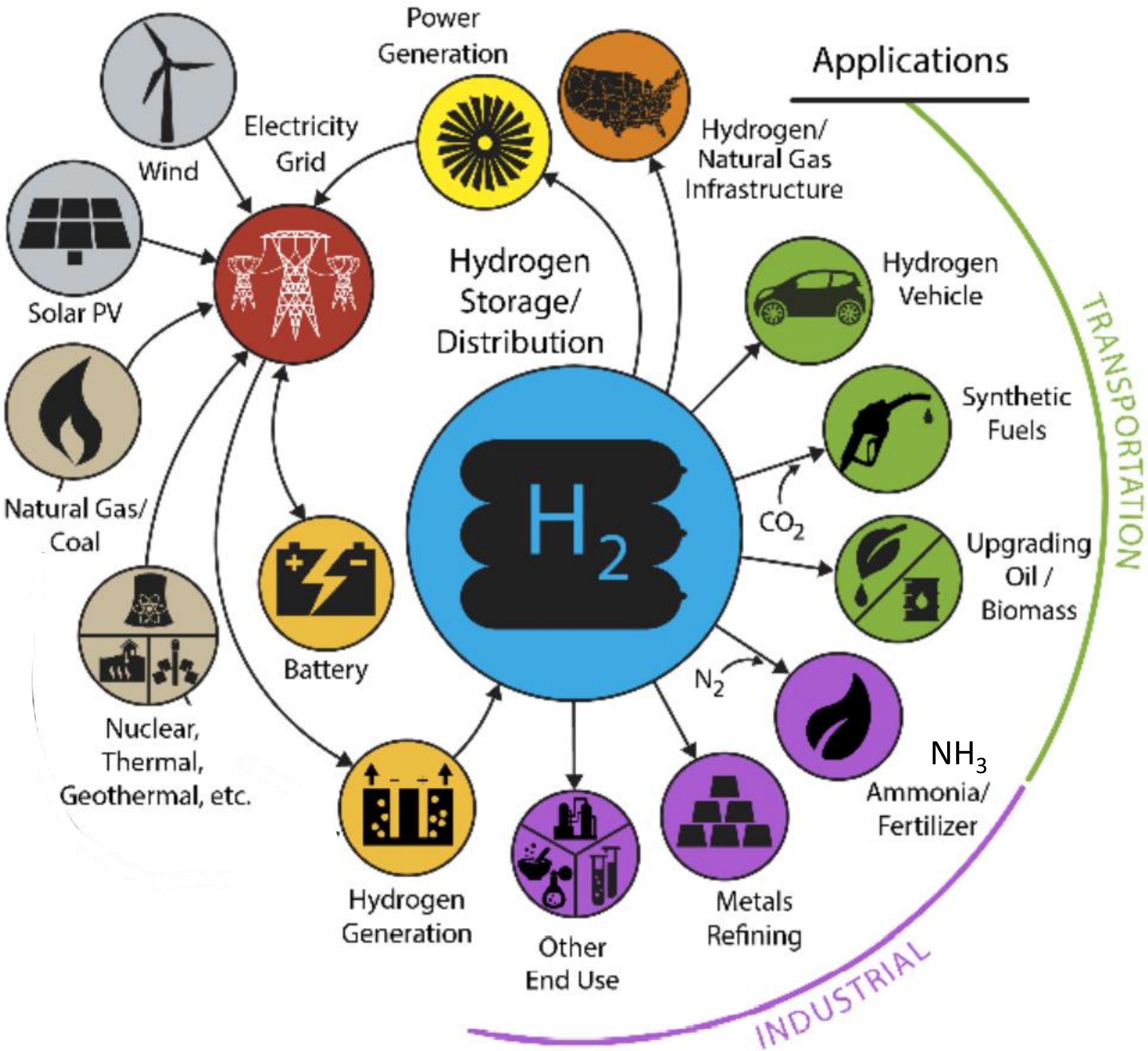
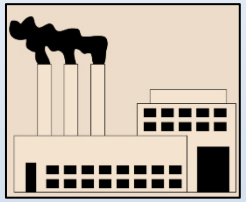
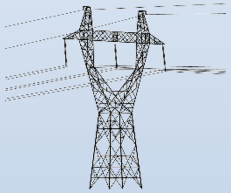
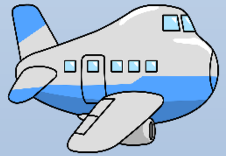


Mitigation

- Making Things 31%  Manufacturing
- Plugging In 27%   Electricity
- Growing Things 19%   Agriculture
- Getting Around 16%    Transportation
- Keeping Warm 7%   Space Heating

Battery Electric Vehicles Emerging Rapidly

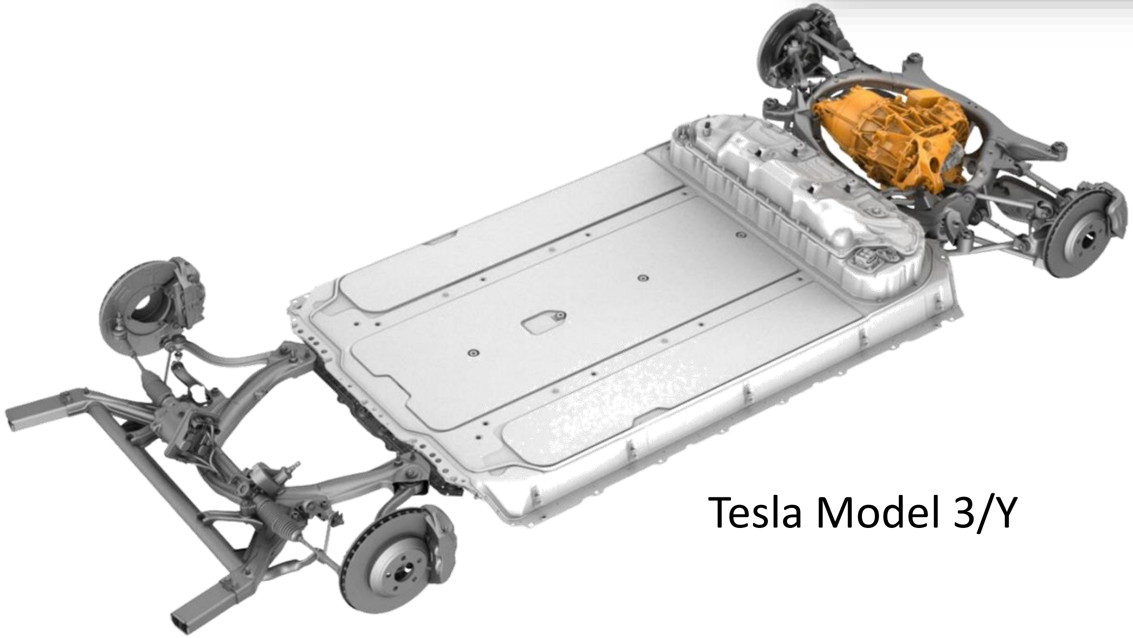
IMHO

Nearly all Light Duty Vehicles
on track to go
Li-Ion Battery Electric

√

Rivian Normal, IL

VW MEB



Tesla Model 3/Y

Battery Electric Vehicles Emerging Rapidly

IMHO

Nearly all light vehicles on track to go Battery Electric

√

Rivian

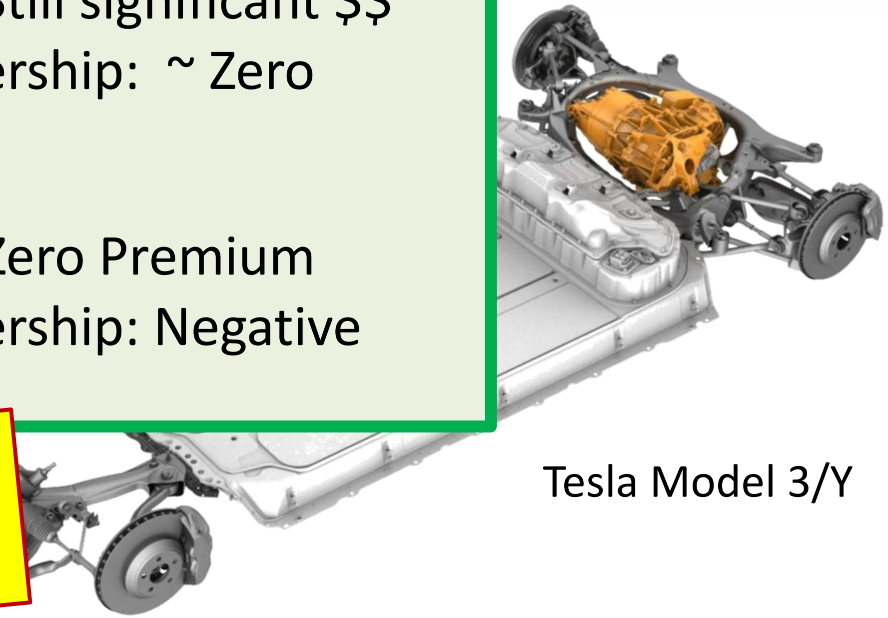
Green $$ Premium

Now:

- Initial Cost: Still significant $$
- Cost of Ownership: ~ Zero

In a few years:

- Initial Cost: Zero Premium
- Cost of Ownership: Negative



Tesla Model 3/Y

Underlying reasons:
Simplicity, performance,
low maintenance, low “fuel” cost.

Heavy Duty Vehicle Options

Delayed by battery shortages, now expected late 2021

Electric Drives

- Battery Electric
- Hydrogen Fuel Cell

?

Diesel Engines

- Bio-Diesel
- Synthetic e-Fuels
- Ammonia

+

Rail

- **Overhead Electrification** already common
  - All high speed trains
  - 100% in Holland, e.g.
- Almost all locomotives use Electric motors anyway
- **Battery-electric** for use on Non-electrified routes
- **Hydrogen Fuel-Cell** Passenger Trains in use

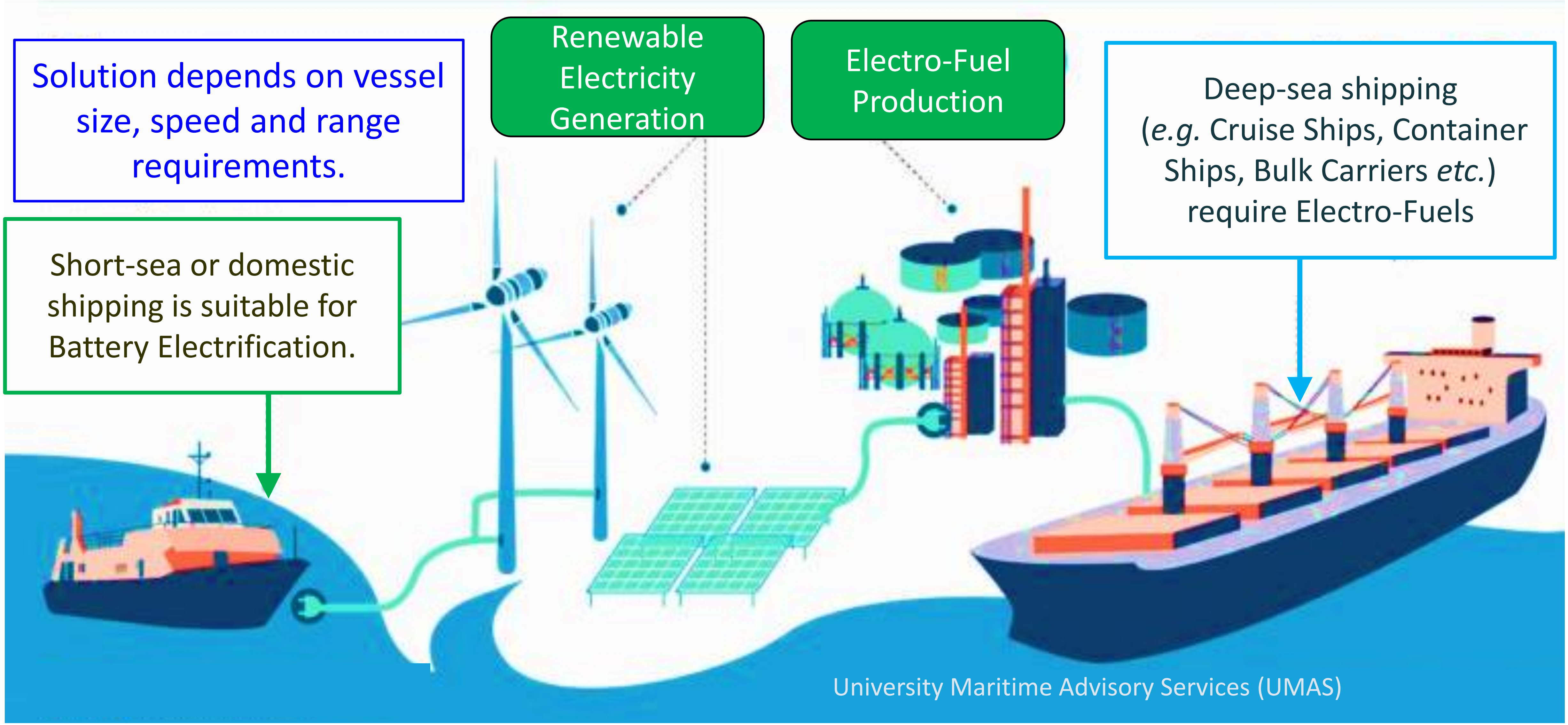
Acela Next-Gen Train under test in Colorado

Alstom Hydrogen Fuel-Cell Train (Austria)
600km range, 140 km/h speed

BNSF/GE Battery Electric Locomotive under test (California)

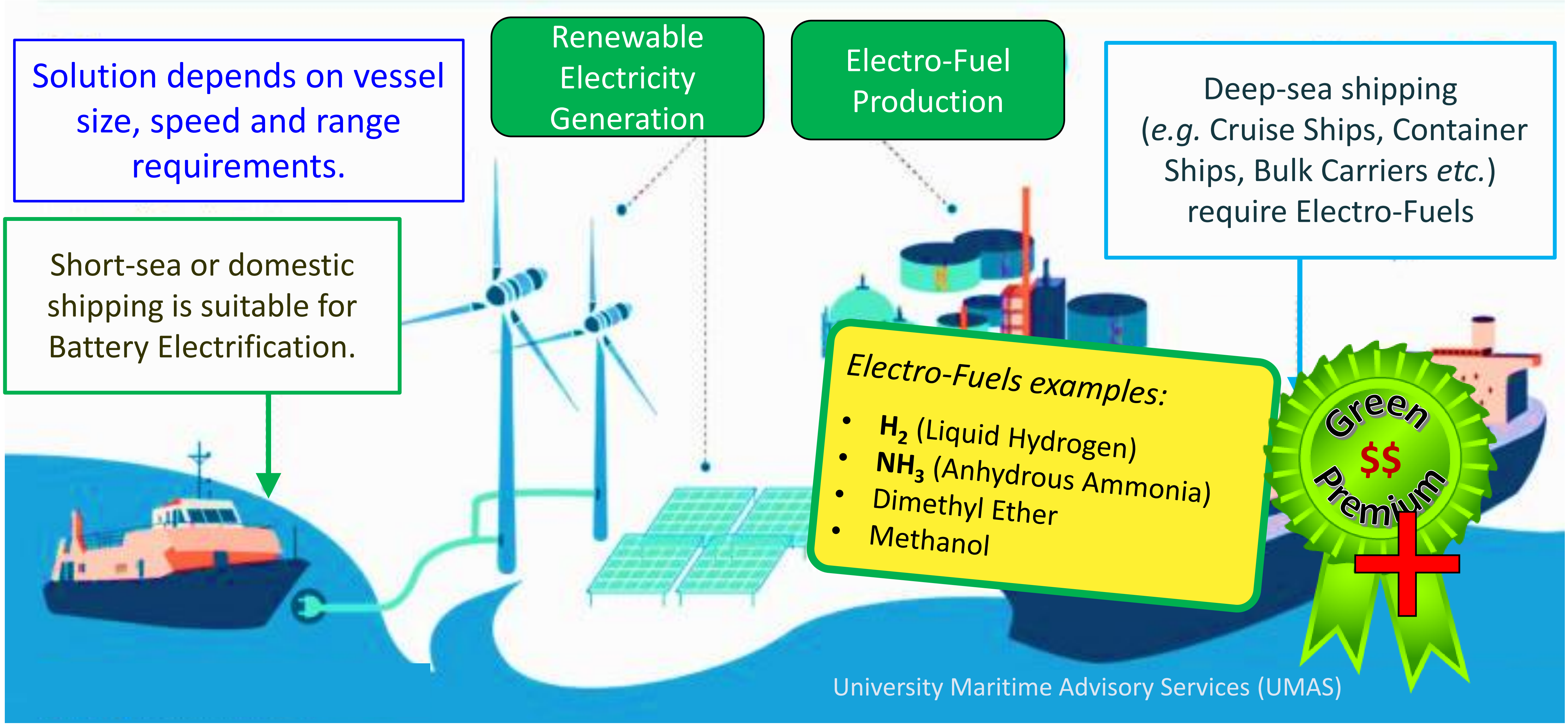
Weight/space for Batteries or Hydrogen storage not a big issue – add a couple of cars behind loco.

Maritime



Solution depends on vessel size, speed and range requirements.
Renewable Electricity Generation
Electro-Fuel Production
Deep-sea shipping (*e.g.* Cruise Ships, Container Ships, Bulk Carriers *etc.*) require Electro-Fuels
Short-sea or domestic shipping is suitable for Battery Electrification.
University Maritime Advisory Services (UMAS)

Maritime



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Short-sea or domestic shipping is suitable for Battery Electrification.
Electro-Fuels examples:
• H_2 (Liquid Hydrogen)
• NH_3 (Anhydrous Ammonia)
• Dimethyl Ether
• Methanol
Green $$ Premium
University Maritime Advisory Services (UMAS)

Long Range Aviation

- Round trip ORD-London: 2.2 tons CO_2
  - *2% of global emissions, 3% by 2050*

Some options:

- Drop-in Fuels
  - **S**AF (**S**ustainable **A**viation **F**uels)
    - *Mostly biofuels from waste, oil crops, algae (similar to BioDiesel)*
    - *Eventually synthetic e-fuels*

Tiny amounts so far: 0.015%

The most recalcitrant transportation mode due to range, weight and space limitations…

- Alternates (carbon free)
  - Liquid H_2
  - Ammonia NH_3
  - *Major redesign!*

The airline industry really likes drop-ins – aircraft last a long time and new ones expensive to develop….

Long Range Aviation

- Round trip ORD-London: 2.2 tons CO_2
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50-75%

The most recalcitrant transportation mode due to range, weight and space limitations…

Long Range Aviation

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X-15

Tiny amounts so far: 0.015%

50-7

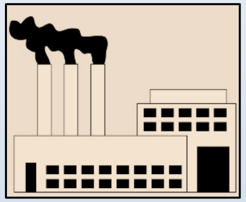
The most recalcitrant transportation mode due to range, weight and space limitations…

Short-Haul Electric Airliners

Battery-electric airplanes may reach 200-300 mile ranges

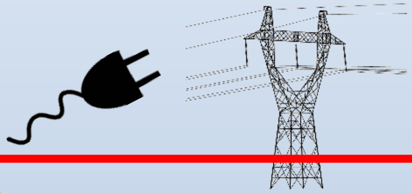
Mitigation

- Making Things 31%



Manufacturing

- Plugging In 27%

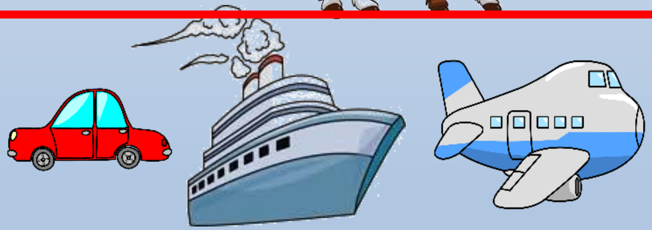


Electricity

- Growing Things 19%

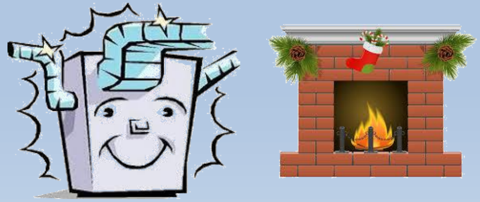
Agriculture

- Getting Around 16%



Transportation

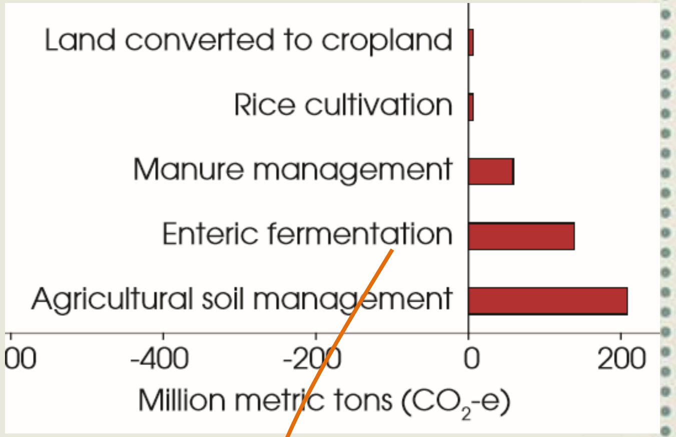
- Keeping Warm 7%

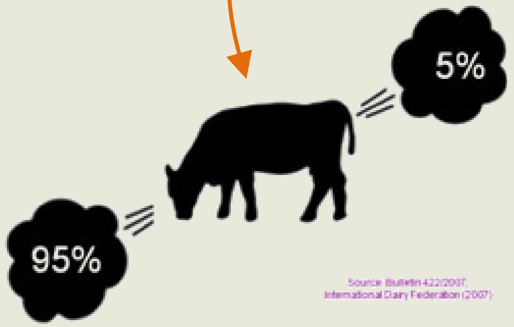


Space Heating

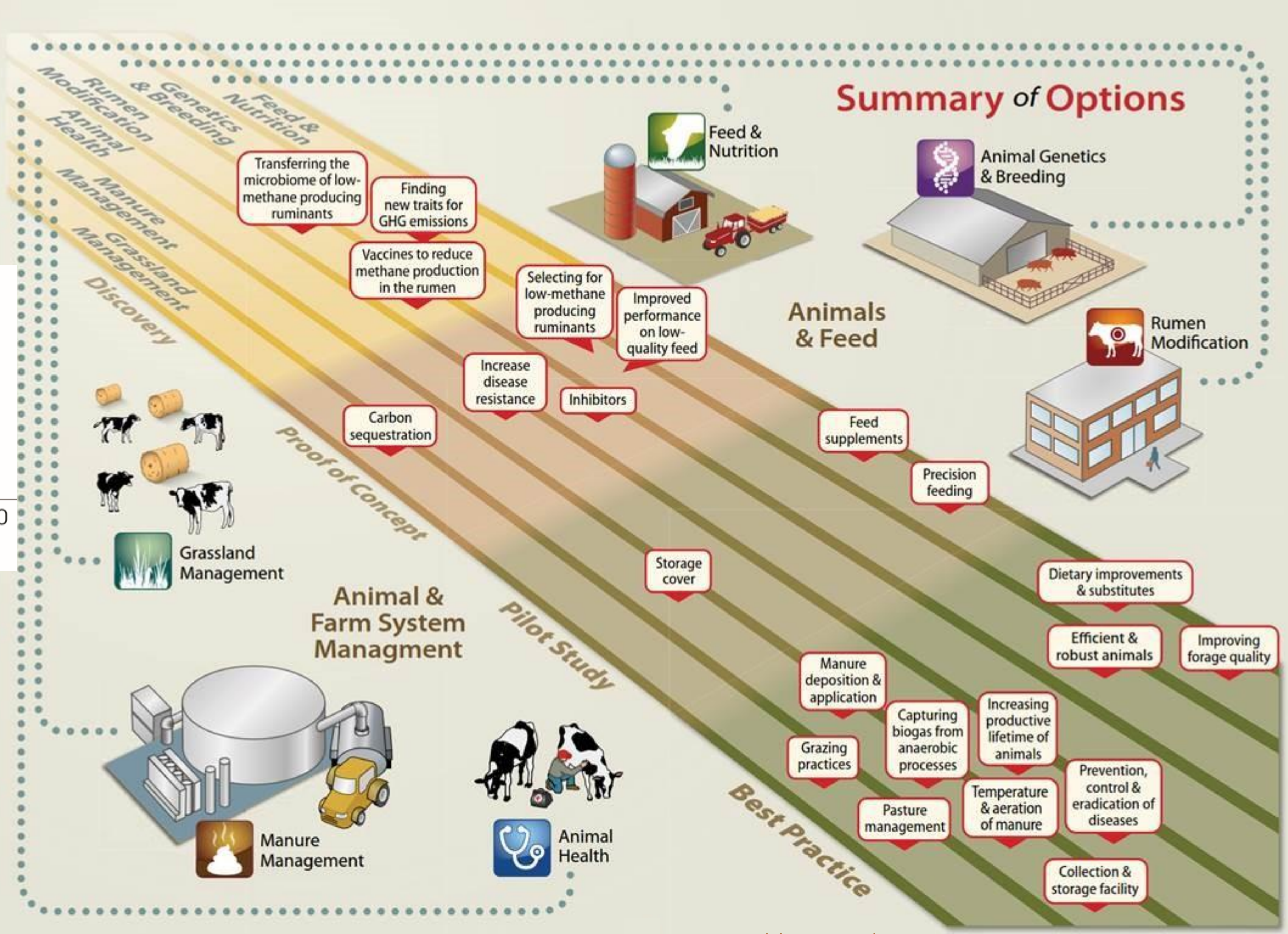
Agricultural GHG Emissions

CH_4 & N_2O





Source: Bulletin 422/2007, International Dairy Federation (2007)



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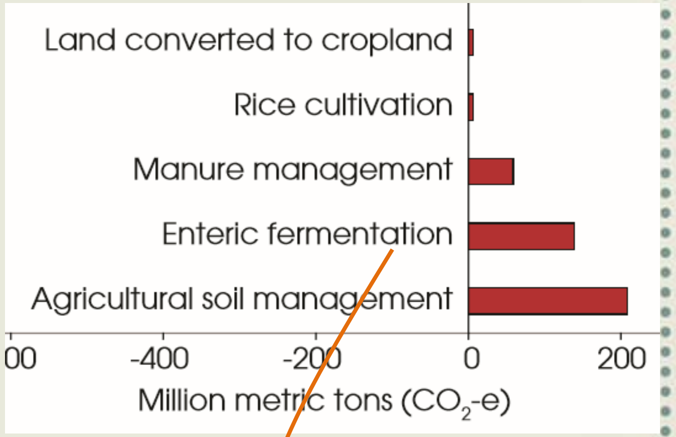
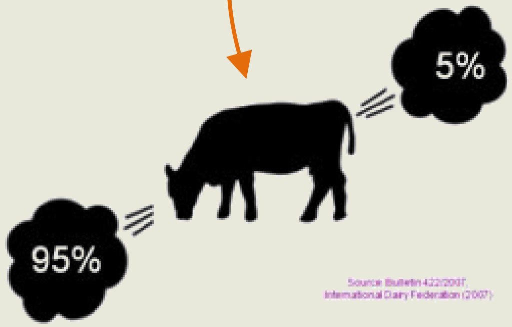
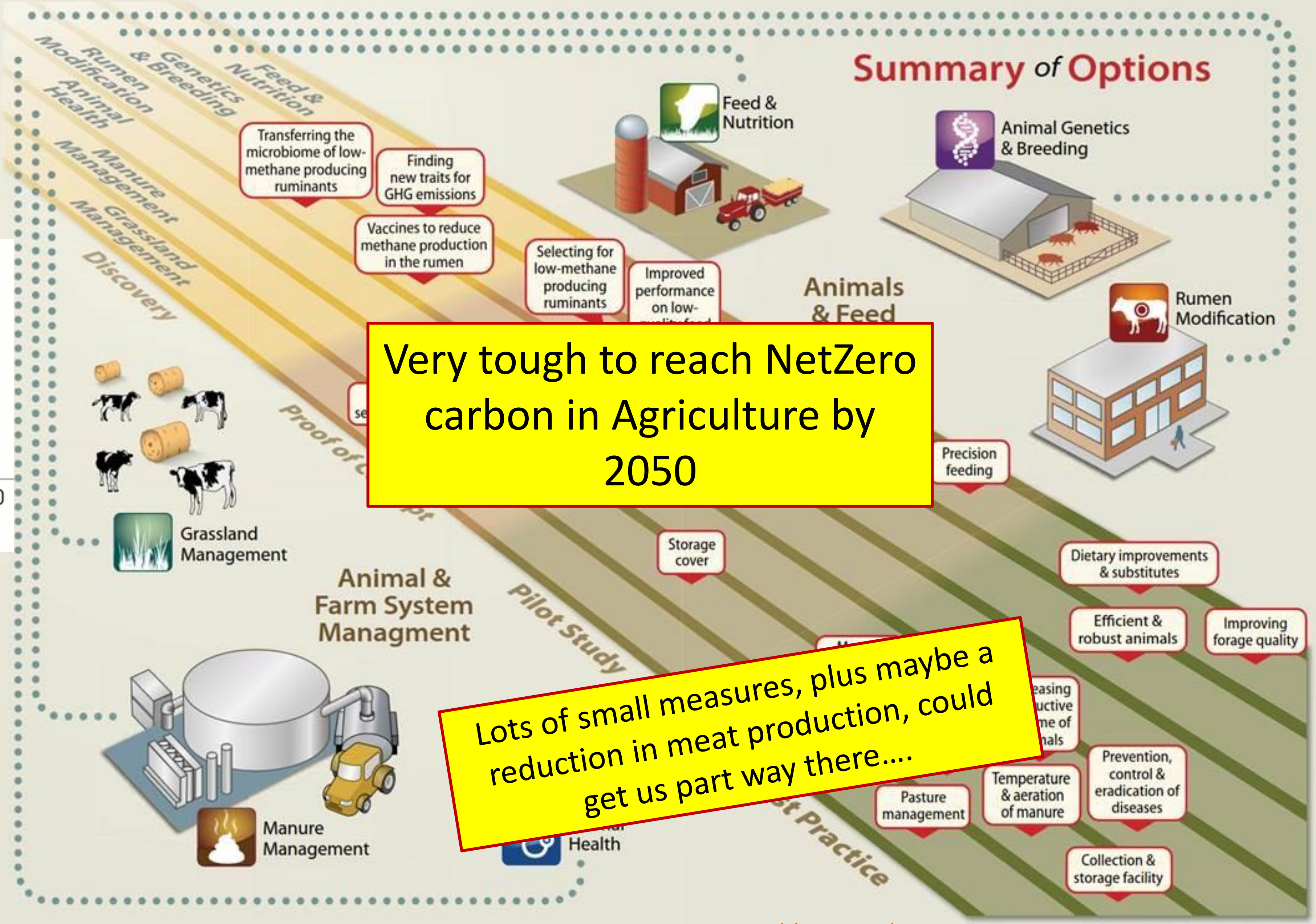


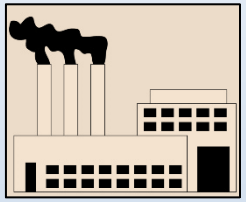
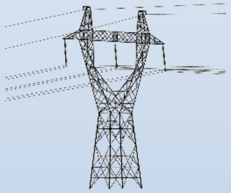




Very tough to reach NetZero carbon in Agriculture by 2050

Lots of small measures, plus maybe a reduction in meat production, could get us part way there....

Mitigation

- Making Things 31%  Manufacturing
- Plugging In 27%   Electricity
- Growing Things 19%   Agriculture
- Getting Around 16%    Transportation
- Keeping Warm 7%   Space Heating

Space Heating/Cooking/Hot Water

1. Biomass

2. H_2 Gas

H2 Furnace
BDR Thermea

H2 Stove

3. Electric

Heat Pump for Heating + Cooling + Hot Water
MiamiHP.com

Inductive or Resistance Stovetop

Space Heating/Cooling/Hot Water

Both of these start with renewable electricity, but have very different results

1. Biomass

2. H_2 Gas

~5x Efficiency

H2 Furnace

BDR Thermea

3. Electric

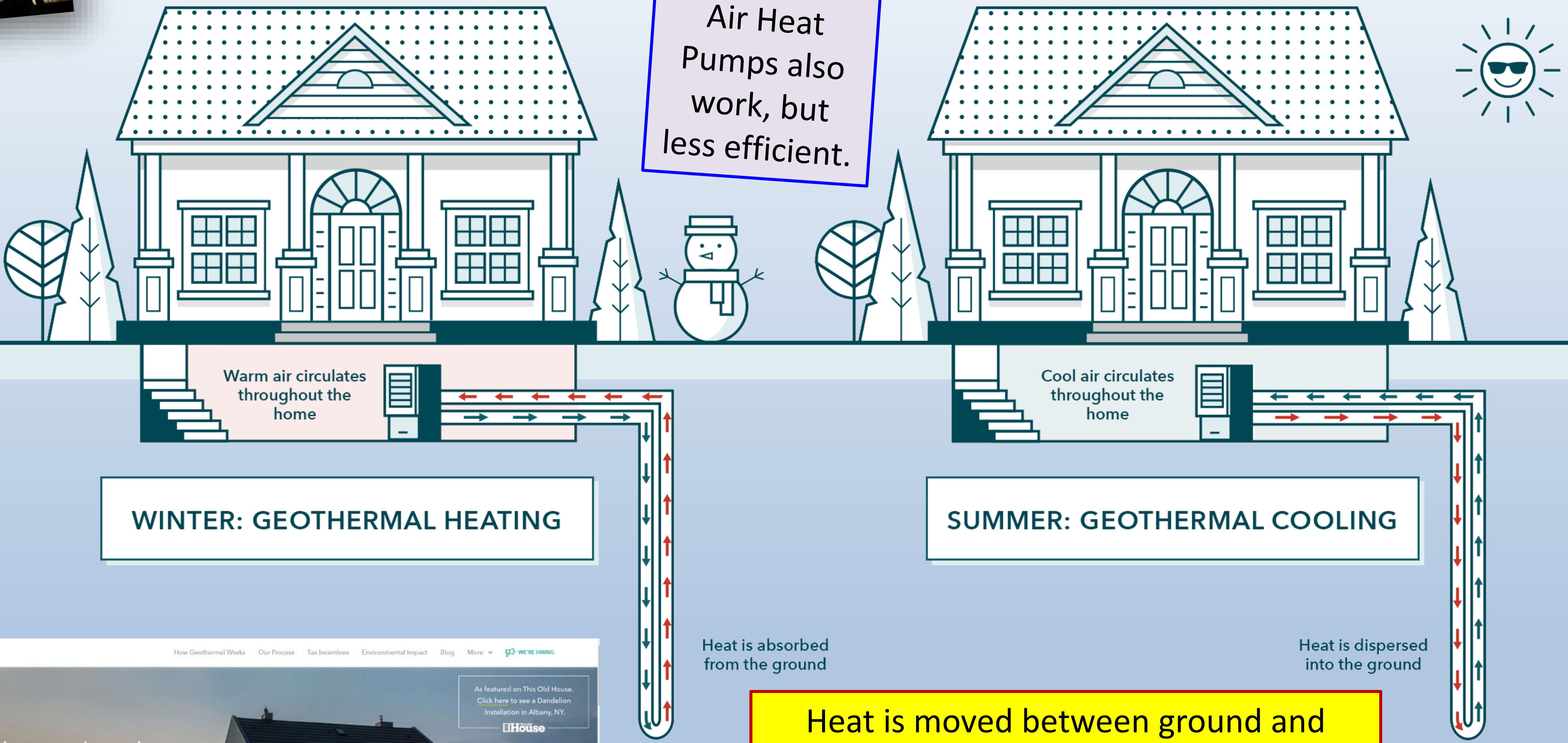
Heat Pump for Heating + Cooling + Hot Water

MiamiHP.com

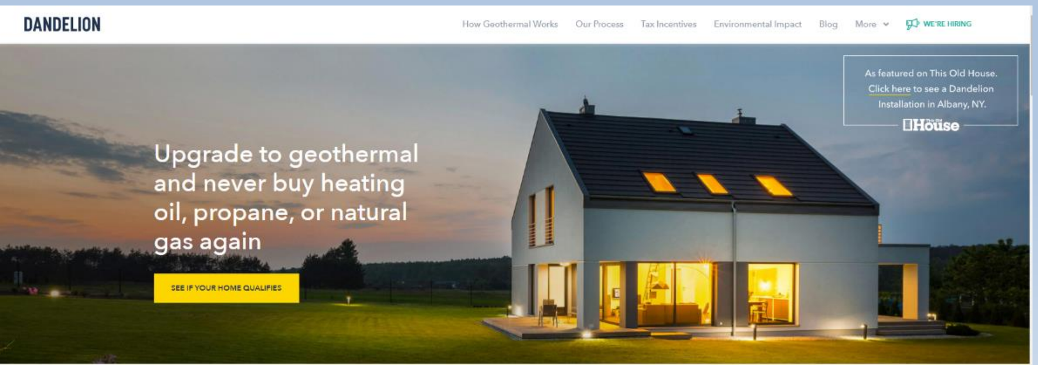
Inductive or Resistance Stovetop

Space Heating: Geothermal Heat Pump

Air Heat Pumps also work, but less efficient.

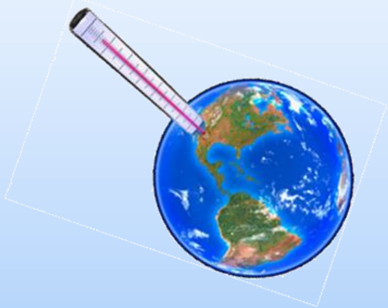


Heat is moved between ground and home. A little juice moves a lot of heat, so very efficient.

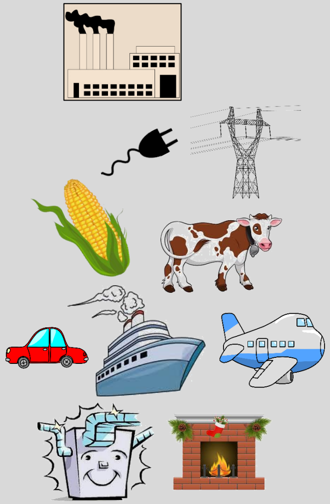


Dandelion.com

Questions about Mitigation?



Mitigation



• Making Things	31%	Manufacturing
• Plugging In	27%	Electricity
• Growing Things	19%	Agriculture
• Getting Around	16%	Transportation
• Keeping Warm	7%	Space Heating

Amelioration: What Can Be Done?

- Mitigation

Reducing or Eliminating the GH Gas Drivers

Global Effect

- Adaptation

Learning to Live with Climate Change

Local to Regional

- Intervention

Active Measures to Counteract Ongoing Climate Change

Regional to Global

Adaptation: What Can Be Done?

Responses to:
- Sea Level Rise & Flooding
- Heat & Drought
- Extreme Weather Events

- Migration
  - Domestic
  - International
  - Interplanetary?
- Sea walls and hardening of structures
- Infrastructure Resilience remember Texas?
- Agricultural Adaptations
- Air Conditioning (especially in tropics)

most
All of these are already underway…

Amelioration: What Can Be Done?

- Mitigation

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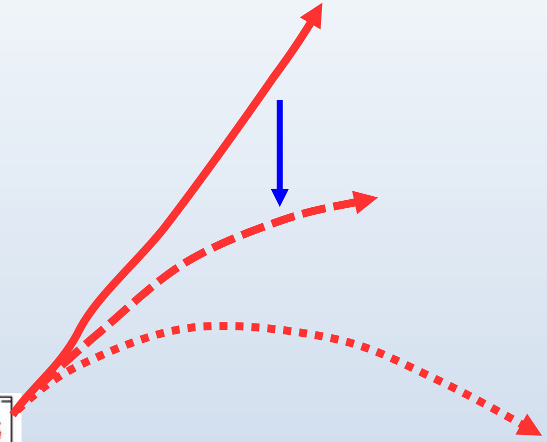
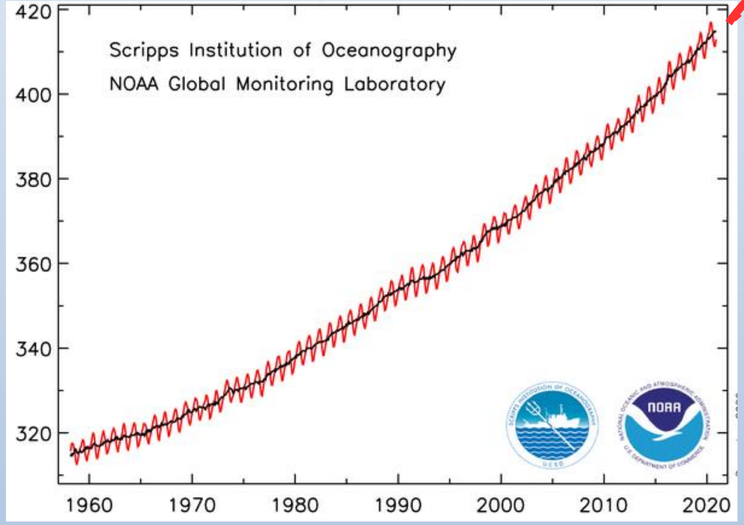
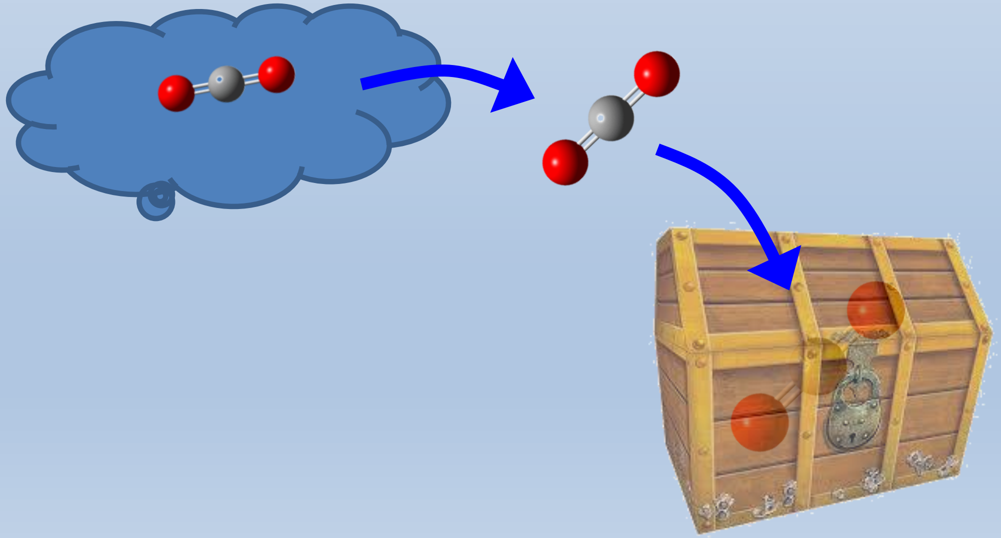
Interventions



① Suck CO_2 out of the Atmosphere

"Negative Emissions"





Interventions

① Suck CO_2 out of the Atmosphere

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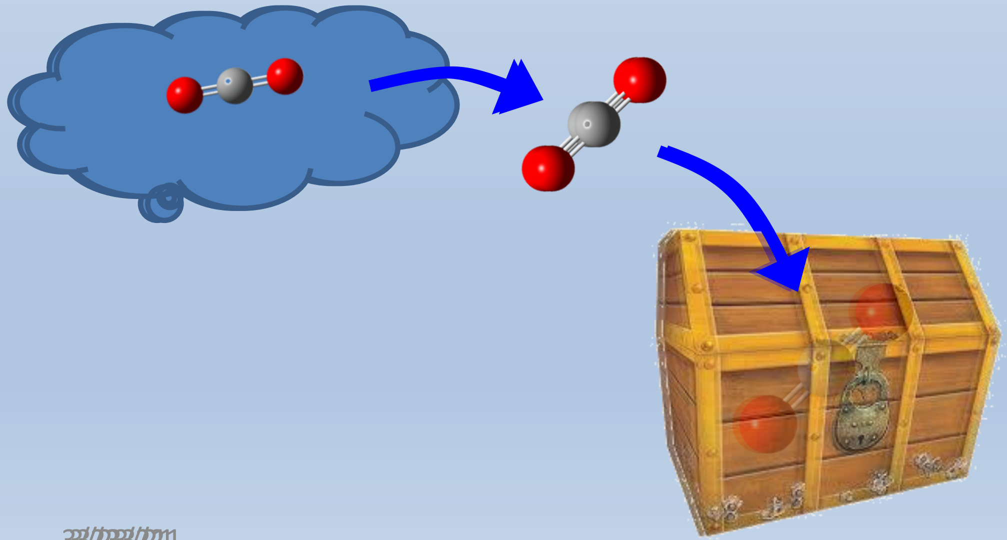
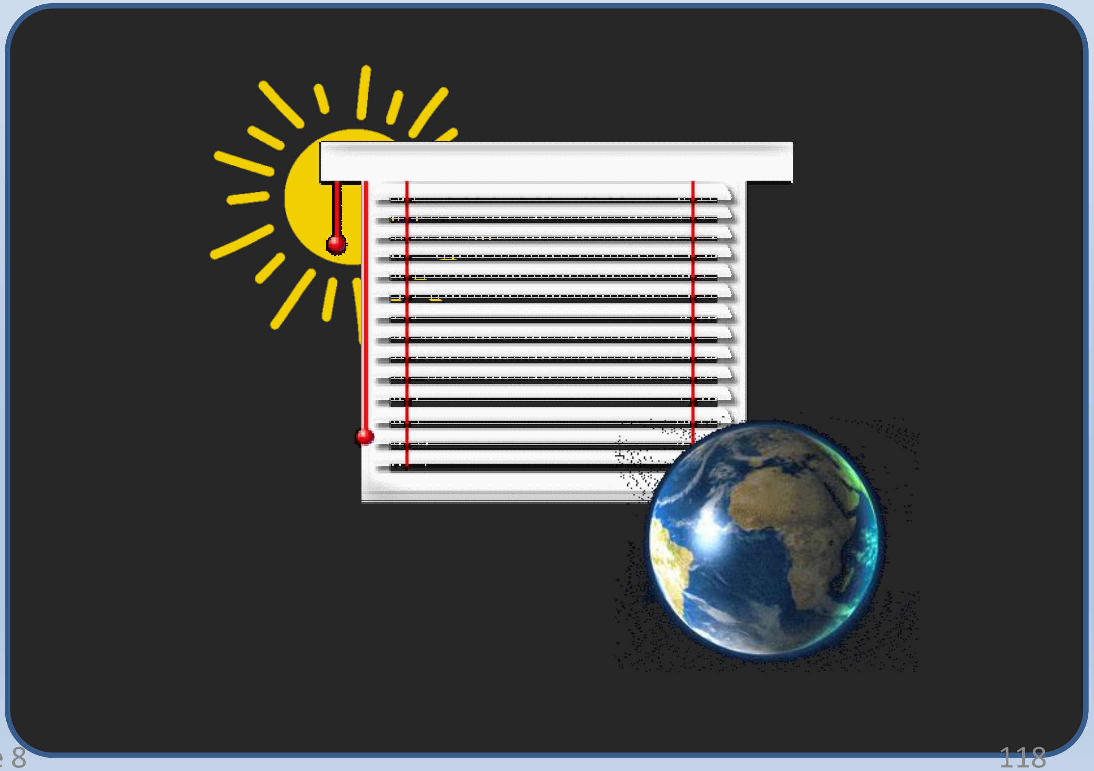


② Cut down on Solar Heating

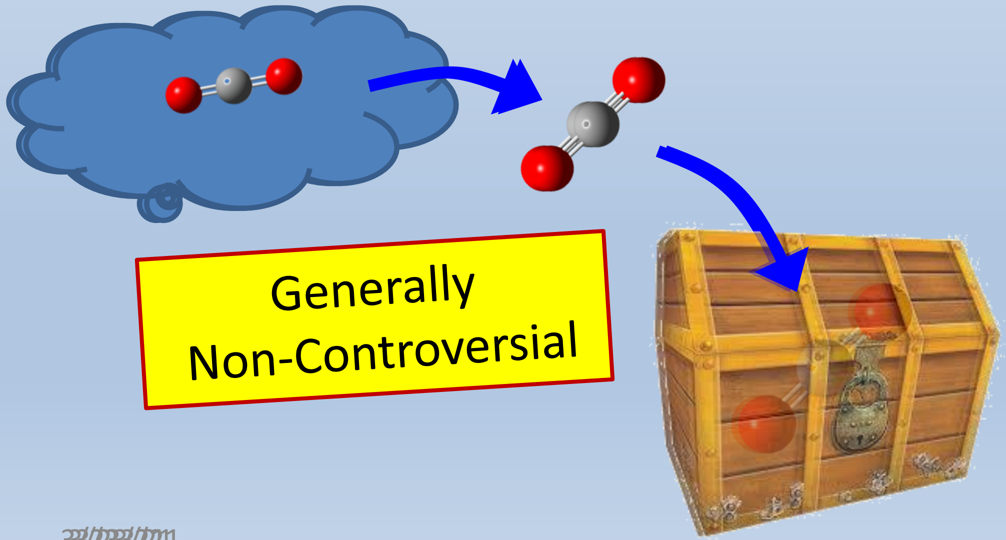
"Geo-Engineering"



Interventions

① Suck CO_2 out of the Atmosphere

"Negative Emissions"



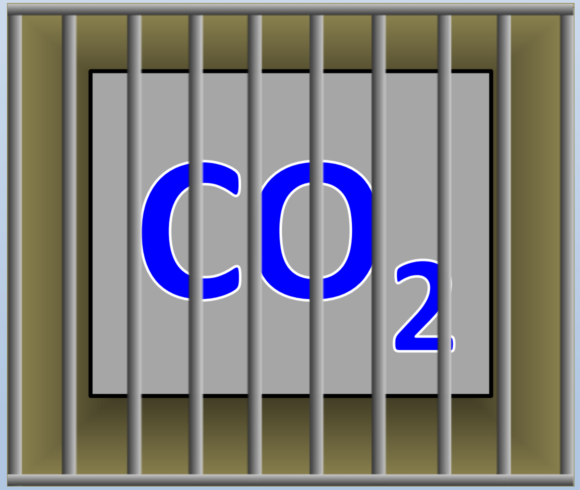
Generally Non-Controversial

② Cut down on Solar Heating

"Geo-Engineering"

Extremely Controversial

Negative Emissions



Afforestation: Great Green Walls

Three-North Shelter Forest Program

(66 Billion Trees planted as of 2017)

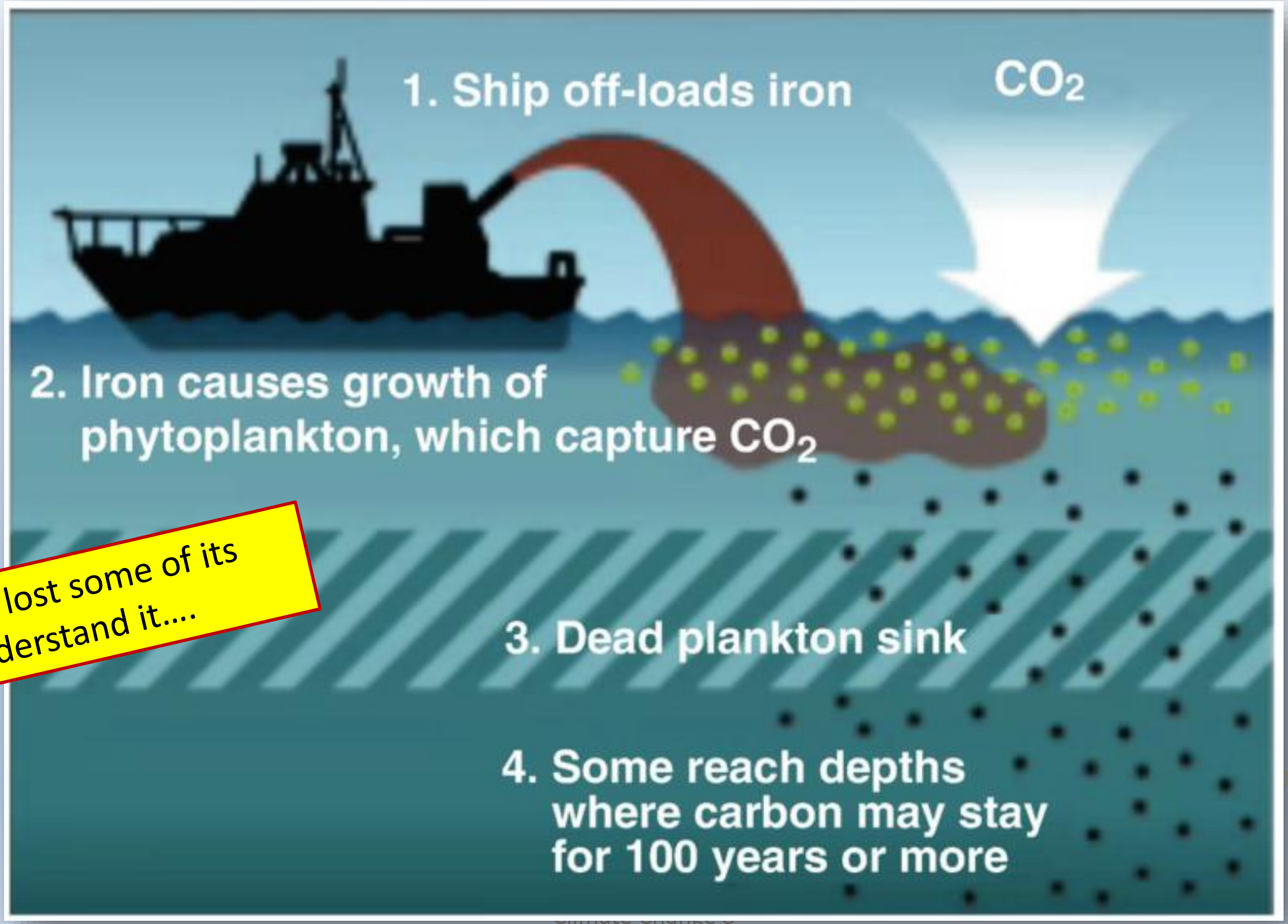
Sahel Great Green Wall

(Started 2007, 15% ?)

Worldwide, reforestation can provide some carbon sequestration, but not nearly enough.

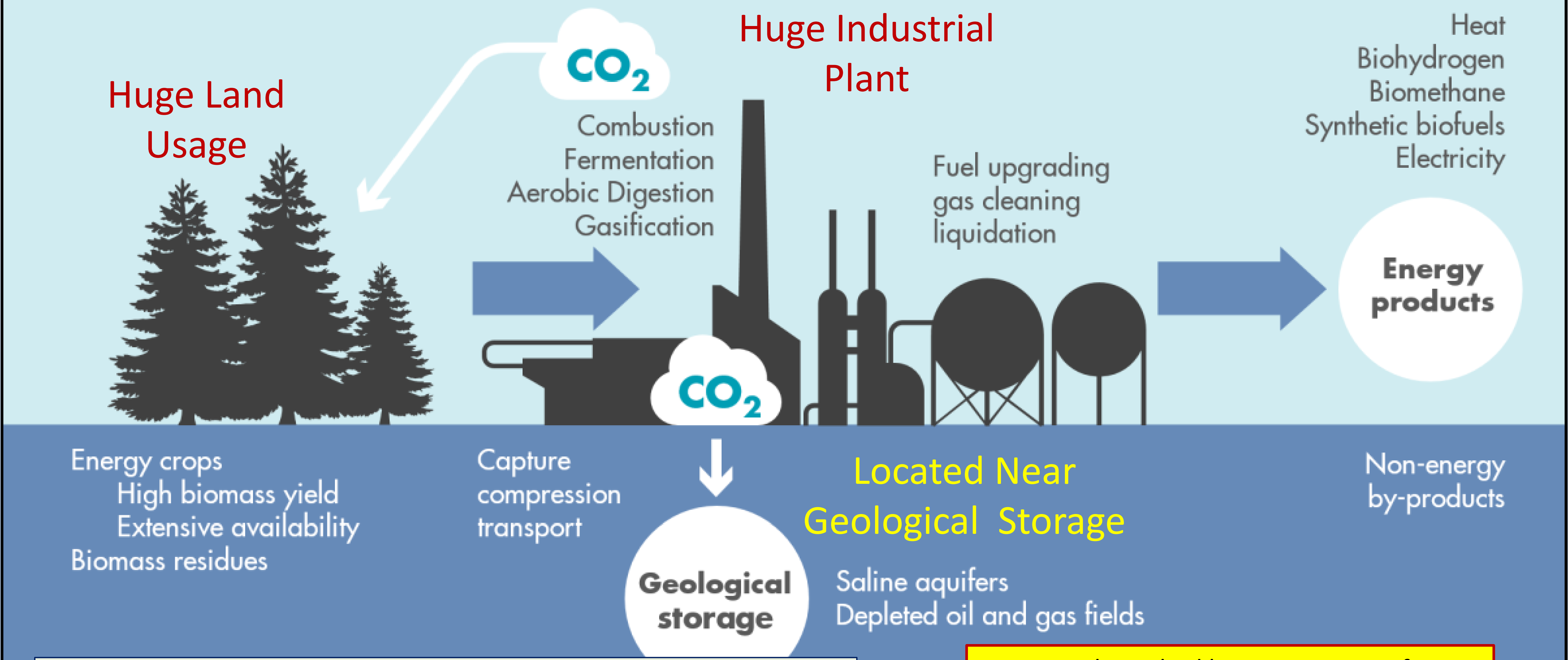
Green Walls have had mixed results, Chine doing somewhat better. Sahel Green Wall now recast as a development project.

Ocean Fertilization



This proposal has lost some of its luster, as I understand it….

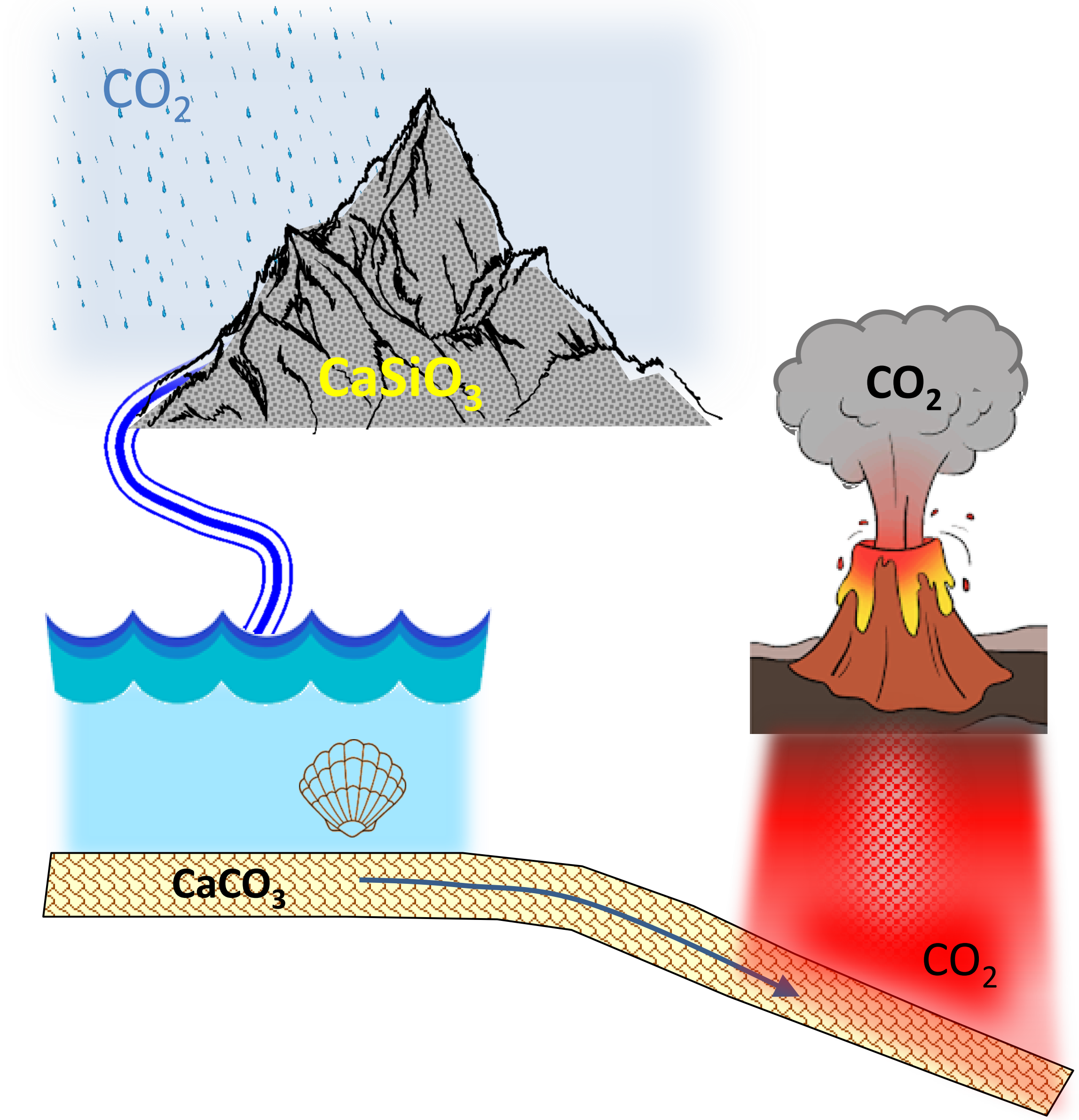
BECCS* Concept

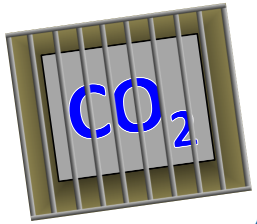


* **B**io **E**nergy with **C**arbon **C**apture & **S**torage

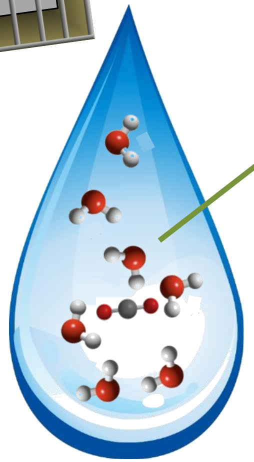
Strongly pushed by IPCC as a two-fer:
Remove CO2 from atmosphere AND get synthetic biofuels for transportation.

Remember the Weathering Reaction?



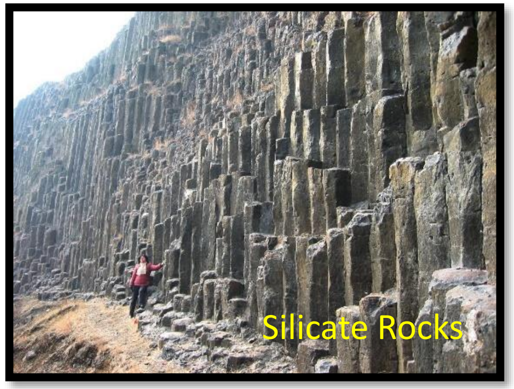


Weathering Reaction



pH **5.6**

Simple Example:
Wollastonite
Calcium Silicate
$CaSiO_3$



Rivers to Ocean

Silicic Acid

$$\underbrace{2\,CO_2 + 3\,H_2O}_{\text{Rain Water}} + \underbrace{CaSiO_3}_{\text{Rock}} \rightarrow \underbrace{Ca^{++} + 2\,HCO_3^{=}}_{\text{Makings of CaCO}} + H_4SiO_4$$

$\downarrow$ **Diatoms**

H_2O + $\mathbf{SiO_2}$

What if we sped this reaction up **100,000x** ?

“Enhanced Weathering” to Remove CO_2

- Grind up Basalt Rocks (Gigatons/year) into fine powder
- Sprinkle on Oceans *or* Land

Enhanced Weathering Proposal

PERSPECTIVE
2018
https://doi.org/10.1038/s41477-018-0108-y
nature plants
Corrected: Publisher Correction

Farming with crops and rocks to address global climate, food and soil security

David J. Beerling[1*], Jonathan R. Leake[1], Stephen P. Long[2,3,4], Julie D. Scholes[1], Jurriaan Ton[1], Paul N. Nelson[5], Michael Bird[5], Euripides Kantzas[1], Lyla L. Taylor[1], Binoy Sarkar[1], Mike Kelland[1], Evan DeLucia[2,3], Ilsa Kantola[2], Christoph Müller[6], Greg H. Rau[7] and James Hansen[8]

The magnitude of future climate change could be moderated by immediately reducing the amount of CO_2 entering the atmosphere as a result of energy generation and by adopting strategies that actively remove CO_2 from it. Biogeochemical improvement of soils by adding crushed, fast-reacting silicate rocks to croplands is one such CO_2-removal strategy. This approach has the potential to improve crop production, increase protection from pests and diseases, and restore soil fertility and structure. Managed croplands worldwide are already equipped for frequent rock dust additions to soils, making rapid adoption at scale feasible, and the potential benefits could generate financial incentives for widespread adoption in the agricultural sector. However, there are still obstacles to be surmounted. Audited field-scale assessments of the efficacy of CO_2 capture are urgently required together with detailed environmental monitoring. A cost-effective way to meet the rock requirements for CO_2 removal must be found, possibly involving the recycling of silicate waste materials. Finally, issues of public perception, trust and acceptance must also be addressed.

Rising concentrations of atmospheric CO_2, and other greenhouse gases (GHGs) emitted by human activities, are already having substantial adverse climate impacts that threaten global food security[1,2]. These impacts include more intense heat waves and droughts, as well as more extreme and variable rain- needed for meeting the United Nations targets requires rapid phasing out of fossil fuel emissions and the deployment of scalable approaches for CO_2 removal (CDR) from the atmosphere with so-called negative CO_2 emissions in the second half of the twenty-first century[7–9]. The danger of sea-level rise with the loss of productive

Prof. Stephen P. Long

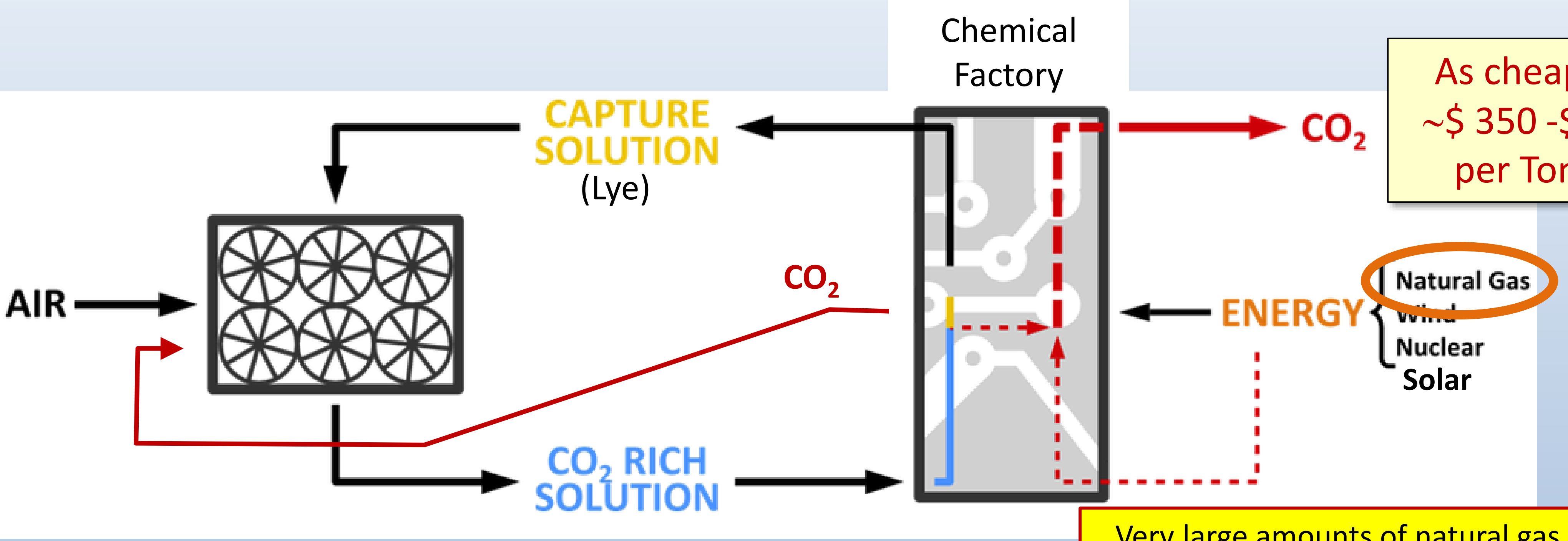
Carl Woese Institute for Genomic Biology
&
Dept. of Plant Biology

Suggest dusting most croplands worldwide with ~20 Gton/year of powdered basalt rock.
This is similar to total raw mineral mining worldwide.

Very large <u>energy input</u> required to pulverize and transport the rock.

Direct Carbon Capture

Direct Carbon Capture

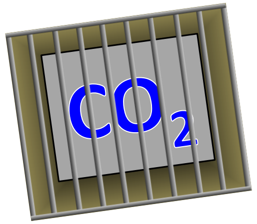


As cheap as ~$ 350 -$500 per Ton C

Very large amounts of natural gas needed for heat to run process at full scale… Even so, net CO2 capture is achieved.

Carbon Engineering Ltd.
Squamish, B.C.

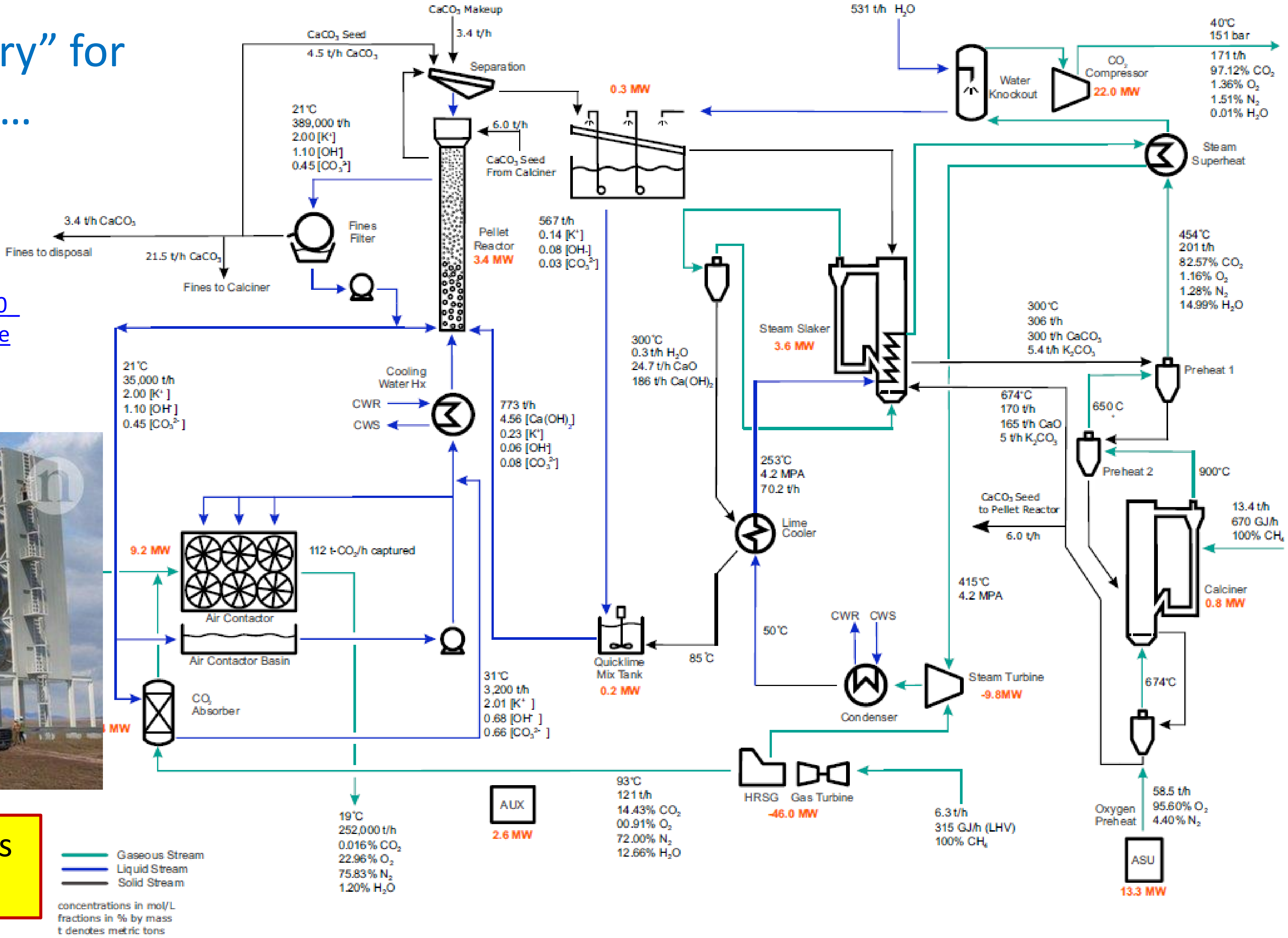
Bill Gates is an investor in Carbon Engineering….



A "Simple Factory" for Carbon Capture…

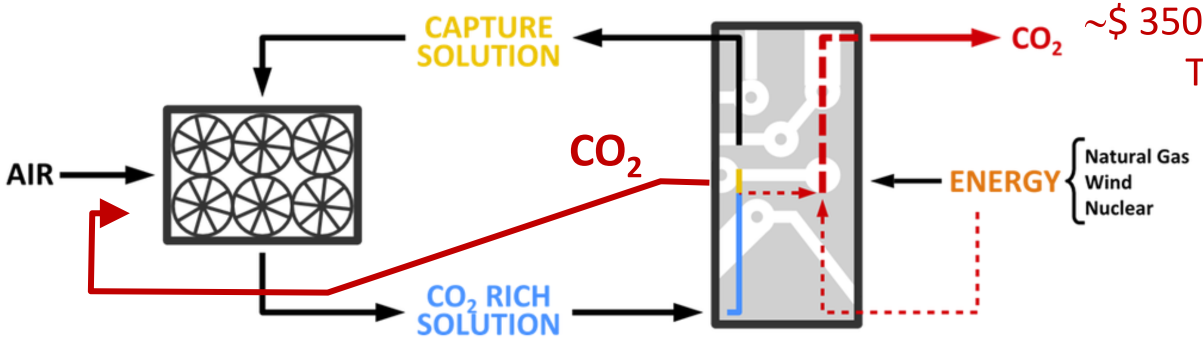
David Keith *et al*
Joule (June 2018)

https://www.researchgate.net/publication/325639480_A_Process_for_Capturing_CO2_from_the_Atmosphere



Full details published, making process quite credible.

Direct Carbon Capture: What's It Good For?



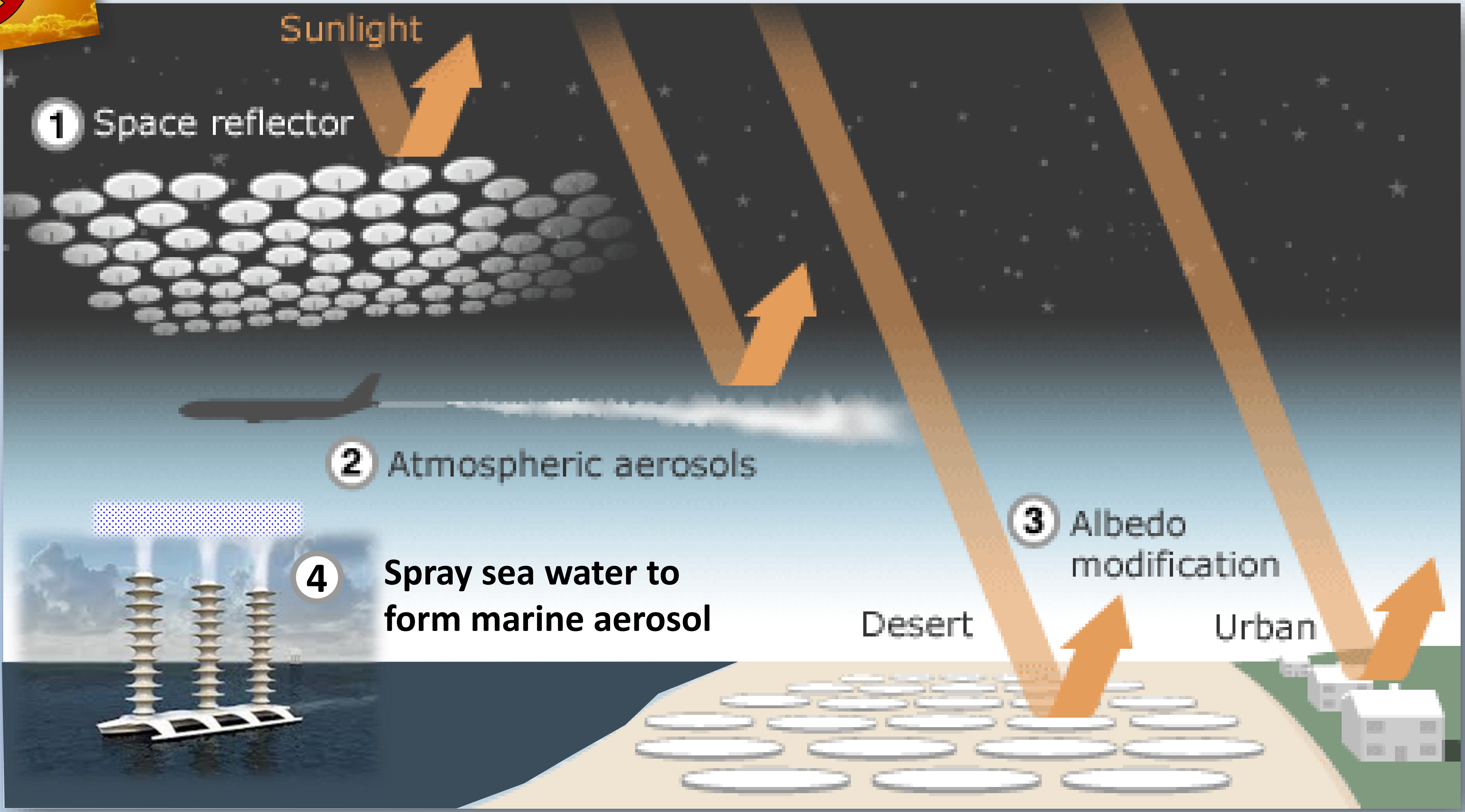
~\$ 350 -\$500 per Ton C

- Justify Keeping Fossil Fuel Power Plants Working? Economically Ridiculous
- Massive program to Lower Atmospheric CO_2 ? Maybe, but very expensive
- Extract Carbon to Make Synfuels? Yes, this is Carbon Engineering's Goal
  - Combined with Renewable Hydrogen

Make Drop-In Transportation Fuels, for Aircraft e.g.

Geo-Engineering: Sun Control

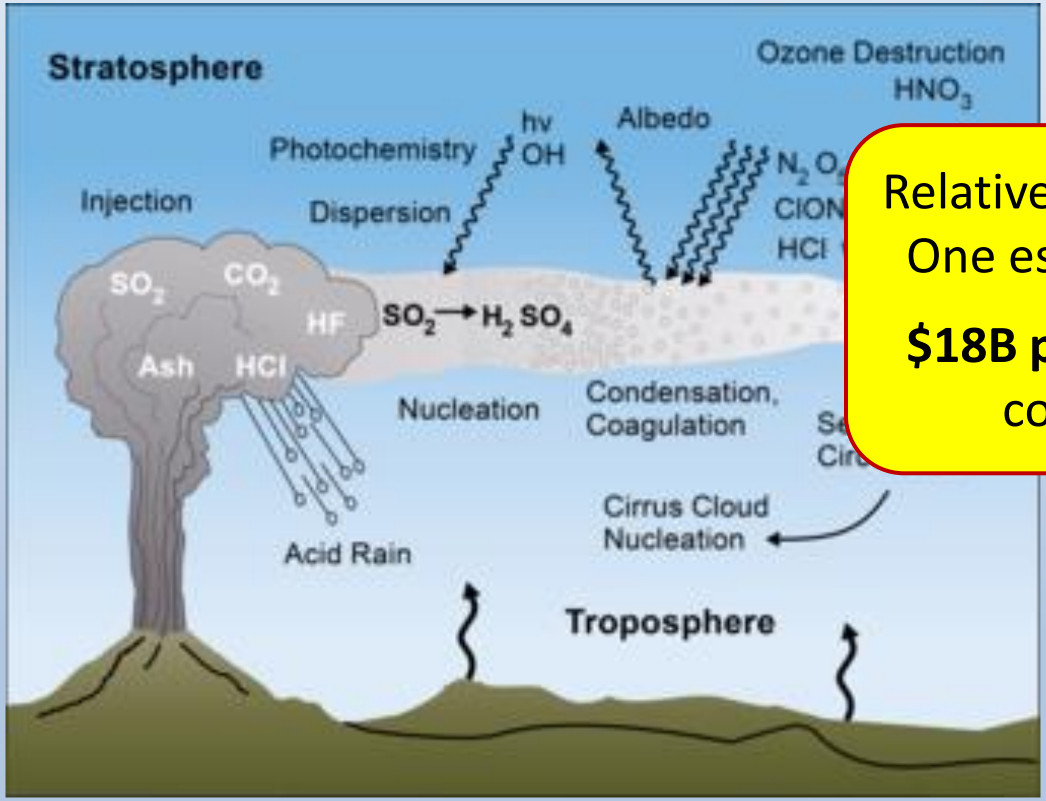
Some Geoengineering Proposals



4 **Spray sea water to form marine aerosol**

Stratospheric Sulfate Aerosols

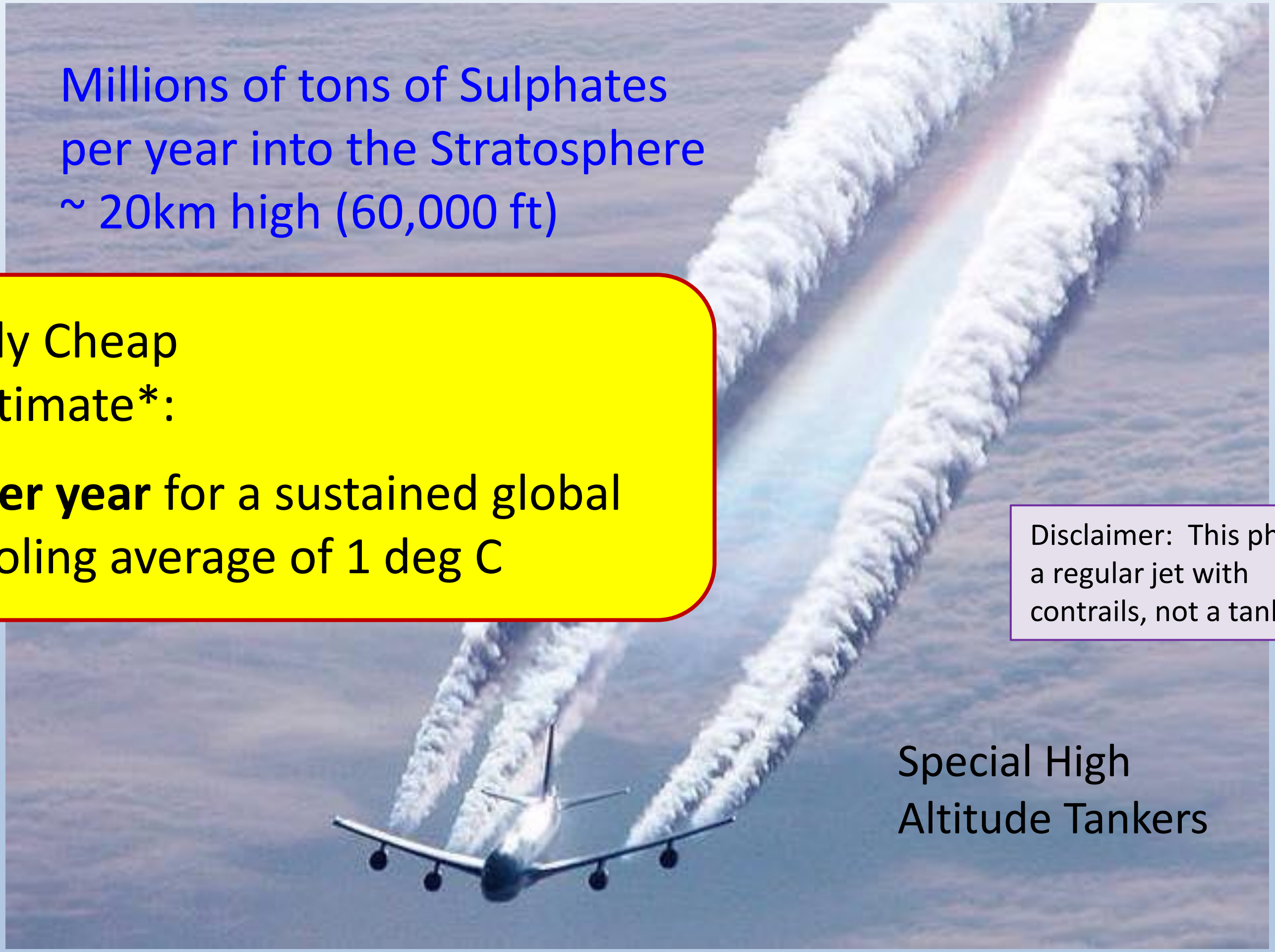
This is the main proposal – mimics major volcanic eruptions



Relatively Cheap

One estimate*:

$18B per year for a sustained global cooling average of 1 deg C



Millions of tons of Sulphates per year into the Stratosphere ~ 20km high (60,000 ft)

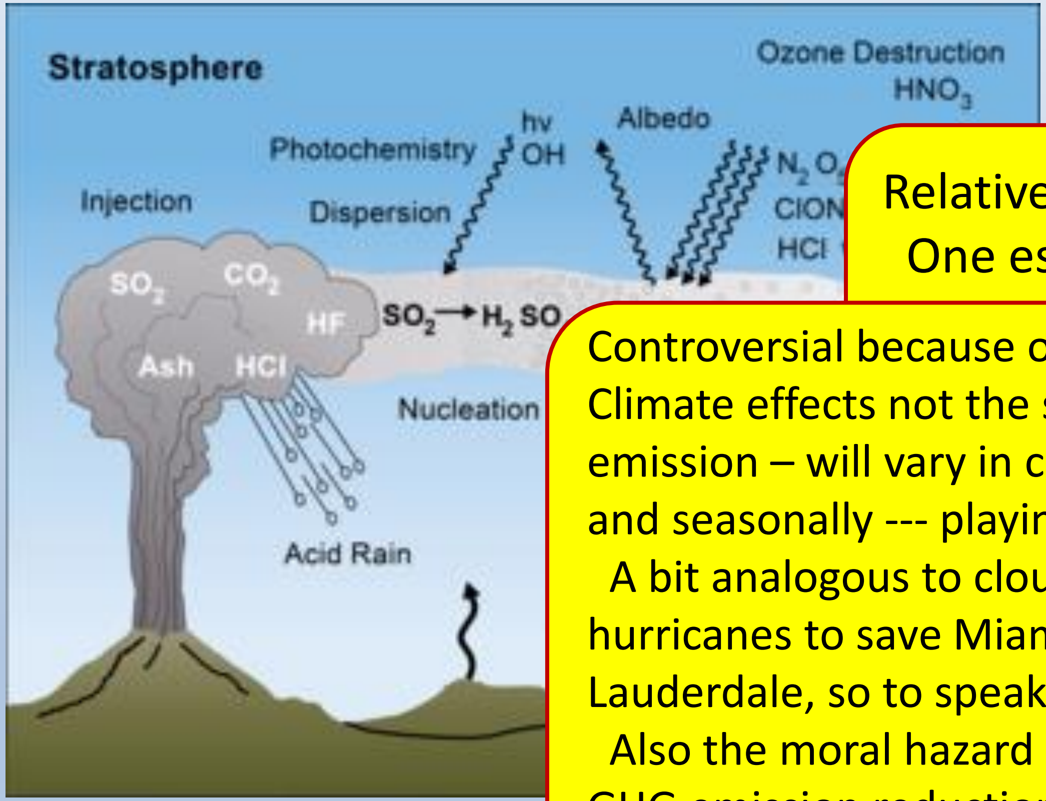
Special High Altitude Tankers

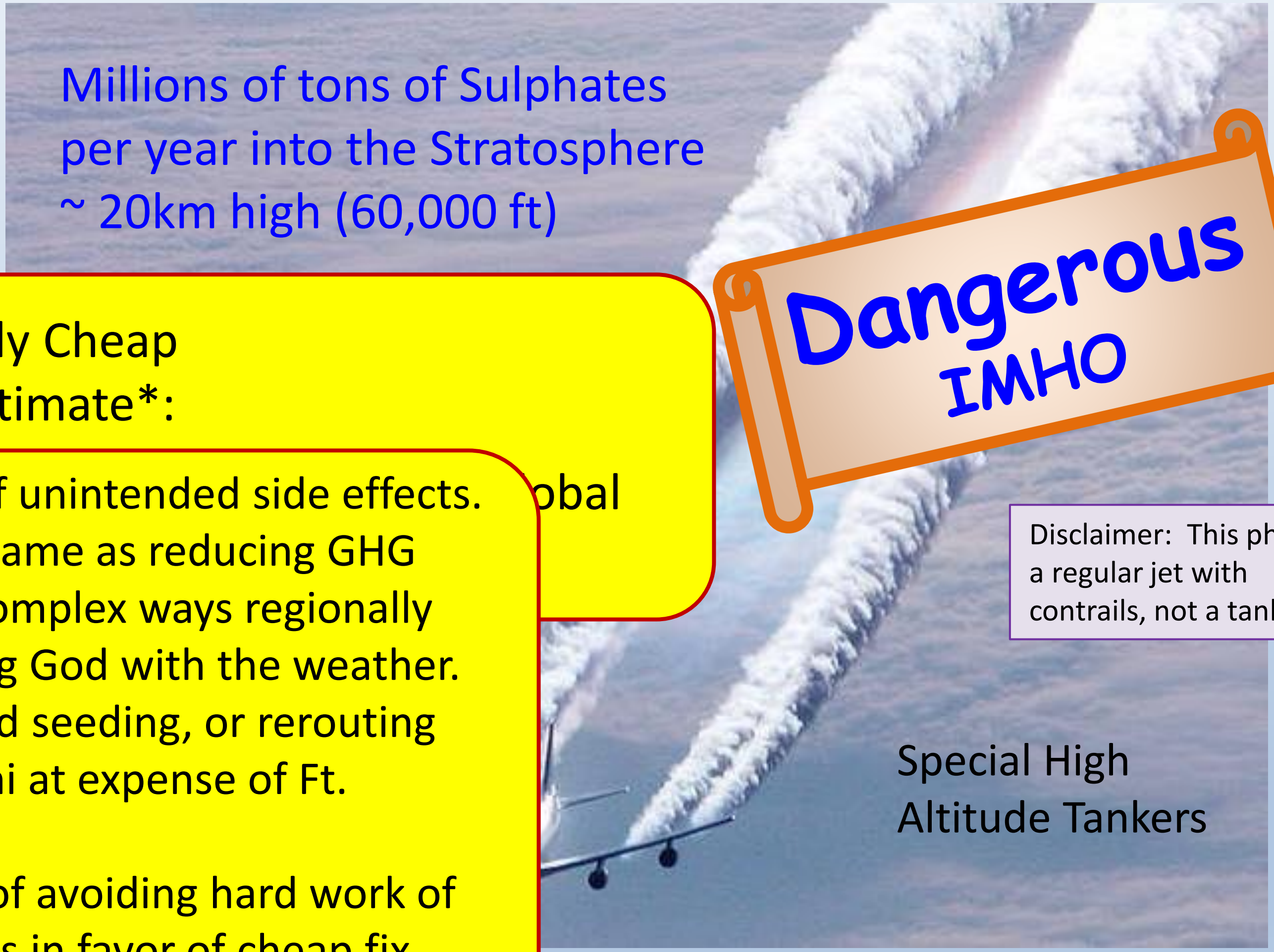
Disclaimer: This photo is a regular jet with contrails, not a tanker.

* Wake Smith, *The Cost of Stratospheric Aerosol Injection through 2100*, Environmental Research Letters (2020)

Stratospheric Sulfate Aerosols

This is the main proposal – mimics major volcanic eruptions





Millions of tons of Sulphates per year into the Stratosphere ~ 20km high (60,000 ft)

Relatively Cheap
One estimate*:

obal

Controversial because of unintended side effects. Climate effects not the same as reducing GHG emission – will vary in complex ways regionally and seasonally --- playing God with the weather.

A bit analogous to cloud seeding, or rerouting hurricanes to save Miami at expense of Ft. Lauderdale, so to speak.

Also the moral hazard of avoiding hard work of GHG emission reductions in favor of cheap fix that has to be kept up indefinitely – centuries.

In any case, would not prevent ocean acidification, e.g.

Disclaimer: This photo is a regular jet with contrails, not a tanker.

Special High Altitude Tankers

tratospheric Aerosol Injection through 2100,
ental Research Letters (2020)

OP-ED

Questions?