Science and Technology Challenges and Opportunities for Net-Zero Emissions Energy Systems

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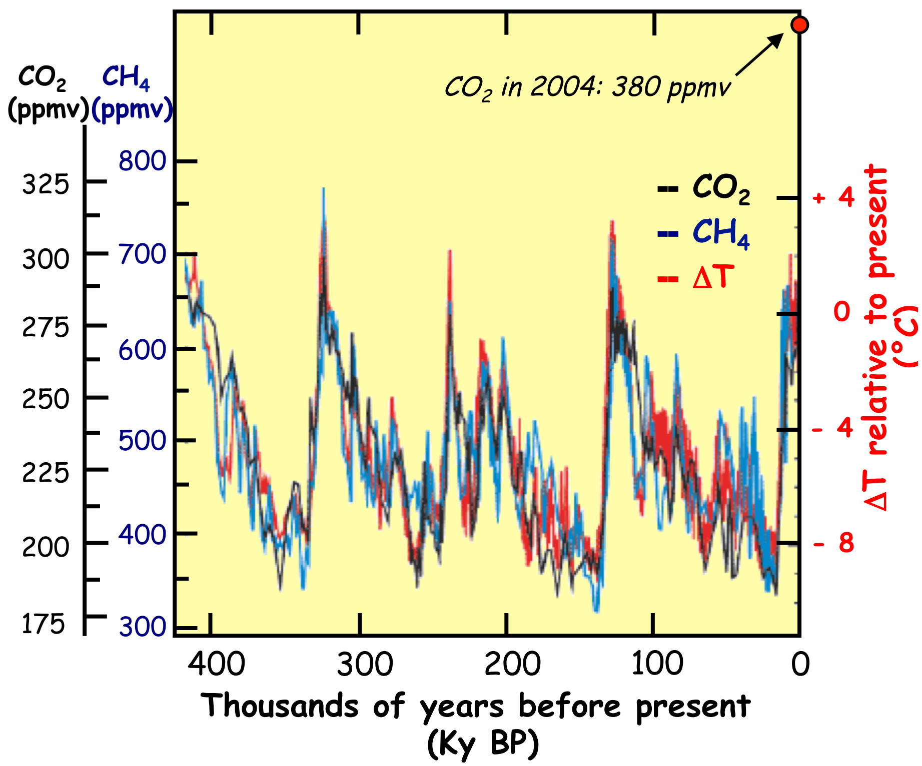
Humanity's Top Ten Problems for next 50 years

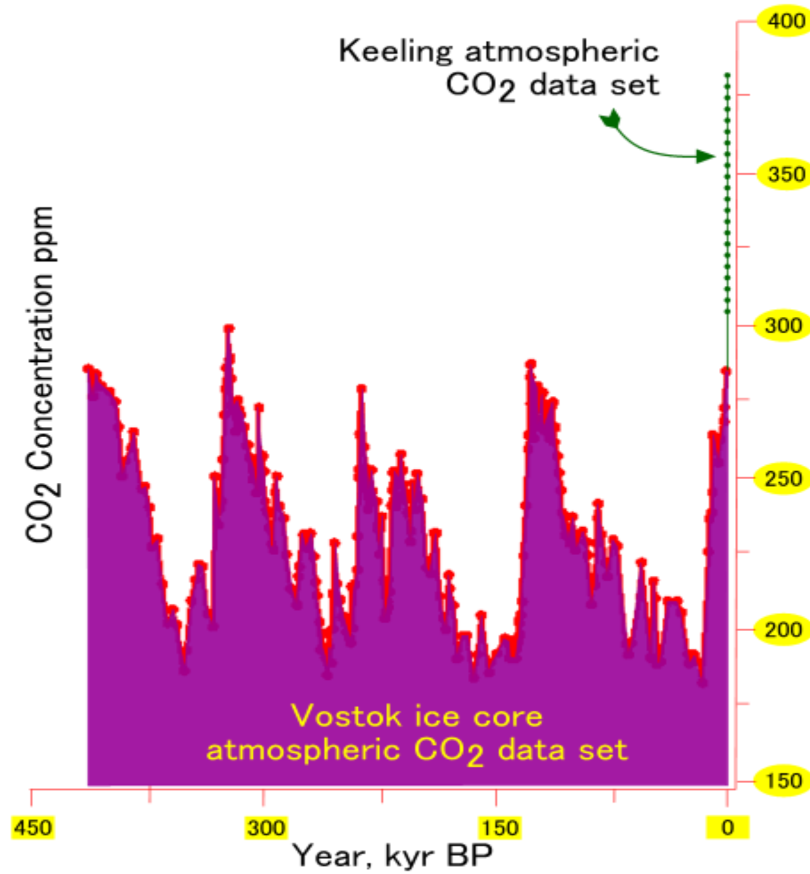
1. **ENERGY**
2. WATER
3. FOOD
4. ENVIRONMENT
5. POVERTY
6. TERRORISM & WAR
7. DISEASE
8. EDUCATION
9. DEMOCRACY
10. POPULATION

2003	**6.5**	**Billion People**
2050	**8-10**	**Billion People**

Fossil: Climate Change



Climate Change 2001: The Scientific Basis, Fig 2.22



Intergovernmental Panel on Climate Change, 2001
http://www.ipcc.ch
*N. Oreskes, Science **306**, 1686, 2004*
*D. A. Stainforth et al, Nature **433**, 403, 2005*

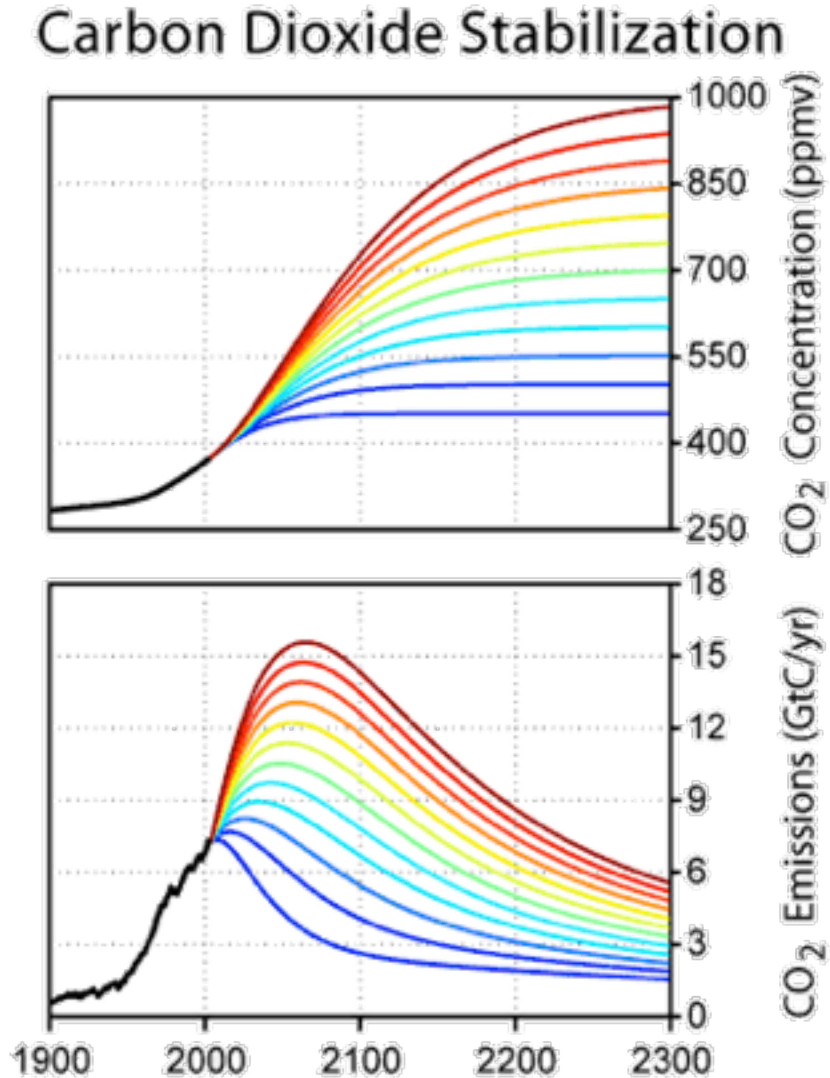
Relaxation time

transport of CO_2 or heat to deep ocean: >3000 years

How Much do Emissions Need to Reduce?

Net cumulative emissions drive concentrations…

- **Carbon emissions trajectories versus CO_2**
  - Cumulative emissions total determines the resulting CO_2 concentration
  - To stabilize the CO_2 concentration, emissions must go to *net* zero



Renewable Energy

Solar
120,000 TW at Earth's surface

energy gap
~ 14 TW by 2050
~ 33 TW by 2100

Wind
2-4 TW extractable

Biomass
5-7 TW gross
all cultivatable
land not used
for food

Tide/Ocean Currents
2 TW gross

Hydroelectric

4.6 TW gross
1.6 TW technically feasible
0.9 TW economically feasible
0.6 TW installed capacity

Geothermal

12 TW gross over land
small fraction recoverable

EES Vol 1, Issue 1, July 8, 2008

According to the Journal Citation Reports, the journal has a 2017 impact factor of 30.067, ranking it 4th out of 163 journals in the category "Chemistry, Multidisciplinary",[2] first out of 88 journals in the category "Energy & Fuels",[3] first out of 135 journals in the category "Engineering, Chemical",[4] and first among 225 journals in the category "Environmental Sciences".[5]

The challenge and need for *Energy & Environmental Science*

DOI: 10.1039/b810864c

> "Energy is the single most important challenge facing humanity today."
> *Nobel Laureate Rick Smalley, April 2004, Testimony to U.S. Senate*

Energy issues—encompassing generation costs, security of supply, and the environmental consequences of waste streams—are foremost among the world's geopolitical concerns. The fossil fuels—coal, natural gas, and petroleum—supply approximately 85% of all the energy consumed today by the world's industrialized nations. Energy is vitally needed to bring electric power to the one quarter of the world's population that currently lacks it, to support the industrialization of developing nations to bring billions out of poverty, and to sustain economic growth and productivity in developed countries. Ensuring security of the domestic energy supply is currently a major national security issue for many countries. In addition, climate change considerations are receiving unprecedented levels of importance in affecting regional, national and global energy policy decisions.

Yet the historical approach to addressing increased energy supply needs, fossil fuel consumption coupled with energy conservation, will not be scaleable to meet future energy demands. U.N. projections indicate that meeting global energy demand in a sustainable fashion by the year 2050 will require not only increased energy efficiency and entirely new methods of utilizing existing carbon-based fuels, but will additionally require a very significant fraction of the U.S. and global energy supply to be in the form of carbon-free power.

Where will this energy come from, and how can it be produced and utilized in an environmentally sustainable fashion?

The answers are not presently known, but several aspects are clear. First, the most important energy problems hinge upon fundamental advances in science and technology. Second, ultimately we as a society will have to replace fossil fuels for much of our energy needs, yet at the present time we are not positioned to do so, and hence continued short-term reliance on fossil fuels appears inevitable. The most fruitful research directions will thus be ones that embrace these realities.

Energy research can be broadly categorized into three themes: increased that range from new insights into photovoltaics to the synthesis of important new hydrogen storage materials; from new developments in hydrogen production from biomass to global climate change; from artificial photosynthesis to fuel cells; and from environmental catalysis to nanostructured materials for energy applications. In addition, position papers and perspectives from key thought leaders on the economic, social, political and environmental impacts of energy use, of changes in the energy mix, and of changes in the value proposition offered by new and different energy efficiencies and energy services will also be a key part of the journal.

Progress in transitioning to a globally scalable and sustainable energy system is a world-wide problem and demands contributions from scientists, engineers, economists, policy makers, and decision makers around the world. Rapid progress on this urgent issue depends on the integration of perspectives in all of these areas, which is the underlying and unique charter of *Energy & Environmental Science* as a leading, interdisciplinary journal.

Professor Nathan Lewis
George L. Argyros Professor of Chemistry, California Institute of Technology

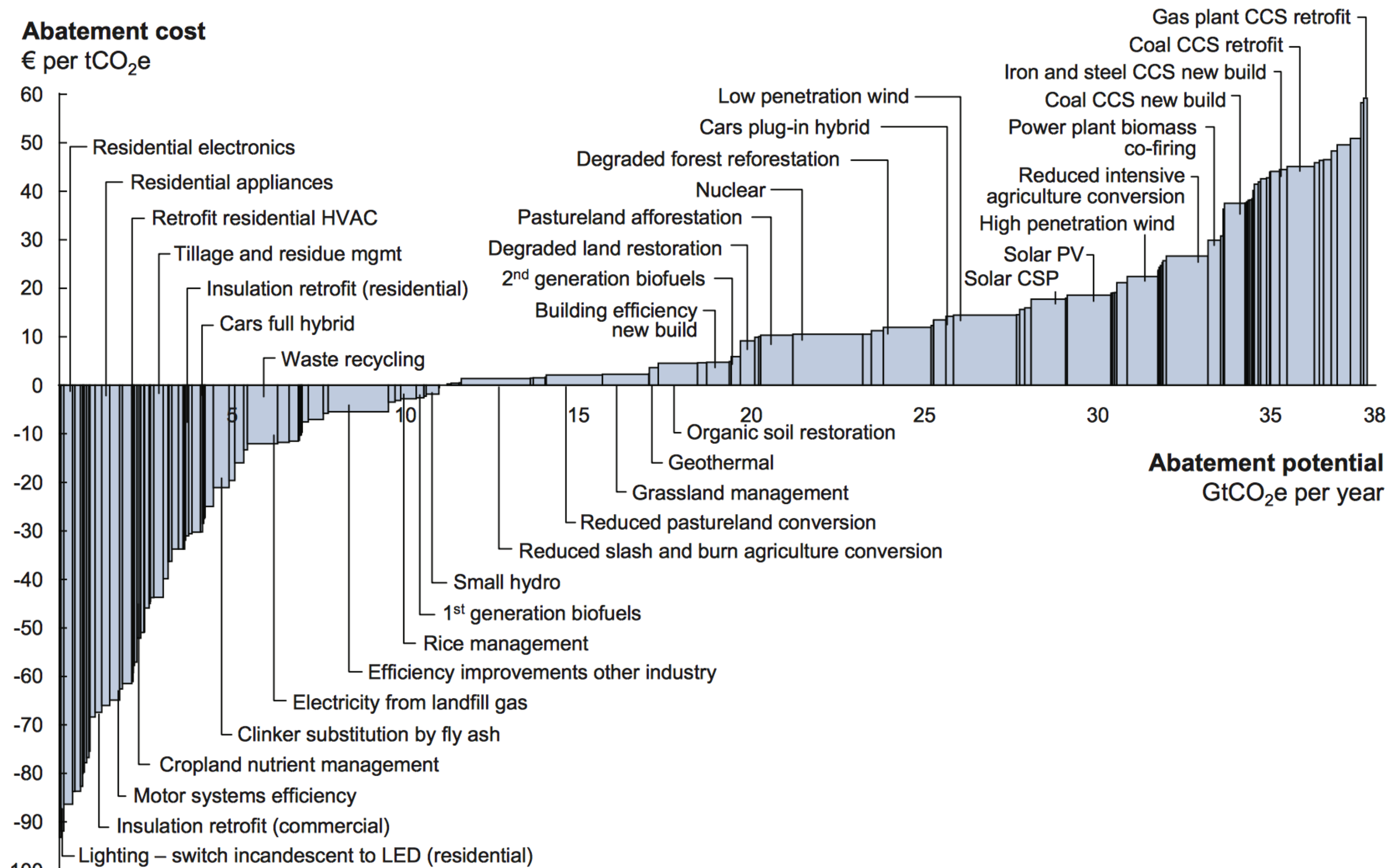
Opportunities and Challenges in Energy R&D

Focus on Materials (science, engineering, chemistry, physics…)

- Materials for the built environment
- Materials in extreme environments
- New wind turbines
- Rethinking Solar PV
- Low-cost grid-scale energy storage
- Structural Materials: cement, steel
- Carbon-neutral transportation fuels
- Negative emissions
- Legal/liability
- Geoengineering
- Ocean Chemistry

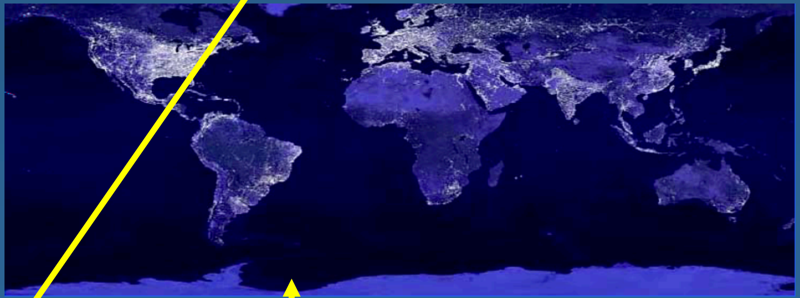
Global Costs of CO_2 Abatement: McKinsey

Global GHG abatement cost curve beyond business-as-usual – 2030



Note: The curve presents an estimate of the maximum potential of all technical GHG abatement measures below €60 per tCO_2e if each lever was pursued aggressively. It is not a forecast of what role different abatement measures and technologies will play.
Source: Global GHG Abatement Cost Curve v2.0

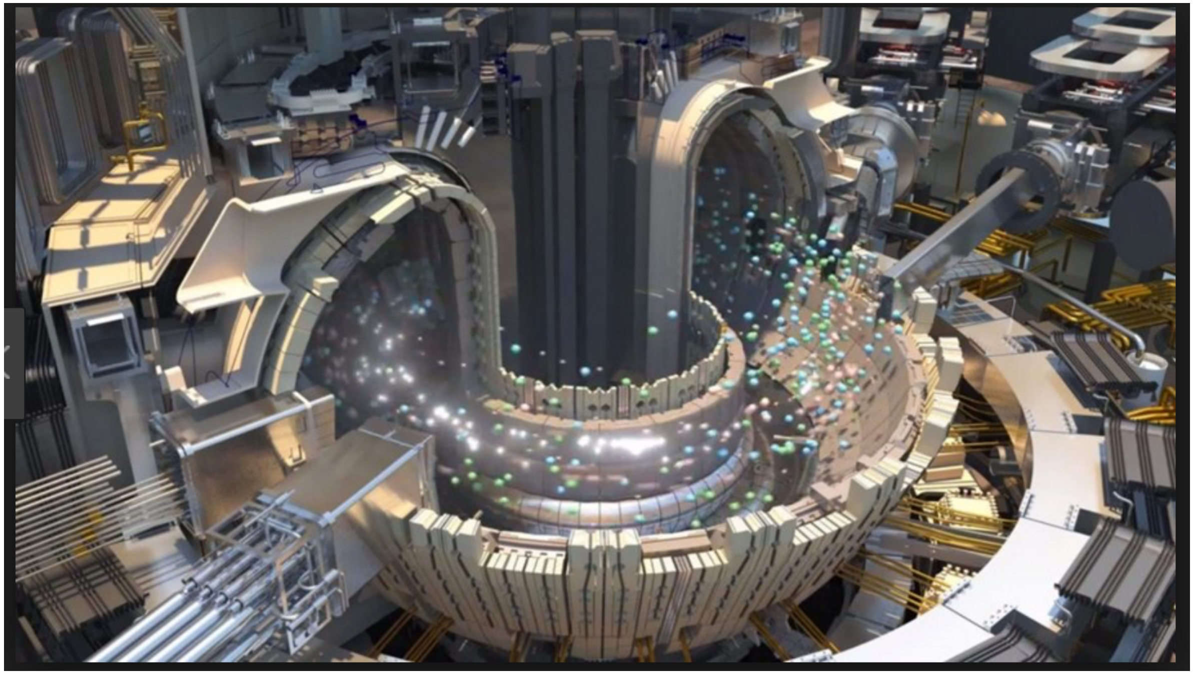
Power Units: The Terawatt Challenge



	1	10^3	10^6	10^9	10^{12}
Power	1 W	1 kW	1 MW	1 GW	1 TW

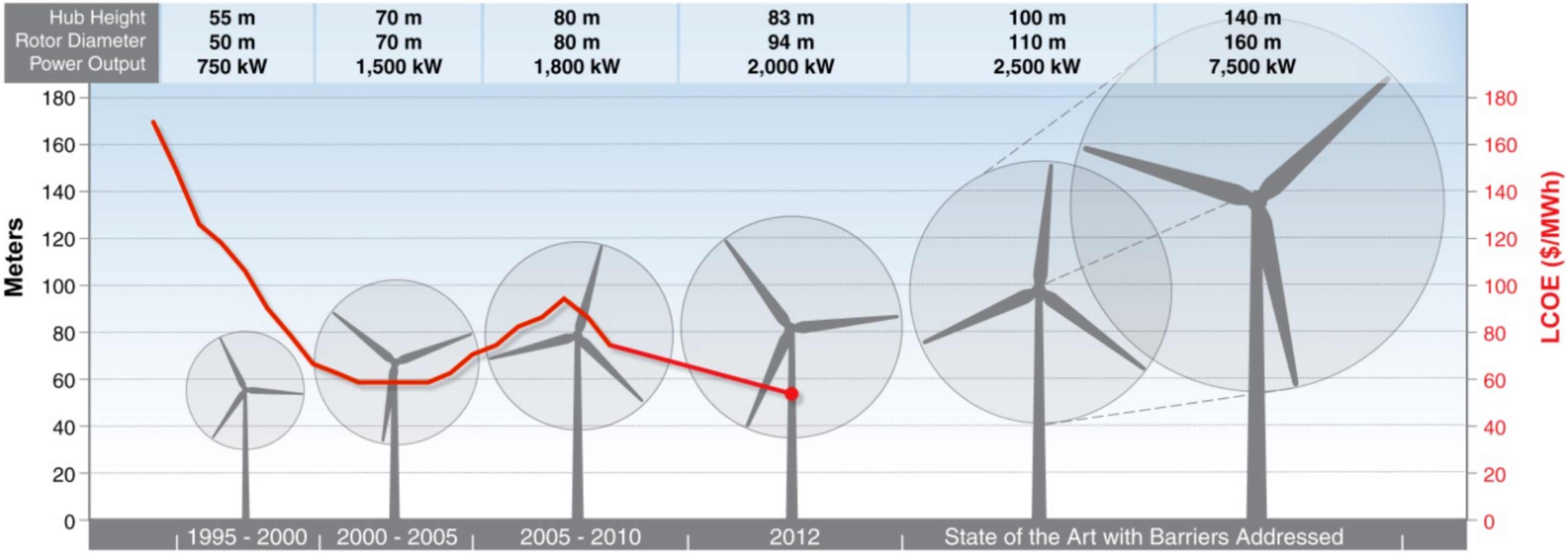
Nuclear fission and fusion power

- Materials in extreme environments
  - fusion (ITER)
  - small modular reactors (SMR's)
  - gas cooled reactors
  - U-Th cycles



Wind Power

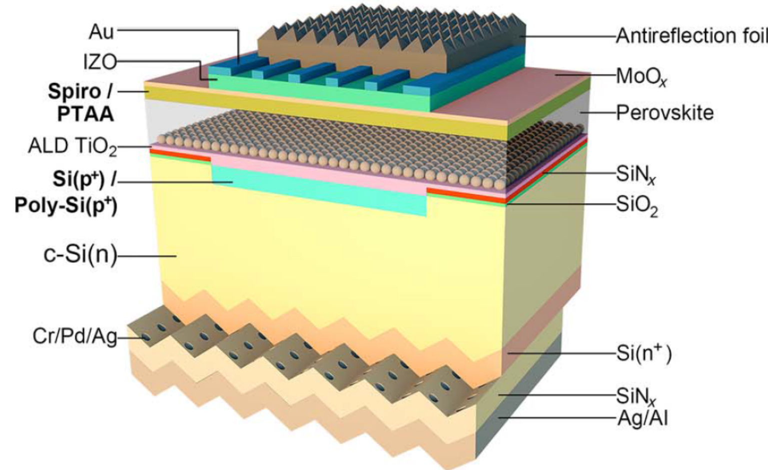
On-site manufacturable or self-assembled blades
Nd substitutes



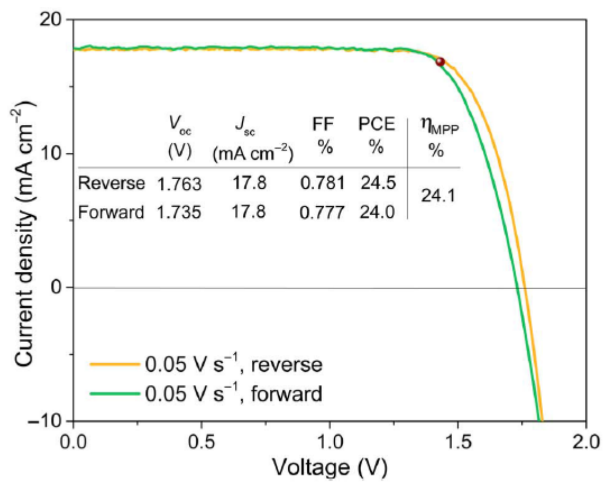
TiO_2 Junction for Perovskite/Si Tandem Photovoltaic Cell

T(3)3.19 Develop and characterize engineered interface layers.

- **Extended "leaky" ALD TiO_2 used for stabilization layers to tunnel junction for perovskite tandems, with potential 1 Sun efficiencies of 30%**
- Low contact resistance between ALD TiO_2 and Si allows a two-terminal perovskite/Si tandem cell to be built with fewer optical losses and processing steps than cells with conventional interlayers.
- Stabilized photovoltaic efficiencies of 22.9% (Si homojunction) and 24.1% (Si heterojunction) were obtained for the perovskite/Si tandem cells.
- ALD TiO_2 may enable straightforward integration of Si solar cells with other light absorbers to create efficient tandem cells.



Schematic of the interlayer-free perovskite/Si tandem cell.



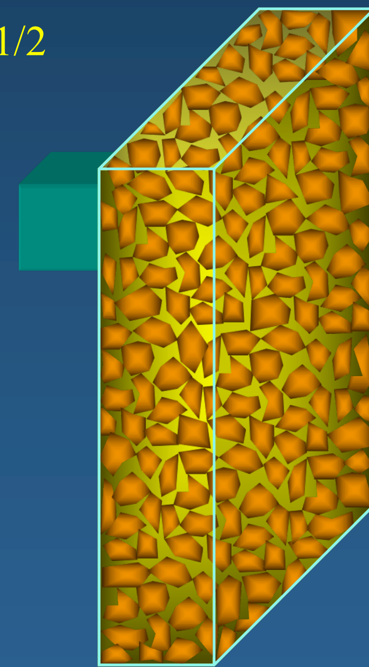
Performance of the perovskite/Si tandem cell made with the heterojunction poly-Si subcell.

Shen, H.; Omelchenko, S. T.; Jacobs, D. A.; Yalamanchili, S.; Wan, Y.; Yan, D.; Phang, P.; Duong, T.; Wu, Y.; Yin, Y.; Samundsett, C.; Peng, J.; Wu, N.; White, T. P.; Andersson, G. G.; Lewis, N. S.; Catchpole, K. R., *Science Advances* **2018**, *4* (12), eaau9711.

JCAP
JOINT CENTER FOR ARTIFICIAL PHOTOSYNTHESIS

Cost vs. Efficiency Tradeoff

Efficiency $\propto \tau^{1/2}$



Large Grain
Single
Crystals

Small Grain
And/or
Polycrystalline
Solids

d

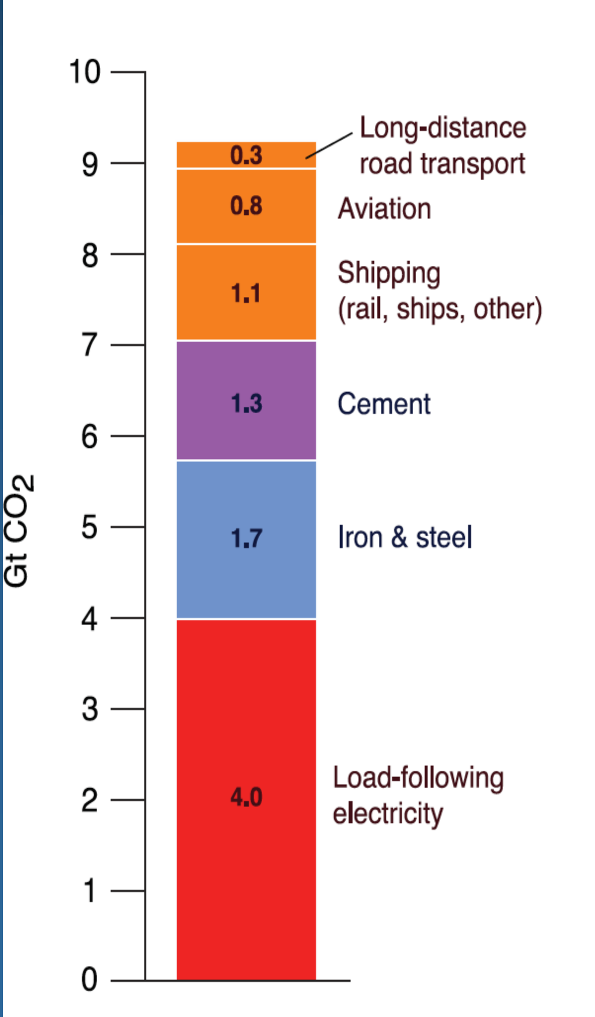
d

Long d
High τ
High Cost

Long d
Low τ
Lower Cost

τ decreases as grain size (and cost) decreases

Difficult to Decarbonize Energy Services

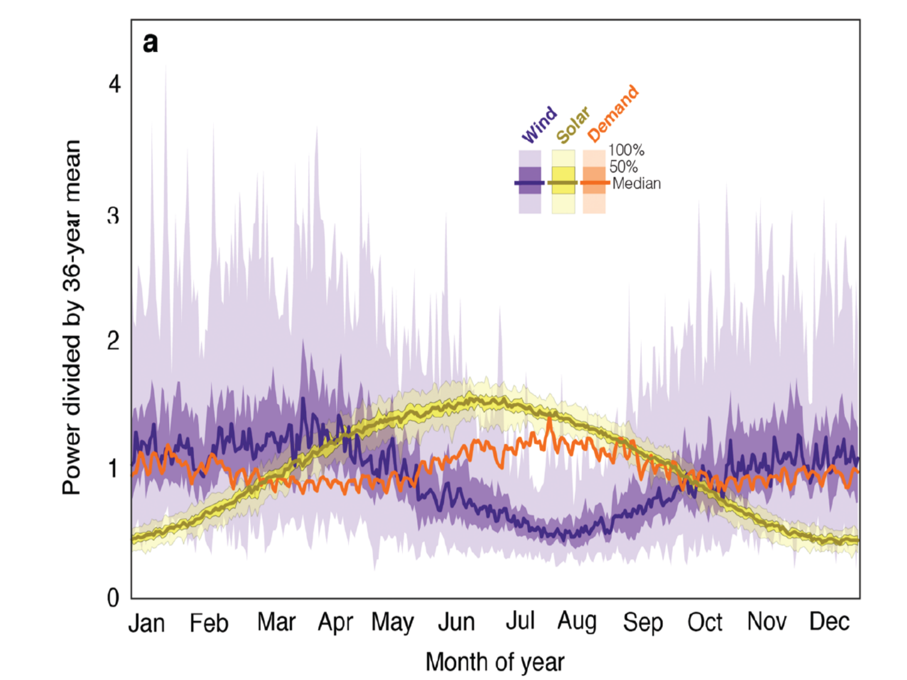


B **Difficult-to-eliminate emissions, 2014 (9.2 Gt CO_2)**

Scientific Challenges

- long-duration electricity storage
- substitutes for cement, steel
- liquid fuels for freight, commerce transport

S. Davis, N. Lewis, K. Caldeira et al, Science, 360, eaas9793 2018

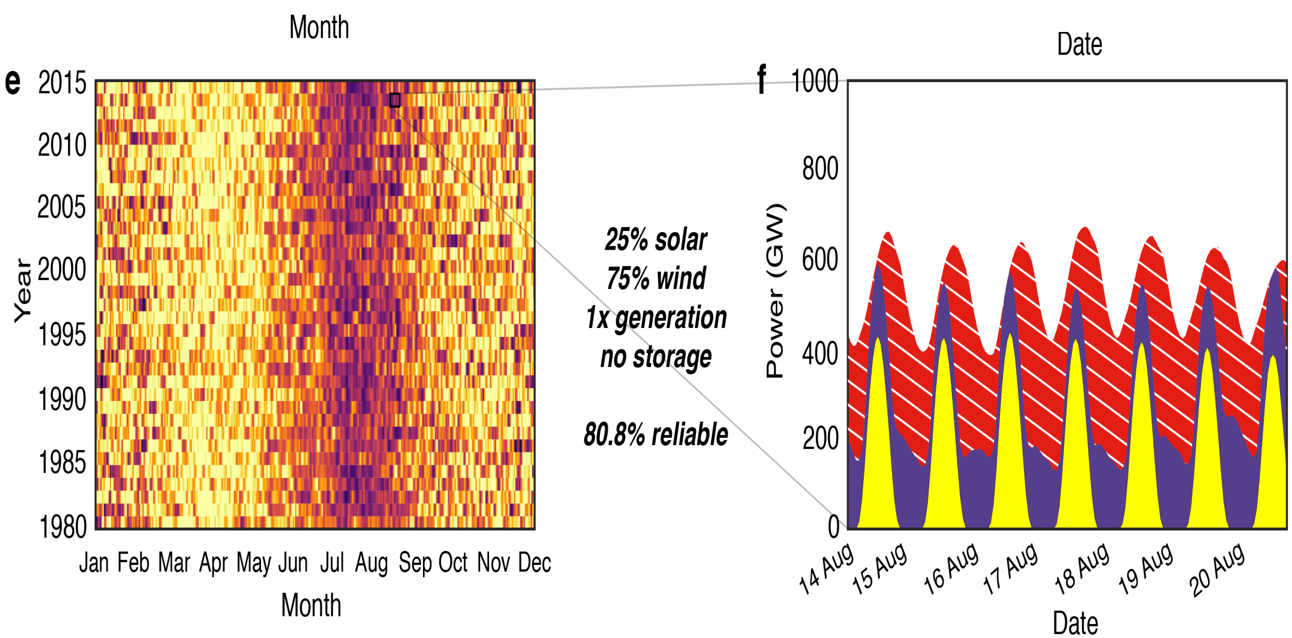


Geophysical constraints on the reliability of solar and wind power in the U.S.
M. Shaner, S. Davis, N. Lewis, K. Caldeira, EES, 2018, 11, 914-925

Renewables for Power Generation

Increases in reliability are very costly…

- With either 12 hours of storage ($2.7 trillion) or continental scale Power Super Highways ($400 billion), possible to get 80% of energy needs with solely wind + solar,
  But with only a sacrifice of reliability over multi-decade timescales … unpredictable massive blackouts of days/weeks
- Marginal increases in reliability only obtained with large *additional* increases in cost
- Natural gas is wind + solar's "best friend"
- No existing carbon-neutral storage technology combines low capex with modest opex/fuel costs, which is mandatory for cost-effective utilization of low-capacity-factor assets
- Over-capacity shifts the problem into under-utilization of assets



M. Shaner, S. Davis, N. Lewis, K. Caldeira, EES, 2018

Electricity Storage

- **Lead-acid**
  - Energy density:
    - Conventional $0.80-$1.00/KW-h
    - Advanced $0.40-0.50/KW-h
- **Na-S**
  - High temperature (so not suitable for cold starts in transportation)
  - Energy density: ~100 W-hr/kg
    - $0.30-$0.40/kW-h

GVEA 40 battery in Fairbanks, Alaska

- 1300 tons; 120 m x 26 m building
- 40 MW for 15 minutes, i.e. 10 MW-h
- Project Cost: $35 MM

- **Cost of storage higher than cost of generation**

- **Battery chemistry with no Li but C, S, O, Fe and other ultra-low cost materials**
- **Power-to-gas-to-power**

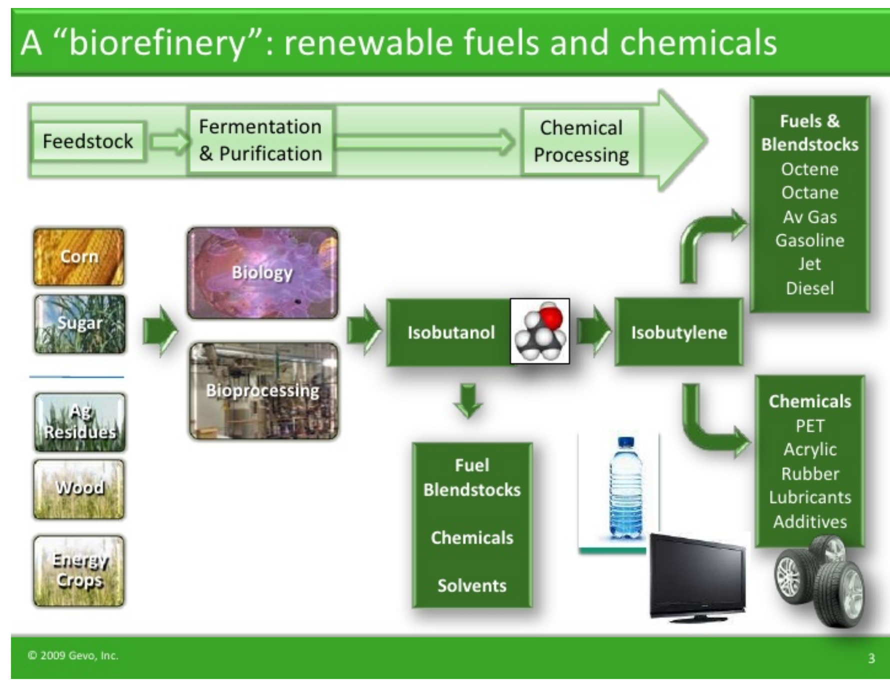
Structural Materials for Developed Civilization

- Per capita demand for cement, steel relatively constant (or increasing)
- Cement: $CaCO_3 \rightarrow CaO + CO_2$
- Steel: CO in blast furnace; grey cast iron: 4% C; up to 2% C for strength

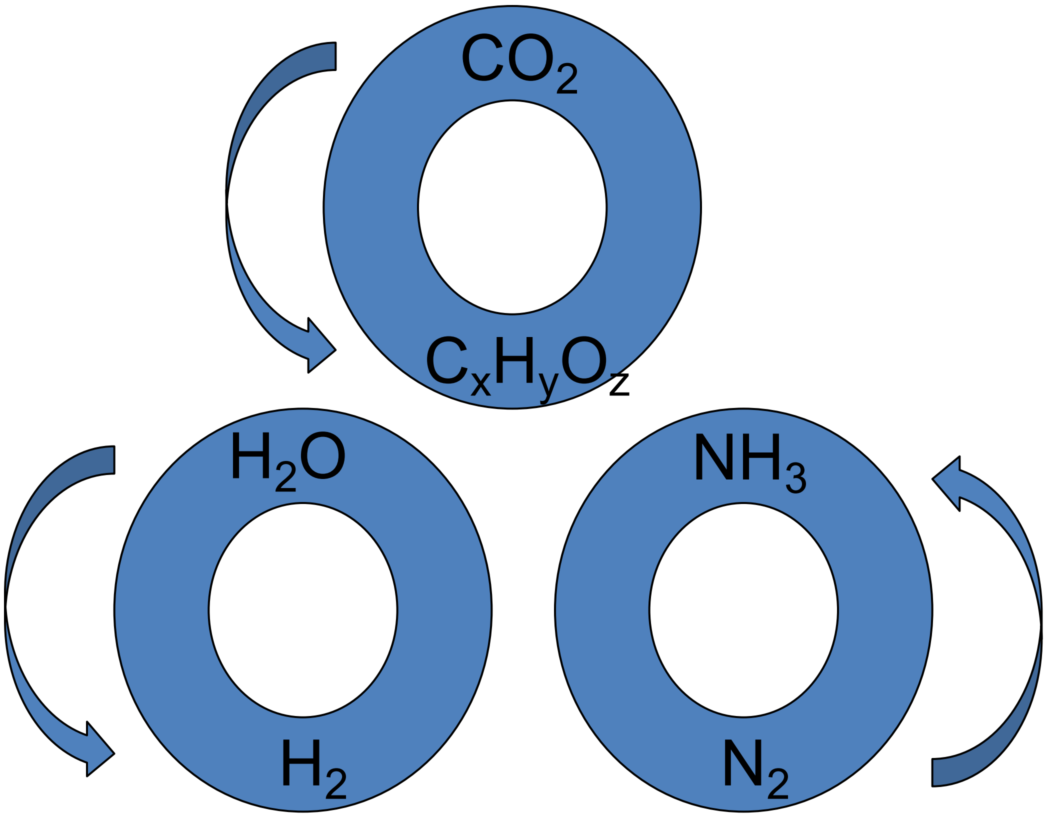
Alternative Transportation Fuels

Bio-fuels value proposition unfavorable…

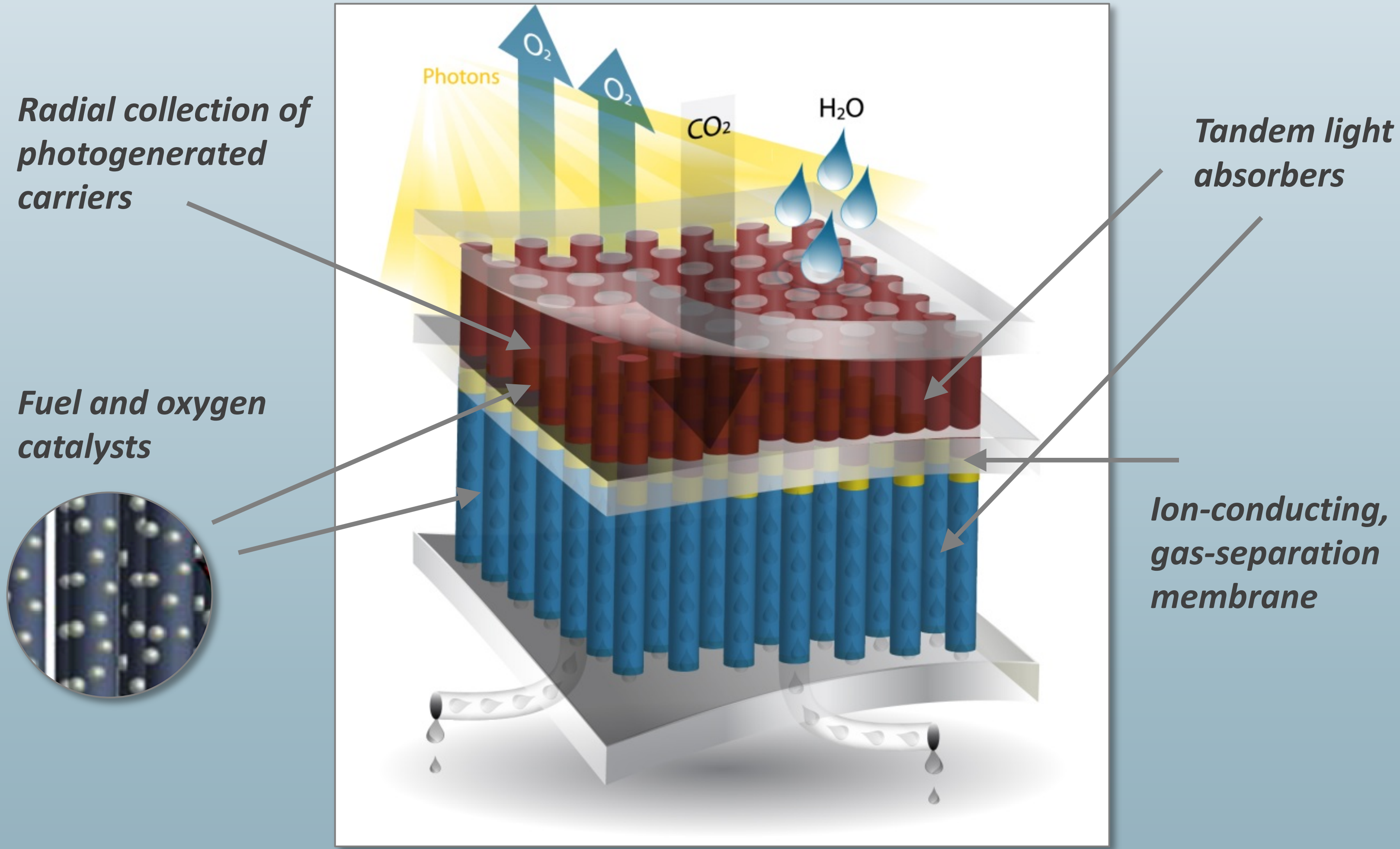
- **Land use concerns of biofuels**
  - Primary: "food for fuel"
  - Secondary: re-purpose more land for more food
  - Tilling releases trapped soil carbon, requires 50 - 500 years to "pay back"
- **Advanced (cellulosic) biofuel technology largely stalled**
  - "Recalcitrance" of cellulose
  - Goal: synthetic biology to selectively produce bio-butanol or actual diesel fuel in either plants or algae
  - Algae expensive: "farming in the desert"



Sustainable Biogeochemical Energy Cycles

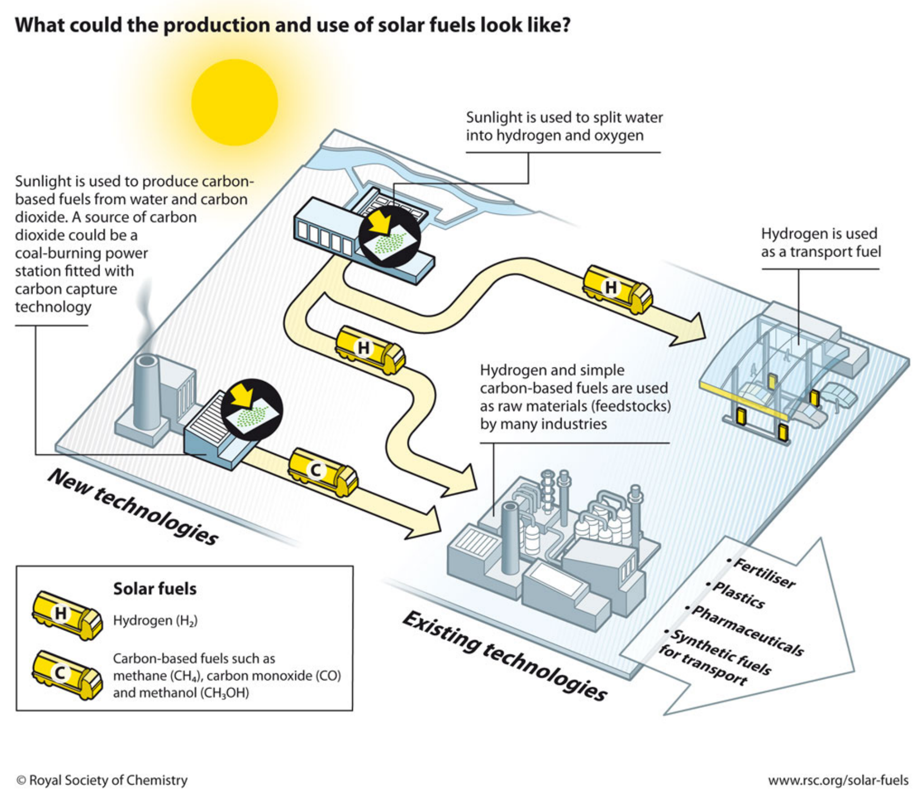


Blueprint for an Integrated Solar-Fuel Generator



Alternative Transportation Fuels

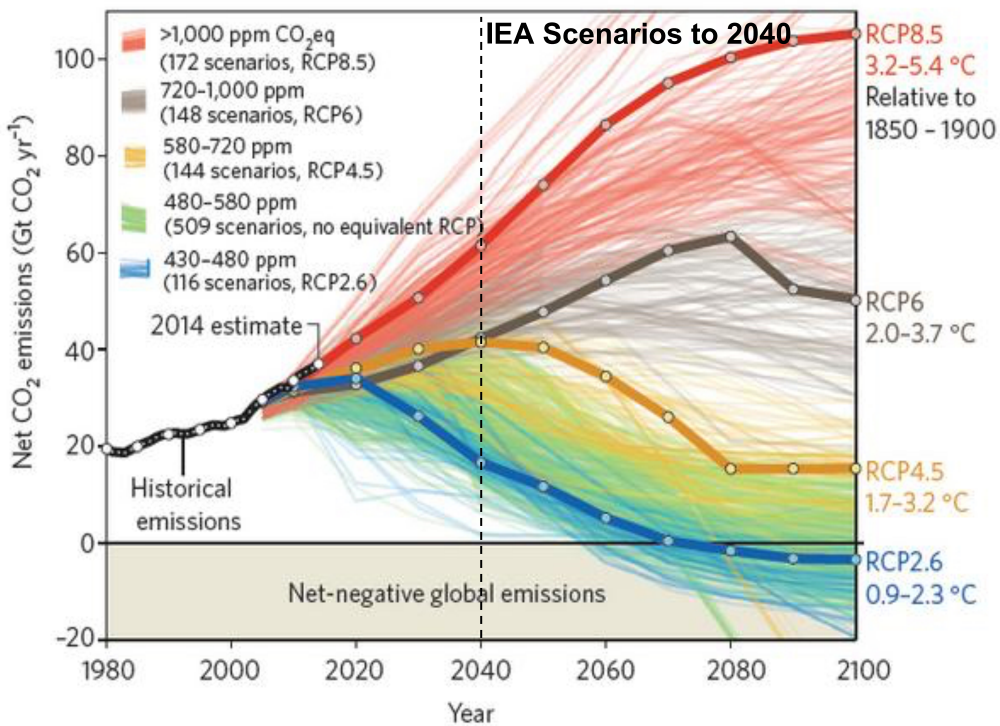
- Photosynthesis and "synthetic" fuels / solar fuels use sunlight, water, CO_2
- H_2 by electrolysis from wind / solar / nuclear electricity
- Capture CO_2 from atmosphere, or cement manufacture
- Use $H_2 + CO_2$ to make liquid fuels
- Key cost / scale driver is electrolysis
- Requires cheap carbon-free electricity
- Would bridge stationary and mobility sectors



Integrated Assessment Models Include Very Large Contributions from Negative Emissions

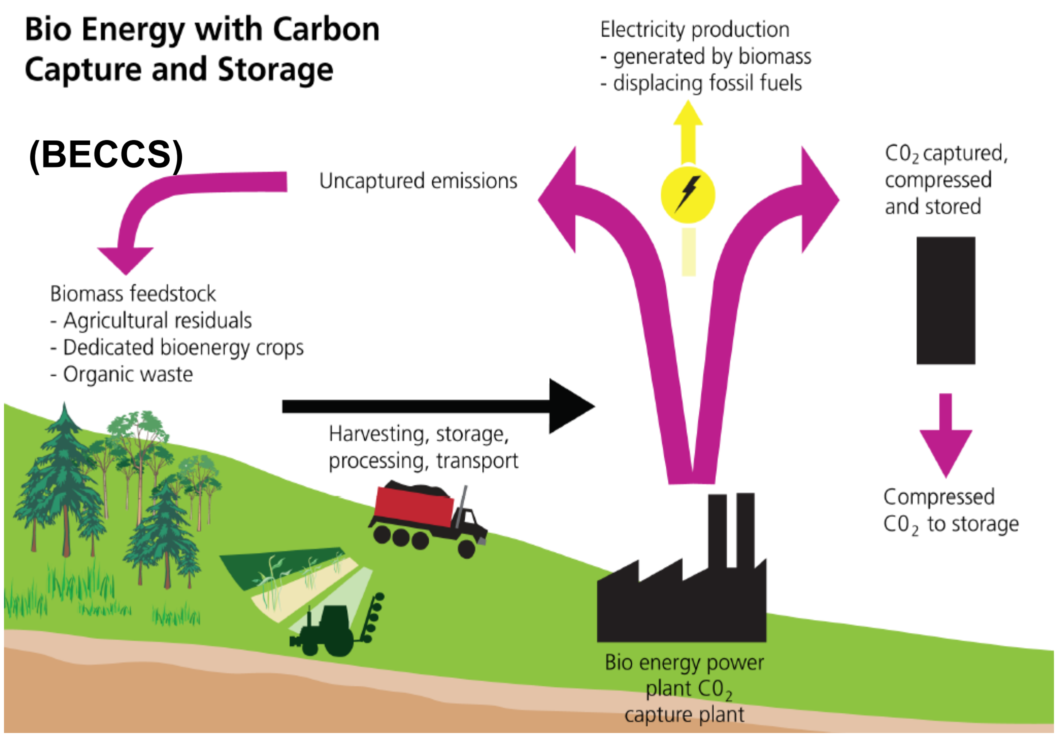
- IAMs attempt to predict costs associated with specific emissions profiles
- Some costs are negative, most are positive, some very large
- Total extra costs generally guess-timated as 1 ± 3% of global GDP
- **Substantial / large "negative emissions" technologies to meet 2° C climate goals of 450 ppm CO_2 stabilization by mid / late 21st century**
- Game changers do occur (with new actors)
    - Semiconductor into solar
    - LED lighting
    - Energy system controls and operational optimization
- Developing Nations will have different costs and challenges than OECD countries

IPCC Representative Concentration Pathways (RCP)



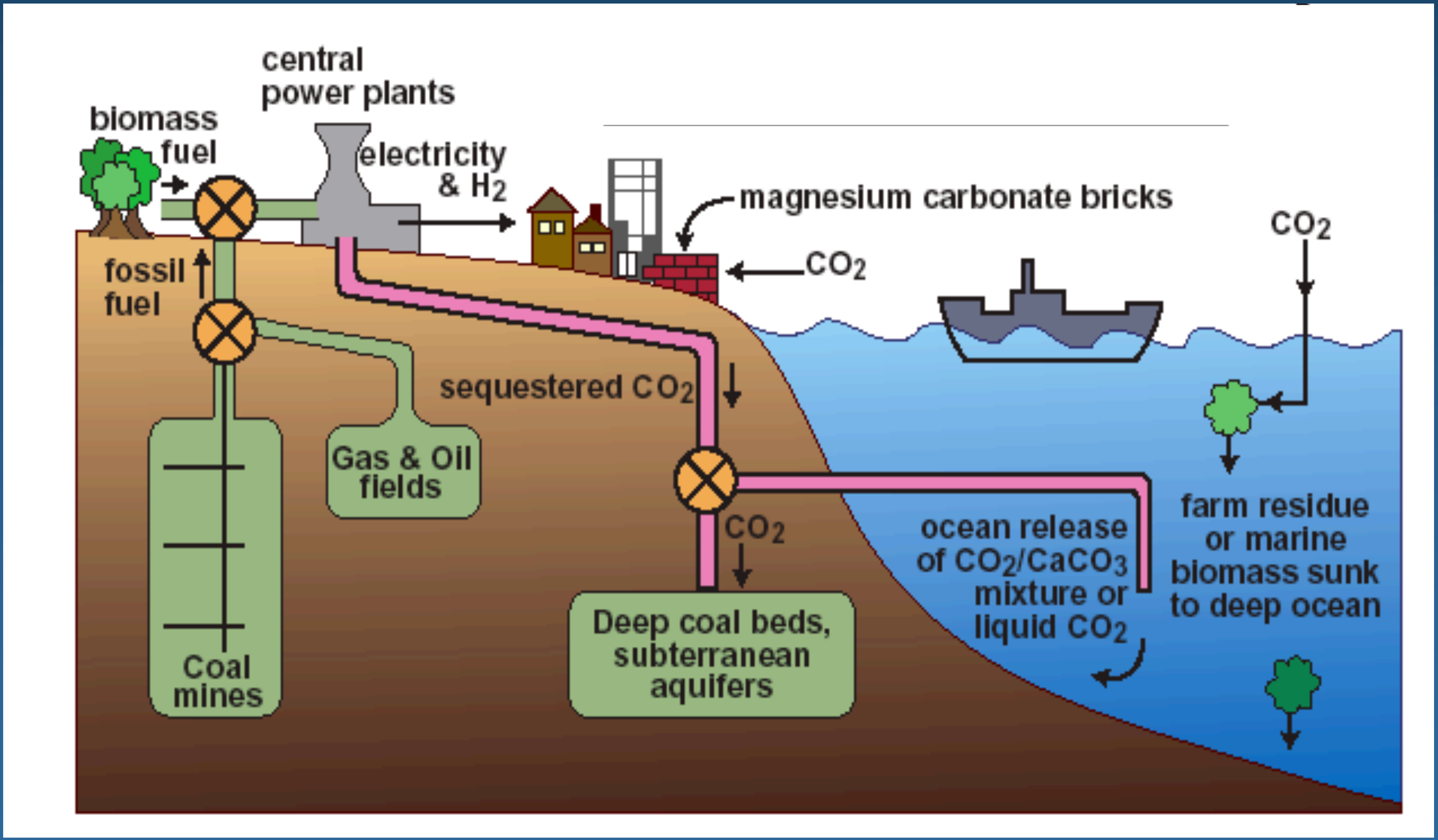
Carbon capture and storage:
Direct Air Capture vs Photosynthesis

- Carbon Capture & Storage (CCS) or BioEnergy with CCS
- Average reservoir leak rate must be 0.1%/year for 1000 years
- Capacity in geological reservoirs:
  - 30-50 years
  - 50-150 years in underground aquifers
- Most obvious disposal sites are depleted hydrocarbon-bearing reservoirs (30-50 years global capacity in total)
  - Complexities in relation to re-use
  - Distance from sources increases costs
- Liability and site remediation issues not settled



- BECCS can yield “negative emissions” and could favorably offset HC liquid emissions for transportation if sufficient land is available and provided that CCS is validated technically

Carbon Sequestration



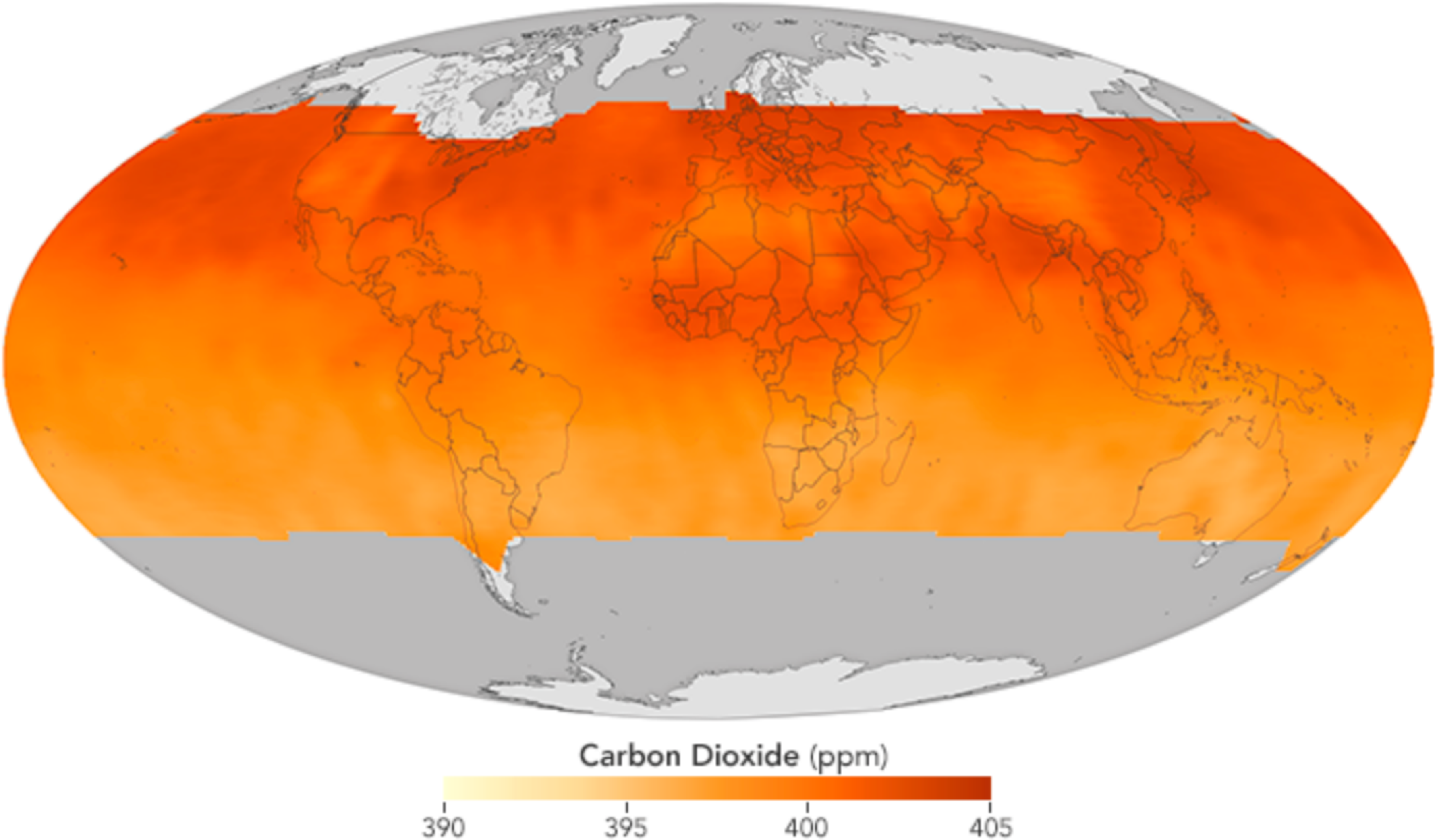
Paris COP21 Outcomes and Implications

- Resolved: Over 190 countries *should* take actions to *"hold the increase in global temperature to well below 2 ˚C above pre-industrial levels"*
- Auxiliary goal: *"achieving a balance between anthropogenic* emissions by sources and removal by sinks of greenhouse gases in the second half of this century"*
- Not legally binding, no specified emissions targets or overall CO_2 emissions budgets

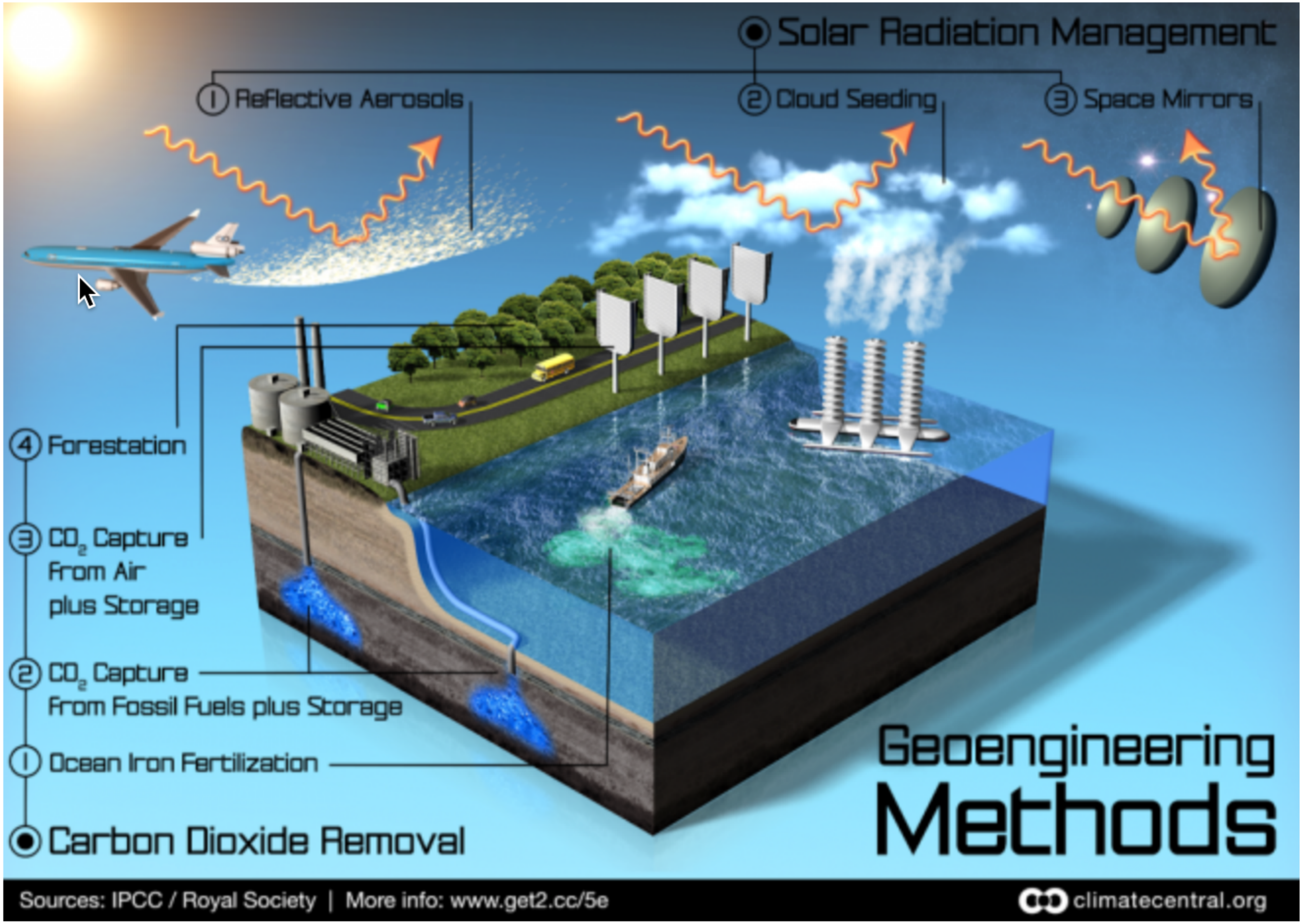
* Attributable to human activity

Global CO_2 Concentration Map from OCO Satellite

Solving the "inversion" problem: whose CO_2 is that?



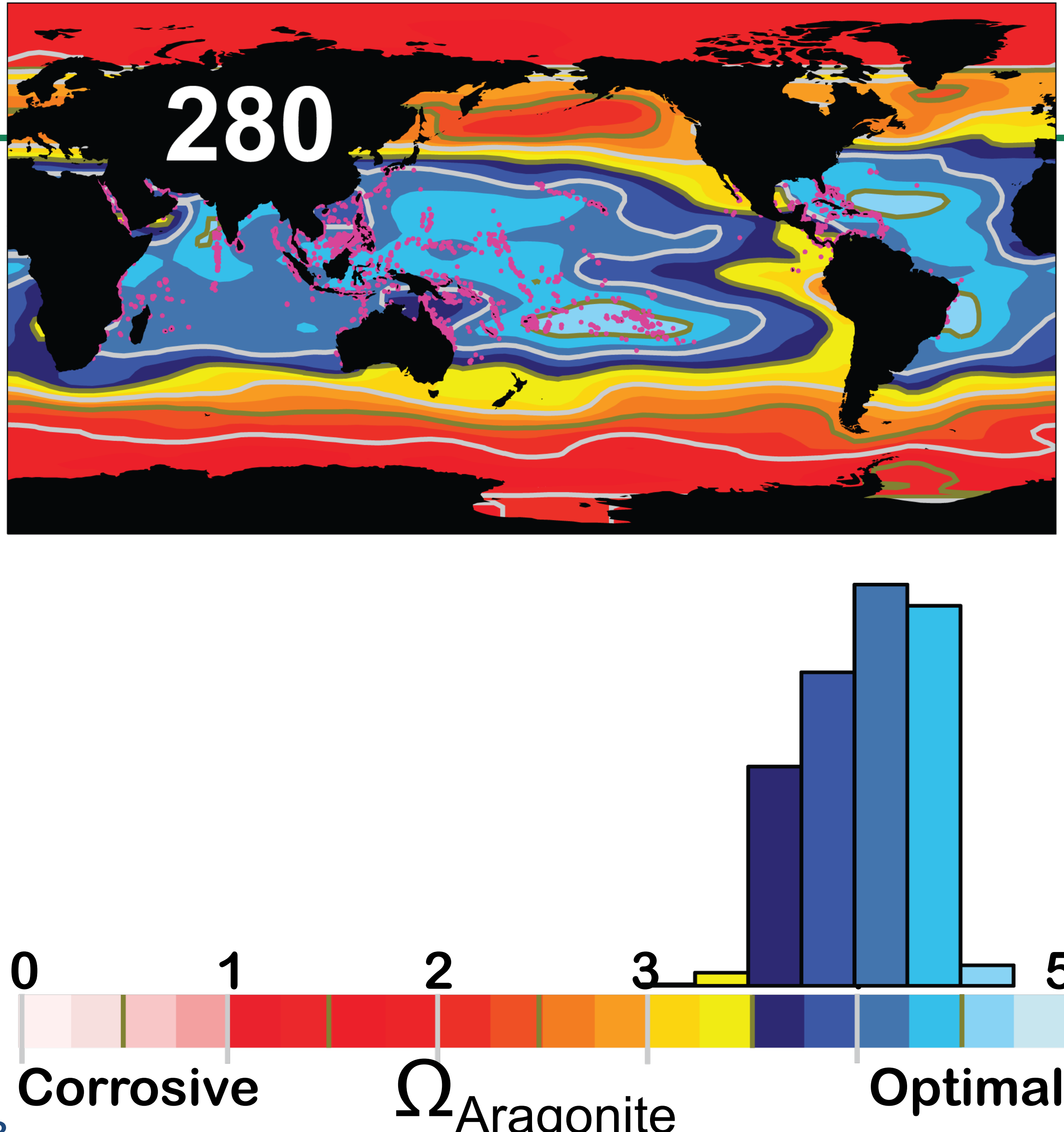
Geoengineering
Global Monitoring and Measurement Challenges



Carbon dioxide level,

Coral reef distribution,

and chemical conditions helping drive reef formation



Cao and Caldeira, 2008

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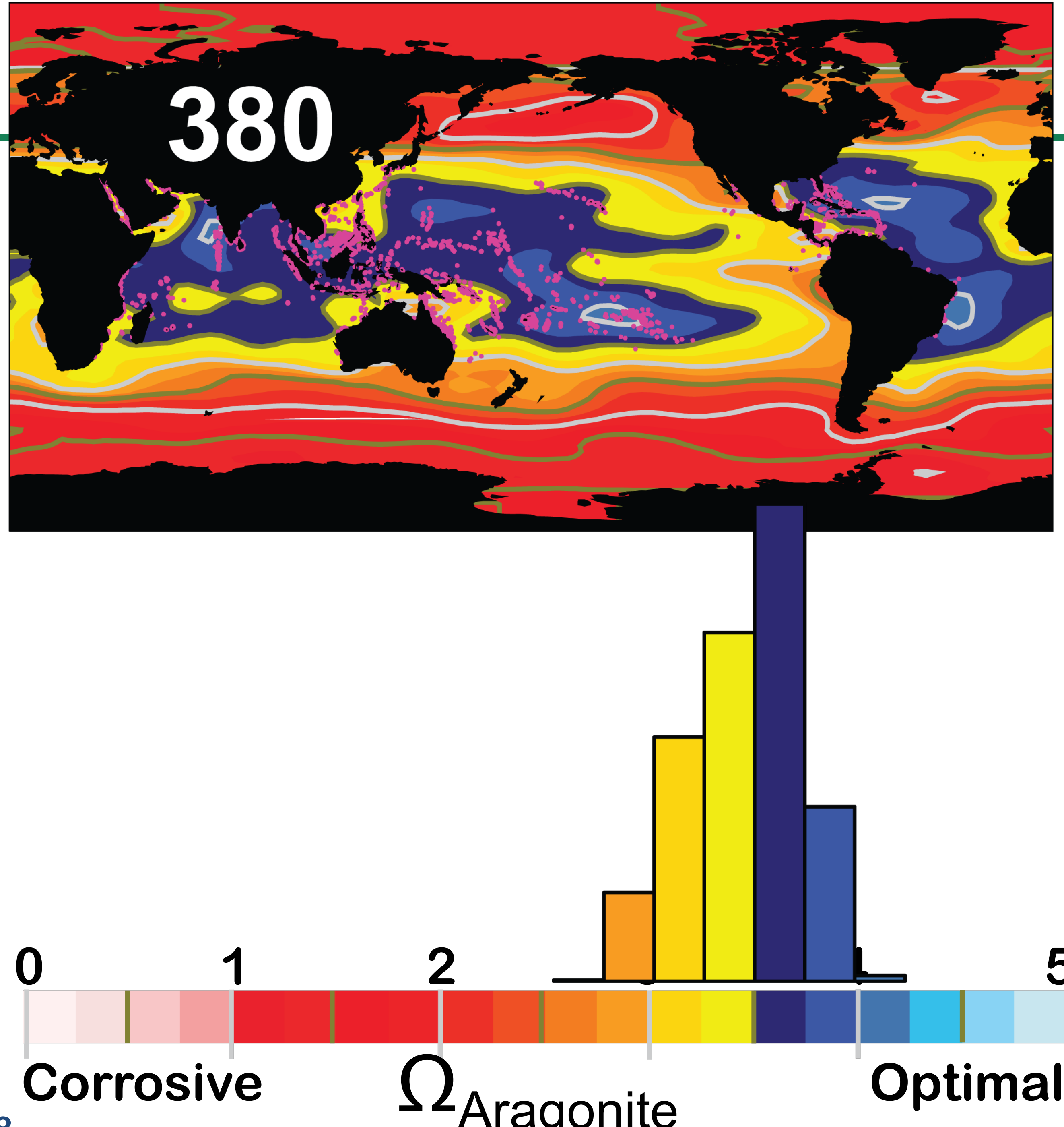

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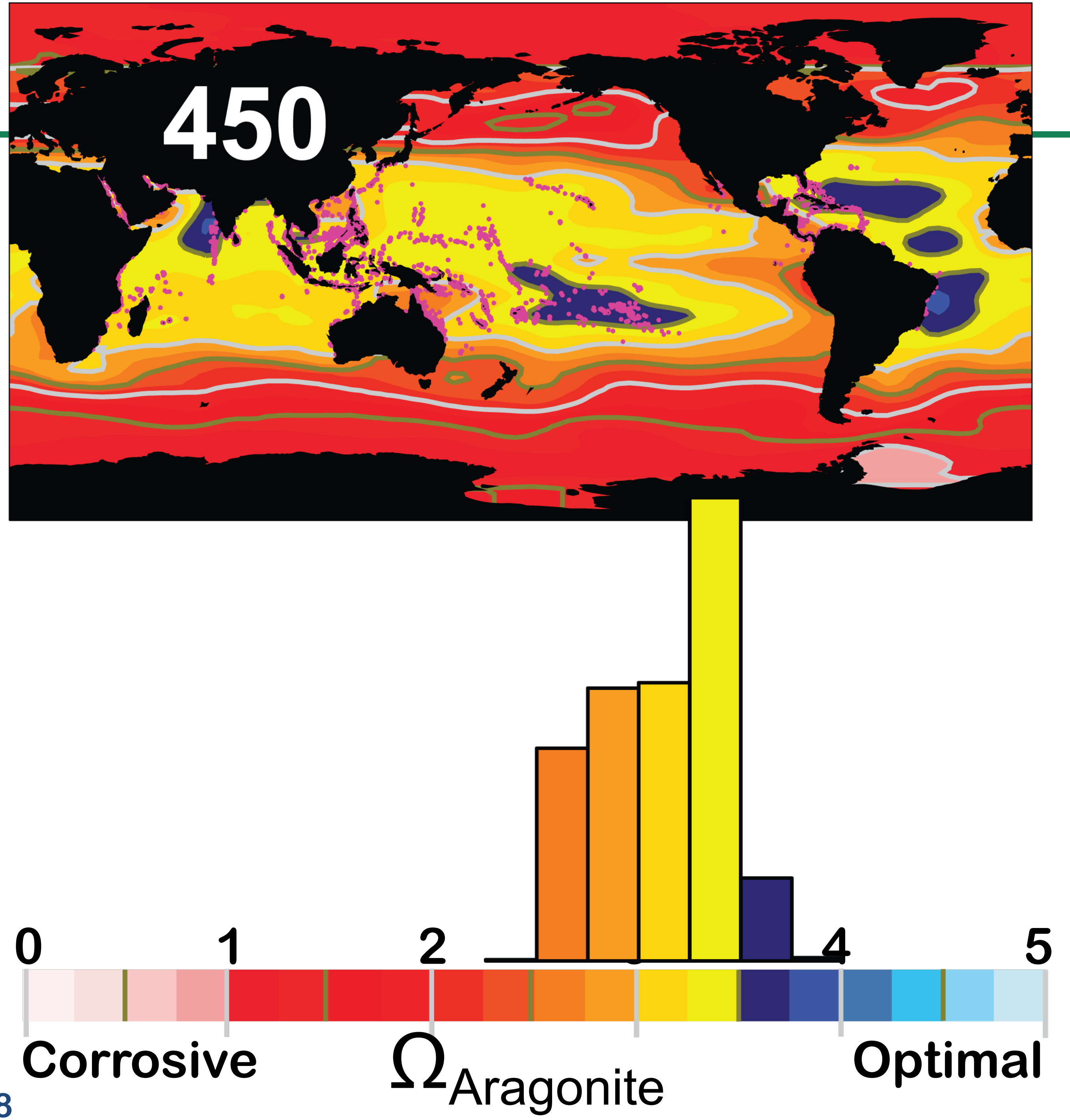

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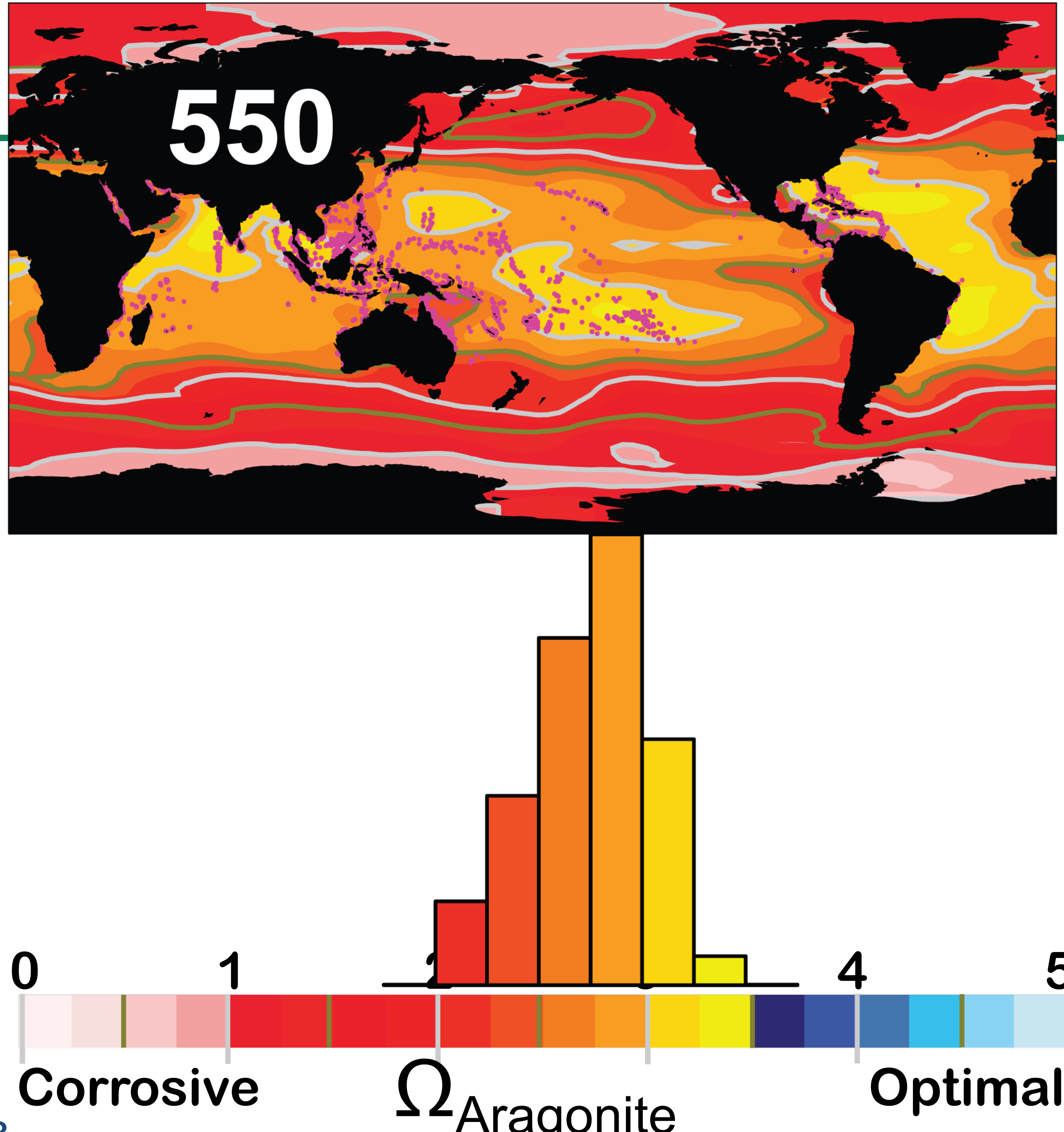


Cao and Caldeira, 2008

Opportunities and Challenges in Energy R&D

Focus on Materials (science, engineering, chemistry, physics…)

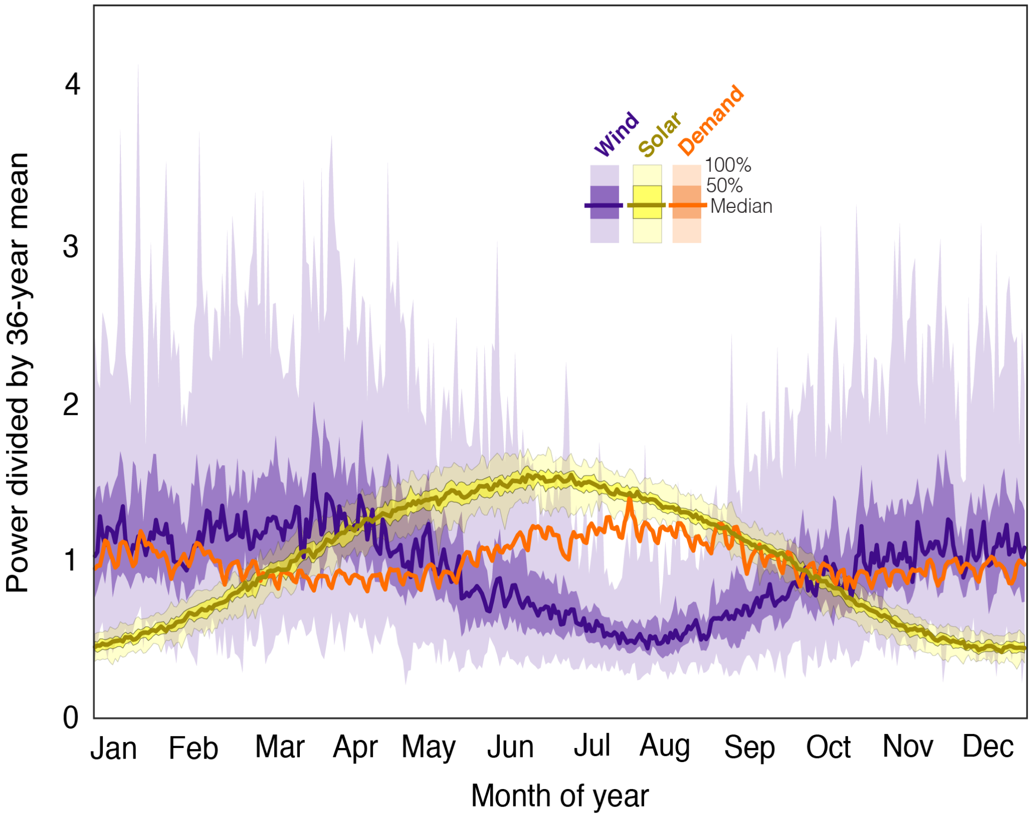
- Materials for the built environment
- Materials in extreme environments
- New wind turbines
- Solar paint
- Low-cost grid-scale energy storage
- Structural Materials: cement, steel
- Carbon-neutral transportation fuels
- Negative emissions
- Legal/liability
- Geoengineering
- Ocean chemistry
- Systems approach to highly reliable energy systems
- **Solve problems that are problems, and don't solve problems that are not problems**

Acknowledgments

Renewables for Power Generation

Geophysical reliability of solar/wind on continental scale?...

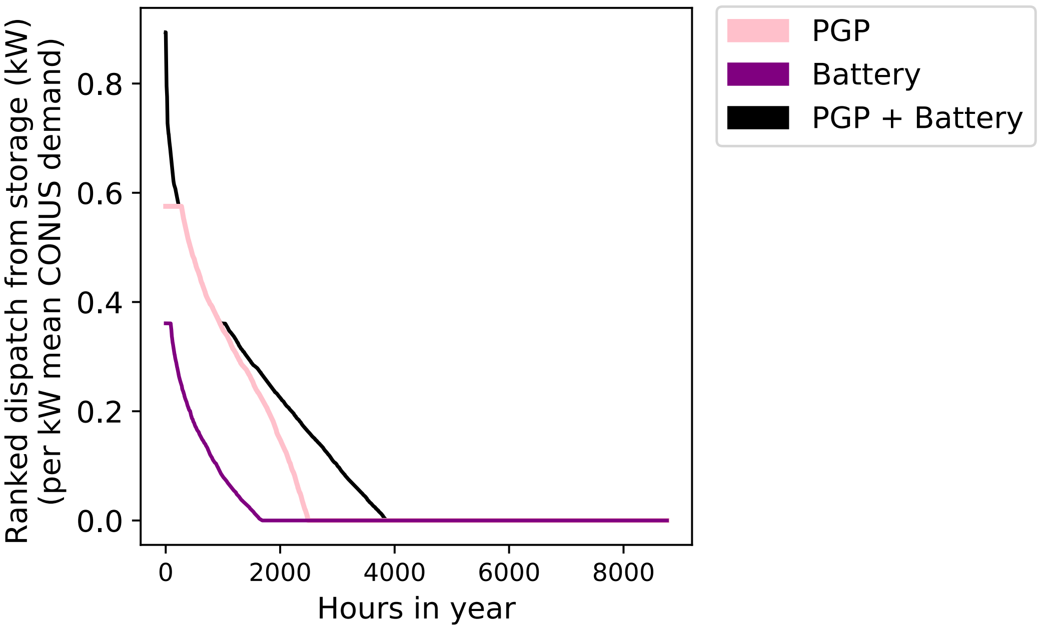
- Consideration / adoption of 80-100% renewable electricity mandates
- Claims workable using 100% wind, water (pumped hydro) and solar
- "Always windy somewhere or sun will be shining somewhere" ?
- 99.97% reliability is a blackout for <1 hour per decade
- Infrastructure lifetime of grid is ~40 years
- Assessment requires wind/solar co-variability over 30-40 year periods

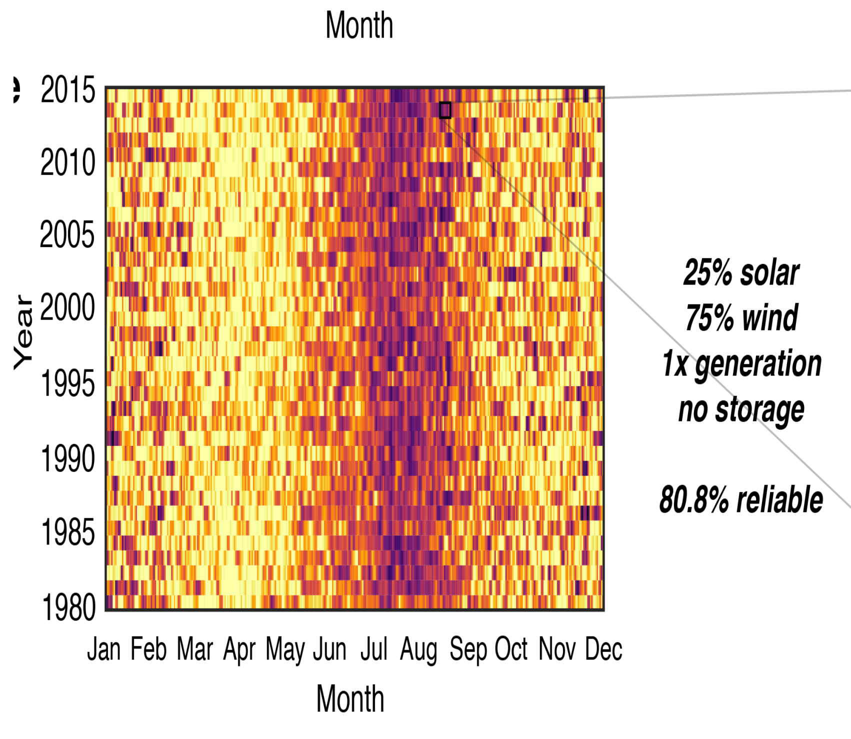


Source: M. Shaner, S. Davis, N. Lewis, K. Caldeira, 2018

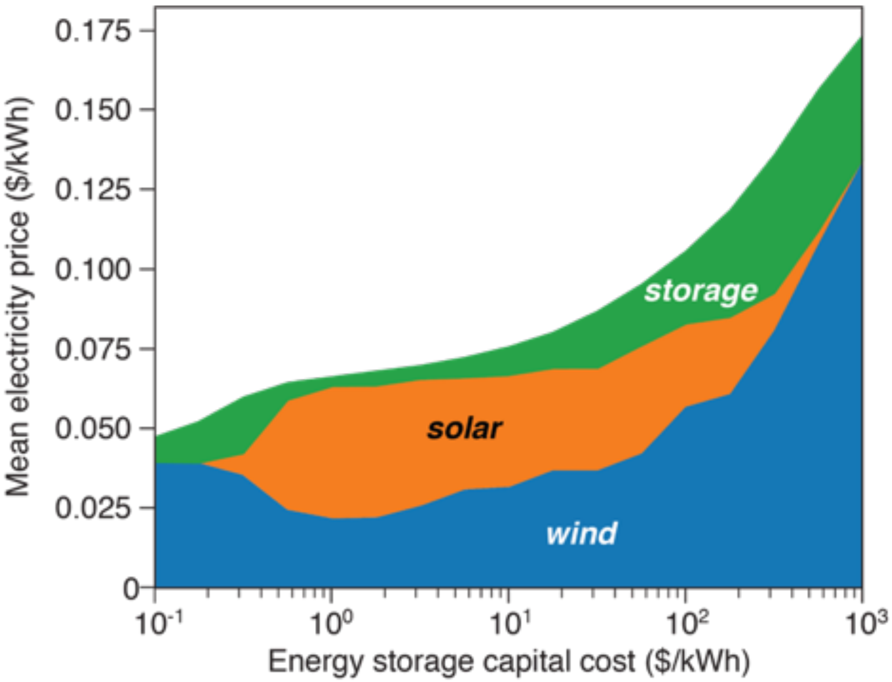
Geophysical Resource Data-Driven Assessment of Gaps Between Supply and Demand

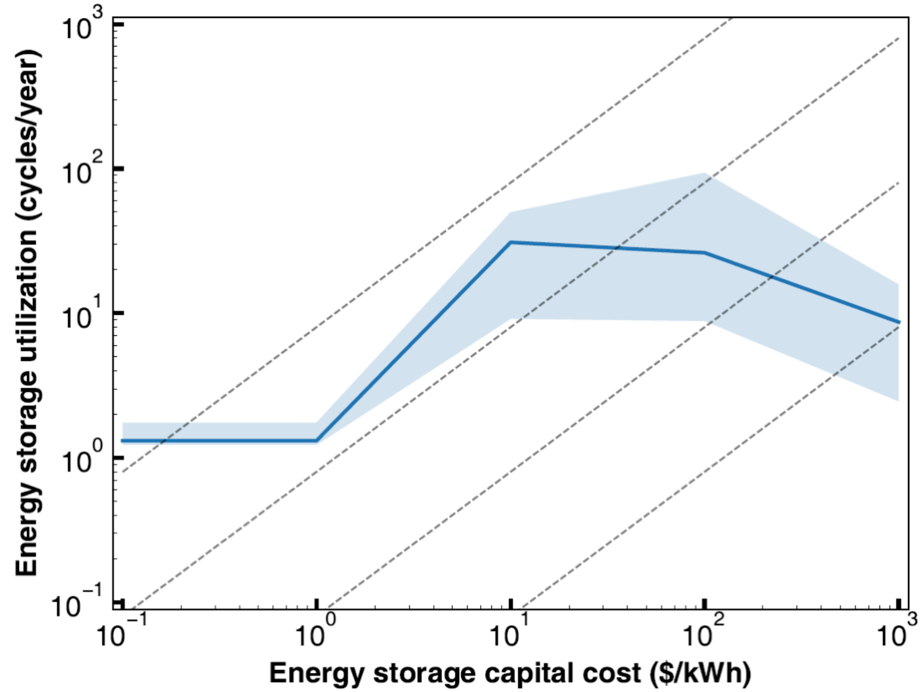
- Wind and Solar Generation over contiguous U.S.
- Ideal, lossless transmission over contiguous U.S. between all generation and load
- Generation based on 39 years of hourly ~50 km reanalysis (weather) data
- Demand based on hourly EIA data (for 2015-2018)





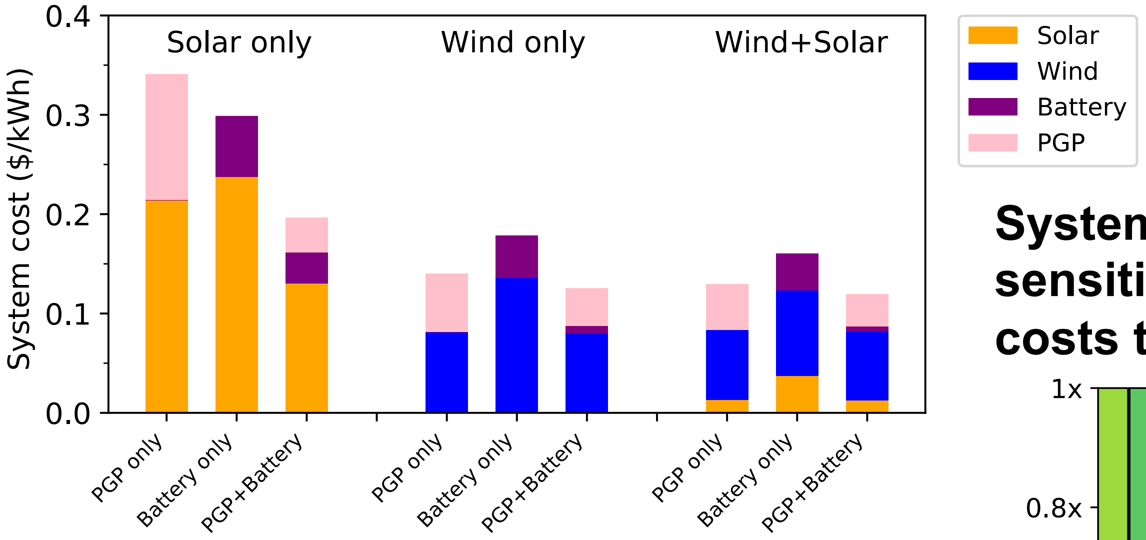
System Costs in >99.97% Reliable Electricity System vs Battery Costs



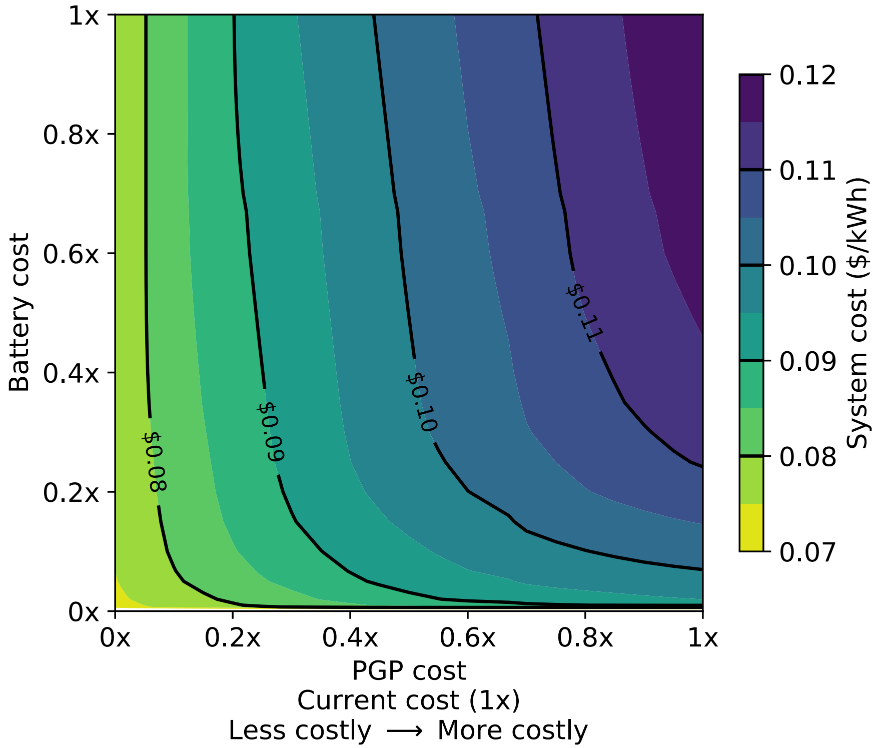


- System costs are relatively insensitive to storage costs until cost is reduced >50-fold relative to present; always cheaper to overbuild wind/solar than to deploy storage
- Least-cost reliable systems are wind heavy with 2-3 hours of storage; solar heavy systems require much larger storage costs to achieve high reliability
- Storage is not cost-effective for seasonal (few cycles/year) applications until costs decline by >100-fold relative to present; need to store more and more energy used less and less frequently

System Costs vs Cost of Storage Assets

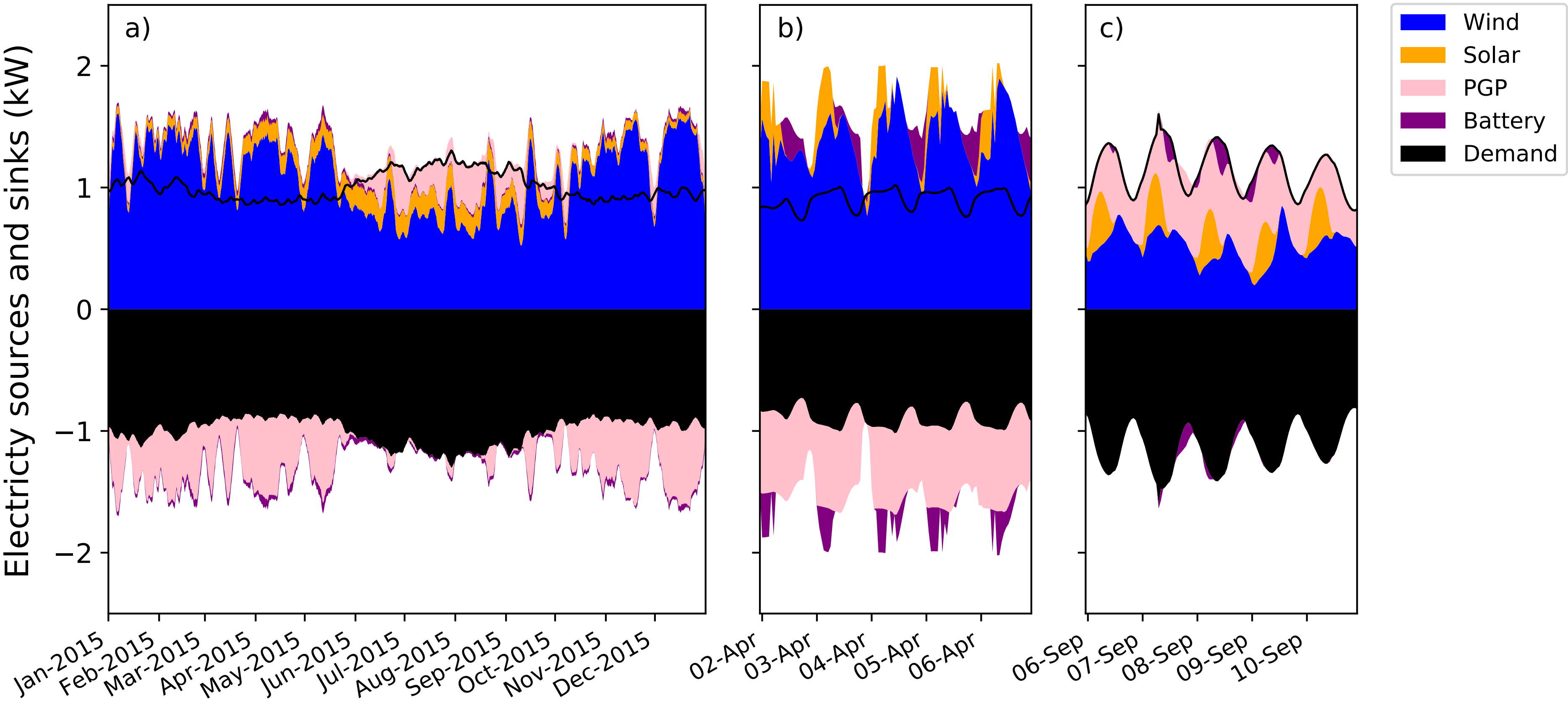


System costs are much more sensitive to reductions in PGP power costs than battery storage costs



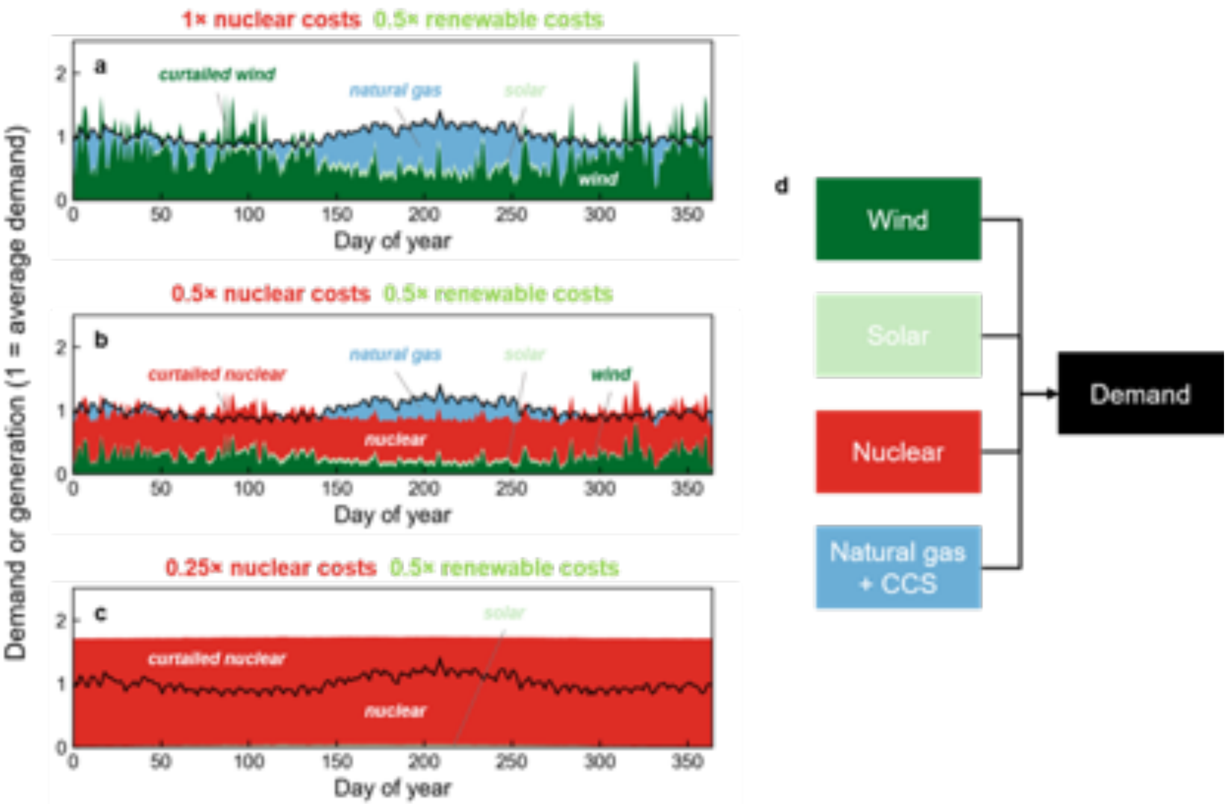
- Even at current costs, PGP (Power-to-Gas-to-Power) reduces system costs in all cases
- Batteries (>85% round trip efficiency) are energy-cost limited; PGP (~30% round trip efficiency) is power-cost limited
- Least-cost solutions are wind heavy and solar and battery-light

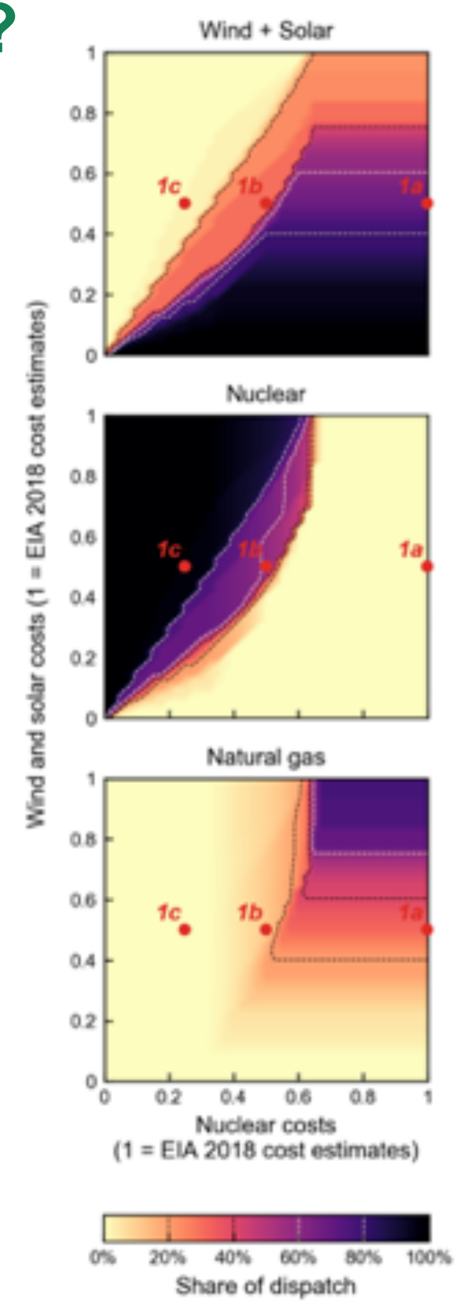
Dispatch Curves for Wind/Solar/Batttery/PGP >99.97% Reliable Electricity System



- Least-cost system is wind/heavy with ~3 hours of battery storage and PGP for low frequency storage
- PGP stores energy/ batteries smooth variations in power
- Analogous to gasoline/battery (Prius) hybrid vehicles
- Also energy exchange between battery and PGP storage assets

Does nuclear power complement or compete with variable (wind+solar) renewable power?

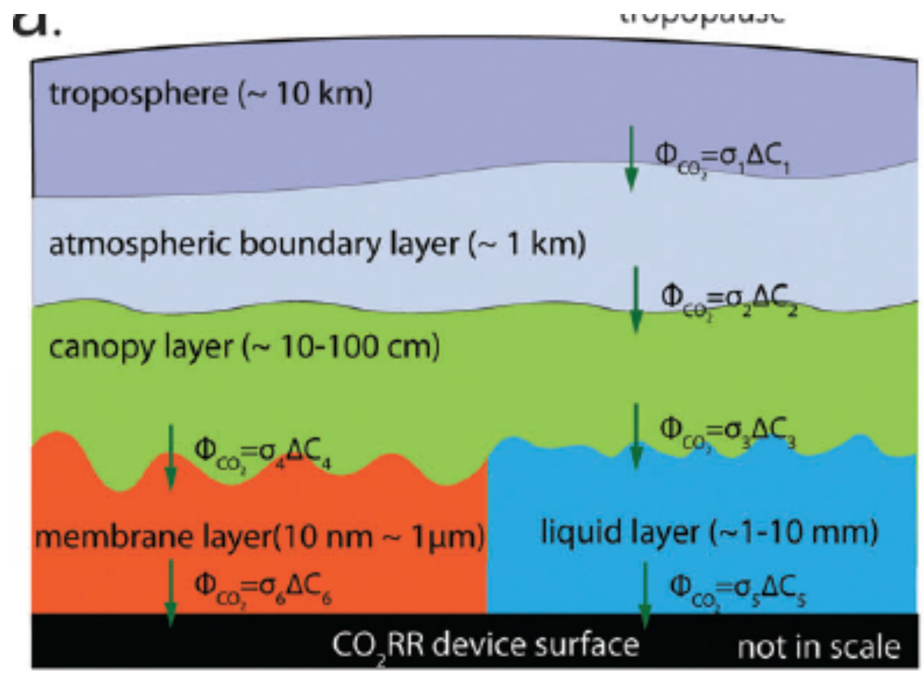




- At current costs, natural gas dominates least-cost energy mix
- Wind/solar or nuclear ~3x more costly in highly reliable (>99.97%) electricity systems
- Nuclear directly competes with wind/solar; all have high capex low/no opex, favoring operation at high capacity factors
- Hardly any value associated with flexible nuclear generation

•Transport Limitations for Sustainable CO_2 Reduction Systems

- Established CO_2 flux limits from global scale to microscale
- Low CO_2 solubility in H_2O combined with 400 ppmv CO_2 concentration in atmosphere leads to low (10 μA/cm^2) limiting electrode fluxes
- Consistent with global carbon cycle measured and modeled CO_2 fluxes at air/ocean interface
- CO_2 flux limit is 100-fold smaller than solar photon flux
- Terrestrial net ecosystem exchange is 10-fold larger than flux into oceans due to high contact area/geometric area of plants and gas-phase diffusion
- Consistent with observed 50-100 ppm CO_2 draw-down over midwest corn and in Amazon in peak growing season
- Establishes design constraints for sustainable CO_2R systems at scale



Modeling and Simulation

Chen, Y.; Lewis, N. S.; Xiang, C., *Energy Environ. Sci. 2015, 8, 3663-3674.*