# Net-zero emissions energy systems

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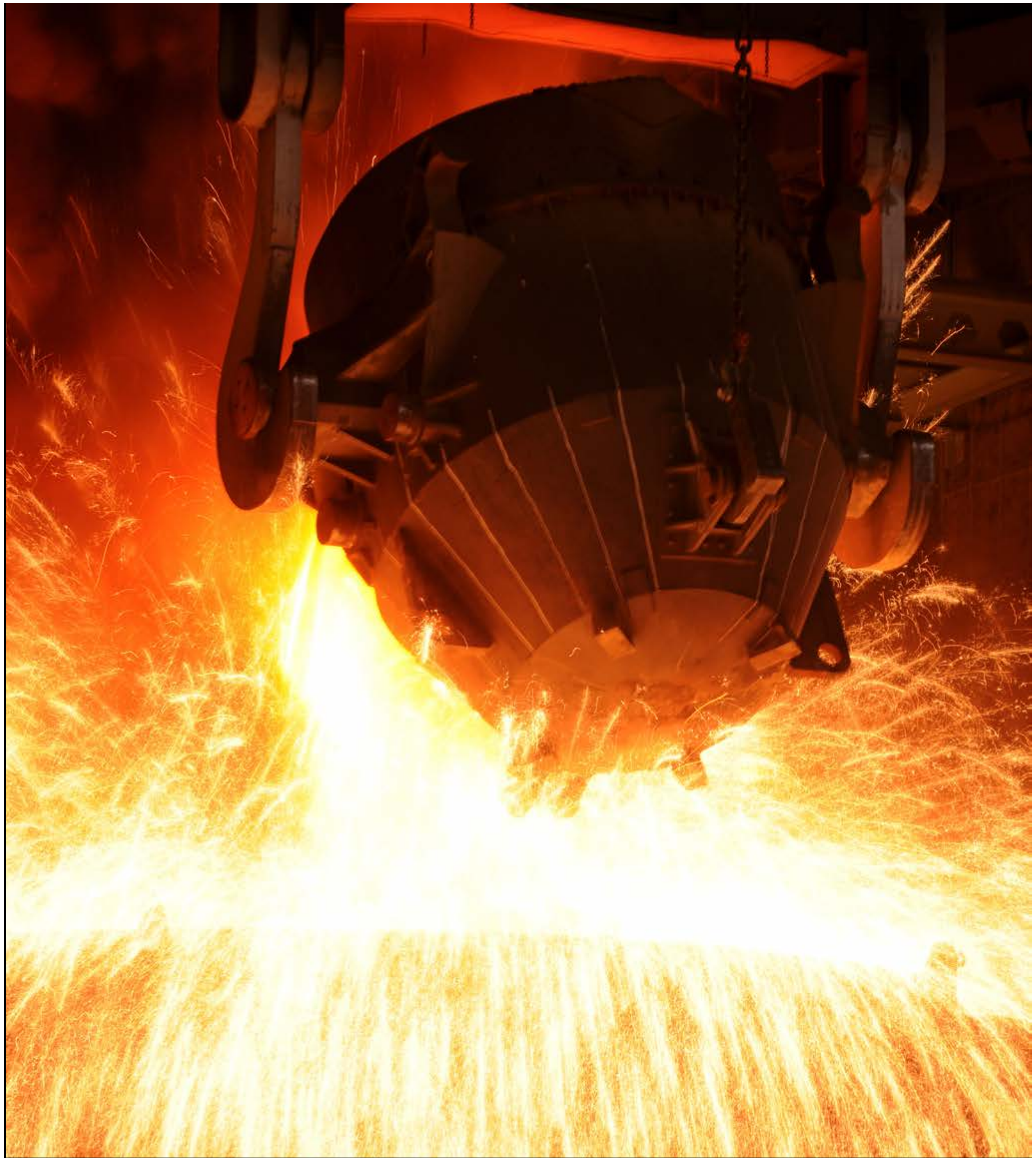
UCI Solutions that Scale



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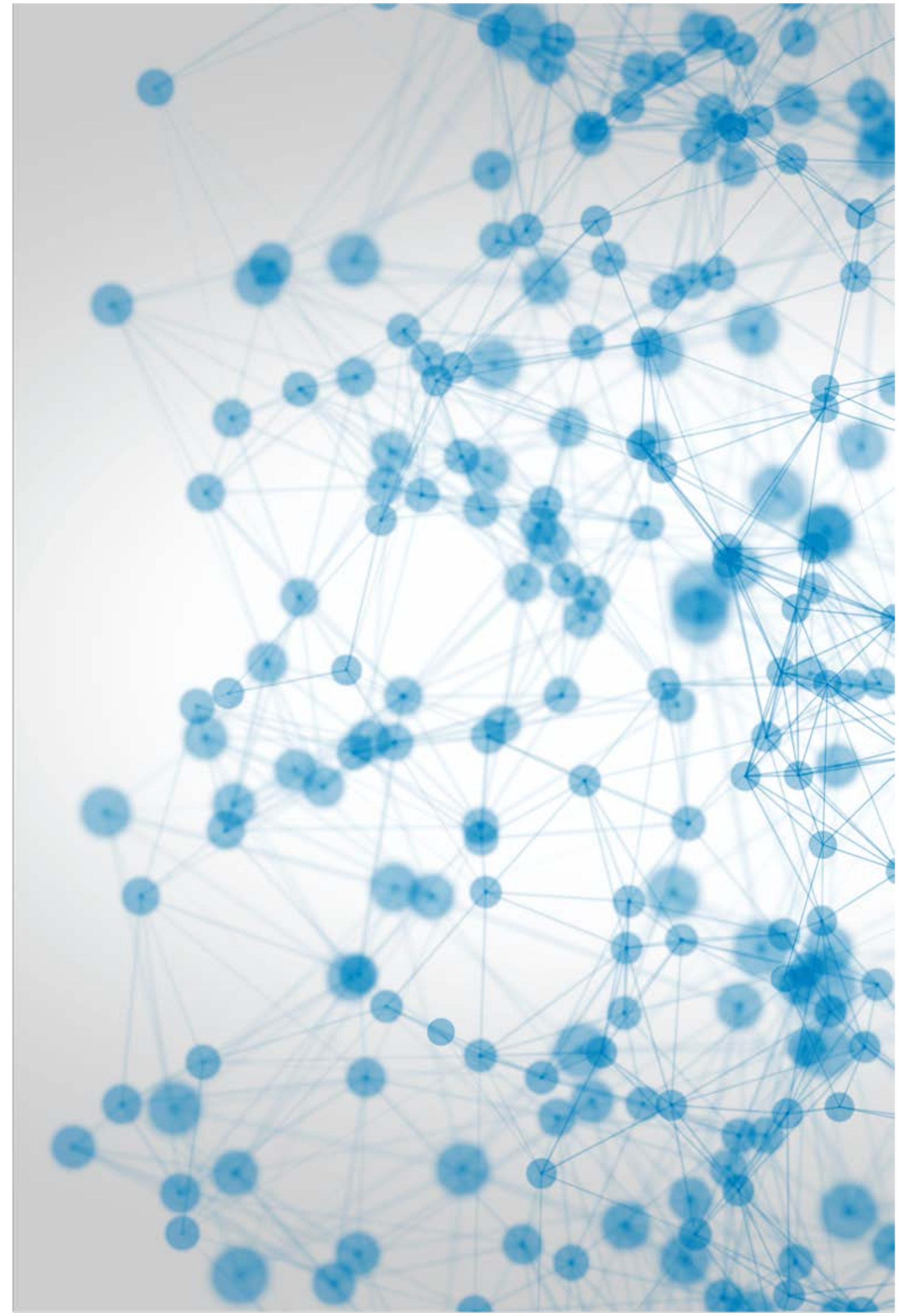
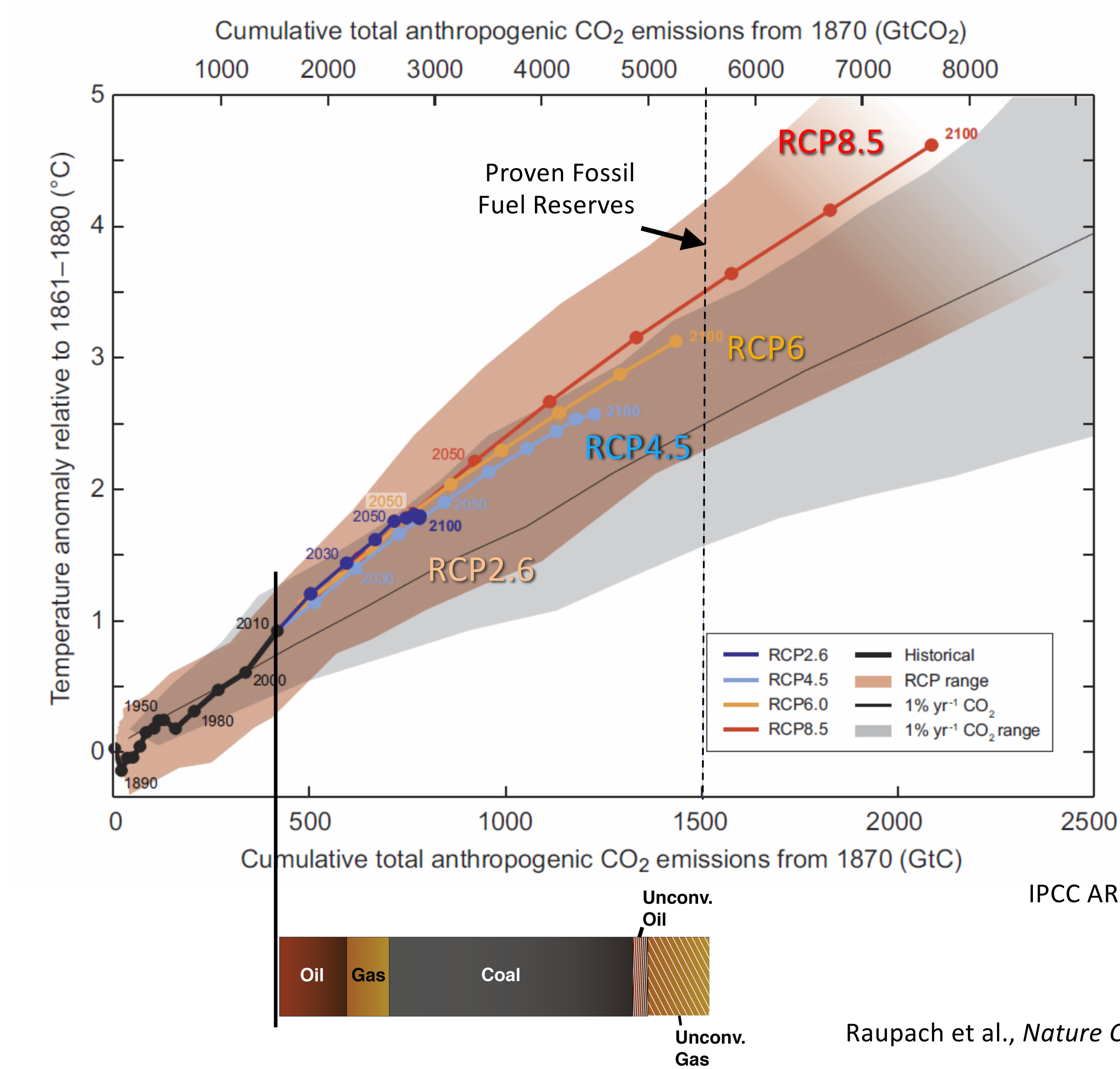


# Why net-zero? Warming will be proportional to cumulative $CO_2$ emissions




IPCC AR5, WG2 SPM (2014)

Raupach et al., *Nature Climate Change* (2014)

Pathways to “deep decarbonization” are clear

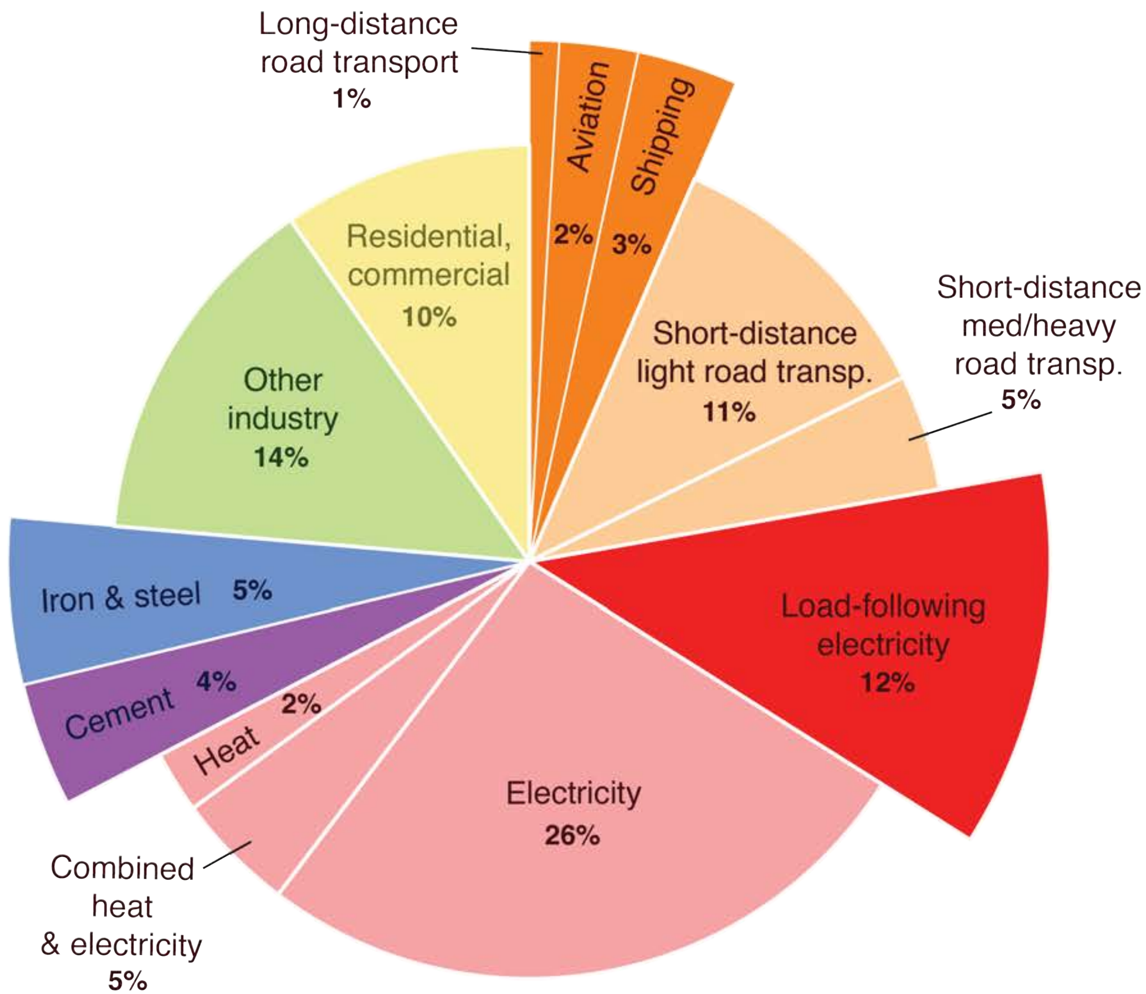
But some modern energy services will be difficult to fully decarbonize

Aviation and long-distance transport

Industrial materials

Highly-reliable electricity

# How much "difficult" $CO_2$ are we talking about?




**A** **Global fossil fuel & industry emissions, 2014 (33.9 Gt $CO_2$)**

>9 billion tons of $CO_2$ and almost ¼ of global emissions in recent years

Davis et al. *Science,* 2018


Aviation
Shipping

High (gravimetric) energy density

Bituminous Coal
22-25 MJ/kg


Refined Oil Products (Gasoline)
42-46 MJ/kg

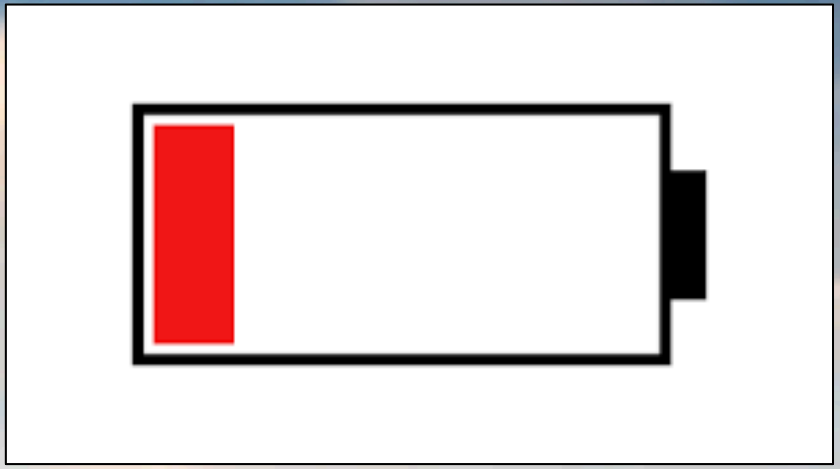

Lithium Ion Battery
<1 MJ/kg

High (volumetric) energy density


Hydrogen Gas
143 MJ/kg
but
0.01 MJ/L

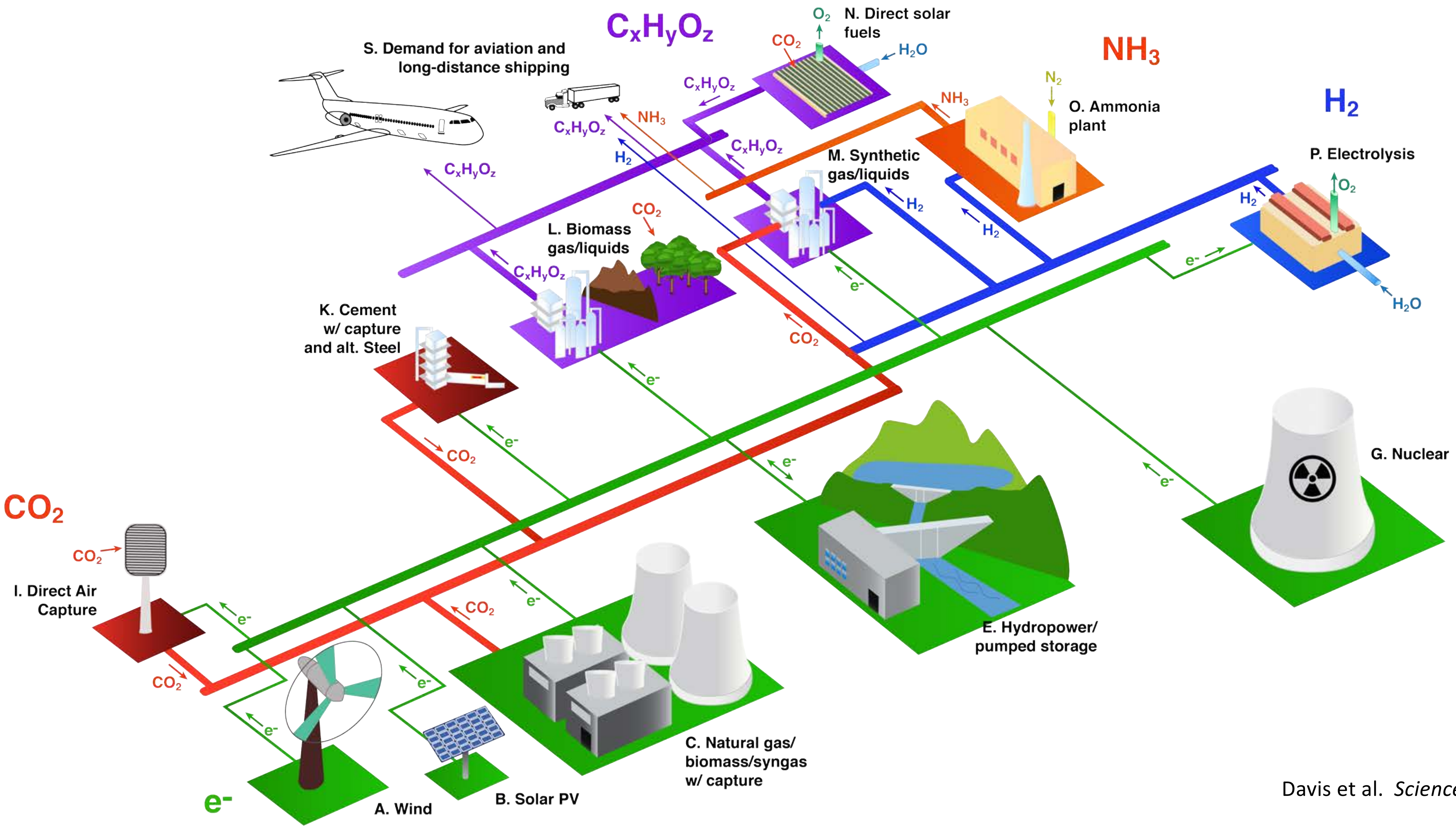
Jet Fuel
33 MJ/L
(3,300 times greater)

## Long-distance transport



Given current Li-ion energy densities, closely-packed cells capable of 700 mile range in a Class 8 truck would take up **~30% of the volume** of an 18-wheeler, and **~40% of the payload capacity**.

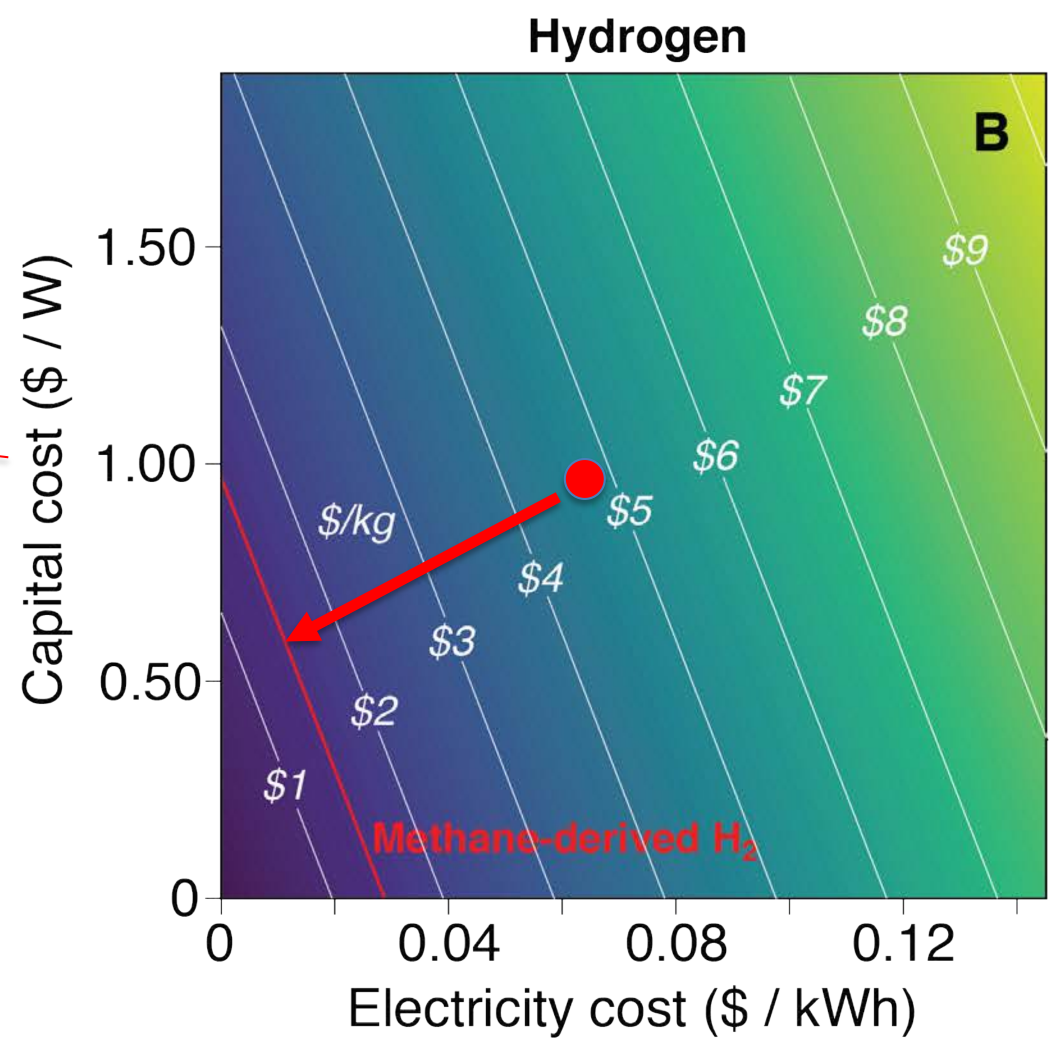
# Net-zero emissions options for liquid fuels with high energy density




Davis et al. *Science,* 2018

Costs of electrolytic (climate-friendly) hydrogen are high relative to fossil fuel sources

**Cost of electrolyzer is a major barrier**

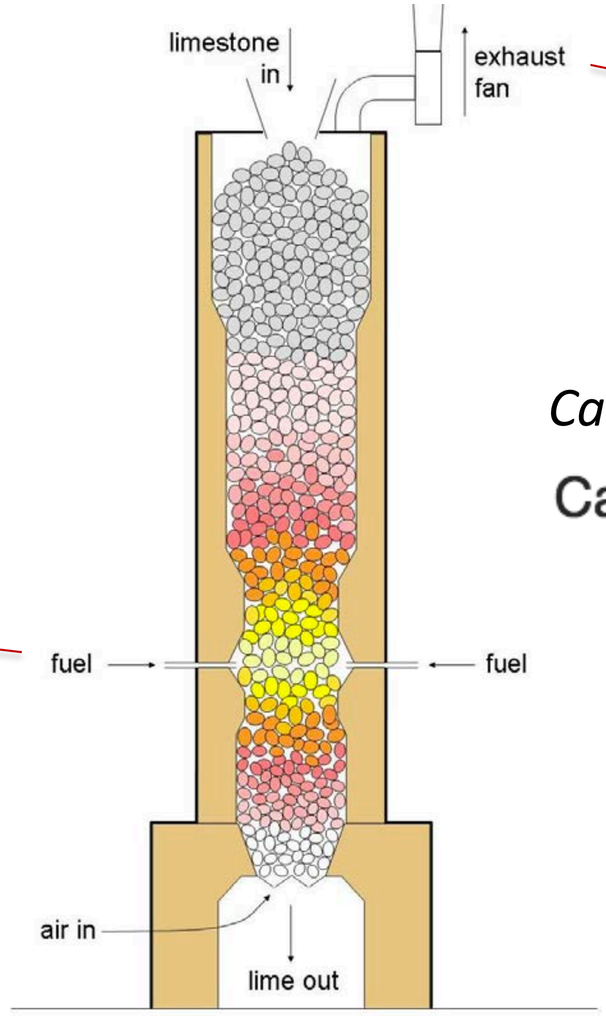



Davis et al. *Science,* 2018

# Take-aways – Aviation and long-distance transport

- High energy density liquid fuels likely to remain necessary for some transportation
- Currently options for making such fuels without adding $CO_2$ to the atmosphere are limited and costly
- Making electrolysis cheaper is a research priority

Roughly 8% of global $CO_2$ emissions is related to the manufacture of cement (~2.6 Gt $CO_2$ in 2014).




"process" = ~50% cement emissions

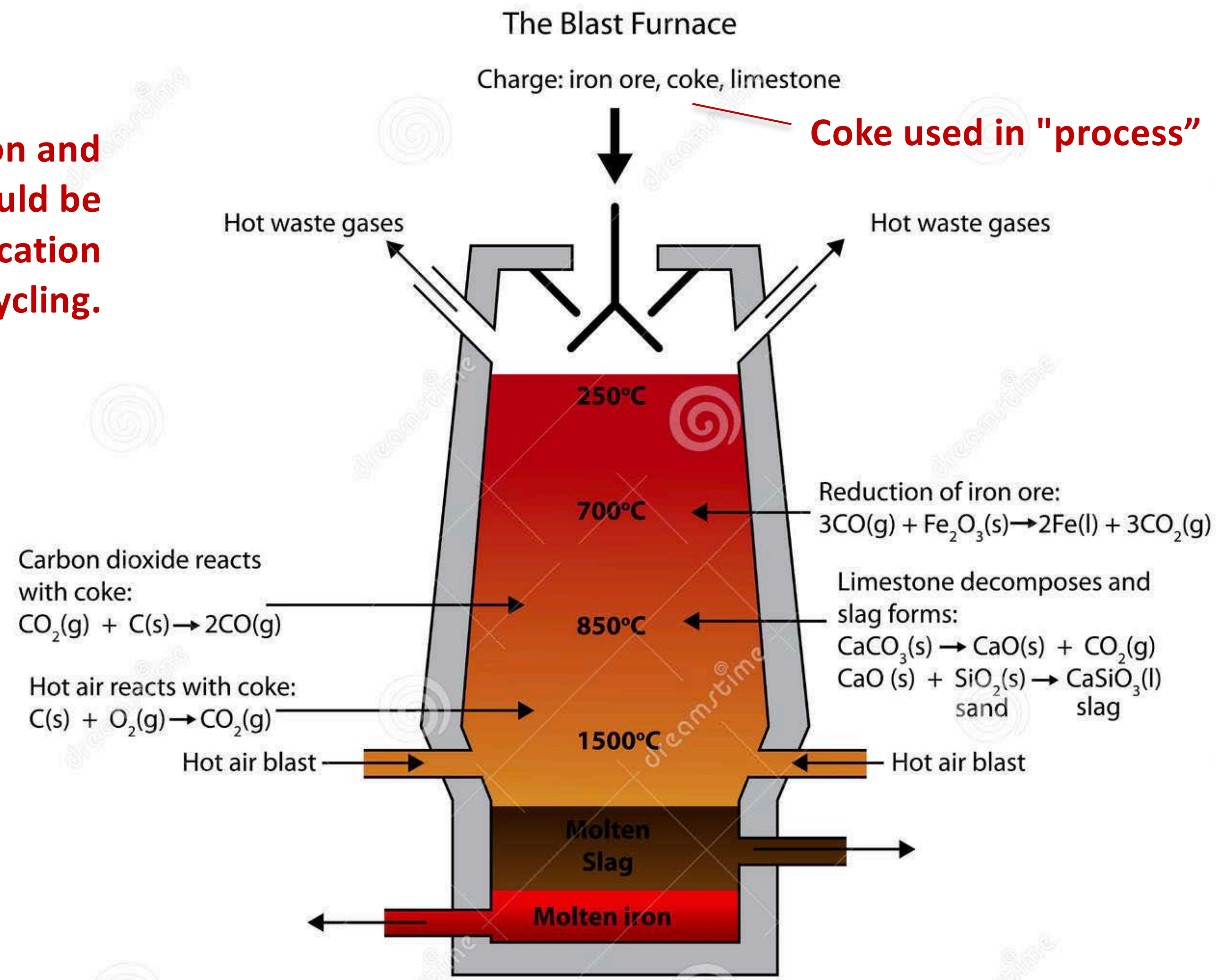
fossil energy = ~50% cement emissions

*Calcination*:

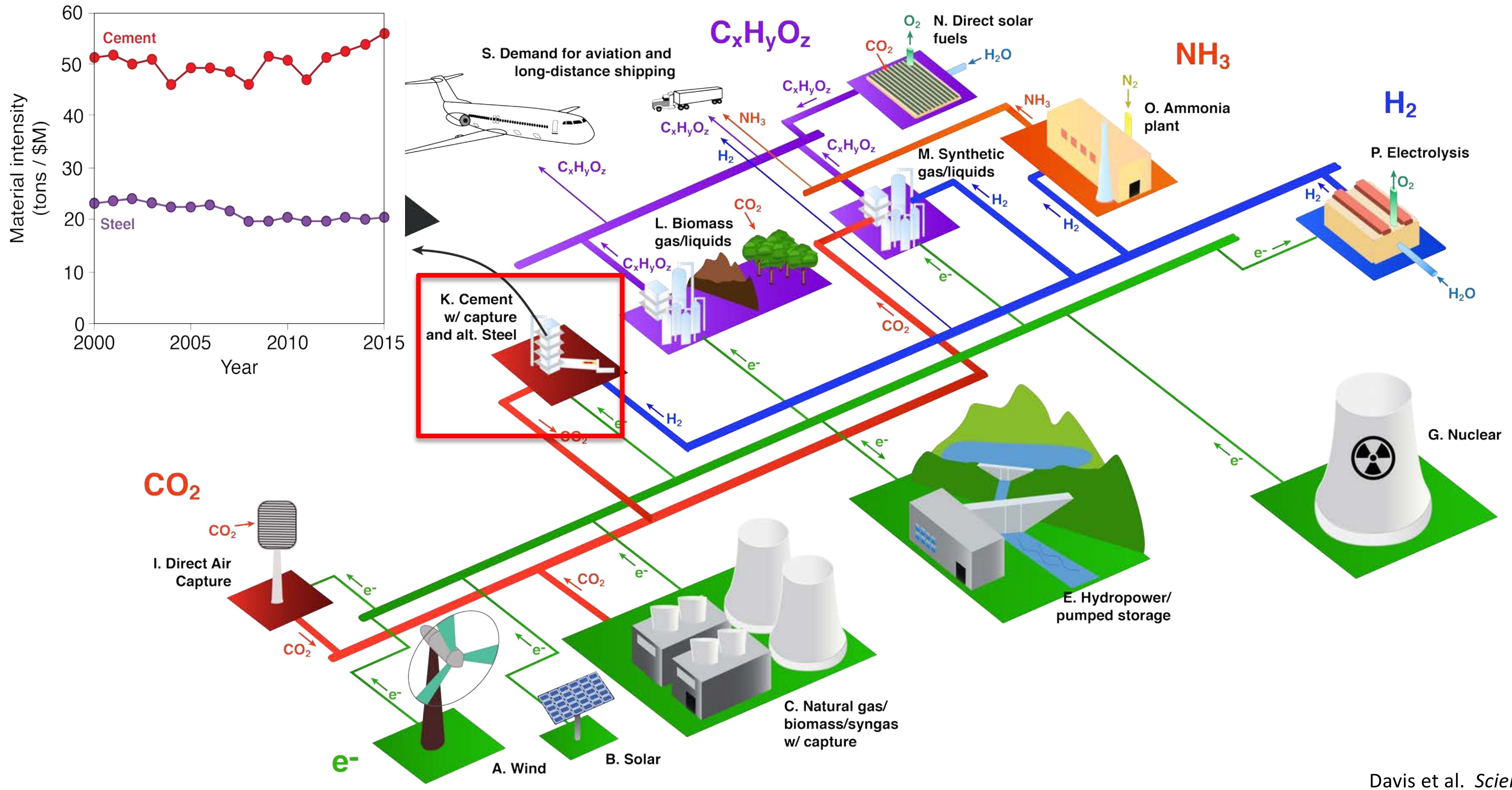
$$CaCO_3 \rightarrow CaO + CO_2(g)$$

Roughly 6% of global $CO_2$ emissions is related to the manufacture of iron and steel (~2 Gt $CO_2$ in 2014).

**Only ~25% of total iron and steel emissions could be avoided by electrification and recycling.**

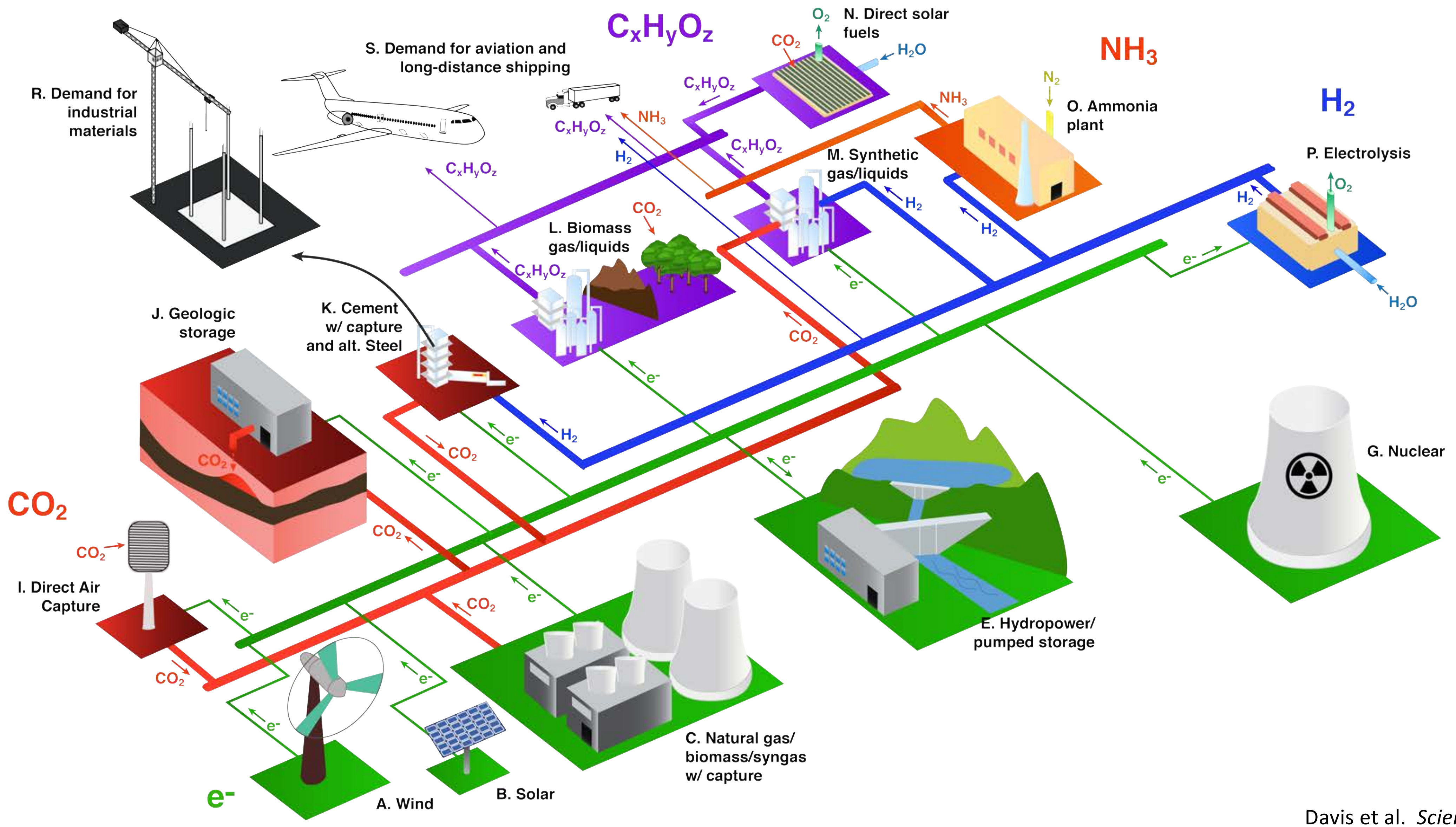


# Materials efficiency, alternative processes




Davis et al. *Science,* 2018

# And/or carbon capture, utilization, and storage (CCUS)



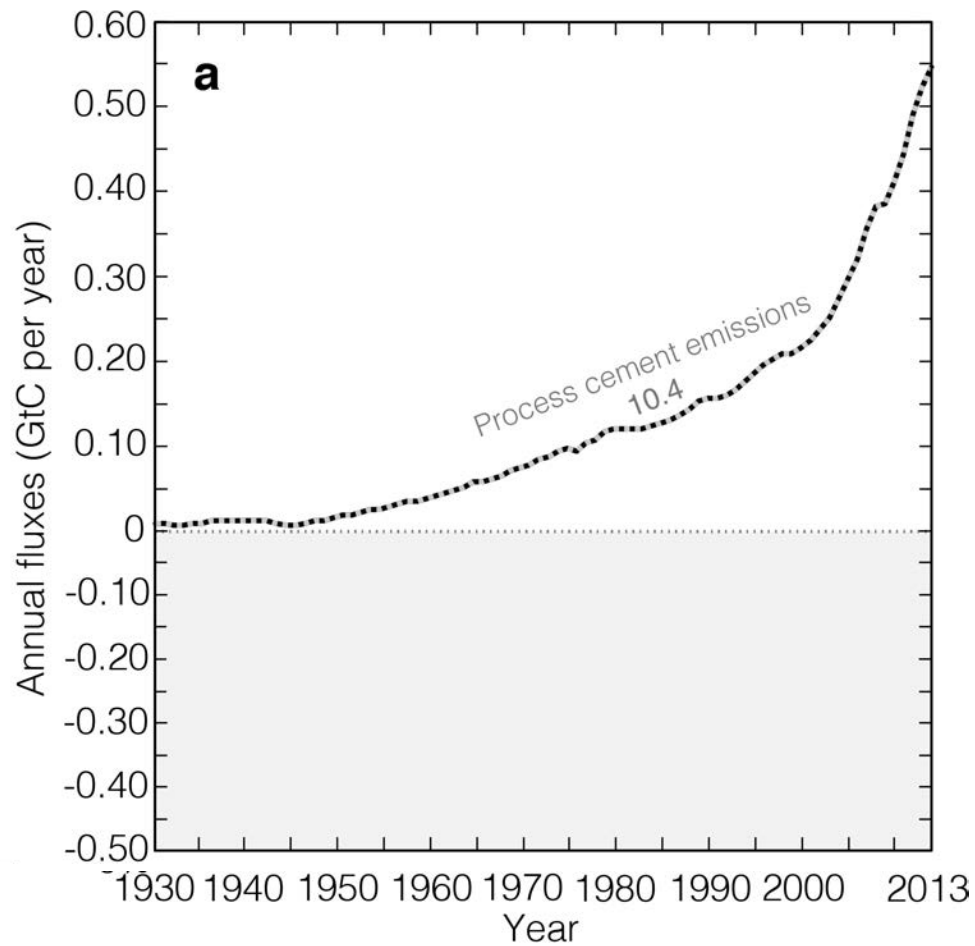

Davis et al. *Science,* 2018

Over time, the lime in cement reacts with moisture and absorbs ambient $CO_2$ in a process called *carbonation*

*Carbonation*:

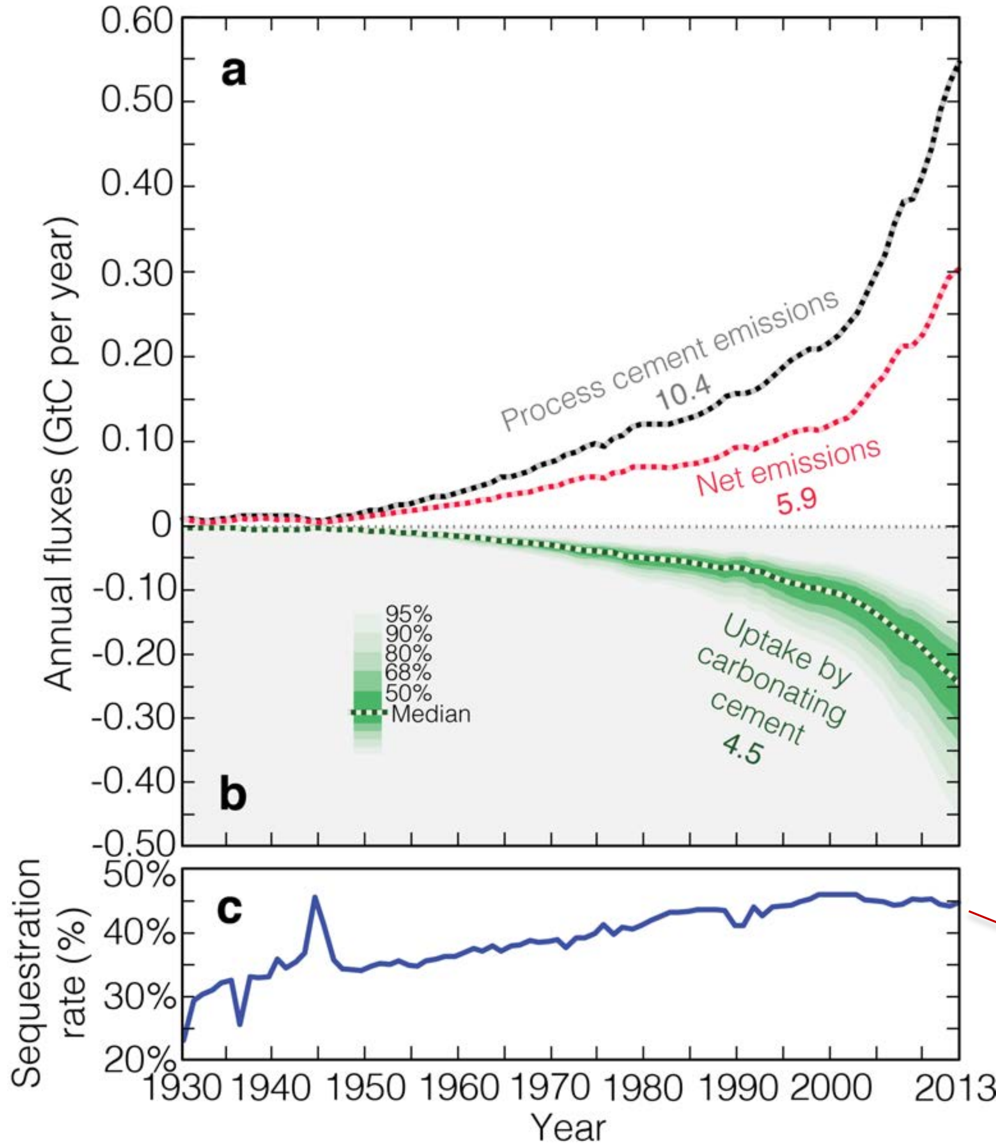
$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O$$

## Cement process emissions 1930-2013




Xi et al., *Nature Geoscience,* 2016

Cumulative cement process emissions



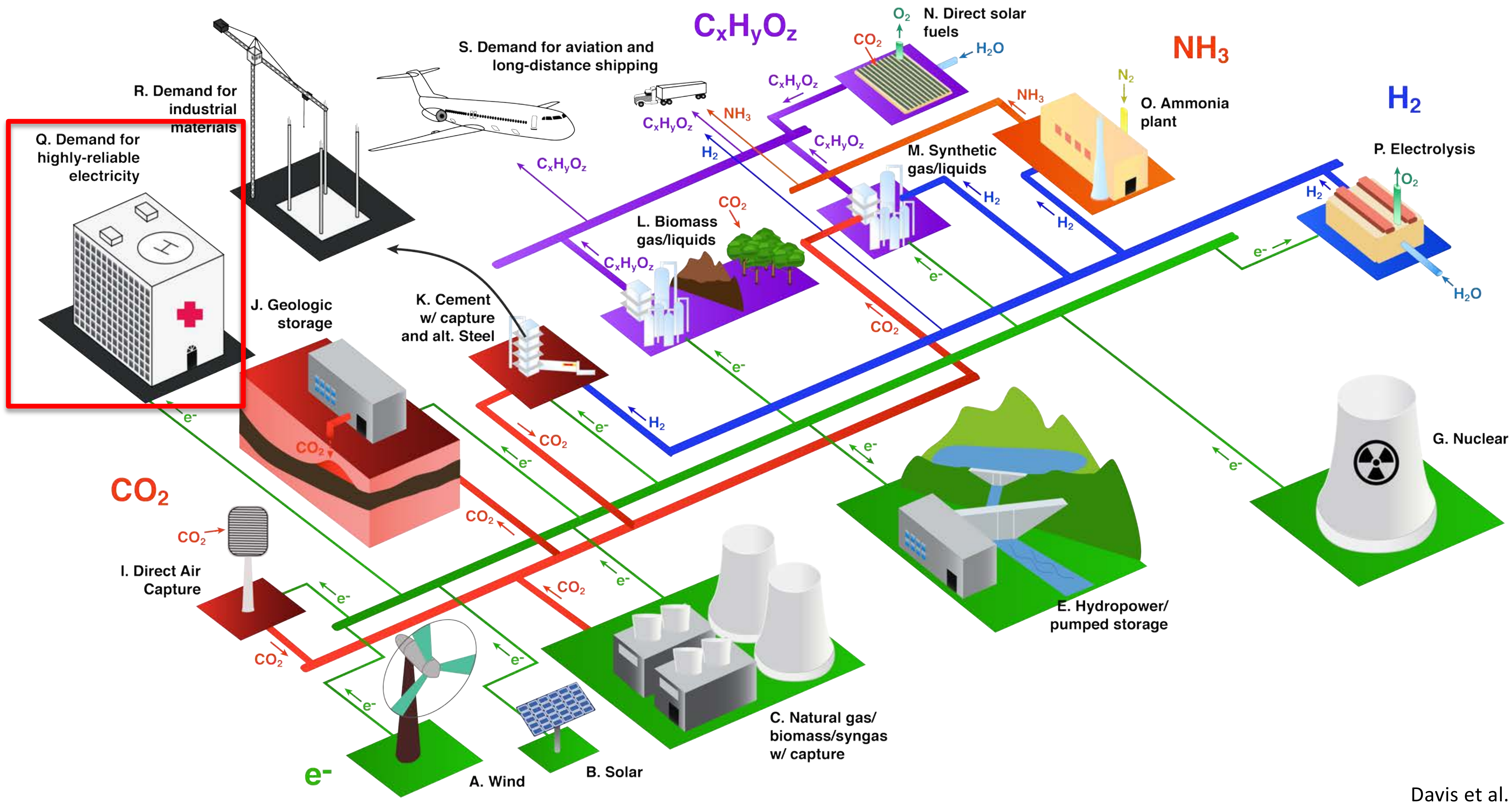

**~45% of process emissions re-absorbed In recent years**

Xi et al., *Nature Geoscience,* 2016

# Take-aways – Industrial materials

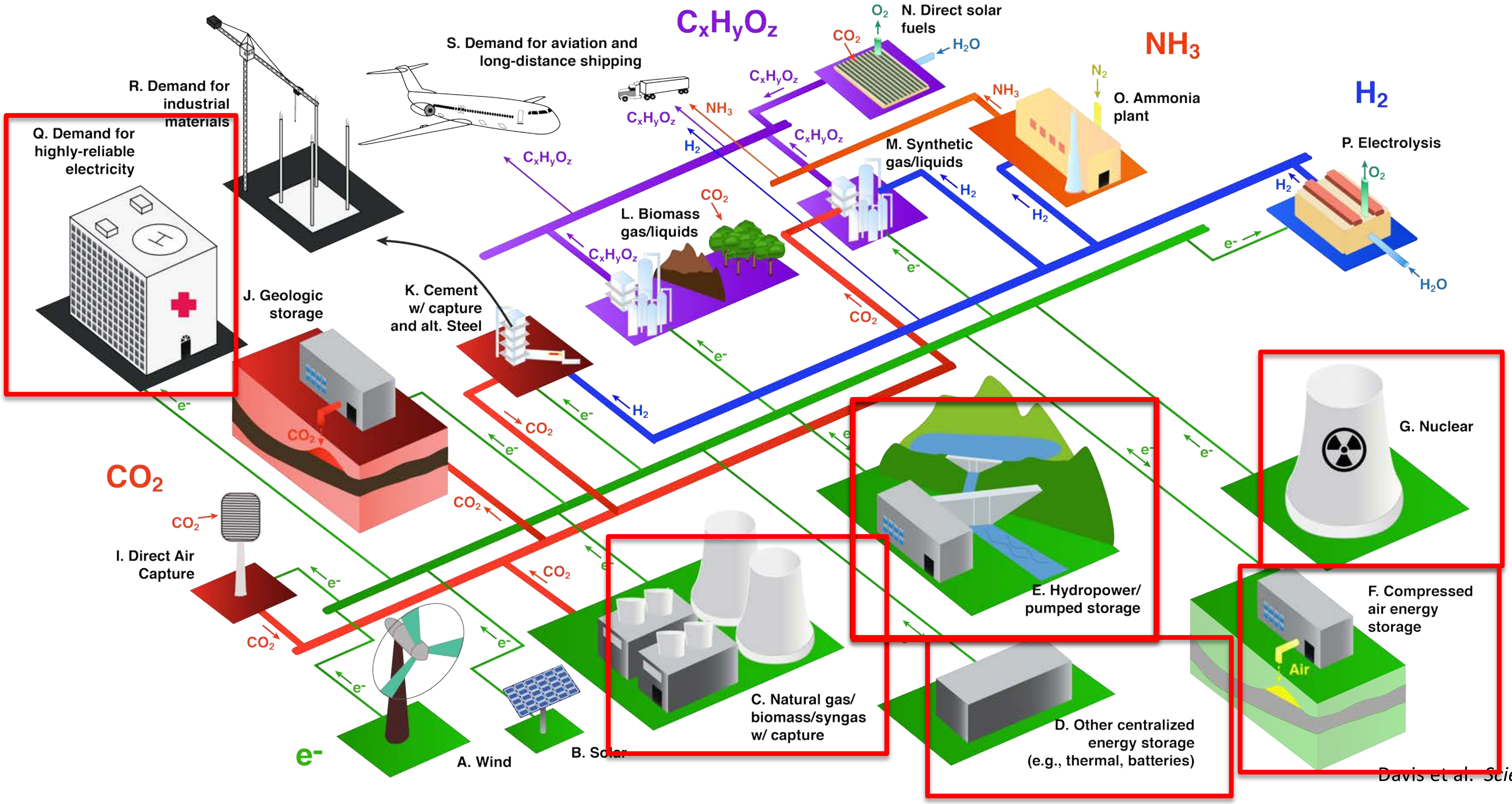
- Fossil-free, alternative processes of materials production and CCUS will likely be necessary
- Pursue manufacturing processes and waste management methods to accelerate carbonation of cements
- Carbon capture, utilization, & storage (CCUS) of cement process emissions could be a source of negative emissions

# Highly-reliable electricity (assuming substantial but variable and uncertain renewable energy)



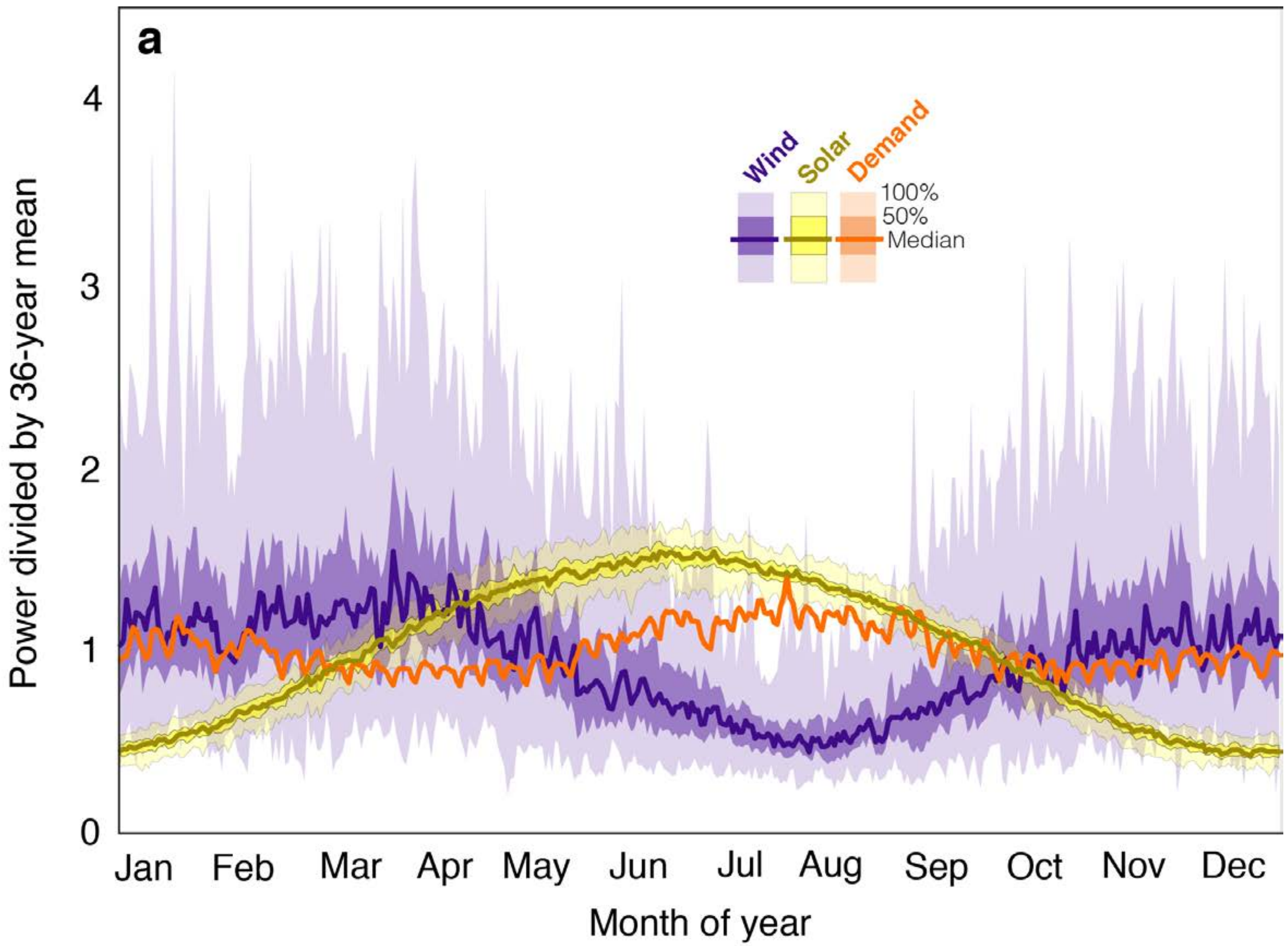

Davis et al. *Science,* 2018

...will require some combination of flexible generation, demand management, and energy storage




Davis et al. *Science*, 2018

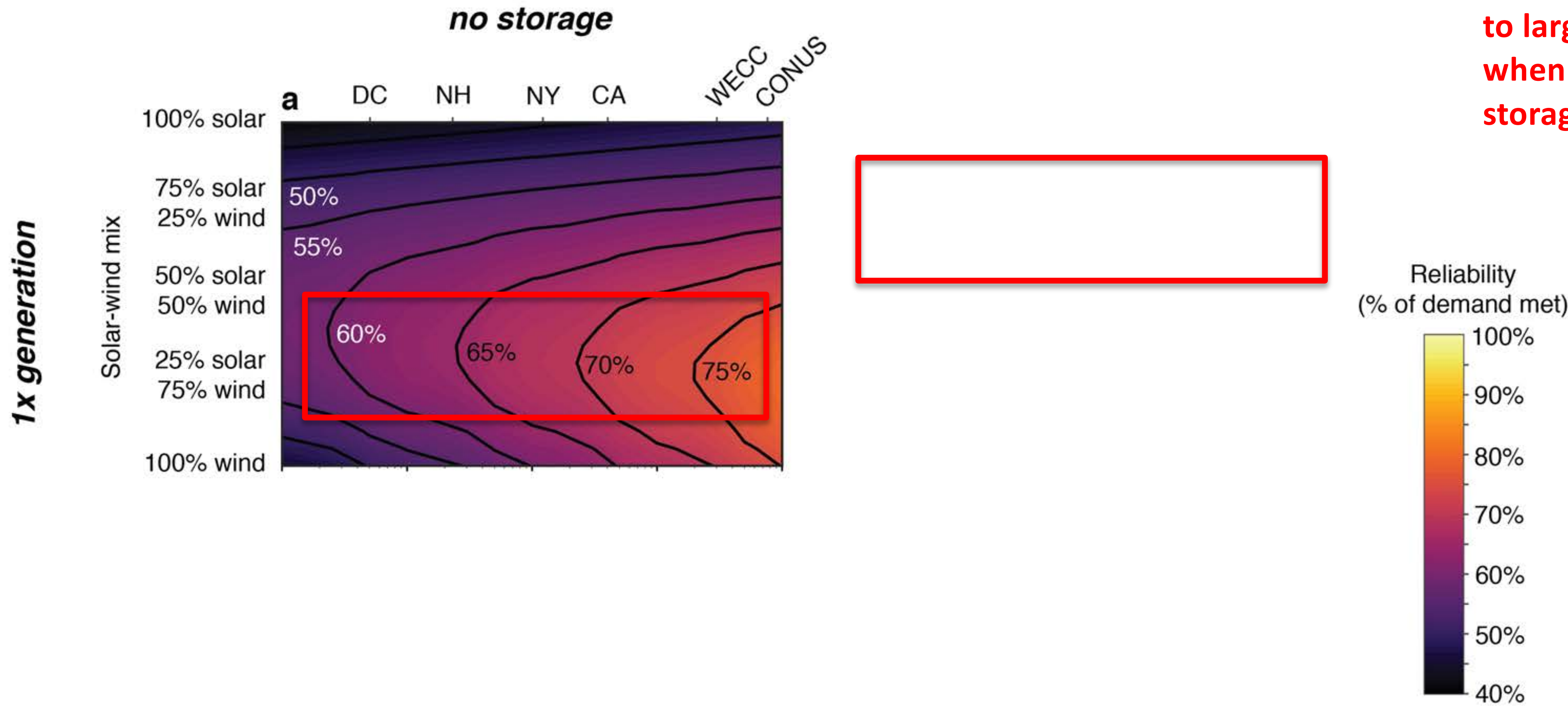
Temporal variability of wind and solar resources and power demand in the continental U.S.




Shaner et al., *Energy and Env. Science*, 2018

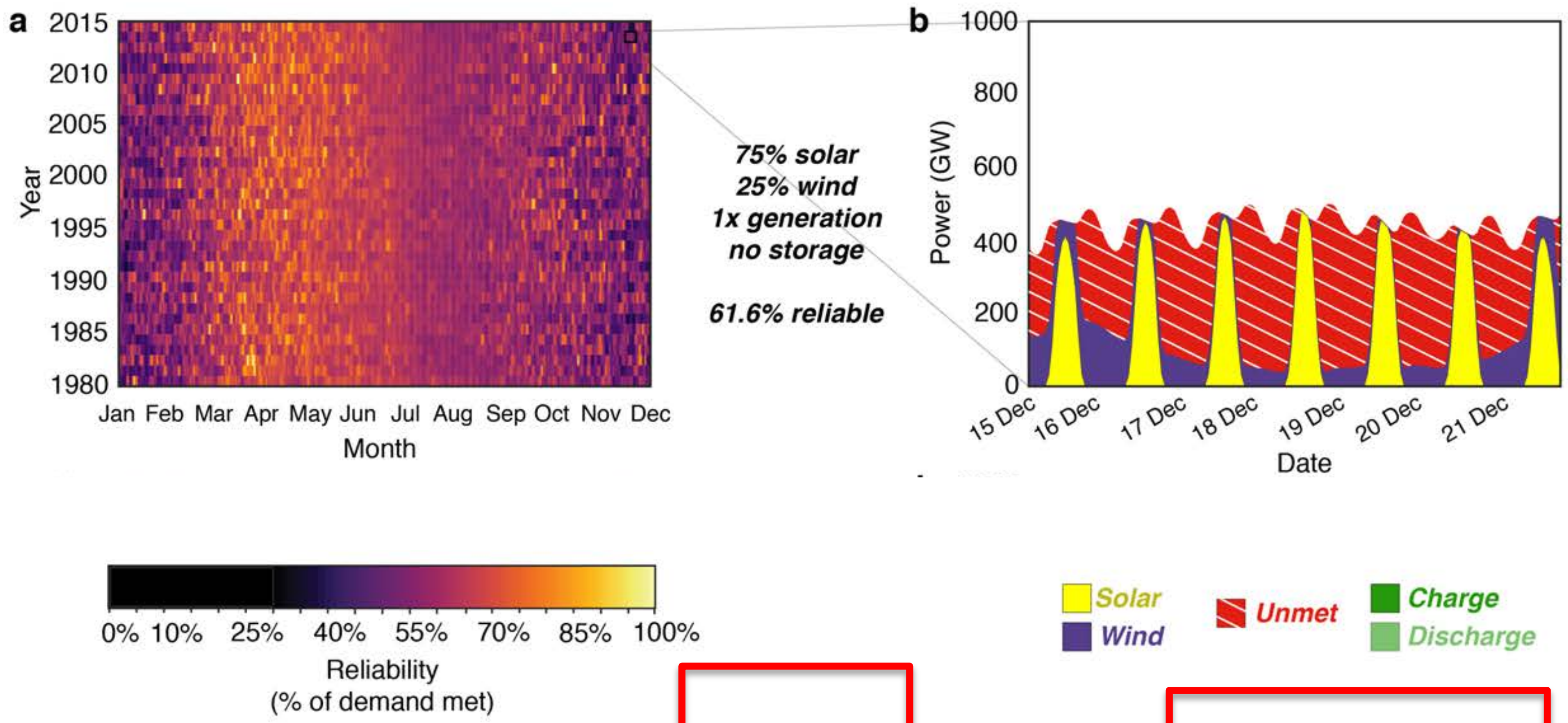
Increase reliability by spreading out, overbuilding generation, and installing storage

**Limited benefit to large areas when you have storage?**




Shaner et al., *E&ES* (2018)

But even when you do *all* that, there are still multi-day periods with lots of unmet demand





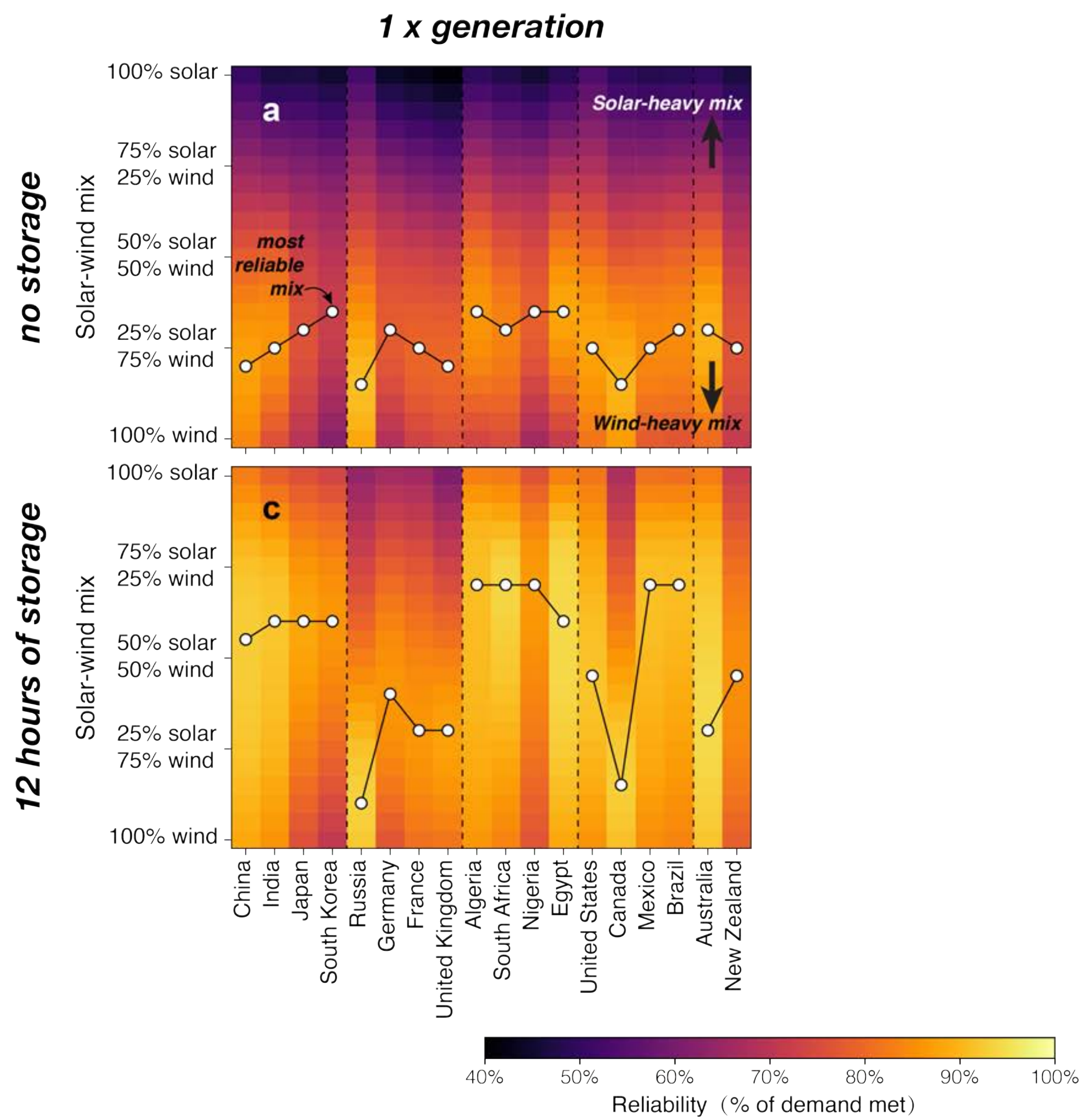
Shaner et al., *E&ES* (2018)

# Reliability of electricity supply by varying solar and wind resource mix, generation and energy storage

**Increasing excess generation by 10% is equivalent to adding 3.9 hours of storage**

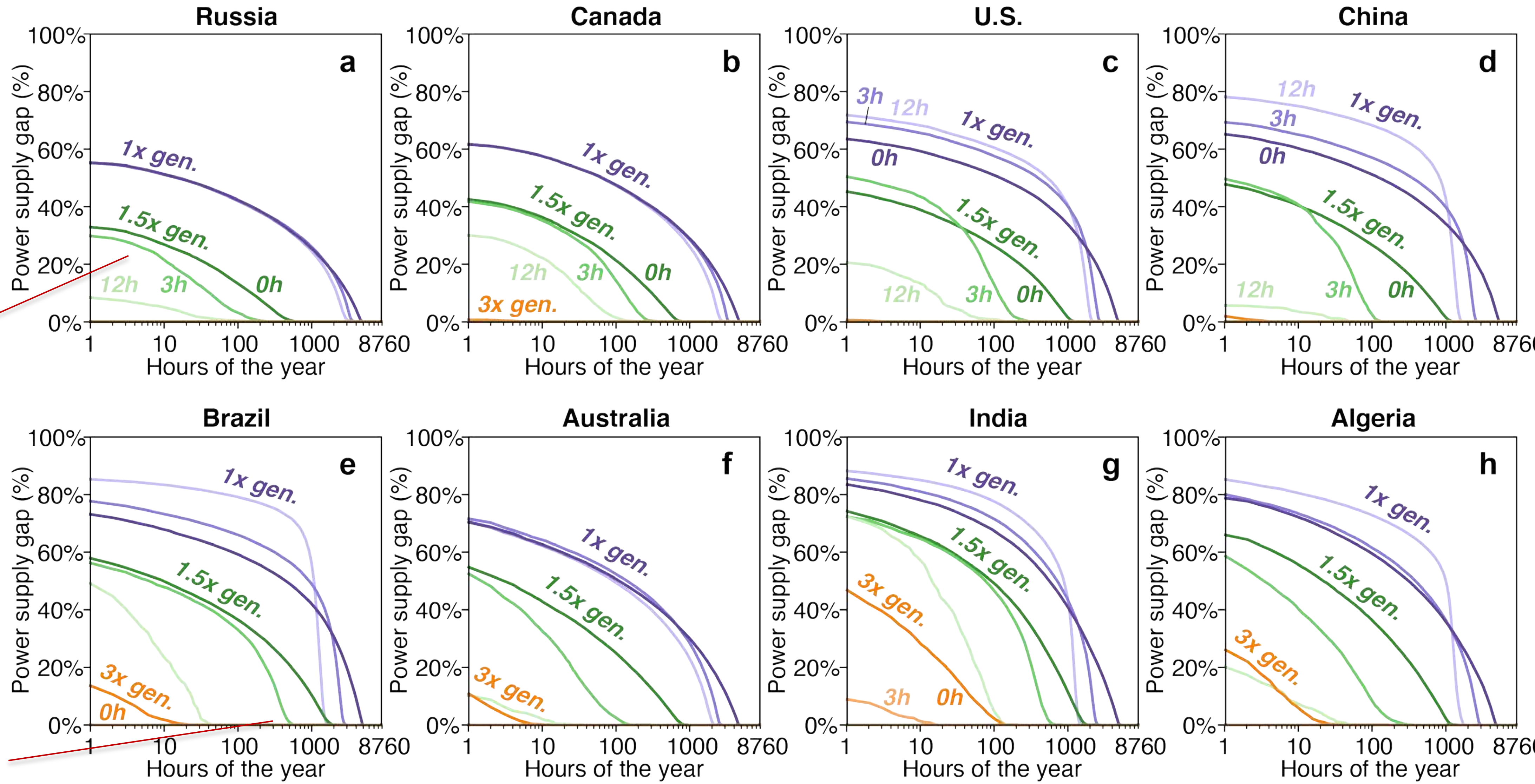
**72-92% reliable**

**83-94% reliable**




Tong et al., *in review*

# Average power supply gaps in "most reliable" systems



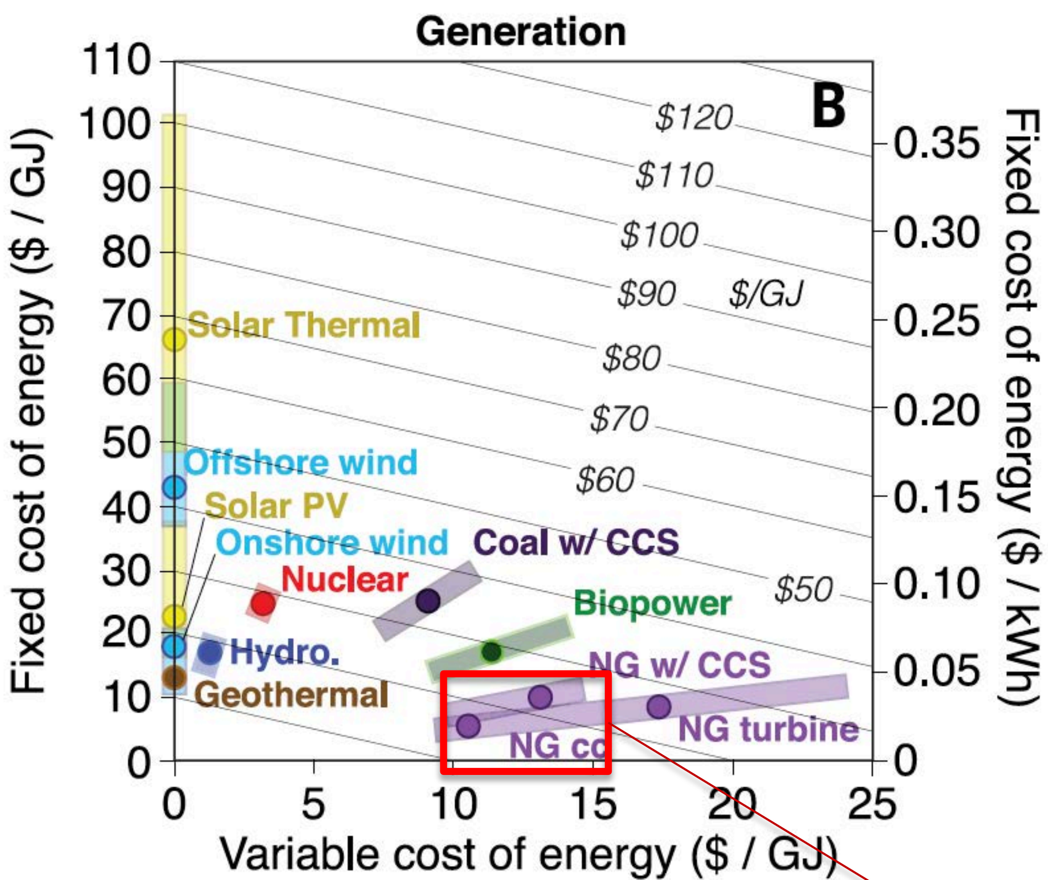

**Areas under these curves are load-duration curves of backup technologies**

**Maybe 25-50% of generating capacity for few hundred hours per year**

Tong et al., *in review*

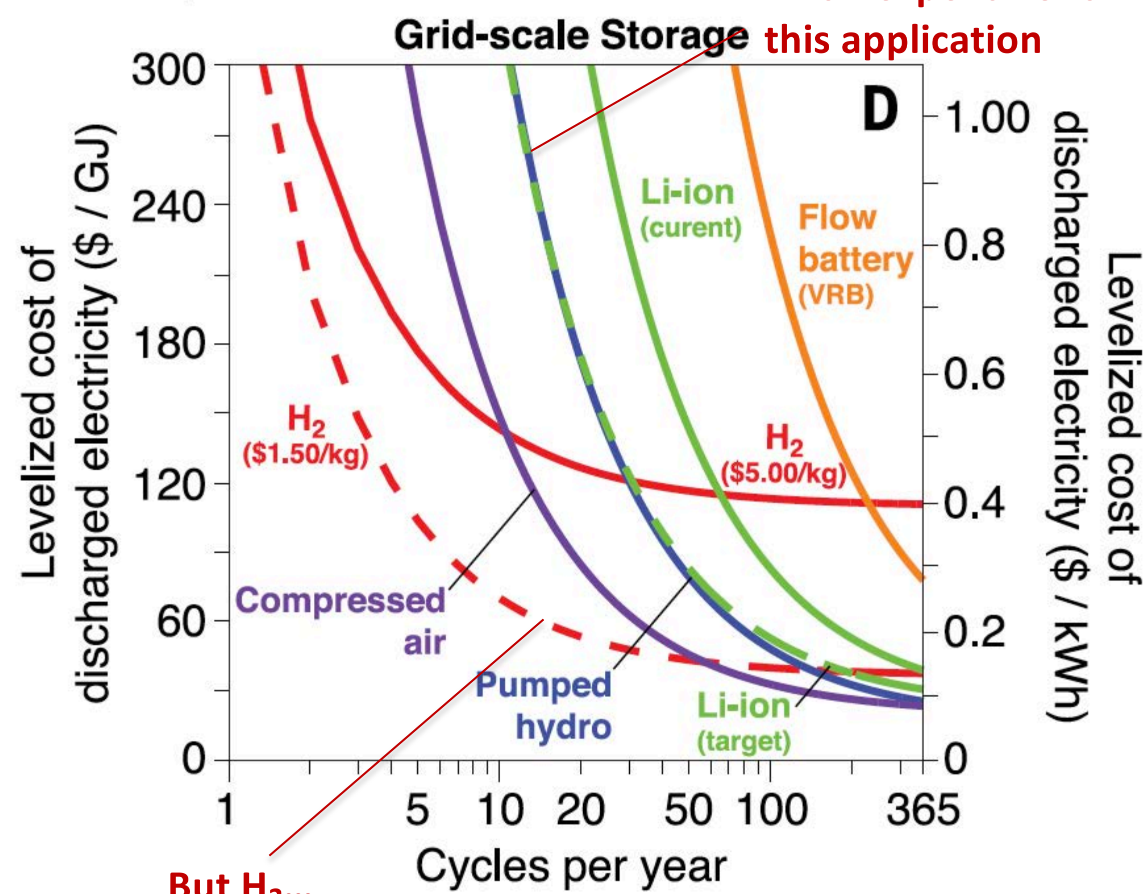
Given that gaps are big but infrequent, utilization rate of back-up resources will be low—

We need electricity sources ***with low fixed costs*** or that can ***meet other demands*** when electricity is not needed




Like the natgas we use now, but w/o the $CO_2$

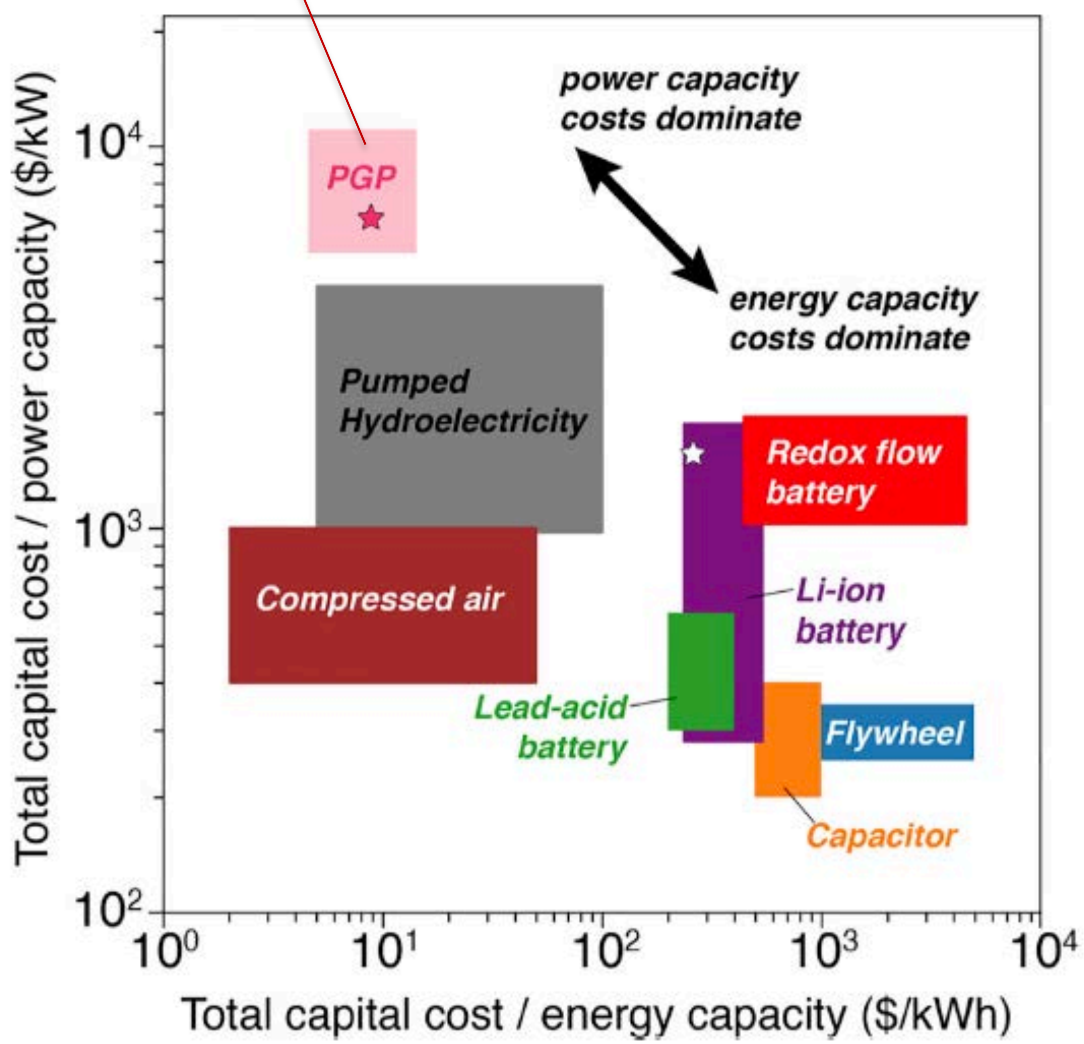
Li-ion expensive for this application




But $H_2$…

Davis et al., *Science*, 2018

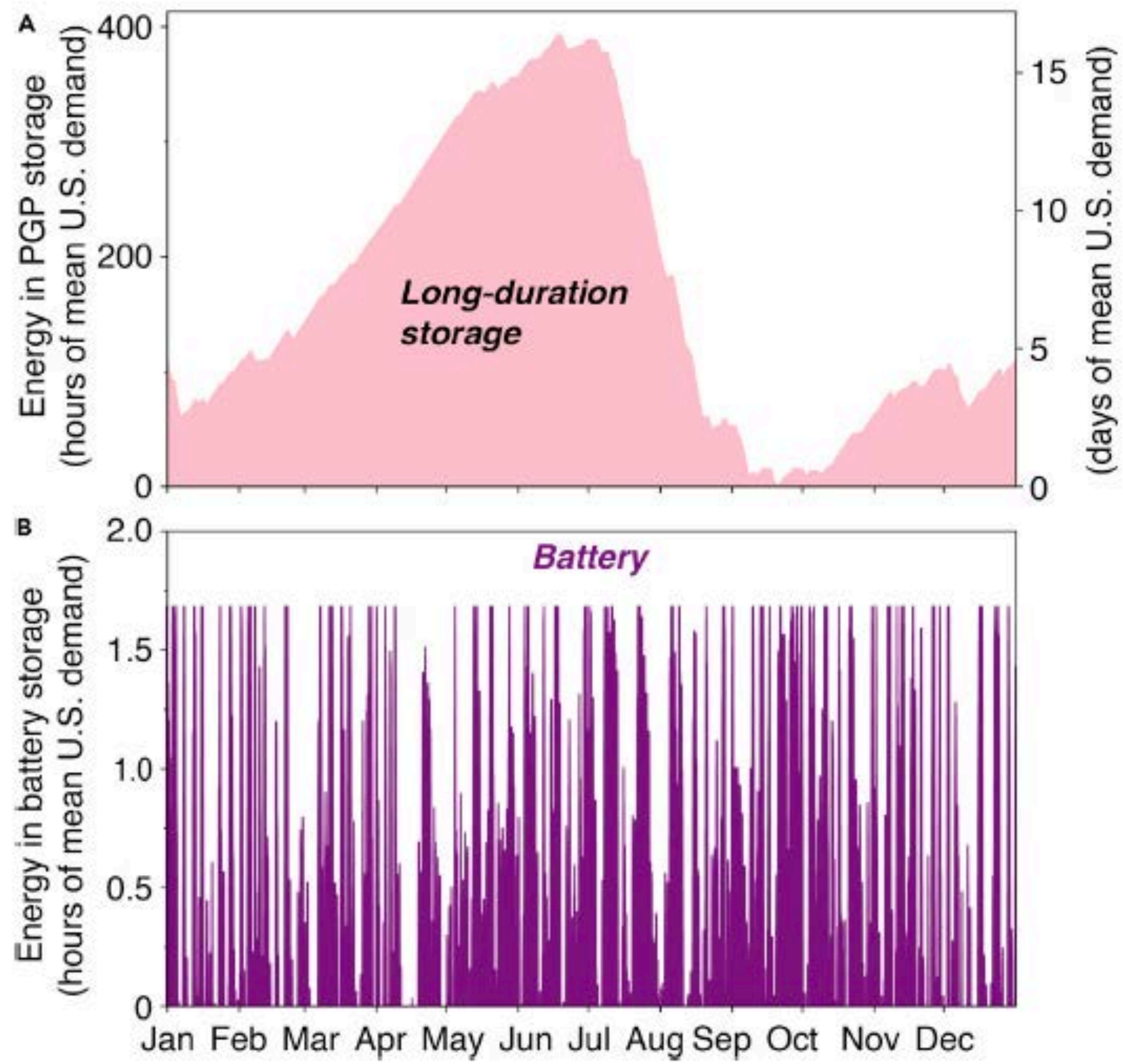
Hydrogen (e.g. power-to-gas-to-power PGP) is attractive because its costs are dominated by power capacity not energy capacity




A relatively low-power electrolyzer can generate large quantities of hydrogen (energy) by operating all but the few hundred hours when it is needed.

Dowling et al., *Joule*, 2020

Hydrogen is thus economically better-suited to filling long-duration gaps




Dowling et al., *Joule*, 2020

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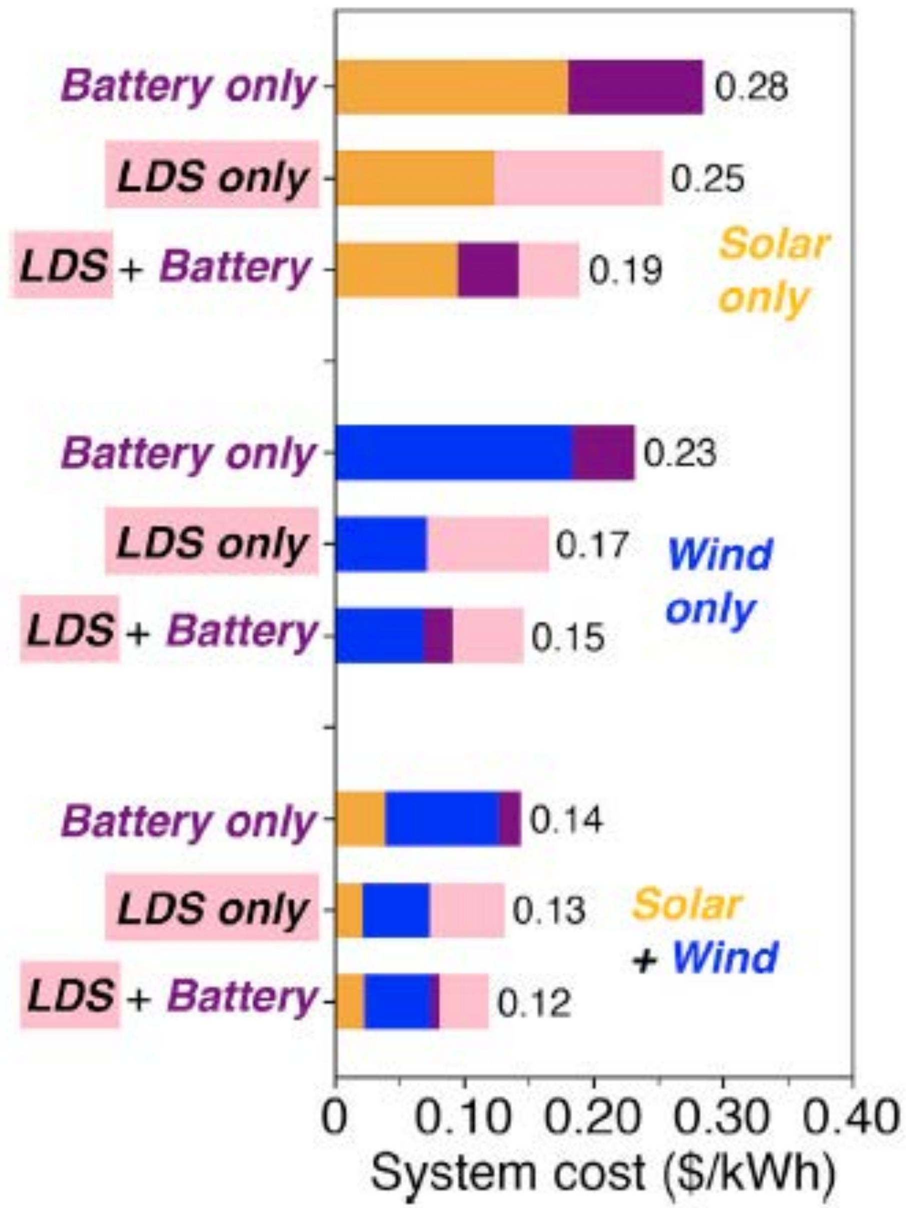
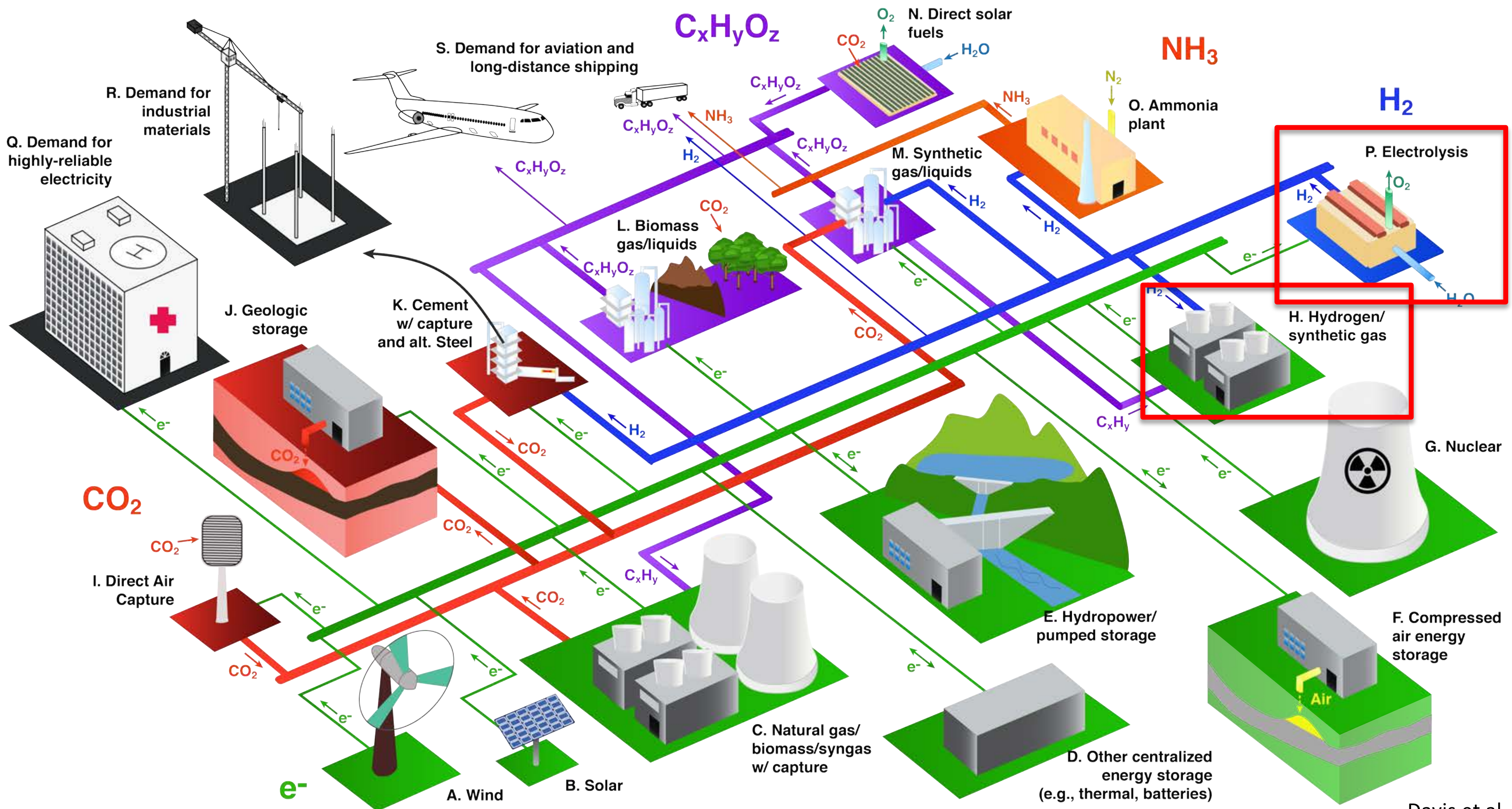



Even at current costs, long-duration storage by hydrogen are consistently cheaper than solar, wind and battery-only systems

Dowling et al., *Joule*, 2020

Also big opportunities for hydrogen to integrate electricity, transport, and industry sectors




Davis et al., *Science*, 2018

# Take aways – Highly-reliable electricity

- Geophysical variability in solar and wind resources reveal the need for back-up technologies (flexible generation, demand management, or energy storage)

- At regional- and continental-scales, the gaps in power production are large and long-duration—thousands of GWh (tens of PJ) over days or weeks

- Economic analyses show consistent benefits of long-duration storage of hydrogen over

Summary

Tremendous prospects for decarbonization in the near-term

Remaining challenges that require further innovation, systems analysis and coordination with policymakers and businesses

# Thank you.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