Net zero emissions energy systems

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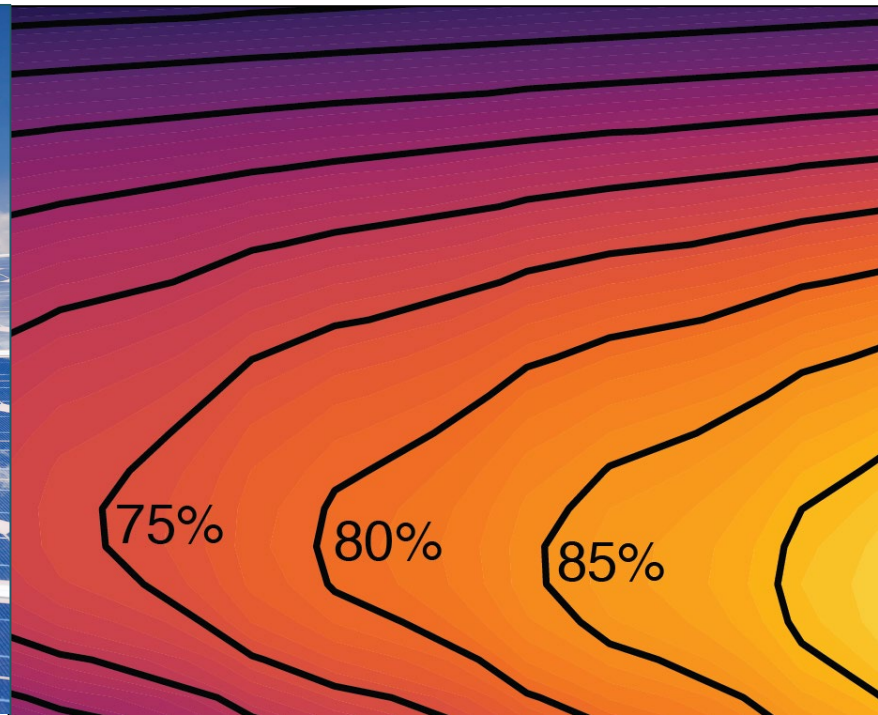


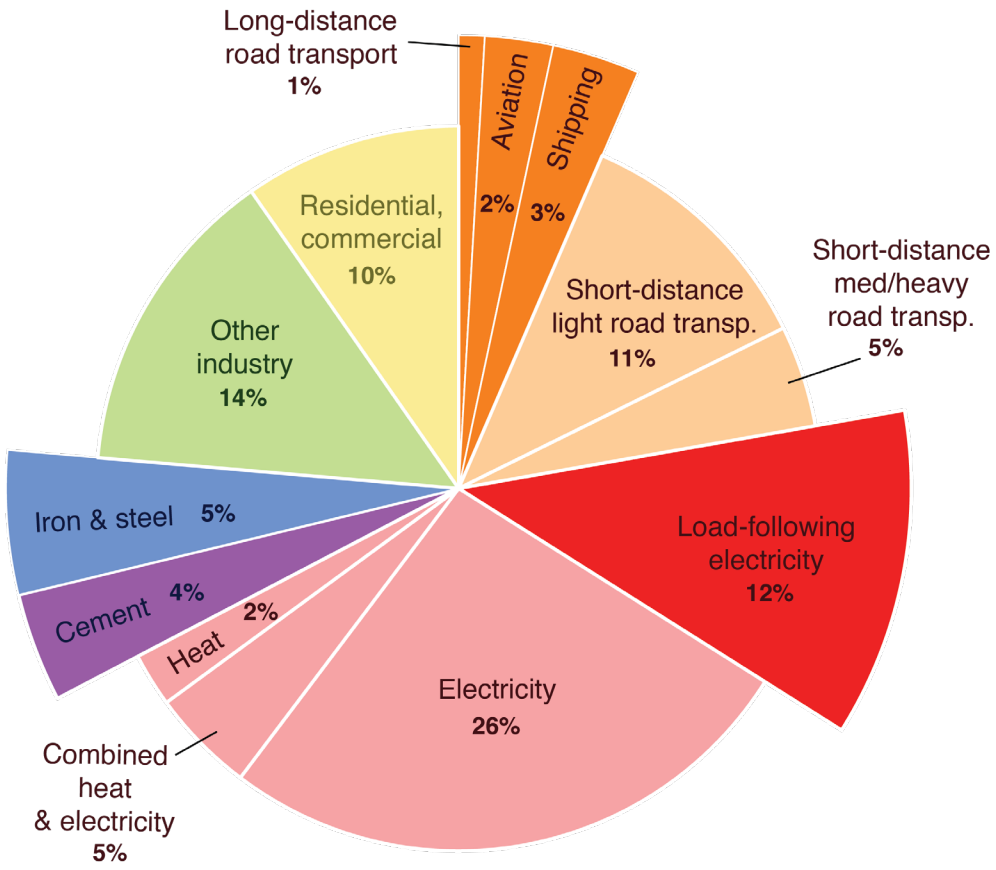
Some modern energy services will be especially challenging to decarbonize

Aviation and long-distance transport

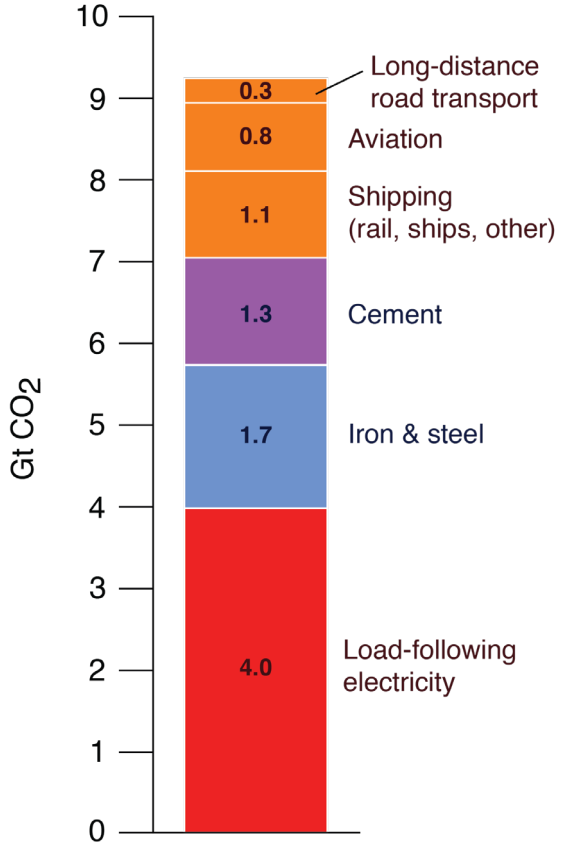
Industrial materials

Highly-reliable electricity

How much "difficult" CO_2 are we talking about?



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



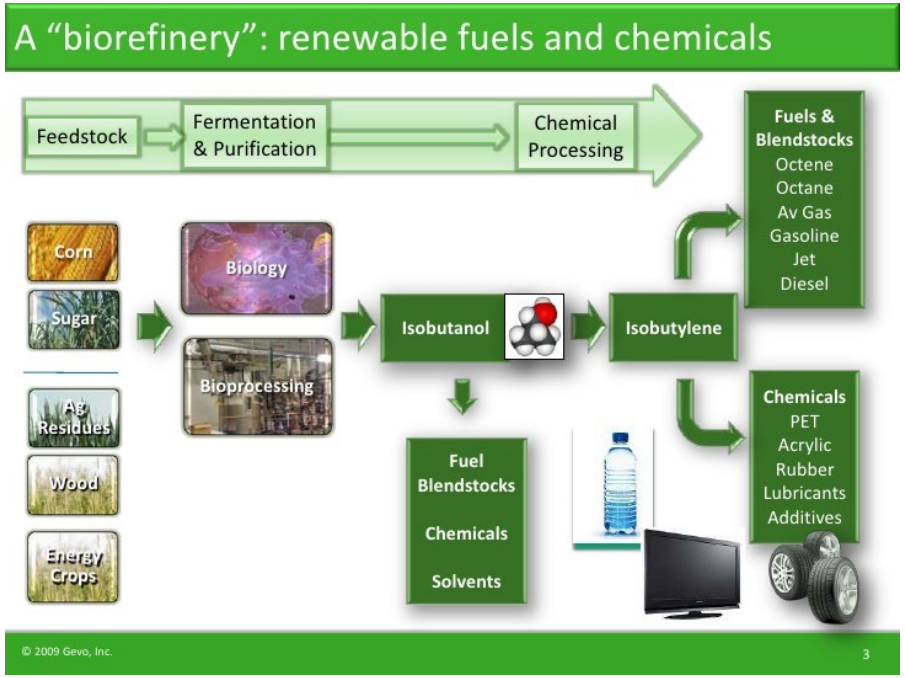
B **Difficult-to-eliminate emissions, 2014 (9.2 Gt CO_2)**

Davis et al. *Science,* 2018

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”



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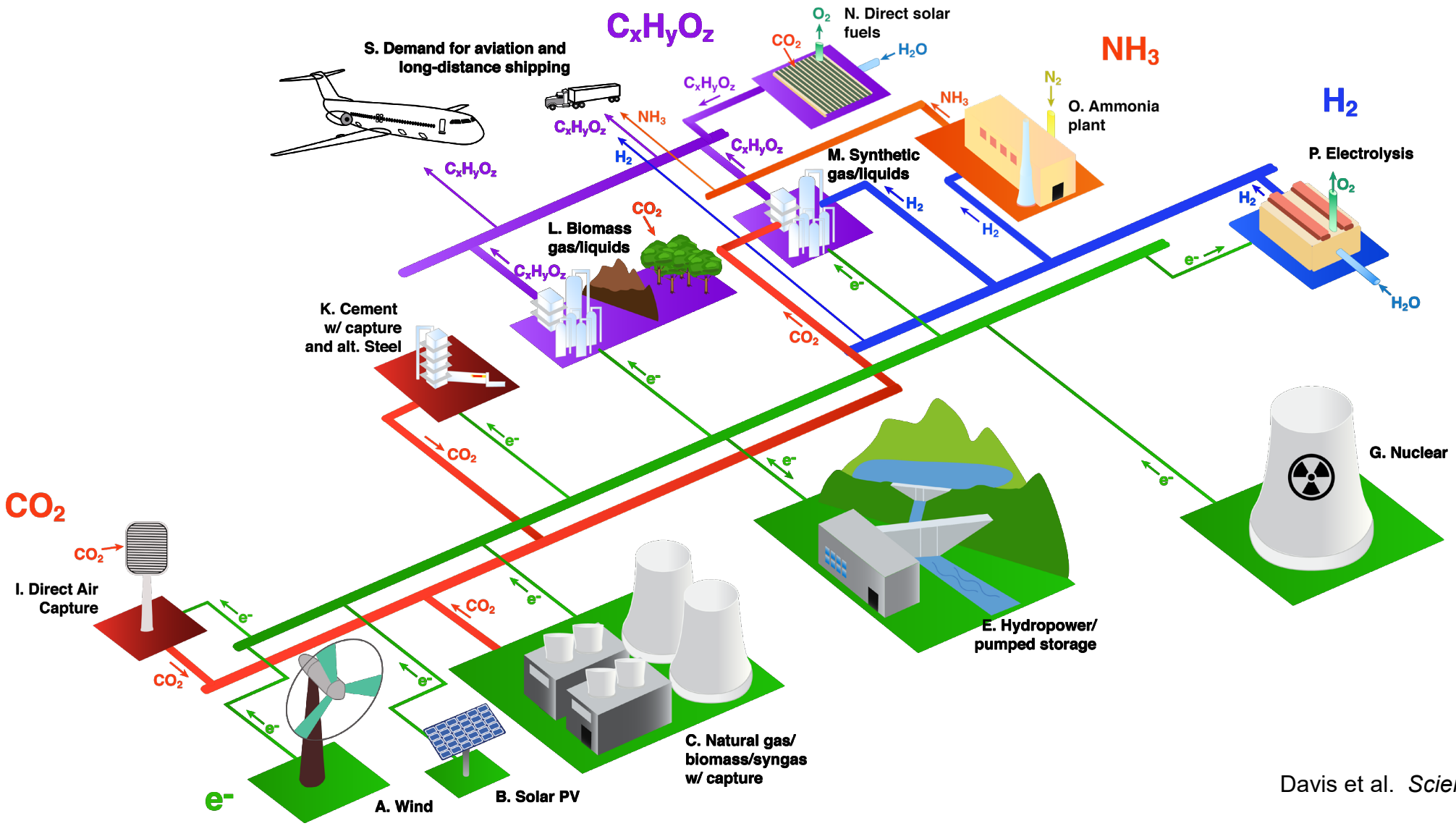
Carbon-free options for liquid fuels with high energy density



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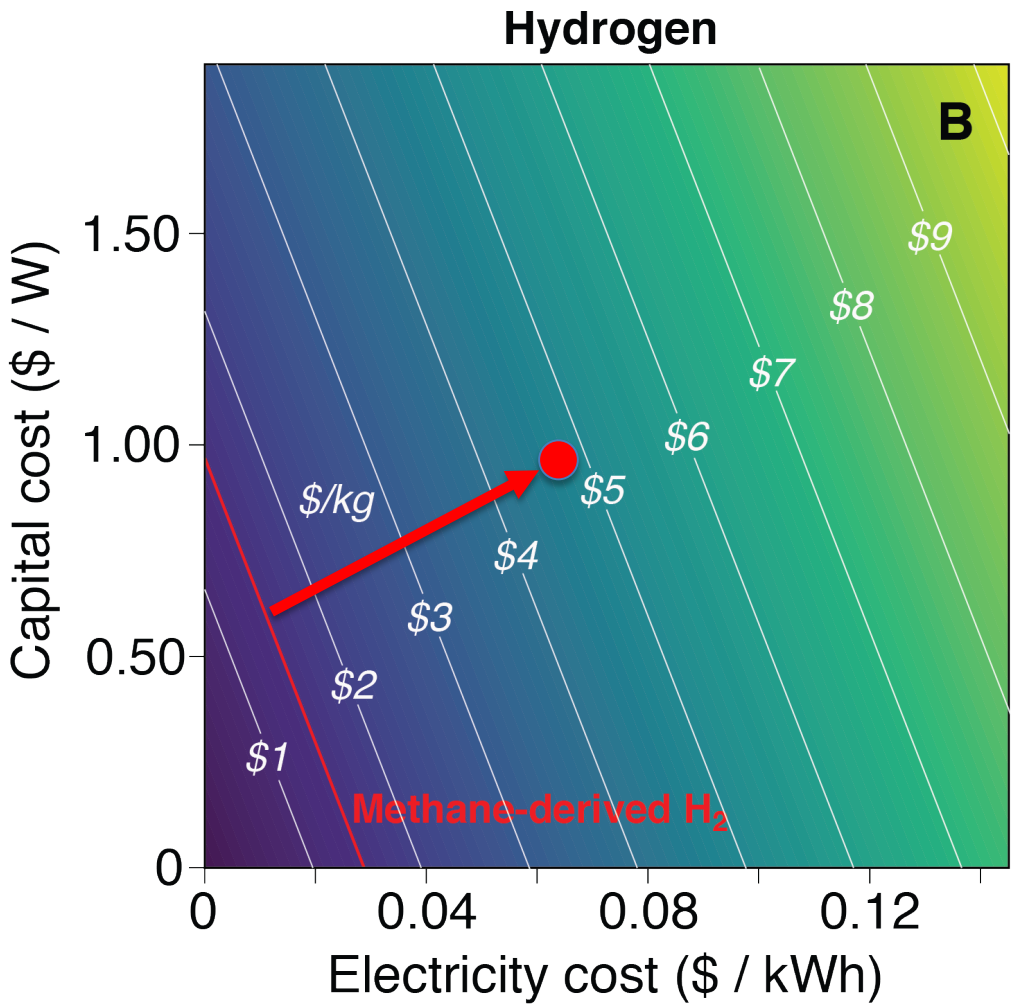
Costs of carbon-free hydrogen are high relative to fossil fuels

Cost of electrolyzer is a major barrier



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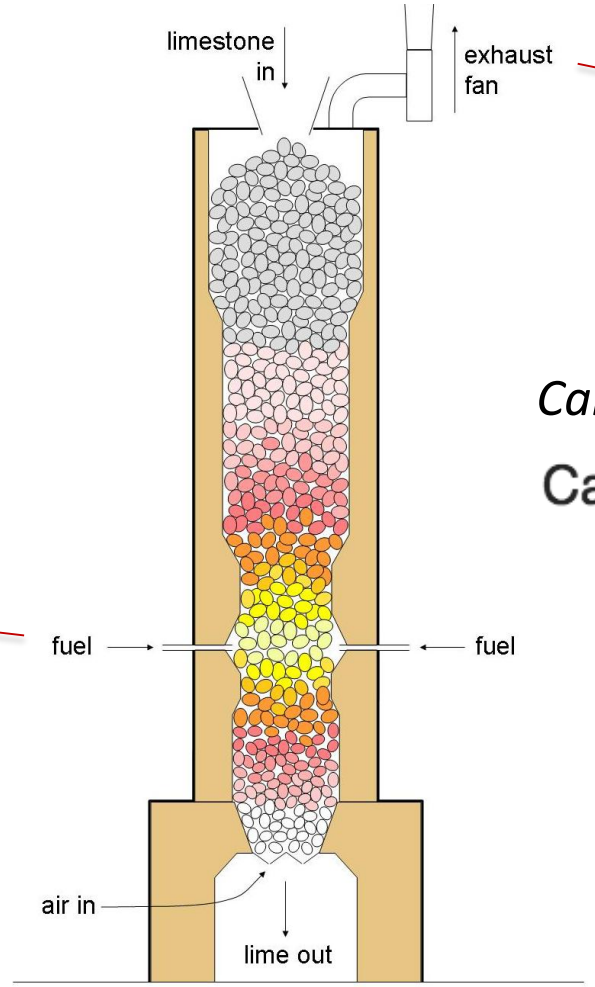
Structural Materials for Developed Civilization

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

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

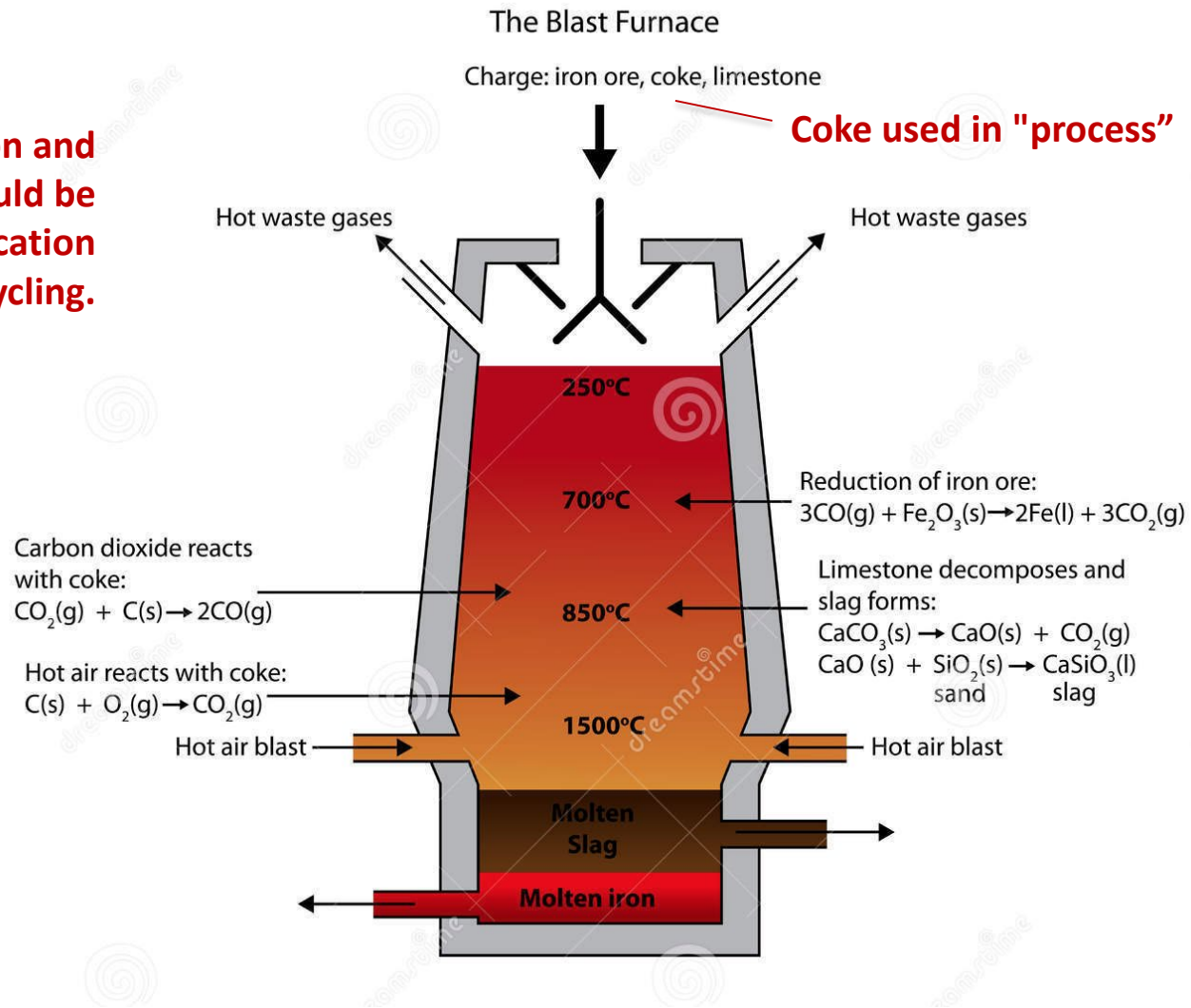
Calcination:

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

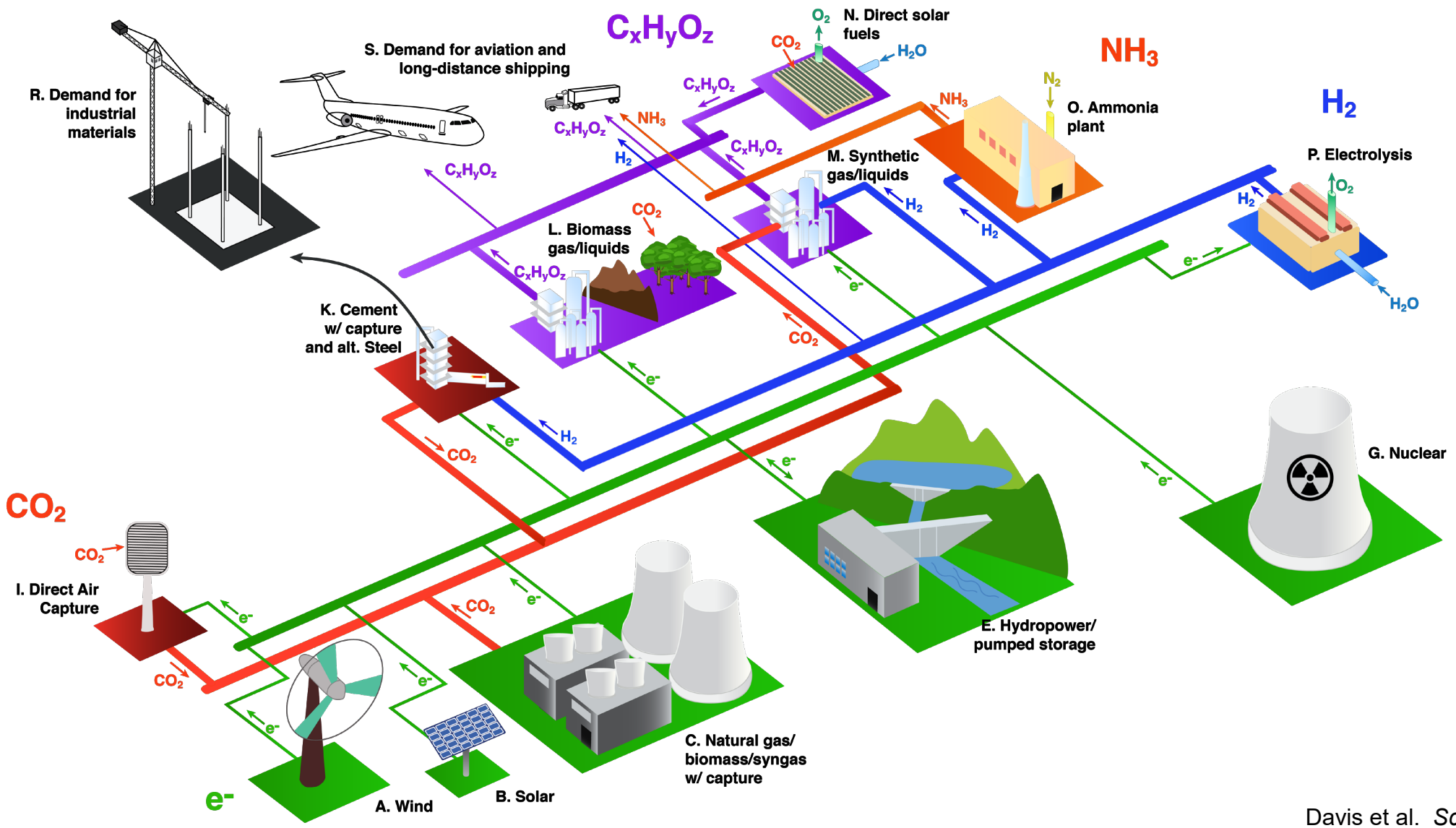
fossil energy = ~50% cement emissions

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.



Alternative processes



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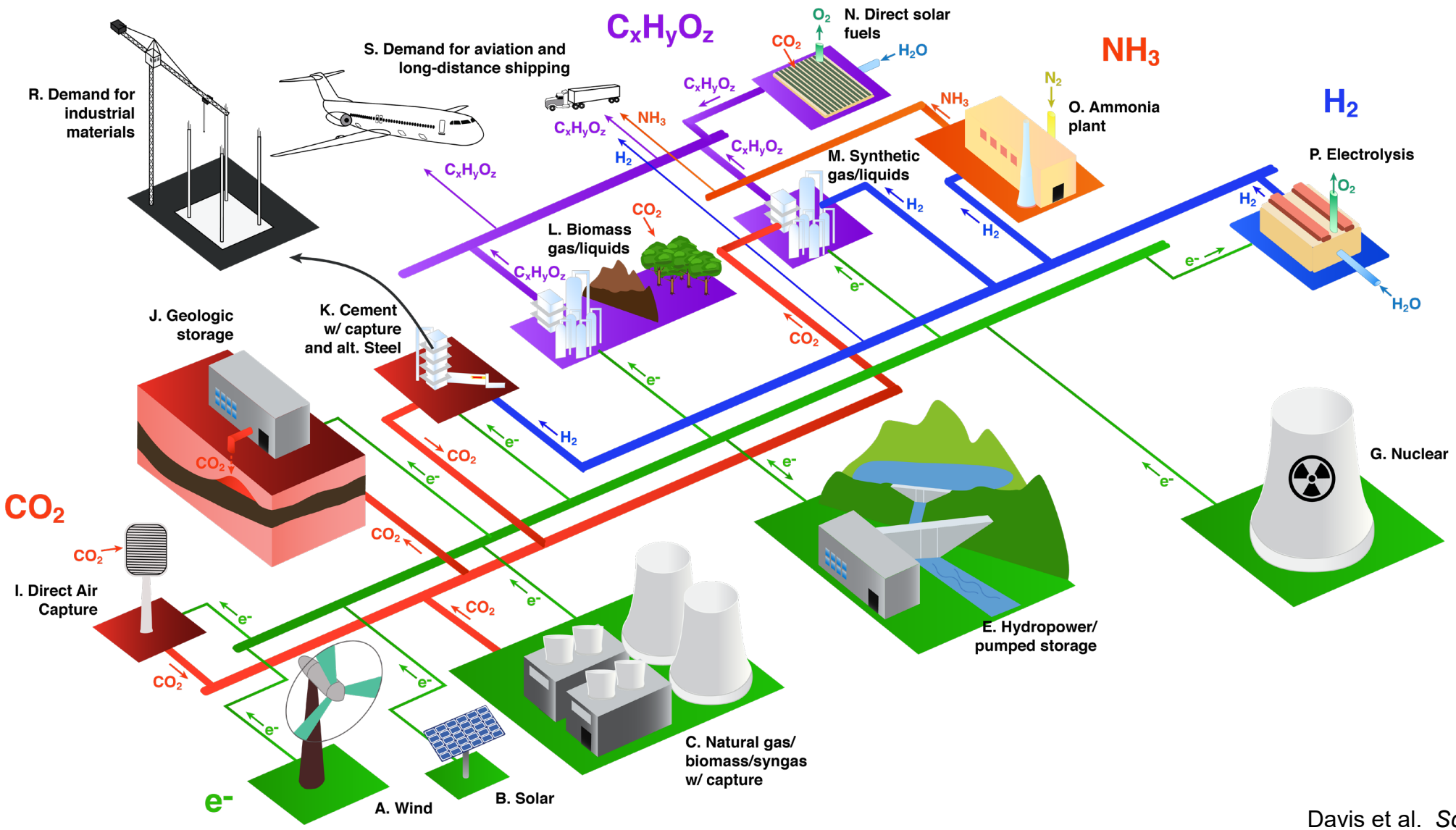
And/or Carbon capture and storage (CCS)



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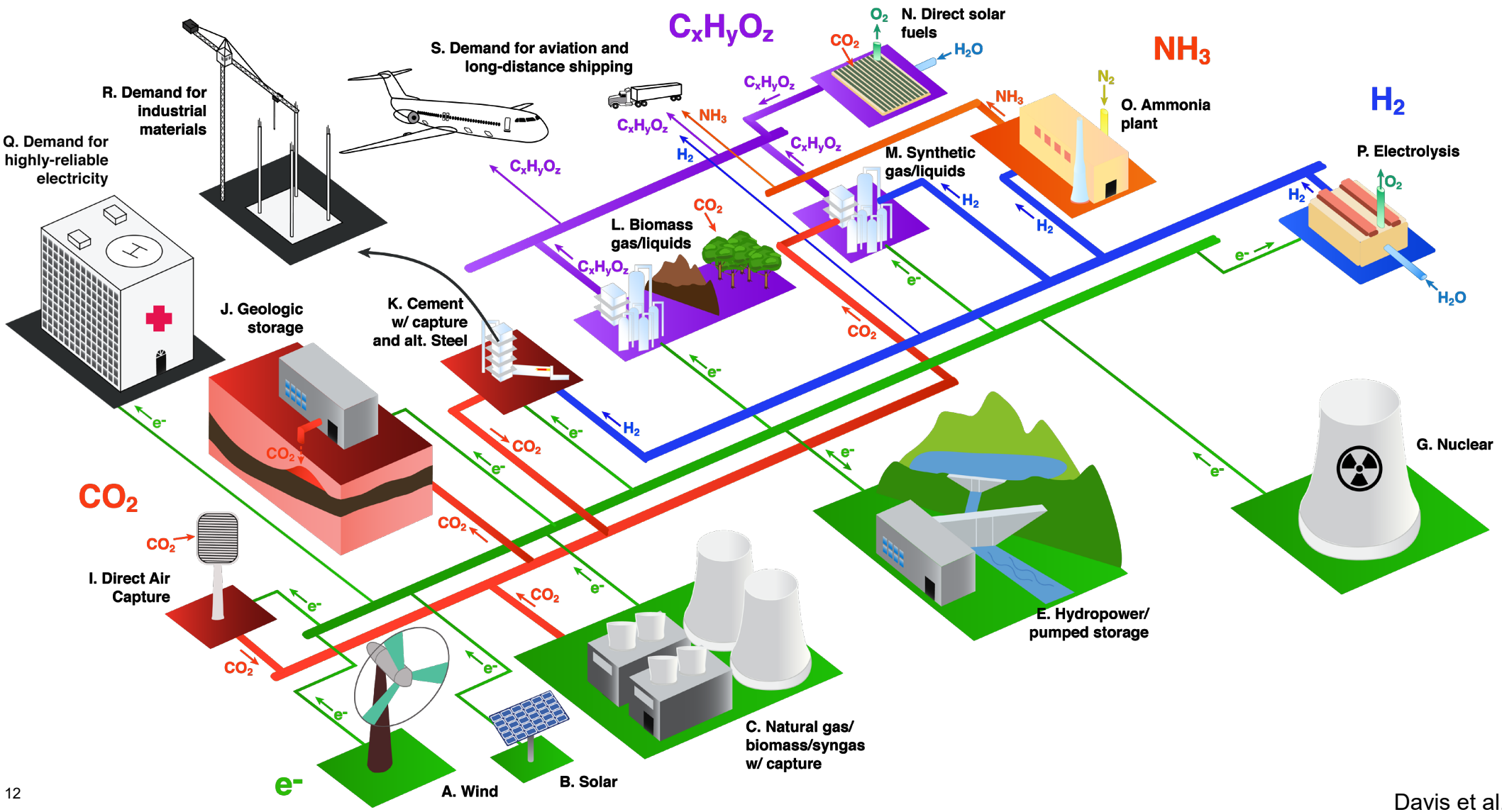
Highly-reliable electricity (assuming substantial but variable and uncertain renewable energy)



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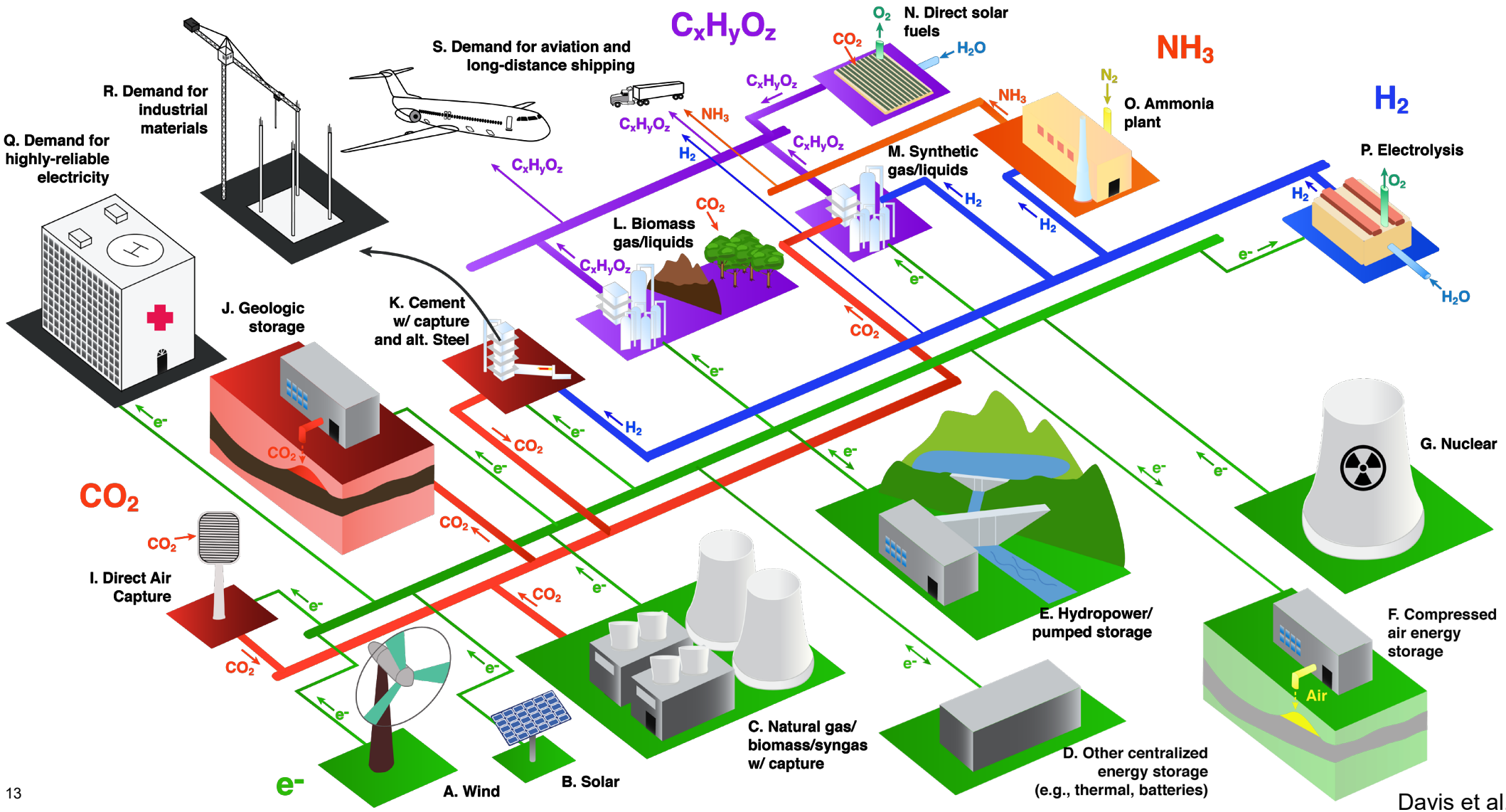
…will require some combination of flexible generation, demand management, and energy storage



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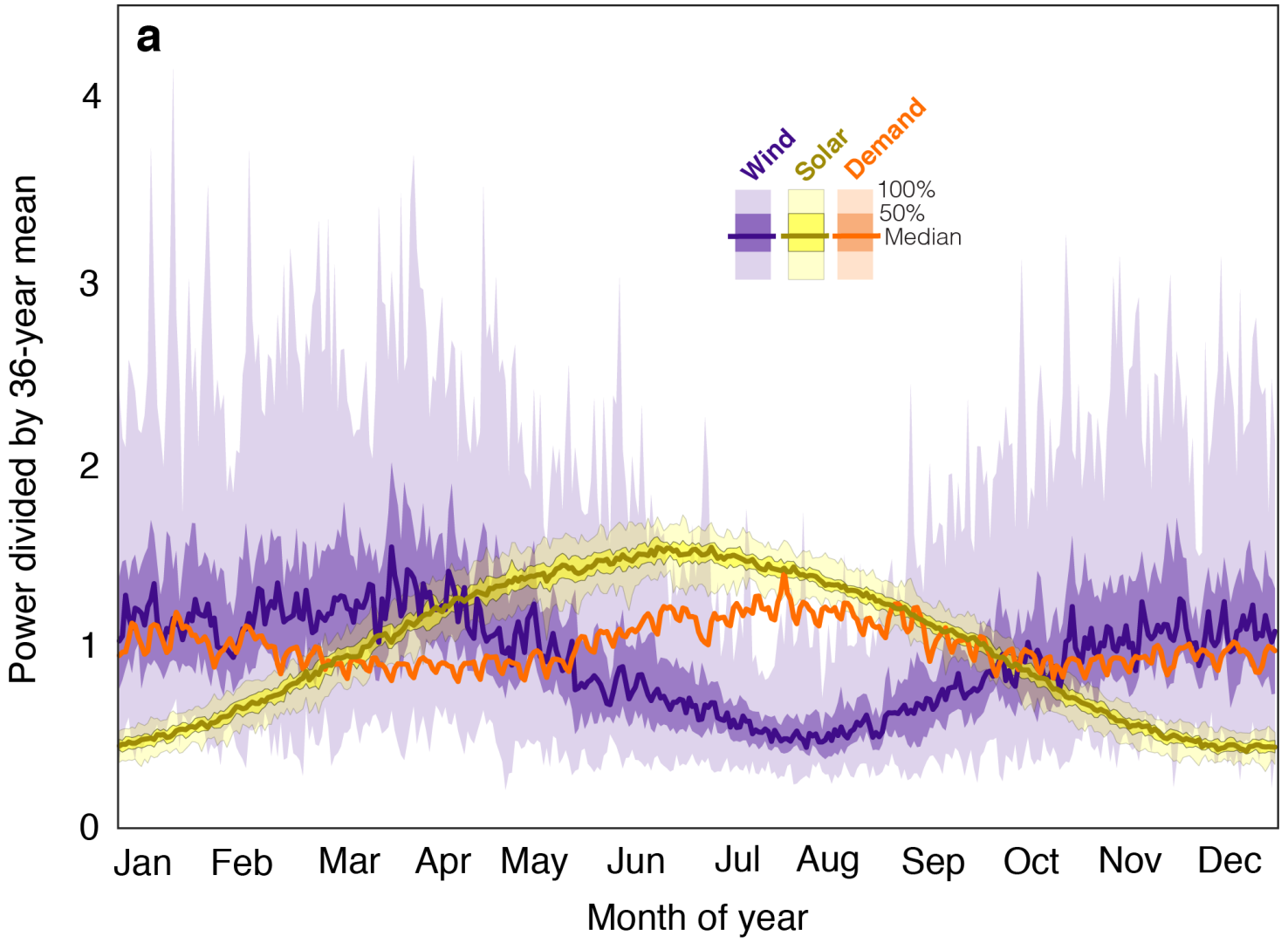
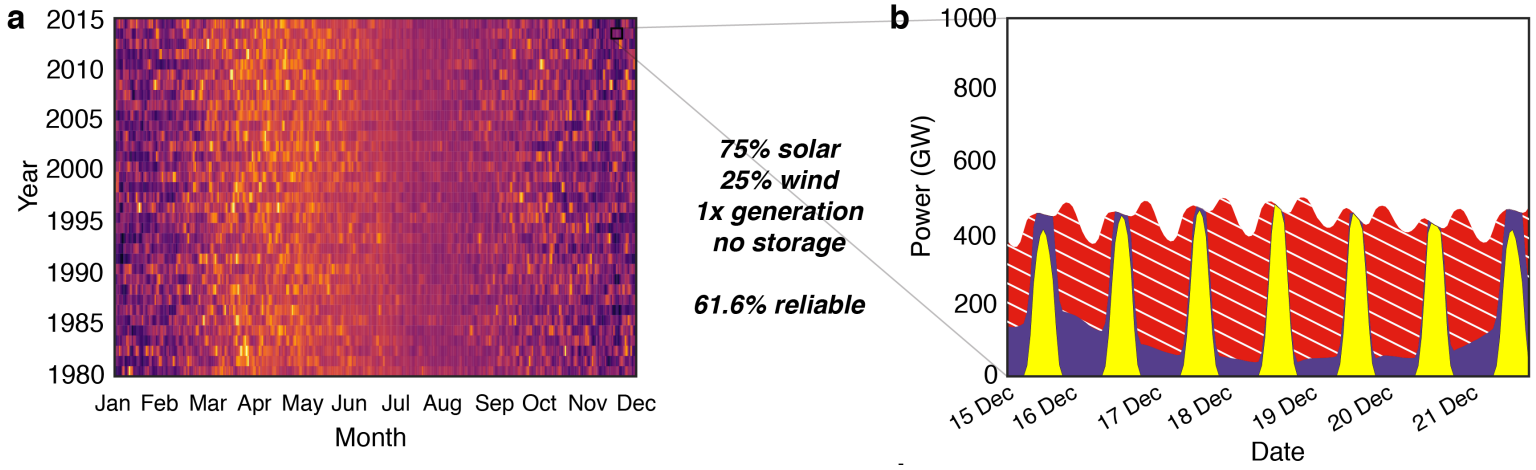
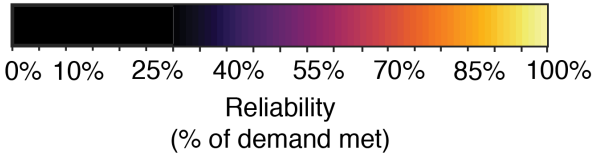
Temporal variability of wind and solar resources and power demand (CONUS)



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

Unmet demand as a function of resource mix, overcapacity and energy storage





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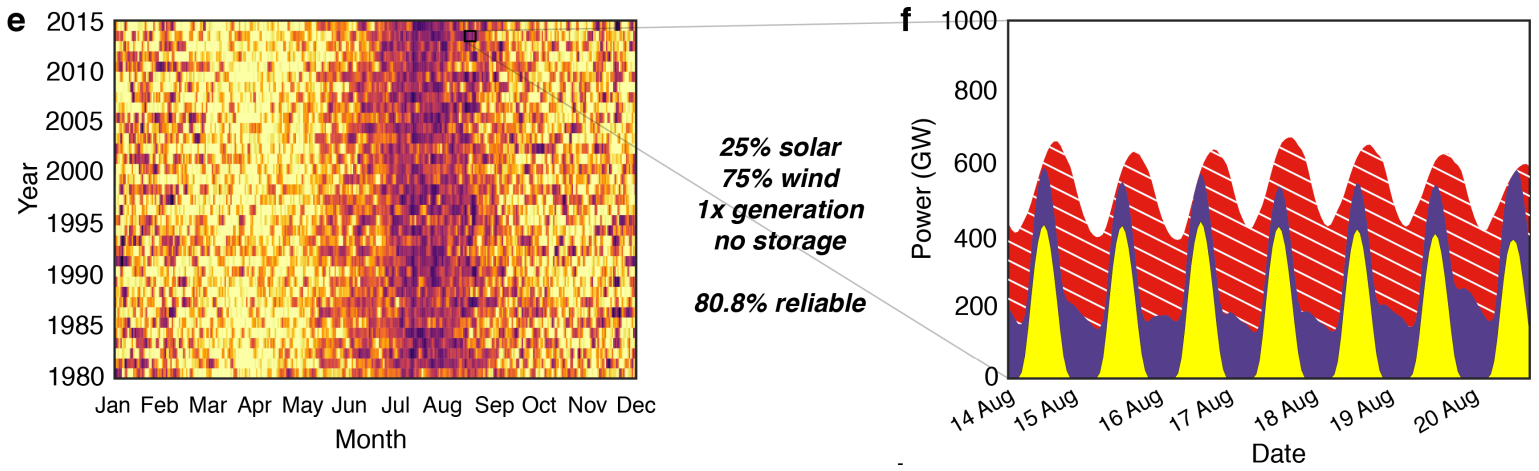

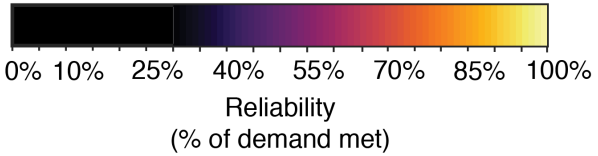

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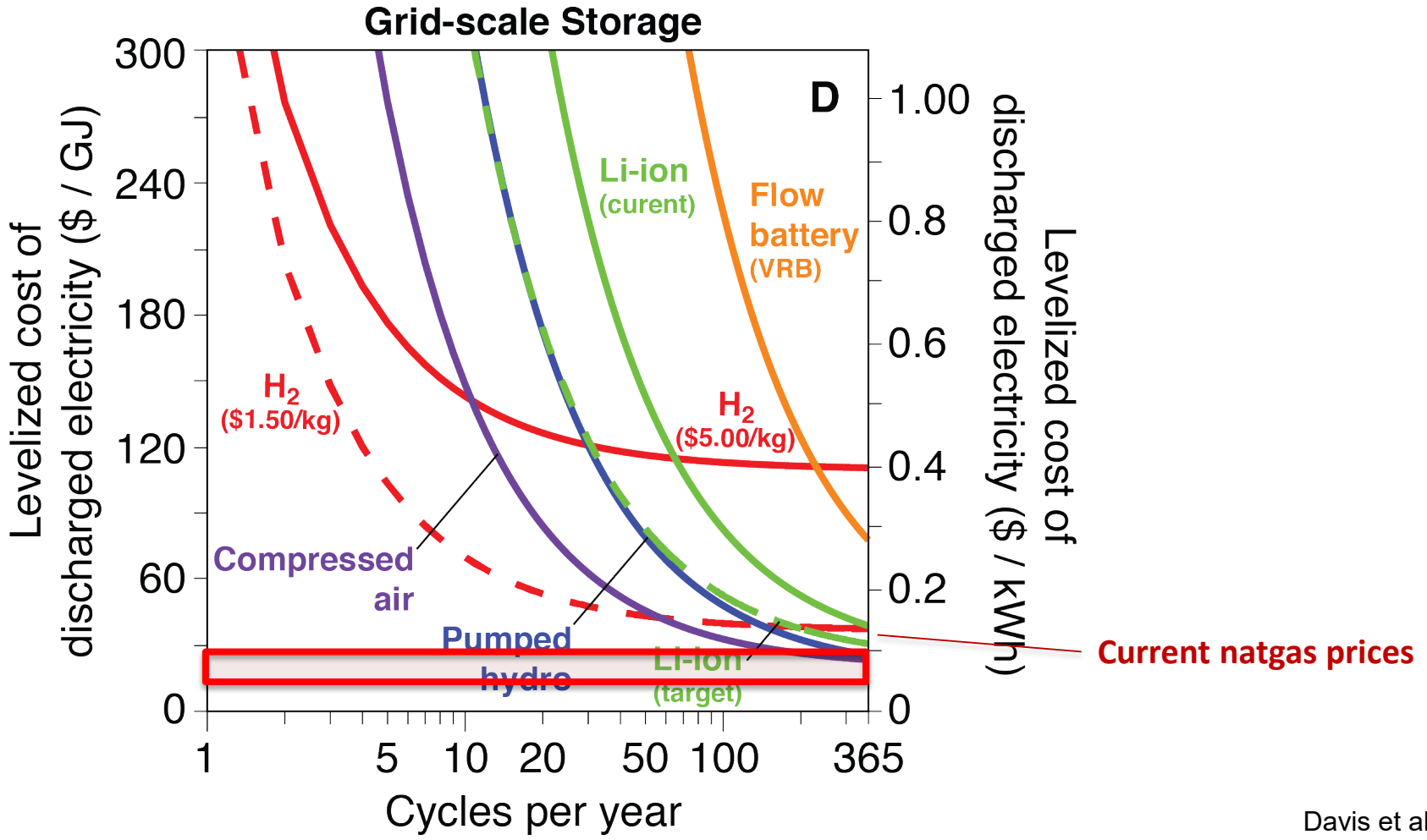
Given these gaps are infrequent, utilization rate of back-up resources will be low—so we either need non-emitting electricity sources *with low fixed costs* or *flexibility to meet other demands* when electricity is not needed



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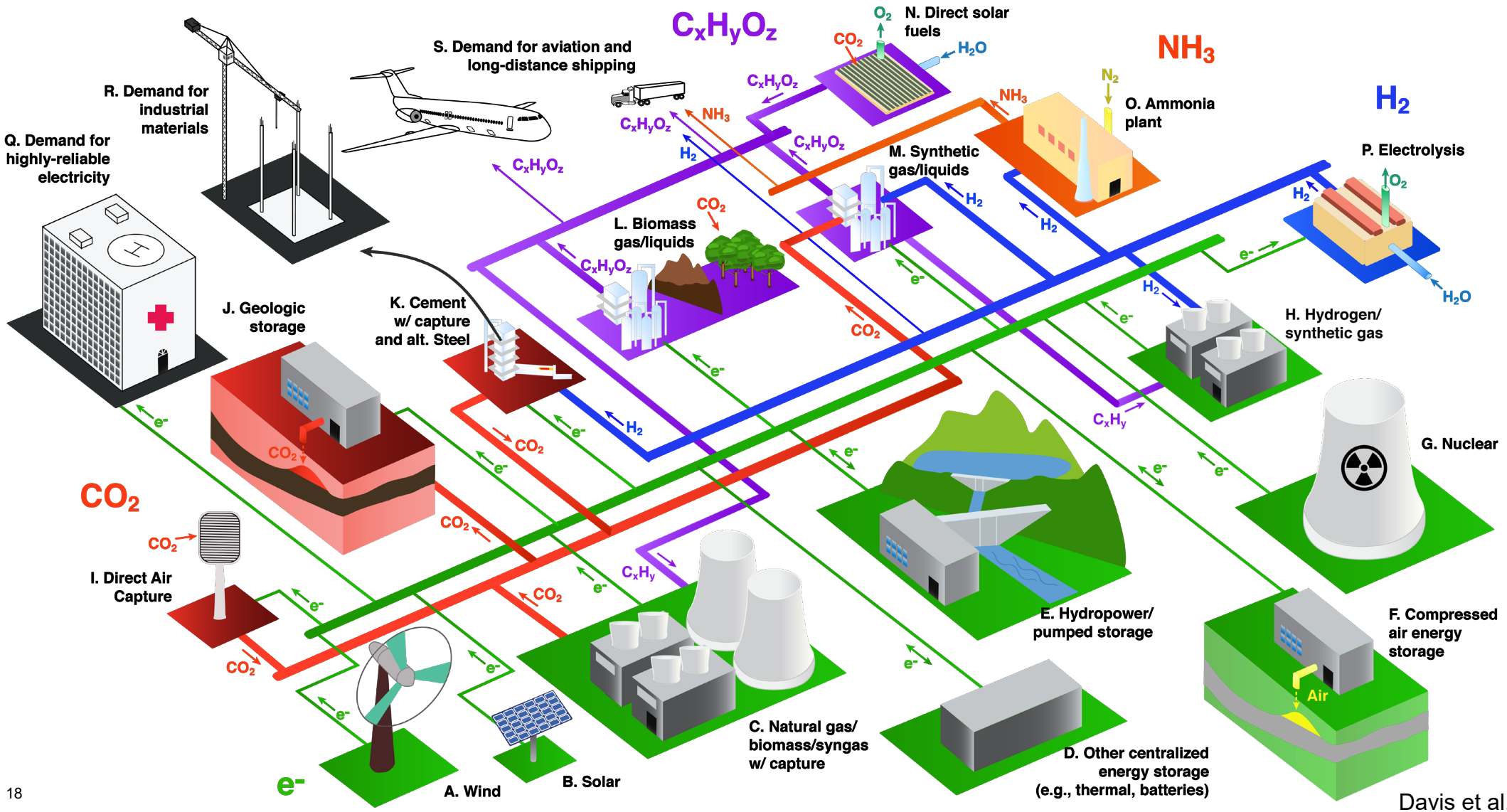
Given low capacity factors involved, integrating technologies may be critical



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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

Take-aways

- Physical and techno-economic characteristics make a net-zero emissions system challenging:
  - Aviation and long-distance transport
  - Industrial materials
  - Highly reliable electricity

- Energy-dense liquid fuel could be:
  - Biofuels
  - Synthesized hydrocarbons (e.g., combining renewable hydrogen and CO_2 captured from the atm)
  - Ammonia
  - Direct solar fuels

- To achieve high reliability in a power sector with a large share of variable, uncertain renewables, need storage or flexible generators that have low fixed costs and/or alternate products.
  - Hydrogen, carbon capture, and/or synthesized hydrocarbons for the transportation sector seem most promising, but currently too expensive

Thank you.

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