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Silicon in renewable power generation and storage: Decarbonizing the grid and automobile transport

Kurt W. Kolasinski

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WCU Sustainability Research & Practice Seminar Series

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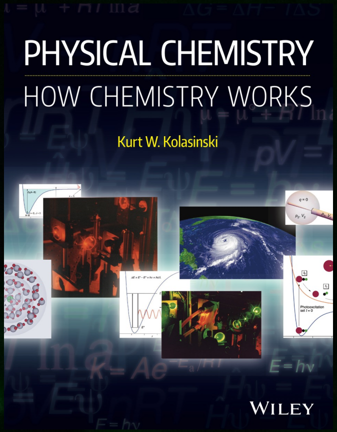
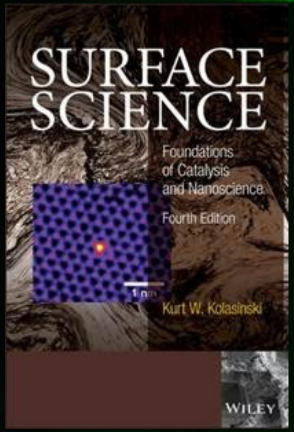
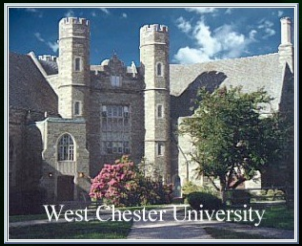






Motivation

- Intergovernmental Panel on Climate Change (IPCC)
  - https://www.ipcc.ch/
- IPCC Goal: Net zero by 2050
- 27% of US greenhouse gas emissions from transportation
- 25% of GHG emissions from electric power (EPA)
  - https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions

❖ Energy is conserved and transformed not made and consumed as in common terminology

Outline

- IPCC Goal: Net zero by 2050
- Could we just do without transforming so much energy?
- Electrification: What would it take to go solar?
    - Silicon PV cell
- Transportation sector requires energy storage
    - Replace diesel/gasoline with solar fuels
        - Direct use of light requires photocatalysts
        - Electrochemistry requires electrocatalyst
    - Replace gasoline with batteries
        - Lithium ion batteries
        - Extending battery range by adding silicon
- How much silicon would it take and at what cost in energy and installation?
- 27 years = 2050

Too Precious to be Expensive – The Nexus of Food–Water–Energy

- Food

  The world can't feed itself without fertilizer = ammonia

- Water

  70% of water withdrawn from aquifers used for agriculture

- Energy

  Nothing possible without transforming energy

1965

World population surpasses 3.3 billion
2023: 7.9 billion

- Modern agriculture dependent on ammonia-based fertilizer (ammonia = NH_3)
- This cannot be replaced by dung
- NH_3 requires fossil fuels both for hydrogen (H_2) and for the energy to run the chemical reaction

Globalized trade in agriculture and fertilizer has coupled the price of food to oil

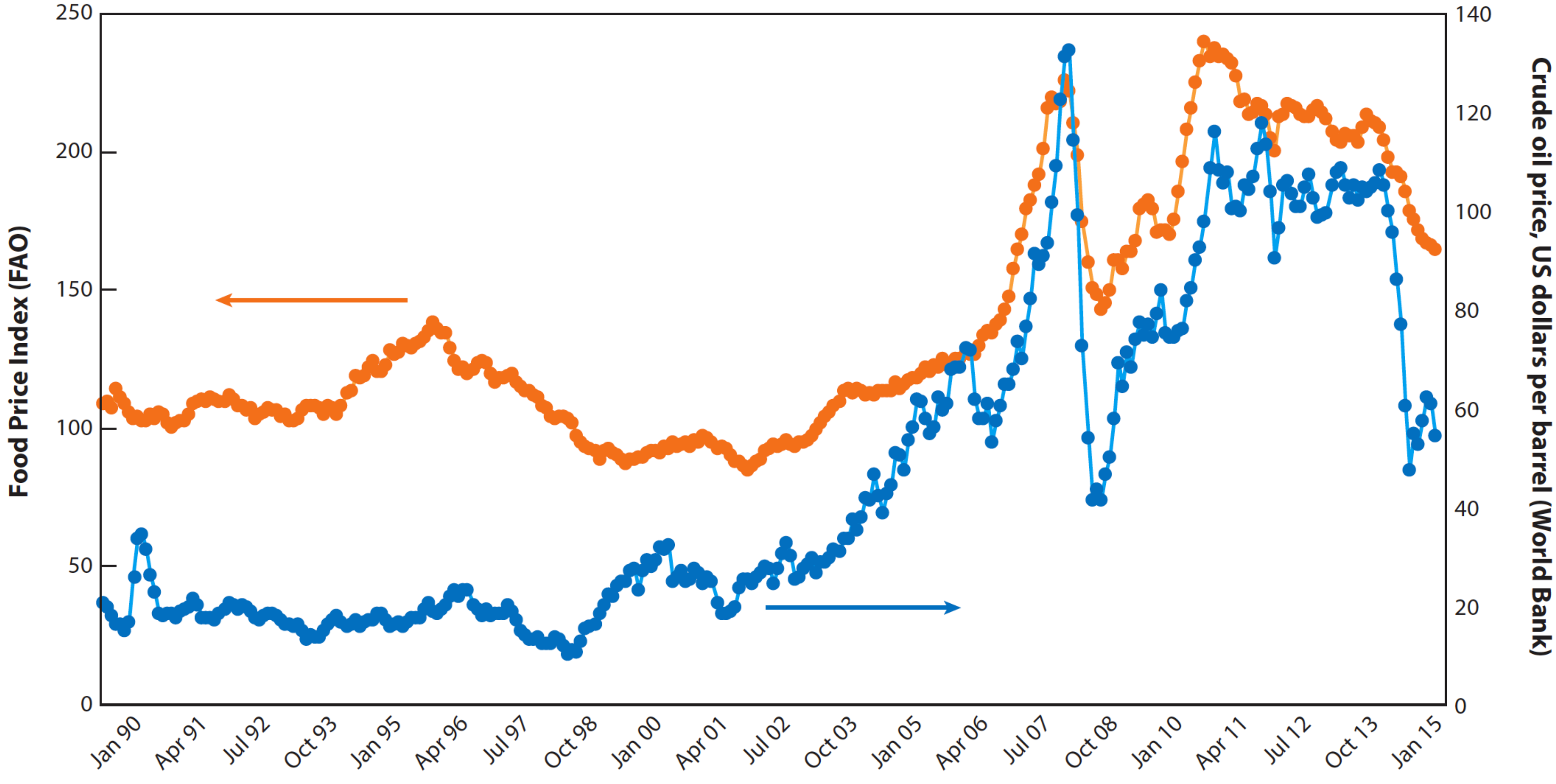


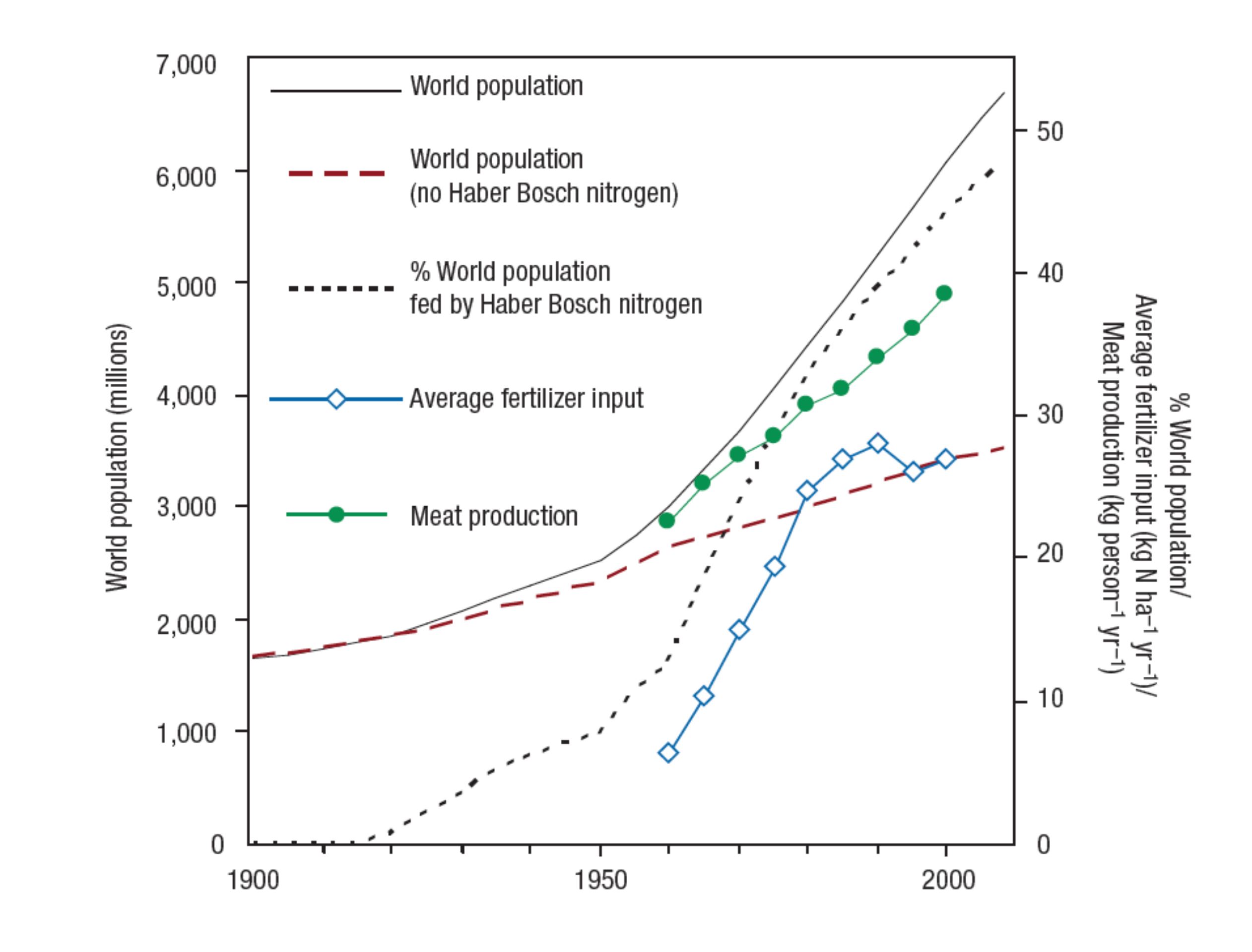
Figure 1

Food and oil prices 1990–2015. Data from Food and Agriculture Organization and EIA (111, 112).

D. L. Keairns, R. C. Darton, A. Irabien, *The Energy-Water-Food Nexus*, Annu. Rev. Chem. Biomolec. Eng. 2016, 7, 239-262.

NH_3 Synthesis is, arguably, the single most important industrial chemical reaction

4.6 billion people could not be supported by agriculture without NH_3 production



Erisman, Sutton, Galloway, Klimont & Winiwarter, Nature Geoscience 1 (2008) 636

Human Impact of Energy

The Human De asure
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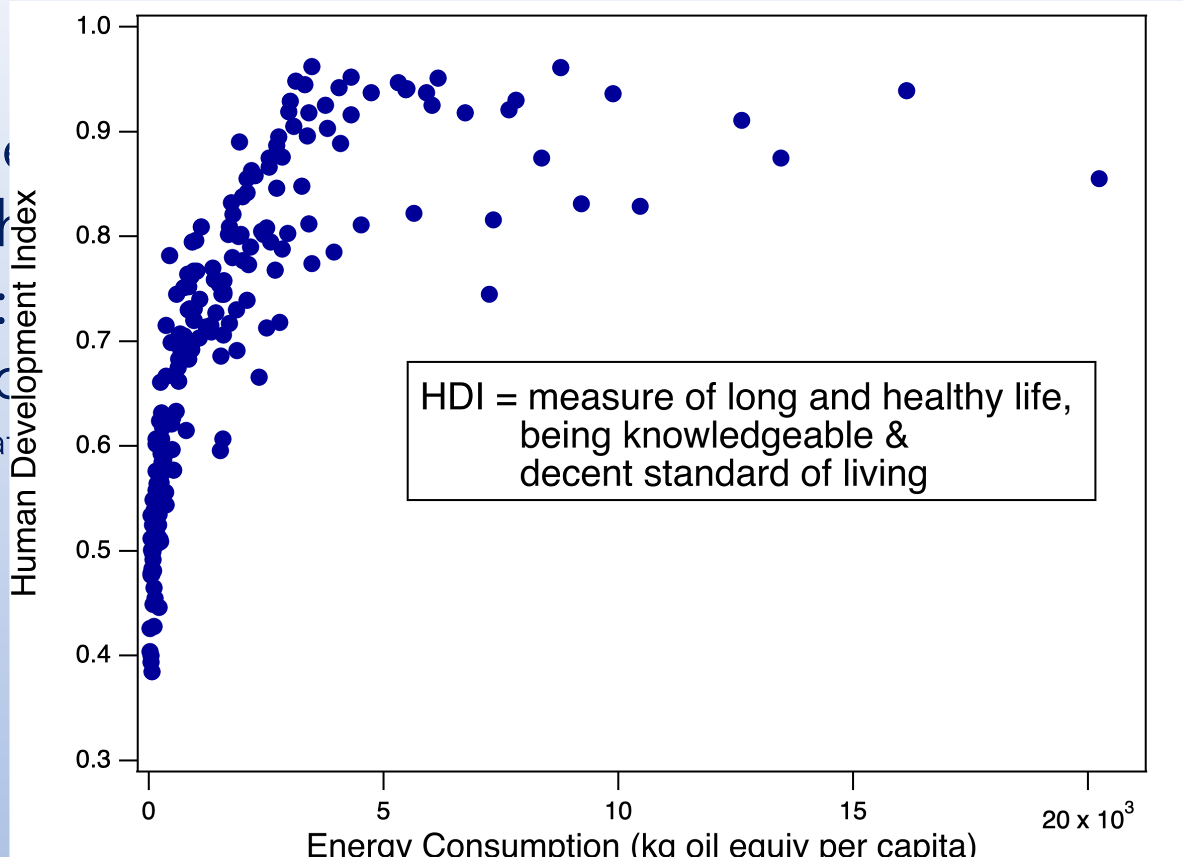
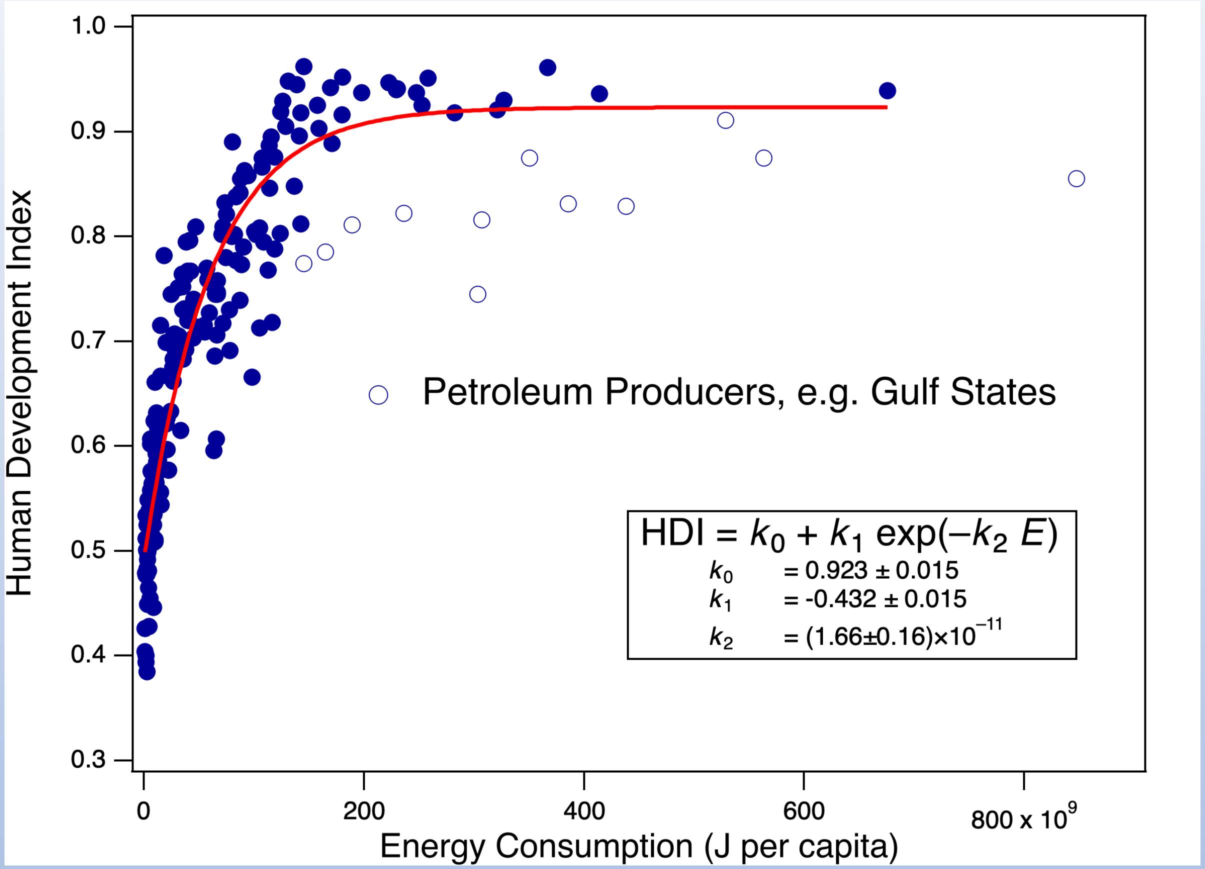
development: eable
and having a c
https://hdr.undp.org/da



- Strong correlation between HDI & energy consumption
  - V. Smil, *Energy at the Crossroads: Global Perspective and Uncertainties*, MIT Press, Cambridge, MA, 2003
  - Energy Information Administration https://www.eia.gov/

Human Impact of Energy



- Strong correlation between HDI & energy consumption
  - V. Smil, *Energy at the Crossroads: Global Perspective and Uncertainties*, MIT Press, Cambridge, MA, 2003
  - Kolasinski, *Curr. Opin. Solid State Mater. Sci.* **2006**, *10*, 129

Human Impact of Energy

Switzerland
Norway
Iceland
Hong Kong, China (SAR)
Australia
Denmark
Sweden
Ireland
Germany
Netherlands
Finland
Singapore
New Zealand
Belgium
Canada
Liechtenstein
Luxembourg
United Kingdom
Japan
Korea (Republic of)
United States
Israel
Malta
Slovenia
Austria
United Arab Emirates
Spain
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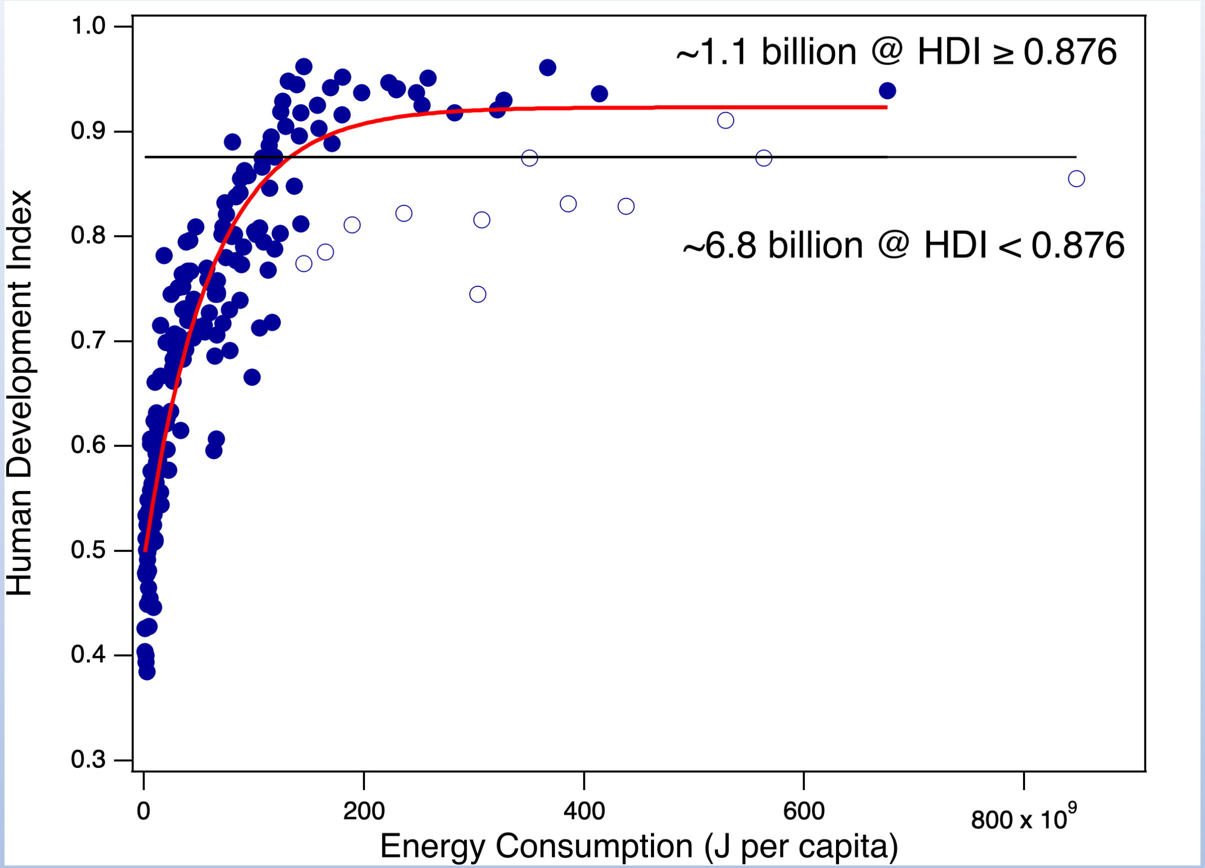
Cyprus
Italy
Estonia
Czechia
Greece
Poland



- ~1.1 Billion people live at and above the HDI of Poland ≥ 0.876 (34 countries)
- ~6.8 billion people live HDI < 0.876 (~160 countries)

Human Impact of Energy

Switzerland
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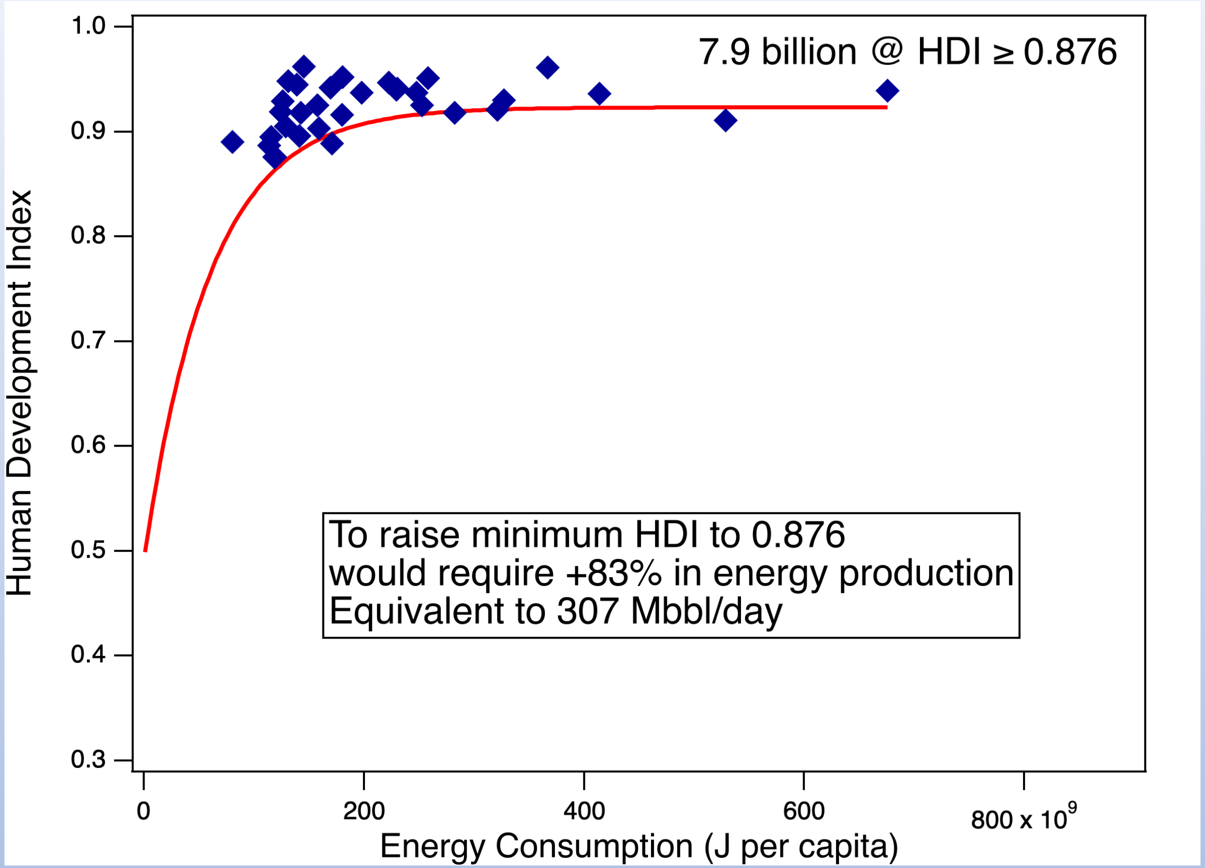
Singapore
New Zealand
Belgium
Canada
Liechtenstein
Luxembourg
United Kingdom
Japan
Korea (Republic of)
United States
Israel
Malta
Slovenia
Austria
United Arab Emirates
Spain
France
Cyprus
Italy
Estonia
Czechia
Greece
Poland



- ~1.1 Billion people live at and above the HDI of Poland ≥ 0.876 (34 countries)
- ~6.8 billion people live HDI < 0.876 (~160 countries)
- To elevate Developing World to HDI = 0.876 requires 529 EJ annually vs 636 EJ currently
- Without +83% increase in energy use, development will cease

- Energy is consumed to provided basic services and a good standard of living
- Without more and cleaner sources of energy, world development will cease, conflict will increase
- What's the source?
- More energy from the Sun hits the Earth in one day than humans use in a decade

  Nathan S Lewis, Caltech, http://nsl.caltech.edu

- What about solar?

Is it feasible to supply the US electrical grid via solar PV cells?

- US land area = 9.1×10^{12} m^2
- Average insolation = 200 W m^{-2}
- Electricity consumption ~0.44 TW (EIA)
- 0.44×10^{12} W/ (0.15 x 200 W m^{-2}) = 1.47×10^{10} m^2
- 0.16% of US land area required at 15% cell efficiency
- 3.9 million miles of roads in US (Fed Highway Admin)
- Would have to cover each with 2.5 m wide roof
- US spent $177 billion on roads in 2017 (FHA)
- Solar panel = $3 W^{-1} (retail), $1 W^{-1} (farm), $0.25 (to make)
- ~2.5 years to install panels

Is it feasible to supply the US electrical grid via solar PV cells?

- Unfortunately, those are "peak production" values
- $6 \times 1.47 \times 10^{10}$ m^2 = 8.8×10^{10} m^2
- Would have to cover road area with 15 m wide roof
- ~15 years to install panels spending as for roads
- 48 MMt Si required for panels = 3.2 MMt Si/year
- 8.8 MMt Si produced worldwide in 2022

How much energy to refine Si for PV?

- From sand to Si ≈ 60 kWh / kg
- From sand to wafer ≈ 100 kWh / kg
- 2–4 months to recoup energy to make Si
- ~1 year to recoup energy to make and install panel

C. Ballif, F. J. Haug, M. Boccard, P. J. Verlinden, G. Hahn, *Status and perspectives of crystalline silicon photovoltaics in research and industry*, Nature Reviews Materials 2022, 7, 597-616.

What about all US power consumption?

- 2021 primary power consumption = 3.37 TW
- $6 \times 3.37 \times 10^{12} / (0.15 \times 200) = 6.6 \times 10^{11}\ m^2$
- 7.8% of US land area required at 15% cell efficiency
- $6 \times 3.37 \times 10^{12} / (0.20 \times 200) = 5.1 \times 10^{11}\ m^2$ (5.9%)
- Would have to cover each with 95 m wide roof
- US spent $177 billion on roads in 2017
- >100 years to install panels if same rate & $1 W^{-1}
- 263 MMt Si required (=9.7 MMt Si /year for 2050)
- $750 billion/year for full coverage by 2050
- Not all processes can be directly electrified, other power sources also need to be developed

Solar and wind are intermittent, need storage

Carbon is too valuable & versatile to burn and dispose of as CO_2

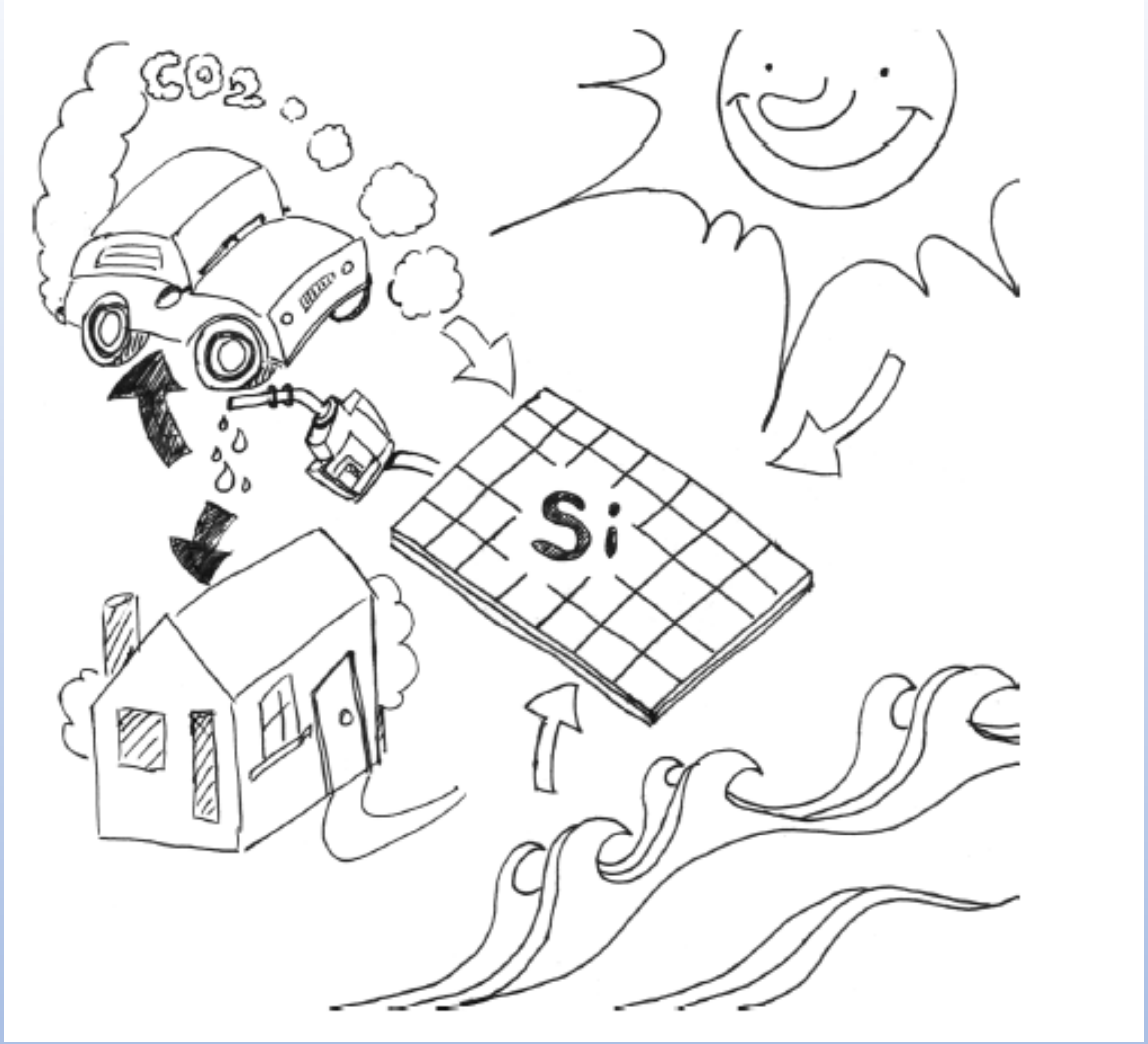
Make recyclable things from carbon

Recycle atmospheric CO_2 into solar fuels

Requires photo/electrocatalysts

Recycle graphite in batteries

Better batteries require Si



K. Sun, S. Shen, Y. Liang, P. E. Burrows, S. S. Mao, D. Wang, *Enabling Silicon for Solar-Fuel Production*, Chem. Rev. 2014, 114, 8662-8719.

Replacing Gasoline for Ground Transportation

US consumed 134.55 billion gal gasoline in 2022 (EIA) to fuel 280 million cars

@ $3.50 per gallon = $475 billion spent on gasoline

1.61×10^{19} J = 0.5 TW annually = 4.47×10^{12} kWh

Need 2x US electrical generation to accommodate

Huge demand for solar panels

Huge demand for batteries and solar fuels

How much C is required for all those batteries?

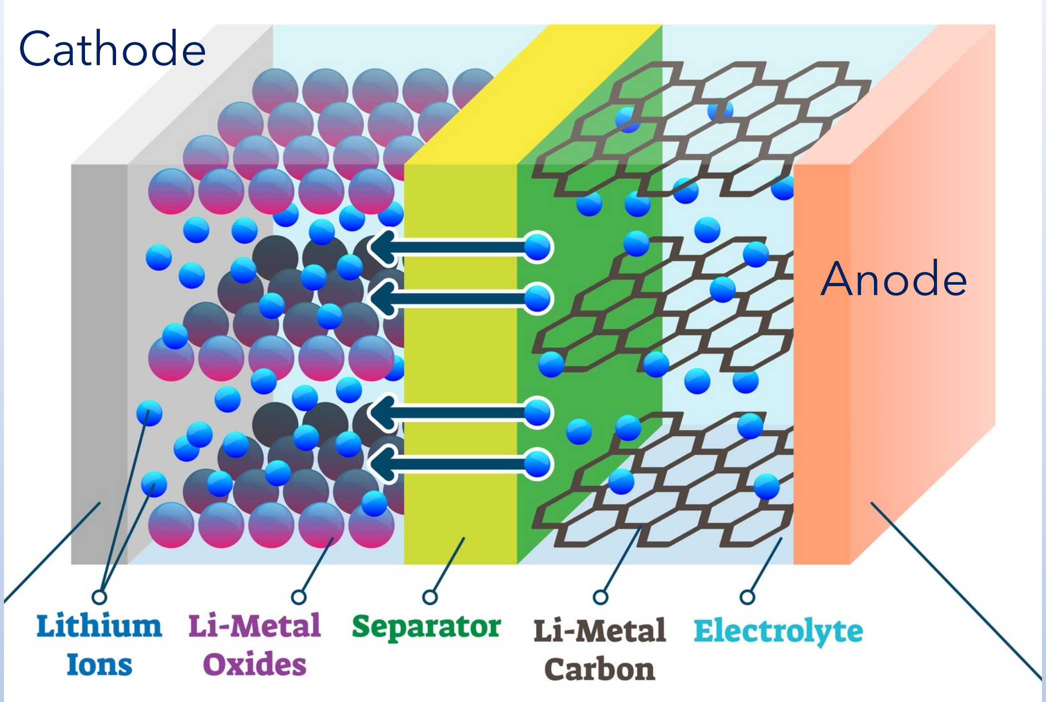
Cathode = Li + Ni/Mn/Co (NMC) oxide or $FePO_4$

Anode = graphite (+ Si)

How much C is required for all those batteries?

28 wt% C

300 Wh / kg



https://www.biolinscientific.com/blog/wettability-in-li-ion-batteries

To provide 0.5 TW annually = 4170 MMt C of installed battery anodes

135 billion gal gasoline ≈ 320 MMt C

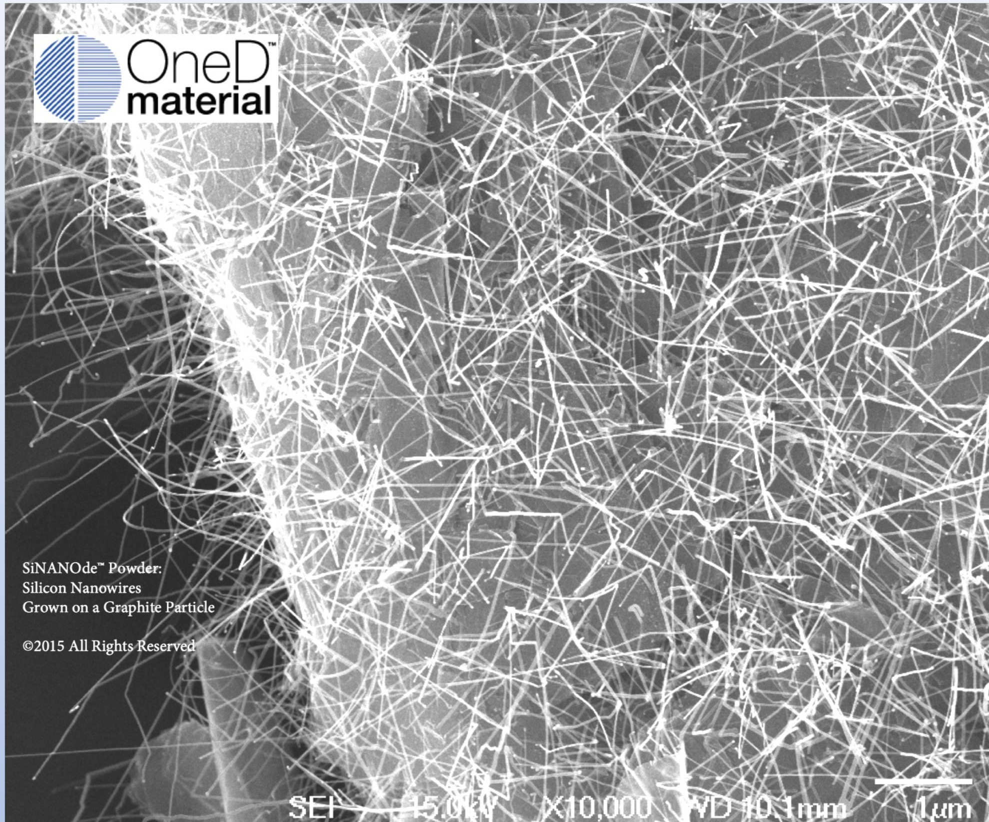
13 years' worth of gas to graphite

Not oil → gasoline, but oil → graphite + H_2 (for NH_3, chemistry, fuel)

Making a Better Battery

- Si outperforms graphite
- 3579 mA h g^{-1} vs 372 mA h g^{-1} specific capacity
- Should last 1500+ recharging cycles, 20+ years
- Bulk Si cracks because extreme volume changes upon lithiation, poor cycling behavior
- Surface electrolyte interphase (SEI) on Si surface is highly resistive

CVD growth of Si Nanowires on graphite for Li battery anodes



https://www.onedmaterial.com/

- Adding Si to graphite extends range. Good cyclability when nanostructured
- Improves power density, target 400 Wh/kg with 10% Si
- Reduces C to 2817 MMt
- Requires 313 MMt Si
- 35 years at current production
- 27 years to 2050

How much energy to refine Si for batteries and how much build out for electrical grid?

- From sand to Si ≈ 216 MJ / kg
- To replace 10% C with Si = 313 MMt Si = 6.76×10^{19} J
- To achieve by 2050 = 0.08 TW per year
- All electric passenger vehicles require ~+0.6 TW
- Current US electrical production 0.44 TW
- Need to 2.5x the grid to make & charge batteries

Conclusions

- Energy use is essential for civilization
- Without access to clean power, development stops, and climate becomes unstable
- The sun provides more energy in a day than humans use in decades
- If we spent as much on solar panel installation as we do on roads, electric grid could go solar in 15 years, requires 3.2 MMT per year vs ~9 MMT yearly output
- 20.2 GW installed in 2022, >160 years to make full grid at this rate.
- To convert ICE cars to Li-ion-battery-powered cars: Need to ~triple size of electrical grid
- Batteries for those cars: convert oil to graphite, recycle batteries
- Improved battery performance with addition of Si
- Solar fuels required to replace diesel
- Other electrical generation also required
- We are not investing nearly enough to decarbonize power generation

Thank you for your attention