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

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

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Motivation

- Intergovernmental Panel on Climate Change (IPCC)
  - [https://www.ipcc.ch/](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](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  70% of water withdrawn from aquifers used for agriculture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).

NH₃ Synthesis is, arguably, the single most important industrial chemical reaction.

4.6 billion people could not be supported by agriculture without NH₃ production.

The Human Development Index (HDI) is a summary measure of average achievements in a country in three key dimensions of human development: a long and healthy life, being knowledgeable, and having a decent standard of living.


- Strong correlation between HDI & energy consumption
  - Energy Information Administration https://www.eia.gov/
• Strong correlation between HDI & energy consumption
• ~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)
• ~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 = $9.1 \times 10^{12}$ m$^2$
- Average insolation = 200 W m$^{-2}$
- Electricity consumption $\sim$0.44 TW (EIA)
- $0.44 \times 10^{12}$ W/ $(0.15 \times 200 \text{ W m}^{-2}) = 1.47 \times 10^{10}$ 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)
- $\sim$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
- $6 \times 1.47 \times 10^{10} \text{ m}^2 = 8.8 \times 10^{10} \text{ m}^2$
- 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

What about all US power consumption?

- 2021 primary power consumption = 3.37 TW
- $6 \times 3.37 \times 10^{12} / (0.15 \times 200) = 6.6 \times 10^{11} \text{ m}^2$
- 7.8% of US land area required at 15% cell efficiency
- $6 \times 3.37 \times 10^{12} / (0.20 \times 200) = 5.1 \times 10^{11} \text{ m}^2 (5.9\%)$
- 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 & $1 \text{ W}^{-1}$
- 263 MMt Si required (=9.7 MMt Si /year for 2050)
- $750 \text{ billion/year for full coverage by 2050}$
- 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

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 \times 10^{19} \text{ J} = 0.5 \text{ TW annually} = 4.47 \times 10^{12} \text{ 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

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

- 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

https://www.onedmaterial.com/
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 = 6.76x10^{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