America's ZERO CARBON ACTION PLAN

Transforming Industry in America's Zero-Carbon Action Plan

November 18, 2020

Chris Bataille
Paul Fennell
Emily Grubert

Plan for the Next Hour

- Introduction to ZCAP by me, Chris Bataille of IDDRI.org
- Chris will talk about the overall net-zero challenge and what this means for industry for about 10 minutes
- Paul Fennell of Imperial College will talk about decarbonization of cement and steel, the two largest emitters, for ~20 minutes
- Chris will talk about decarbonization bulk chemicals for ~5 minutes
- Emily Grubert of Georgia Tech will talk about policy tools and recommendations for 10 minutes
- The final 15 minutes will be reserved for audience Q&A. Questions will be accumulated through the Q&A chat function – please stick to questions.

ZCAP Coverage

6 Major Sectors

- Power Generation
- Transportation
- Buildings
- Industry
- Land Use for Agriculture, Forestry, & Other Purposes
- Materials

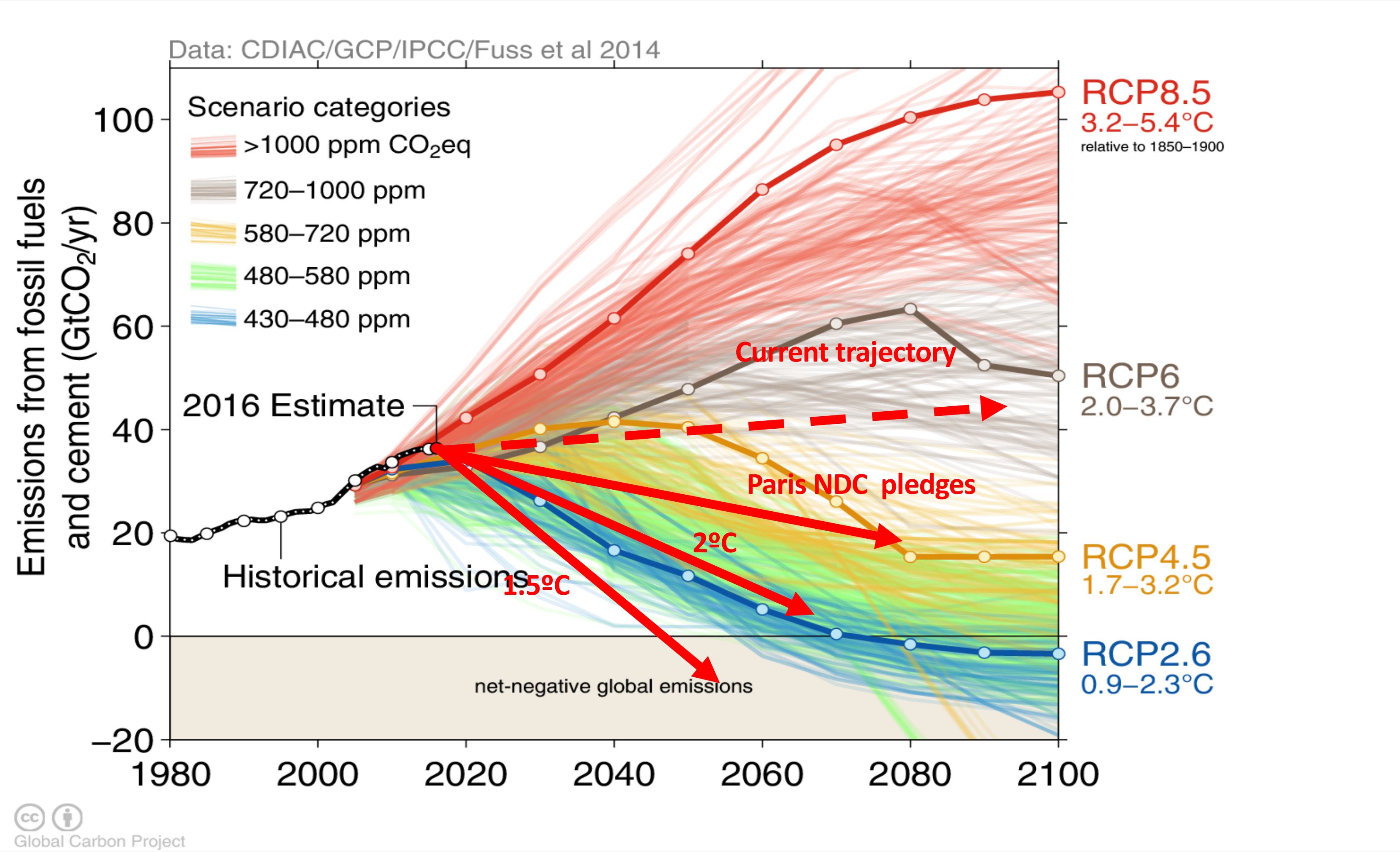
Key Components of Net Zero Transition

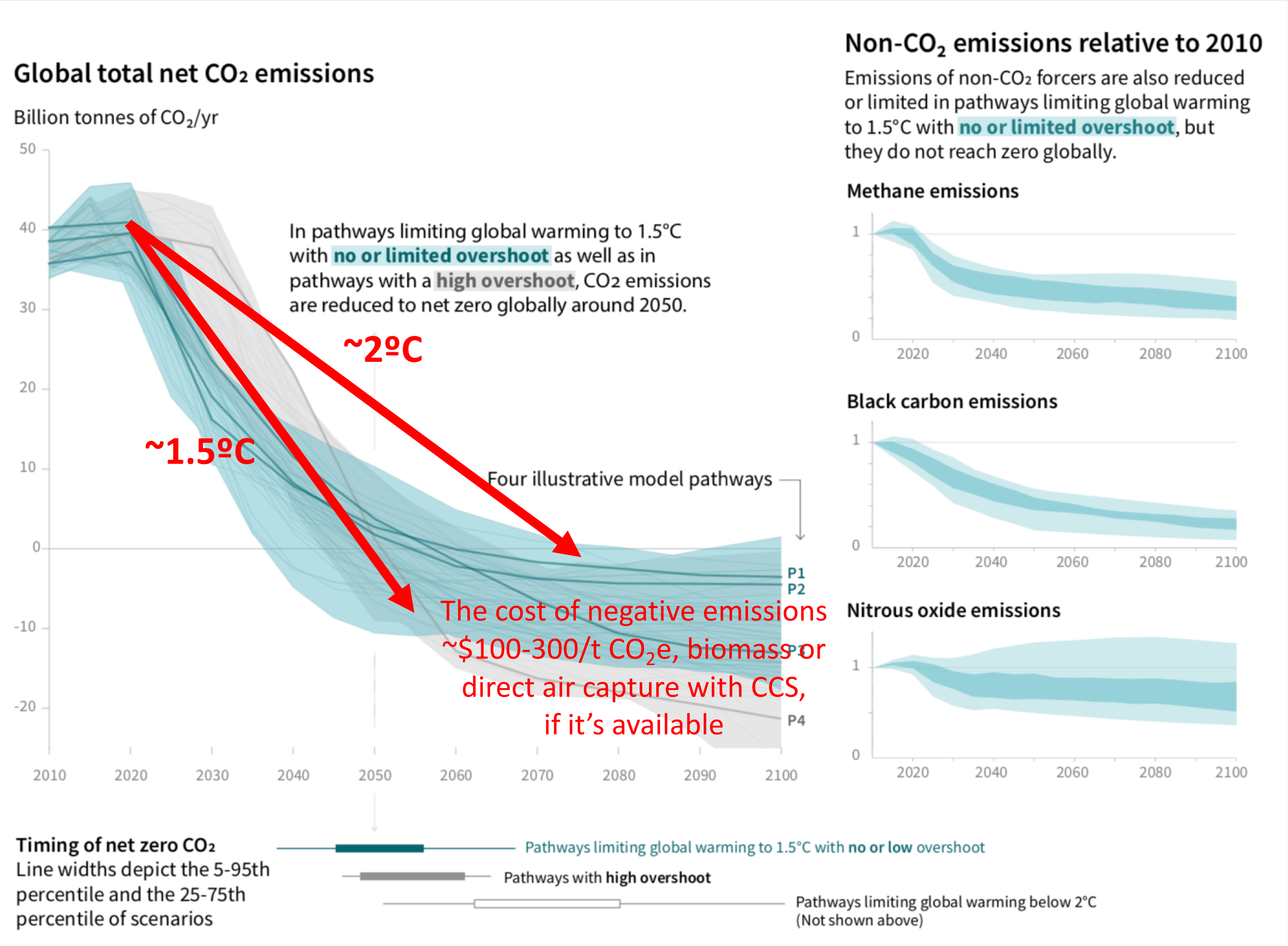
- Rapid upscaling of renewable energy
- Electrification of the economy wherever electricity-based energy is economically feasible and practical
- Transition to hydrogen, advanced biofuels, and other clean fuels manufactured with zero-carbon power
- Sustainable forest and agricultural lands
- Reduced material wastes through Sustainable Materials Management (SMM)
- Rejuvenation of the industrial heartland of America in the Appalachian Region and the Midwest
- Government-backed financing, investments, and regulatory support at all critical stages of the transformation, including for job training in the new sectors
- A national RDD&D strategy (research, development, demonstration & deployment)

A Framework for Large-Scale Change

- Technology
- American Federalism
- Foreign Policy
- Industrial Policy

The global carbon budgets for +1.5-20C and the implications for heavy industry

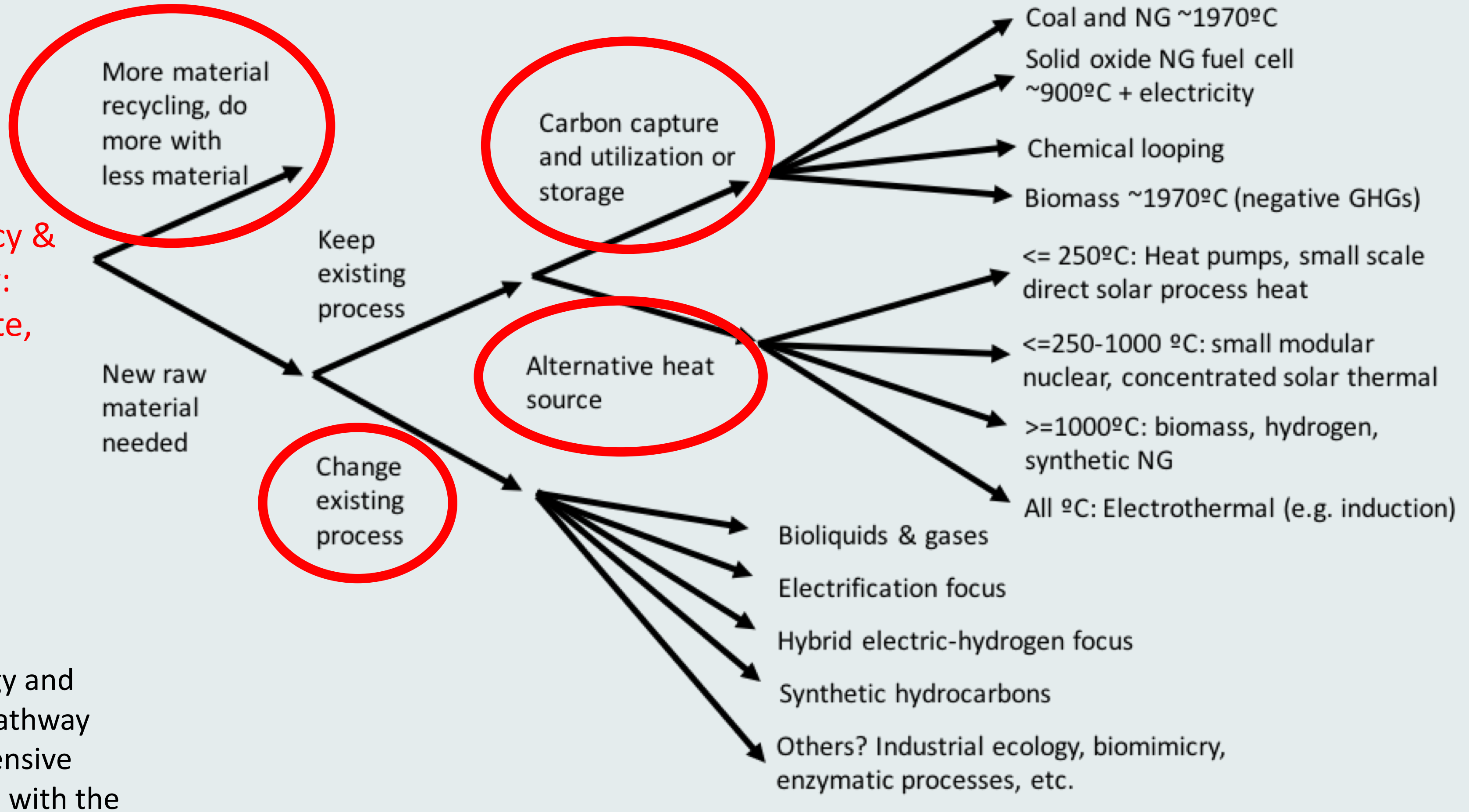



Global total net CO₂ emissions
Billion tonnes of CO₂/yr
50
40
30
20
10
0
-10
-20
2010
2020
2030
2040
2050
2060
2070
2080
2090
2100
In pathways limiting global warming to 1.5°C with no or limited overshoot as well as in pathways with a high overshoot, CO₂ emissions are reduced to net zero globally around 2050.
~2ºC
~1.5ºC
Four illustrative model pathways
P1
P2
P4
The cost of negative emissions ~$100-300/t CO₂e, biomass or direct air capture with CCS, if it's available
Timing of net zero CO₂
Line widths depict the 5-95th percentile and the 25-75th percentile of scenarios
Pathways limiting global warming to 1.5°C with no or low overshoot
Pathways with high overshoot
Pathways limiting global warming below 2°C (Not shown above)
Non-CO₂ emissions relative to 2010
Emissions of non-CO₂ forcers are also reduced or limited in pathways limiting global warming to 1.5°C with no or limited overshoot, but they do not reach zero globally.
Methane emissions
Black carbon emissions
Nitrous oxide emissions
1
0

While much of industry can be electrified, there are big sector specific challenges

- The "extract-use-throw away" model for most material use (steel & aluminum as exceptions)
- Maxed out thermodynamic efficiency of core technologies (but not systems)
- Low (<=250ºC), medium (250-1000ºC) & high (>1000ºC) process heat
- Steel iron ore "deoxidization" CO_2 process emissions (& melting heat)
- Cement lime calcination CO_2 process GHGs (and 850/1450ºC process heat)
- Hydrogen production for ammonia for fertilizers and other chemicals; coal & steam methane reforming CO_2 process emissions
- Non-ferrous metals & alloys (big progress in bauxite electrolysis, i.e. Elysis)
- Carbon feedstock needed for chemicals
- **Making sure new materials aren't GHG combustion or process intense!**

Material efficiency & circular economy: Reduce, substitute, reuse, recycle



Source: "A review of technology and policy deep decarbonization pathway options for making energy-intensive industry production consistent with the Paris agreement", Bataille et al (2018) Journal of Cleaner Production

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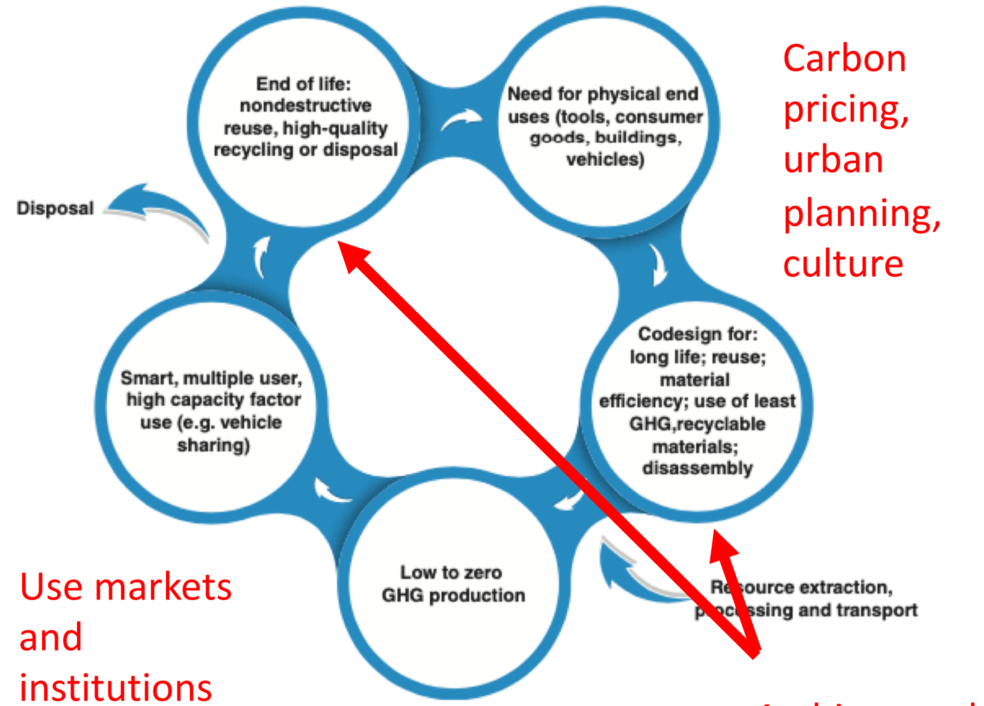
Dynamic questions that have to be addressed

1. *Material efficiency & circular economy*: High potential, but what happens if it isn't easy, cheap, or fast? Where are the levers?
2. *Electrification*: Capacity constraints matter and could be very expensive (electric steel example).
3. *Carbon capture, utilization, storage:* What happens if CCS reservoirs, CCUS opportunities in a given region are limited?
4. *Alternative heat sources:* Regional limits on biomass, solar, etc.
5. *What about long-lived legacy facilities?* e.g. Chinese BF-BOFs
6. *How can we build situation specific technology and policy hybrids to solve for all of the above?*



Carbon pricing, urban planning, culture

Use markets and institutions

Architectural, engineering and trades education, buildings codes

Production decarbonization – take it away Paul

- In the long run we need to work towards a material circulation system that meets our needs but lives within the planet's boundaries
- While we can probably get rid of fossil fuels eventually after a transition involving some level of CCS, steel, cement, chemicals, nonferrous metals, ceramics, etc. will be with us for awhile
- How?

Source: Bataille, C., 2019. Physical and policy pathways to net-zero emissions industry. WIRES Wiley Interdisciplinary Reviews 1–20. doi:10.1002/wcc.633

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Decarbonization of Cement

Paul Fennell

“Focus on those industrial activities which produce large quantities of process emissions, require very high temperatures, and/or whose equipment and infrastructure are especially long-lived.”

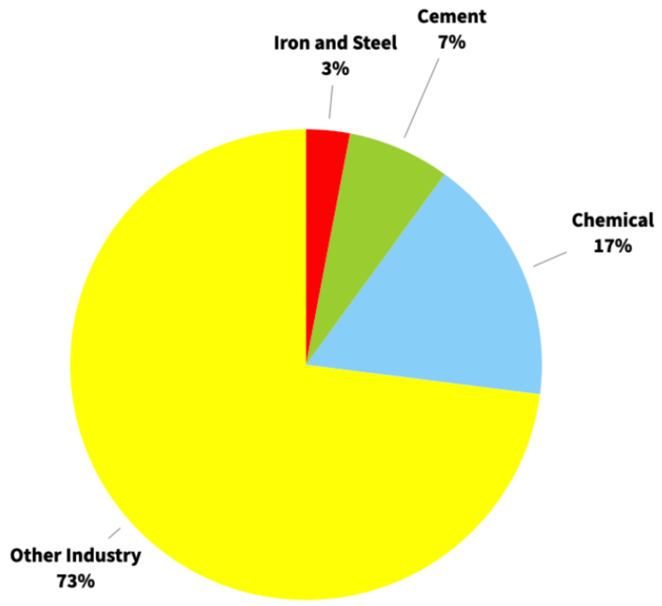


Figure 5.3.1. U.S. Industry emissions as of 2014 (Hoesly et al., 2018).

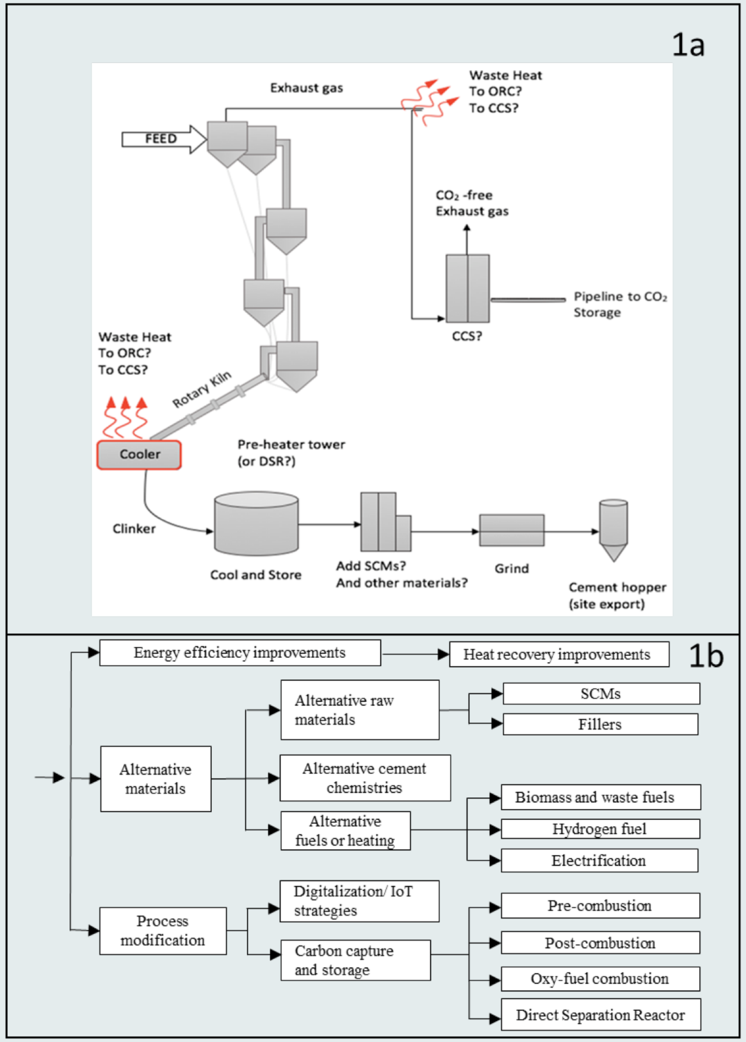
Cement – major kiln refurbishments / replacement only once every 25 years[1]

60 % of emissions from cement production are from the intrinsic chemistry.

Requires very high temperatures.

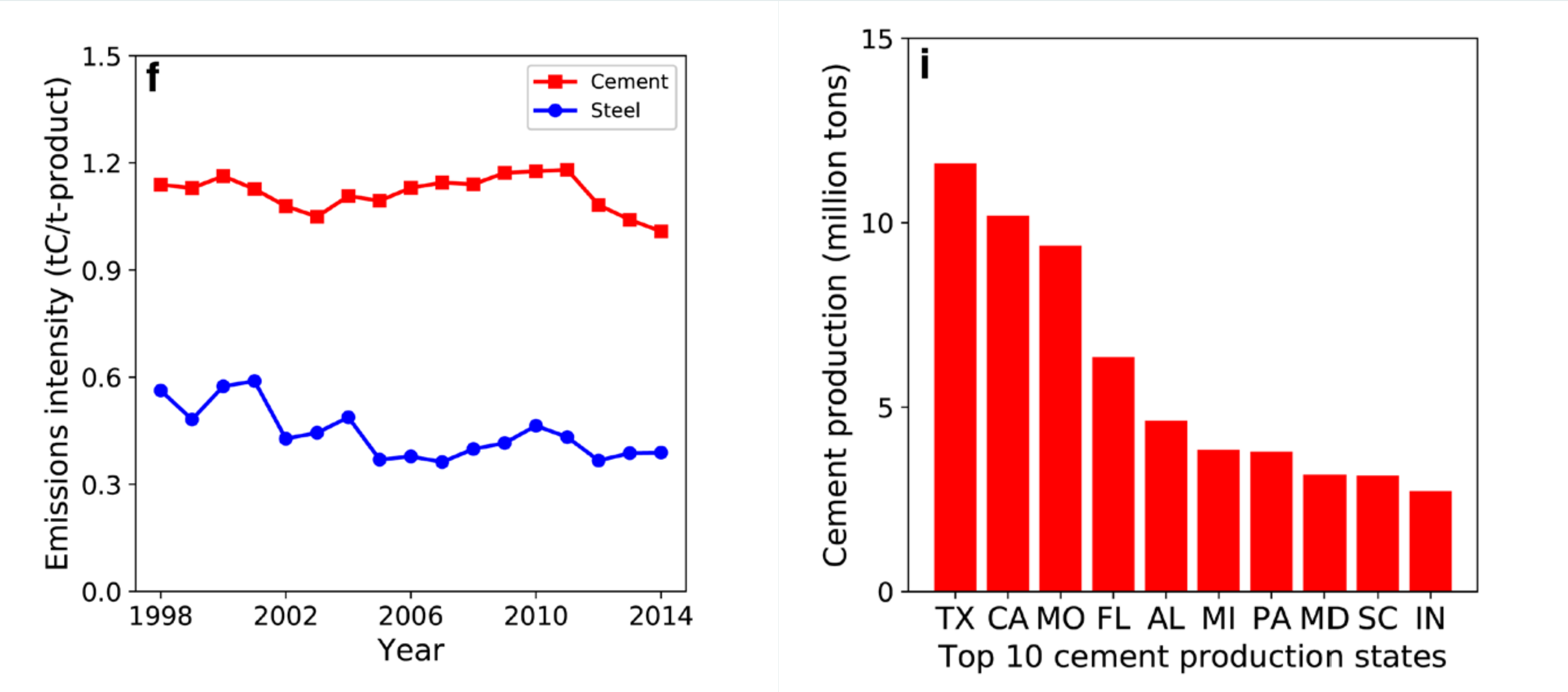
Very difficult to substitute for.

[1]Thomas Hills, Nicholas Florin, Paul S. Fennell, Decarbonising the cement sector: A bottom-up model for optimising carbon capture application in the UK, Journal of Cleaner Production, Volume 139, 2016, Pages 1351-1361,



"Cement production relies on driving two sets of reactions: firstly, calcination (the removal of CO_2 from $CaCO_3$ to produce CaO) and secondly the clinkering reactions, where the CaO reacts with silica and other materials including clay (at very high temperatures > 1600°C) to produce cement clinker (which is then ground and mixed with other materials to produce cement).

The initial calcination means that a large amount of CO_2 is produced intrinsically [around 60 %] during cement production, and this cannot easily be avoided."



From Figure 5.3.2. Economic and emissions data on heavy industries in the U.S.

Minor progress in emissions intensity now.
A modern plant requires ~ 3.3 GJ of thermal energy per ton of clinker
Average thermal intensity globally fell from 3.75 GJ/t for clinker in 2000 to 3.5GJ/t in 2014

Not a vast amount of gains left to be had from efficiency.

Cement production well distributed across the USA.

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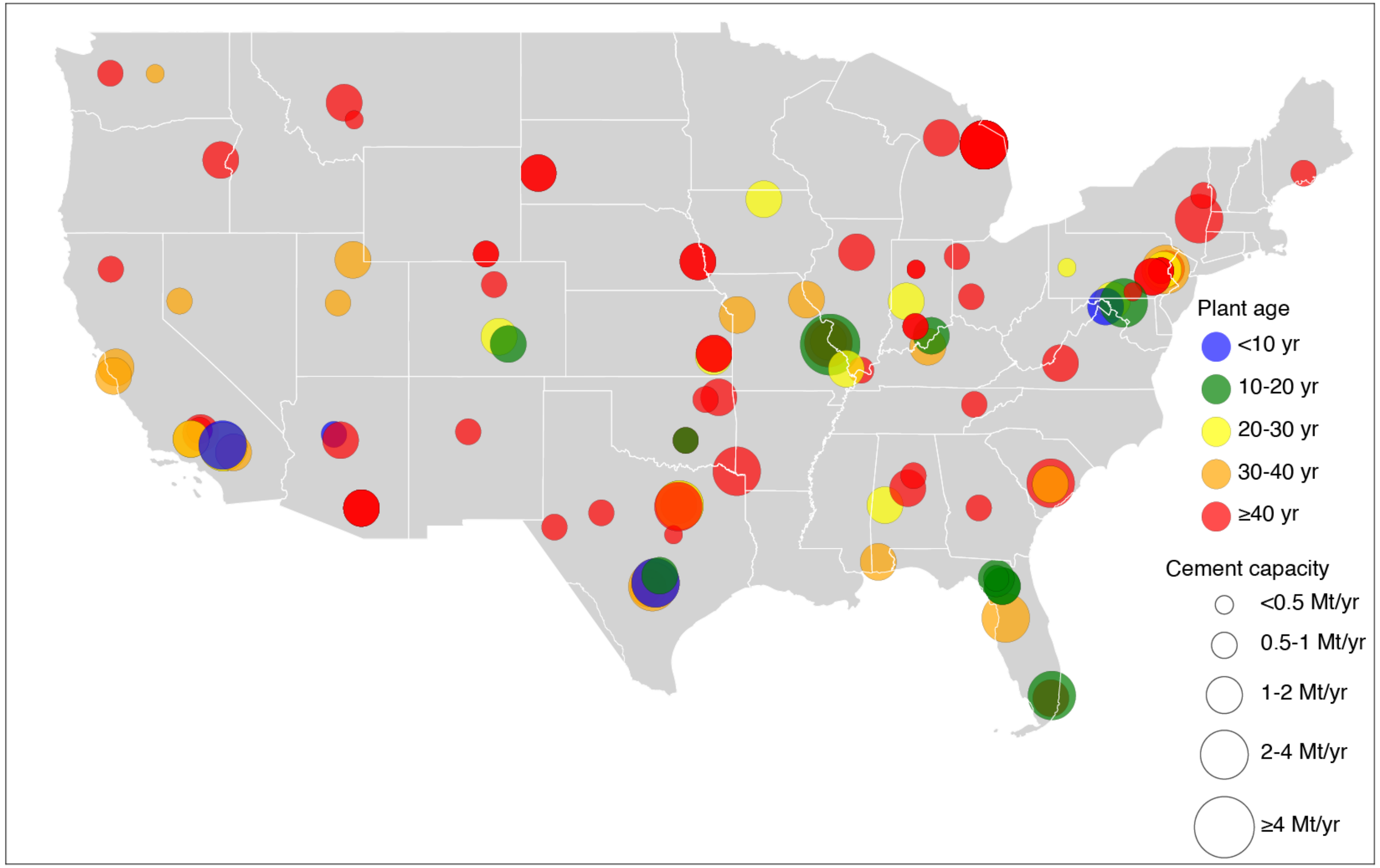

Figure 5.3.3. Locations, capacity (size of points), and age (color of points) of U.S. cement plants as of 2018 (figure original; data from Global Cement, 2020)

To reiterate – there are a lot of older cement plants around.

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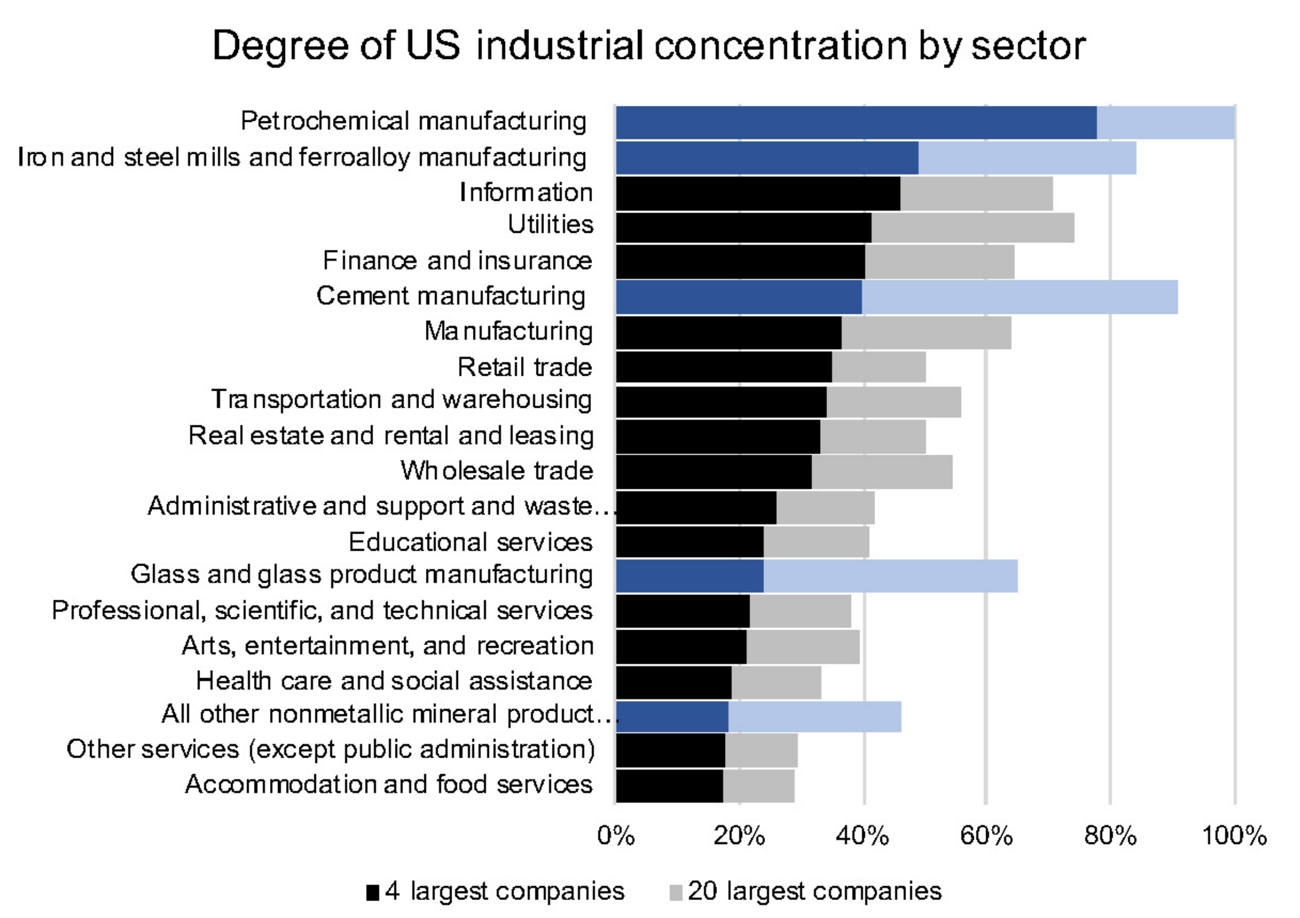

Figure 5.3.4. Degree of U.S. industrial concentration by sector. Sectors of interest highlighted in blue. Note: concentration in manufacturing sectors is measured as percent of total value of shipments and receipts; concentration in other sectors is measured as percent of total revenue. (U.S. Census Bureau, 2015; 2017 data to be released November 2020).

"Although the U.S. heavy industry as a category is highly heterogeneous, the magnitude of capital investments in steel, cement, and chemical industries tends to make the industries relatively concentrated and location-bound."

Technical Options

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"The initial calcination means that a large amount of CO_2 is produced intrinsically **[around 60 %] during cement production, and this cannot easily be avoided.**"

"Carbon capture and storage (CCS), directly removing CO_2 from the exhaust of the cement plant, is therefore likely to be required for cement production."

"Electrical heating is potentially of interest to drive both the calcination and clinkering reactions, **but approximately 60 percent of the CO_2 emitted** in a cement plant is directly from the calcination reaction."

"The use of hydrogen for decarbonization of cement production suffers from the same issue as electrification; that **use of hydrogen to provide heat again fails to address the CO_2 emissions from calcination of the limestone**."

Are we spotting a theme yet?

CCS Costs

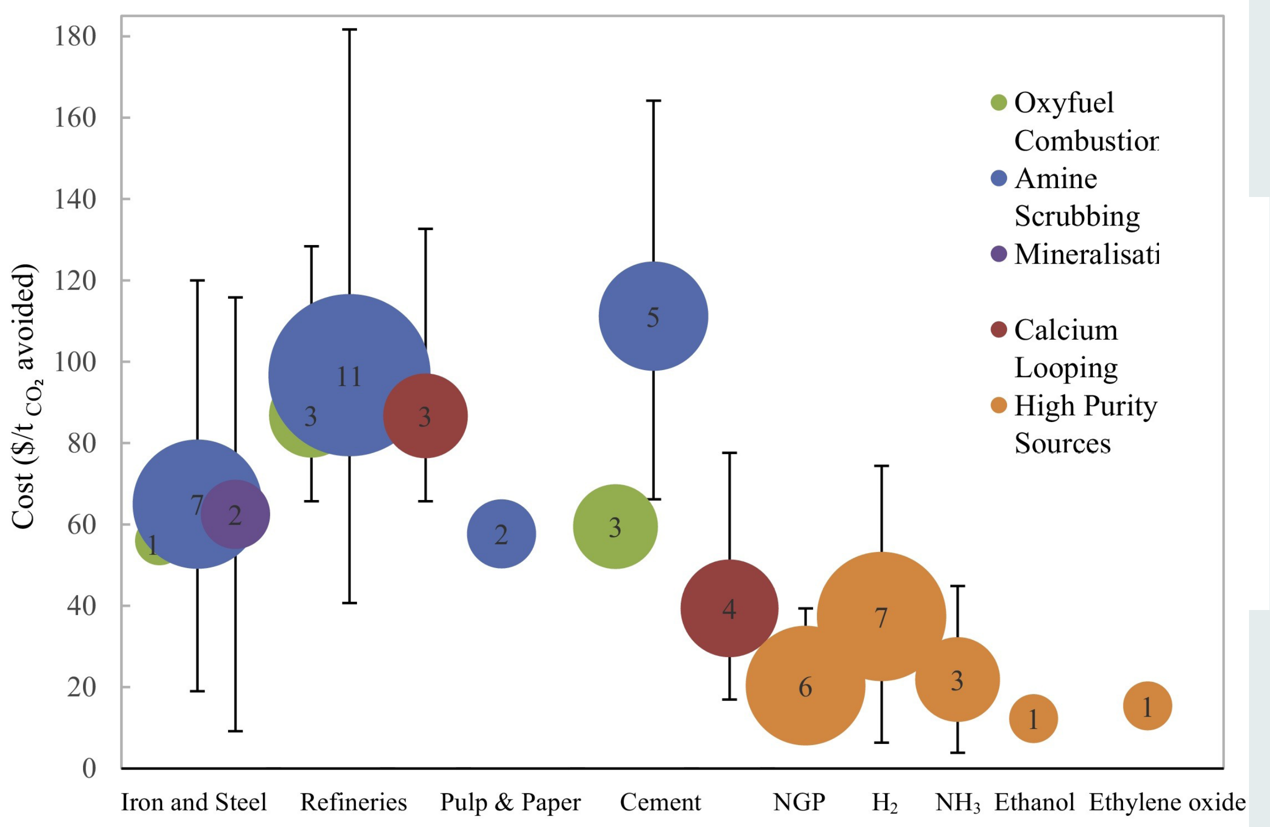

Figure 5.3.5. Costs of CO_2 avoided for a variety of different processes, using a number of different CCS technologies (Leeson, et al., 2017).

"A review of different CCS technologies described in a literature survey suggests that the addition of CCS to any system will end up significantly increasing the cost of the process. Approximately, a doubling in price of cement would be necessary to account for the additional costs."

D. Leeson, N. Mac Dowell, N. Shah, C. Petit, P.S. Fennell,
A Techno-economic analysis and systematic review of carbon capture and storage (CCS) applied to the iron and steel, cement, oil refining and pulp and paper industries, as well as other high purity sources, International Journal of Greenhouse Gas Control, Volume 61, 2017, Pages 71-84,

Supplementary Cementitious Materials

It is possible to directly replace cement clinker with a number of alternative materials

- coal ash
- ground granulated blast furnace slag
- naturally occurring rocks (pozzolans)
- biomass and other ashes.

China: replacement rate of more than 40 percent in the recent past.

Directly reduces the emissions from cement manufacture while meeting current building standards (up to a level) for Ordinary Portland Cement.

Some of the materials used (coal ash and blast furnace slag) may become scarcer moving to a decarbonised future.

Direct Air Capture

CO_2 is at high concentration – capture preferred from this source rather than emission and Direct Air Capture: basic thermodynamics

Cement actually carbonates over a few decades when in situ (~ 30 % of process emissions).

Alternative Cements

Various types of alternative cements could reduce CO_2 emissions by 20-100 percent.

Advanced technological and experimental methods are needed to establish the viability of these alternative cements.

Establishing codes, standards, and setting guidelines with training will be essential in developing alternative cement concepts.

As a friend in industry once said:

"Build a bridge, have it stand up for 20 years, and we might examine your cement substitute"

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Summary

Supplementary Cementitious Materials offer rapid decarbonisation at low cost.

Electrification or Hydrogen use miss 60 % of the emissions

CCS is extremely important

CCS is not a single technology – some types of CCS will be better-suited to cement than others.

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Decarbonization of Iron & Steel

Paul Fennell

"In addition to substantial emissions from combustion of fossil fuels for required heat, the process emissions from steel production (i.e., excluding fossil energy inputs) accounts for roughly 5 percent of global CO_2 emissions in recent years, mainly related to the coking coal used to reduce iron ore in blast furnaces (i.e., removing oxygen from raw Fe_2O_3)."

Again, there's a significant *process* emission, due to the intrinsic chemistry of the ironmaking process.

Variations on a theme…

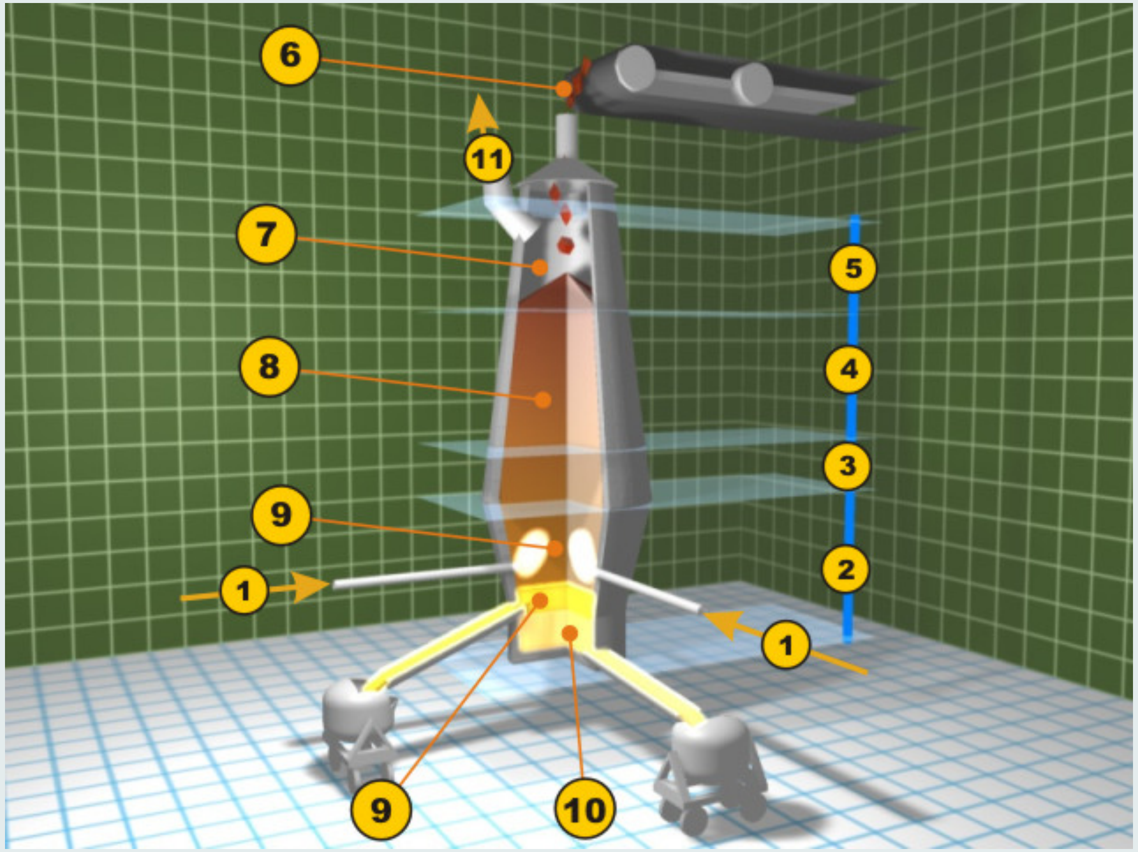
Two main pathways for producing steel from raw iron ore.

1. Integrated steel mill:
    - iron ore, coke, and flux materials (e.g., lime, to remove impurities) are melted in a blast furnace to produce pig iron
    - Pig iron is then converted to steel in a basic oxygen furnace (i.e., blast furnace-basic oxygen furnace (BF-BOF).

2. Directly Reducing Iron:
    - Use a reducing gas or carbon from natural gas or coal to remove oxygen from the ore at temperatures below the melting point of the iron
    - converting the DRI iron to steel using an electric arc furnace (EAF).

(1) Is much more common, and has much higher specific emissions

Blast Furnace



Source: Wikipedia. Public Domain.

1. Hot blast from Cowper stoves
2. Melting zone
3. Reduction zone of ferrous oxide
4. Reduction zone of ferric oxide
5. Pre-heating zone
6. Feed of ore, limestone and coke
7. Exhaust gases
8. Column of ore, coke and limestone
9. Removal of slag
10. Tapping of molten pig iron
11. Collection of waste gases

Conventional Iron-making.

Highly integrated, but needs coke to structure the ore as it moves down the furnace.

Coke is costly and its production has significant environmental challenges.

Recycling

Already, more than half of the steel produced in the U.S. is via processing of scrap steel in EAFs.

The electricity required to energize this process can be decarbonized, and such recycling avoids the process emissions associated with reducing raw iron ore.

Impurities (tin, copper, nickel, molybdenum, chromium, lead) may compromise the quality and integrity of the steel.

Better sorting and product design required.

Biocharcoal

It is possible to replace fossil coke in the BF-BOF process with charcoal derived from biomass, as has been demonstrated at scale by the Brazilian steel industry.

Costly and may not work in the very largest of BFs.

CCS can also be added, but again costly.

Hydrogen

Another option is to use renewable hydrogen as the reducing gas in the DRI-EAF process.

Demonstrations are ongoing (see the Al-Reyada demonstration, UAE).

Shows promise.

Not for blast furnaces.

Future

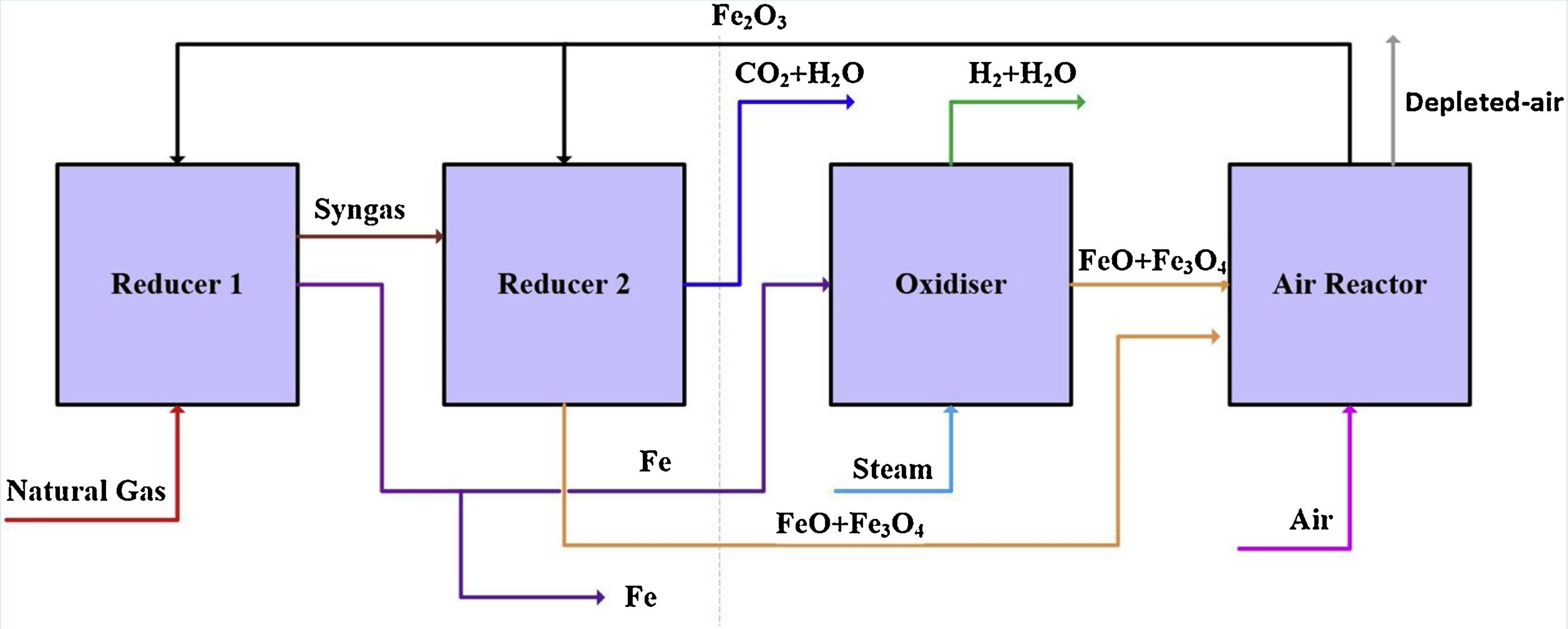
Electrowinning

Electrolyze iron ore in an acid or alkaline solution.
(separating oxygen from iron ore by adding electrons to Fe_2O_3).

Although the low temperatures of ore reduction may enable a wide range of cathodes and anodes, this process remains far from commercial-ready.

Novel thermochemical cycles?

Integrate Hydrogen Production with Steel Manufacture?



Husain Bahzad, Kazuaki Katayama, Matthew E. Boot-Handford, Niall Mac Dowell, Nilay Shah, Paul S. Fennell, Iron-based chemical-looping technology for decarbonising iron and steel production, International Journal of Greenhouse Gas Control, Volume 91, 2019,102766.

Chemical Production

- There are well over 20,000 human-made chemicals in use, with more being added every day. Almost everything around you passed through the chemical sector in multiple stages.
- The big eight feedstocks are: hydrogen, ammonia (NH_3); methanol (CH_3OH); ethylene (C_2H_4) and propylene (C_3H_6), or “olefins”; benzene (C_6H_6), toluene (C_7H_8), and mixed xylenes (C_8H_{10}) and aromatics, or “BTX” – note the prevalence of carbon and hydrogen
- While demand for ammonia, which is used to make fertilizers and is currently made from hydrogen made from NG, has largely stabilized, demand for other chemicals is going up ~5%/yr, almost double typical global economic growth
- Decarbonization of chemicals is about: 1) Process heat, 2) hydrogen production, and 3) the carbon source & end of life handling

Chemical Production

- Decarbonizing process heat
  - Low <150-200C (“steam”): solar, waste heat capture, energy & heat cascading, industrial heat pumps
  - Medium 200-1000C(“process heat”): focussed solar, heat cascading, nuclear
  - High >1000C(”flame front”): bio/synth methane, hydrogen, coal & NG with CCS
- Hydrogen production – big pros and cons
  - Blue - steam reformation + water gas shift of coal or methane plus CCS
  - Green – electrolysis of water using clean electricity
- Carbon sourcing & Post use handling – *all carbon is carbon, but where it comes from matters*
  - Recycled fossil carbon (“CCU”)
  - Biomass, e.g. through gasification
  - Direct air capture
  - Disposal? Recycling or CCS always preferred, can lead to negatives

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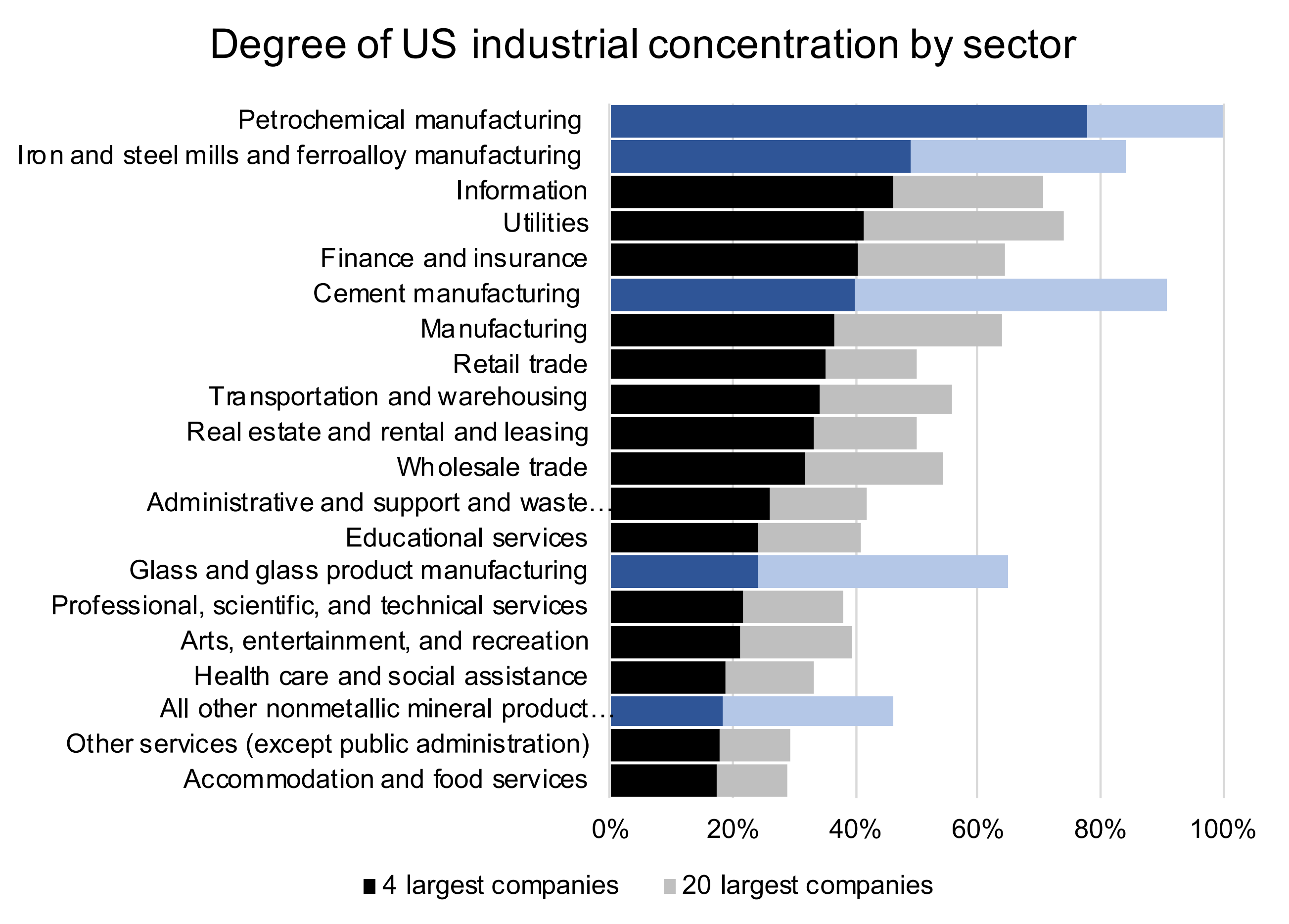
Policy Tools & Recommendations

Emily Grubert

Policy for decarbonizing long-lived, concentrated, and heterogeneous industry is challenging



- Industries are concentrated
- Industrial **interests** are concentrated
- Industry organizations (e.g., the Portland cement Association) are well organized and influential – an opportunity, and a challenge

Where to act? Industrial regulation is relatively disperse

- Utilities are overseen by utility commissions – industries are often not
- Where to act?
- Regulatory targets are typically
  - Environmental
  - Safety-oriented
  - Anti-trust oriented
- Historical precedent suggests that plant closures are often permanent, sometimes with long-lasting negative impacts that tend to motivate strong opposition

We have multiple decarbonization levers

- Material efficiency
- Technology (and fuel) shifting
  - Diverse industries require diverse solutions
    - Feedstock substitution
    - Fuel switching (e.g., electrification)
    - Carbon capture

https://i0.wp.com/csengineermag.com/wp-content/uploads/2017/06/BuildSteel-Details-643.jpg?fit=643%2C530&ssl=1

We have multiple policy levers

- **Target funding** to decarbonizing processes, particularly where challenges are blocking private investment
- **Develop markets** for decarbonized industrial commodities, e.g., via procurement policies and subsidies
- **Revise codes and regulations** to allow and encourage testing and use of lower carbon materials
- **Convene and coordinate** forums of stakeholders to map complex system transitions

Decarbonization is not just an investment story

- Carbon-intensive processes and facilities will need to close
  - Careful management of phase outs, and a just transition, will be important for success

- The industrial transition will disrupt existing supply chains
  - The system reflects substantial effort to use waste resources
    - What happens to coal ash users (early movers) when coal plants retire?

- The past might not predict the future
  - How do we account for long-term investments that perform better in the future?
    - Electricity will (probably) continue to get cleaner over time
  - How do we anticipate emergent conditions?
    - Materials might be available as byproducts now, but would require new mines at scale
    - Climate change will affect industrial activities

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Upcoming Webinars – Eastern Time

Food & Land-Use
November 24
3:00 – 4:00 pm