Decarbonization To Address Climate Change And Maintain Competitiveness

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Net-zero emissions: how big is the problem?

Challenge #1 - Quantity

- 1 gigaton = 10^{12} kg = 10^{15} g
- US GHG emission = 7 Gt CO_2-equiv/yr
- US p-xylene production = 0.004 Gt/yr = 0.016 Gt CO_2/yr if all C comes from CO_2
- US plastics production = 0.06 Gt/yr = 0.24 Gt CO_2/yr
- US all petroleum products = 1 Gt/yr

To have impact at gigaton scales, society-wide changes are needed

Challenge #2 - Timing

- Typical lab-scale process might work with 1 g CO_2
- Must scale up 1000x five times (without failure) to reach 1 gigaton
- If scaling 1000x takes 5 years can reach 1 gigaton in 2046
- Cost and time for scale up escalates strongly with scale, so later stage failure is massively inefficient

We must look far ahead in the scale up journey and anticipate challenges

Net-zero emissions: how important is manufacturing?

All from industry (e.g. HFC-134a ~100 Mt CO_2-eq/yr)

Almost all from fertilizer

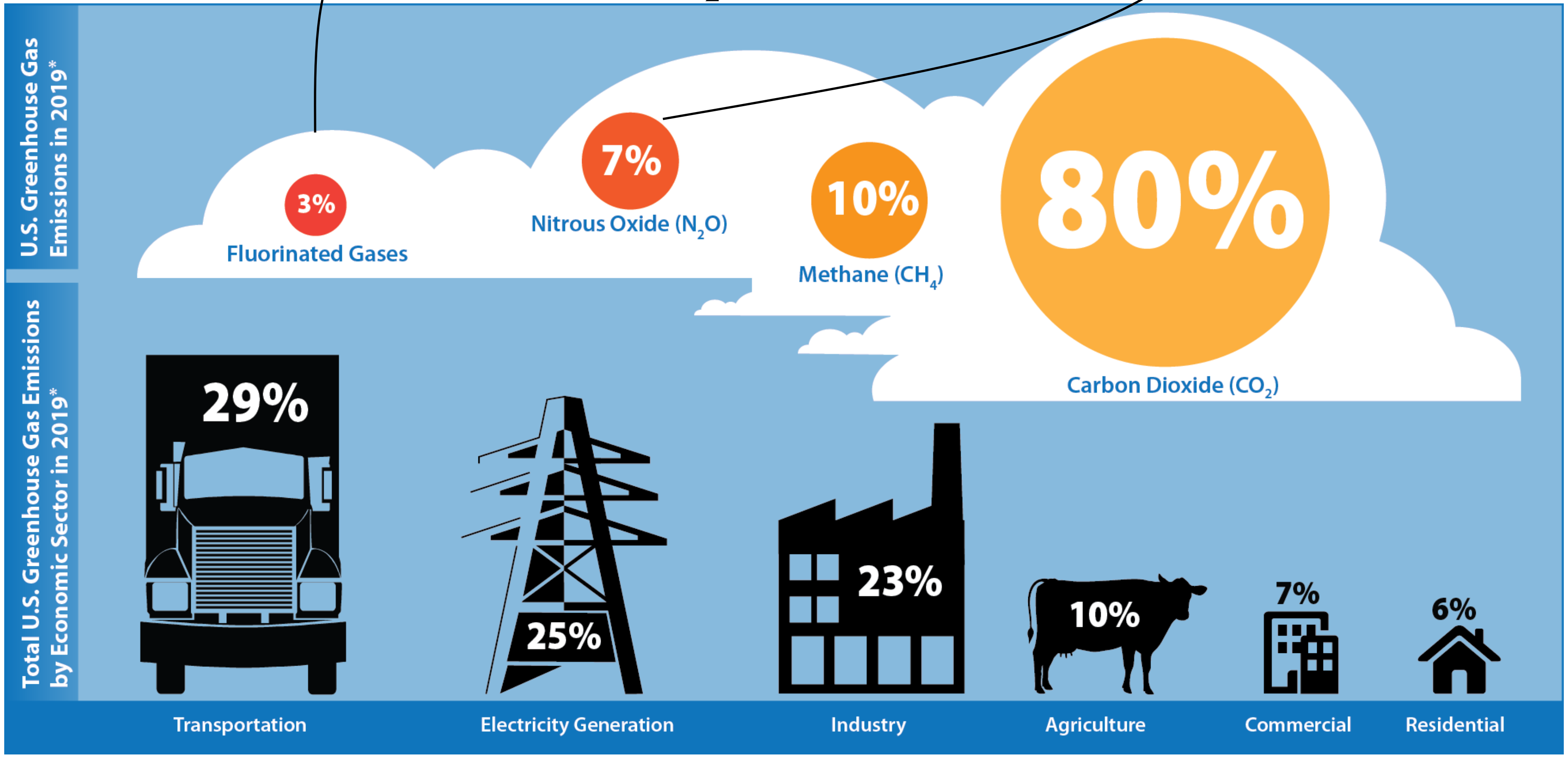


Image: epa.gov

+7%

30%

Historical examples of energy systems changes

Image: Pittsburgh Post-Gazette

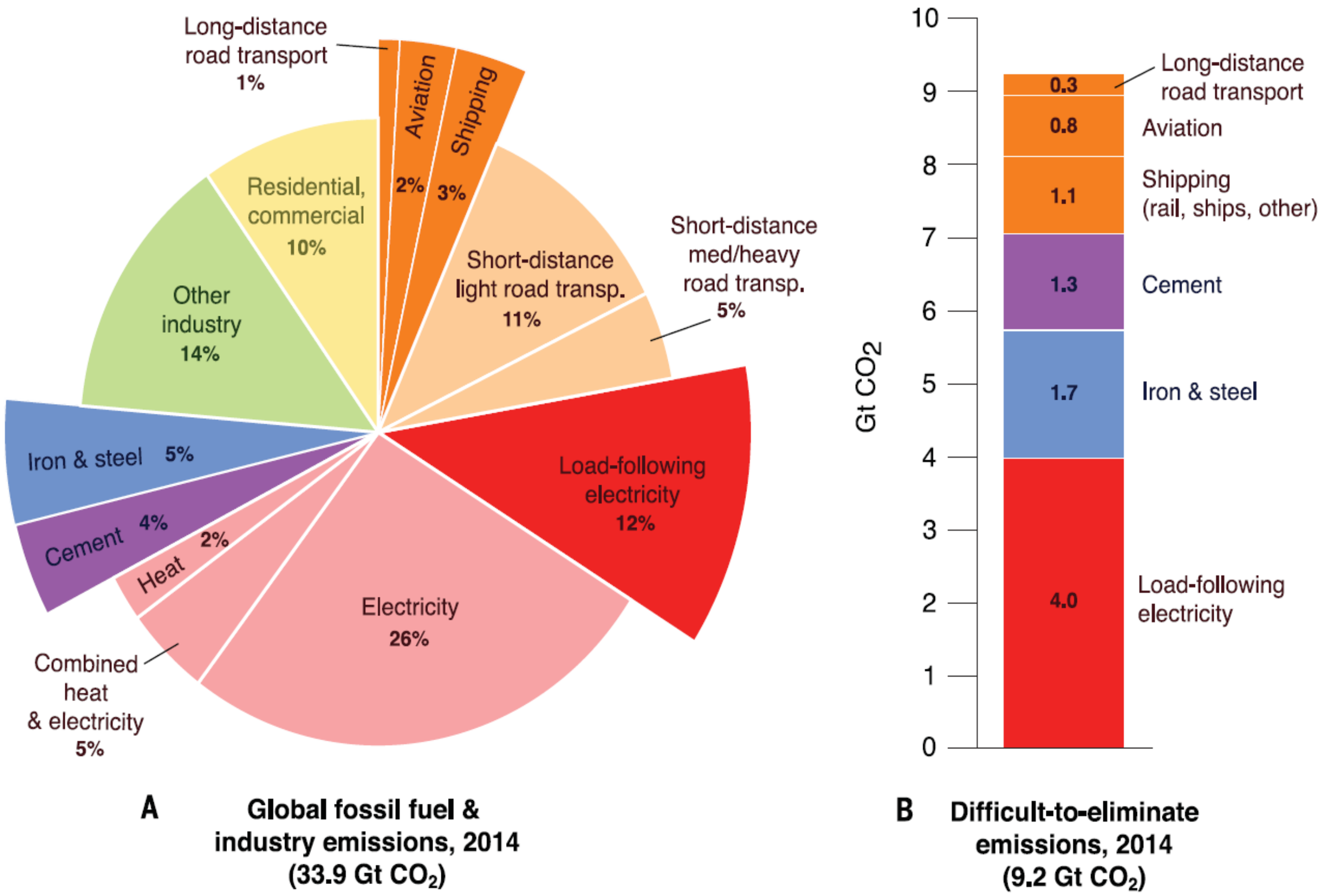
Nuclear power in US (data from eia.gov)
Year 0 (1951): 1 unit – Shippingport, PA
Year 20 (1971): 22 units - 2.4% of total electricity
Year 50 (2001): 104 units - 21% of total electricity

Coal in US (data from eia.gov)
2009: 1150 Mt
2019: 700 Mt (-39%)

TVA New Johnsonville, July 2021
1.5 GW coal plant, 1951-2021

OAK RIDGE National Laboratory

Ease of decarbonization



Davis et al., Science 360 (2018) 1419

Difficulty of decarbonization varies from "relatively straightforward" to "difficult to eliminate"

"Straightforward" = electrify all processes and generate electricity from CO_2-free sources(!)

Growth in renewable energy generation in US from 2000-2020 is ~5 quads
Estimate for "straightforward" sectors in chart for US is ~70 quads

CO_2-negative technologies will be needed at gigaton scales to reach net zero

Technology opportunity I: electrifying manufacturing

Dow PDH plant
Freeport, TX
Typical reaction temperature 500-600 °C

Many industrial processes rely on process heat (or cooling)
Many chemical processes rely on thermally-driven catalysis and separations

Means to scale up thermal reactors are well known & taught to undergraduates

Photo/electrocatalysis to replace thermal processes
- 1 eV = 39 $k_B T$
- Format of reaction vessel and media completely different to "standard" processes
- Strong need for scalable, cheap unit operations

Process intensified approaches to delivering energy in industrial processes
- Non-thermal mechanisms (e.g. microwaves)
- Structured contactors

RAPID Transforming Process Industries

Oak Ridge National Laboratory

Technology opportunity II: non-fossil feedstocks

Essentially all chemicals are sourced from fossil-fuel feedstocks
- Supply chains and processing infrastructure has been optimized for ~100 years
- A key lesson from biofuels is that directly competing on cost is *very* difficult

Moving towards a circular economy
- Design and select materials with end-of-life in mind
- Infrastructure needs for recycling are very different than for single use materials

Bioresources as feedstocks
- Must focus on sources that do not compete with foods
- Local/regional processing important to limit GHG emissions from transport
- Bio-derived sources are rich sources of chemical complexity

CO_2 as a carbon source
- Carbon capture should make CO_2 available on enormous scales
- CO_2 conversion could potentially use a (small?) fraction of this source
- CO_2 very thermodynamically stable, so CO_2 conversion requires energy input
- R&D needs are for scalable, durable, low-cost technologies

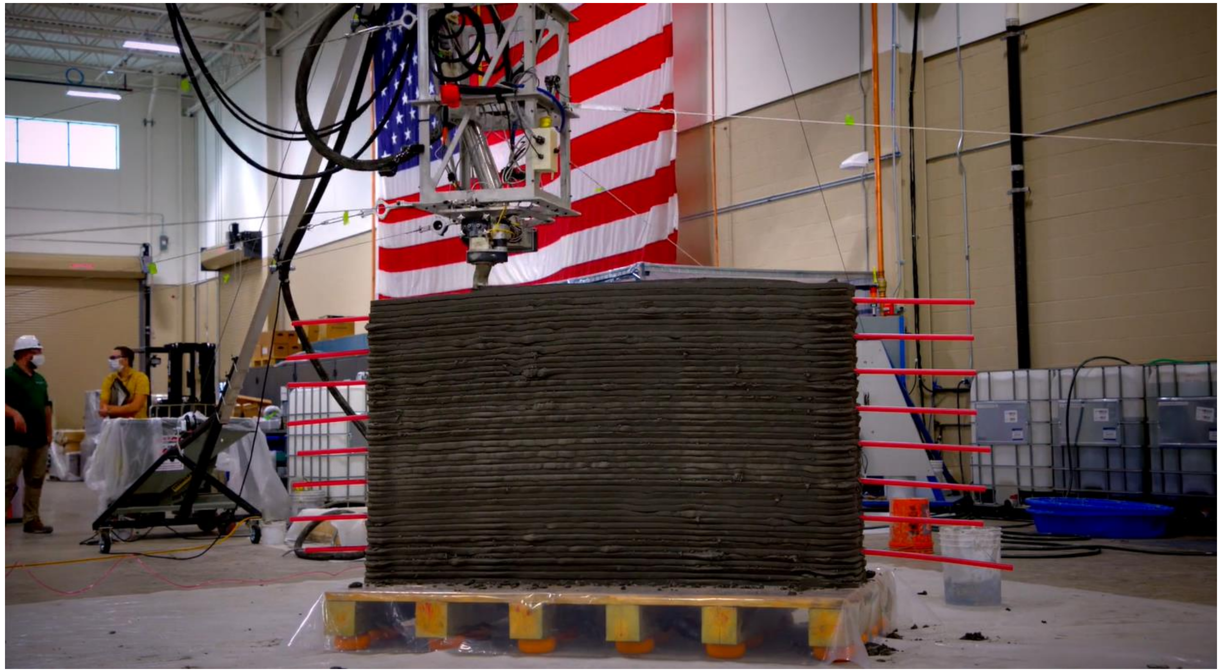
Technology opportunity III: tackling structural materials

Upgrading grid, vehicle fleet, buildings and climate adaptation will require vast amounts of structural materials

New Orleans levee system post-Katrina: $14.5B

Opportunities for direct decarbonization in cement production (e.g. alternative compositions, CO_2 capture…)

Innovative manufacturing processes



ORNL's EMPOWER wall 3D printed with SkyBAAM

Wall includes thermal storage and active insulation

Negative carbon technologies

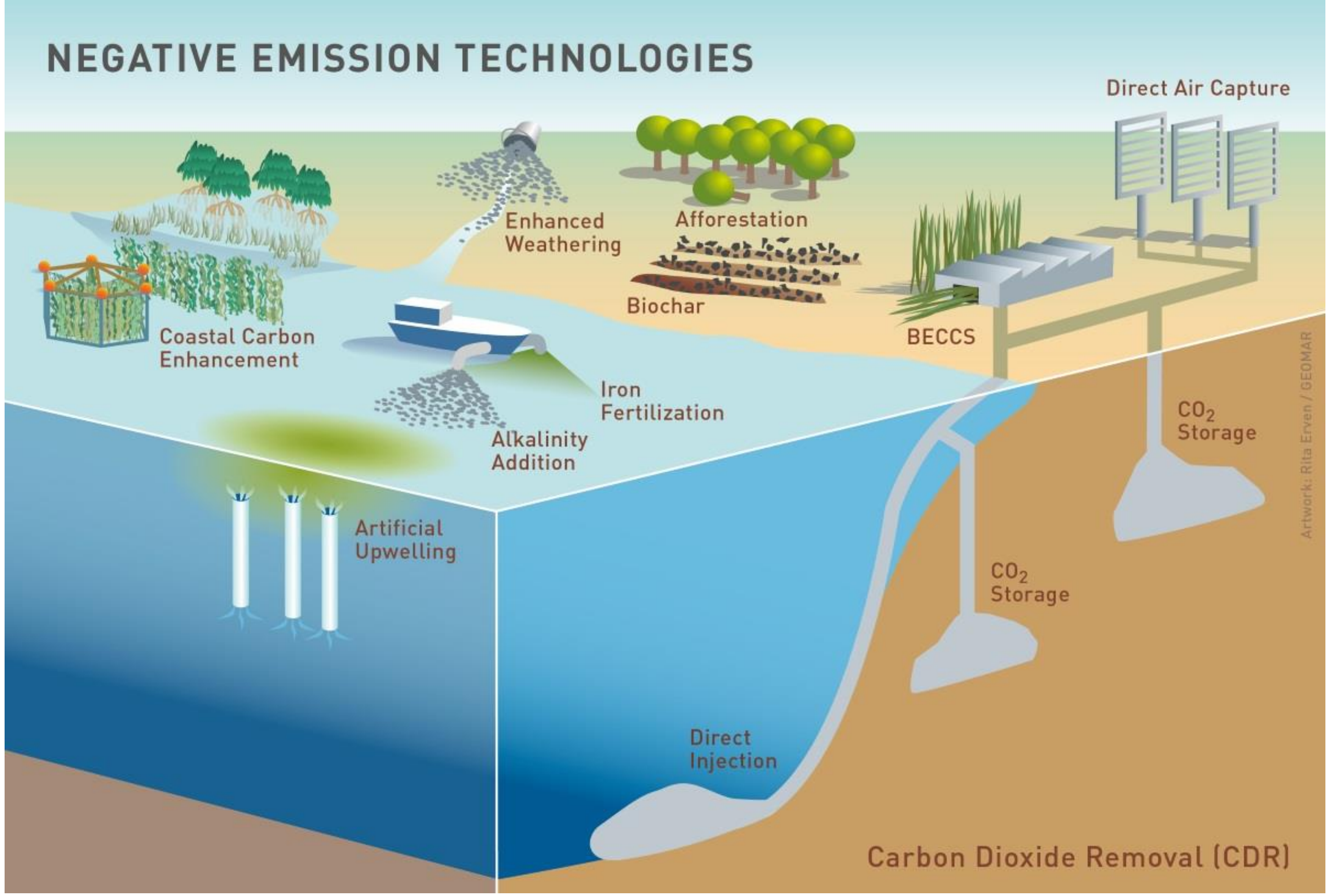


Image: Physics World

- CO_2-negative technologies will be needed at gigaton scales to reach net zero
- Technology leaders will dominate a large sector of global significance
- Significant opportunities for economic development
- Need to tackle integration of capture and storage
- Early TRL concepts need to scale fast (and fail fast)
- NO_x-, HFC-, methane-negative technologies?

Work force development challenges

TVA New Johnsonville, July 2021
1.5 GW coal plant, 1951-2021

Dow PDH plant
Approximate cost $1B

Decarbonization – a challenge where US manufacturing can lead

Net zero emissions is only possible if we decarbonize manufacturing

Decarbonization will upend and create vast sectors of manufacturing

Opportunity 1: Electrify manufacturing (especially chemicals manufacturing)

Opportunity 2: Non-fossil feedstocks (bioresources, CO_2, green H_2, …)

Opportunity 3: Structural materials (especially cement)

Opportunity 4: Negative emissions technologies (direct air capture, BECCS,…)

Images: history.com, Temple University