Quest for Carbon Neutrality in Concrete

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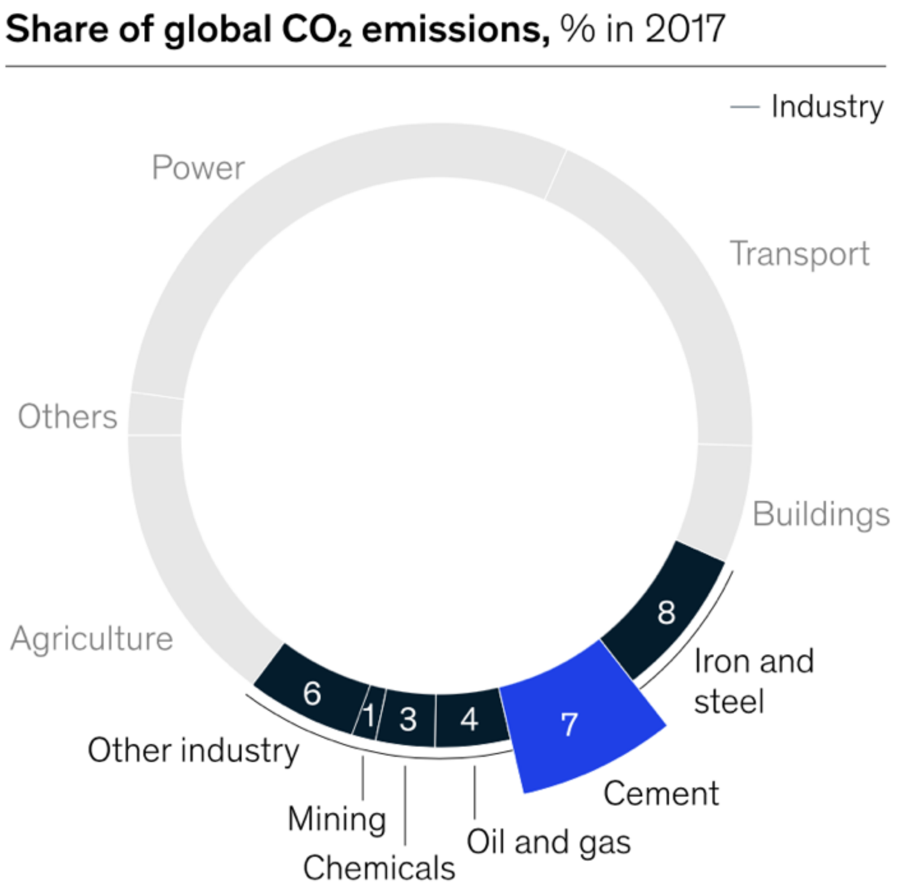

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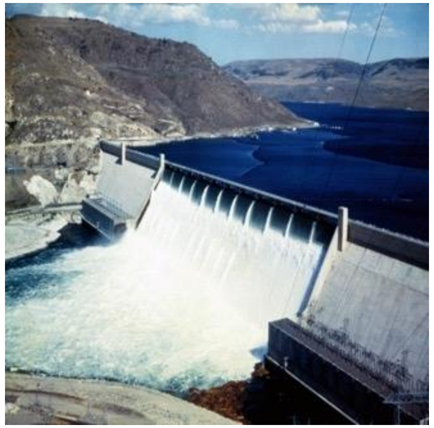
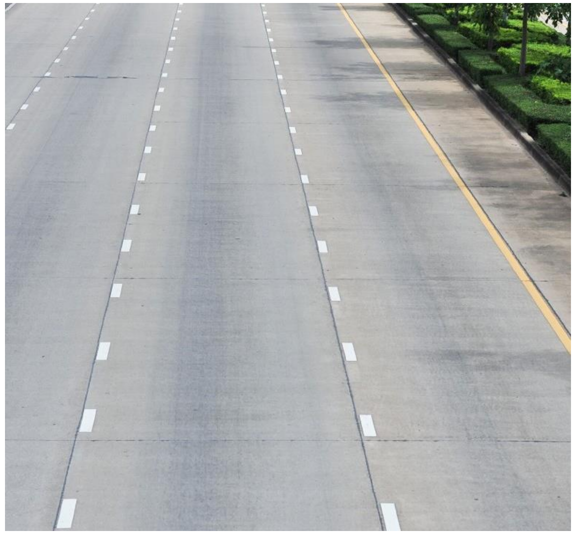
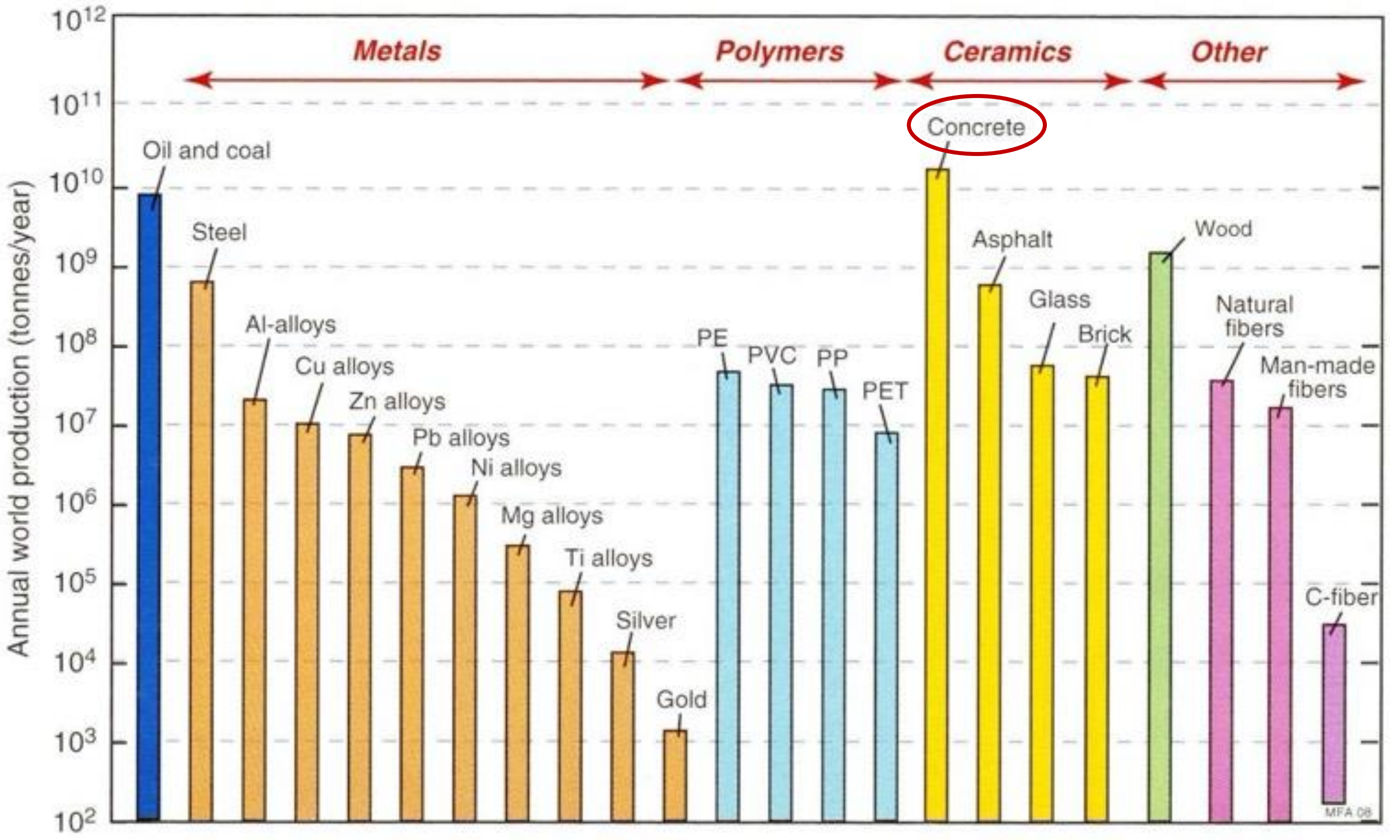
Concrete is the backbone of civil infrastructure that supports and advances people's quality of life





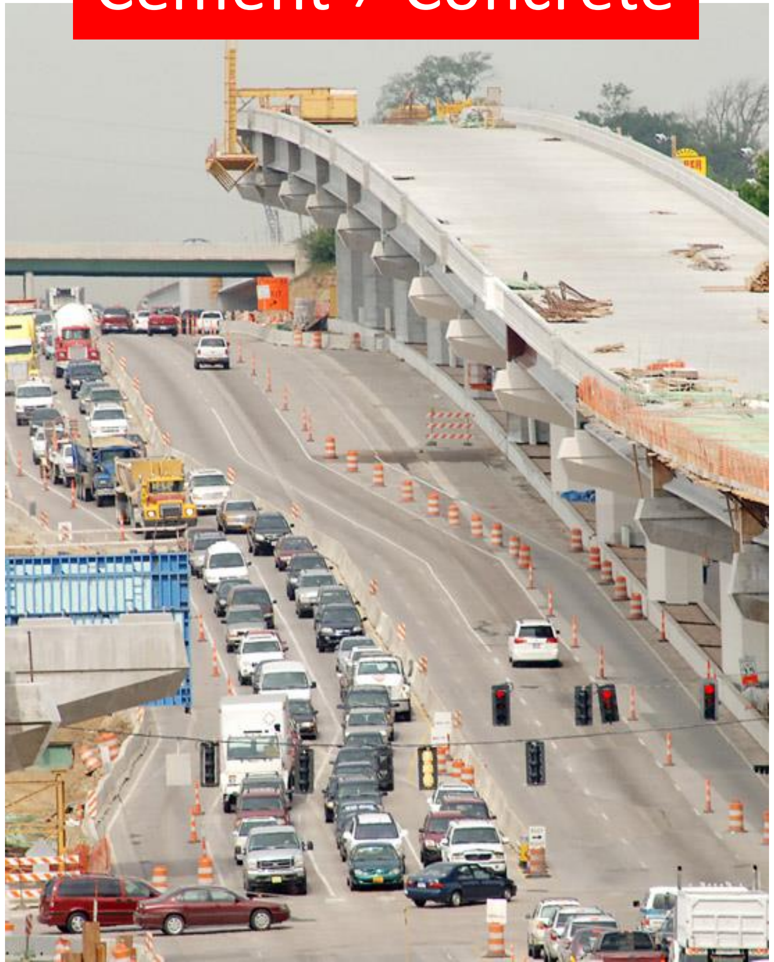




Concrete is the most ubiquitous human-made material

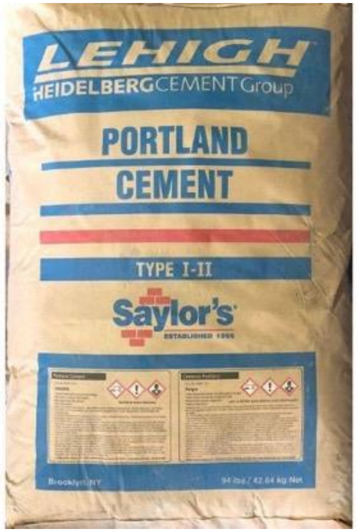


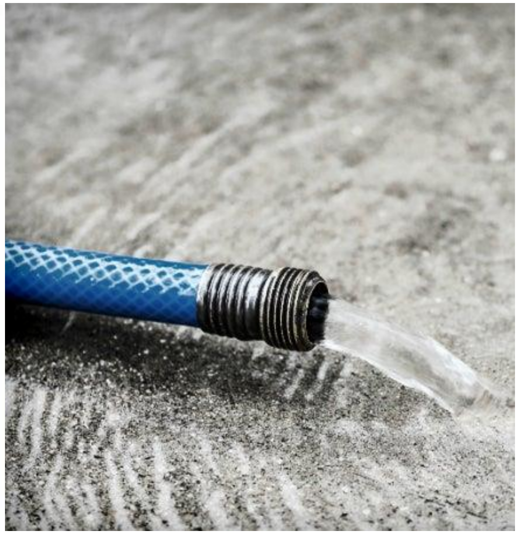
Annual world production:
~30 billion tons = 3.7 tons/person/year

Cement ≠ Concrete



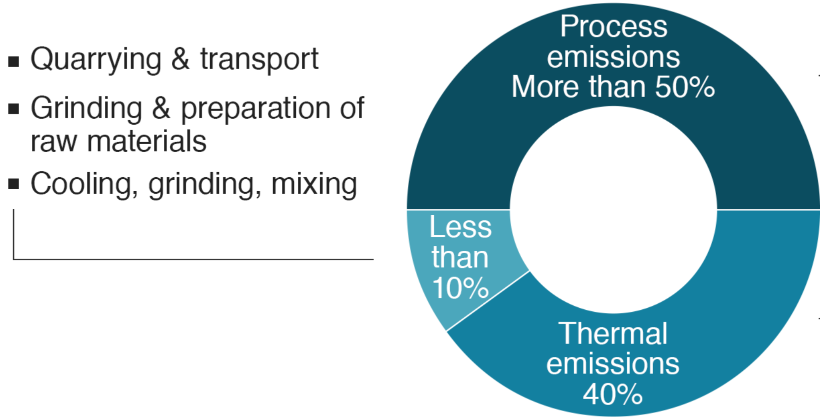
Cement + Water + Aggregates = Concrete



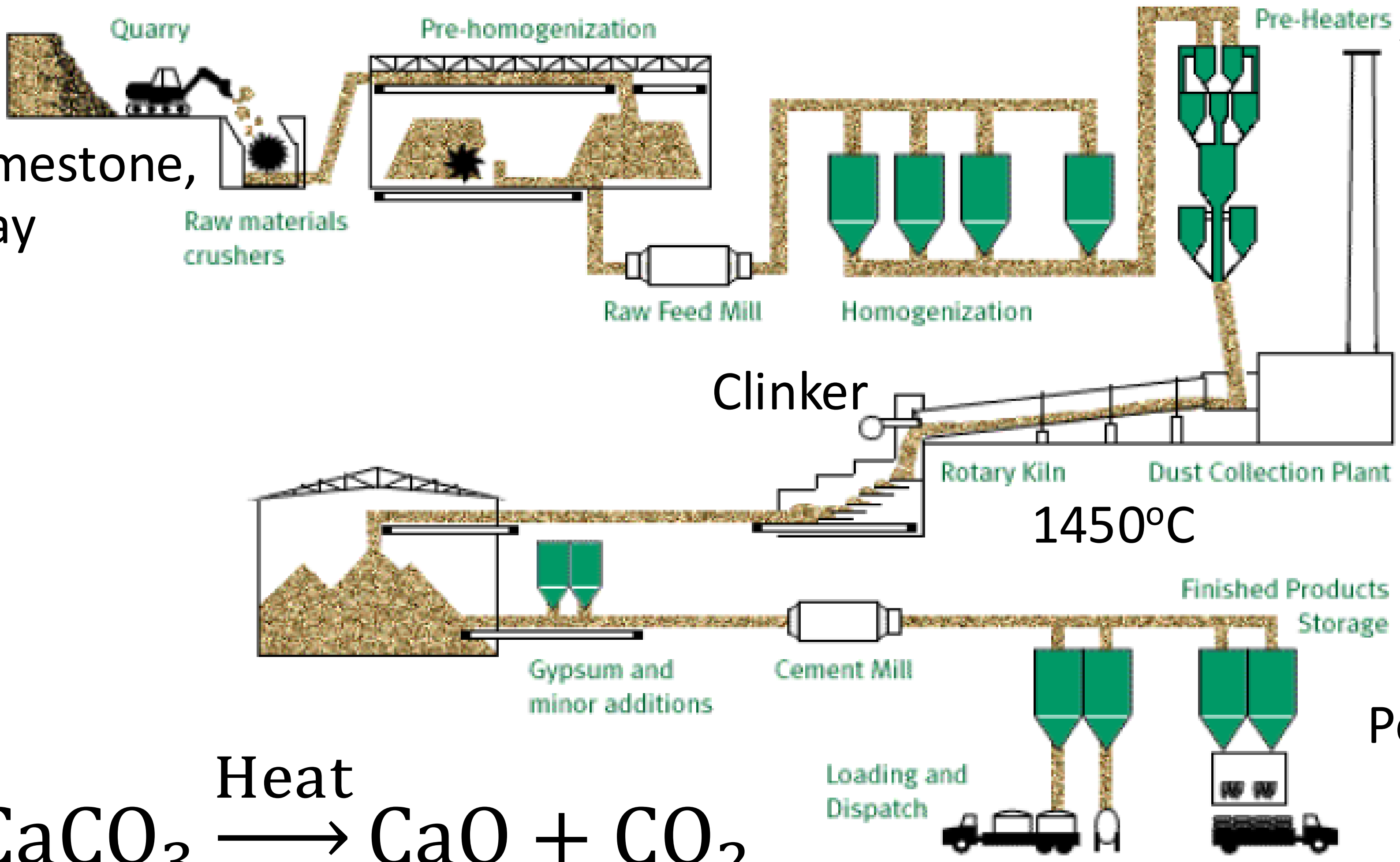


CO_2 emission of concrete primarily comes from manufacturing Portland cement

= 2.5 GT/yr (~7% of total anthropogenic GHG emissions)



Source: Chatham House

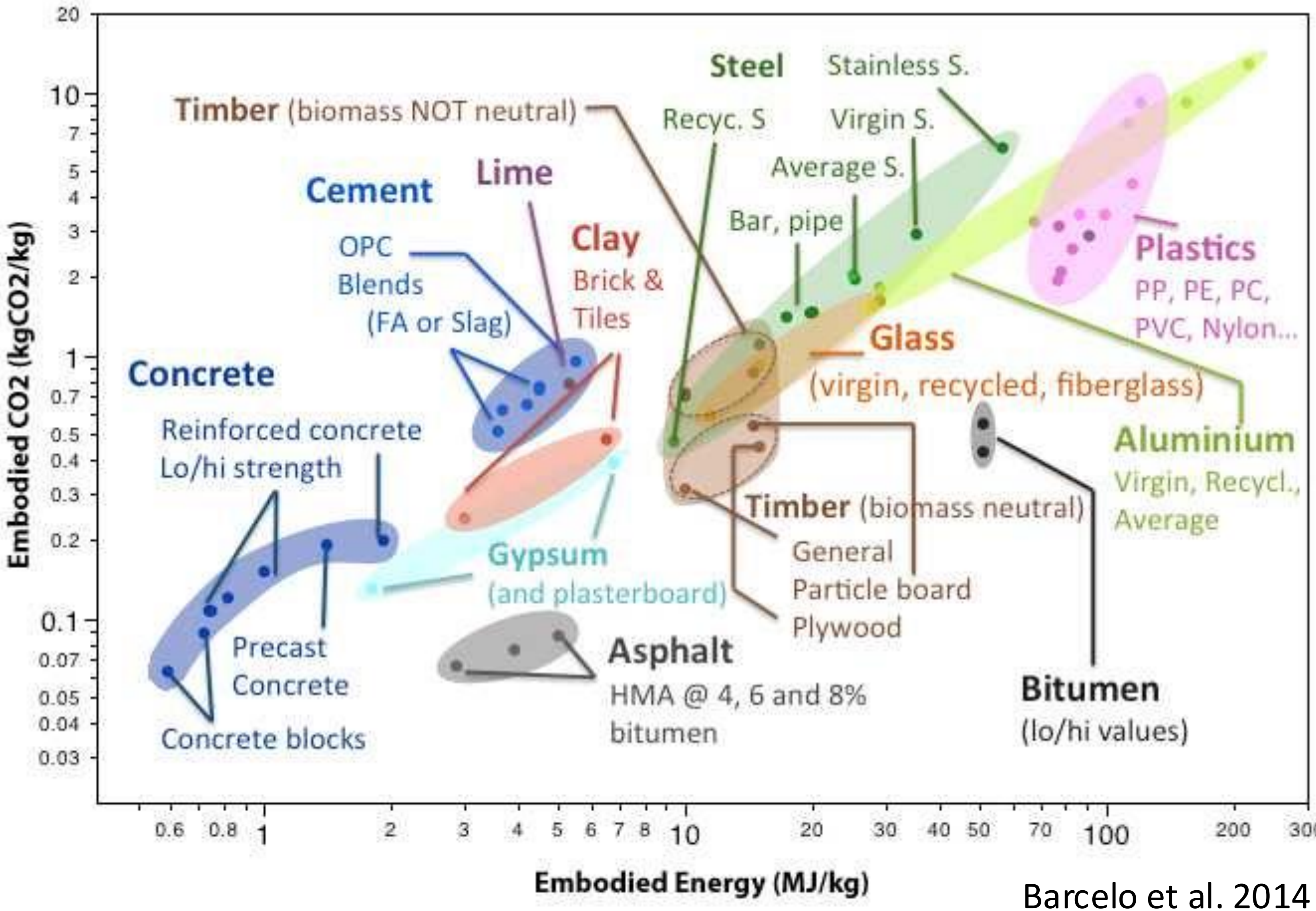


$$CaCO_3 \xrightarrow{\text{Heat}} CaO + CO_2$$

Portland cement

Photo: ACA

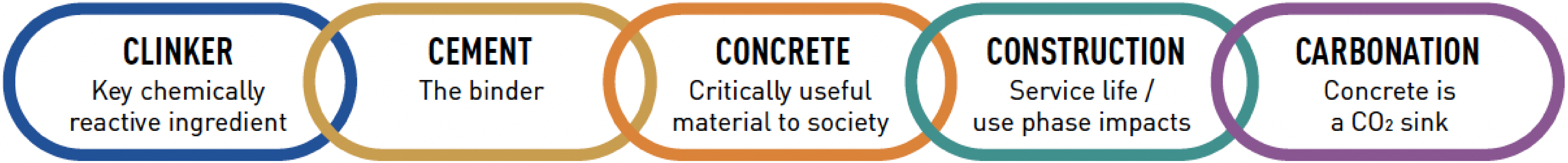
Per Kg CO_2 footprint of concrete is low. But its very large use (30 BTons/yr) leads to large CO_2 contribution.



Barcelo et al. 2014

How to cut concrete’s CO_2 footprint?

ACA Roadmap to Carbon Neutrality by 2050



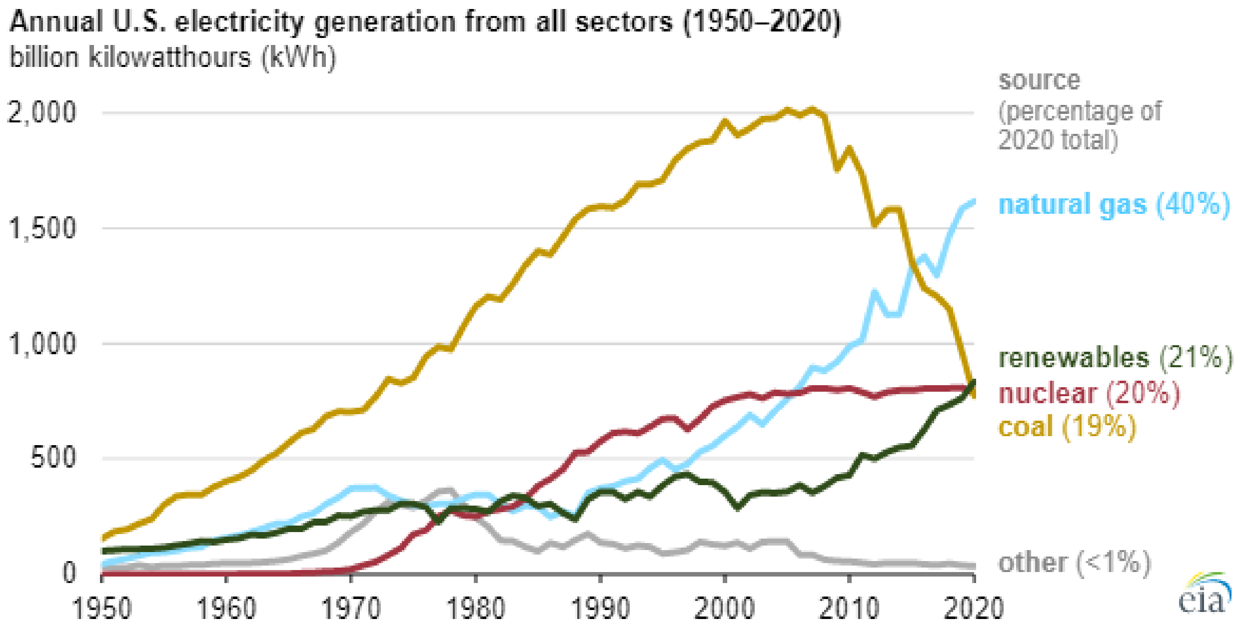
- Less CO_2 in clinker (e.g., energy efficient kilns powered by renewable electricity)
- Less clinker in cement (e.g., IL and IT cements, high SCM, geopolymers)
- Improve concrete (e.g., lean mixtures, avoid over design, recycled aggregates, seawater)
- Improve construction and maintenance (e.g., durability)
- Carbon capture and mineralization

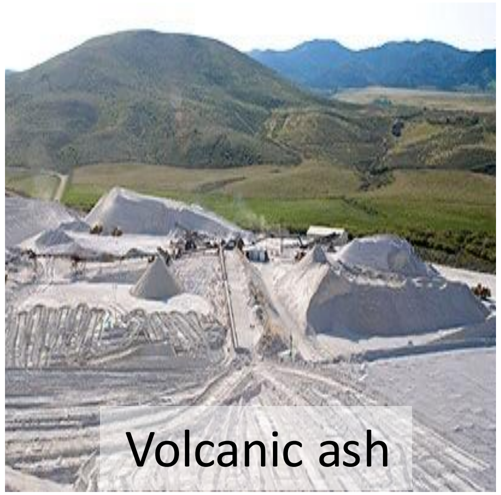
Decarbonization cannot come at a cost of performance and must be economically competitive with incumbent

- Meet performance targets (constructability, strength, durability)
- Cost competitive
- Benefit society and social equity (safety, access to opportunities)
- Must consider the entire service-life of a structure

Project 1: Using supplementary cementitious materials (SCM) to substitute Portland cement

- Portland cement can be partially replaced with SCM to improve durability, CO_2 footprint, long-term strength
- Conventional SCMs (coal ash and iron slag) are not eco-efficient and are in short supply





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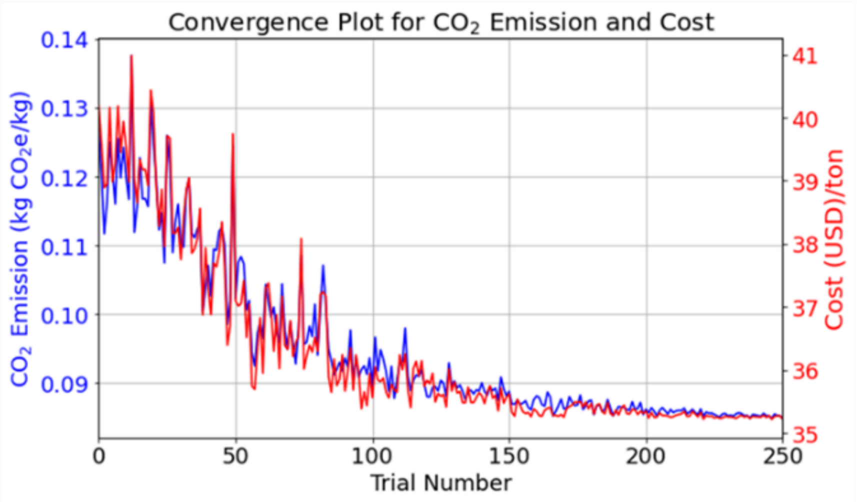
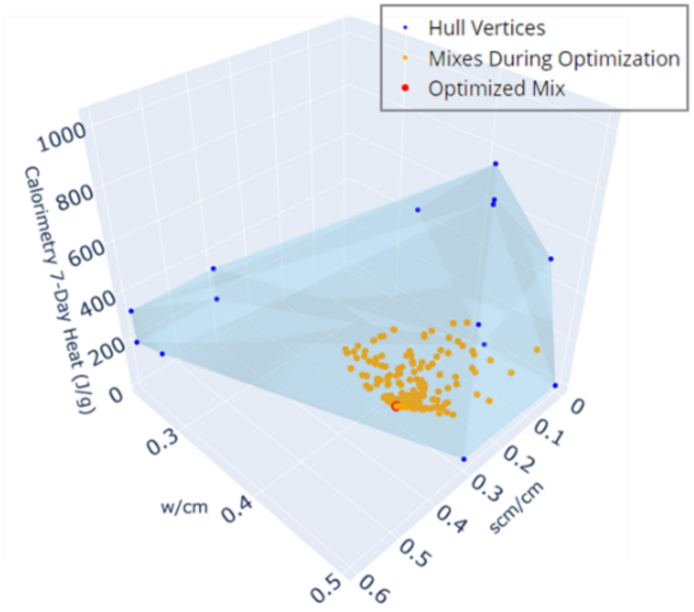
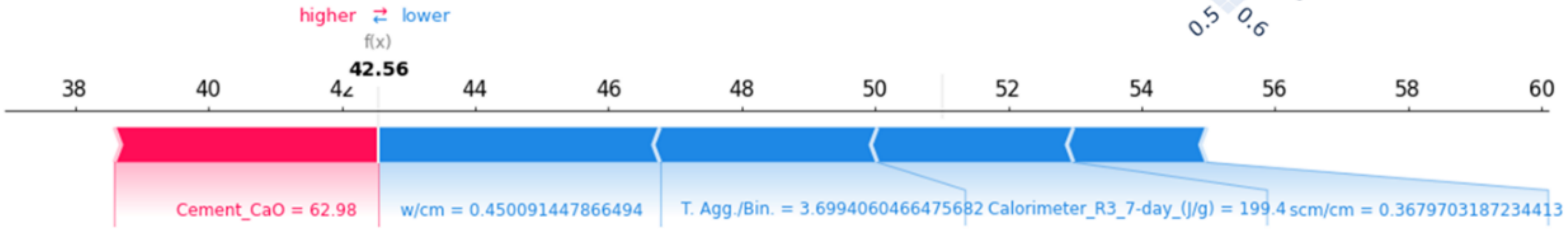
Project 2: Using AI (machine learning and Bayesian optimization) to develop low-carbon concrete mix designs meeting target strength

Predicted strength (fu): 42.56 MPa Blume et al. 2025

scm/cm: 0.37
w/cm: 0.45
T.Agg./Bin: 3.69
Calorimetry Heat (J/g): 199.4
CO_2 Emission: 0.0848 kg CO_2eq/kg
Cost: 35.213 USD/ton







Example opt. mixture with 37% fly ash

Goal:

Develop optimum concrete mix design with strength ≥ 42 MPa with min. CO_2/cost

Model inputs:

Available ingredients

Target performance

Achieves 47% CO_2 reduction vs. incumbent at the same 28-d f'c.

PennState Institute of Energy and the Environment

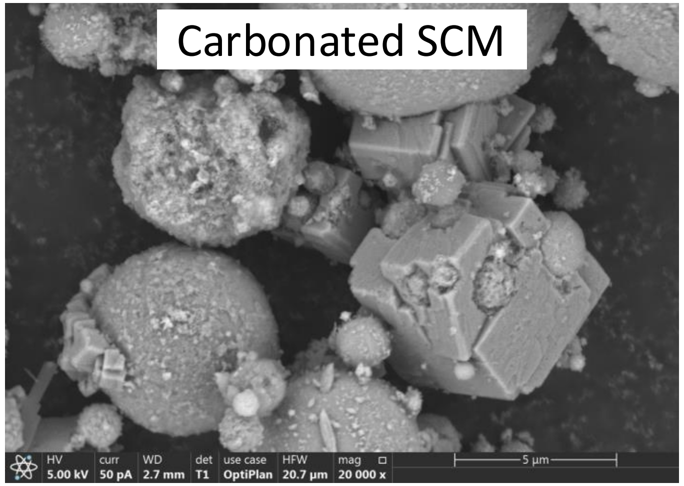
Project 3: CO_2 mineralization in SCMs to produce carbon-negative concrete for buildings

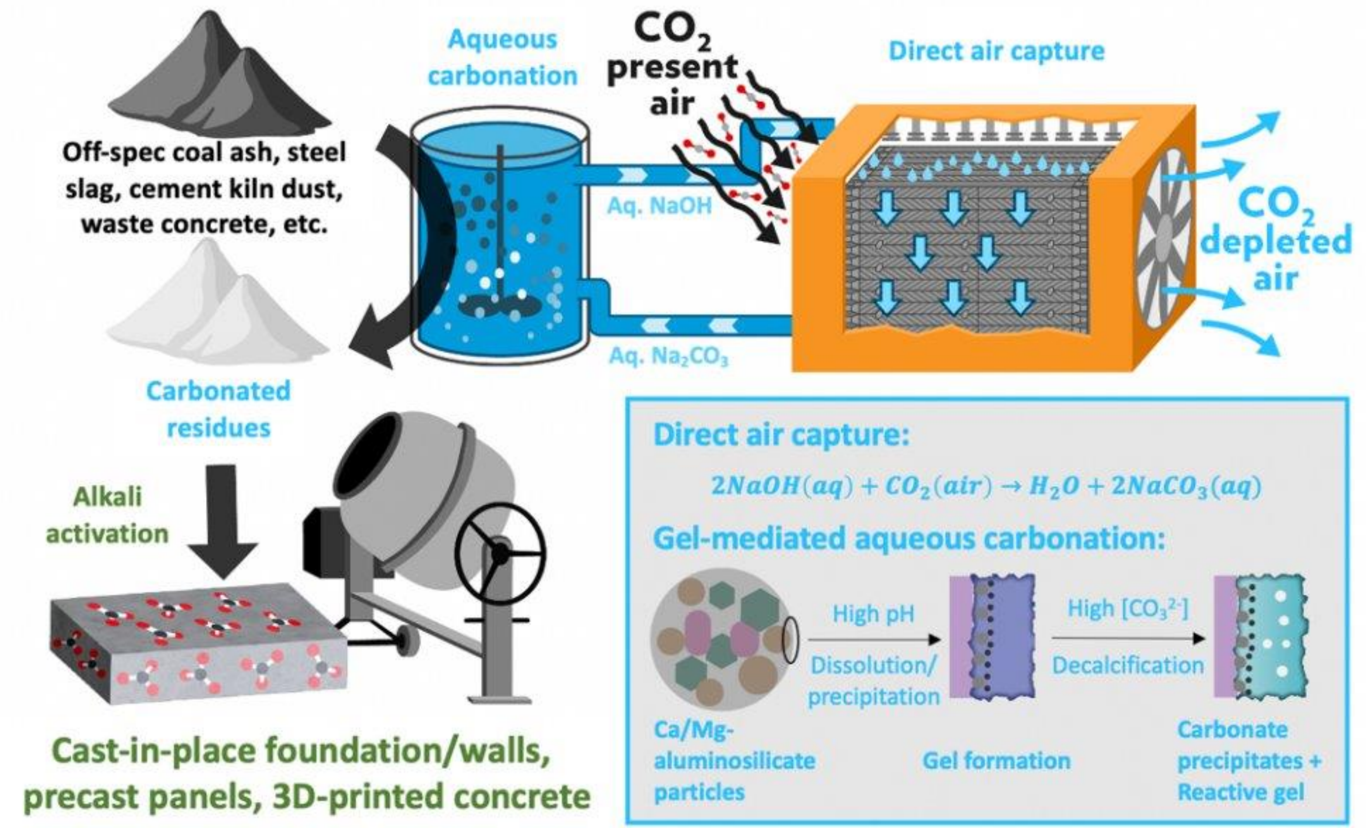
Direct air capture of CO_2

$2NaOH + CO_2 \rightarrow Na_2CO_3 + H_2O$

Locking (mineralizing) CO_2 via pre-carbonating SCMs.

High-Ca SCM + Na_2CO_3 $\rightarrow$
Low-Ca SCMs + $CaCO_3$ + 2NaOH





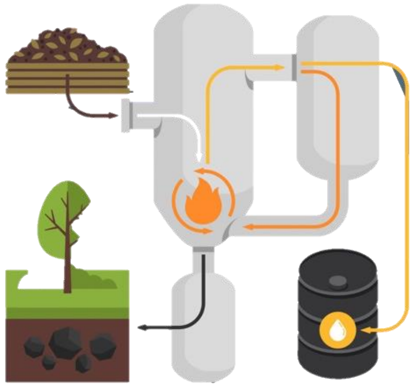
Akbar et al. 2025

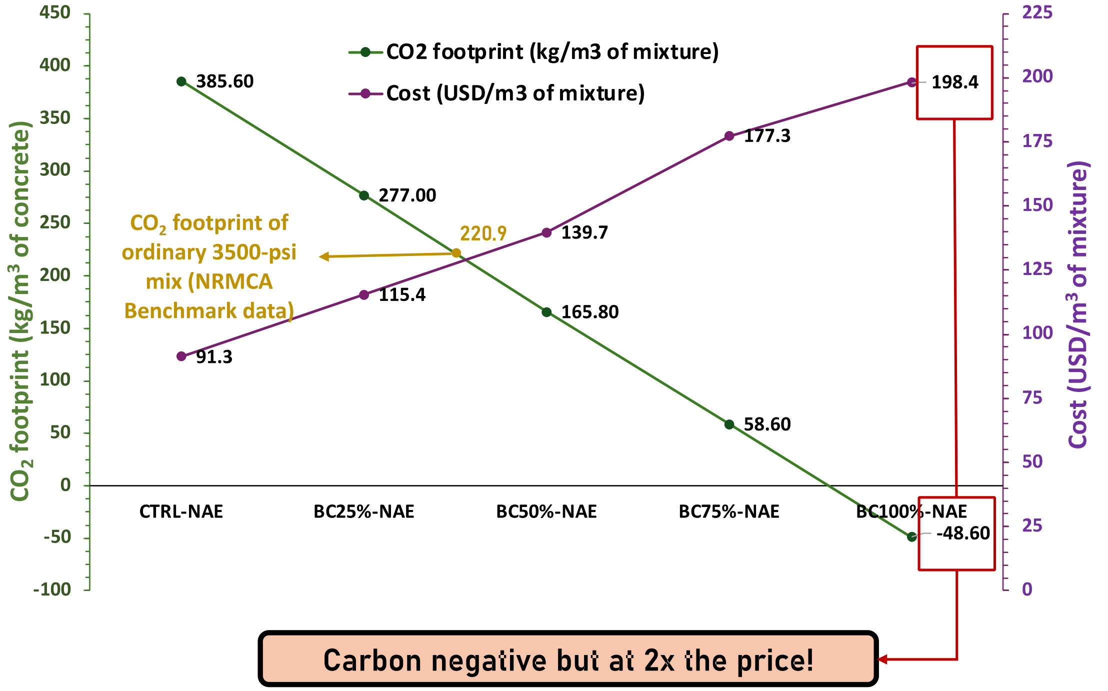
Project 4: Using Biochar (bio-sequestered carbon) as Concrete Sand

Feedstock → **Pyrolysis** → **Biochar**

Wheat Straw

Wood waste





Biochar CO_2 footprint =
-2.4~-2.9 $kgCO_2$ / kg biochar

Challenges:
- Strength loss
- Air entrainment
- Cost

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Mirabrishami and Rajabipour 2025

Final remarks

Thank you very much!
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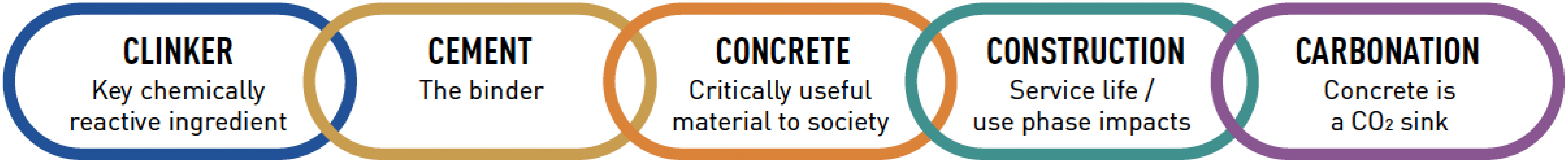

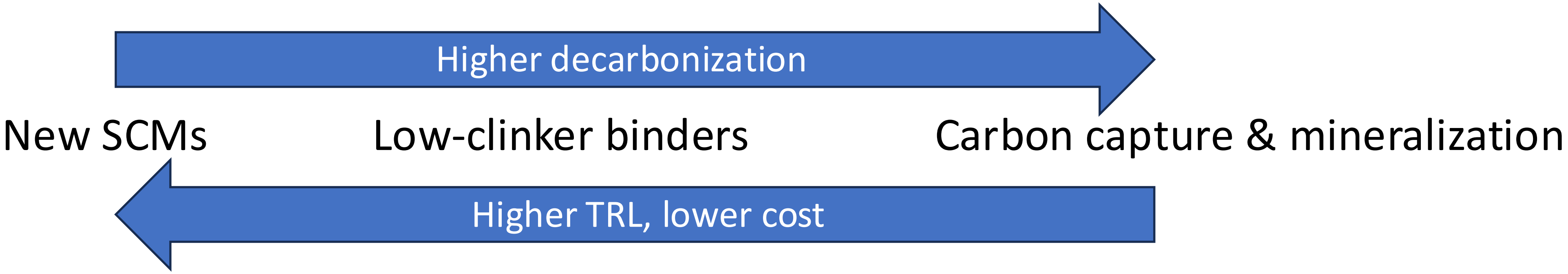

- There are multiple paths to decarbonization, with varying efficiency, cost, scalability, and timeframe for deployment (market readiness)
- Low-CO_2 concrete must meet performance target (constructability, strength, durability, cost, consistency)
- Barriers: Lack of history, Risk avoidance, Cost/CapEx, Policy uncertainty