For California Air Resources Board (CARB)

Cement Decarbonization

20 October 2022

The global cement industry = ~7% of world CO2

Production

4.1 billion tons annual

Emissions

2.3-2.8 billion tons CO_2

6-8% of global

Growth

12-23% to 2050

Location

90% in developing world

The modern cement production process

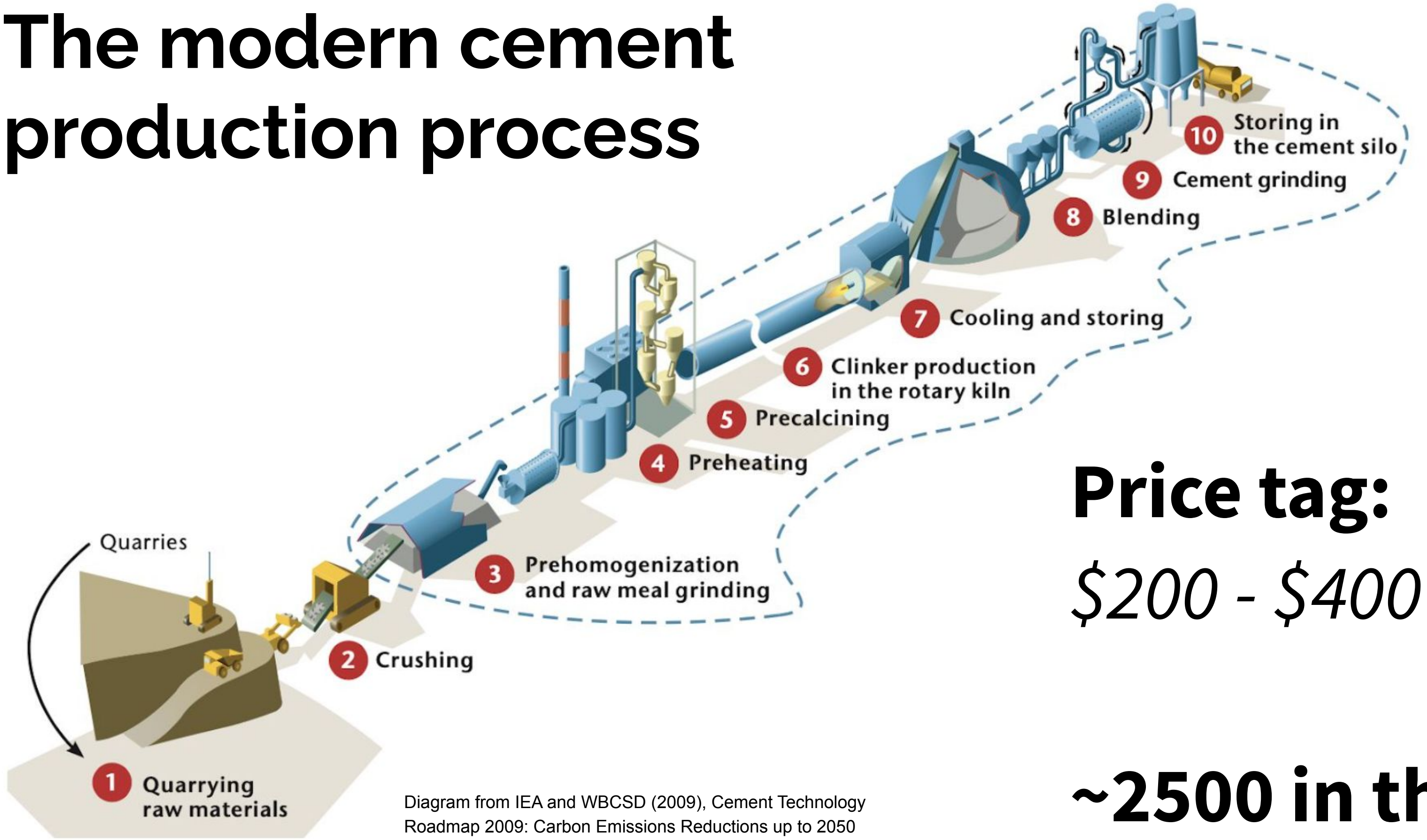


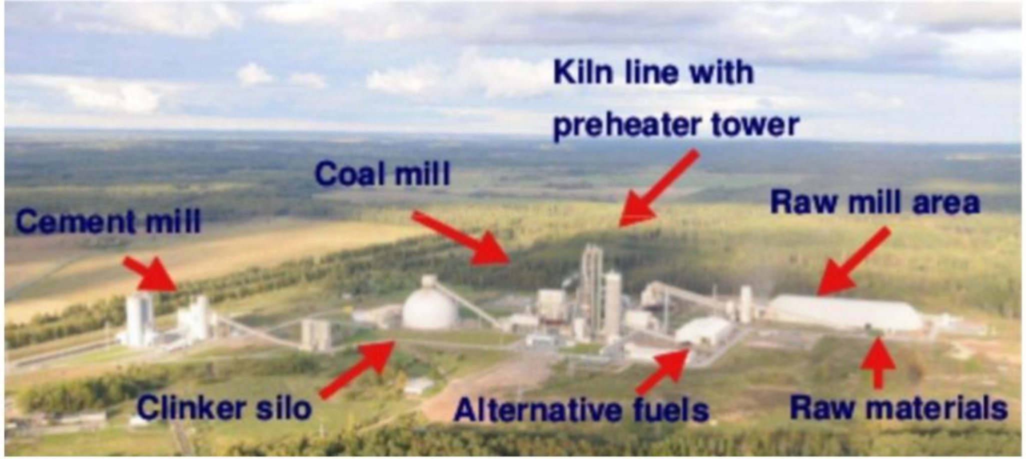
Diagram from IEA and WBCSD (2009), Cement Technology Roadmap 2009: Carbon Emissions Reductions up to 2050

Produces:
> 1 million tons of cement annual

Price tag:

$200 - $400 million

~2500 in the world



Cement plant in Broceni, Latvia

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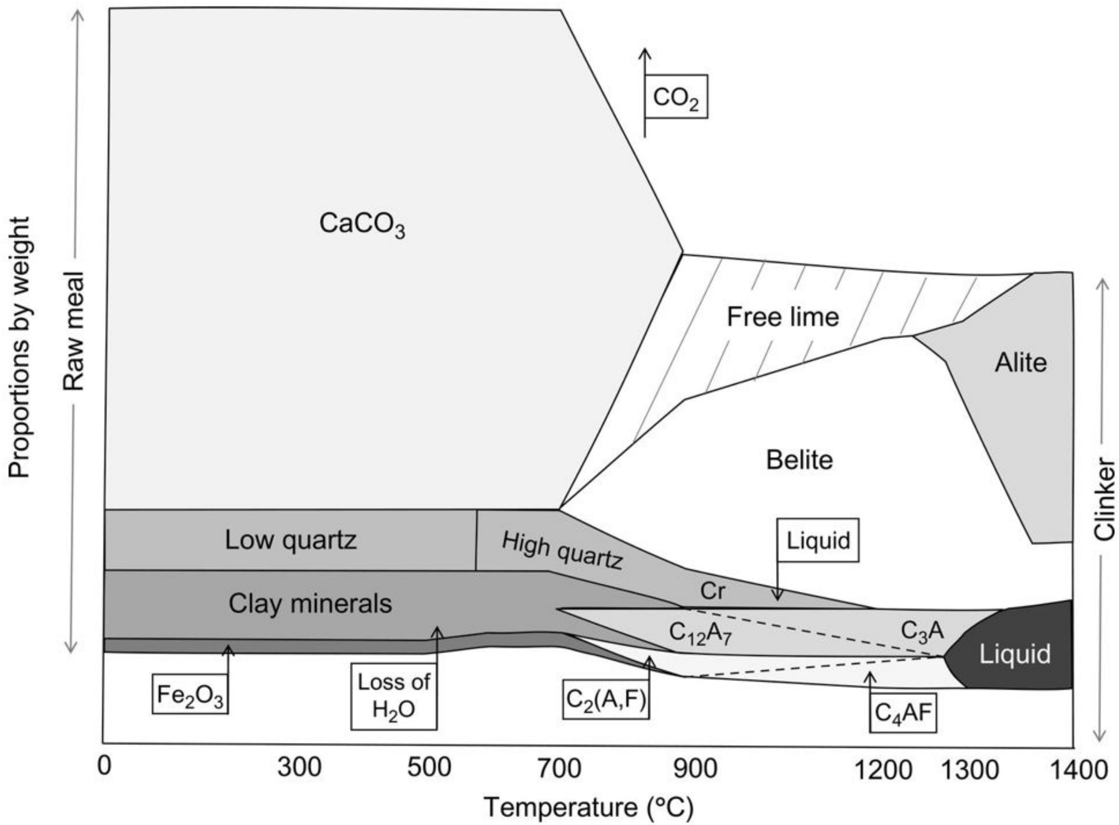
Cement - temperatures up to 1500 C needed



Compound	Formula	Shorthand form	% by weight
Alite or tricalcium silicate	Ca_3SiO_4	C_3S	50 - 70%
Belite or dicalcium silicate	Ca_2SiO_5	C_2S	15 - 30%
Tricalcium aluminate	$Ca_3Al_2O_6$	C_3A	5 - 10%
Tetracalcium aluminoferrite	$Ca_4Al_2Fe_2O_{10}$	C4AF	5-15%

Lea's Chemistry of Cement and Concrete (5th Edition, 2019)

Incredibly cost optimized industry

Marginal cost = *~$20-40 per ton!*

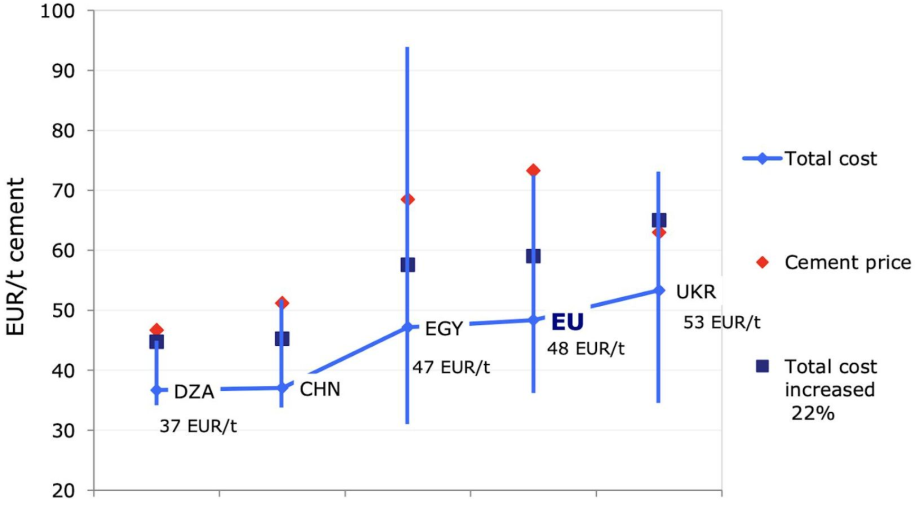


Figure 9: Average cost curve of cement production in 2012, cement price and intervals encompassing the maximum and minimum estimated costs

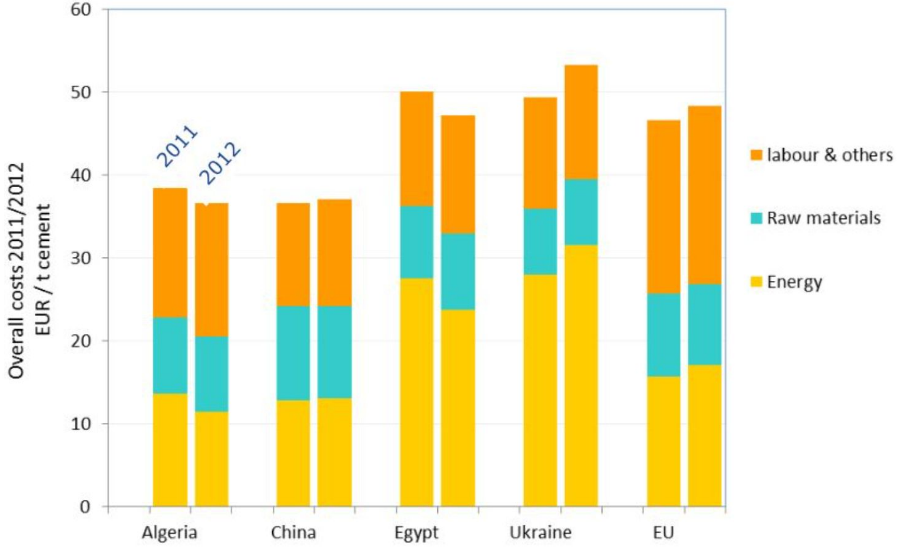
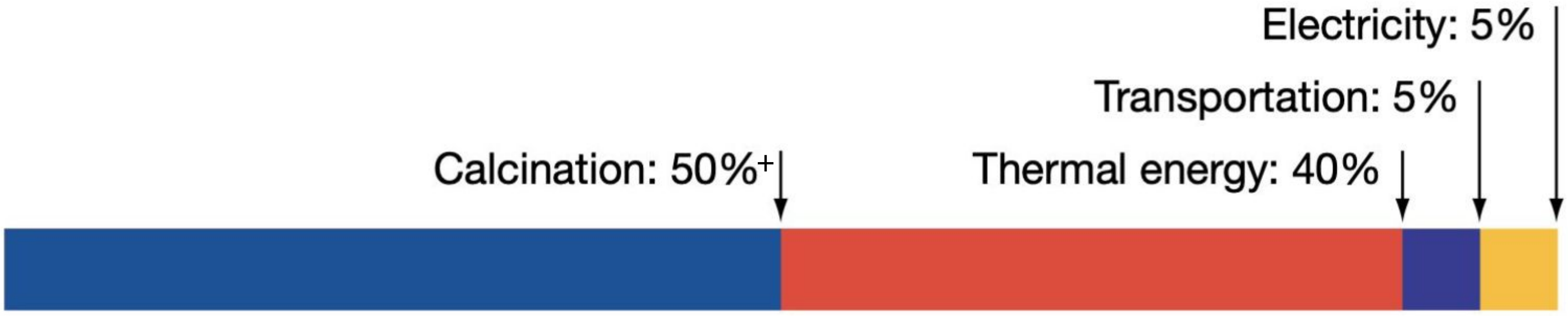


Figure 8: Summary of the cement industry costs in 2011 and 2012

Estimates from: "Production costs from energy-intensive industries in the EU and third countries", Moya & Boulamanti (EC JRC) 2016 and from McKinsey and VDZ 2008 study on clinker costs in Europe vs. Egypt, China and Saudi Arabia; Both charts from "Production costs from energy-intensive industries in the EU and third countries", Moya & Boulamanti (EC JRC) 2016

Main sources of CO_2 emissions in Cement



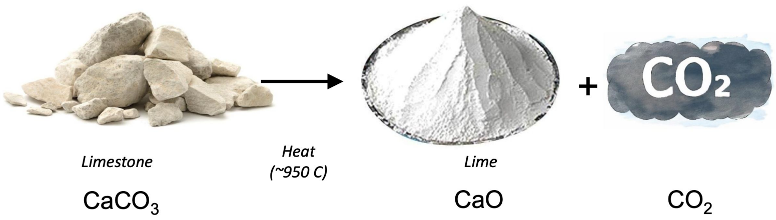


Diagram from LEILAC project

CO_2 in the industry reached a tipping point in 2019

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Concrete is tipping us into climate catastrophe. It's payback time

John Vidal

Cement has transformed the world, but now threatens to wreck the environment. We need to tax it, now

Find the rest of our Guardian concrete week pieces here

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THE GLOBAL ENERGY CHALLENGE

IN ASSOCIATION WITH BP

The cement industry produces more CO2 emissions than most countries. It may not survive

By Charles Riley, CNN Business

Updated 12:49 PM ET, Mon July 22, 2019

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Climate Changed

Cement Companies Are Starting to Get a $33 Trillion Headache

Investors are turning on cement producers, demanding more transparency and action on how they plan to help slow global warming.

By Vanessa Dezem and William Wilkes

July 21, 2019, 7:01 PM EDT

- Climate group calls for 2050 carbon neutrality pledge
- Cement production accounts for 7% of global carbon emissions

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ruction sector

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Cement price rise points to surge in China construction

UK construction sector hit by further fall in new orders

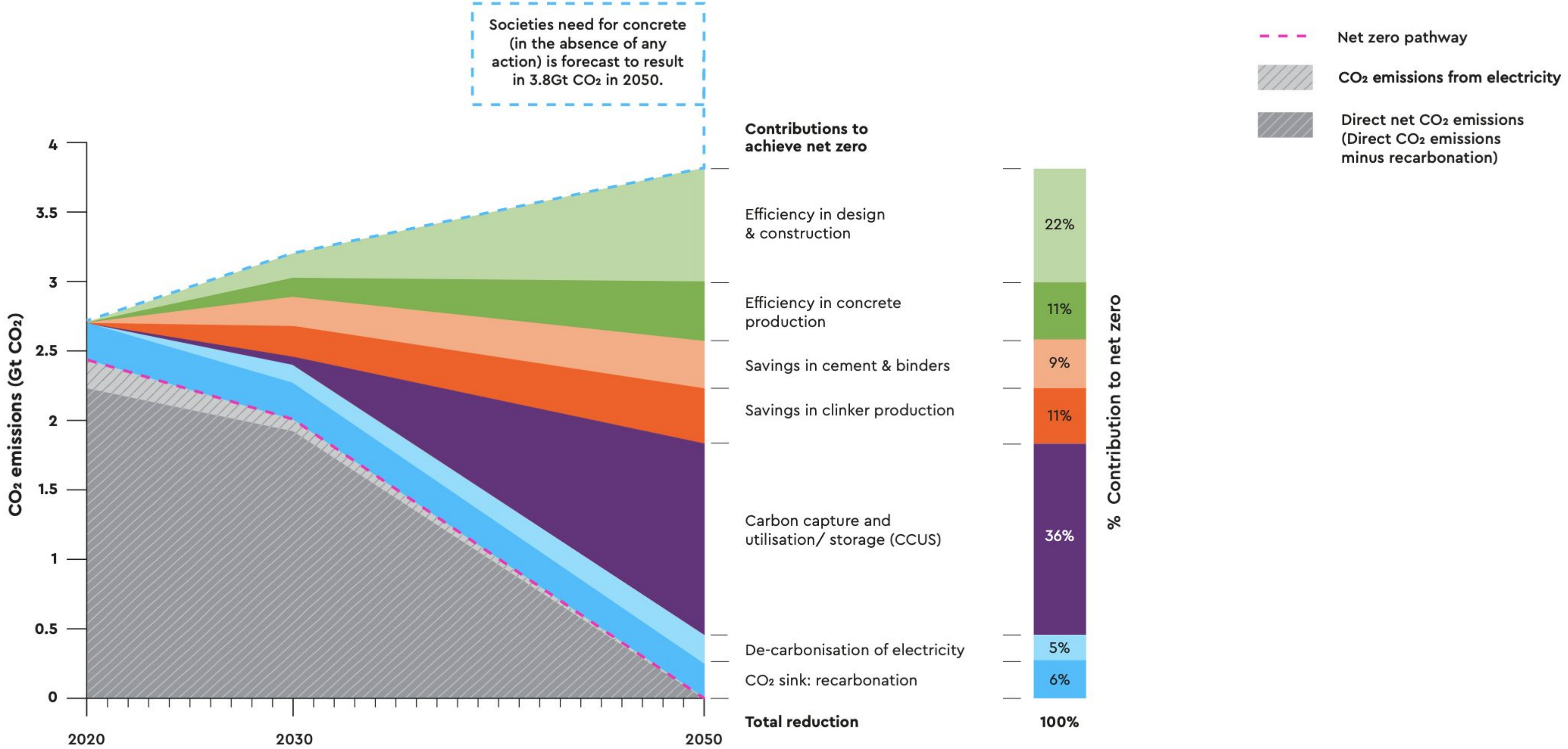
Construction sector + Add to myFT

Investors urge cement makers to cut emissions

Shareholders write to 4 construction groups outlining measures they expect them to take

Press articles

Resulting sector plan for net zero emissions



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An approach to classifying cement CO_2 technologies

Area	Scope *	Group
Material	60%	• **Efficiency** - Decrease of binder needed to achieve the same strength material • **Substitution** - Increase use of binders which are less CO_2 intensive than OPC [116] • **Waste** - Reduction of amount of material containing cement which is wasted [117]
Energy	40%	• **Reduction** - Optimization or change of industrial processes to be more energy efficient • **Substitution** - Replacement of energy used with waste-derived or renewable sources
Capture	80%	• **Post-combustion** - Capturing CO_2 without affecting the production process • **Process-specific** - Modifying production process to emit less or more capturable CO_2 • **Use-focused** - Using waste products of cement or concrete as a CO_2 sink; using CO_2 to make building materials

** Expressed in % of total cement sector emissions theoretically addressable*

Landscape of innovations for cement CO_2

Cement & Concrete

Energy

Efficiency
- Dry process kiln
- Preheater / precalciner
- Roller mills
- Advanced process controls
- Closed loop ML controls
- Best practice in plant control
- Waste heat recovery

Substitution
- Captive renewable generation
- Waste derived fuels usage
- Renewable fuel
  - Electric calcination
  - Hydrogen
  - Plasma

Capture

Post-Combustion
- Liquid chemical sorbent (amine)
- Solid sorbent (amine, MOF)

Process-Specific
- Direct separation
- Oxy-Combustion
- Calcium looping

Use-focused
- Fabrication of building material
- Synthetic aggregates
- Fuels (dependant on renewable H2 source)

Material

Efficiency
Binder efficiency
- Particle packing of fillers (in binder)
- Finer grinding of cement & SCMs
- Enhanced gradation of aggregates (in concrete)
- Enhanced mix design optimization tools

Admixtures
(use with both SCMs and cement)
- Dispersants (plasticizers)
- Accelerators (increase early strength)
- Activators (increase binder efficiency)

Substitution
Raw Material
- Raw material substitution (natural)
  - Natural calcium silicate sources
  - Natural magnesium silicate sources
- Raw material substitution (industrial)
  - Mining tailings
  - Steel slags
  - Hydrated cement paste (from CDW)

Alternative cements
- Hydraulic alternative clinkers (same kiln)
  - Belite-rich clinkers
  - Calcium Sulphoaluminate (CSA)
  - Belite Ye'elimite Ferrite (BYF)
- Hydraulic binders (new process)
  - Hydrothermal processed Belite
  - Precipitated calcium carbonate vaterite
- Non-hydraulic clinkers (CO2 curing)
  - Carbonatable calcium silicate clinkers
  - Magnesium oxide from magnesium silicates
- Activated materials
  - Alkali activated materials / geopolymers

SCMs
- Blast furnace slag
- Coal fly ash
- Calcined clays (>40% kaolinite)
- Powdered limestone (semi-reactive)
- LC3 (calcined clay + limestone)
- Natural pozzolans
- Vegetable ashes
- Waste glass
- Mining tailings
- Beneficiation techniques
  - Physical, chemical, thermal

Beyond

Waste
Design & Execution
- Use of high strength class concrete
- Minimize thickness of walls, number & size of columns
- Use of hollow slabs, lightweight partition walls, prestressed prefab
- Design for maximum service life
- Topology optimization of elements
- Use of minimum class required in design vs. single class per building

Regulation & Government action
- Change to performance vs. prescription based standard
- Pilot new materials' durability testing
- Distinguish separate class of concrete for use with steel reinforcement
- Ban or discourage bagged cement in urban areas
- Strict regulatory enforcement to level playing field for industrial concrete producers
- Target metrics: m3 concrete used per m2 built area
- Training of engineers on use of eco-efficient materials
- Public procurement CO2 targets

Sector-specific considerations for viability & scalability

1. Raw Materials
- Enormous quantity
- Widespread availability
- Limestone is -$5/ton

2. Economics
- Price-sensitive commodity (-$100/ton)
- Extremely low variable cost (-$20-30/ton)

3. Incumbents
- -$1 trillion in existing capital stock
- Oligopolistic control of industry

4. Ease of Use
- Tight standards
- Unskilled labor
- Relunctance to change material

Feasibility framework: Target characteristics

- Have widely available, distributed, and **economic raw materials** for production
- Produce material which maintains **simplicity & reliability of use** downstream
- **Not increase variable cost** of production of the material substantially
- Ideally be **synergistic with capital stock** of $1 trillion already in the industry

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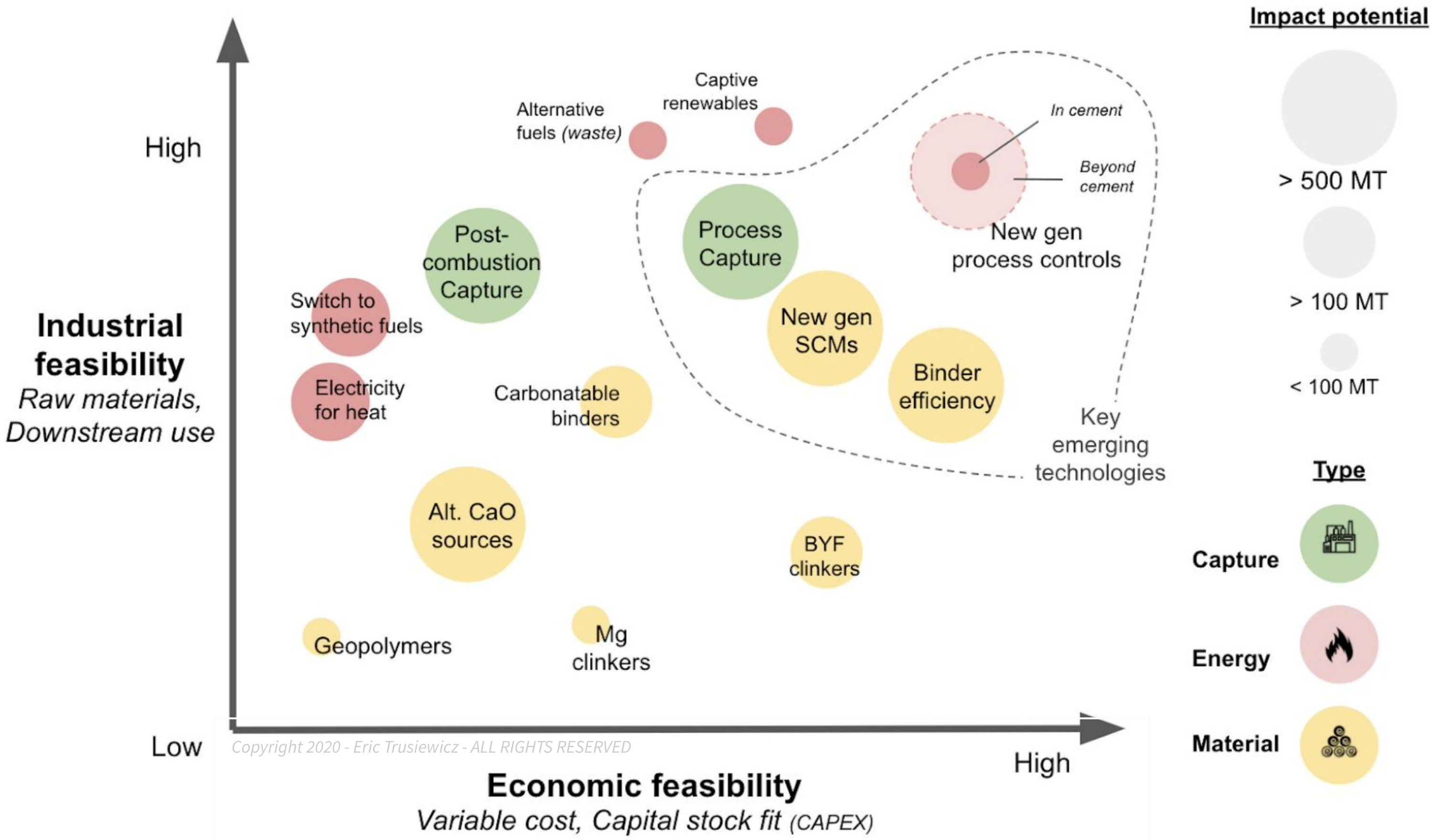
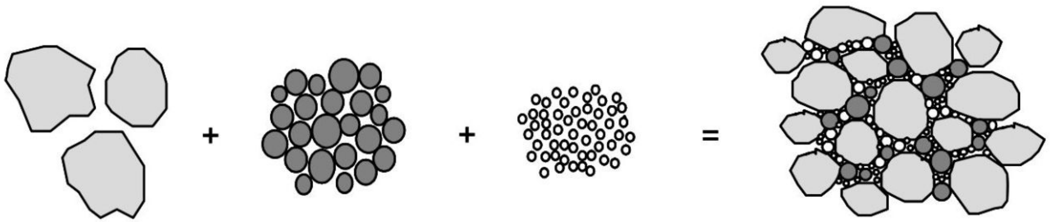
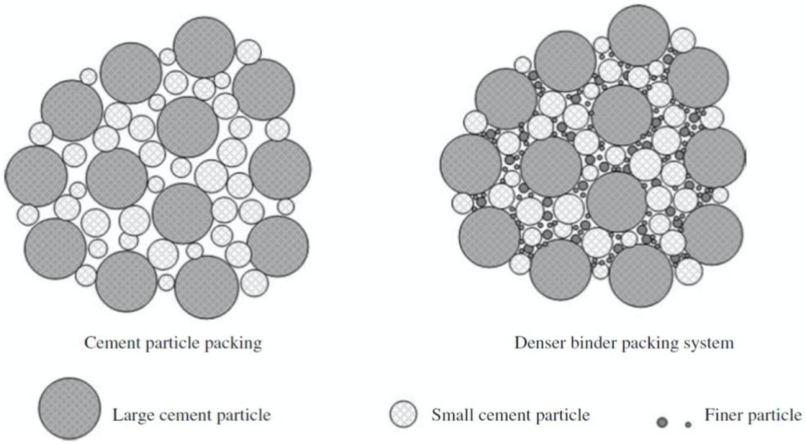
Four interesting emerging innovations



Binder efficiency / particle size optimized fillers





Source: [image source]

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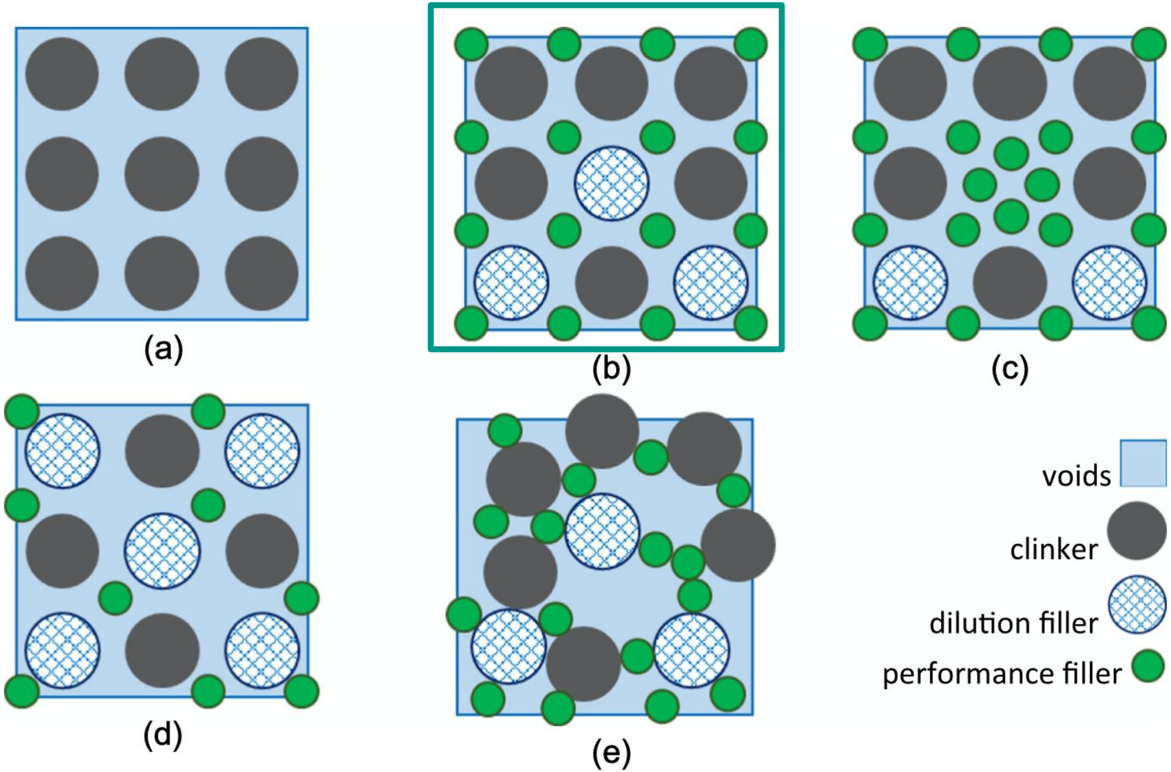
Challenges - Gradation, Dispersion, Workability



“Eco-efficient cements: Potential economically viable solutions for a low-CO cement-based materials industry”; UN Environment, Karen L. Scrivener, Vanderley M. John, Ellis M. Gartner.

Some common Supplementary Cementitious Materials (SCMs)

From course “Cement Chemistry and Sustainable Cementitious Materials”, Ecole Polytechnique Fédérale de Lausanne, https://courses.edx.org/courses/course-v1:EPFLx+cementX+3T2018/course/

New generation of SCMs

- Material sources
  - Mining tailings
  - Low value fly ash
  - Incinerator ash
  - Natural pozzolanic materials
  - Steel slags (vs. blast furnace slag)
  - Waste glass
- Beneficiation techniques
  - Physical - Surface & size modification
  - Thermal - calcination
  - Chemical - activation

Key components:

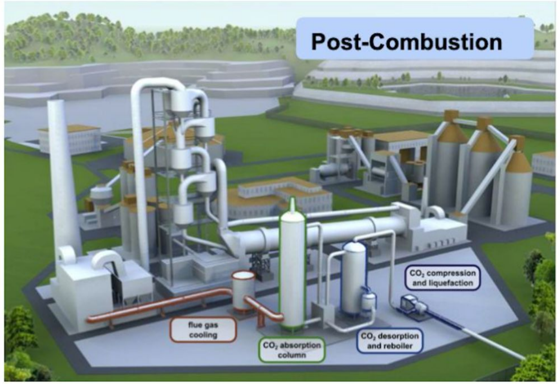
Calcium (or metal) oxides

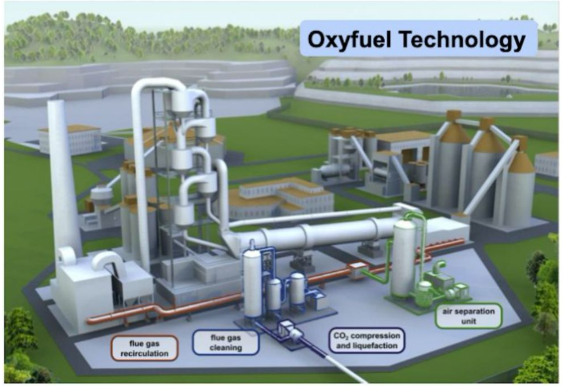
Amorphous silica

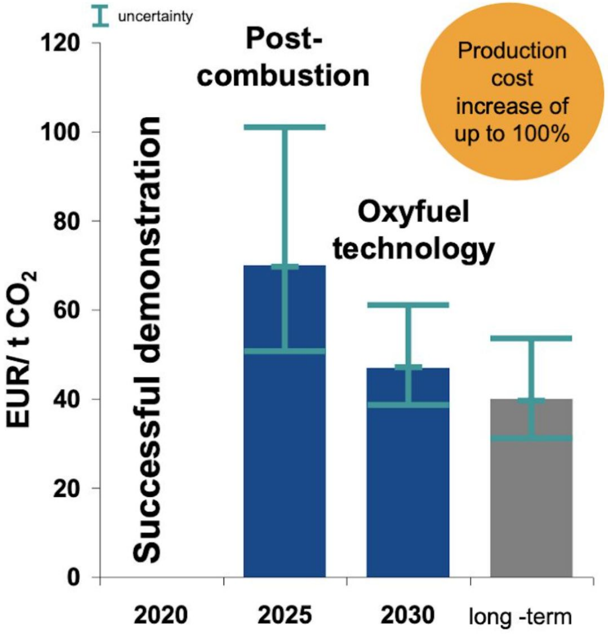
Large scale availability

Consistency of content

Issue with Carbon Capture is cost



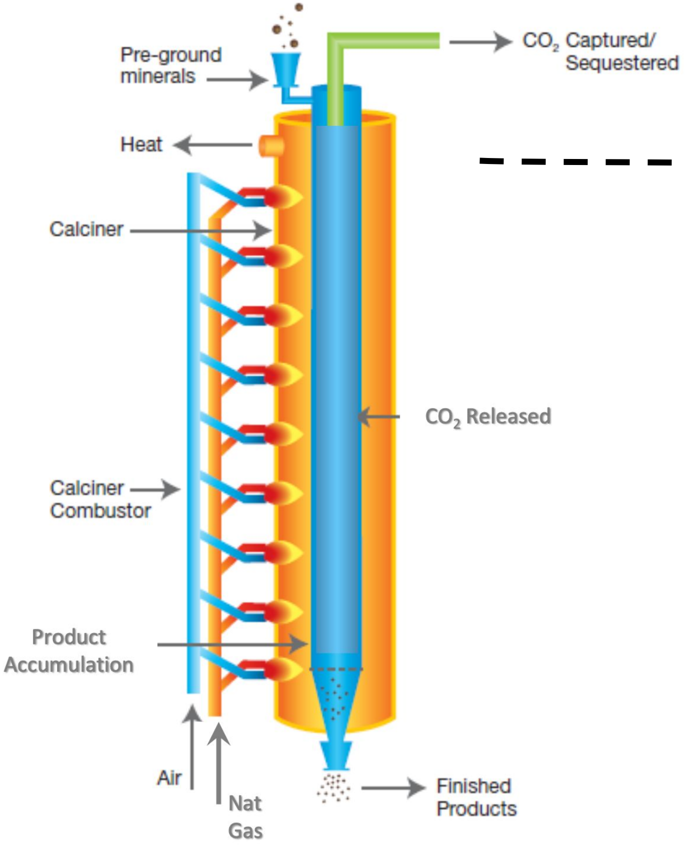




Estimated costs for carbon capture and its corresponding implementation horizon.

Source: ECRA CCS Project: Report on Phase III, 2012

Process capture lowers parasitic load & OPEX



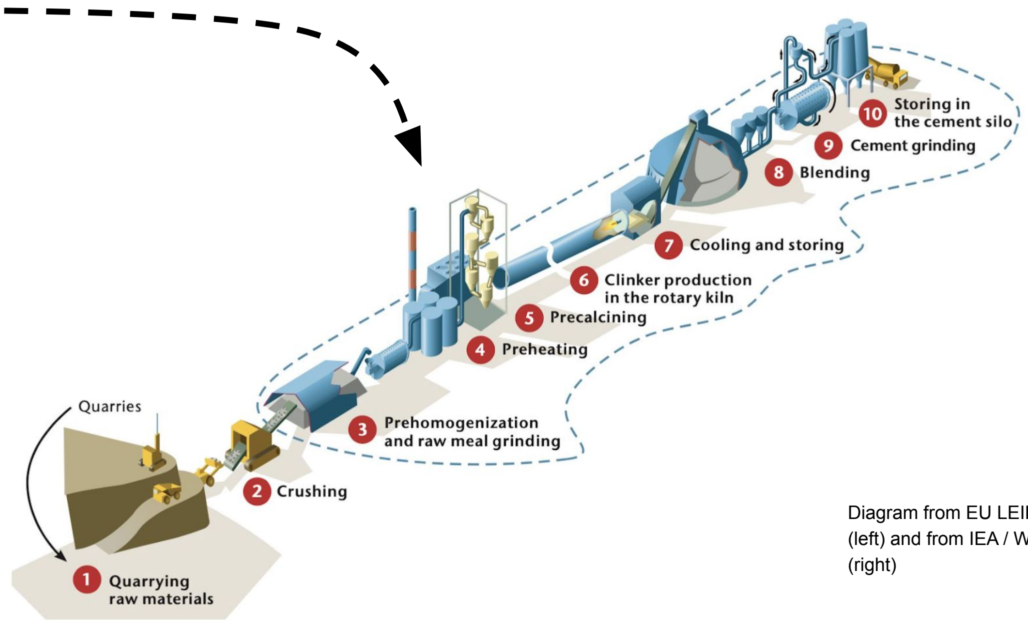
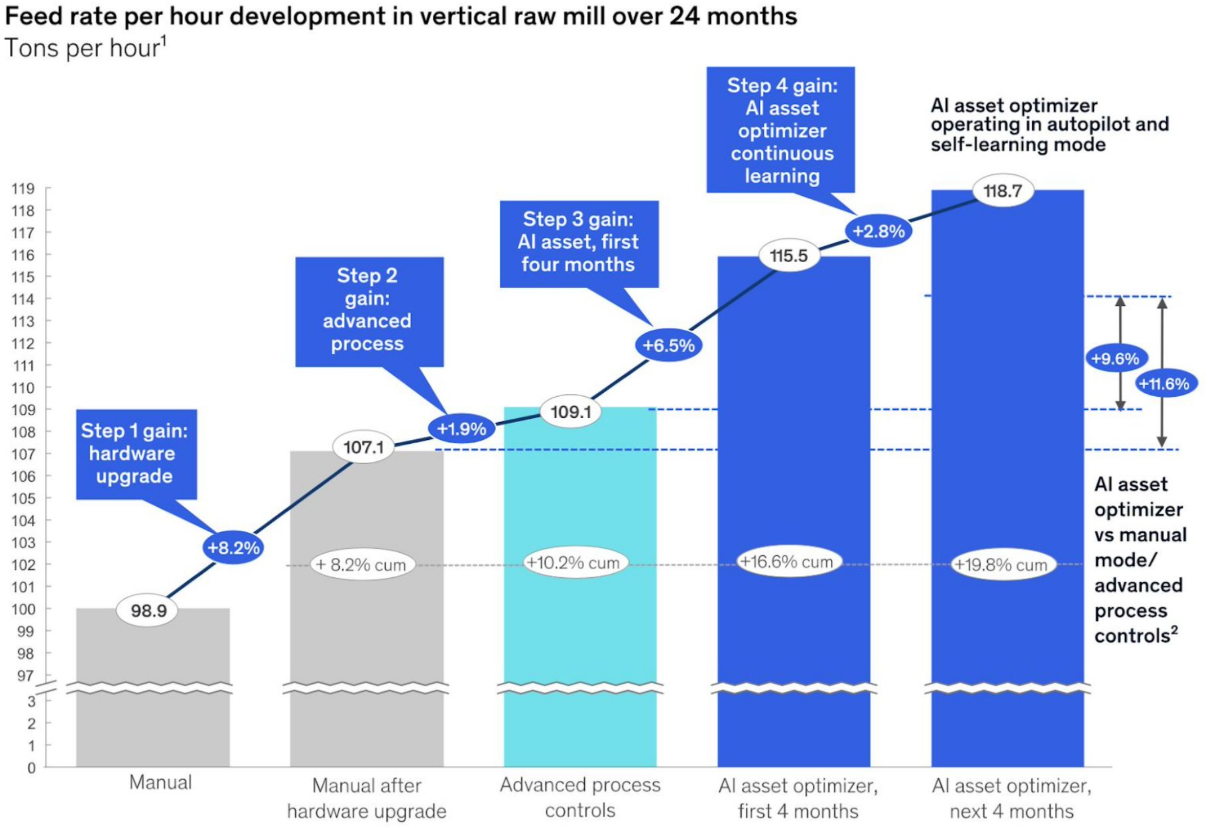


Diagram from EU LEILAC project (left) and from IEA / WBCSD (right)

New process controls = 10-20% increased efficiency



McKinsey study on AI implementation in cement:

https://www.mckinsey.com/business-functions/mckinsey-analytics/our-insights/ai-in-production-a-game-changer-for-manufacturers-with-heavy-assets

Example - Kiln optimization model

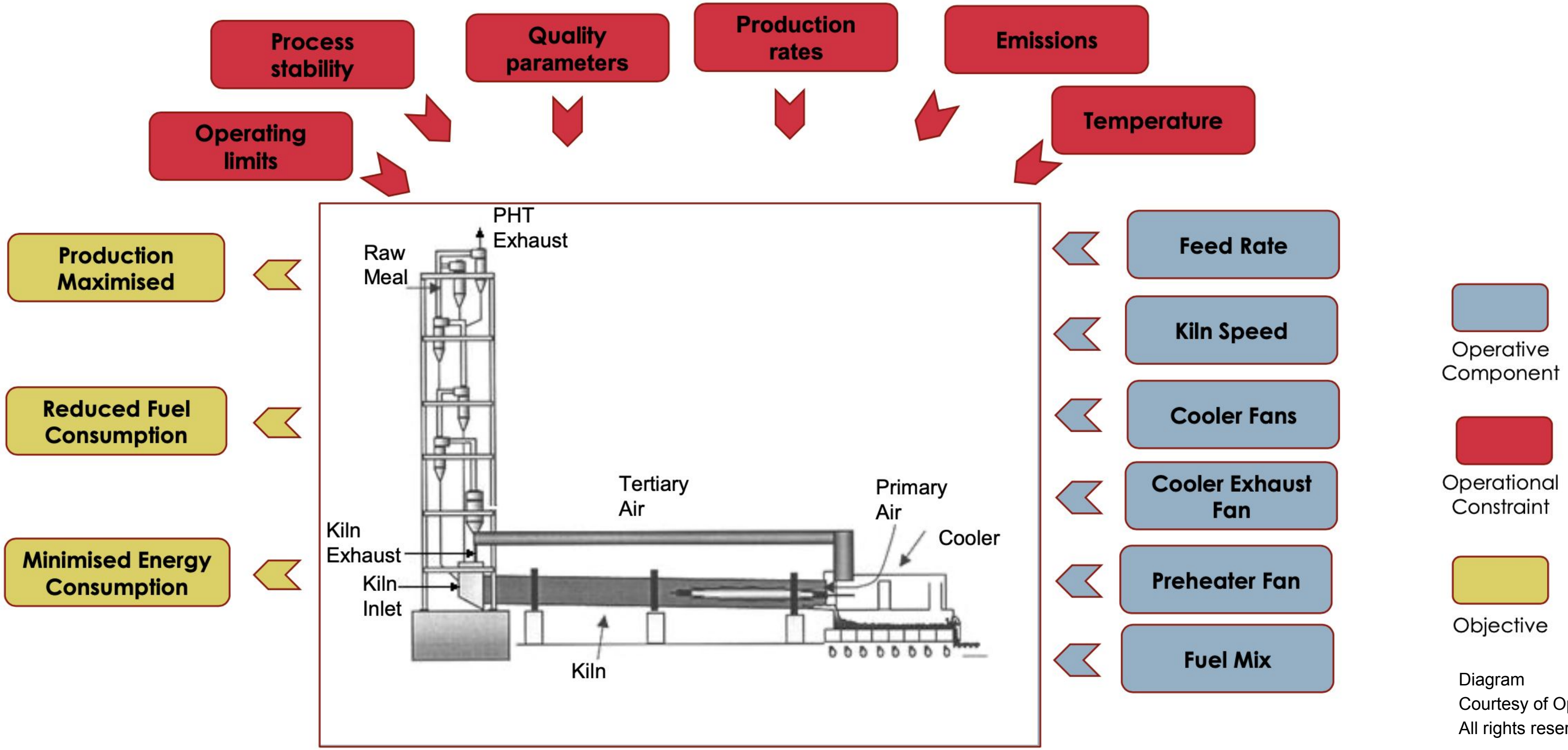
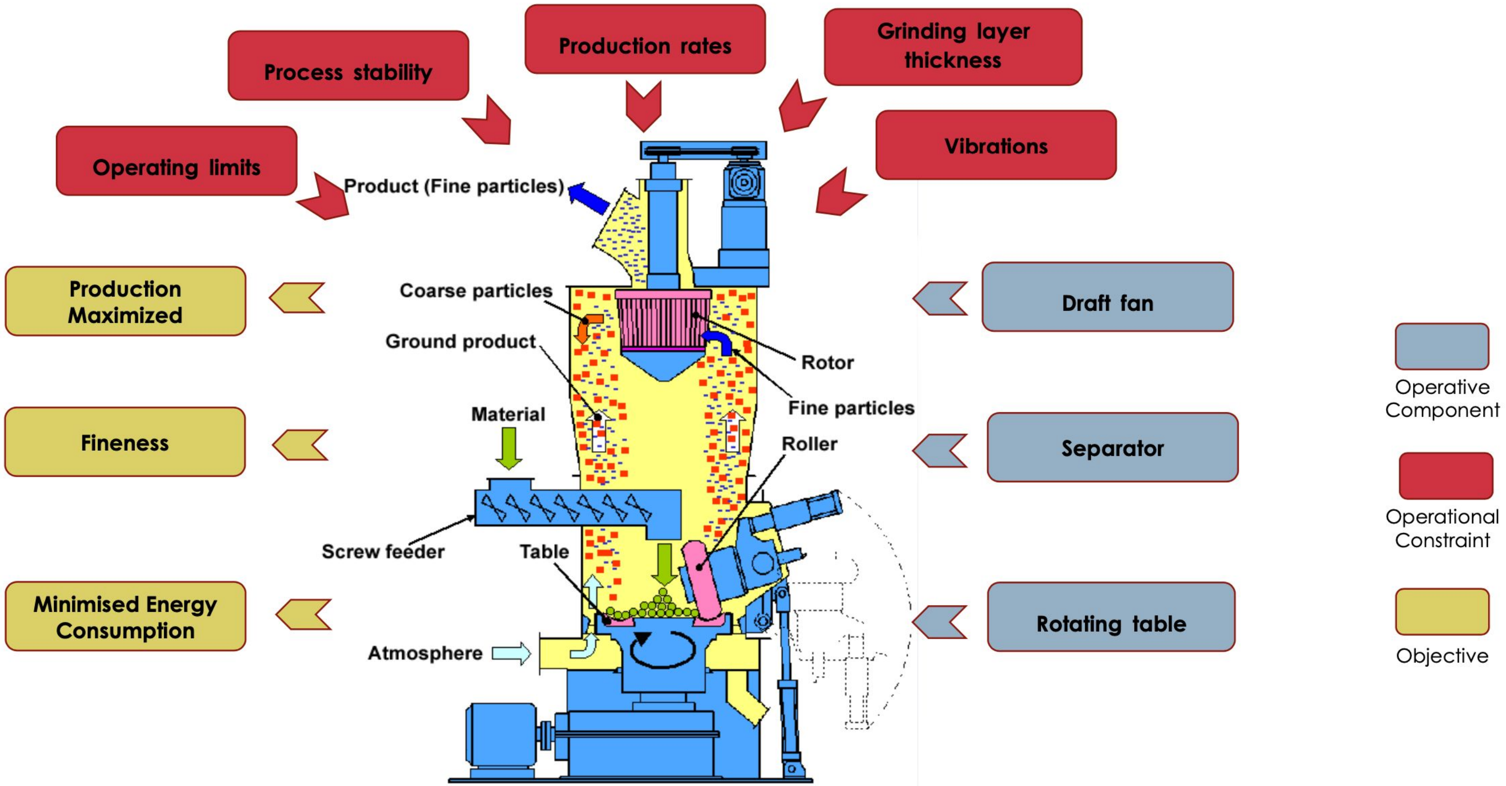


Diagram
Courtesy of Optimitive SL (Spain)

Example - Mill optimization model



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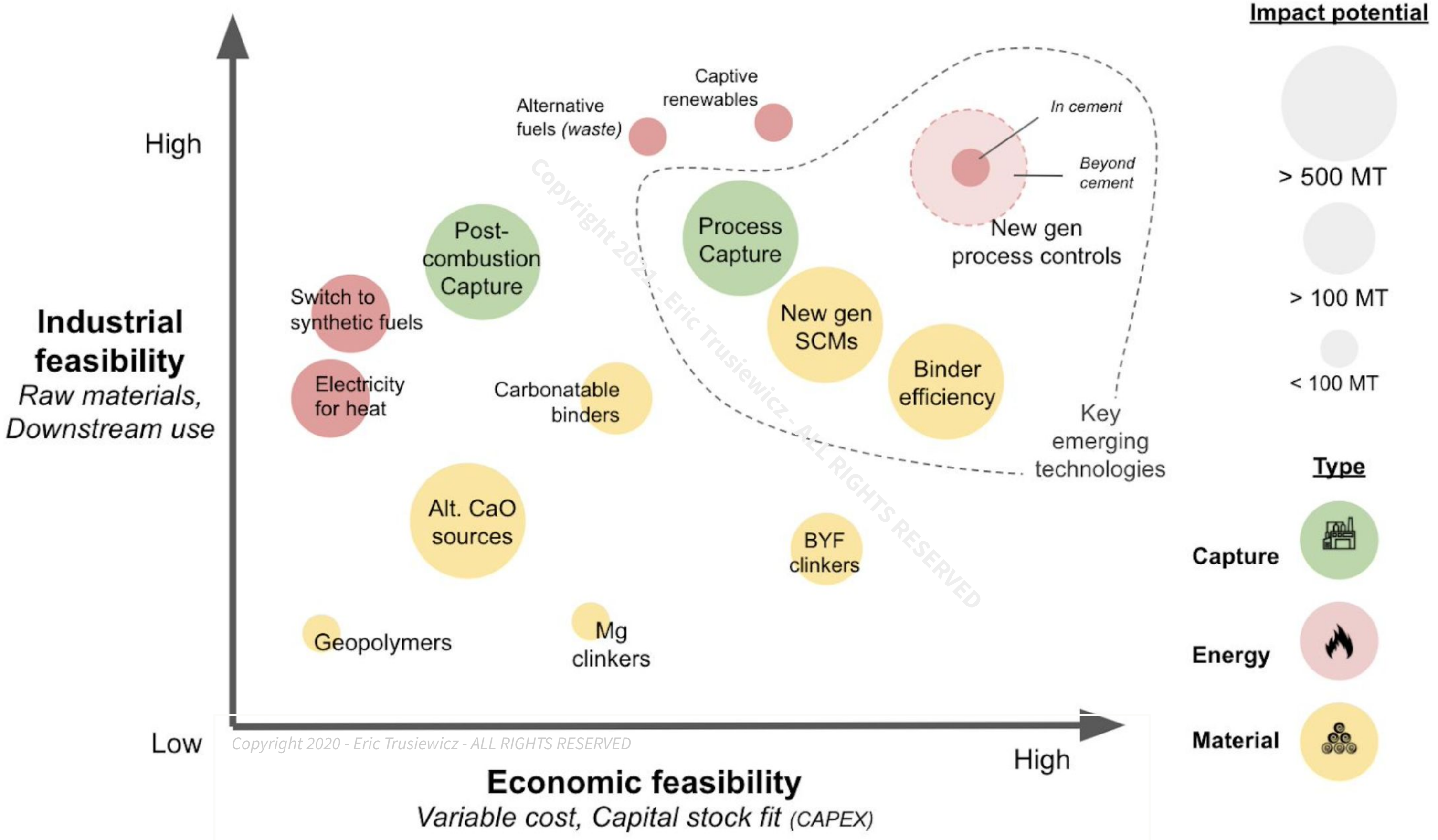
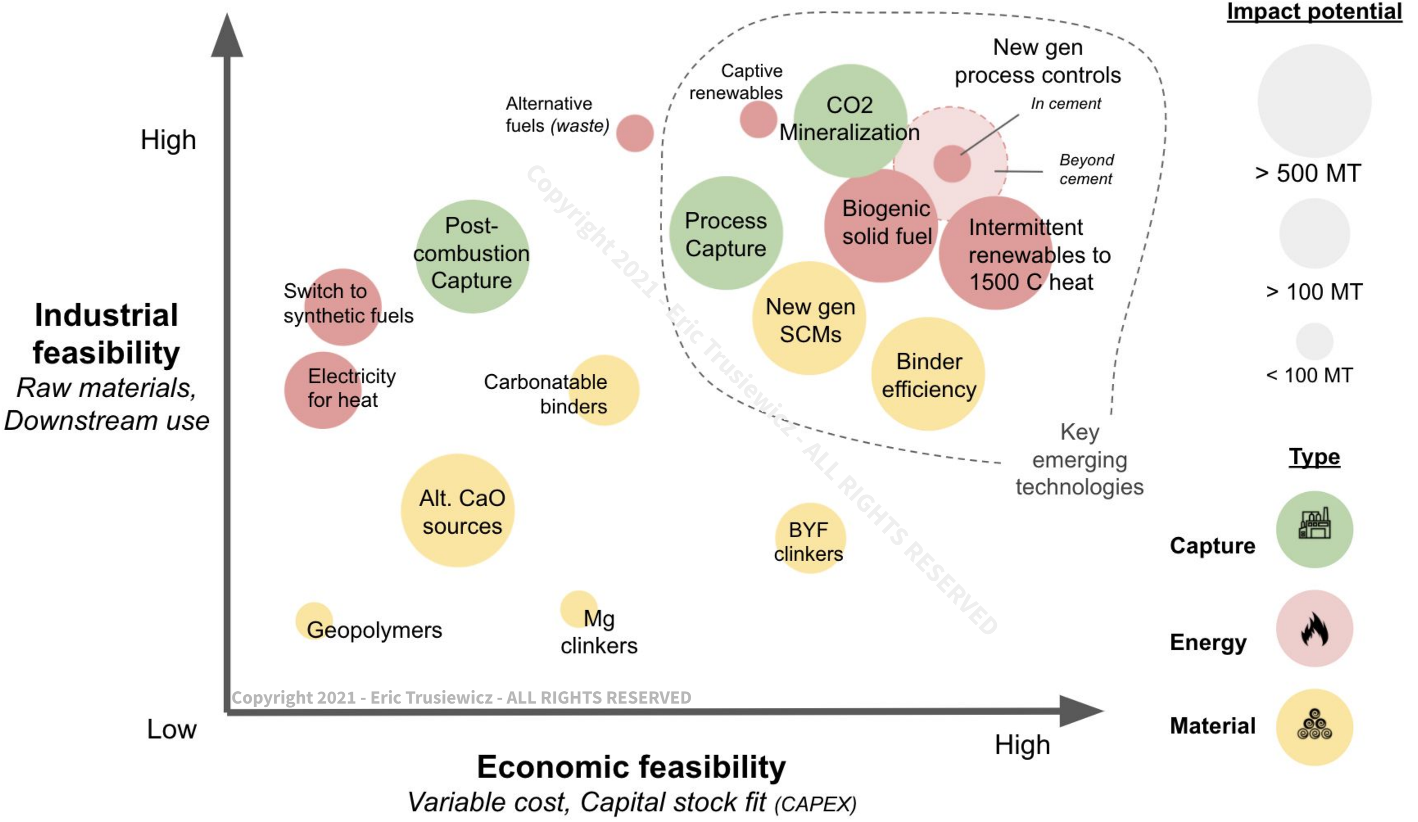


Some new high-potential additions



Cement electrification - projects & barriers

- Calciner electrification is less difficult than kiln (900-1000 C vs. 1450-1500C)
    - Calciner is 50%+ of energy + electrification yields additional benefits (CO2 concentration)

- Projects to electrify various parts of cement production already exist
    - Calciner direct electrification already exists (Calix / LEILAC project)
    - Other types of electrified calciners also under development
    - Plasma fired full cement plant with kiln project in Scandinavia undertaken several years ago

- Electrification is hindered more by cost of electricity than technical hurdles
    - Using direct electrification vs. load shifting to achieve baseload industrial heat
    - Cost of energy from fossil (or waste) combustion is (generally) a fraction of base load electricity cost
    - Harnessing intermittent renewables in thermal storage can yield a much lower cost of baseload heat

Thank you!

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