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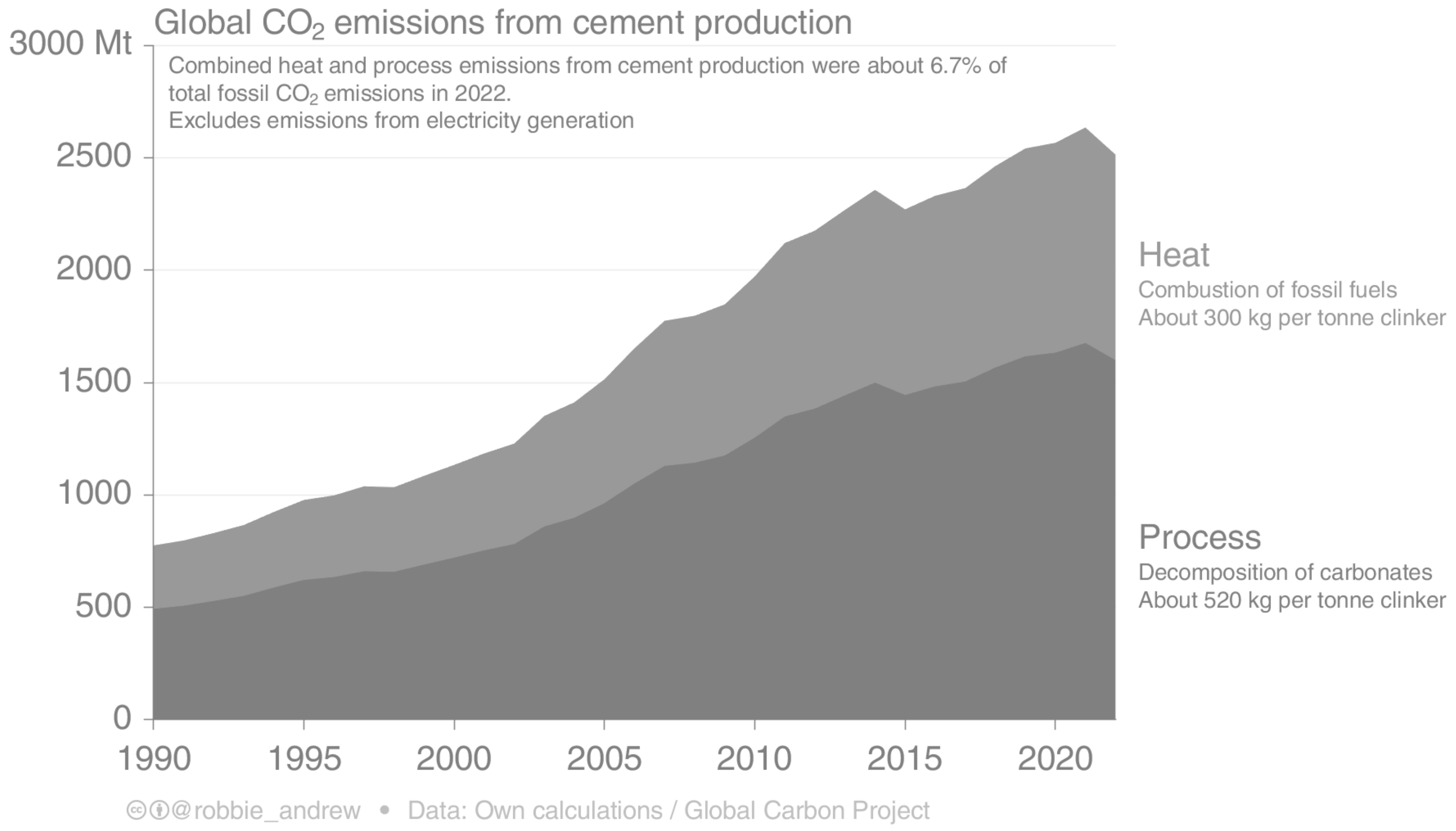
CO_2 emissions from cement production

Robbie Andrew, CICERO

CO_2 emissions from cement production

- Cement production is an energy-intensive process, requiring high-temperature heat, which is normally generated using fossil fuels
- But it also releases CO_2 through a process called calcination, where limestone is decomposed by heat
- Combined, these two sources of CO_2 in the industry contribute about 7% of global fossil CO_2 emissions
- There are also indirect emissions from electricity used by the industry



Cement is an important construction material

- 4.1 billion tonnes produced in 2022
- Said to be the most-consumed substance in the world after water
- Raw ingredients are plentiful
- Cement is mixed with sand, water, and a few other things to create concrete
- About half of the world's cement is produced in China

Hoover Dam. Photo: Arjun R

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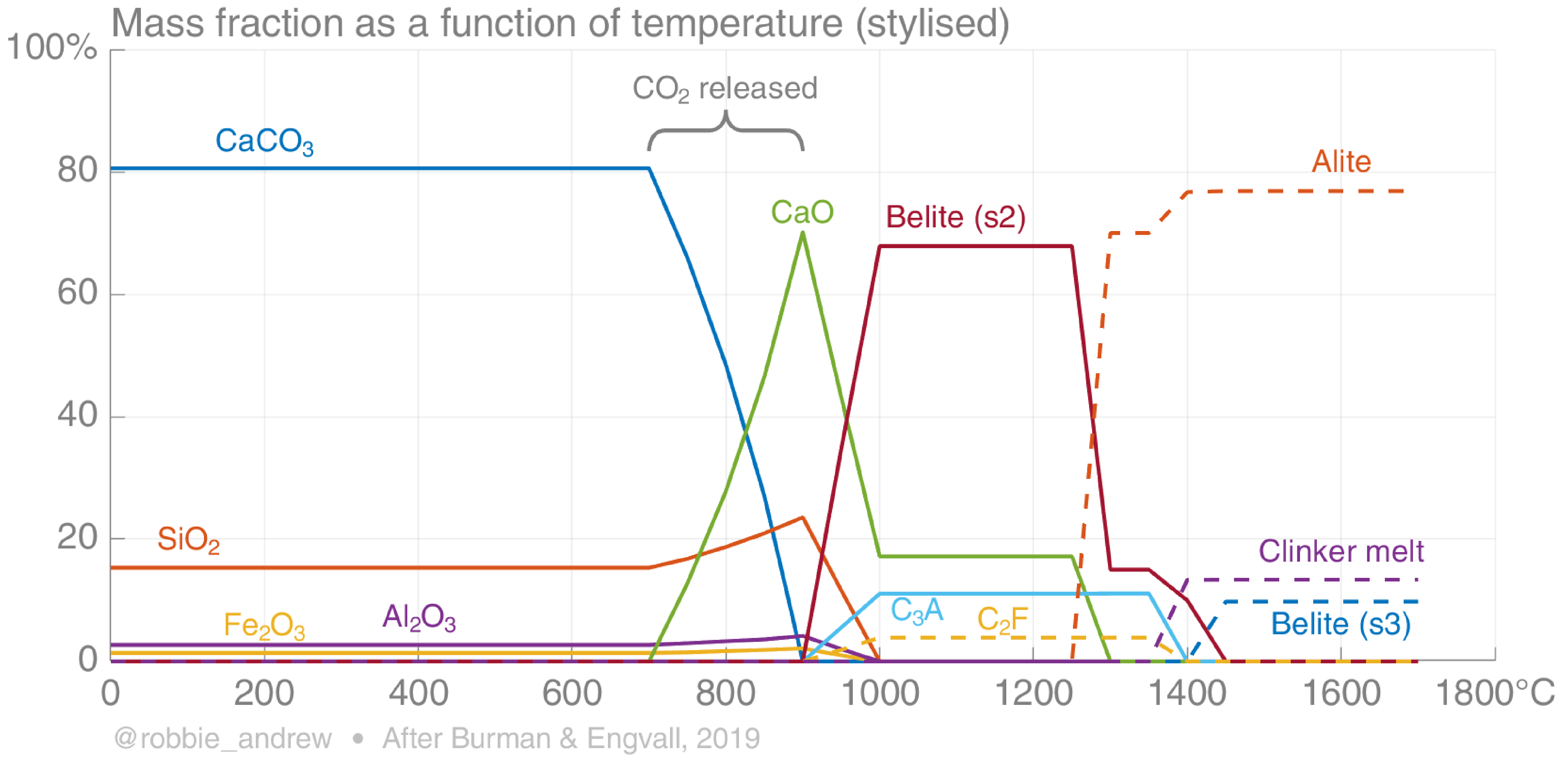
Cement is a “hard-to-abate sector”

- The traditional chemistry of cement production requires high temperatures, which are difficult to achieve without fossil fuels
- It also requires carbonates as inputs, and CO_2 is released when these break down
- There are over 3600 cement plants around the world
- ‘Hard to abate’ means that existing mitigation options are extremely expensive

Cement production: Some chemistry

It's actually a lot more complicated than this

- Limestone and clay (rich in silicates) are baked at 1450°C to produce a concoction that has a lot of calcium silicates, $Ca_xSi_yO_z$
  - $CaCO_3$+heat → CaO+CO_2 "Belite"
  - 2CaO+SiO_2+heat → Ca_2SiO_4 "Alite"
  - CaO+Ca_2SiO_4+heat → $Ca_3O{\cdot}SiO_4$
- CO_2 emissions arise from both:
  - heat generation, where the carbon in fossil fuels combines with oxygen from the air: combustion emissions
  - decomposition of the $CaCO_3$ molecule: process emissions



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Mitigation: options

A non-exhaustive list

- Increase energy efficiency
- Reduce clinker requirement
- Change energy source
- Add CO_2 into the concrete
- Ca from minerals other than limestone
- Recycling
- Change fuel combustion environment
- Use a process that requires less heat
- Capture CO_2 and store it geologically
- Reduce need for cement
- Enhanced carbonation

- Importantly, most mitigation options that are being investigated do not address both sources of emissions
  - But that’s OK: we can mix and match
- Changing technology might require changing the cement kiln ‘fleet’, which could take decades
  - We need a mix of retrofittable options and new-build options
- Changing the chemistry of cement requires gaining trust that physical properties are maintained
  - Structures must stand

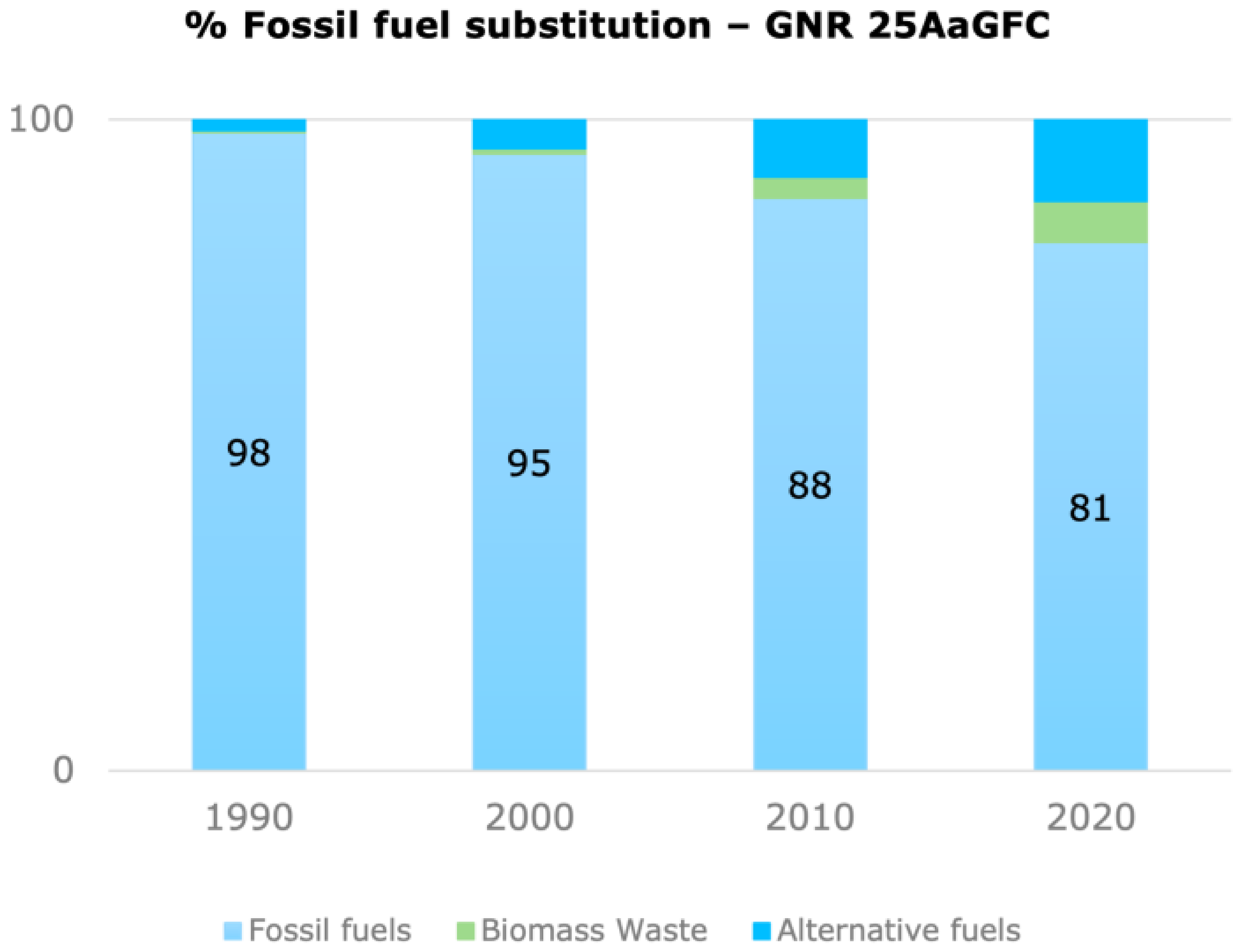
Mitigation: Energy efficiency

- Original cement kilns took a wet slurry as input, which meant that it had to be dried first: lots of energy
- It's not just wet vs dry: there are many variations, and a lot of kilns are not at best-available-tech level
- Preheaters were developed in Germany in the 1930s, while precalciners were developed in Japan in the 1970s
- The highest kiln efficiency is obtained using a dry kiln with both preheater and precalciner

Estonia's only cement kiln was closed in 2020. It was an inefficient wet-process kiln, and the recent increase in the cost of CO_2 in the EU forced it to end operations. Upgrading to a more efficient dry-process kiln was seen as uneconomical. Photo: Kunda.

Mitigation: Biofuels

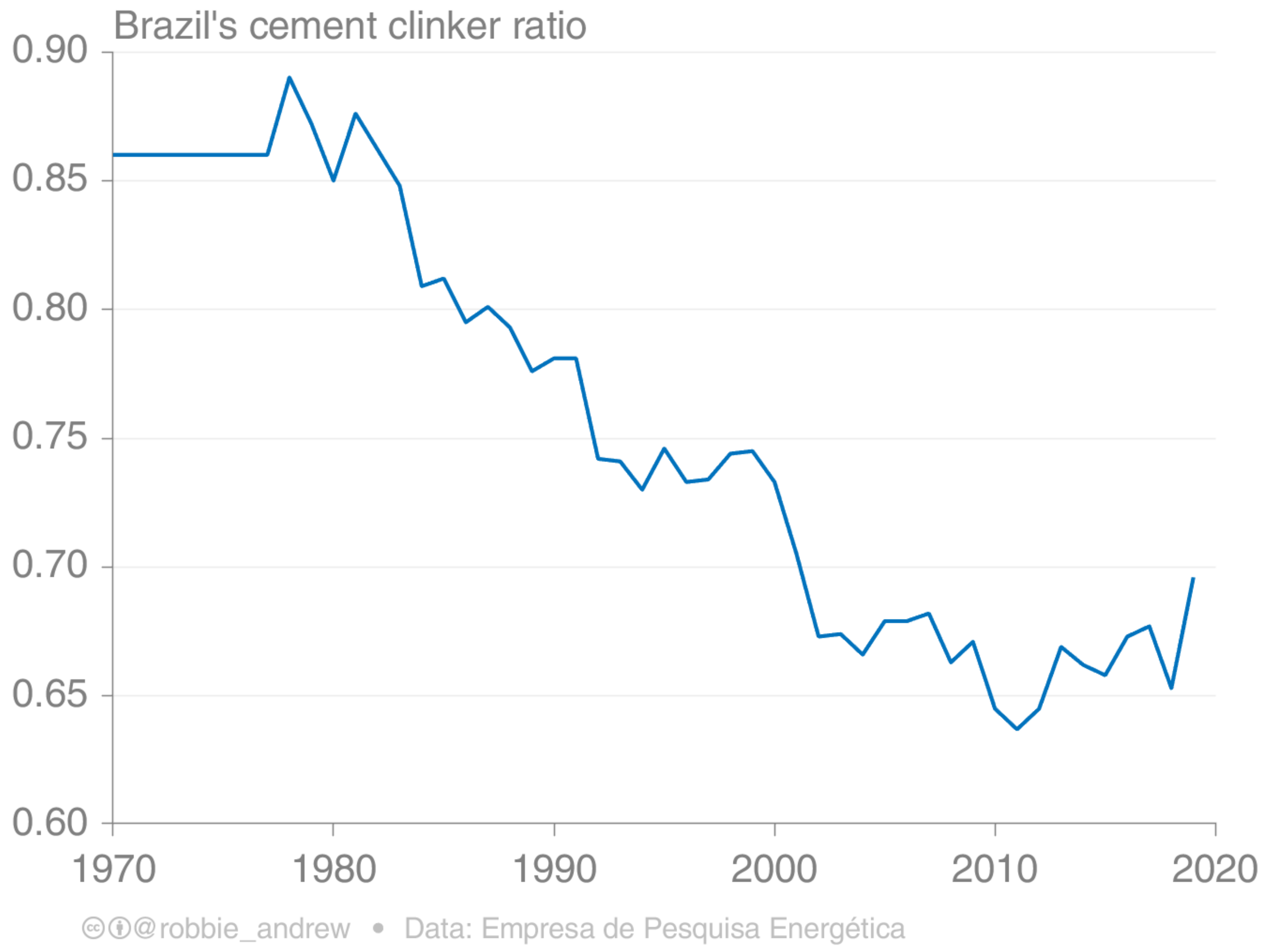
- Replace fossil fuels with biofuels for heating
- Biomass waste + alternative fuels combined had reached 19% of the energy mix by 2020
  - But much of the “alternative” fuel is waste product that was made from fossil fuels, e.g., old car tyres
  - Biomass made up <10% of total fuel mix in 2020
- Sustainable biomass is in limited supply as an energy source
- Generally only supplementary, not a full replacement for fossil fuels



Source: GCCA

Mitigation: Partial clinker substitution

- Been in use for decades
  - Brazil for 50 years
- Use of byproducts of other industries with similar properties to clinker
  - Steel slag, limestone powder, fly ash, silica dust and/or natural pozzolanas
- This is how ‘clinker ratio’ is reduced
- Requires careful control over chemistry to prevent poor-quality cement
- China’s average clinker ratio has recently increased again, a result of cancellation of the standard for a low-quality cement category



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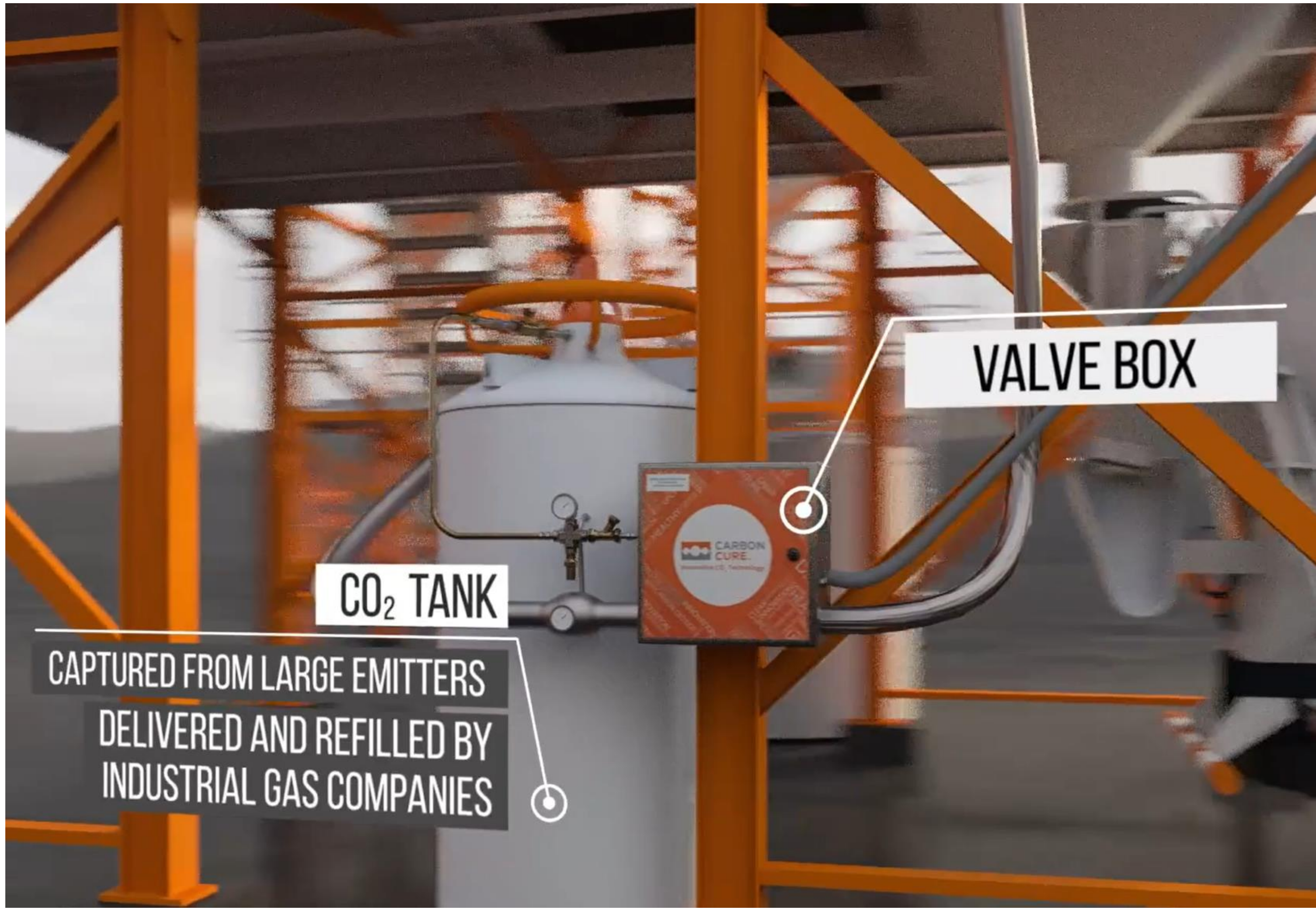
Mitigation: Electricity for heat

- Plasma torches
  - Capable of high temperatures
  - An electric arc is used to phase-change a gas into plasma
  - The most common gases are argon, helium, nitrogen, air and hydrogen
  - Swedish company SaltX has developed what they call an Electric Arc Calciner and demonstrated production of clinker in 2022; construction of a demonstration plant began in March 2023

Photo: SaltX

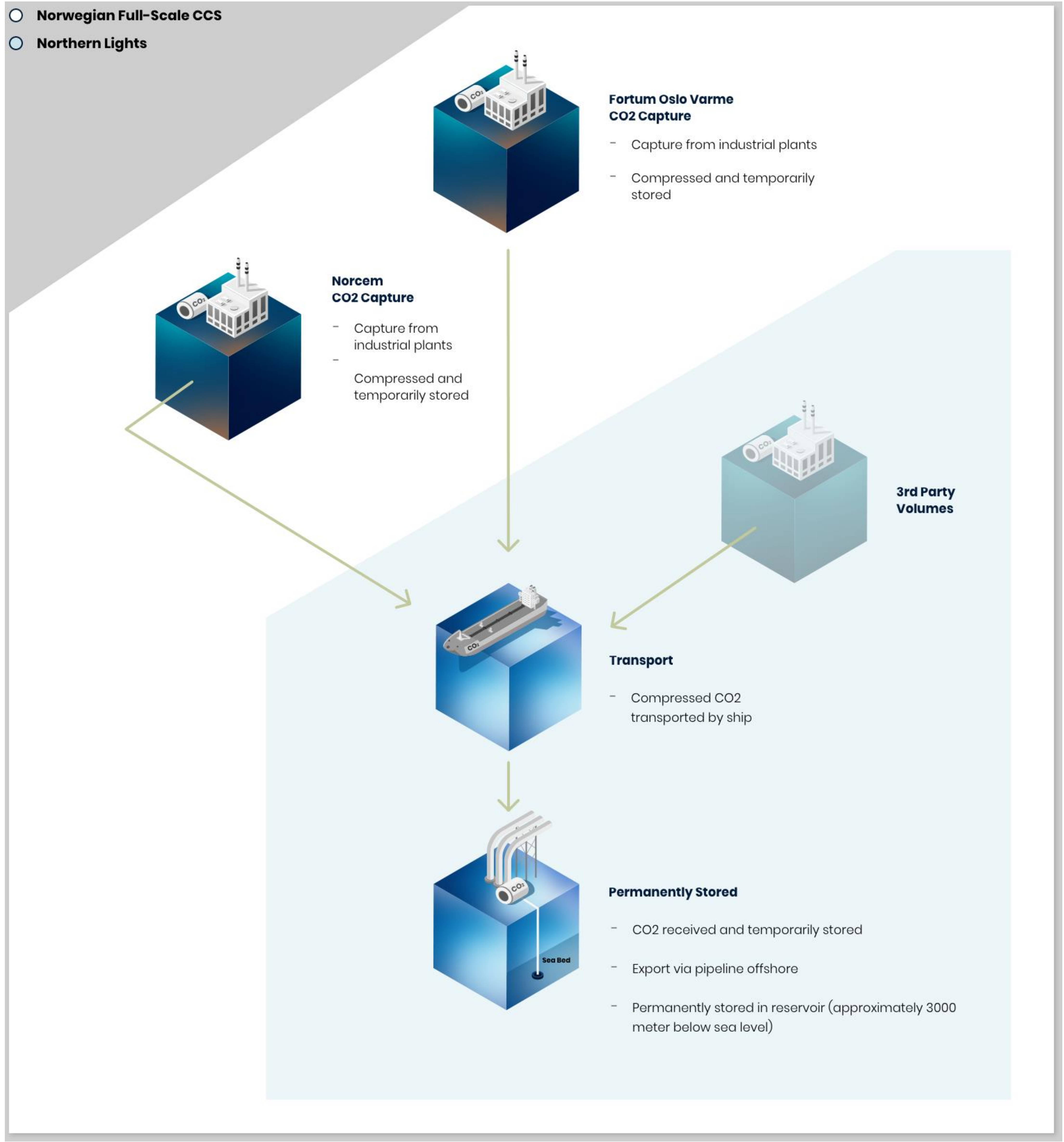
Mitigation: Adding CO_2 to concrete

- Pure CO_2 added to concrete during mixing phase
- E.g., CarbonCure
- Costs more, but increased strength means less is needed: it 'balances out'
- Average 17 kgCO_2 per m^3 concrete
  - Equivalent to about 15%-20% of the CO_2 emitted during clinker production
- Cement/concrete readily absorbs CO_2
  - This process happens anyway over the installed lifetime of concrete, so it's unclear how much is gained here



Mitigation: CCS

- The great promise, to simply capture the CO_2 and bury it in geological storage
- Amine-capture old tech: invented 1930
- Number of cement-CCS projects at the end of 2022: zero
- Capturing CO_2 from exhaust streams is energy-intensive, using amines
  - Use of residual heat
- First complete cement CCS will probably be Norcem plant at Brevik, Norway, as part of Longship project, planned start in mid-2024



Mitigation: Keeping gases separate

- External heating allows exhaust gases from fossil-fuel combustion for heating to be kept separated from the decomposition gas, which is almost pure CO_2
- This means no amines are required. Since re-releasing CO_2 from amines requires a lot of energy, the capture process without them is substantially more efficient
- Replace the pre-calciner, not the whole kiln: retrofitting = low-cost

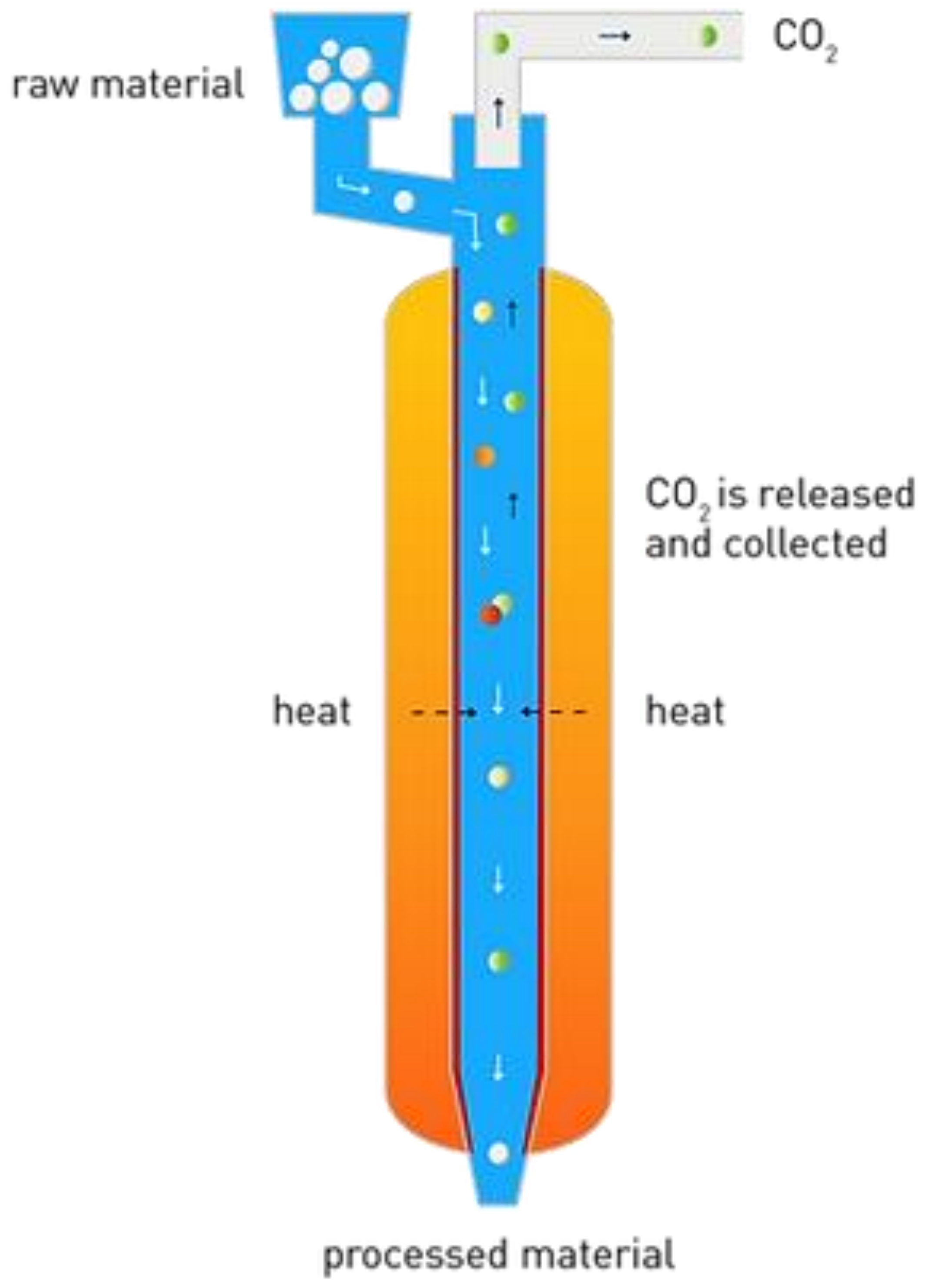
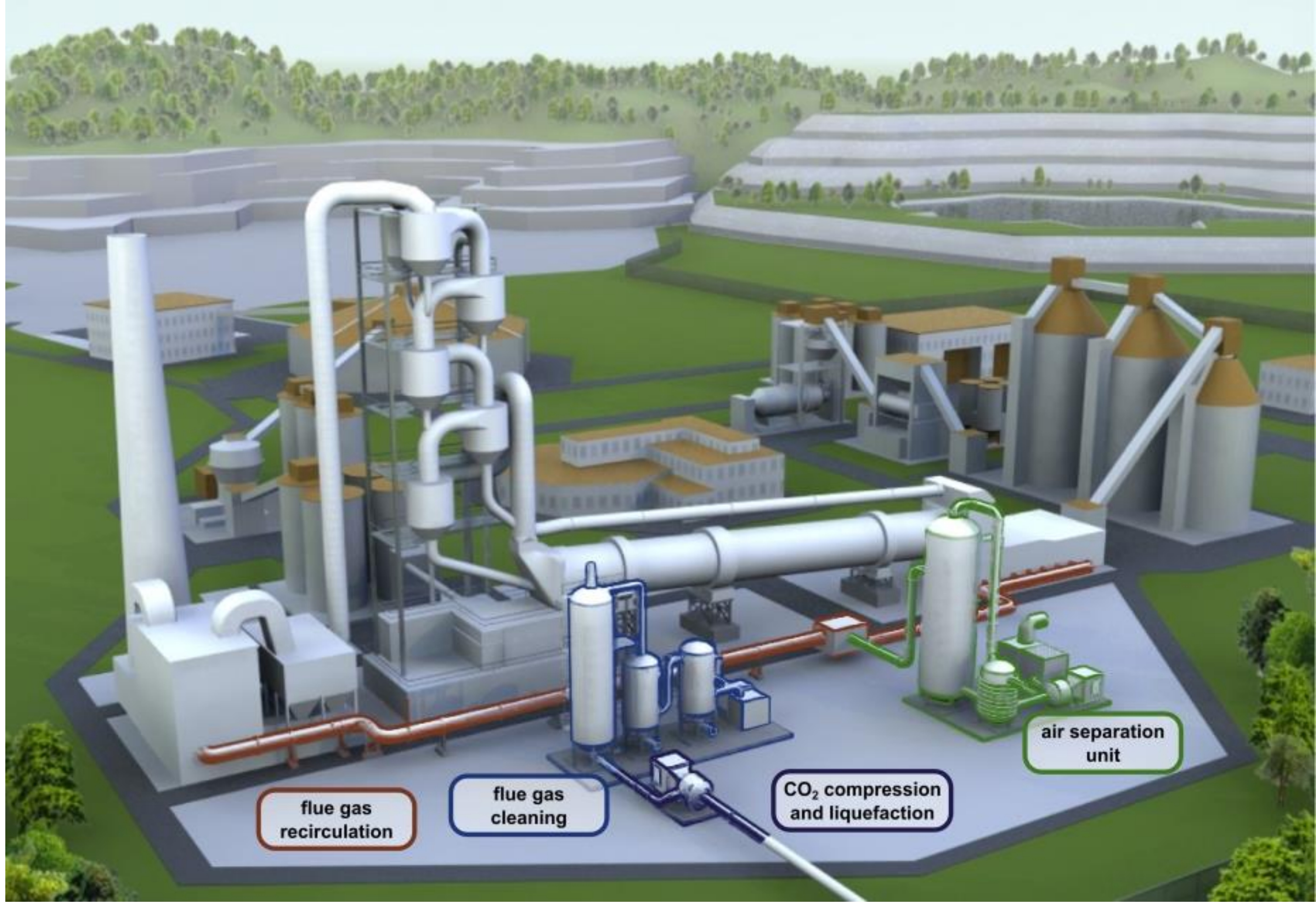


Image: LEILAC

Mitigation: Oxyfuel

- Using oxygen instead of air
- Exhaust gases of combustion in air have a low fraction of CO_2, making capture more difficult
- But in pure oxygen, the exhaust gases are CO_2-rich, so capture is much simpler and therefore less costly
- Also means that NOx-mitigation technology is not required
  - NOx is created when combusting in air because air is 80% nitrogen



“Air separation” = separating out O_2

Mitigation: Hydrogen

- Using ‘green’ hydrogen as an energy source reduces on-site emissions from combustion
- The process of producing hydrogen has several steps, each of which have significant energy losses, which raise costs. It is therefore expected that hydrogen will be used where there are few or no other options.
- If hydrogen is generated via hydrolysis, then oxygen will also be available, allowing oxyfuel with hydrogen

Electrolyser. Photo: HydrogenPro

Mitigation: Concrete recycling

- Decomposition of waste concrete into cement and aggregate
- Use of cement as lime replacement in electric steel recycling
- Slag from steel mill used as clinker replacement
- Dependent on available waste concrete

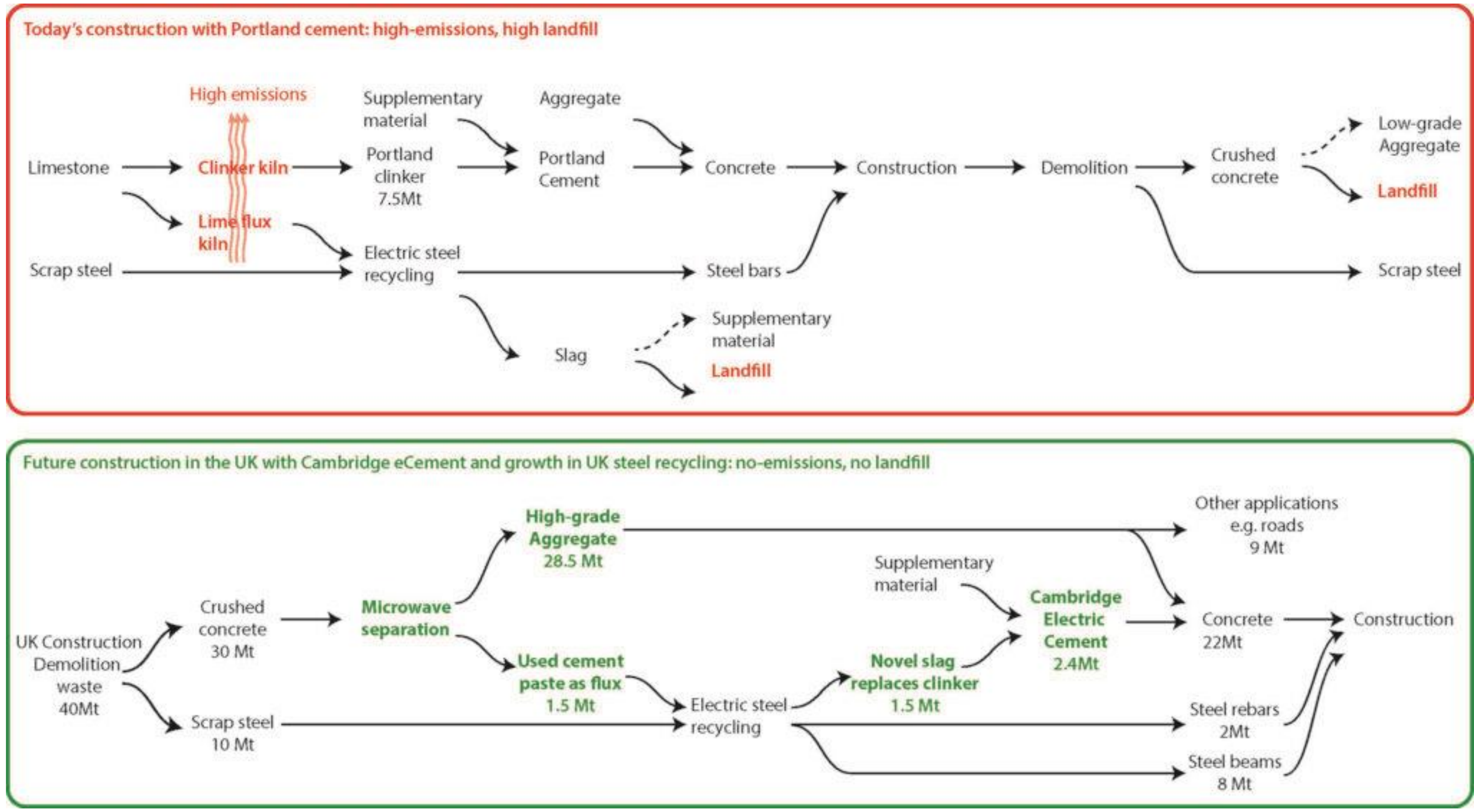
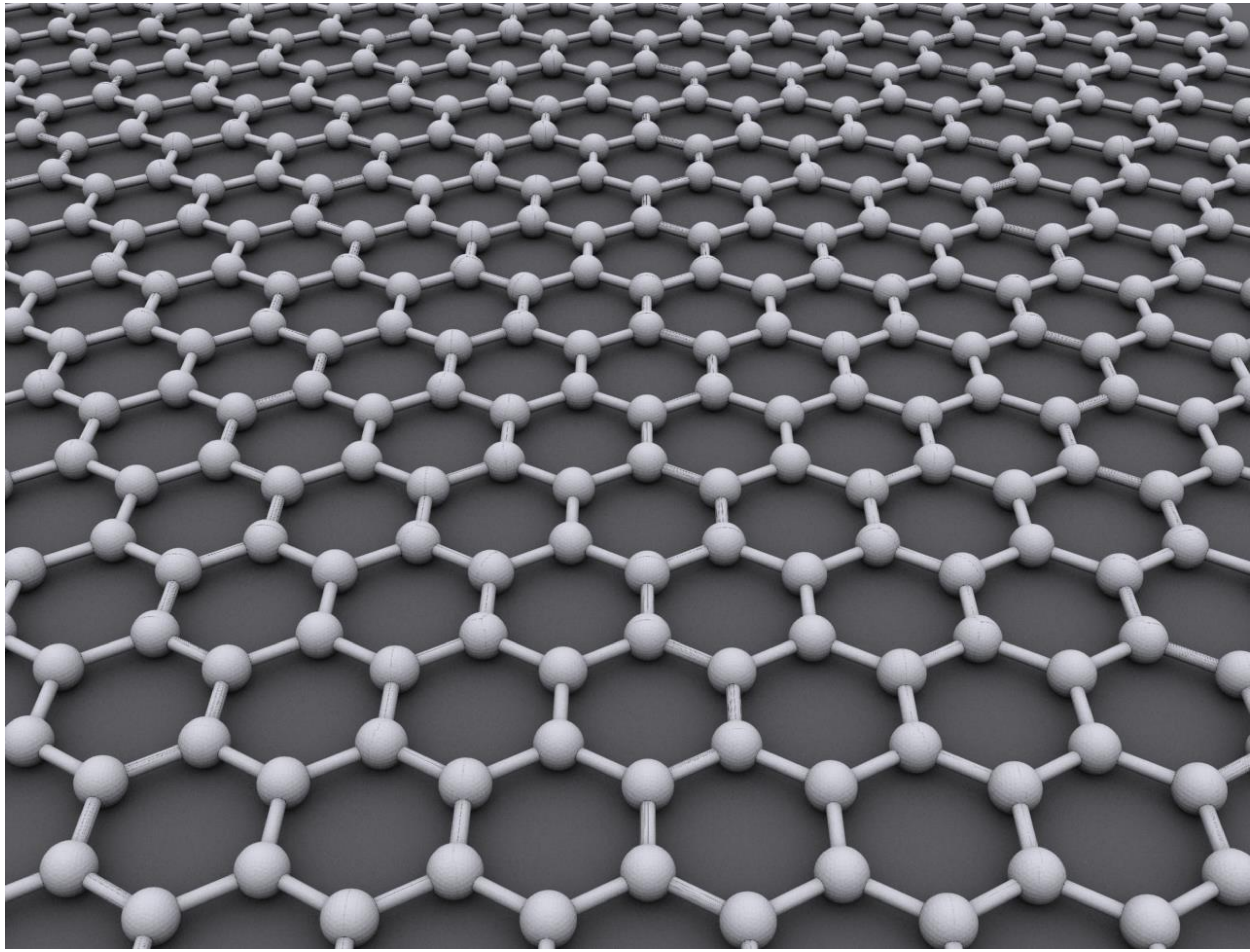


Diagram: Cambridge University

Mitigation: Use of graphene in cement

- Graphene first isolated in 2004
- 200 times as strong as steel
- Addition of very small amounts of graphene (~0.1%) greatly strengthens concrete, reduces brittleness, and prevents water intrusion
- Less concrete and rebar are required for given structural performance



Mitigation: Non-fossil carbonates

- If the carbonate inputs are not from fossil sources, by definition the CO_2 was recently sequestered from the atmosphere
- This means any release of CO_2 in the decomposition of those carbonates in clinker production is net-zero
- Marine microalgae called coccolithophores produce calcium carbonate

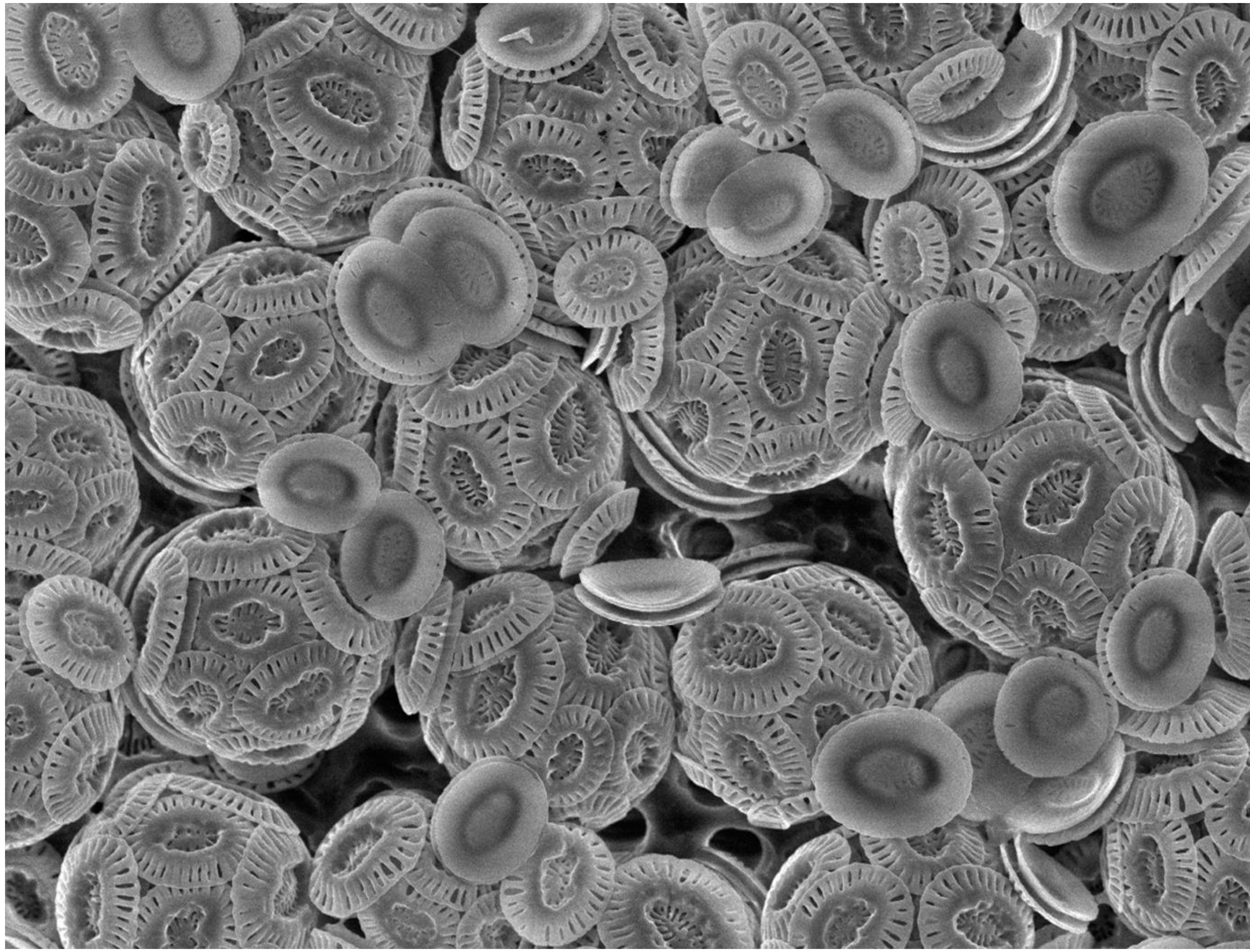


Photo: Alison Taylor

Mitigation: Electrolysis

- Electrolysis of water to produce an acid and a base
- Use the acid to extract calcium from mineral rocks (instead of heat)
  - If limestone is used, then the CO_2 can be captured cheaply since it's pure and low-temperature
  - But other calcium-bearing minerals can be used, with no CO_2 release
- Then react the calcium with the base to produce lime

Photo: Sublime Systems

Mitigation: Calcium silicate instead of limestone

- Brimstone is developing a technology that starts with calcium silicate, which is more abundant than limestone, and contains no carbon
- Their process (still secret) produces both OPC and supplementary cementitious materials (SCM)
- The process also produces magnesium compounds as byproducts, and these absorb CO_2 naturally

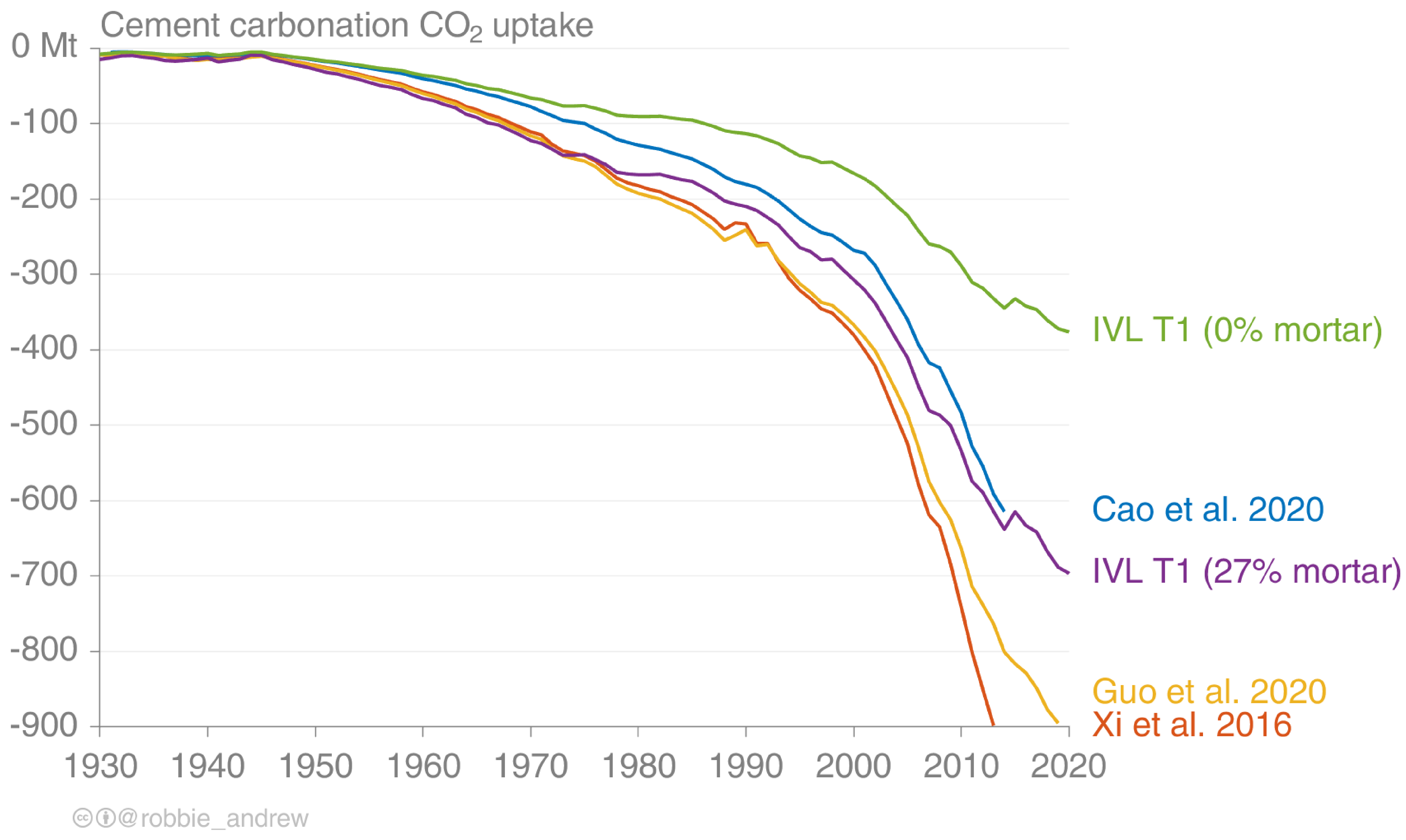
Mitigation: Volcanic ash (natural pozzolans)

- Pozzolans were used by the Romans
- “Energetically modified cement” uses specialised vibratory milling to increase chemical reactivity
- This process permits much higher substitution rates: up to 70% for cement in concrete without loss of performance
- Use of mechanical activation rather than high-temperature chemical reactions: address both sources of CO_2 emissions from traditional cement production

Pozzolana from Mount Vesuvius volcano, Italy

Carbonation: Absorption of CO_2

- A substantial share of the process emissions emitted during production is balanced by re-absorption from the air during installed lifetime
- There is some divergence among estimates
  - But the IVL T1 0% mortar method is a conservative underestimate when mortar share is not known
- Mortar is a very thin application of cement, which means that carbonation is more rapid



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Mitigation: Summary

- There are many promising options being investigated
- In some jurisdictions novel cements face a reluctance to change standards
  - Combination of incumbency effects and distrust of novelty in a sector with criticality of concrete structures standing
- More than 3600 cement kilns around the world, and long lifetimes:
  - Options that don’t require building new infrastructure can lead to faster transition

GCP: Annual cement and clinker datasets

Clinker production dataset

42 Annex 1 countries

"Activity data" from UNFCCC reporting

Eurostat

Data for Bulgaria, Estonia, Greece, Croatia, Poland, and Romania agree well with CRFs

15 Non-Annex 1 countries

Some countries report time-series in their BURs and NIRs

Monthly data

Argentina, Spain, Japan, South Korea, Saudi Arabia, Poland, Turkey, Thailand, Ukraine (through 2021), USA

National annual data

China (through 2020), UK (2021), USA (2022), Norway (2022)

Never produced

Andorra, Sierra Leone, Côte d'Ivoire, Brunei Darussalam, Guinea, Mauritania, Singapore, Papua New Guinea , Tuvalu

Ceased production

Netherlands, Estonia, Fiji

Cement production dataset

USGS

Long time-series of many countries; accuracy varies

Others

Many other smaller datasets

Non-Annex 1 countries

Some countries report time-series in their BURs and NIRs

Monthly data

Argentina, Bolivia, Brazil, China, Colombia, Germany, India, Iran, Japan, Kenya, South Korea, Malaysia, Mexico, Pakistan, Poland, Russia, Saudi Arabia, Spain, Taiwan, Thailand, Turkey, Ukraine

National annual data

China, Norway, Sweden, Iran, Brazil, Kosovo, Egypt, Jamaica

North Korea

South Korean estimates for the North

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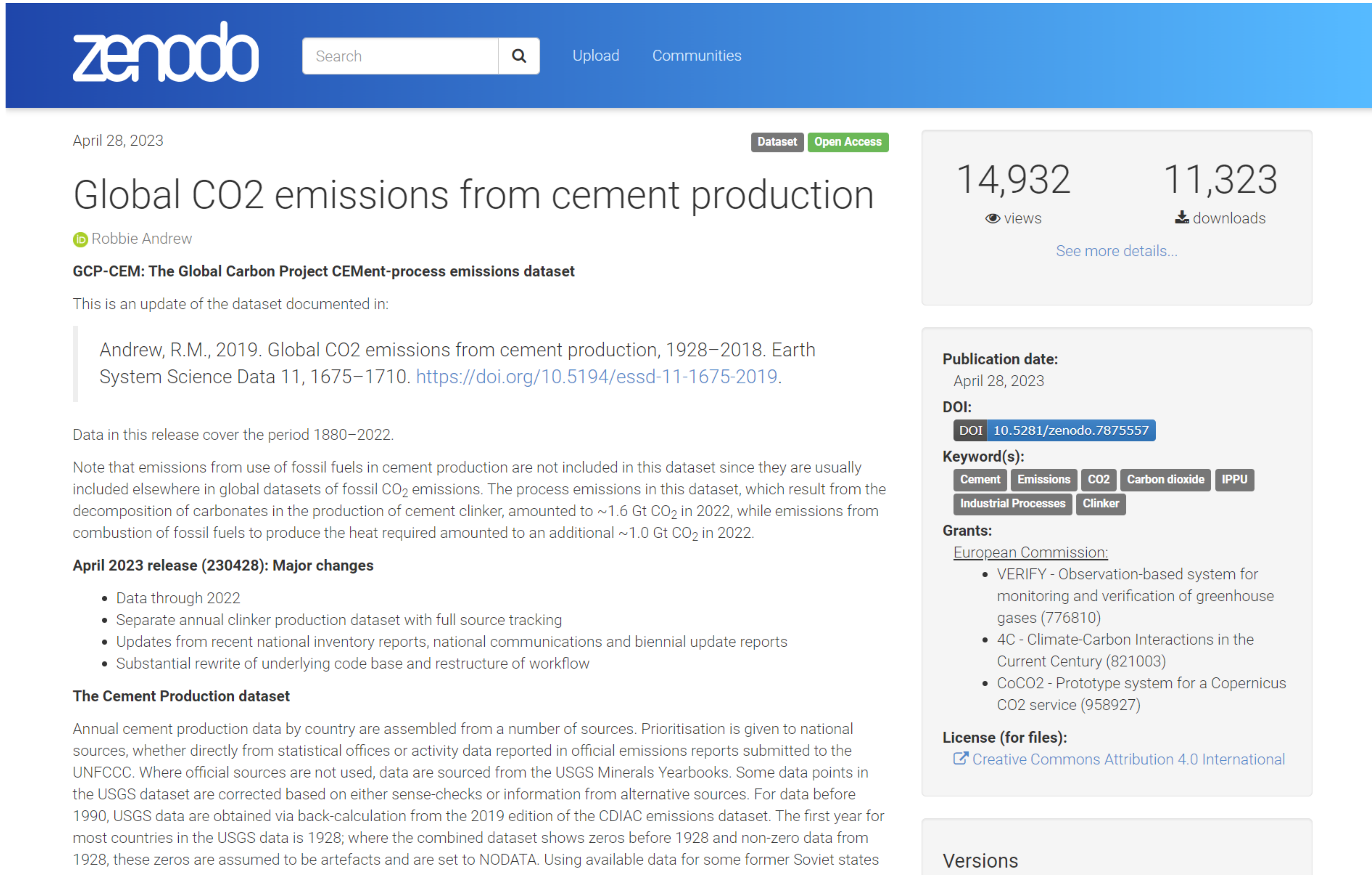
GCP-CEM: Cement-process emissions dataset

- First published in 2017
- Updated once or twice every year
- Used by these global emissions datasets:
  - GCP's Global Carbon Budget
  - CEDS
  - PRIMAP-hist
  - BP
  - WRI's CAIT



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April 28, 2023

Dataset Open Access

Global CO2 emissions from cement production

Robbie Andrew

GCP-CEM: The Global Carbon Project CEMent-process emissions dataset

This is an update of the dataset documented in:

> Andrew, R.M., 2019. Global CO2 emissions from cement production, 1928–2018. Earth System Science Data 11, 1675–1710. https://doi.org/10.5194/essd-11-1675-2019.

Data in this release cover the period 1880–2022.

Note that emissions from use of fossil fuels in cement production are not included in this dataset since they are usually included elsewhere in global datasets of fossil CO_2 emissions. The process emissions in this dataset, which result from the decomposition of carbonates in the production of cement clinker, amounted to ~1.6 Gt CO_2 in 2022, while emissions from combustion of fossil fuels to produce the heat required amounted to an additional ~1.0 Gt CO_2 in 2022.

April 2023 release (230428): Major changes

- Data through 2022
- Separate annual clinker production dataset with full source tracking
- Updates from recent national inventory reports, national communications and biennial update reports
- Substantial rewrite of underlying code base and restructure of workflow

The Cement Production dataset

Annual cement production data by country are assembled from a number of sources. Prioritisation is given to national sources, whether directly from statistical offices or activity data reported in official emissions reports submitted to the UNFCCC. Where official sources are not used, data are sourced from the USGS Minerals Yearbooks. Some data points in the USGS dataset are corrected based on either sense-checks or information from alternative sources. For data before 1990, USGS data are obtained via back-calculation from the 2019 edition of the CDIAC emissions dataset. The first year for most countries in the USGS data is 1928; where the combined dataset shows zeros before 1928 and non-zero data from 1928, these zeros are assumed to be artefacts and are set to NODATA. Using available data for some former Soviet states

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