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Decarbonisation pathways for cement and concrete

Karen Scrivener, FREng

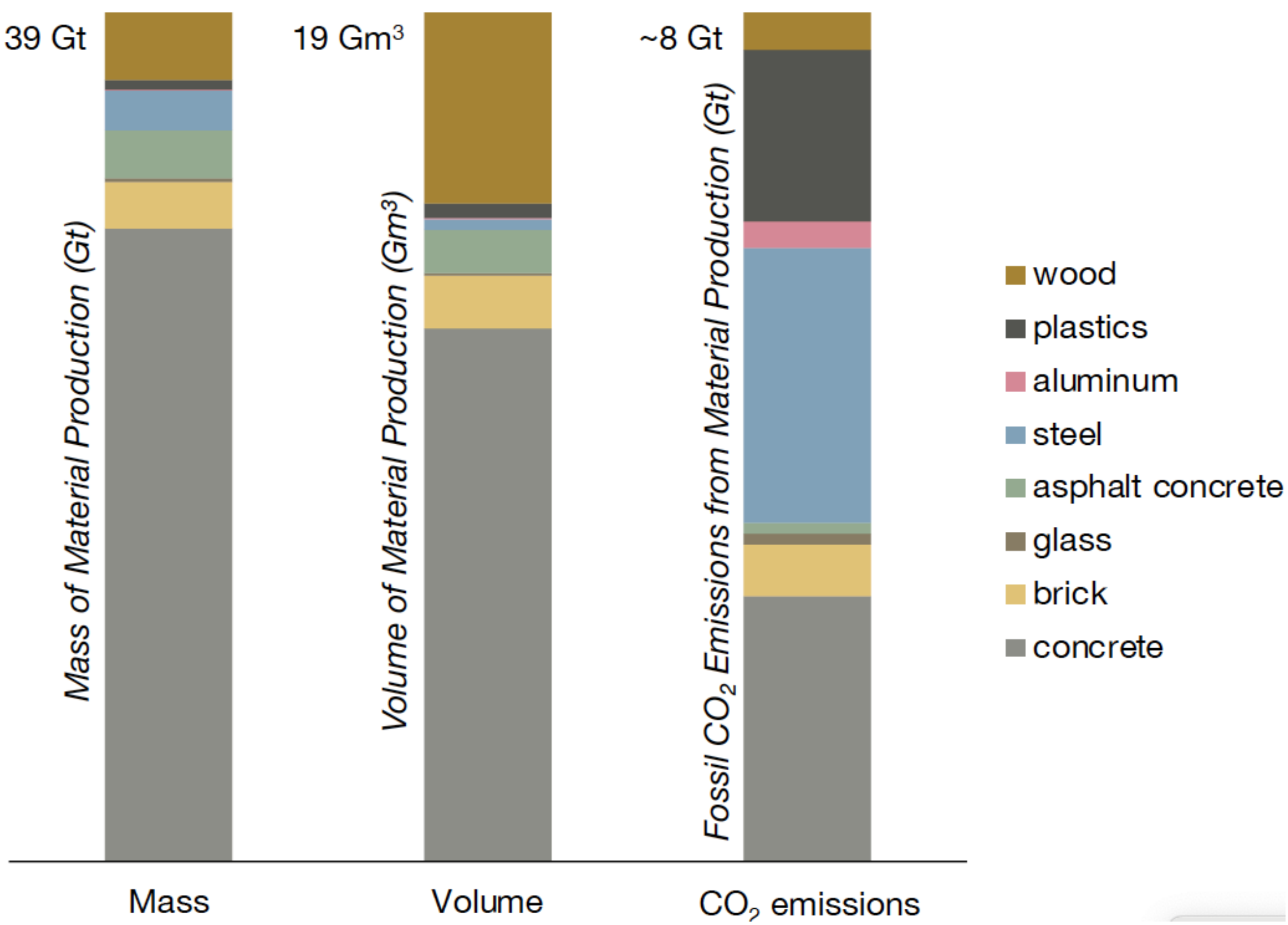
EPFL

Switzerland

École
polytechnique
fédérale
de Lausanne

All the Materials we use

90% construction



Replacing just 25% of concrete with wood sustainably would require new forest 1.5 times the size of India

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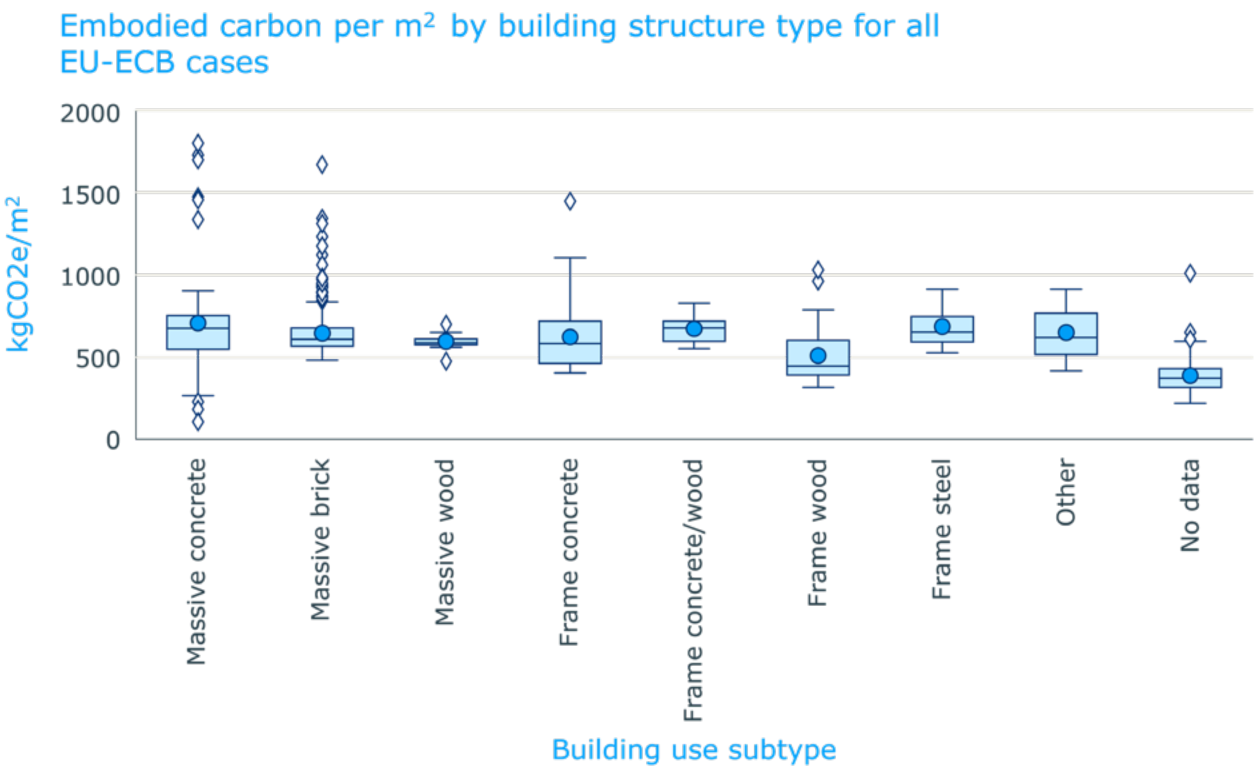
Would it help to replace concrete by other materials?



GLOBE

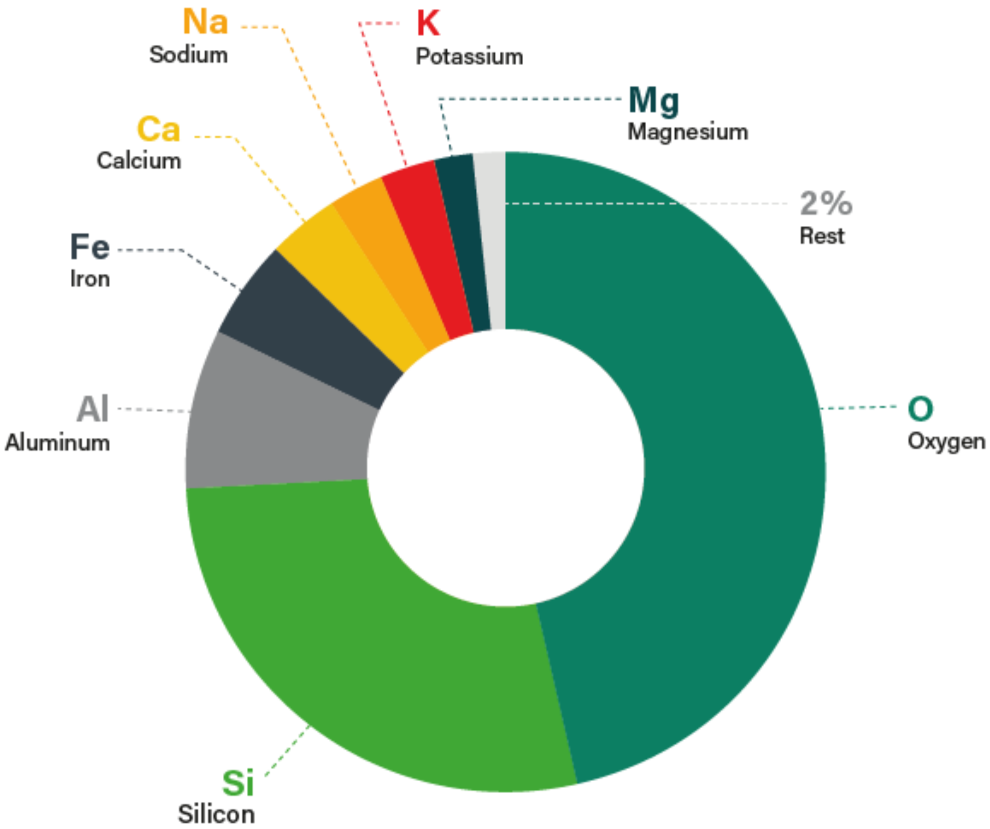
Global Building Data Initiative

- Röck M, Sørensen A, Tozan B, Steinmann J, Le Den X, Horup L H, Birgisdottir H
  Towards EU embodied carbon benchmarks for buildings – Setting the baseline: A bottom-up approach, 2022, https://doi.org/10.5281/zenodo.5895051.

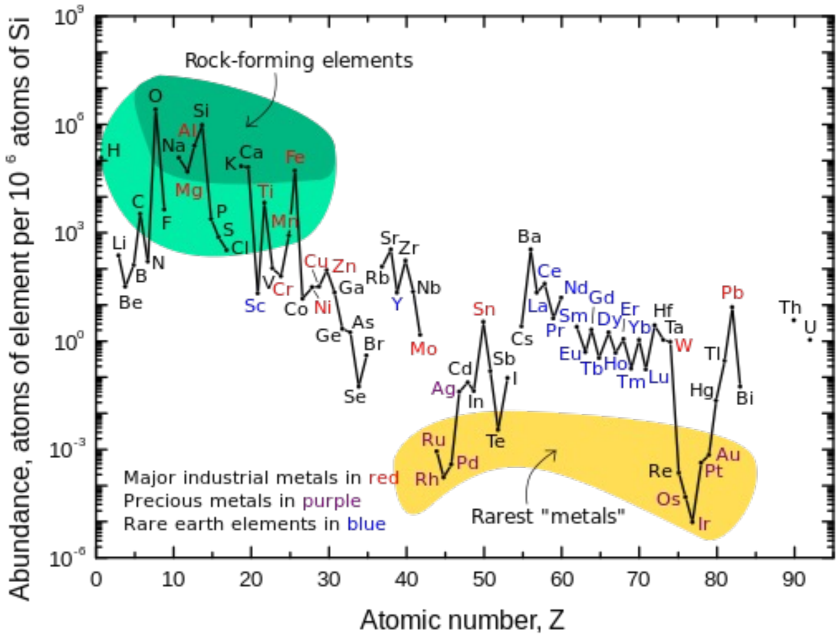
It is not by chance Portland cement is the most used material on earth

It is a direct consequence of chemistry and geology

What is available on earth?



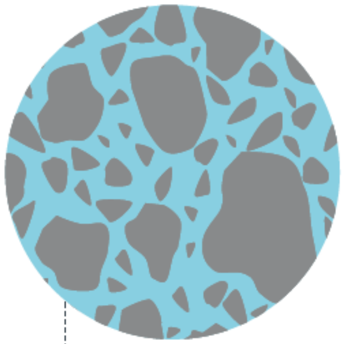
8 elements make up more than **98%** of the earth's crust



Due to the processes of forming elements in stars other rocky planets will be similar

How does cements work?

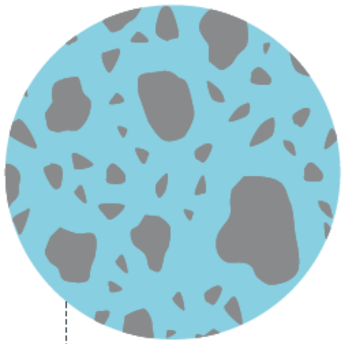
1



We mix the
grey cement powder
with water.

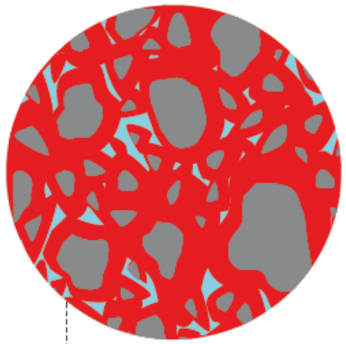
To start with the grains
are just floating about in
the water and we can cast
the concrete into moulds

2



The cement grains
dissolve in the water

3



The cement grains
dissolve in the water

And then precipitate Hydrates –
new solids which have
higher volume and hold
the grains together:
creating a rigid solid

Cement grain

Water

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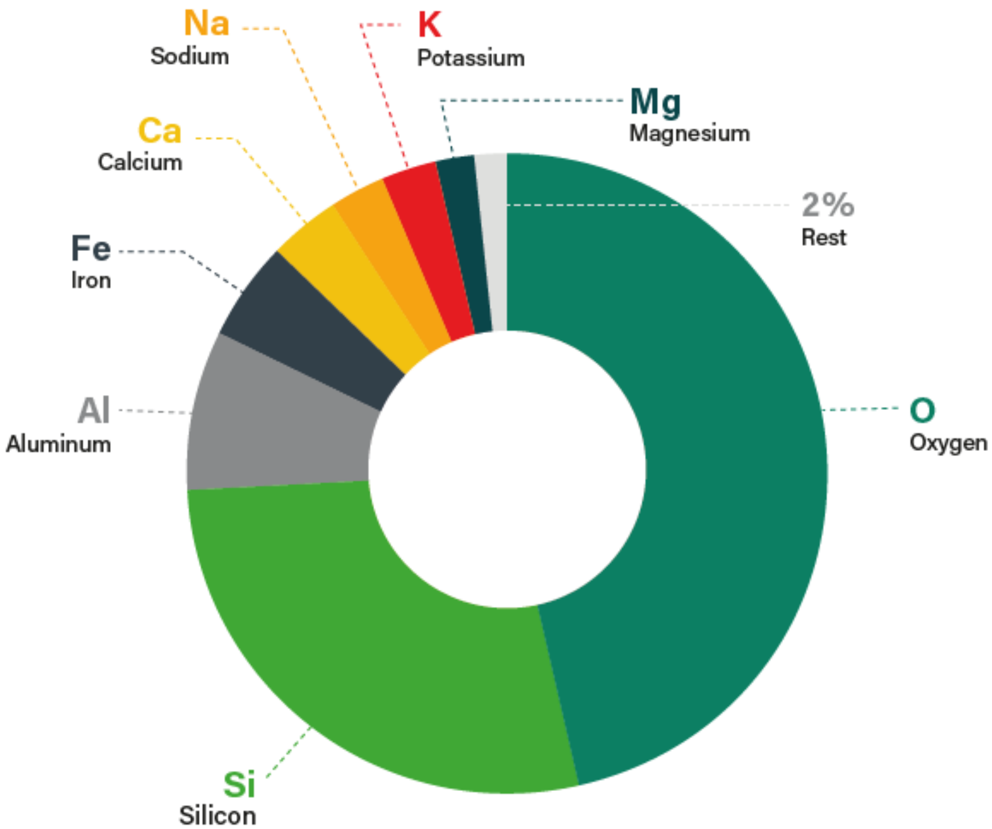
What is available on earth?



Na_2O

K_2O

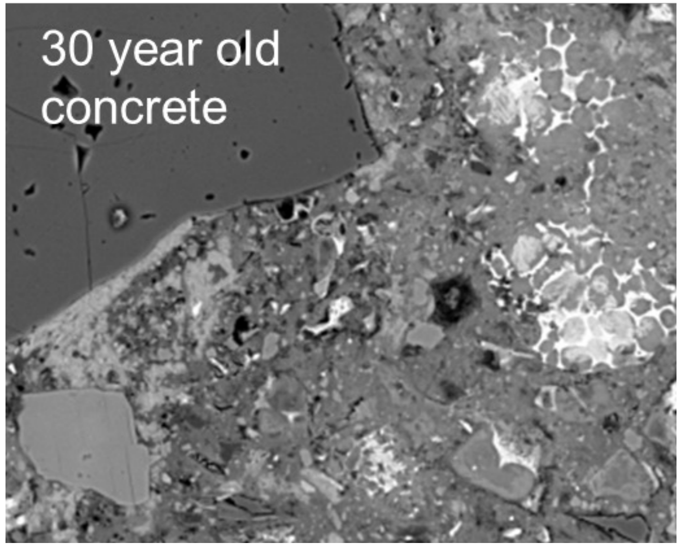
Fe_2O_3

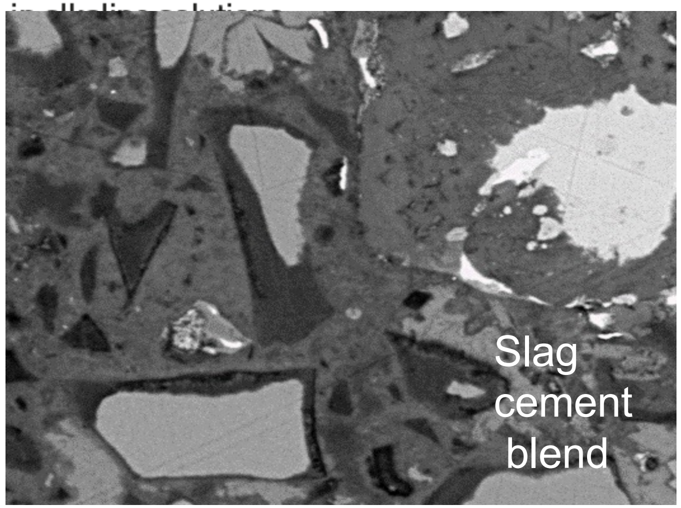
MgO

CaO

SiO_2

Al_2O_3





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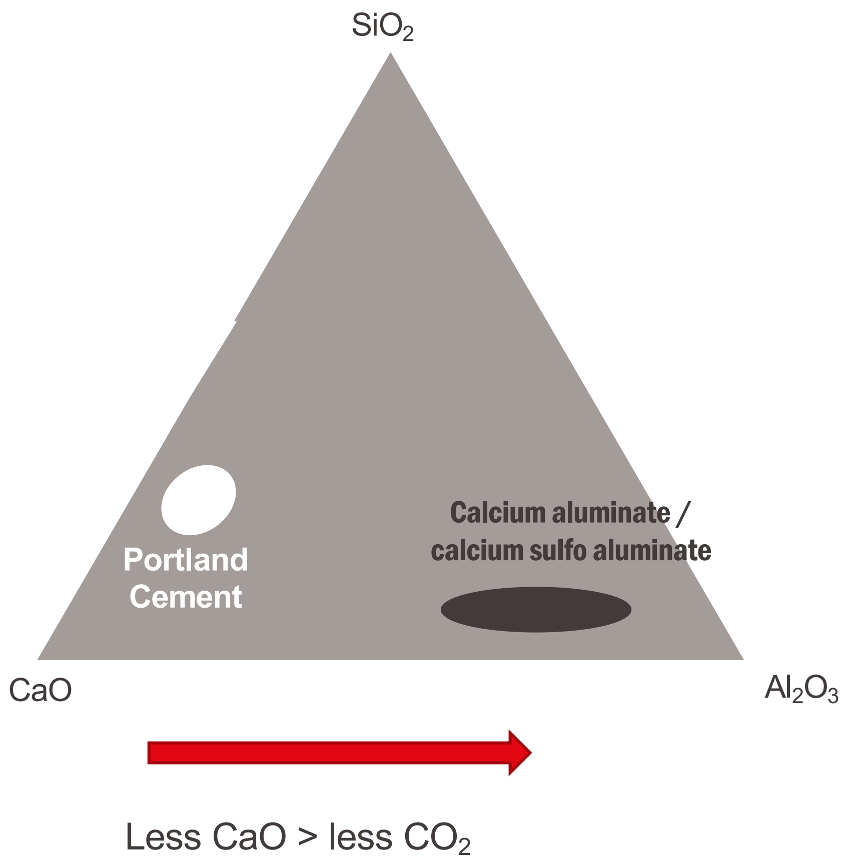
Hydraulic minerals in system $CaO-SiO_2-Al_2O_3$



BUT, what sources of minerals are there which contain $Al_2O_3 >> SiO_2$?

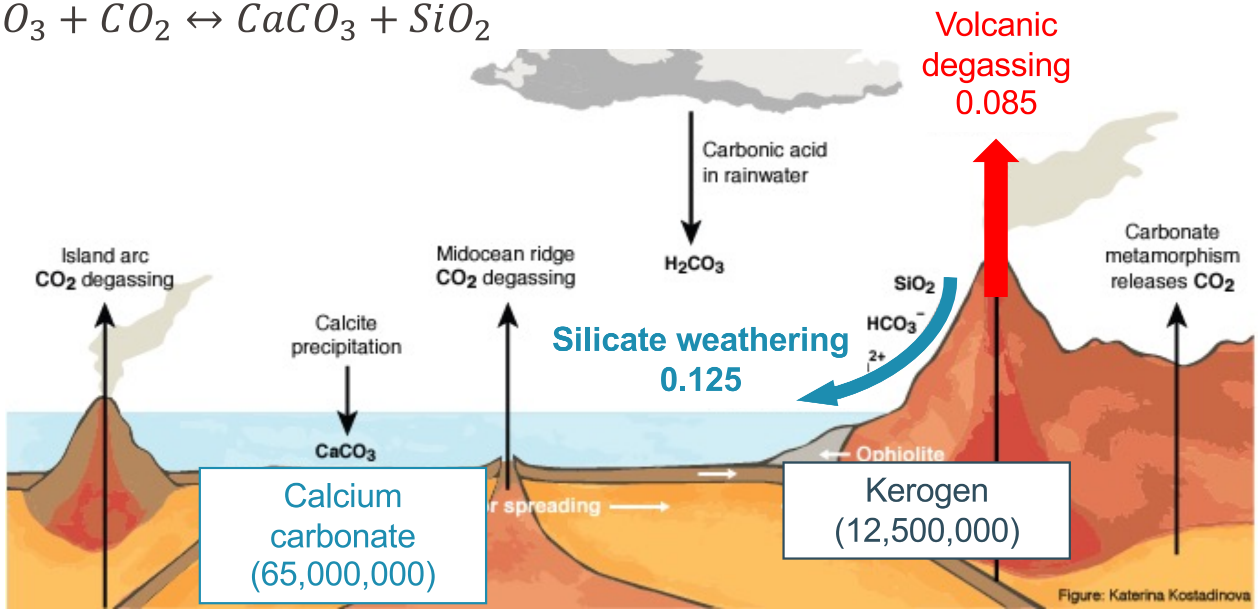
Bauxite – localised,
under increasing demand for Aluminium production,
EXPENSIVE

Even if all current bauxite production diverted would still only replace 10-15% of current demand.

Even after nearly 50 years CSA production in China is <0.1% of OPC

The advantages of limestone

- A concentrated source of calcium due to geological slow carbonate silicate cycle
- Long time scales
  - Lithosphere: Small fluxes, large reservoirs
  - $CaSiO_3 + CO_2 \leftrightarrow CaCO_3 + SiO_2$



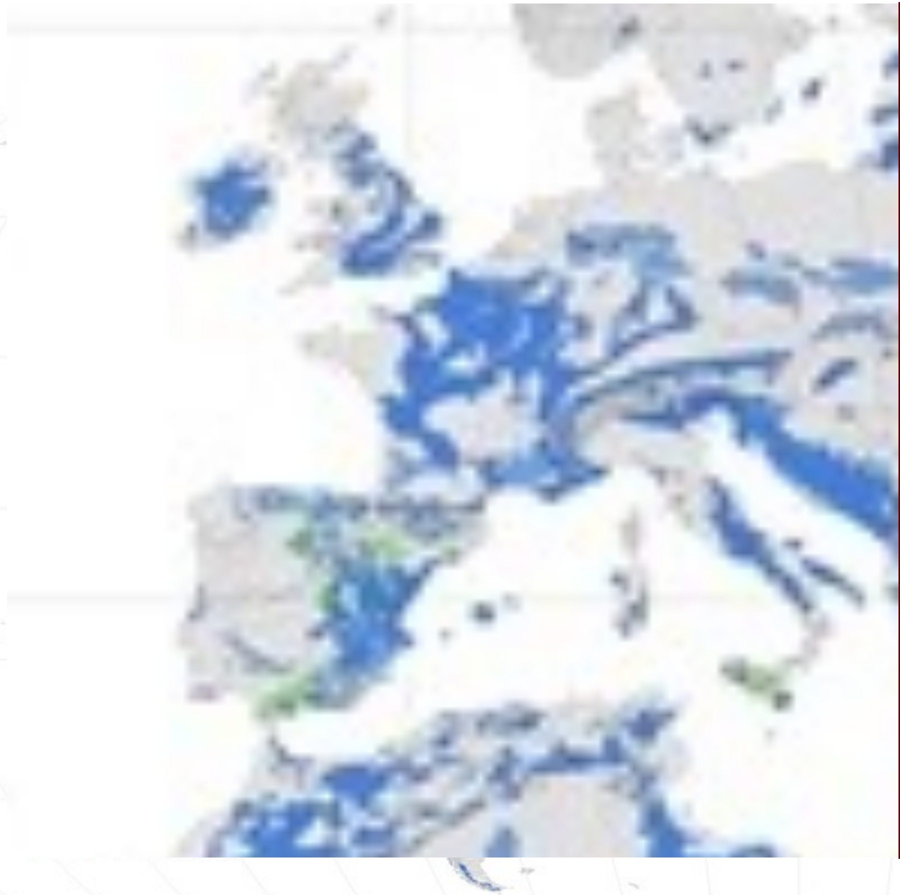
[numbers in Gt C per year, number in parentheses in Gt C; source: Kasting, 2019; Hilton & West, 2020]

Slide from Ruben Snellings

KULeuven

Limestone

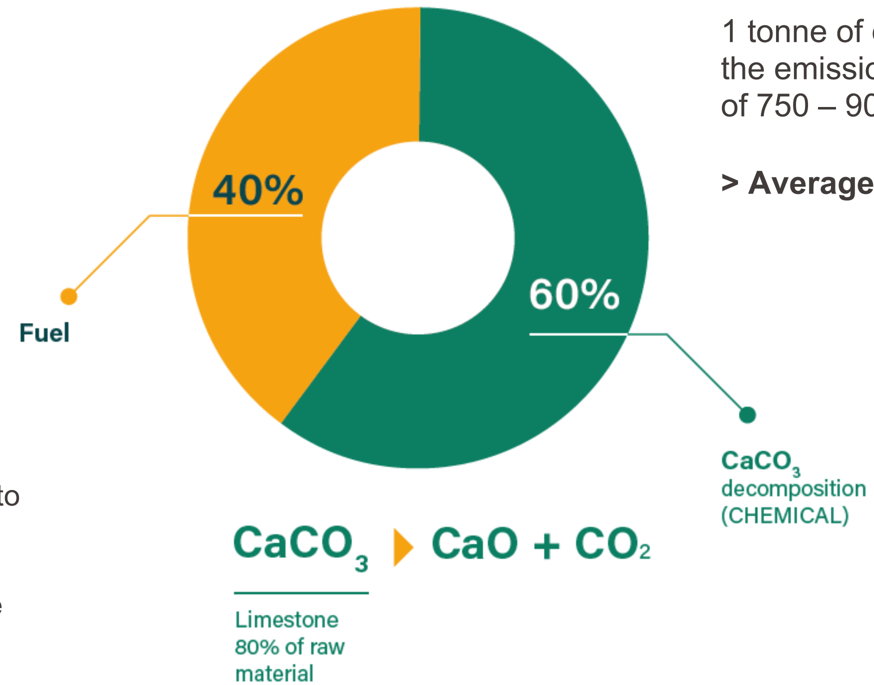
- Because of the weathering process,
  what is not limestone is dominated by aluminosilicate rock, eventually clay



No surprise that the interesting properties of limestone – clay combinations were discovered in Europe about 200 years ago

But unfortunately production of cement from limestone leads to substantial CO_2 emissions

- The production process is highly optimised up to around 80% of thermodynamic limit.
- It is estimated that **< 2%** further savings can be made here
- Use of waste fuels, which can be **> 80%** reduces the demand for fossil fuels



1 tonne of clinker leads to the emission of 750 – 900 kg CO_2

> Average 850kg/t

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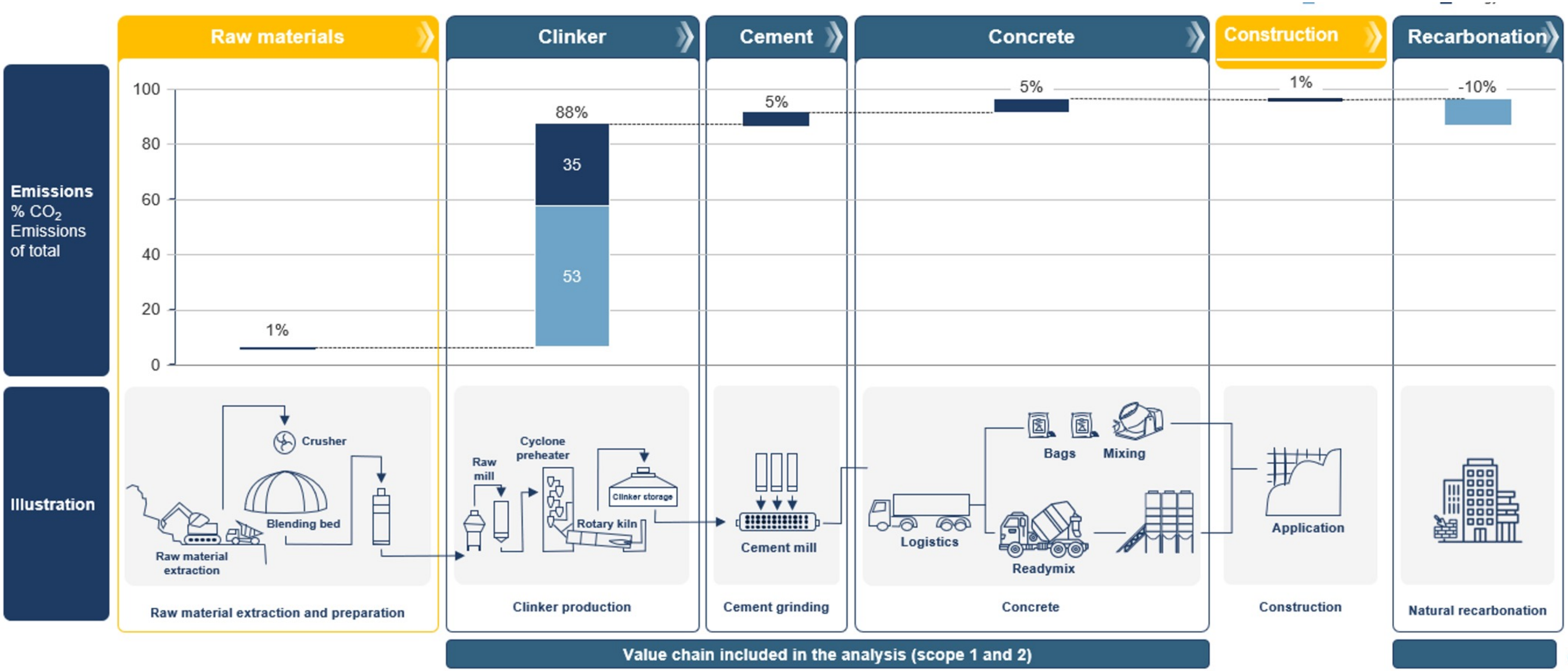
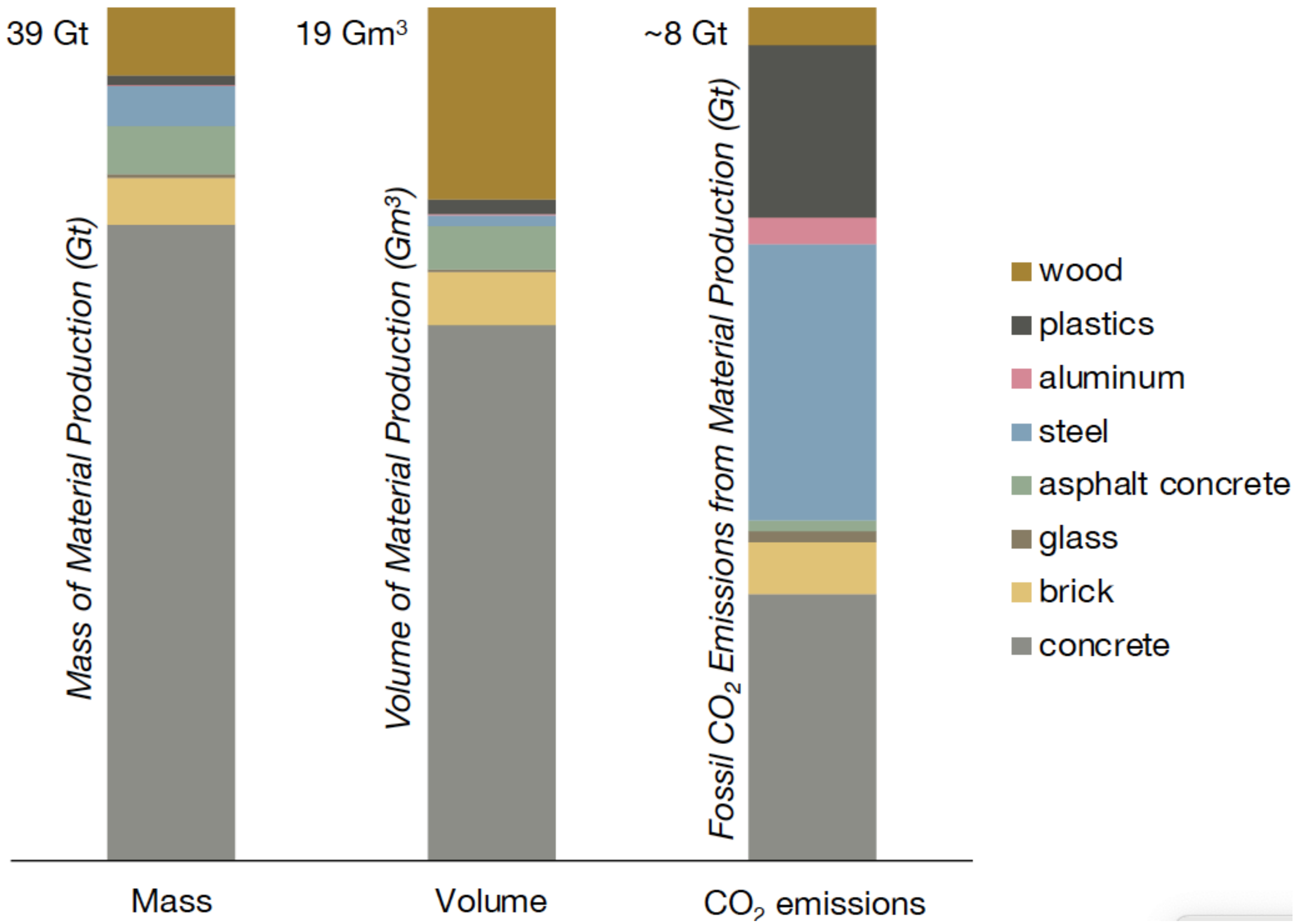
Clinker is responsible for 85-90% of CO2 emissions for cement-based materials



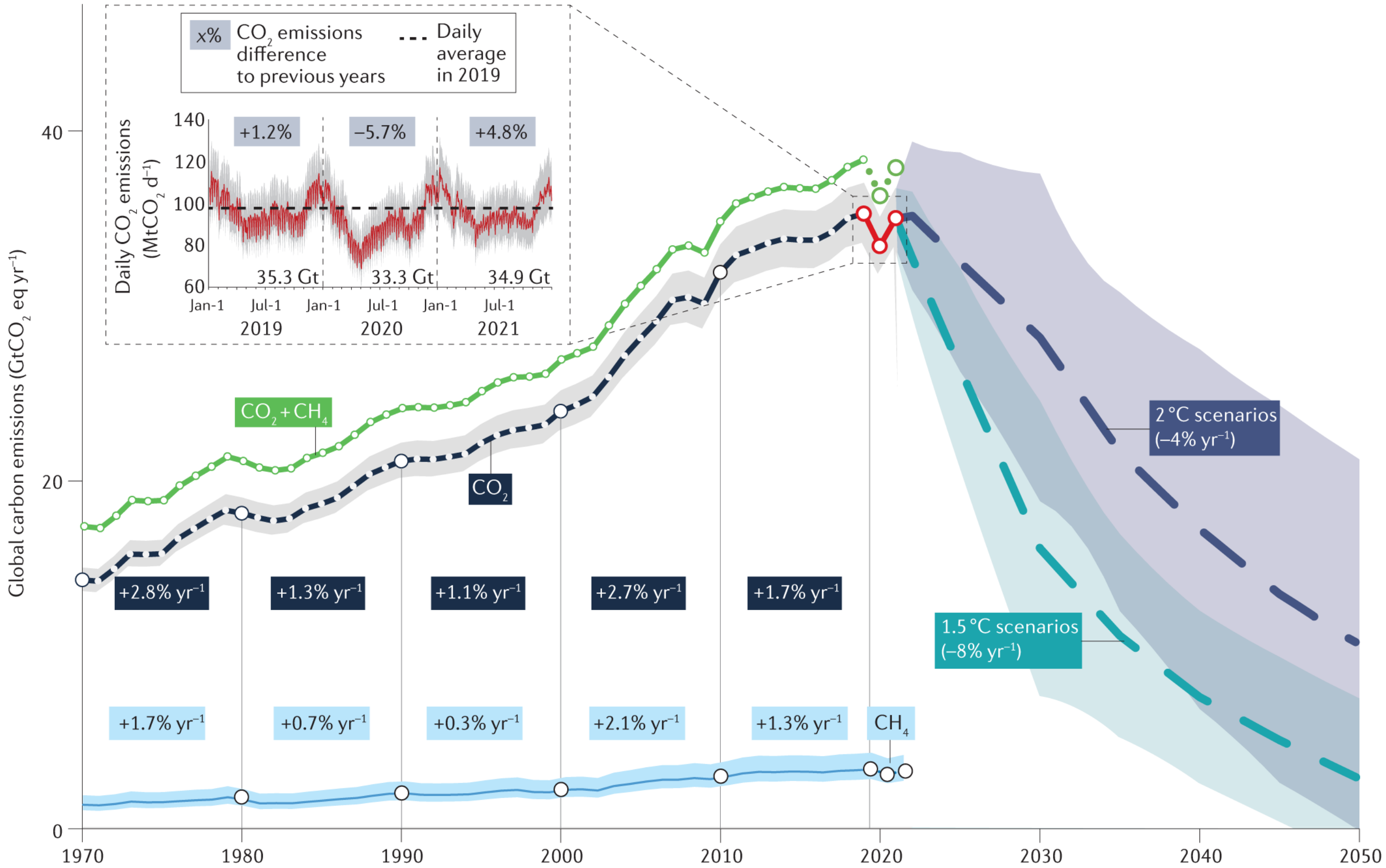
- Source: Mission Possible Partnership

But still very good value for CO_2

World Use of materials: 90% construction

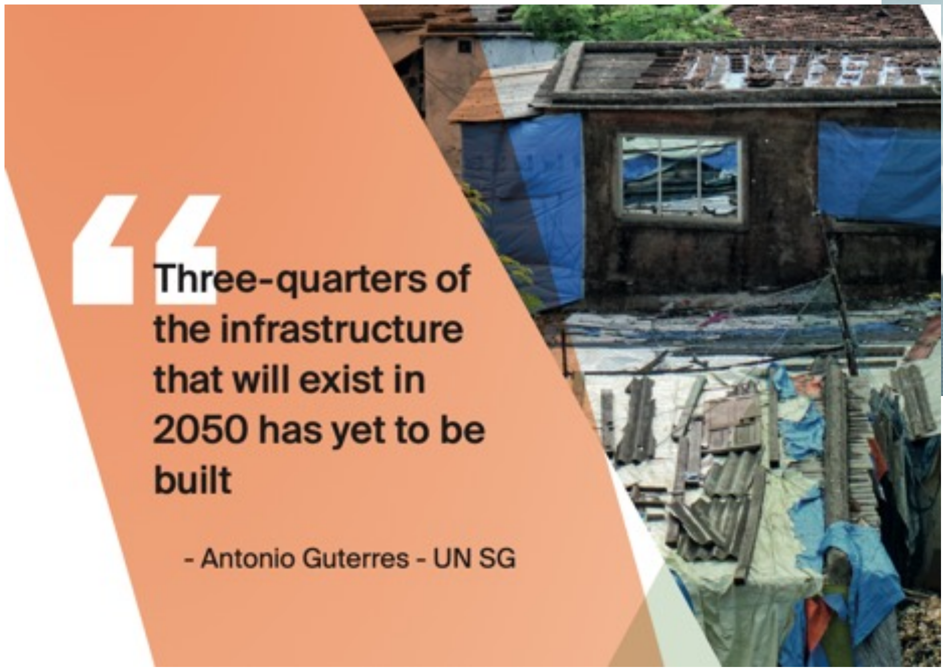


Need to act fast



Liu et al. 2022. Nature Reviews Earth & Environment 3, 217-219

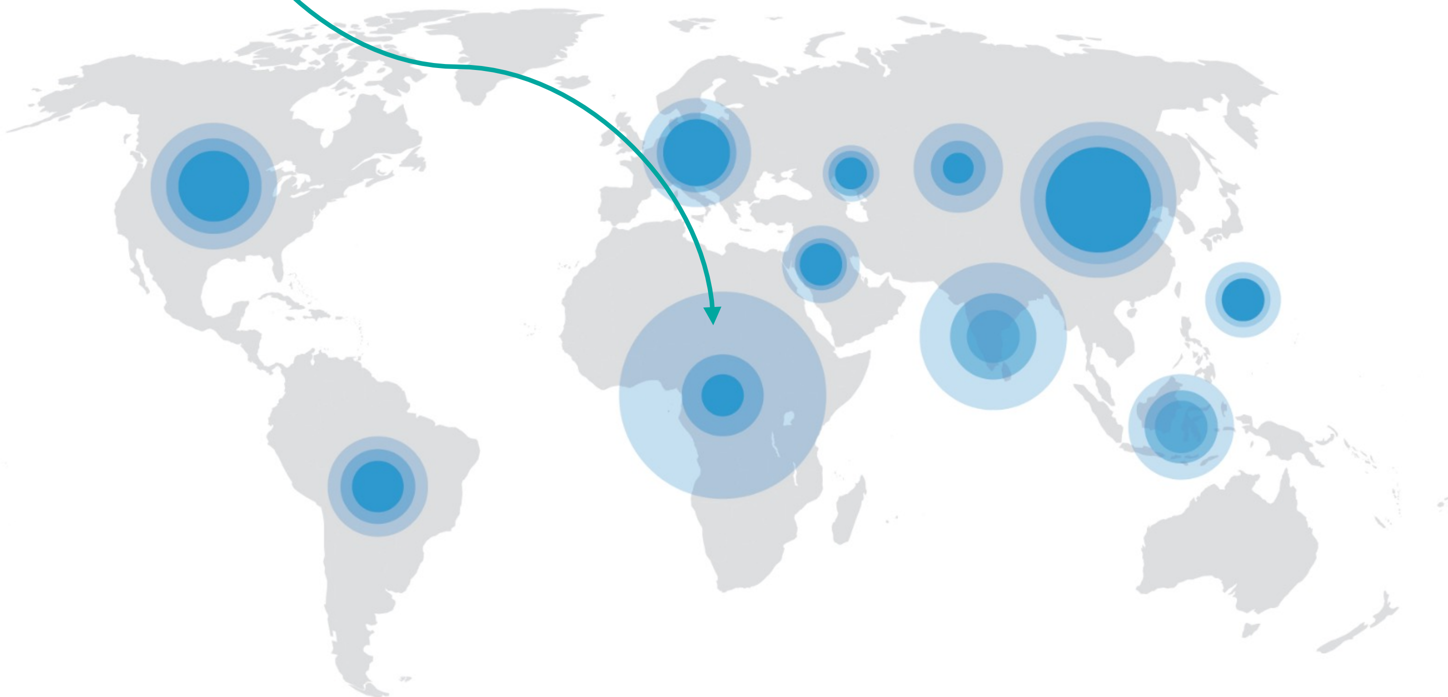
Tomorrow....



This will NOT HAPPEN in the Global North

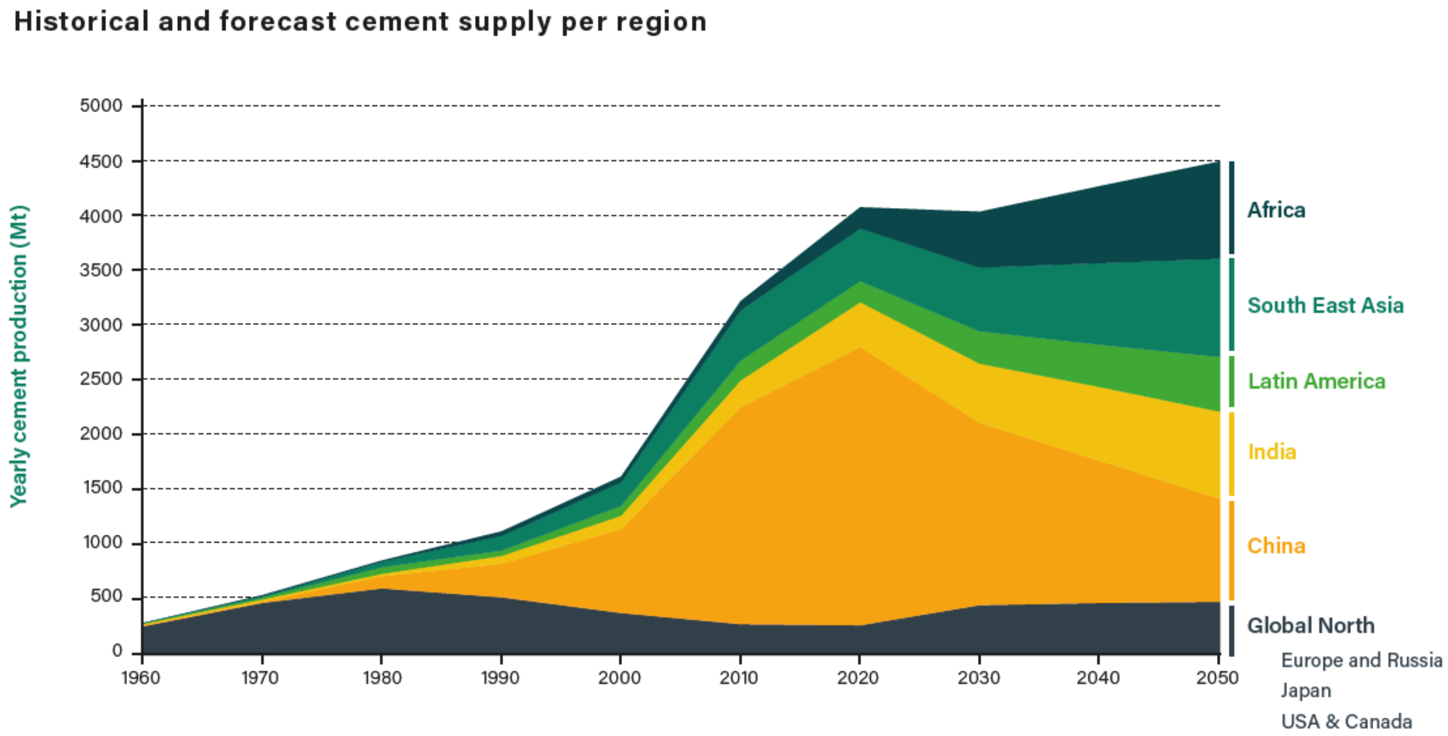
It will happen HERE

Global building floor area
is expected to **double** by 2060.



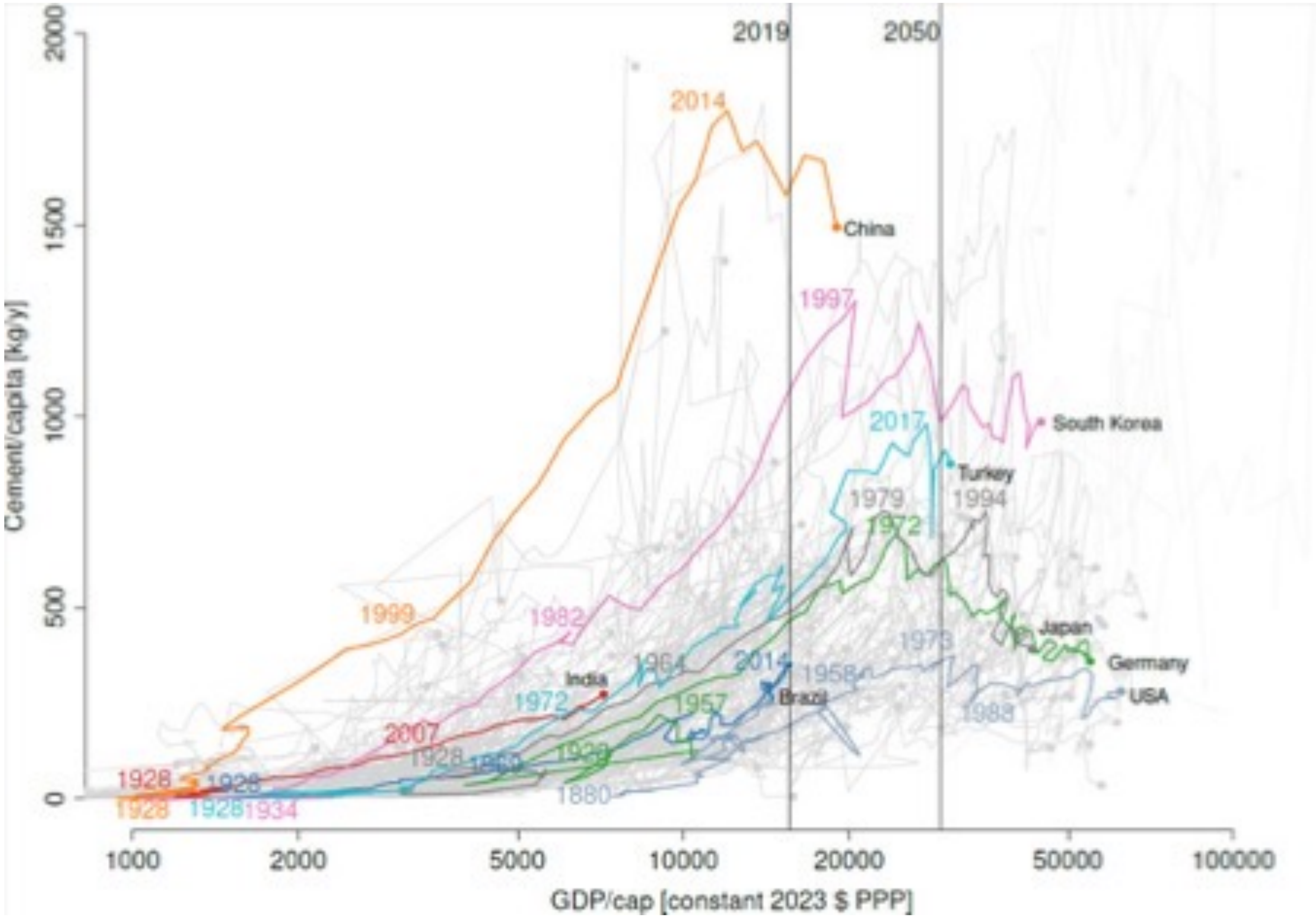
Data Sources: Global ABC, Global Status Report 2017

Changing pattern of cement use



We need solutions for people in developing countries

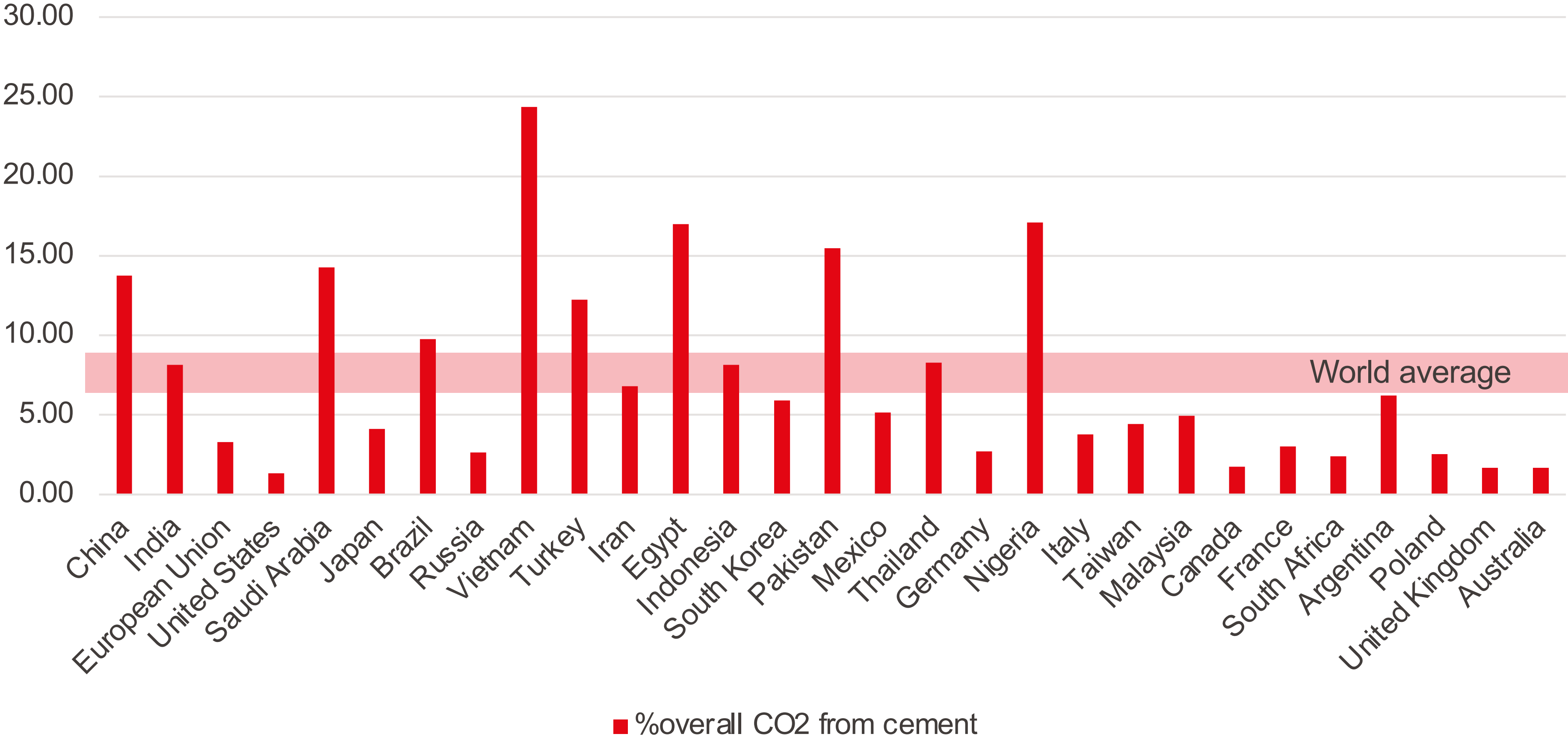
Concrete "Hump" a normal phenomenon of growth



In China maybe 1000 out 1500 cement plants will close

Karen Scrivener

Contribution of cement to CO2 emissions, by country



**Although the USA is the third largest consumer of cement,
it accounts for < 1.5% of the country's emissions**

What can be done?

What about getting Ca not from Limestone?

Basalt

Name of oxide	Content, % by weight
SiO_2	46.5 – 51.5
Al_2O_3	15.0 – 19.0
MgO	4.0 – 10.5
CaO	7.5 – 11.5
$FeO+Fe_2O_3$	8.0 – 12.0
K_2O+Na_2O	3.0 – 6.0
TiO_2	0.3 – 2.5
Cr_2O_3	0.02 – 0.05
MnO	< 0.1
Other	Up to 100

Source research gate

Dissolve in acid

Precipitate oxide separately

Common technology
in mining industry

**Make clinker with
uncarbonated calcium oxide**

Estimated cost ~ $800 / ton

>80% reject materials

Ca from Seawater?

400ppm,

Inverse of desalination

- 3 kWH for desalination of 1 tonne of water
- ~$300 for seawater containing 1 tonne of Calcium
- But the desalination residue is still very wet
- 10X more energy to get a dry residue
- Then have to separate the elements in the residue
- Back to situation of basalt

- Cost range of $1000 - $ 10,000 per tonne of CaO
  (remember clinker<$50, clinker + CCUS <$150)
- All the desalination plants in the world today could potentially supply the equivalent of 5-10 clinker plants

No silver bullet

Despite the media interest they attract, most niche technologies
– such as alkali activated materials, cement from algae, etc are:

- impractical,
- costly,
- unscalable,
- will take too long to mature

so have little to no possibility of delivering any significant impact.

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But there is good news?

We can do a lot
if we act through the value chain

Report for European Climate Foundation 2017

Reduce CO_2 from clinker production → Reduce clinker in cement — Reduce cement in concrete — Reduce concrete in building — More efficient (re)use of buildings

Reduce CO_2 from clinker production
- Efficient plants
- Waste fuels
- Alternate raw materials

Reduce clinker in cement
- SCMs

Reduce cement in concrete
- Aggregate grading
- Good admixtures
- Use filler

More efficient (re)use of buildings

RECYCLE!

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nature communications

Article

https://doi.org/10.1038/s41467-023-40302-0

Near-term pathways for decarbonizing global concrete production

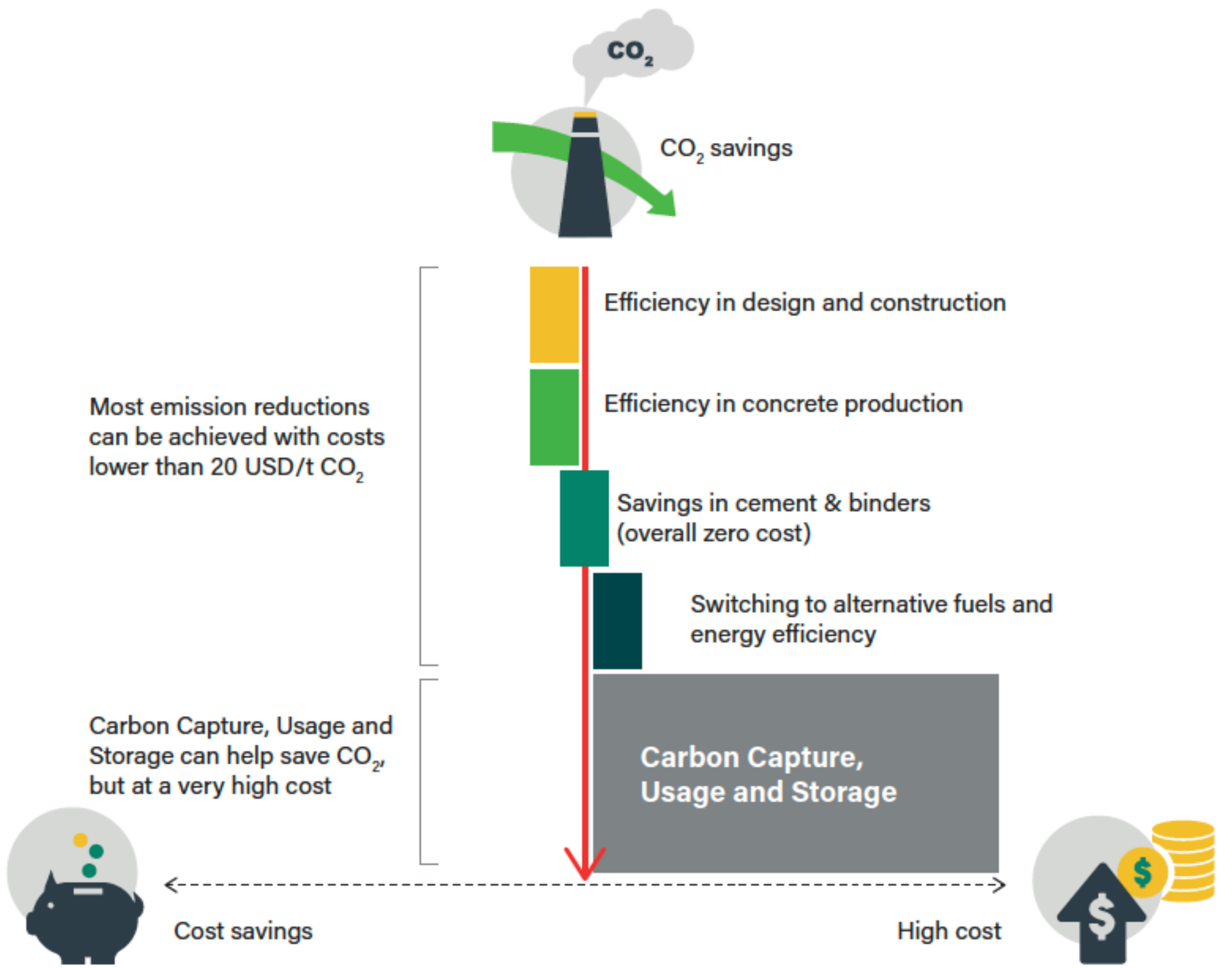
Received: 27 January 2023

Accepted: 21 July 2023

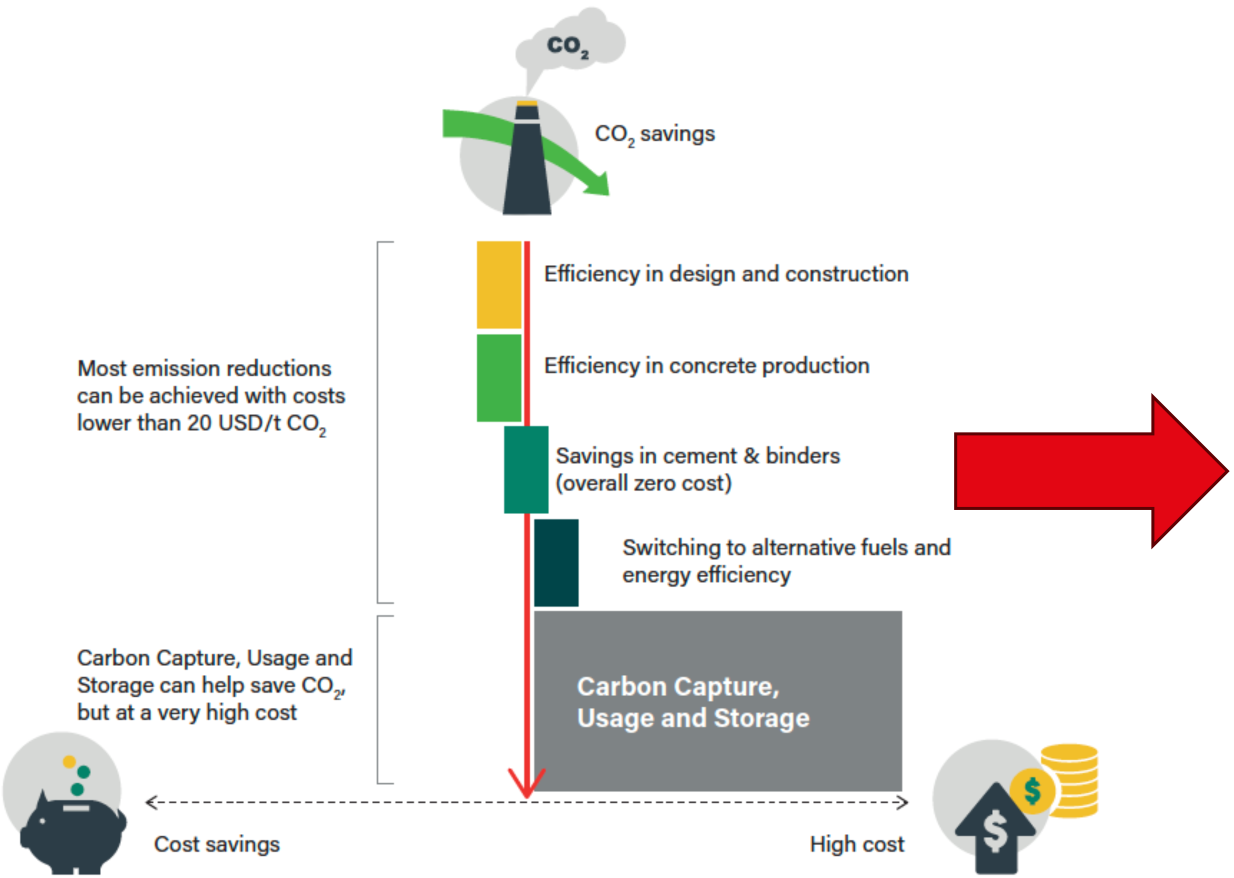
Josefine A. Olsson[1], Sabbie A. Miller[1] & Mark G. Alexander[2]

Calculated **76%** with these strategies

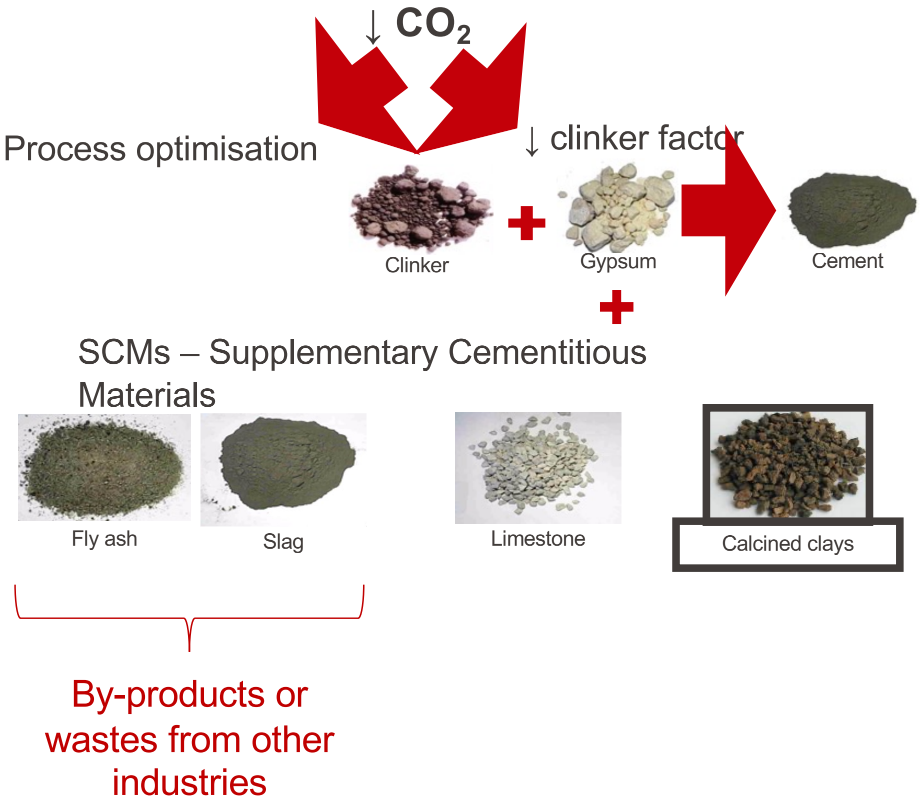
Much of the path to net zero is low cost



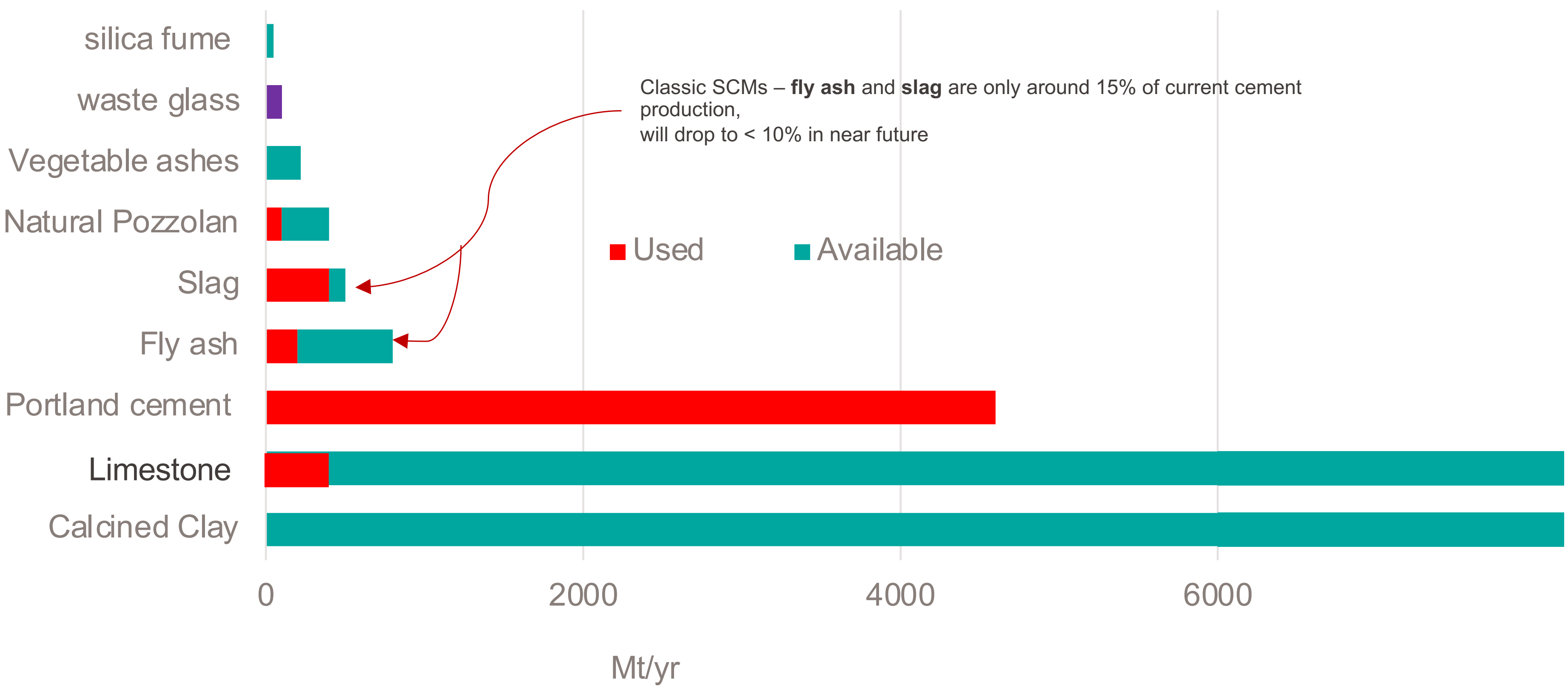
Reducing clinker factor is the most practical to implement



Most promising approach – reducing the clinker factor



Availability of SCMs



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There is no magic solution

- Blended with SCMs will be best solution for sustainable cements for the foreseeable future.
- **Only material** really potentially available in viable quantities **is clay**.
- **Synergetic reaction** of calcined clay and limestone allows high levels of substitution
- EPFL led the LC^3 Project supported by **Swiss Agency for Development and Cooperation (SDC)**, 2013-2022.
- **Climateworks Foundation** supporting the LC^3 Project since 2022.

LC3 PROJECT

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Swiss Agency for Development and Cooperation SDC

climateworks FOUNDATION

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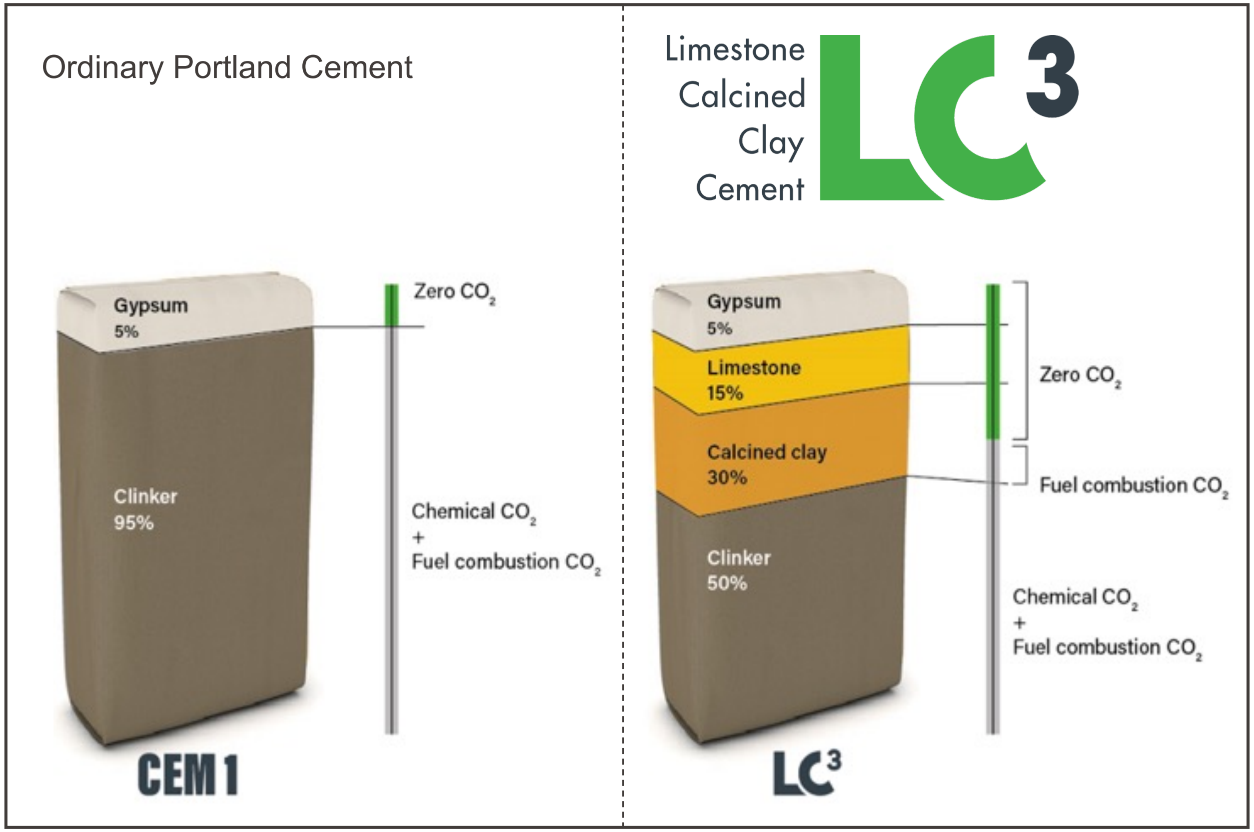
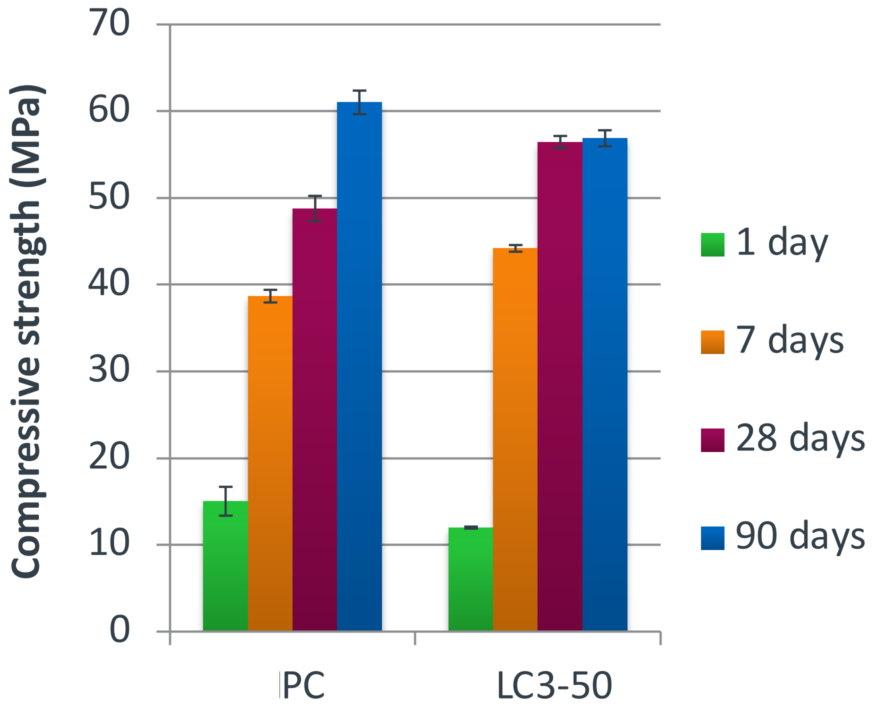
LC³ – Limestone Calcined Clay Cement



- LC³ is a **low-carbon** blended cement type
- **Reduces CO_2 emissions in cement by 40%**

LC^3 has comparable strength to OPC

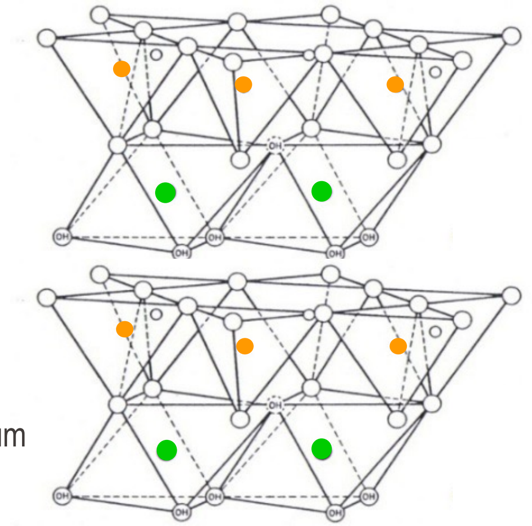


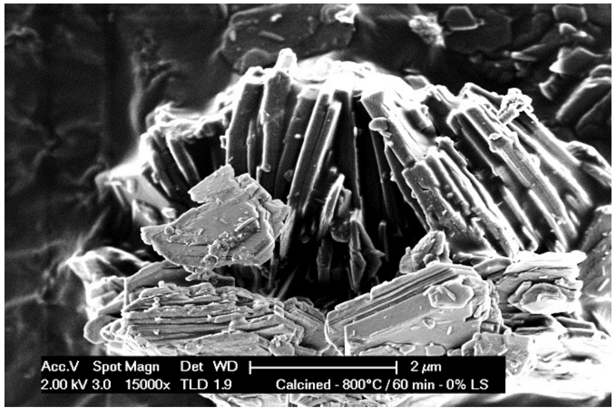
LC3-50 = 50% clinker.

- 50% less clinker
- 40% less CO_2
- Similar strength
- Better chloride resistance
- Resistant to alkali silica reaction

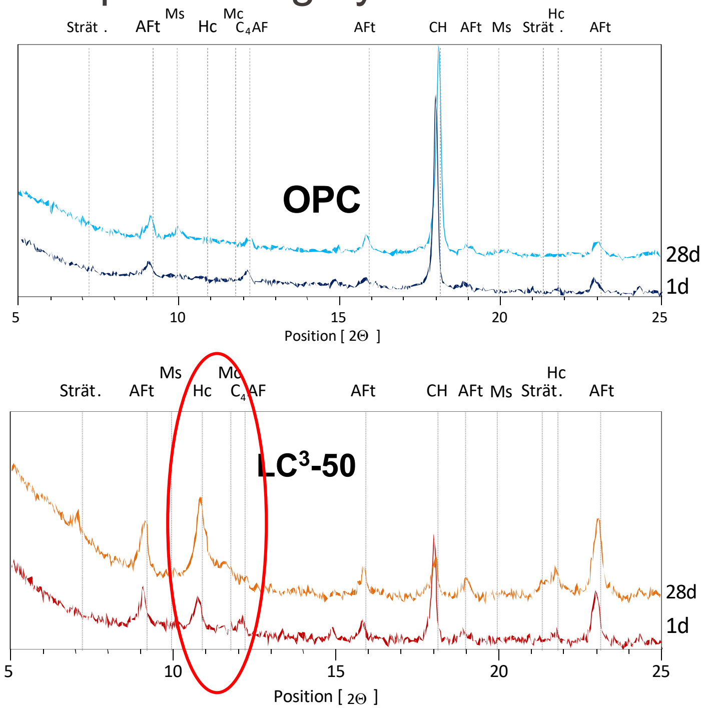
Why can we get such high replacement levels?

- Calcination of kaolinite at **700-850°C** gives metakaolin: much more reactive than glassy SCMs





» **Synergetic reaction** of Alumina in metakaolin with limestone to give space filling hydrates



What kinds of clay are suitable?

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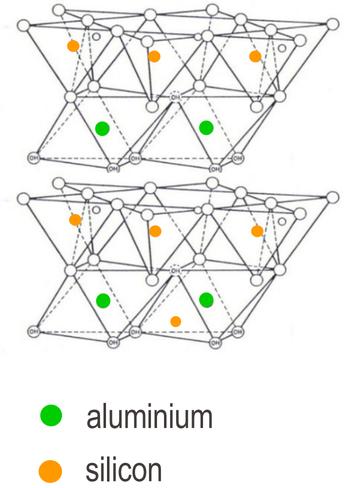
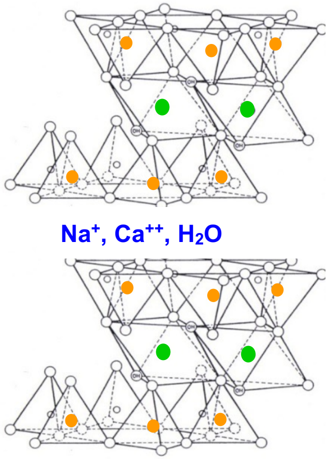
Three basic clay structures

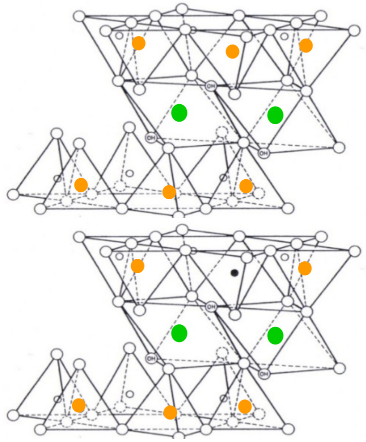
Kaolinite (1:1)



Montmorillonite (2:1)
(Smectites)



Illite (Micas)
(2:1)



"Metakaolin", sold as high purity product for paper, ceramic, refractory industries
Requirements for purity, colour, etc, mean expensive 3-4x price cement

Clays containing metakaolin available as wastes
– over or under burden NOT agricultural soil
Much much less expensive often available close to cement plants

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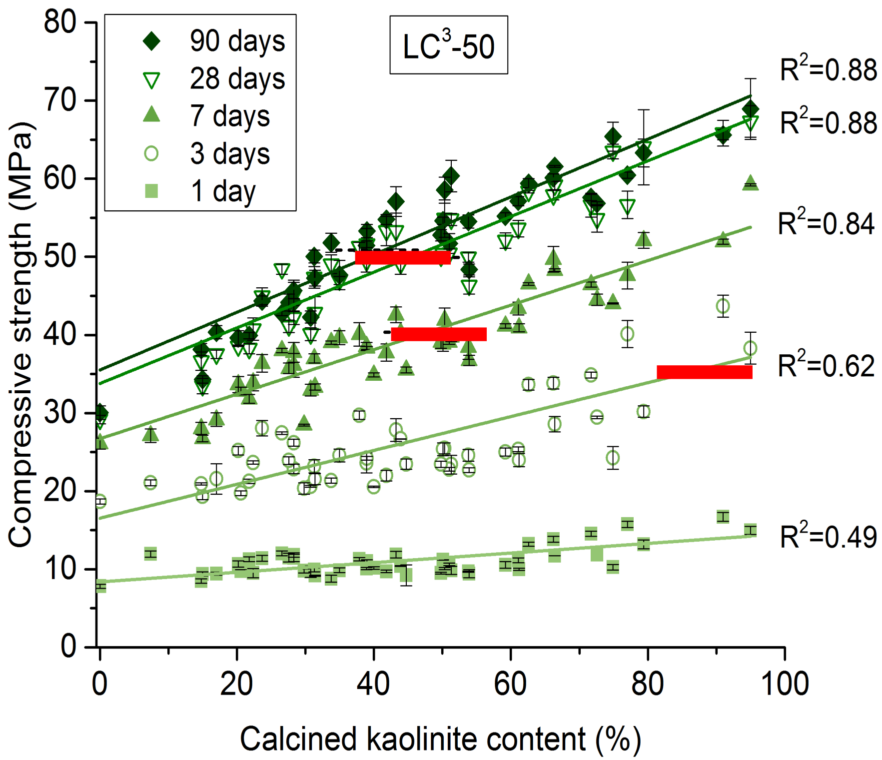
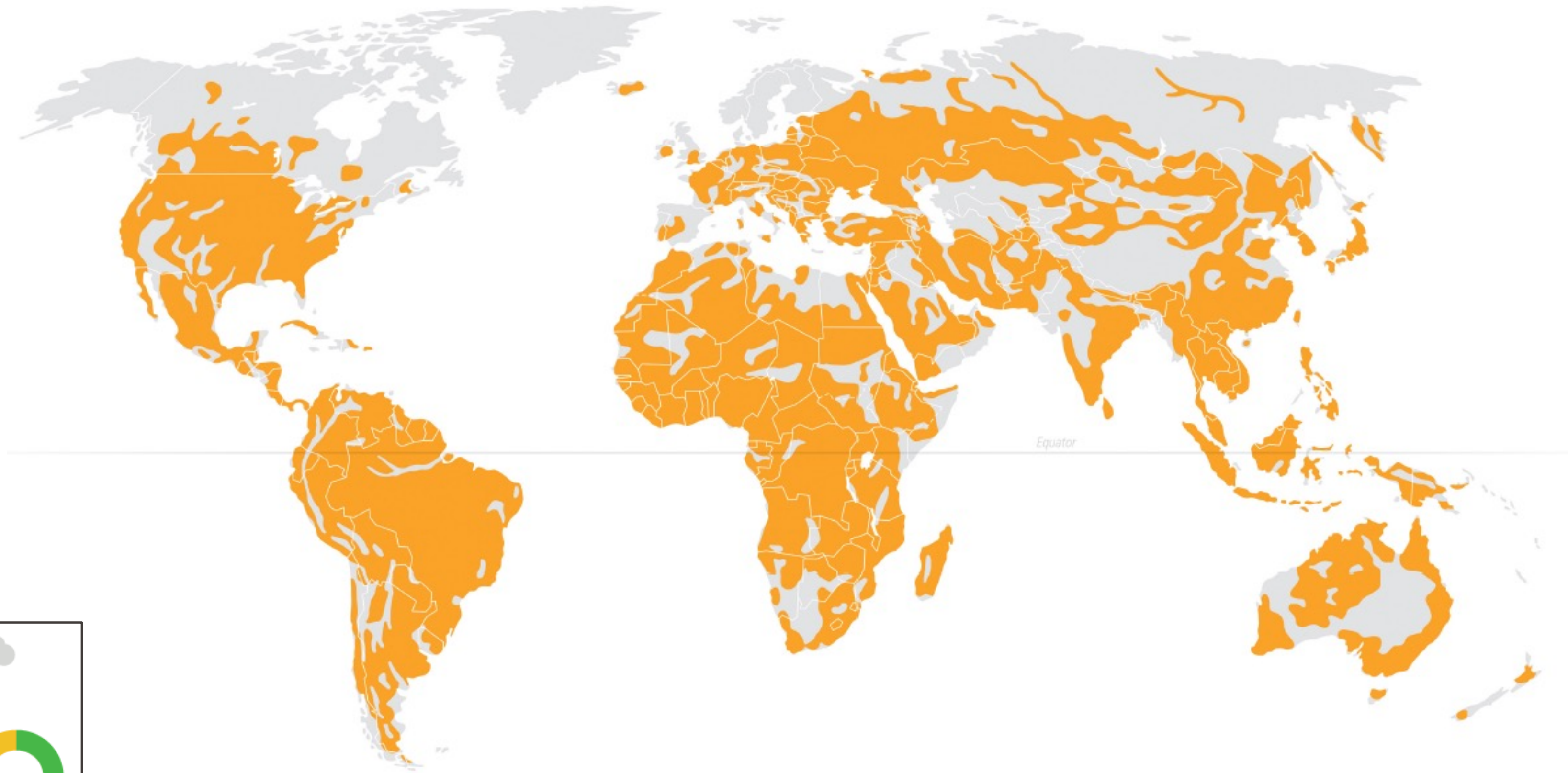
Benchmark test of clay strength

- Compressive strength EN 196-1 at 1, 3, 7, 28, 90 d
- Linear increase of strength with the MK content of calcined clays
- Similar strength to PC for blends containing 40% of calcined kaolinite from 7d onwards
- At 28 and 90 days, little additional benefit >60%
- Minor impacts of fineness, specific surface and secondary phases



Calcined kaolinite content overwhelming parameter

World distribution of kaolinitic clays



Source: Ito and Wagai, Scientific data 2017

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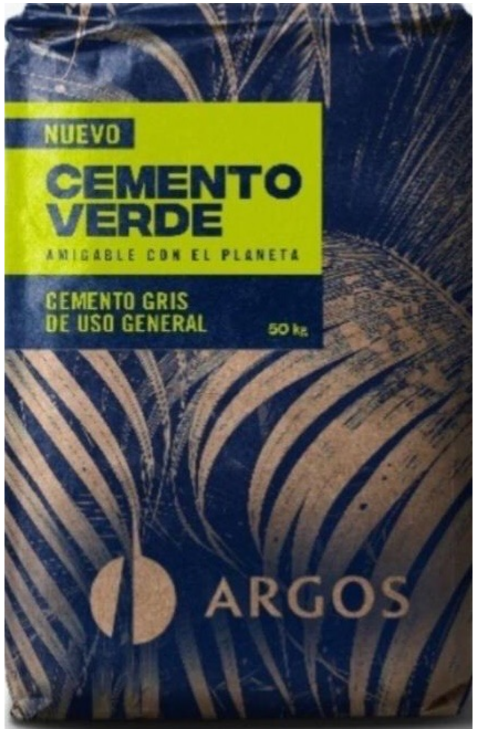
Industrial projects: Cemento Verde ARGOS, Colombia



Argos Colombia 2022

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Industrial projects: CIMPOR, Ivory Coast

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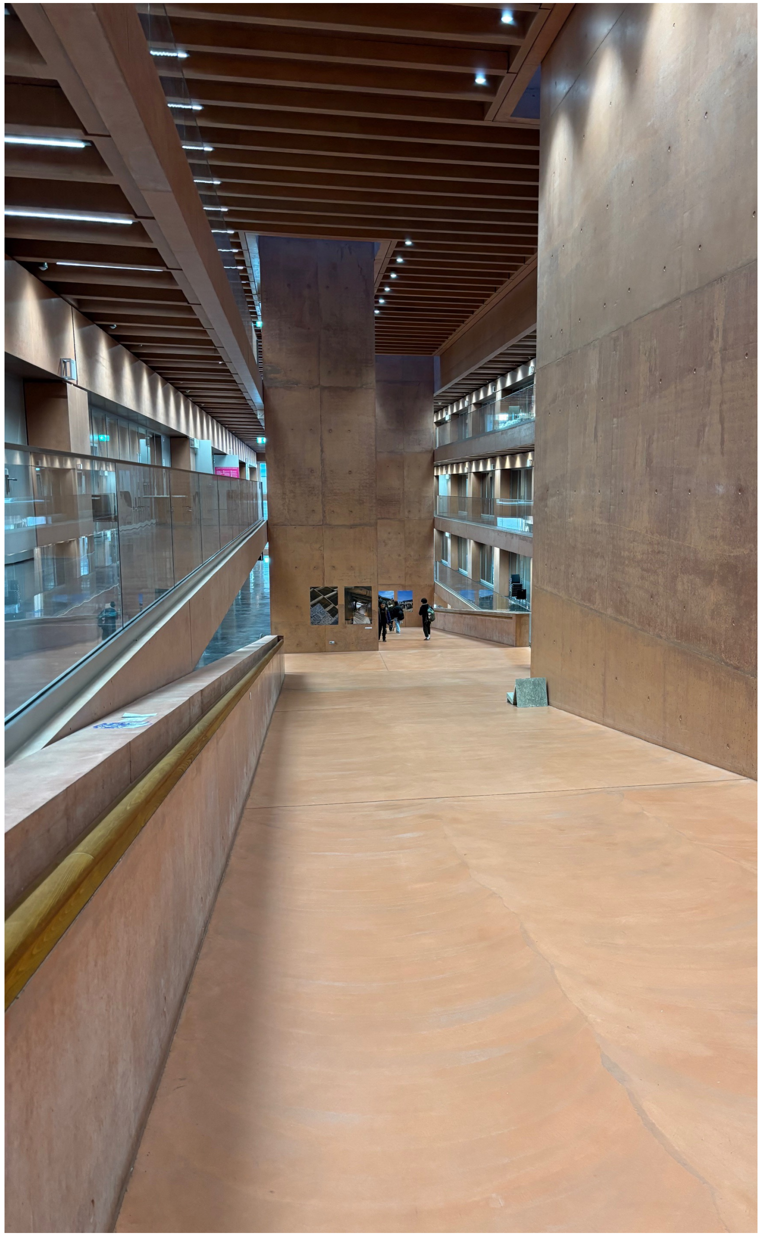
“people don’t want red concrete”



Europe

- Holcim's ECOPlanet LC^3-type cement used for constructing a marina in Marseille, France for the 2024 Olympics.
- Tilia Tower©, Switzerland is an ambitious and sustainable high-rise building.
  - Slabs and internal walls are in LC^3 from Jura Ciment
  - External façade in wood


© Holcim
La Malle calcined clay cement used in marina in Marseille for 2024 Olympics


Tilia Tower©, Lausanne, Switzerland

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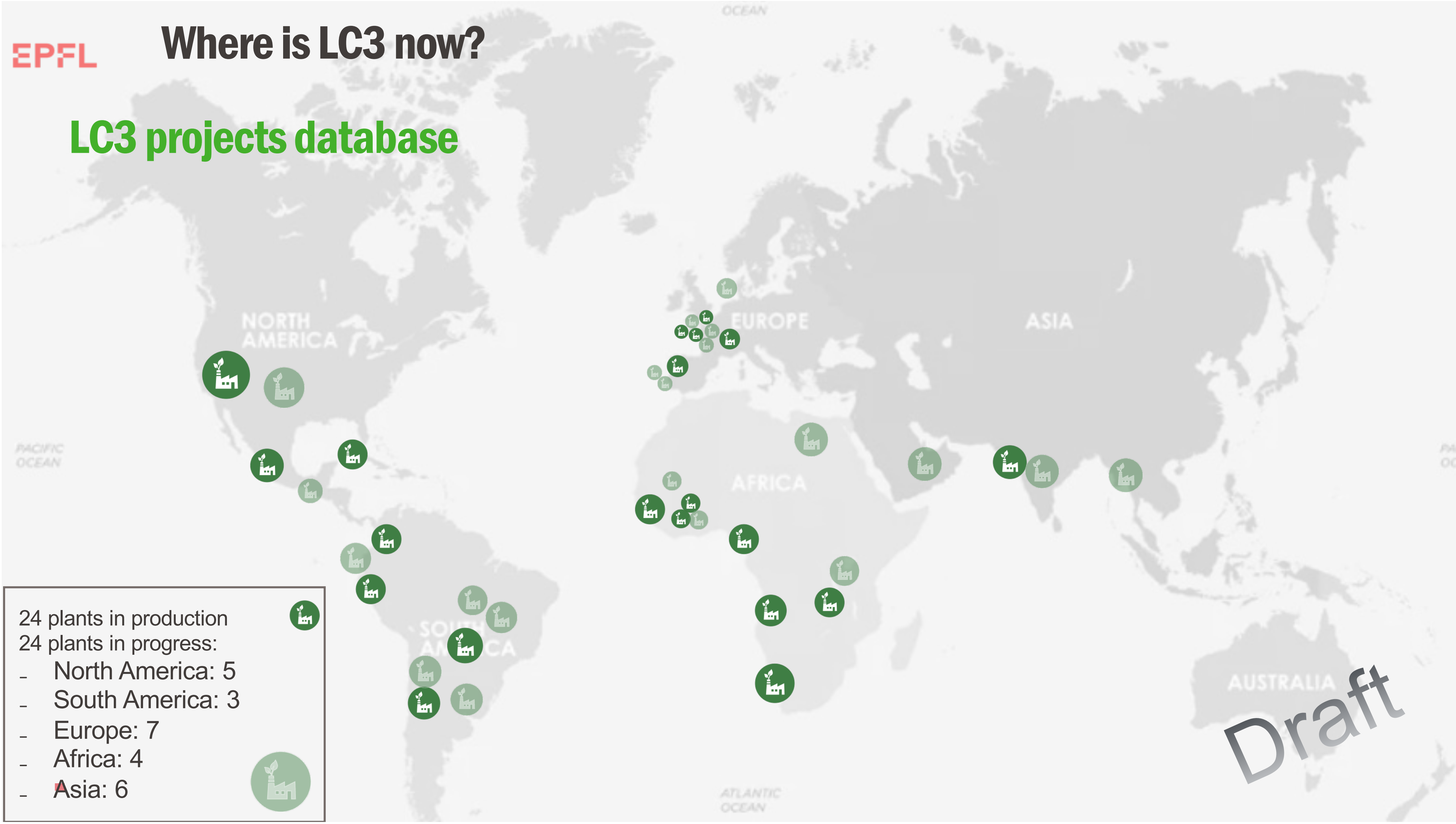
Where is LC3 now?

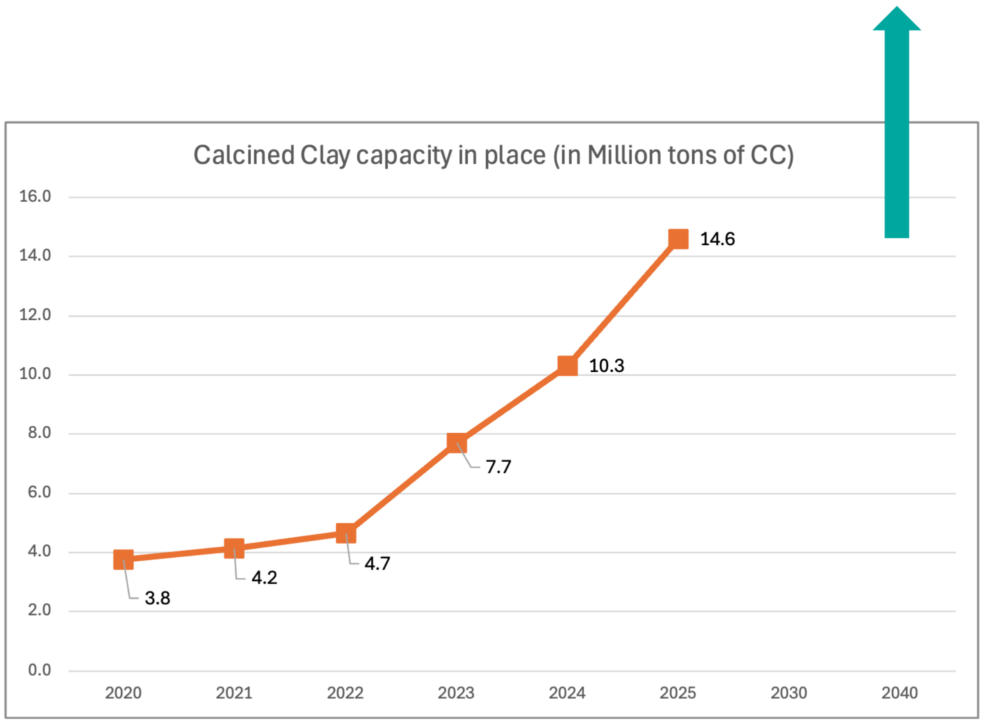
LC3 projects database



24 plants in production
24 plants in progress:
- North America: 5
- South America: 3
- Europe: 7
- Africa: 4
- Asia: 6

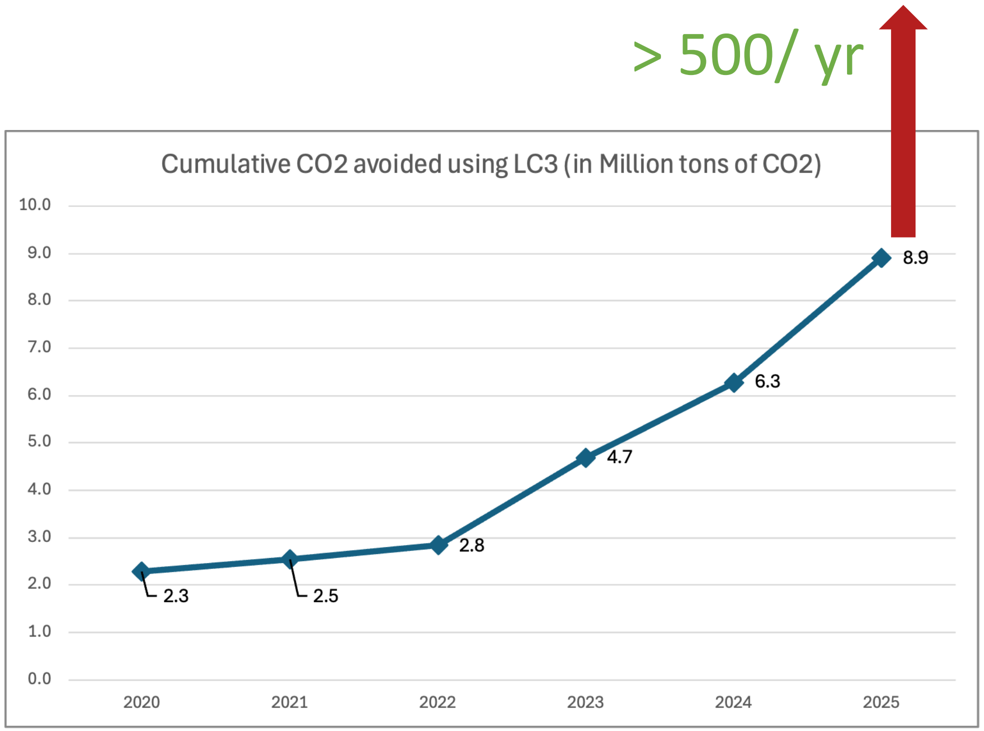
LC^3: where are we now
Capacity and cumulative CO_2 savings

400 million



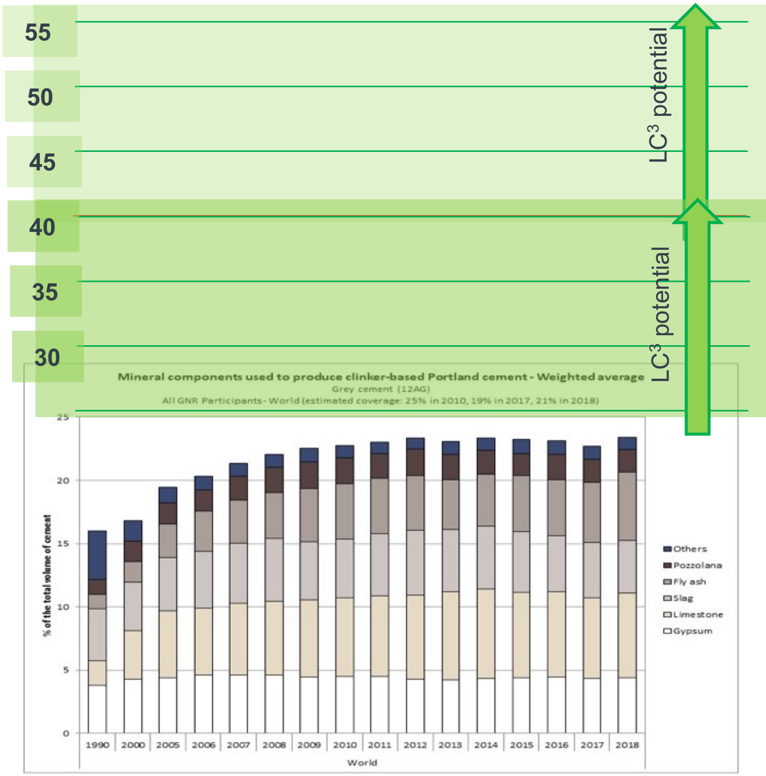
By 2040, the goal of achieving one-third of global cement production with LC3 would require reaching a calcined clay production capacity of 400 million tons, which means an increase of 25 million tons annually.

> 500/ yr

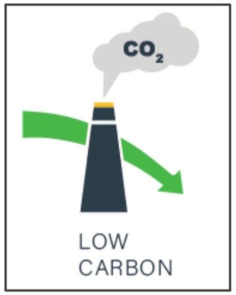


World Potential?

Calcined Clay only SCM which can expand substitution



- ✓ 800 million tonnes CO_2/yr
- ✓ 400 million tonnes CO_2/yr



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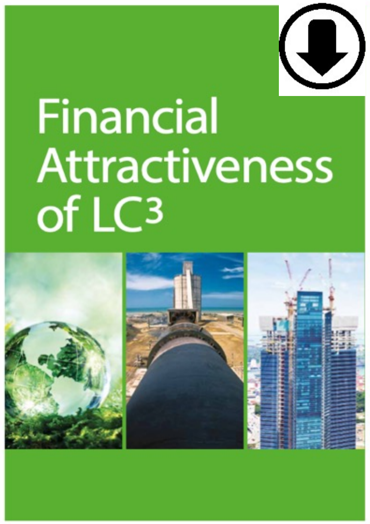
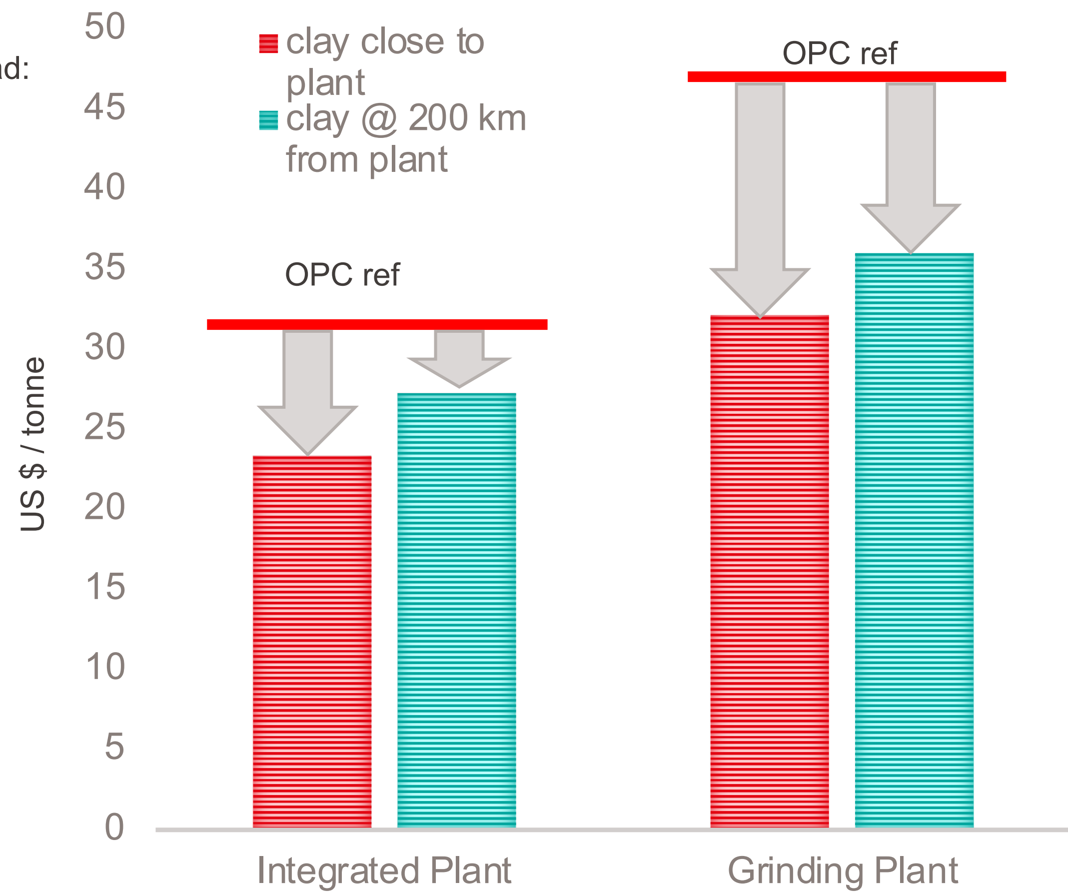
Financial Feasibility



Report available to download:
www.lc3.ch

Study by LC3 Project partner CEMENTIS



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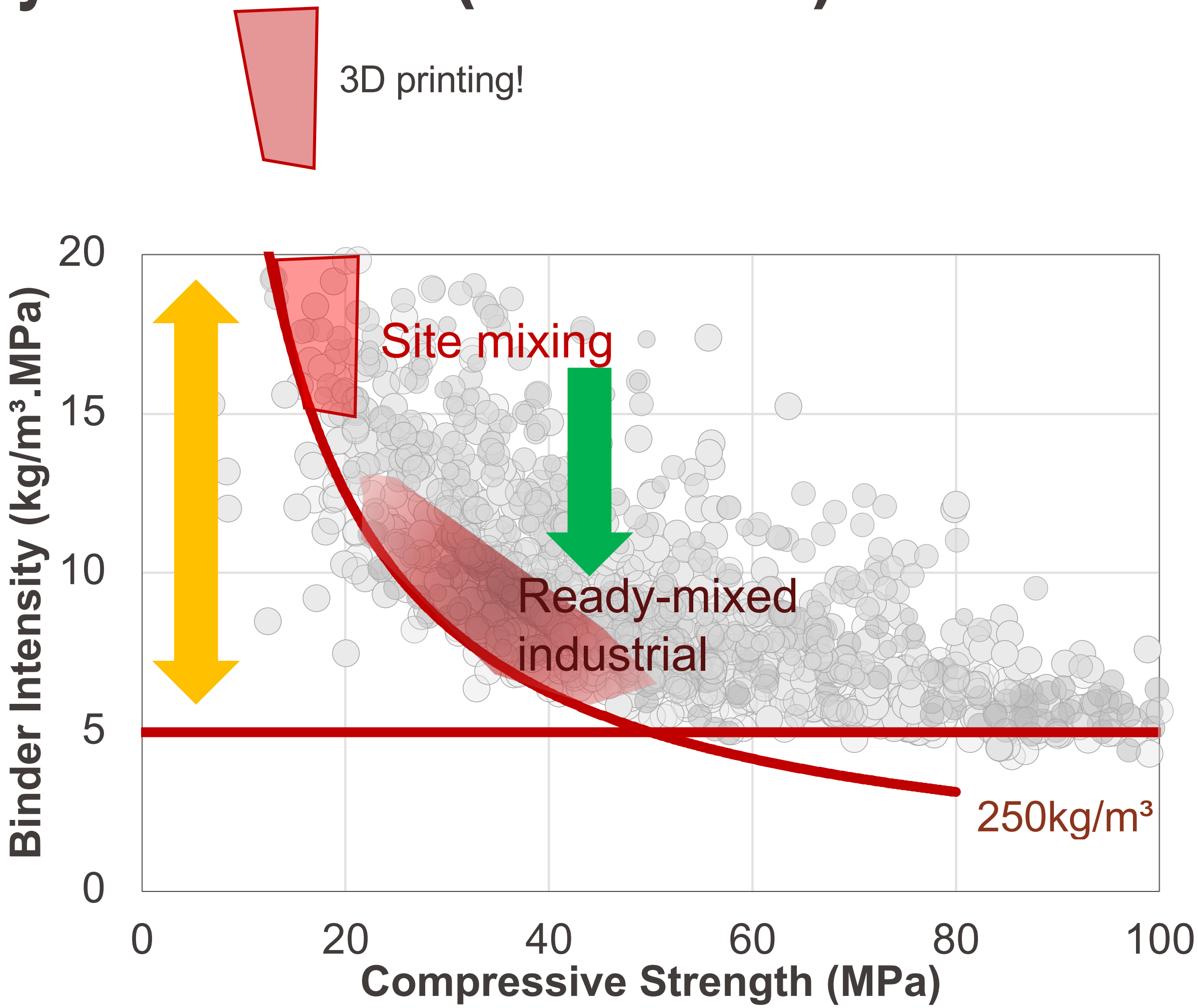
Substantial reductions in emissions >70% could be achieved by working through the whole value chain

Reduce CO_2 from clinker production	Reduce clinker in cement	Reduce cement in concrete	Reduce concrete in building	More efficient (re)use of buildings
Few producers Quick wins implemented	Few producers Large remaining potential	Many producers Implementation very difficult	Chain of deciders Implementation very difficult	Big changes in mindset needed
• Efficient plants • Waste fuels • Alternate raw materials	• SCMs	• Aggregate grading • Good admixtures • Use filler		

Efficiency of binder use (29 countries)



DAMINELI, et al. Measuring the eco-efficiency of cement use. **Cement and Concrete Composites**, 32, p. 555-562, 2010

What are the blockages?

- We have solutions:
  - At cement level: LC3
  - At concrete level: use admixtures, aggregate grading
  - At structure level: lean design, stick to codes, do not over design

- What are the barriers to implementation?

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Cement level

- No time to do anything new
- Cannot find clays
- Need to some investment
- Lack of awareness: largest companies only make up 30% of market
- Allowed in codes and standards

Concrete level

- Difficult to incentivise the v.large number of companies
- “we’ve always done it like that”
- Minimum cement content in codes from days before admixtures

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Structure level

- An engineer's time costs more than extra concrete
- Paranoia about safety
- Difficulty to calculate and compare possibilities

Complexity costs carbon!

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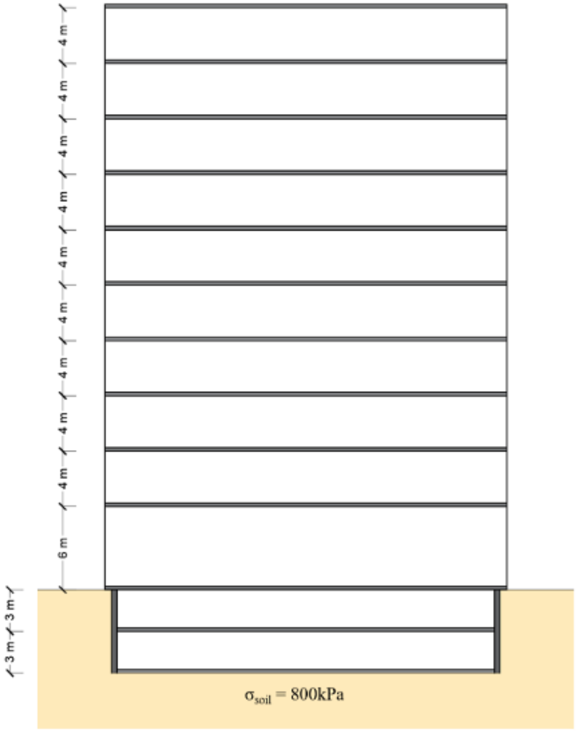
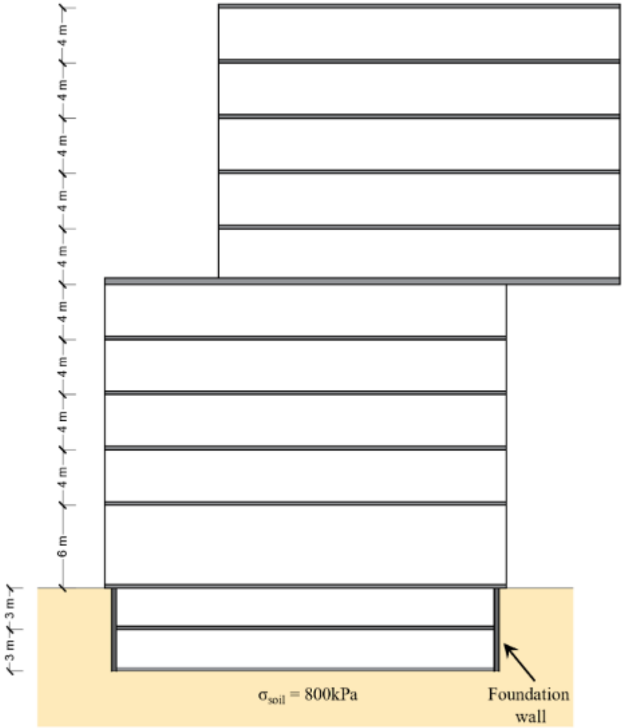
Carbon cost of irregularity



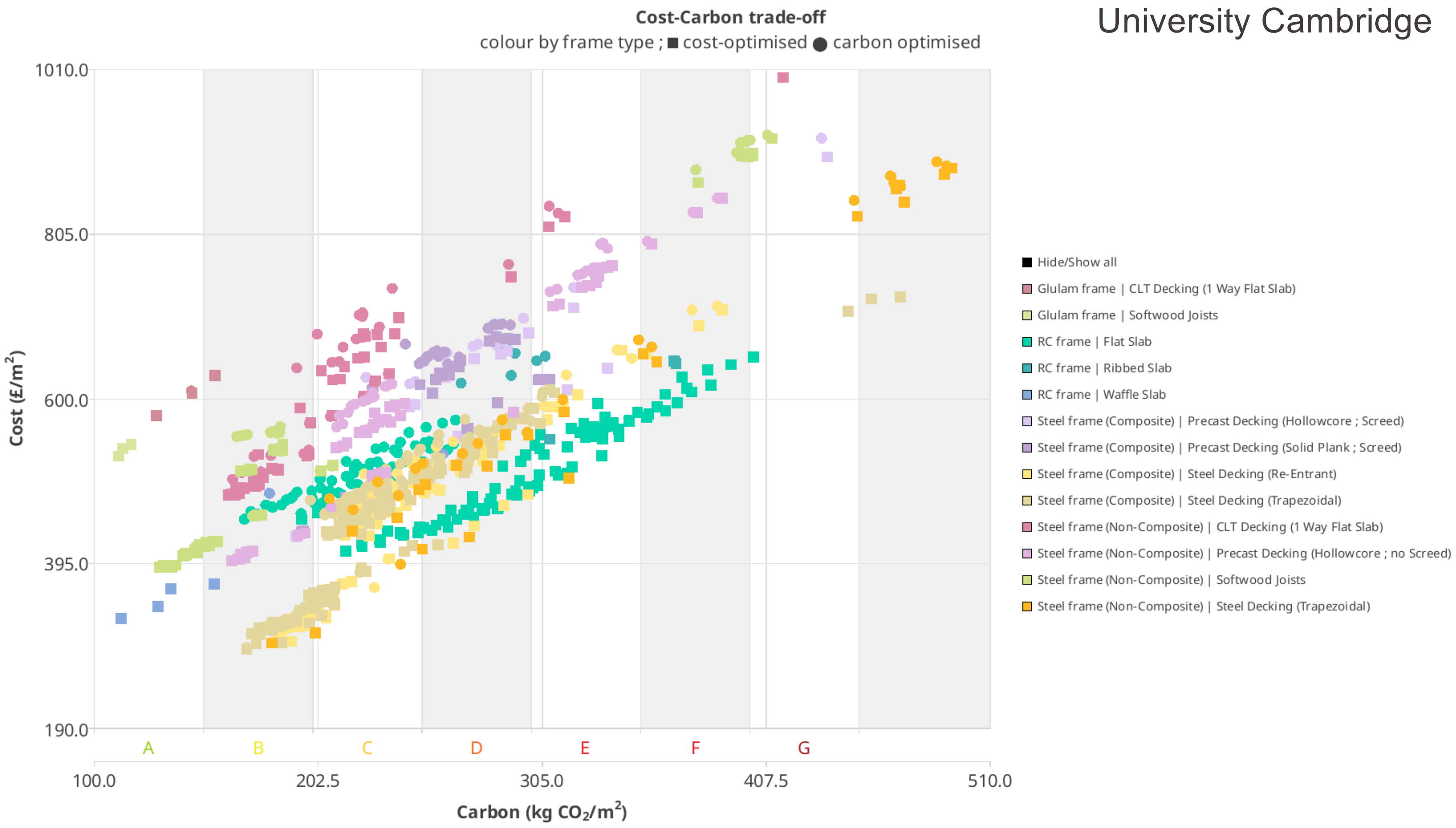
vs.



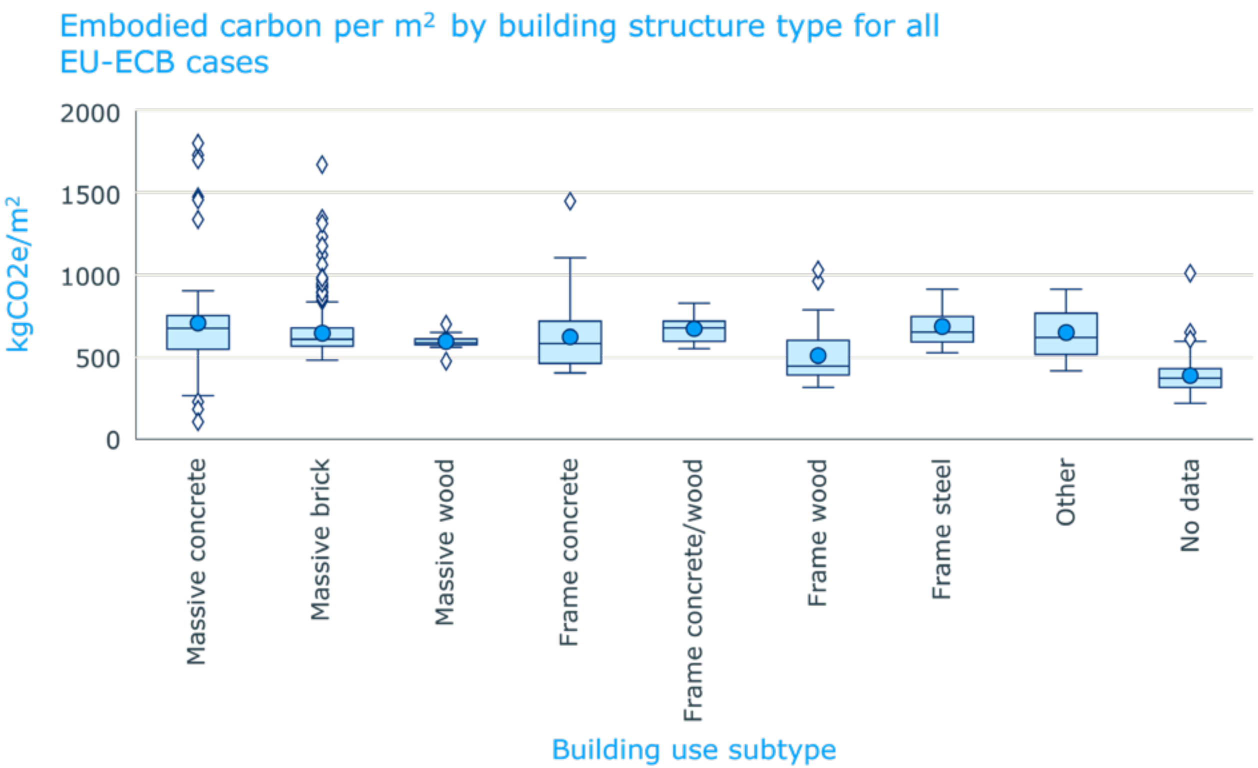
~50% more embodied carbon on average

Source: David Ruggiero

Output of Panda software from Cyrille Dunant, University Cambridge



Need for metric in applications



- Röck M, Sørensen A, Tozan B, Steinmann J, Le Den X, Horup L H, Birgisdottir H
Towards EU embodied carbon benchmarks for buildings – Setting the baseline: A bottom-up approach, 2022, https://doi.org/10.5281/zenodo.5895051.

Overall

- Thinking there are miracle alternatives
- Wasting time, effort and money on unscalable or ideas of dubious honesty

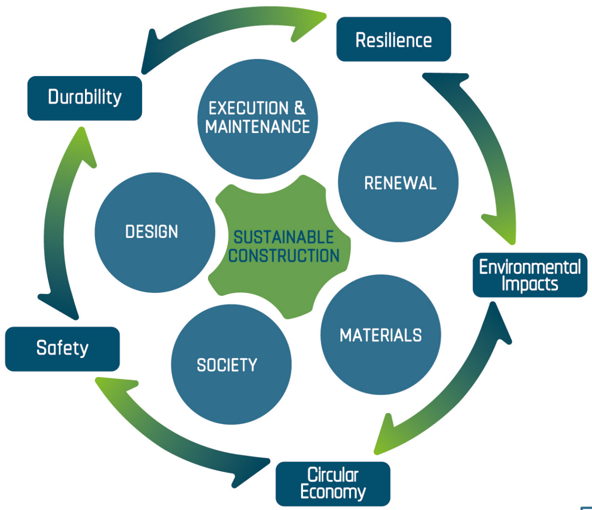
- Getting the different parts of the industry to work together

To realise these gains the industry needs to work together

GLOBE

Global consensus on sustainability in the built environment

- High level policy advice
- More than 150 nations
- 5000+ experts
- 50+ years of expert networks
- Standards and guidelines
- Research and education
- Innovation



www.globe-consensus.com

See on-line presentation from COP28 for more details

rilem

fib CEB•FIP

cib

ECCS CECM EKS

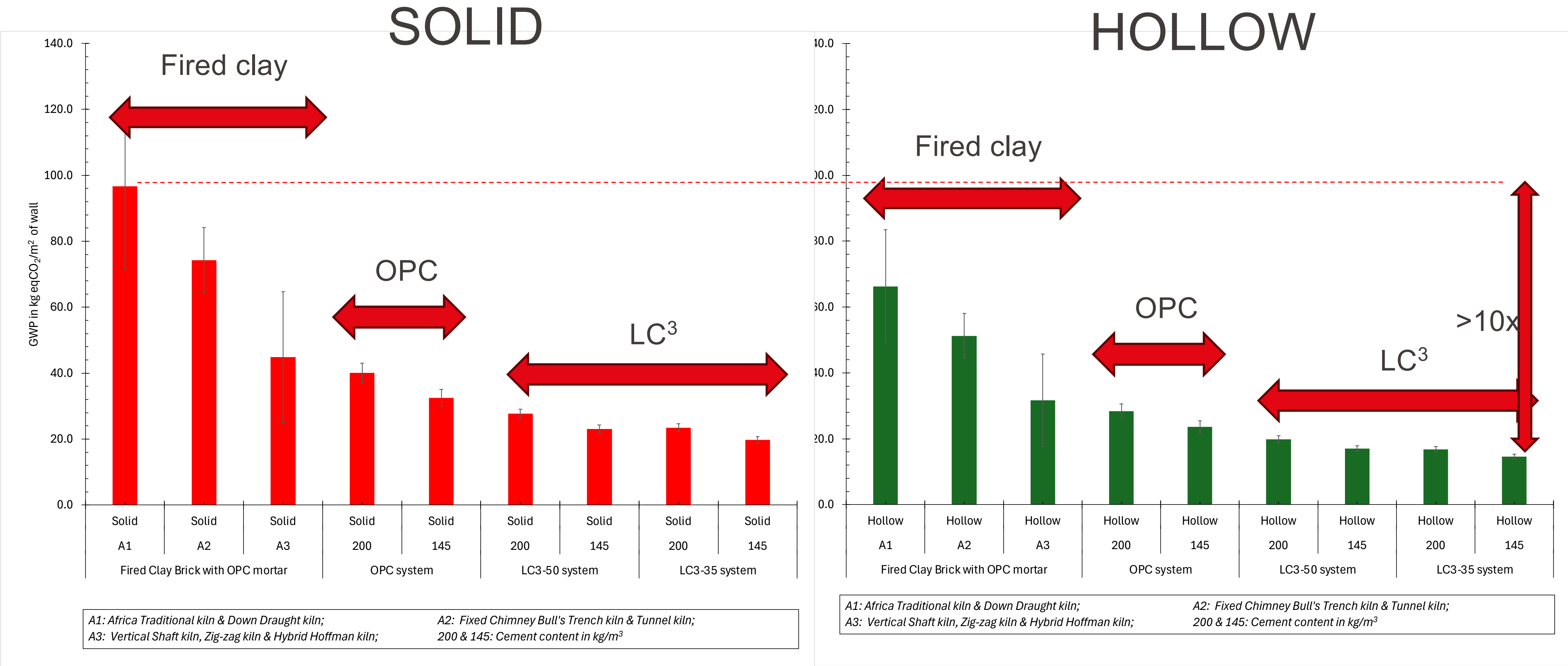
IABSE

iass

Africa Brick by Brick

EPFL

Concrete blocks


SOLID
HOLLOW
Fired clay
OPC
LC3
>10x
GWP in kg eqCO2/m2 of wall
Fired Clay Brick with OPC mortar
OPC system
LC3-50 system
LC3-35 system
A1: Africa Traditional kiln & Down Draught kiln;
A2: Fixed Chimney Bull's Trench kiln & Tunnel kiln;
A3: Vertical Shaft kiln, Zig-zag kiln & Hybrid Hoffman kiln;
200 & 145: Cement content in kg/m3

EPFL

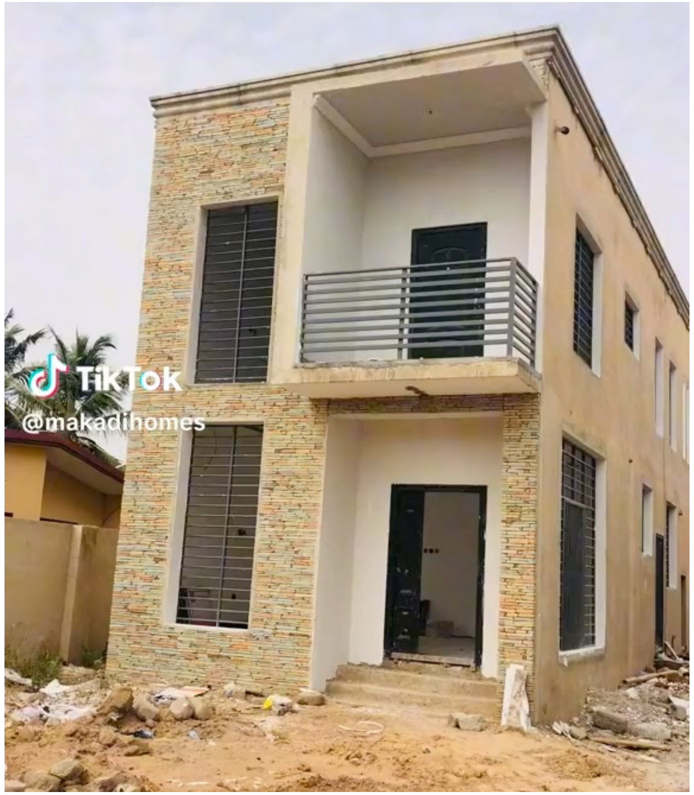
Dr. Alice Titus Bakera (Civil Engineer)

Postdoctoral researcher at EPFL

Lecturer at the University of Dar es Salaam, Tanzania

EPFL

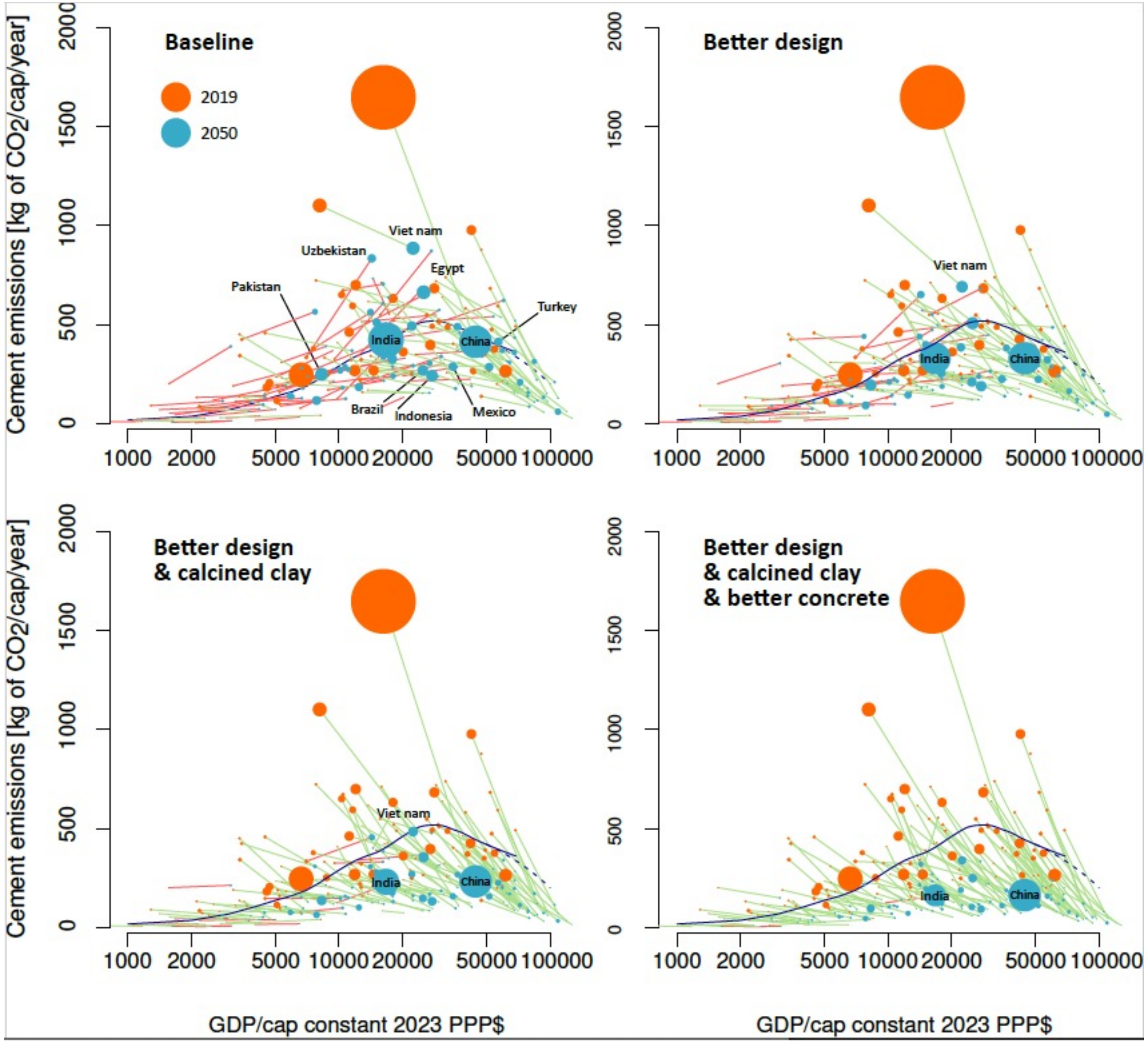
From cliché to real aspiration!



Can we decouple growth from rising emissions

EPFL

Deploying these reduction strategies can allow growth without increasing CO_2 emissions



From Cyrille Dunant, U. Cambridge

Concluding remarks

- ✓ Portland Based cements are here to stay
- ✓ There is no viable alternative
- ✓ Substantial reductions in CO_2 are possible
  - ✓ At cement level by increasing SCM substitution
  - ✓ At concrete level by minimising cement content
  - ✓ At structure level

- ✓ All of the above will also lower cost

- ✓ Remainder CO_2 can only be dealt with by carbon capture and storage at a high cost, infrastructure not in place.

- ✓ Calcined clays are the only realistic option for extending the use SCMs

- ✓ Can be done FAST and at SCALE

Thank You

Karen Scrivener

École
polytechnique
fédérale
de Lausanne