

## Decarbonisation pathways for cement and concrete

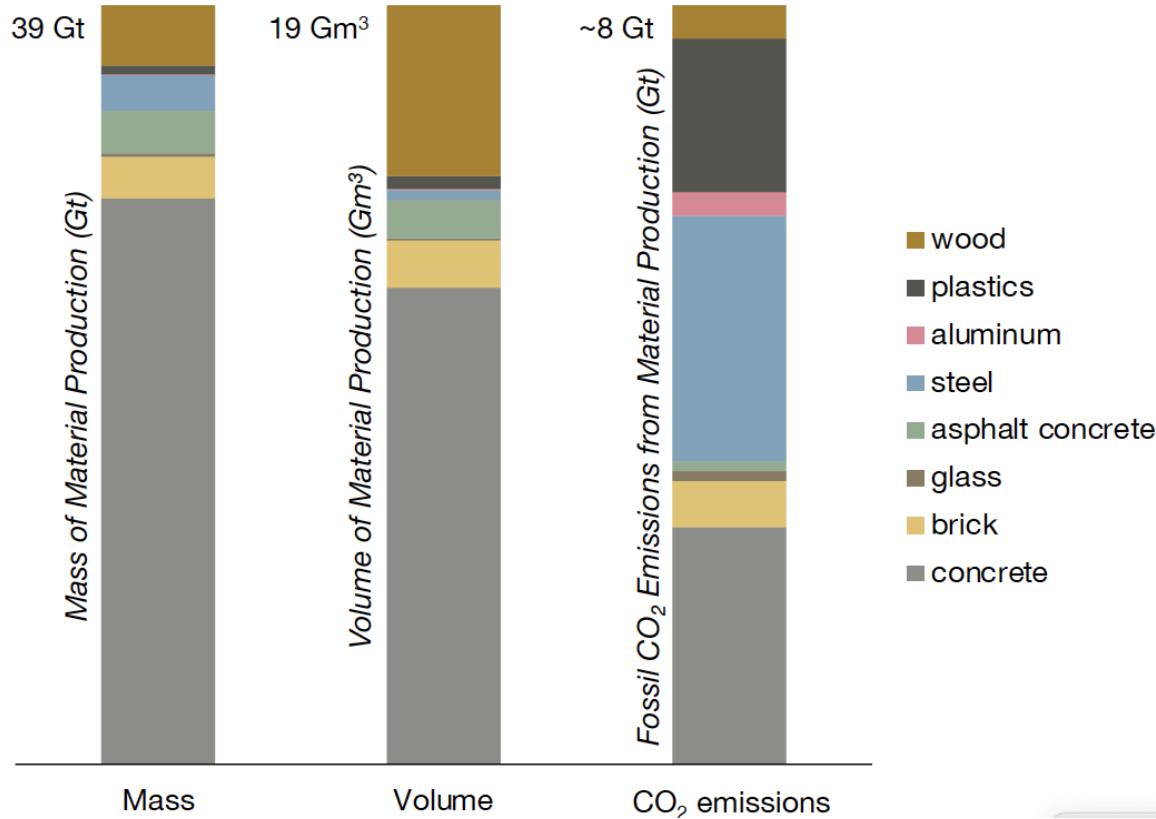
Karen Scrivener, FREng

EPFL

Switzerland

# All the Materials we use

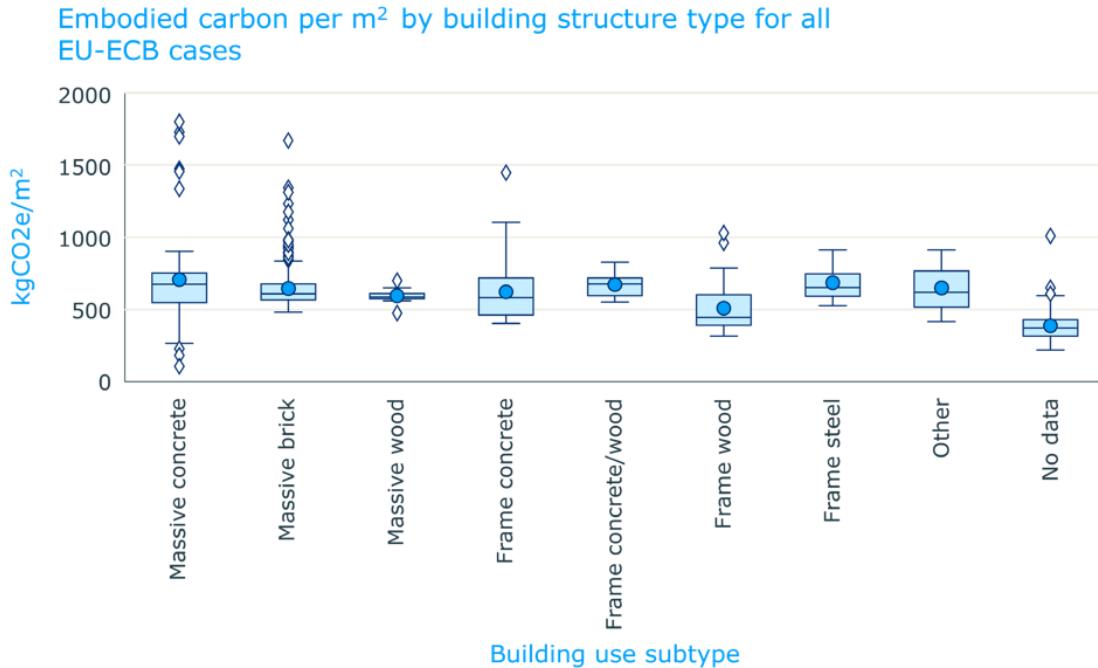
90% construction



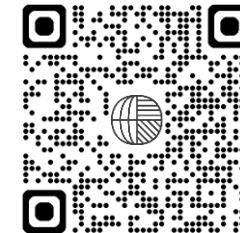
Replacing just 25% of concrete with wood sustainably would require new forest 1.5 times the size of India



# Would it help to replace concrete by other materials?



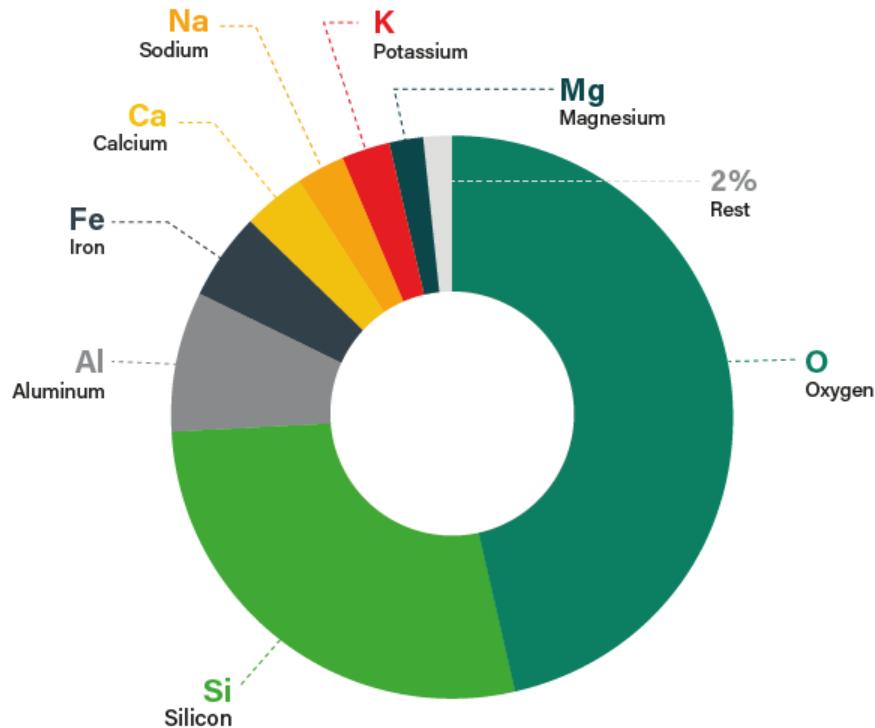
Global Building  
Data Initiative



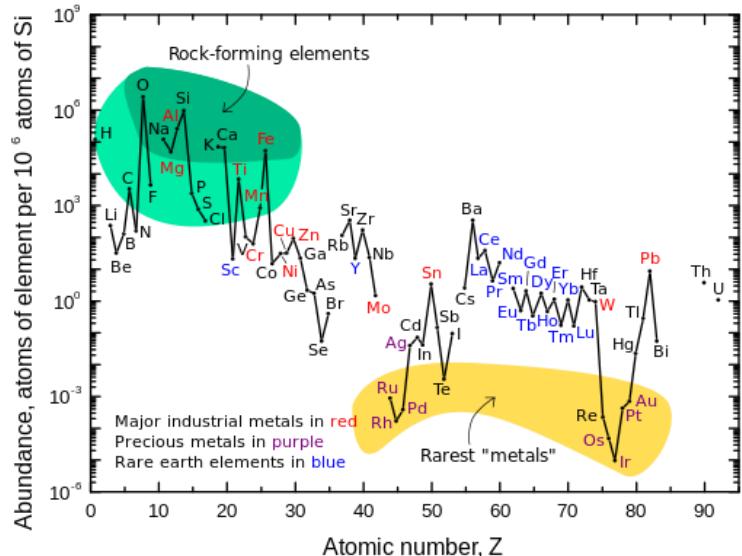
# **It is not by chance Portland cement is the most used material on earth**

It is a direct consequence of chemistry and geology

# What is available on earth?

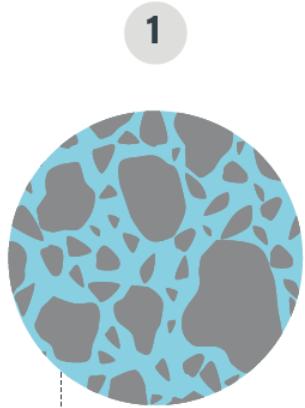


8 elements make up  
more than 98%  
of the earth's crust



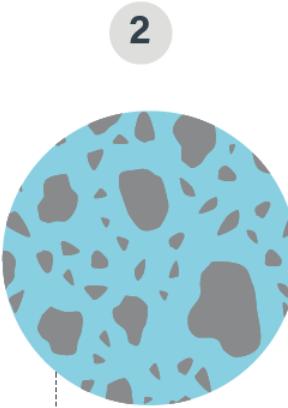
Due to the processes of forming elements in stars  
other rocky planets will be similar

# How does cements work?



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



The cement grains dissolve in the water



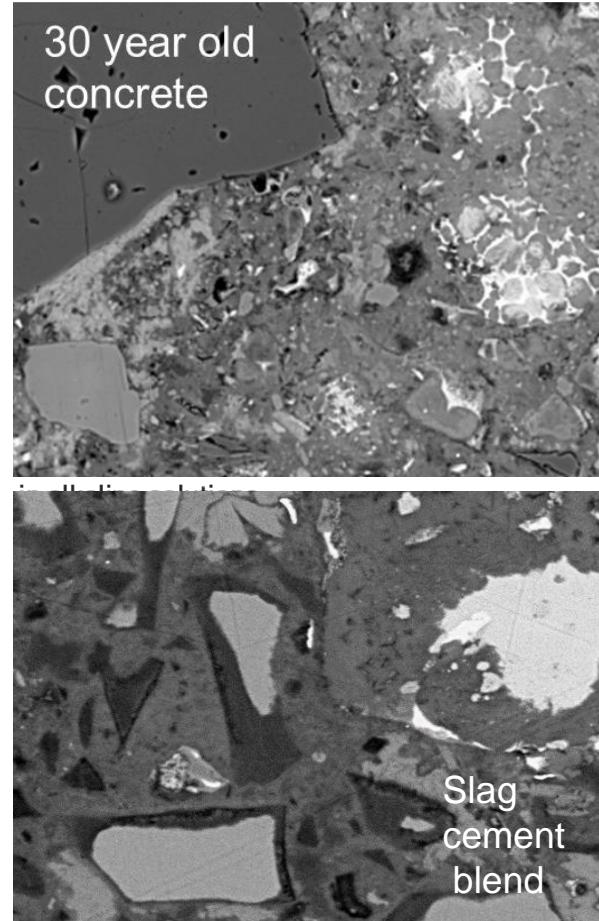
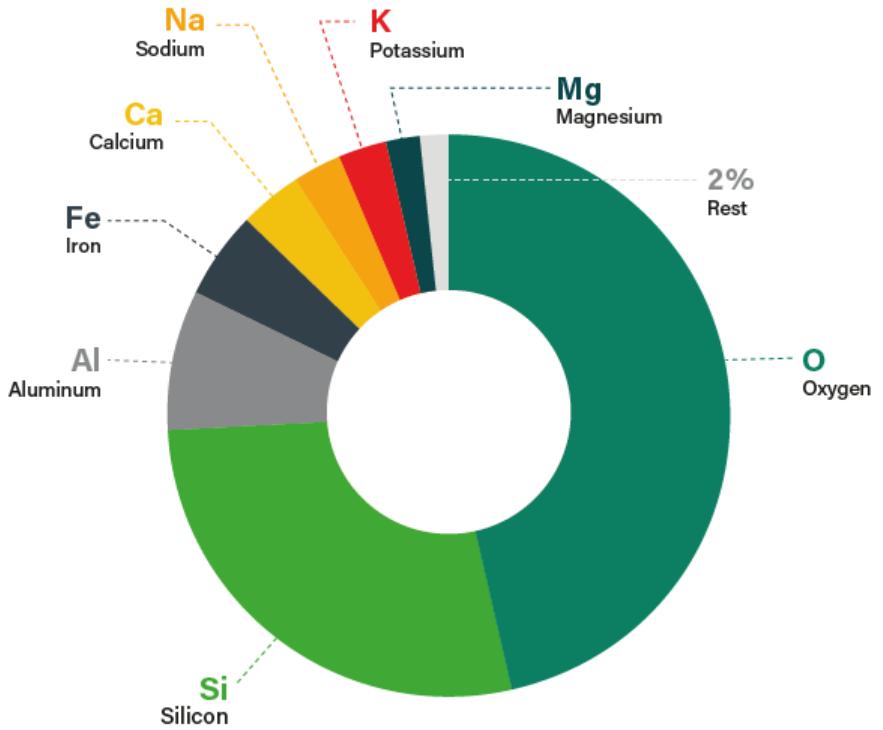
The cement grains dissolve in the water

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

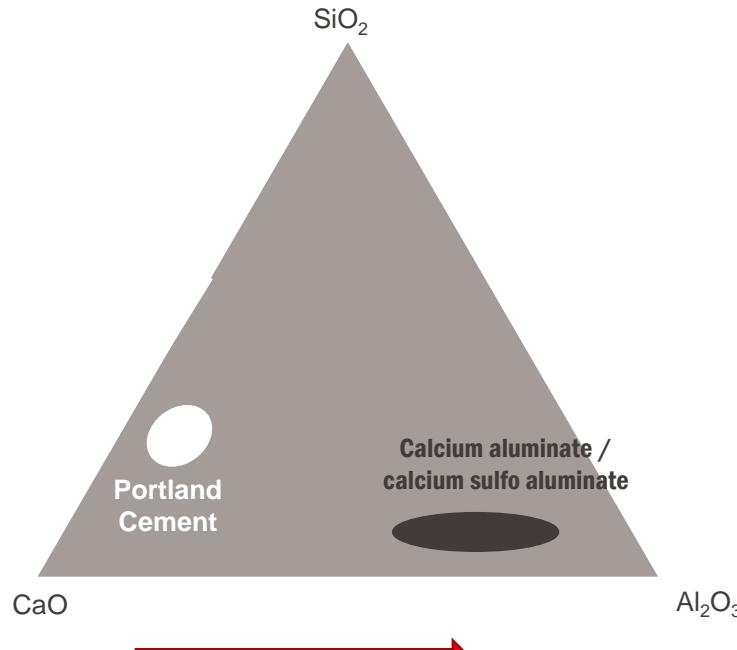
■ Cement grain

■ Water

# What is available on earth?



# Hydraulic minerals in system $\text{CaO}-\text{SiO}_2-\text{Al}_2\text{O}_3$



BUT, what sources of minerals are there which contain  $\text{Al}_2\text{O}_3 \gg \text{SiO}_2$  ?

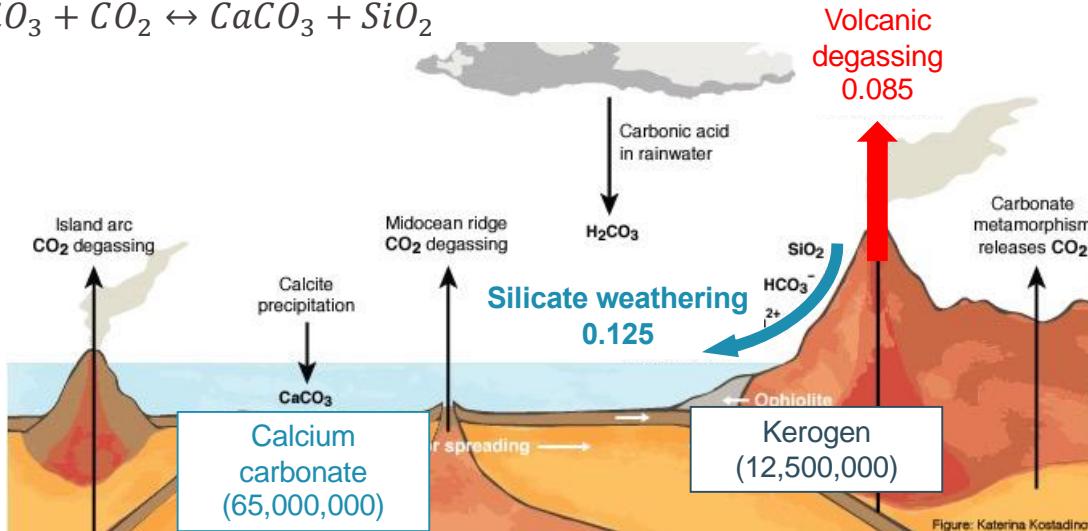
Bauxite – localised,  
under increasing demand for Aluminium production,  
EXPENSIVE

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]

# Limestone

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

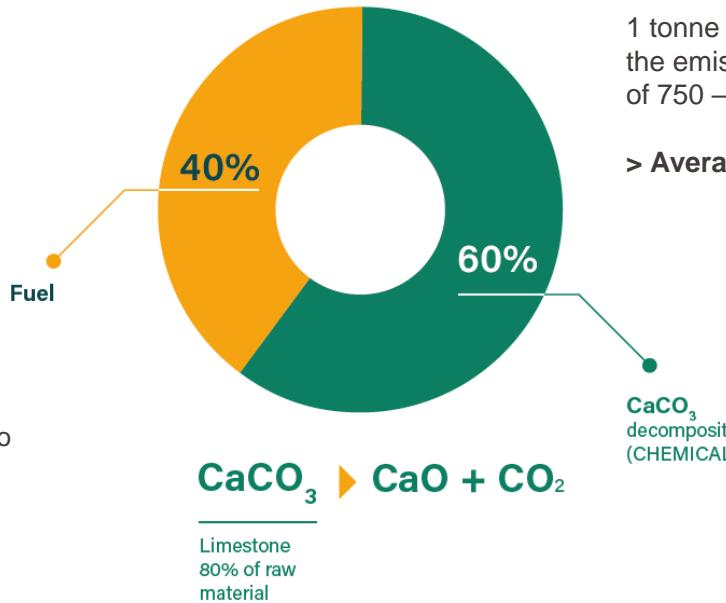


No surprise that the interesting properties of limestone – clay combinations were discovered in Europe about 200 years ago

# But unfortunately production of cement from limestone leads to substantial CO<sub>2</sub> emissions



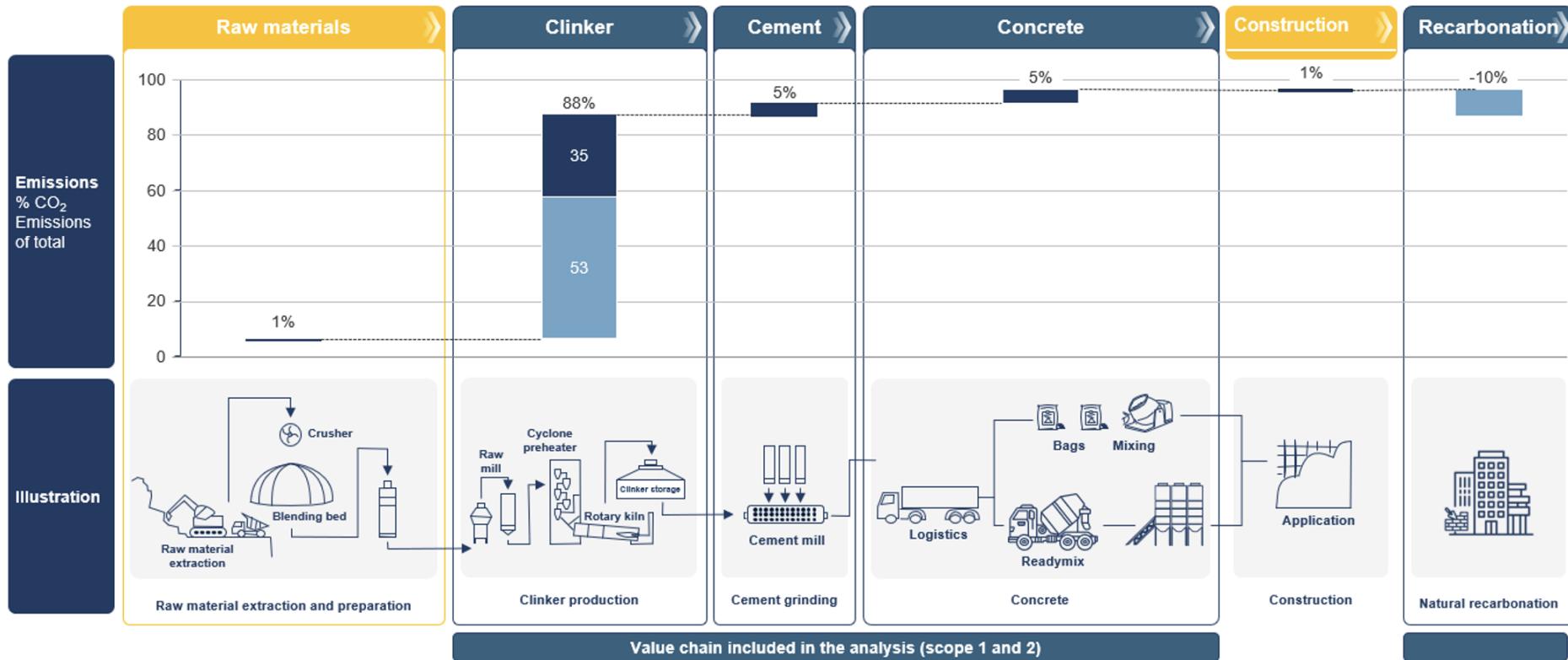
- The production process is highly optimised up to around 80% of thermodynamic limit.
- It is estimated that < 2% further savings can be made here
- Use of waste fuels, which can be > 80% reduces the demand for fossil fuels



1 tonne of clinker leads to the emission of 750 – 900 kg CO<sub>2</sub>

> Average 850kg/t

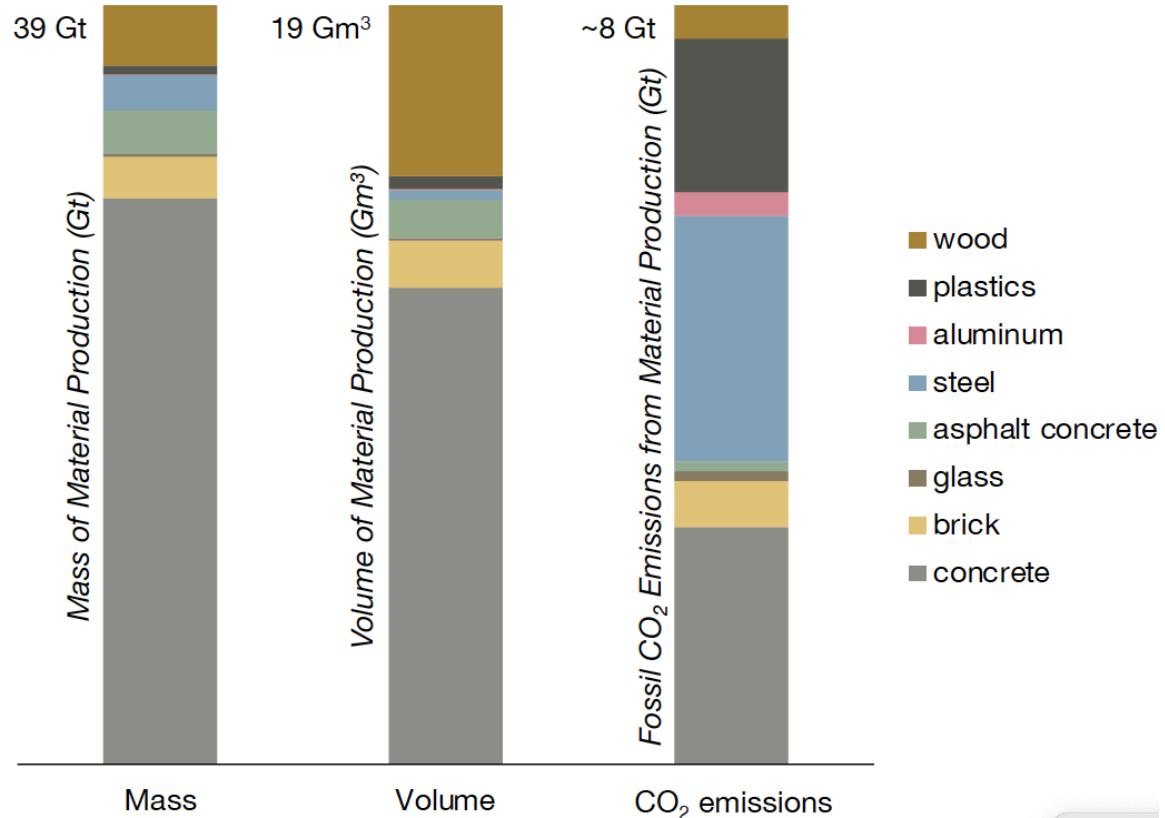
# Clinker is responsible for 85-90% of CO<sub>2</sub> emissions for cement-based materials



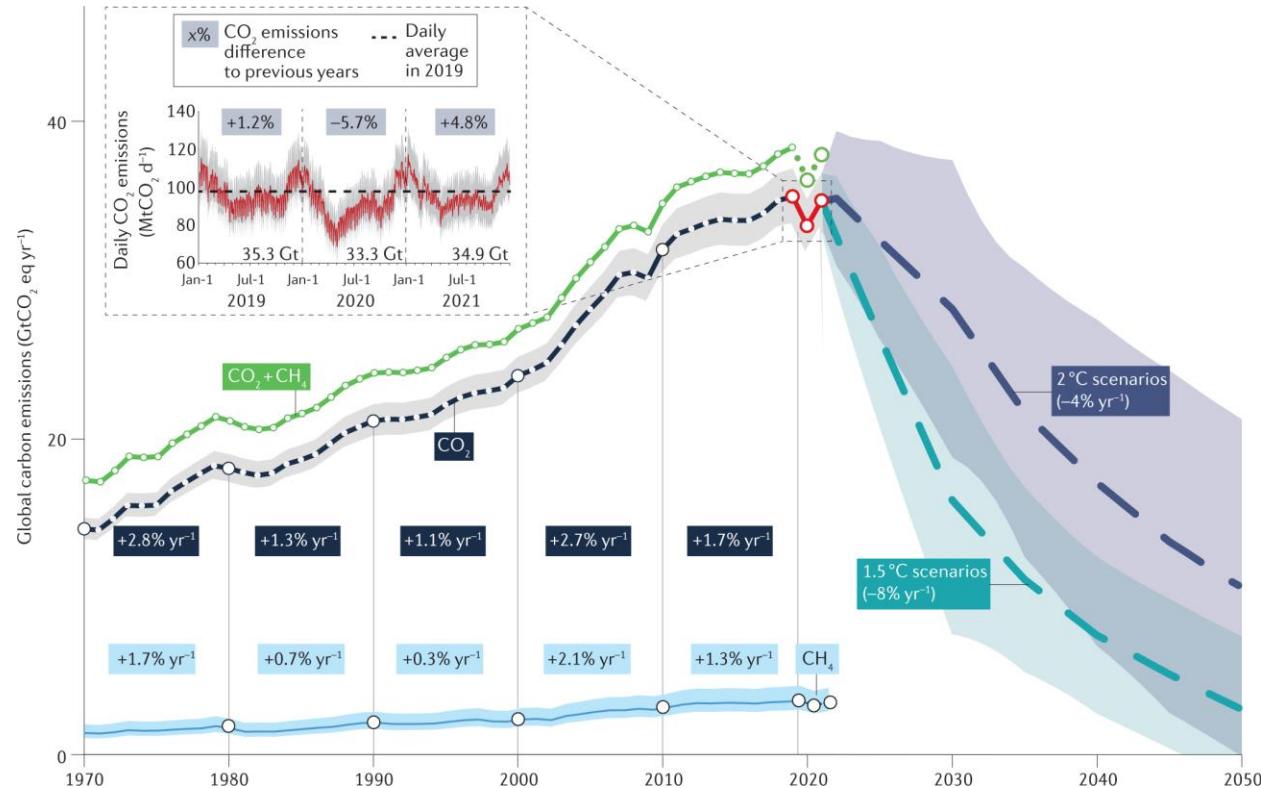
- Source: Mission Possible Partnership

# But still very good value for CO<sub>2</sub>

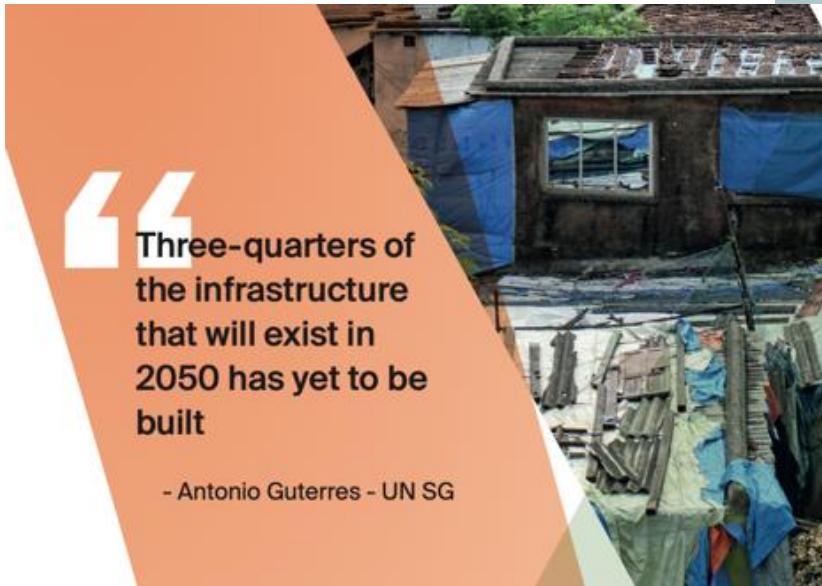
World Use of materials: 90% construction



# Need to act fast



# Tomorrow....



“Three-quarters of the infrastructure that will exist in 2050 has yet to be built

- Antonio Guterres - UN SG



“

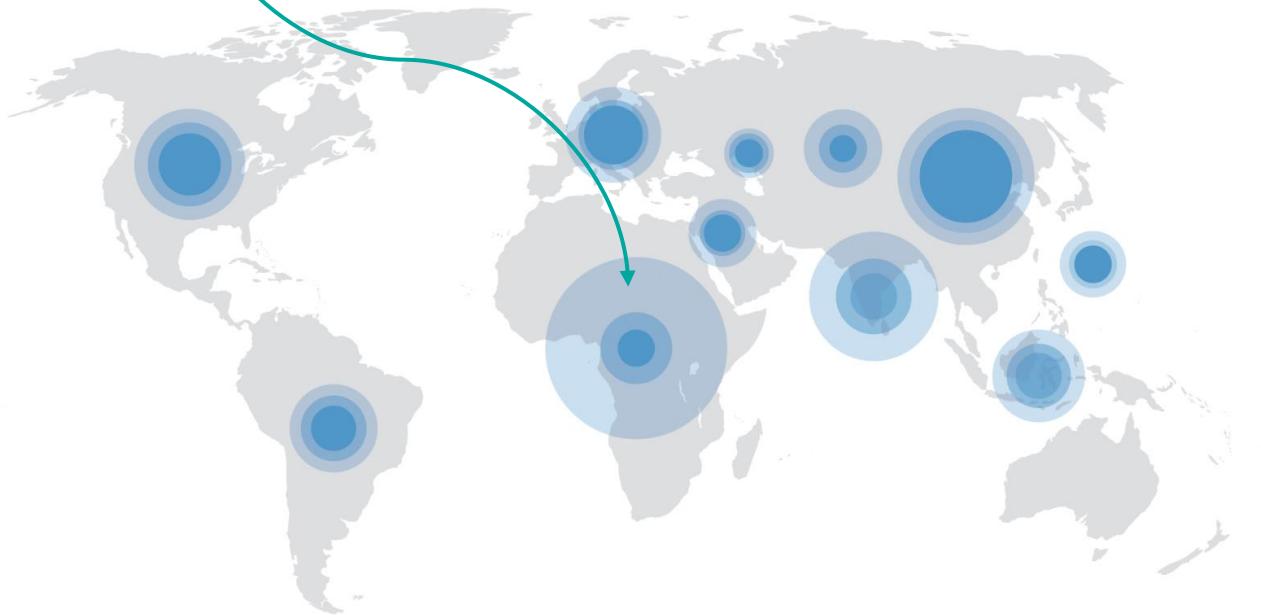
Up to 2060, the world is expected to add the equivalent of an entire New York City to the world, every month, for 40 years.

- Architecture2030.org

This will **NOT HAPPEN** in the Global North

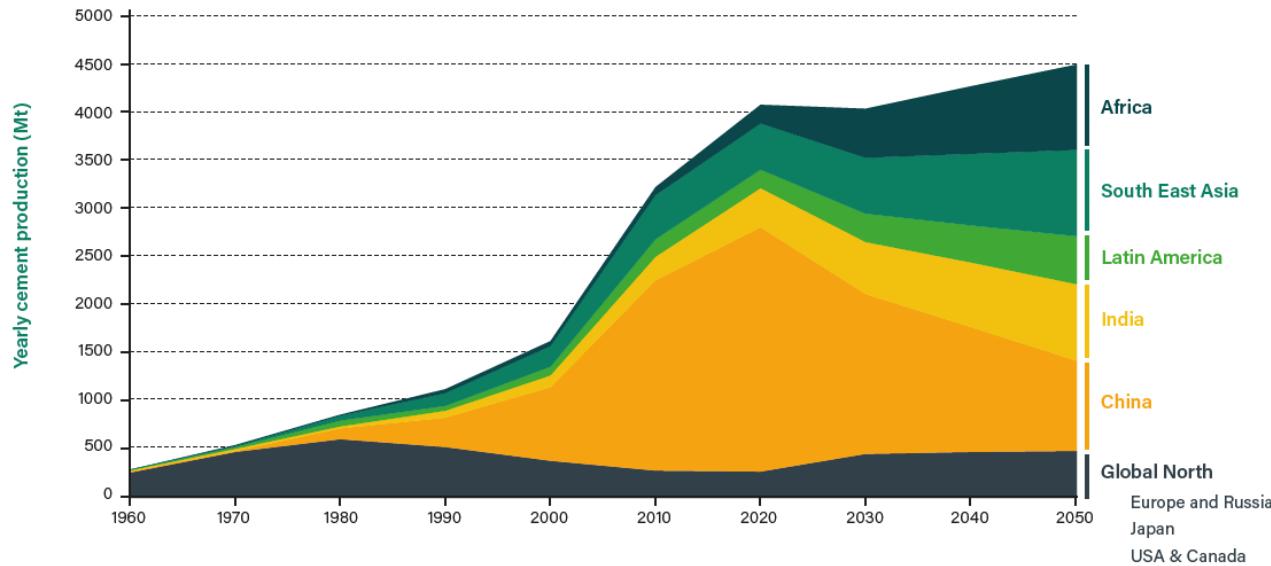
# It will happen HERE

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



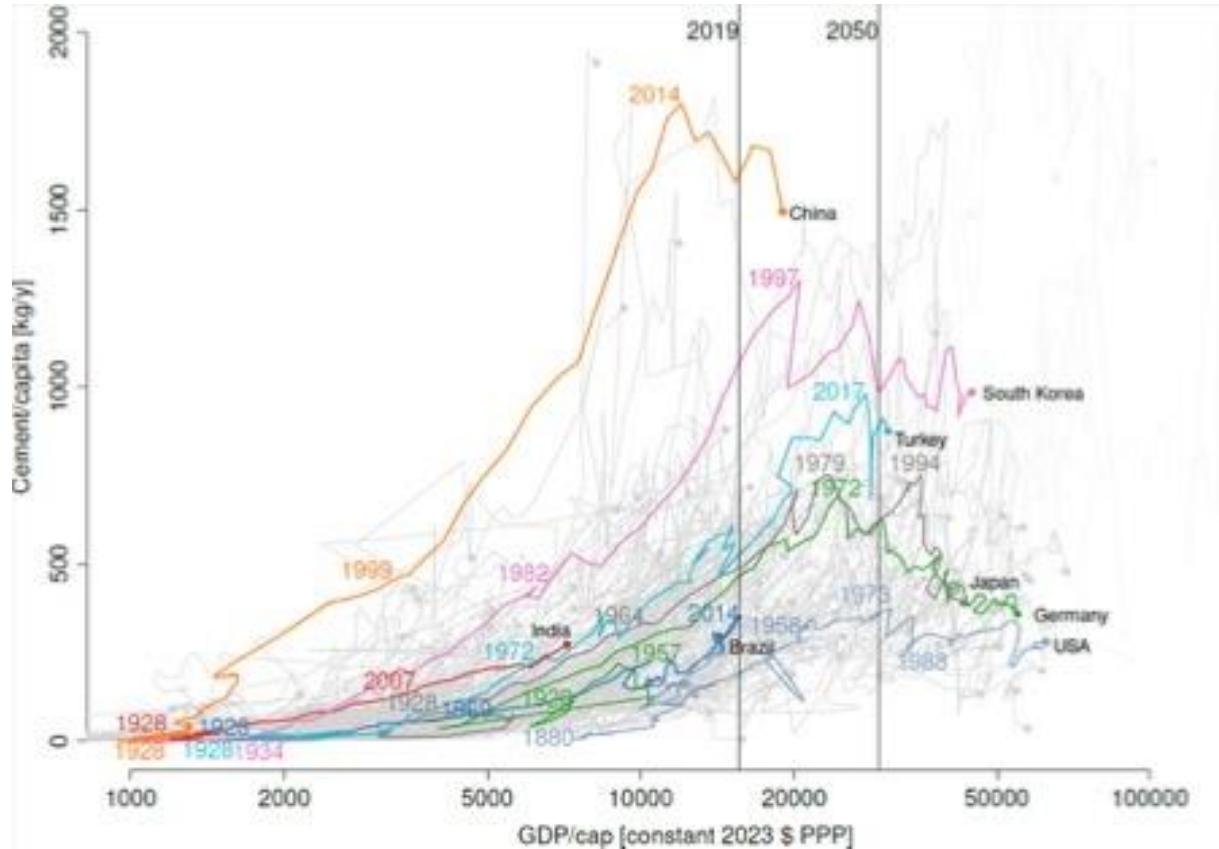
# Changing pattern of cement use

Historical and forecast cement supply per region



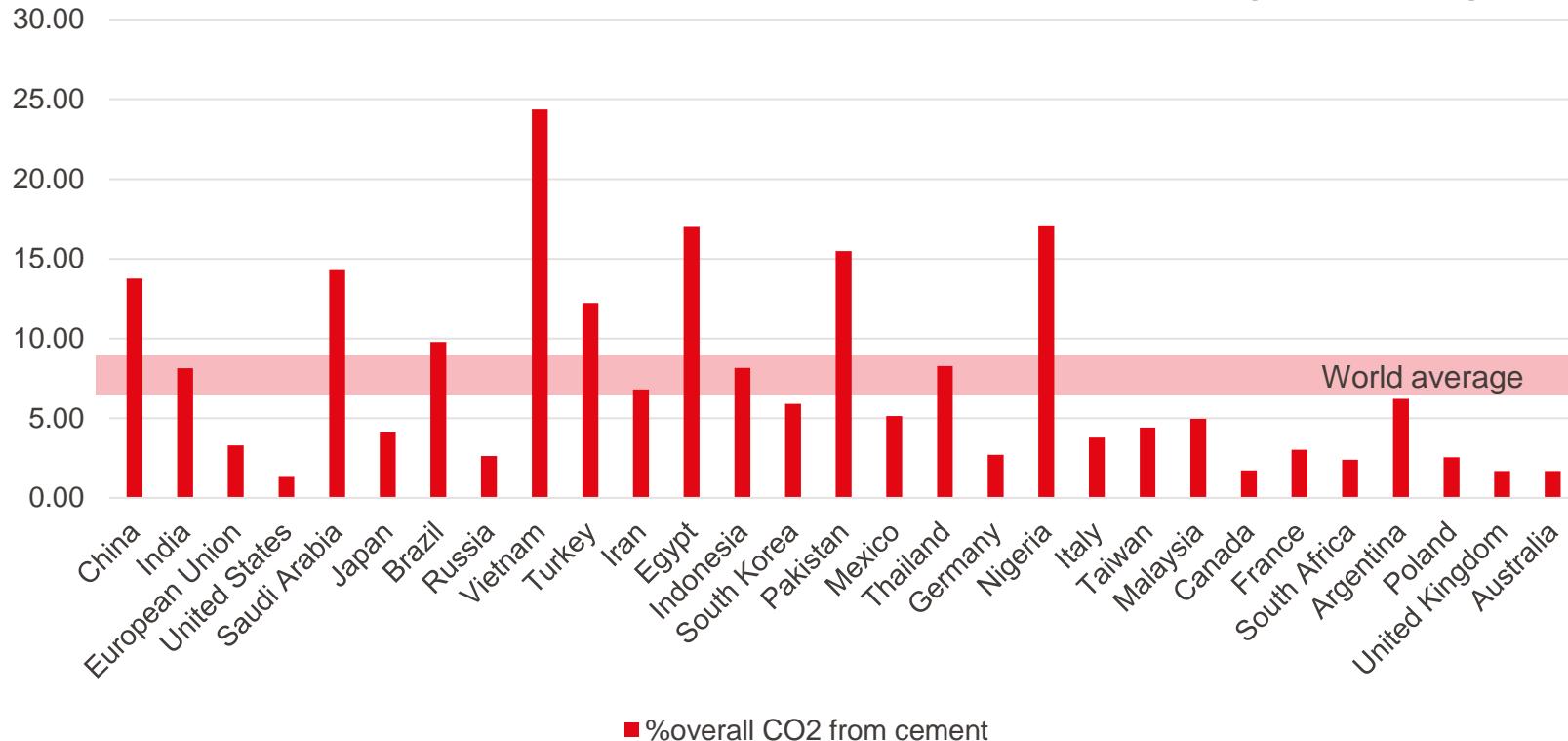
We need solutions for people in developing countries

# Concrete “Hump” a normal phenomenon of growth



In China maybe 1000 out 1500 cement plants will close

# Contribution of cement to CO<sub>2</sub> 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?

Name of oxide	Content, % by weight
SiO <sub>2</sub>	46.5 – 51.5
Al <sub>2</sub> O <sub>3</sub>	15.0 – 19.0
MgO	4.0 – 10.5
CaO	7.5 – 11.5
FeO+Fe <sub>2</sub> O <sub>3</sub>	8.0 – 12.0
K <sub>2</sub> O+Na <sub>2</sub> O	3.0 – 6.0
TiO <sub>2</sub>	0.3 – 2.5
Cr <sub>2</sub> O <sub>3</sub>	0.02 – 0.05
MnO	< 0.1
Other	Up to 100

**Dissolve in acid**

**Precipitate oxide separately**

Common technology  
in mining industry

**Make clinker with  
uncarbonated calcium oxide**

Estimated cost ~ \$800 / ton

Source research gate

**>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

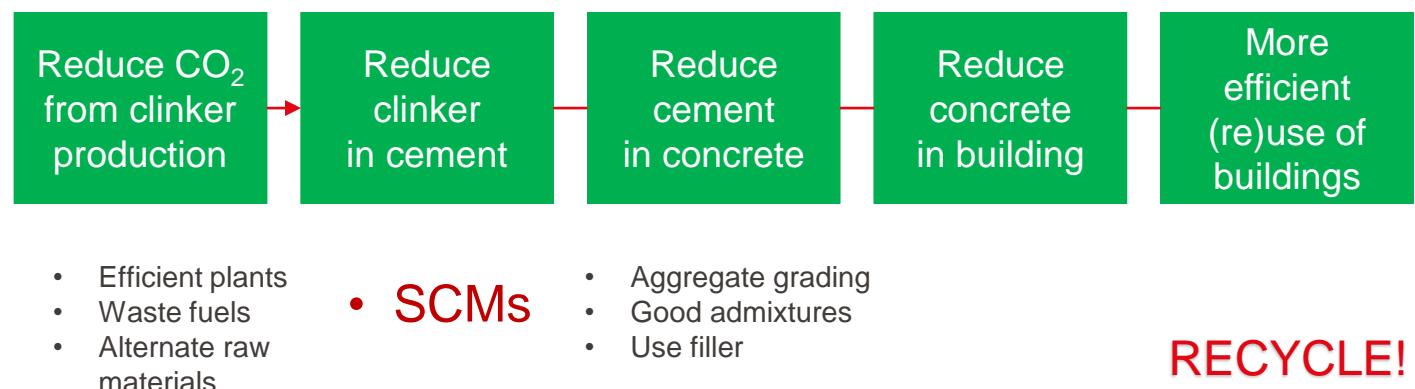
Despite the media interest they attract, most niche technologies – such as alkali activated materials, cement from algae, etc are:

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

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

**But there is good news?**

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





Article

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

# Near-term pathways for decarbonizing global concrete production

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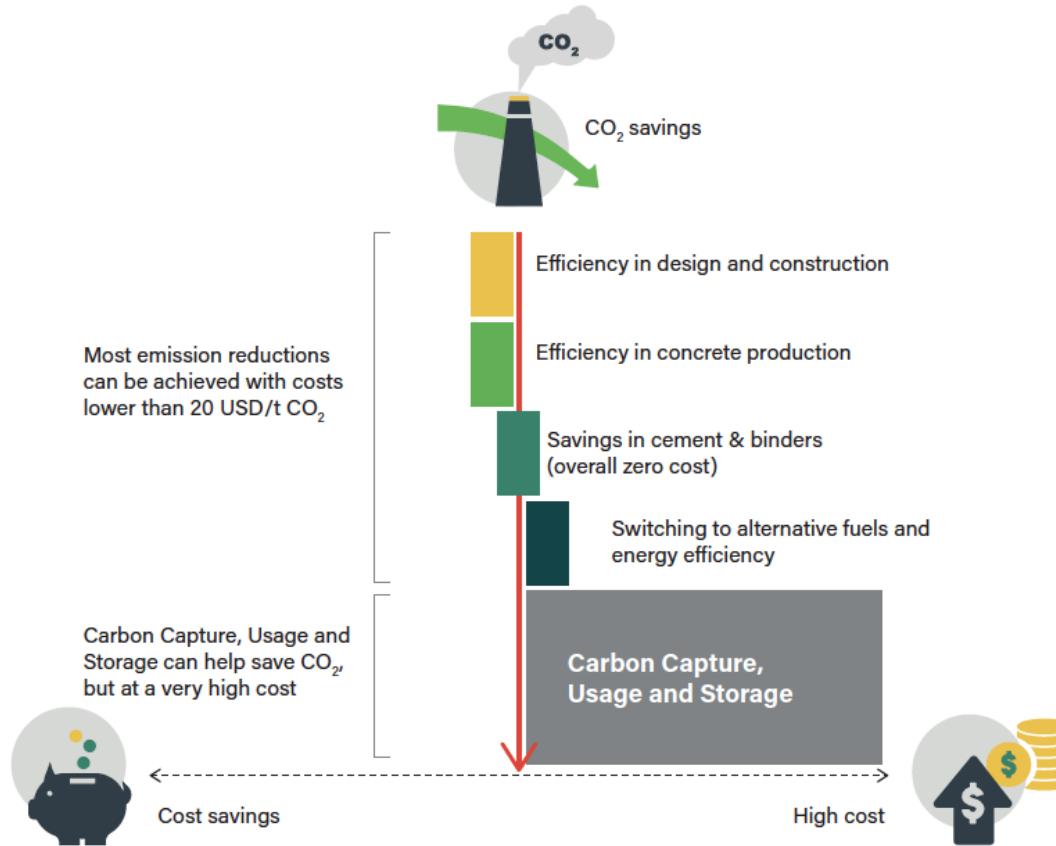
Received: 27 January 2023Josefine A. Olsson <sup>1</sup>, Sabbie A. Miller <sup>1</sup> & Mark G. Alexander <sup>2</sup>

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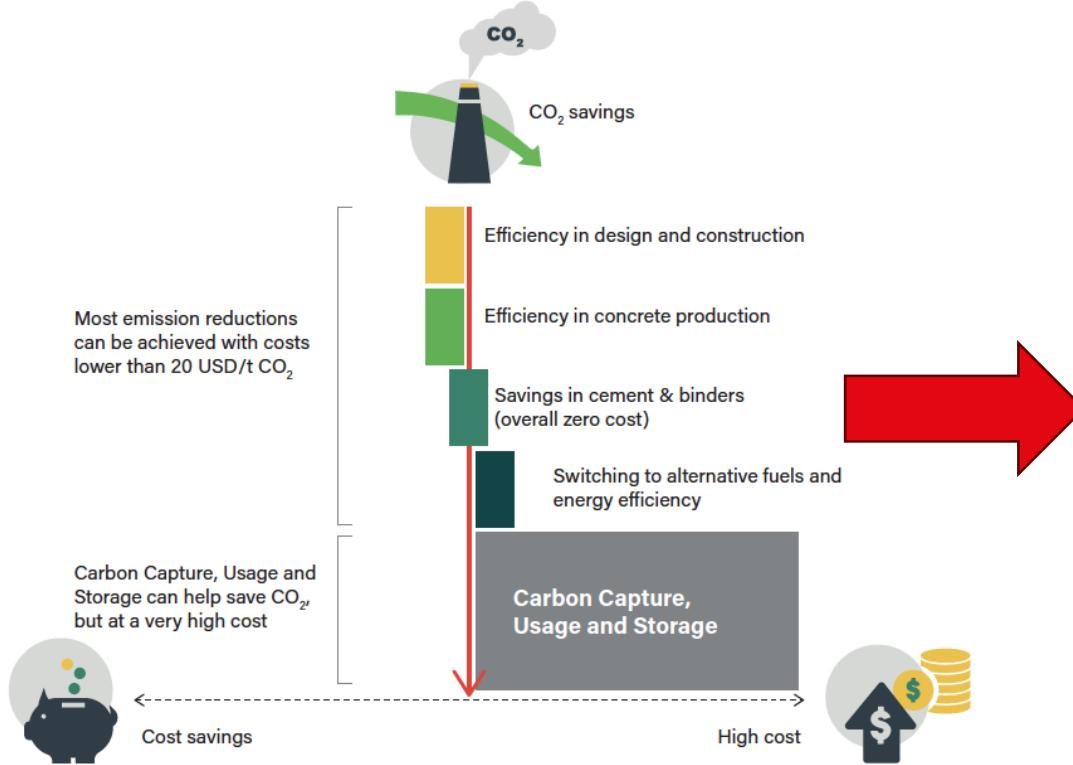
Accepted: 21 July 2023

Calculated 76% with these strategies

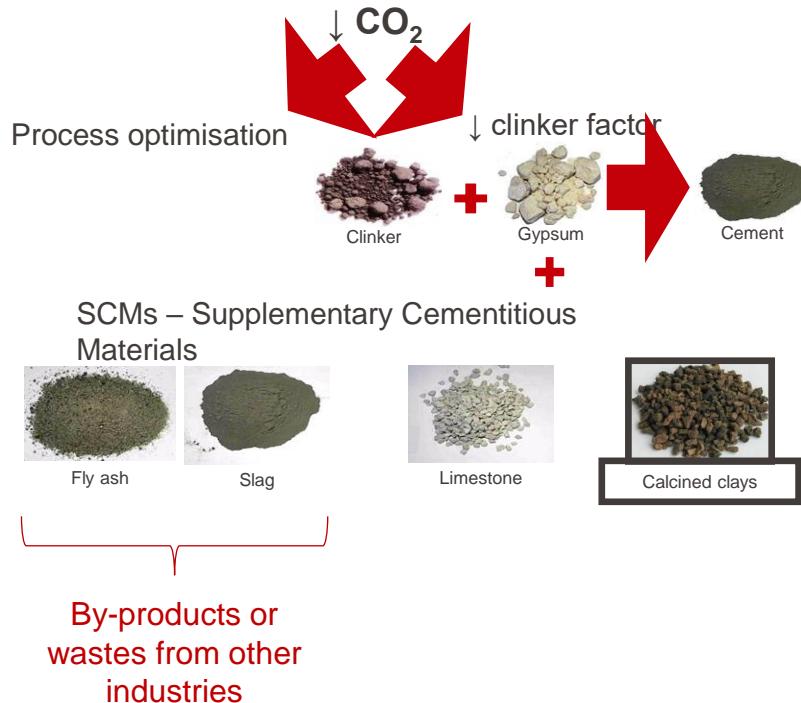
# Much of the path to net zero is low cost



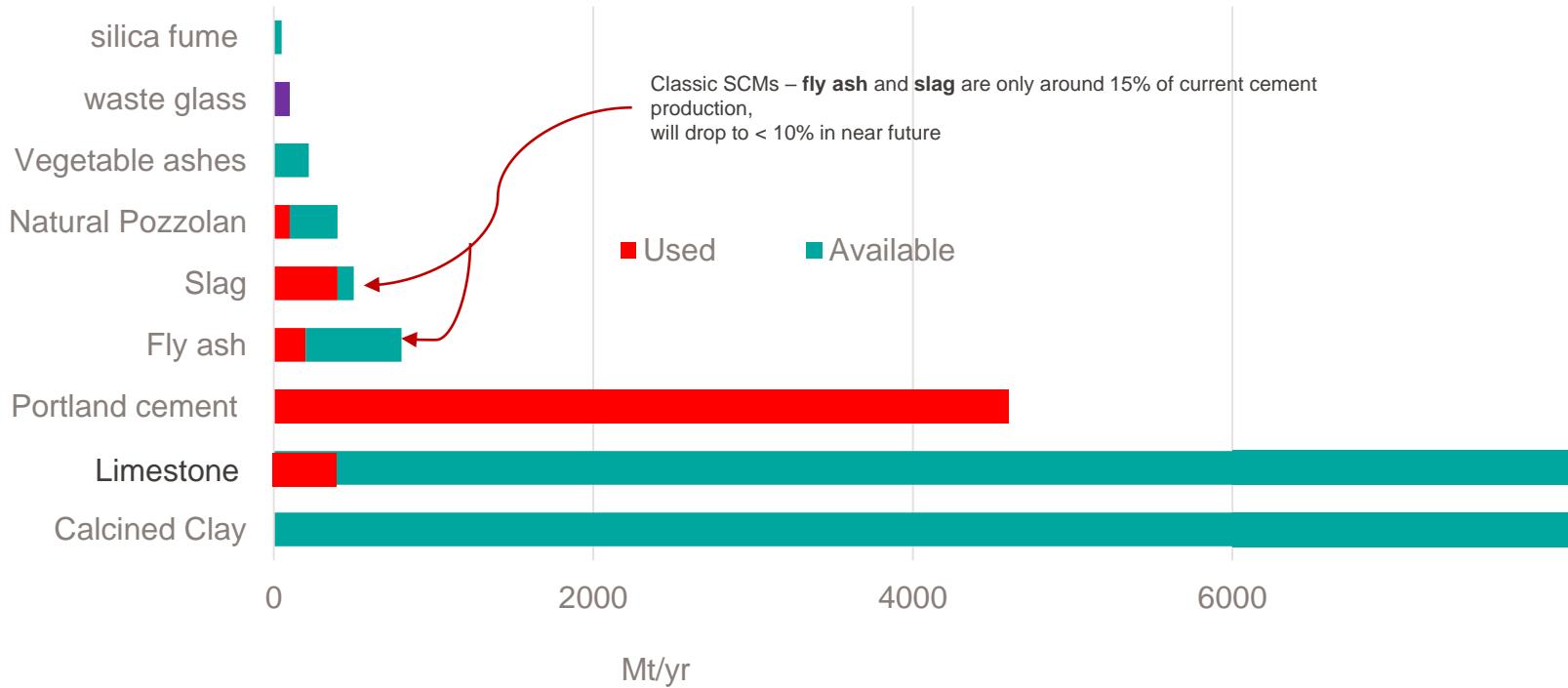
# Reducing clinker factor is the most practical to implement



# Most promising approach – reducing the clinker factor



# Availability of SCMs



# There is no magic solution

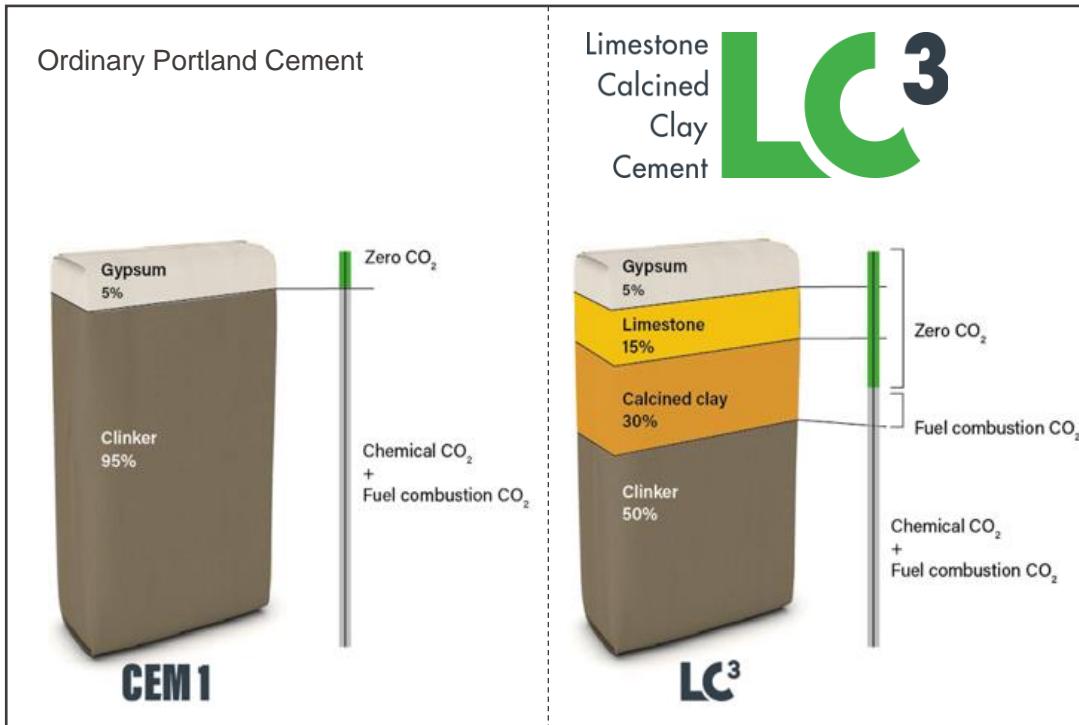
- Blended with SCMs will be best solution for sustainable cements for the foreseeable future.
- **Only material** really potentially available in viable quantities **is clay**.
- **Synergetic reaction** of calcined clay and limestone allows high levels of substitution
- EPFL led the LC<sup>3</sup> Project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



Schweizerische Eidgenossenschaft  
Confédération suisse  
Confederazione Svizzera  
Confederaziun svizra  
  
Swiss Agency for Development  
and Cooperation SDC

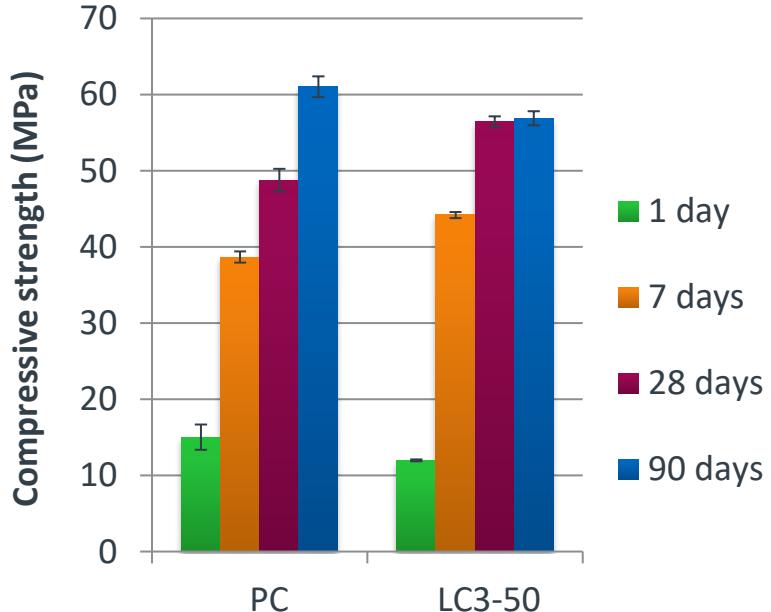


# LC<sup>3</sup> – Limestone Calcined Clay Cement



- LC<sup>3</sup> is a **low-carbon** blended cement type
- **Reduces CO<sub>2</sub> emissions in cement by 40%**

# LC<sup>3</sup> has comparable strength to OPC



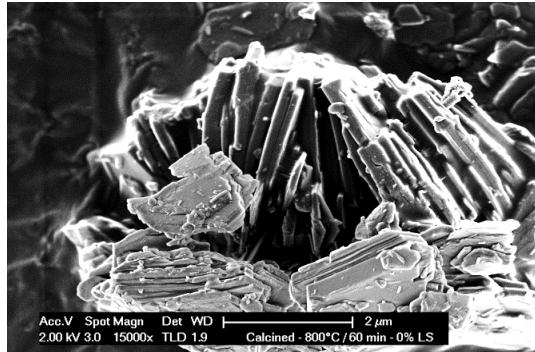
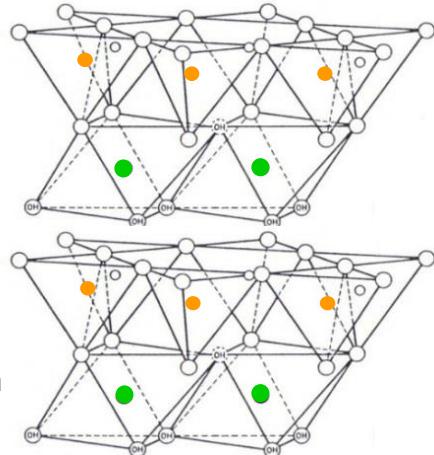
LC3-50 = 50% clinker.

- 50% less clinker
- 40% less CO<sub>2</sub>
- Similar strength
- Better chloride resistance
- Resistant to alkali silica reaction

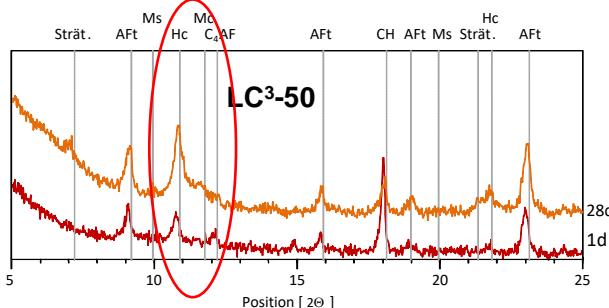
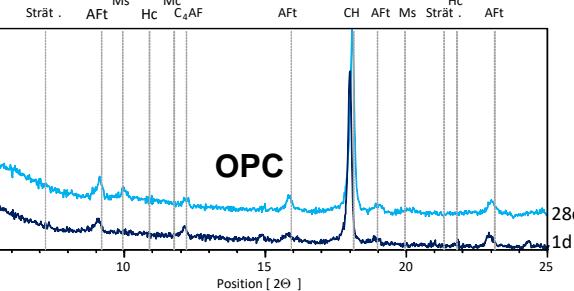


# Why can we get such high replacement levels?

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

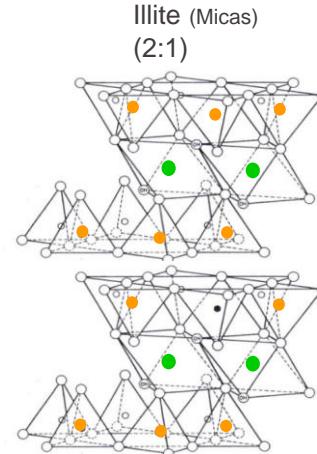
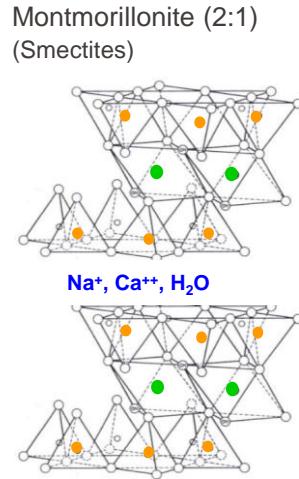
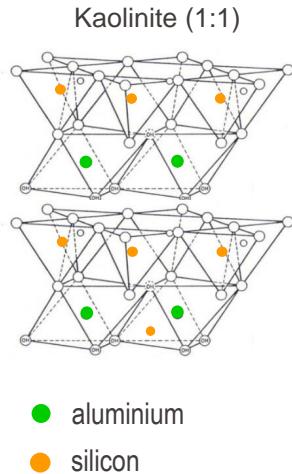


- » Synergetic reaction of Alumina in metakaolin with limestone to give space filling hydrates



# **What kinds of clay are suitable?**

# Three basic clay structures



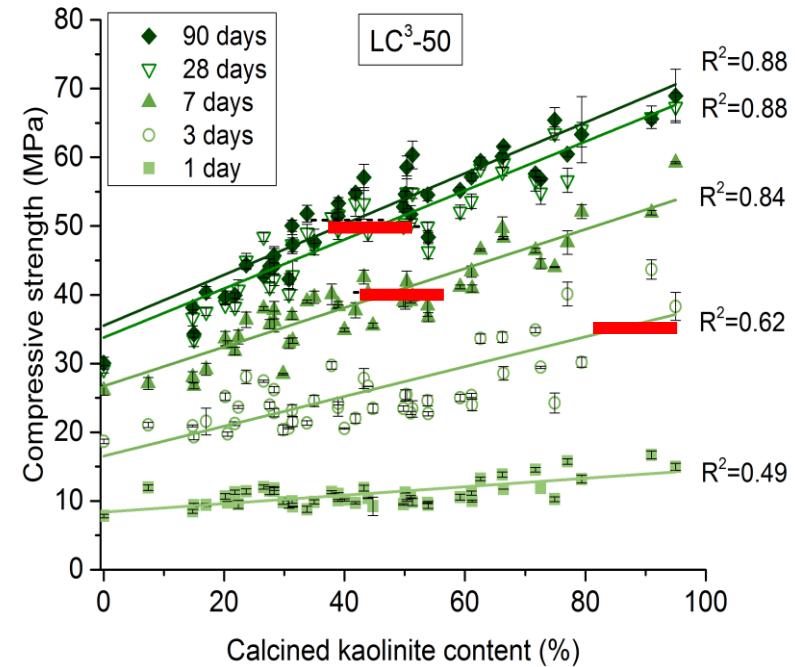
“Metakaolin”, sold as high purity product for paper, ceramic, refractory industries  
Requirements for purity, colour, etc, mean expensive 3-4x price cement

Clays containing metakaolin available as wastes  
– over or under burden NOT agricultural soil

▪ *Much much less expensive often available close to cement plants*

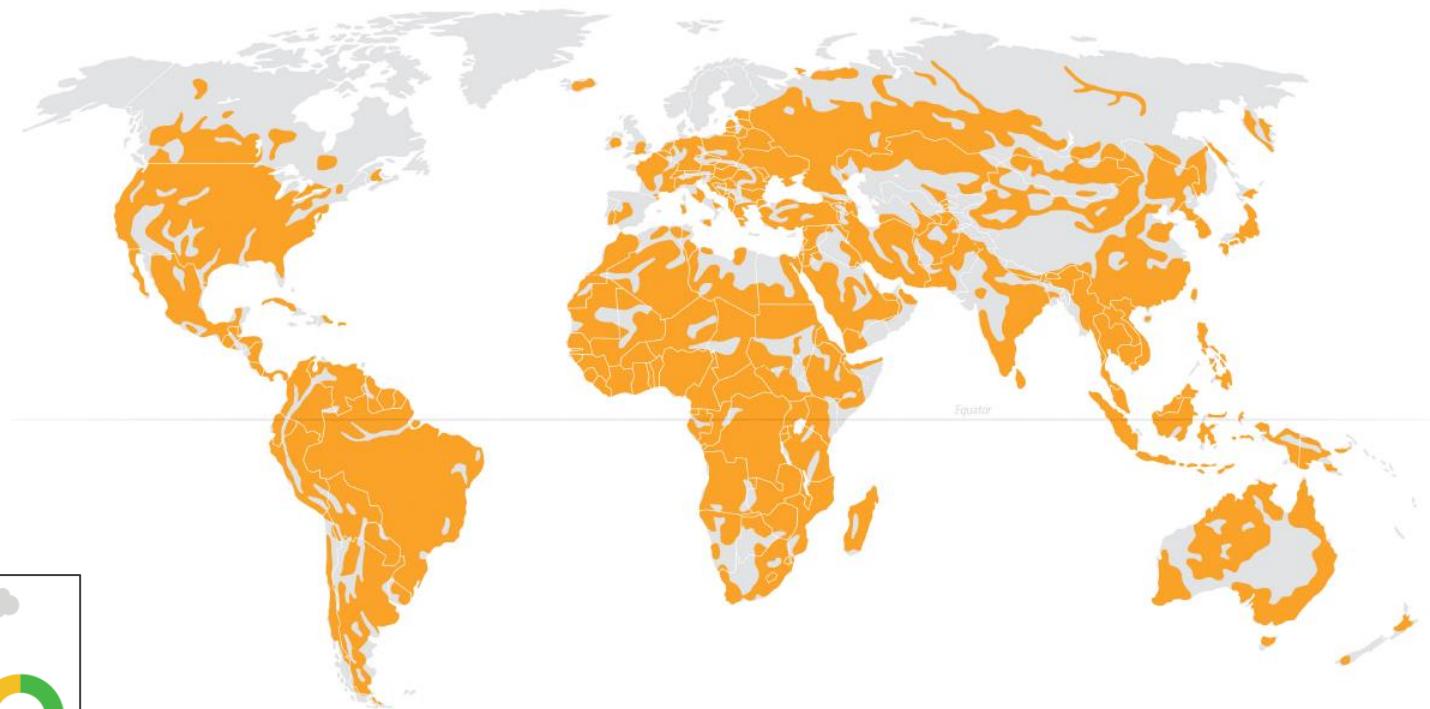
# Benchmark test of clay strength

- 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



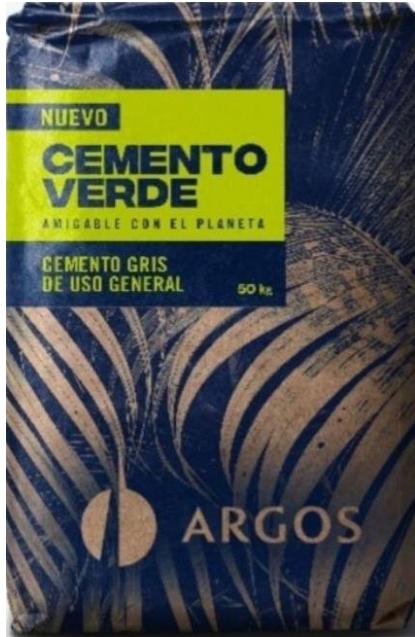
Calcined kaolinite content overwhelming parameter

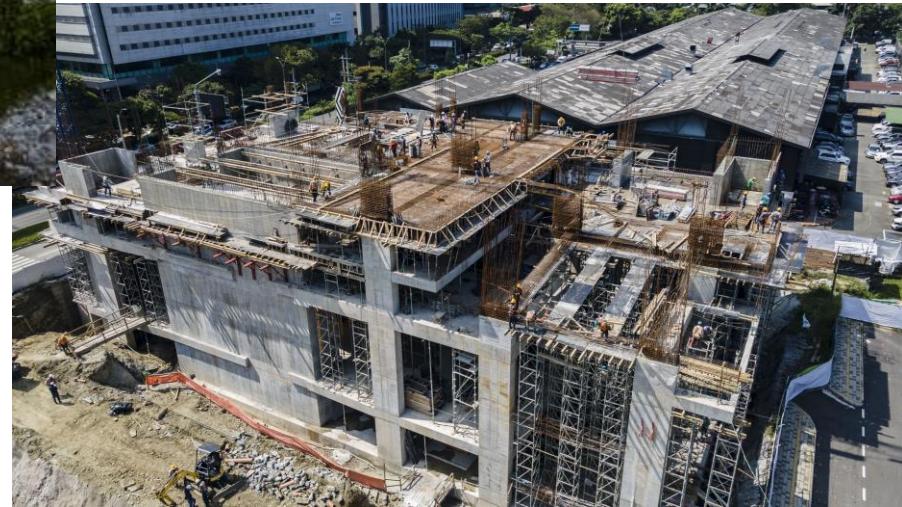
# World distribution of kaolinitic clays



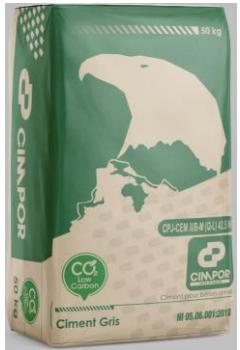
Source: Ito and Wagai, Scientific data  
2017

# Industrial projects: Cemento Verde ARGOS, Colombia





# Industrial projects: CIMPOR, Ivory Coast

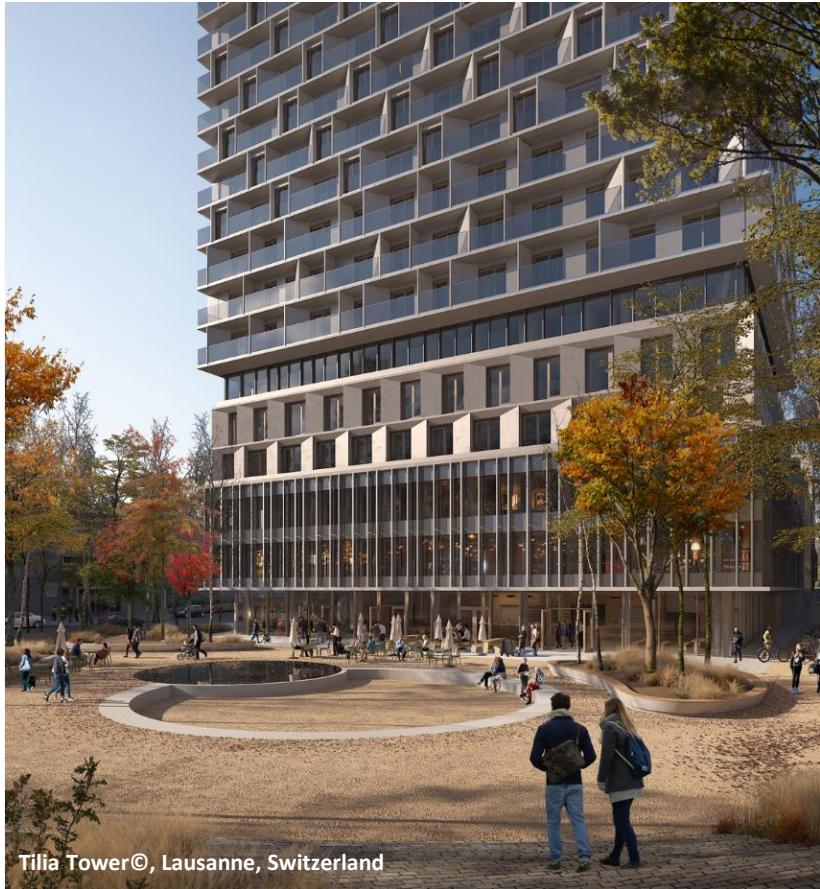


# “people don’t want red concrete”



# Europe

- Holcim's ECOPlanet LC<sup>3</sup>-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<sup>3</sup> from Jura Ciment
  - External façade in wood







~15 plants in operation

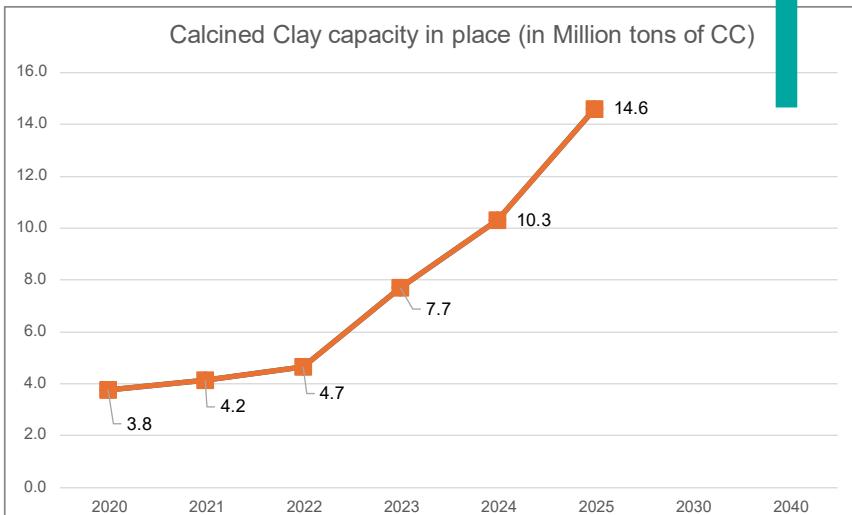
>43 plants in progress:

- North America: 10
- Cent & South America: 23
- Europe: 14
- Africa: 14
- Asia: 7

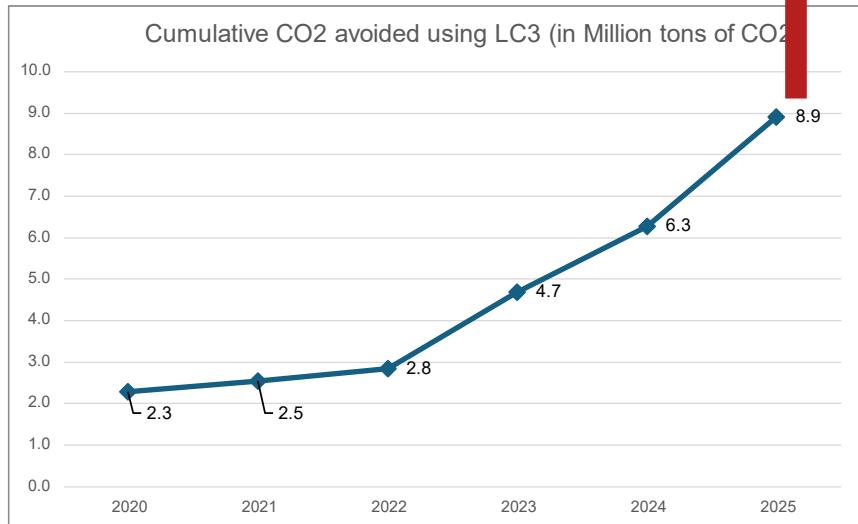
# LC<sup>3</sup>: where are we now

## Capacity and cumulative CO<sub>2</sub> savings

400 million



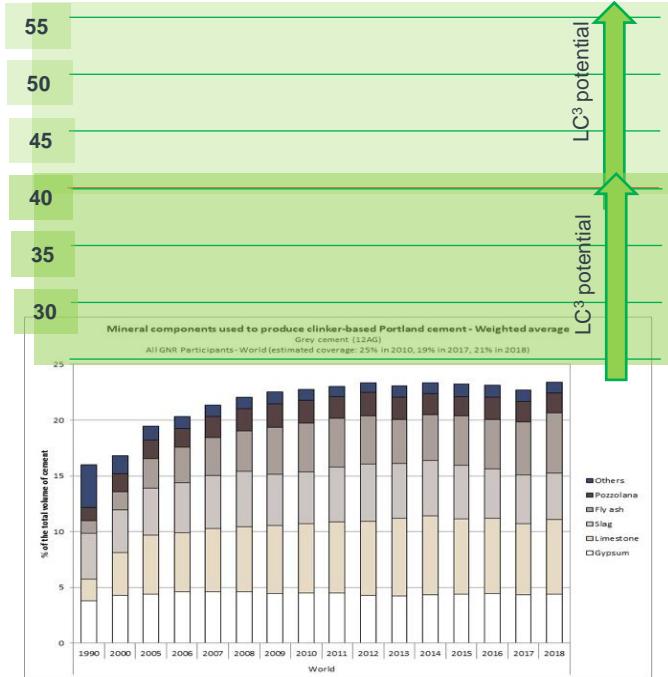
> 500/ yr



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.

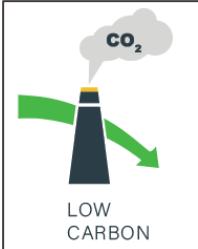
# World Potential?

# Calcined Clay only SCM which can expand substitution

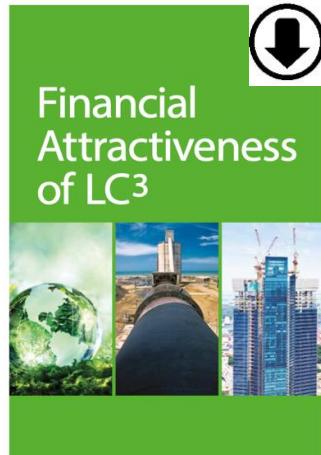


✓ 800 million tonnes CO<sub>2</sub>/yr

✓ 400 million tonnes CO<sub>2</sub>/yr



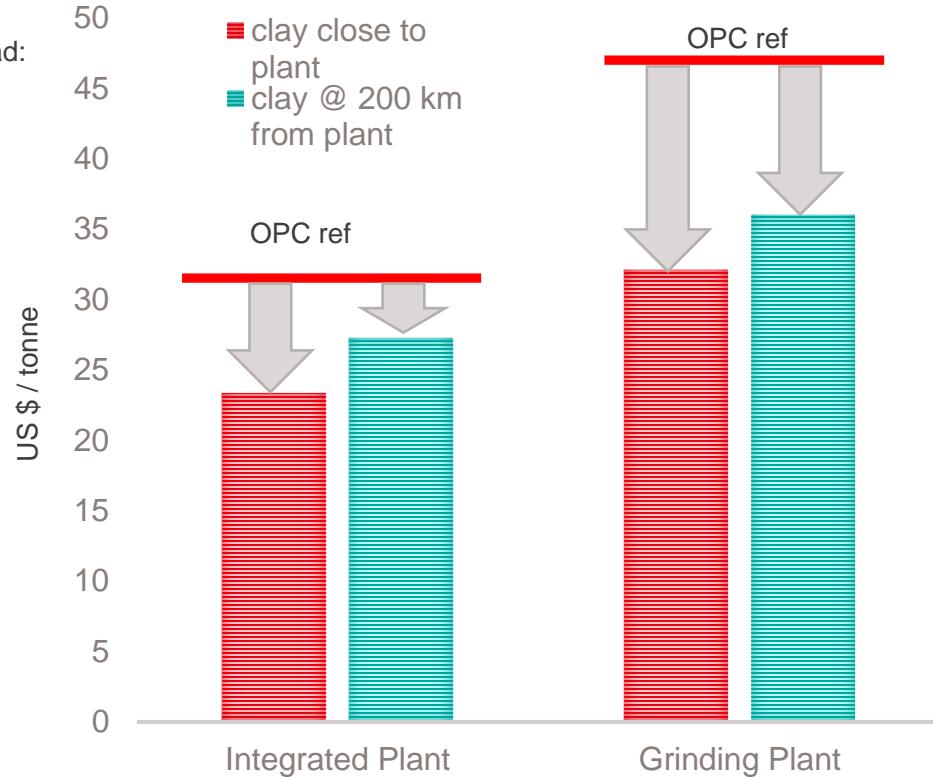
# Financial Feasibility



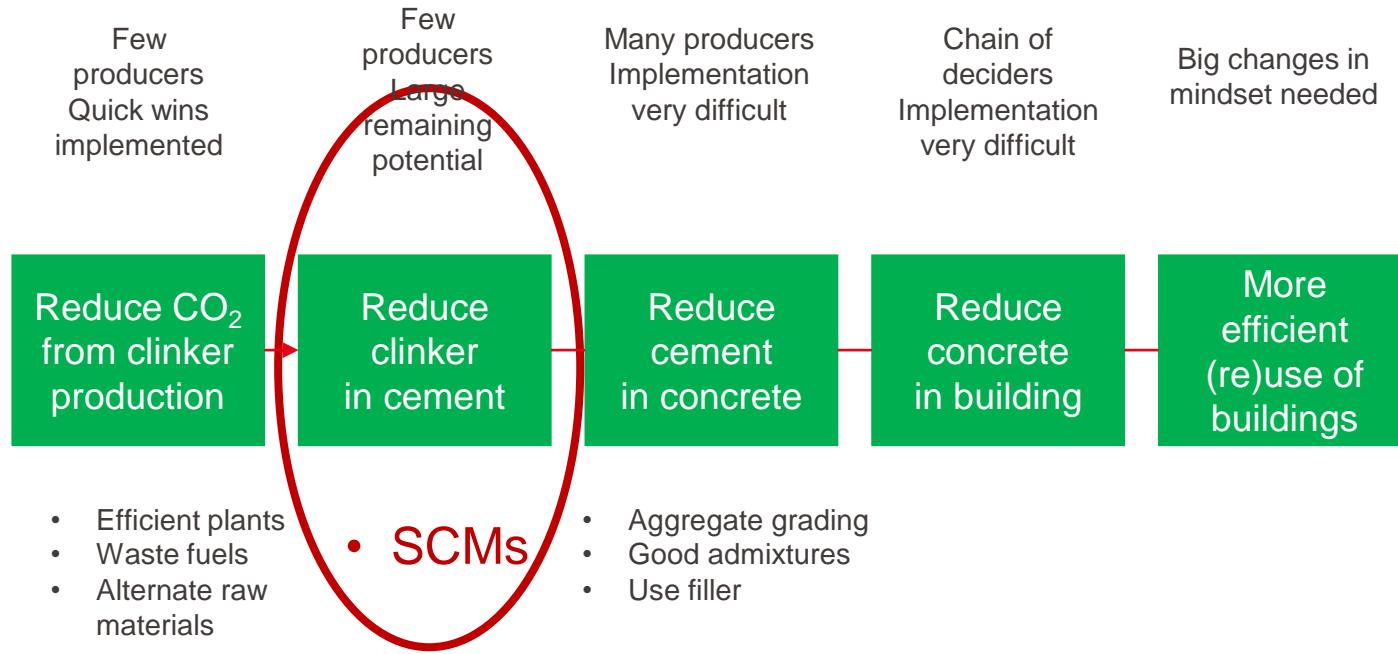
Report available to download:  
[www.lc3.ch](http://www.lc3.ch)



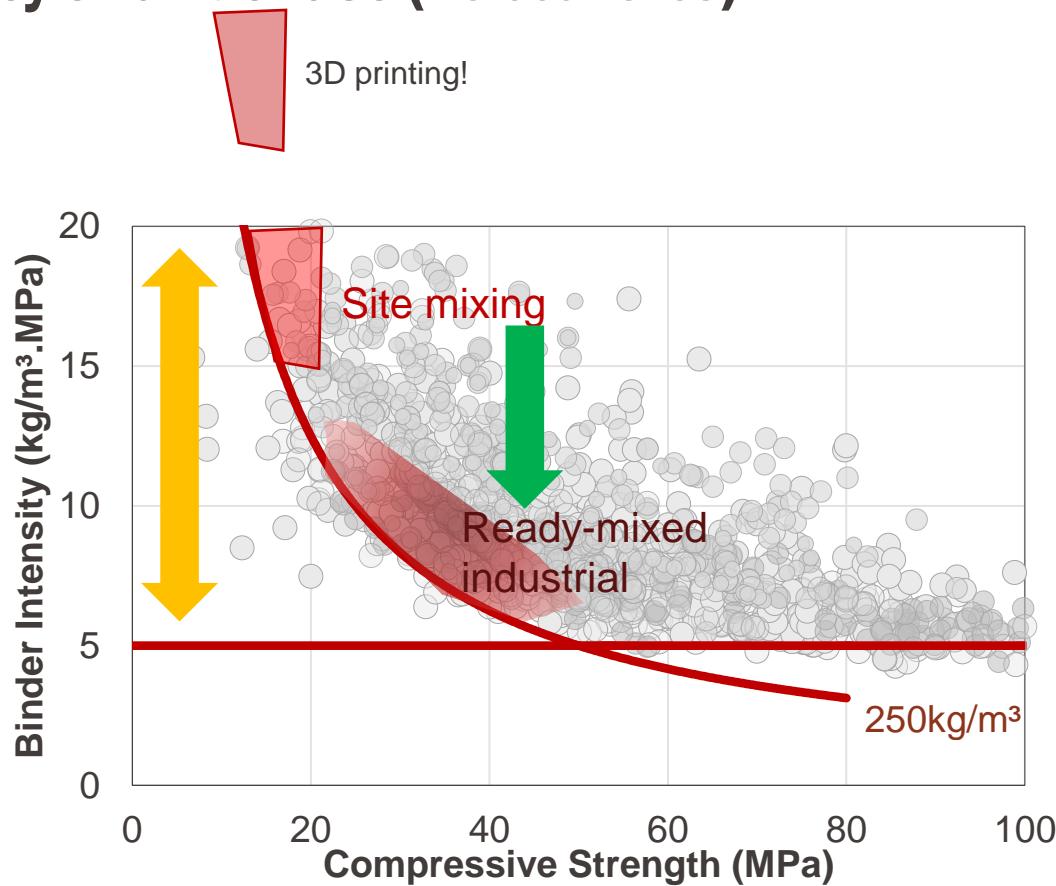
Study by LC3 Project partner



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



# 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?

## 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**

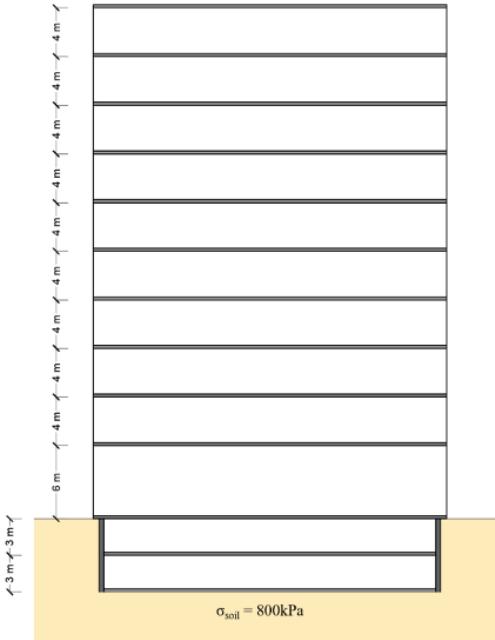
## Structure level

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

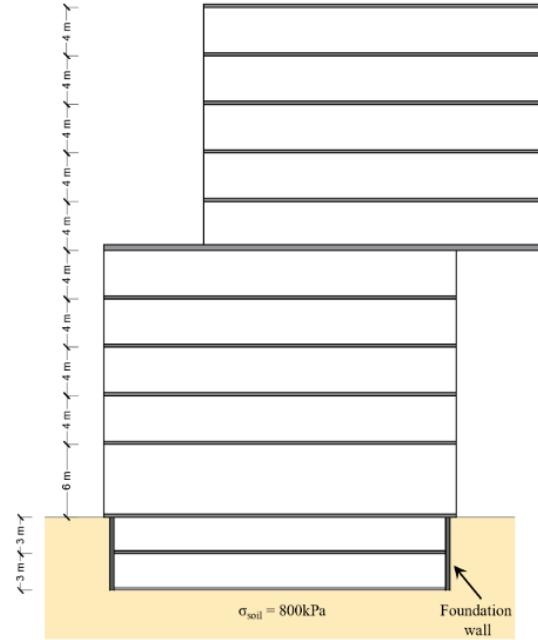
# Complexity costs carbon!



# Carbon cost of irregularity



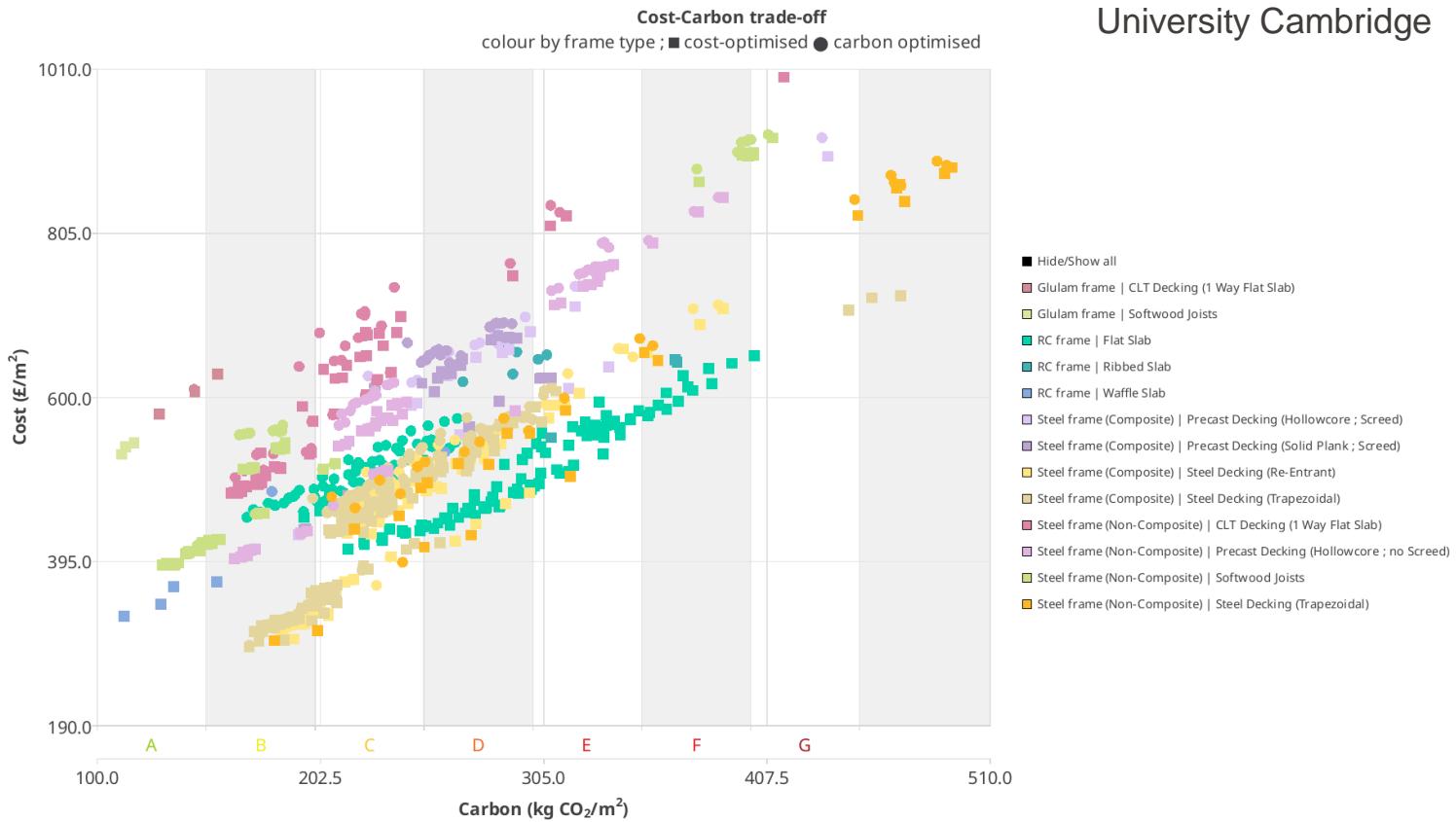
VS.



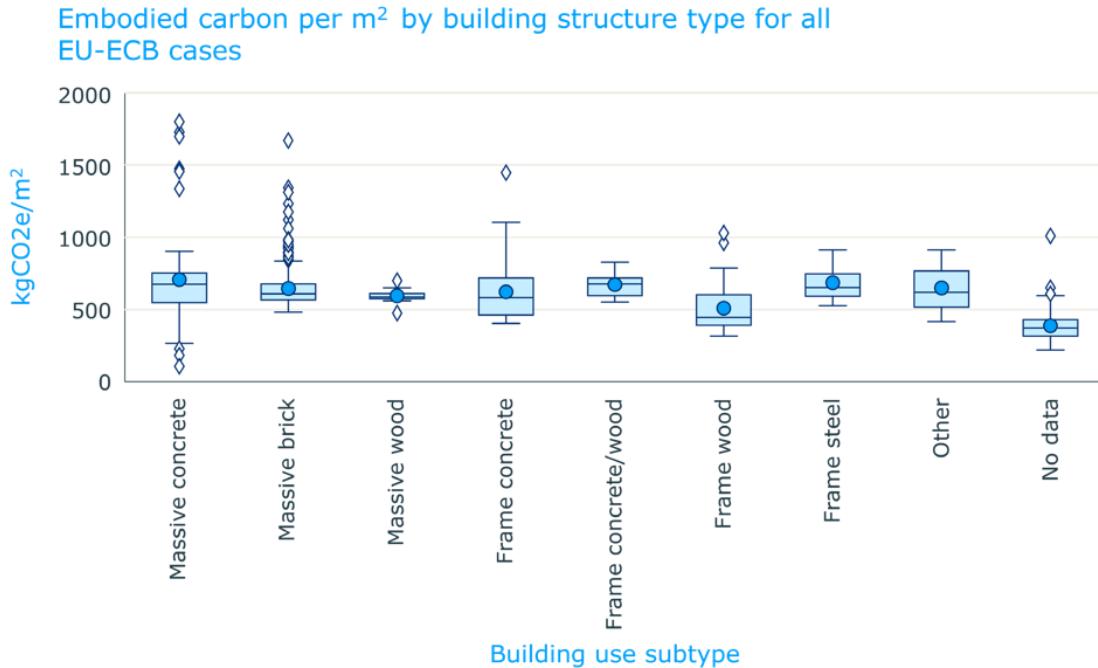
~50% more embodied carbon on average

Source: David Ruggiero

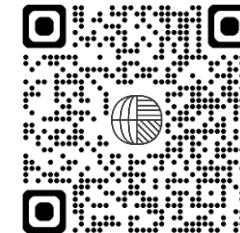
Output of Panda software  
from Cyrille Dunant,  
University Cambridge



# Need for metric in applications



Global Building  
Data Initiative



## 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

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](http://www.globe-consensus.com)

See on-line presentation from COP28 for more details



# Africa Brick by Brick

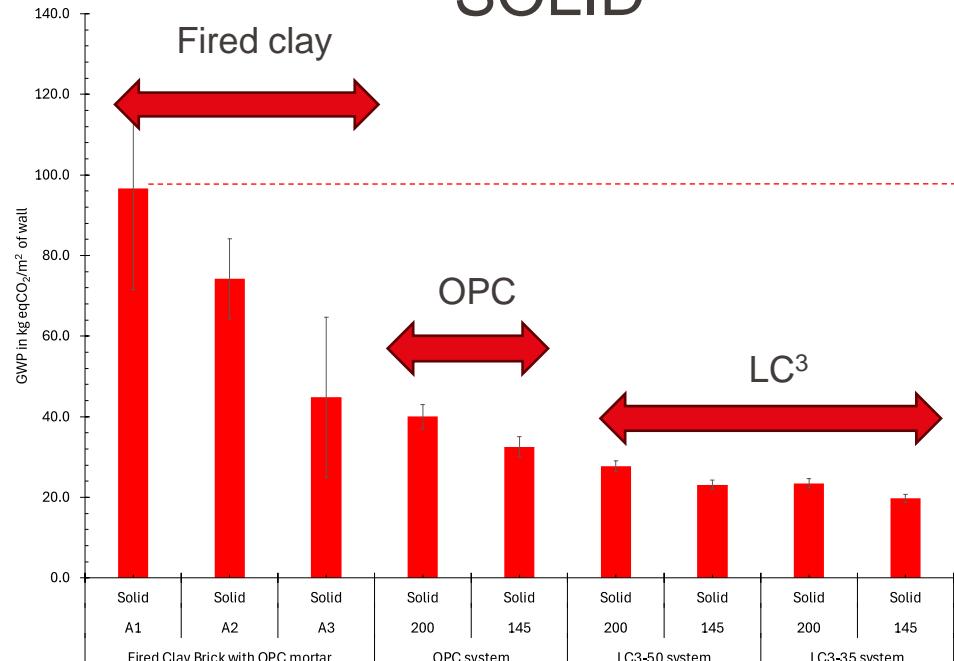




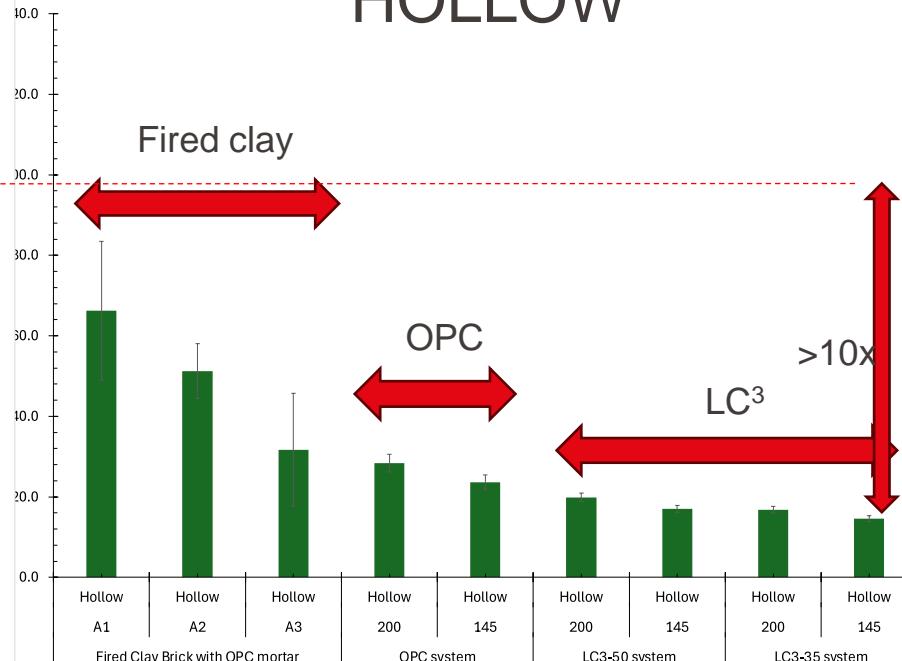
# Concrete blocks



## SOLID



## HOLLOW



A1: Africa Traditional kiln & Down Draught kiln;  
A3: Vertical Shaft kiln, Zig-zag kiln & Hybrid Hoffman kiln;

A2: Fixed Chimney Bull's Trench kiln & Tunnel kiln;  
200 & 145: Cement content in kg/m<sup>3</sup>

A1: Africa Traditional kiln & Down Draught kiln;  
A3: Vertical Shaft kiln, Zig-zag kiln & Hybrid Hoffman kiln;

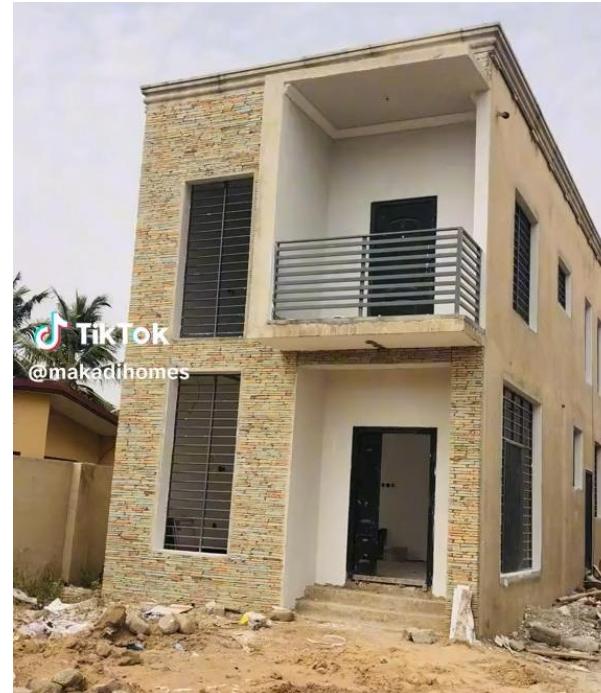
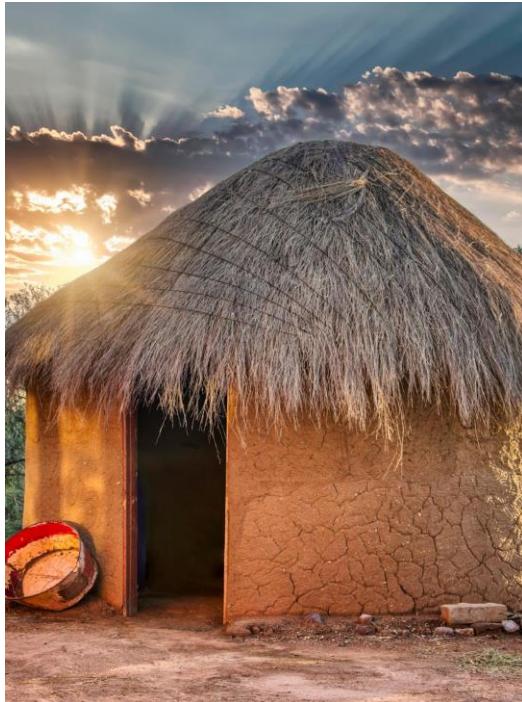
A2: Fixed Chimney Bull's Trench kiln & Tunnel kiln;  
200 & 145: Cement content in kg/m<sup>3</sup>



**Dr. Alice Titus Bakera (Civil Engineer)**

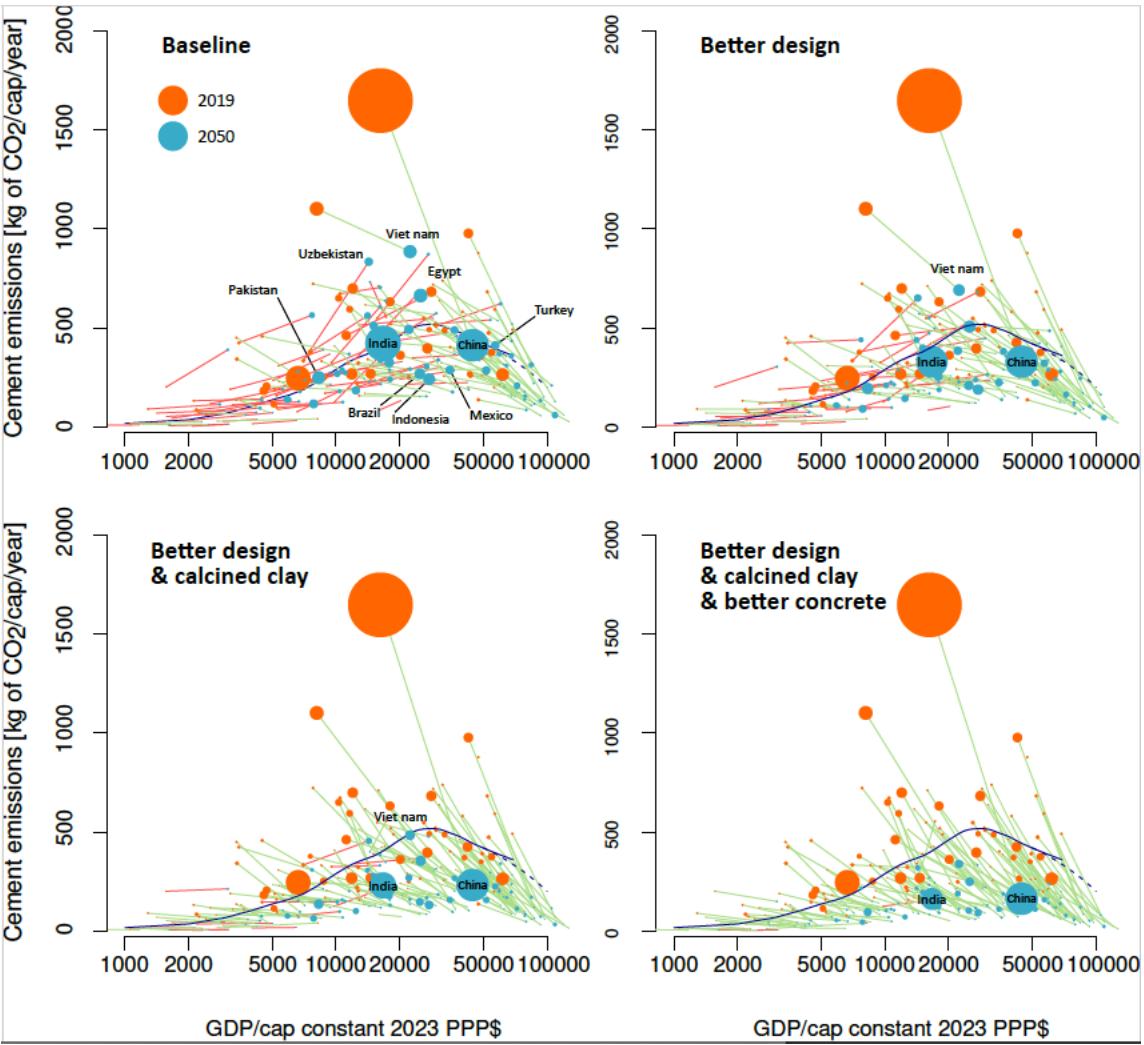
Postdoctoral researcher at EPFL  
Lecturer at the University of Dar es Salaam, Tanzania

# From cliché to real aspiration!



# Can we decouple growth from rising emissions

Deploying these reduction strategies can allow growth without increasing CO<sub>2</sub> emissions



# Concluding remarks

- ✓ Portland Based cements are here to stay
- ✓ There is no viable alternative
- ✓ Substantial reductions in CO<sub>2</sub> 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<sub>2</sub> 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