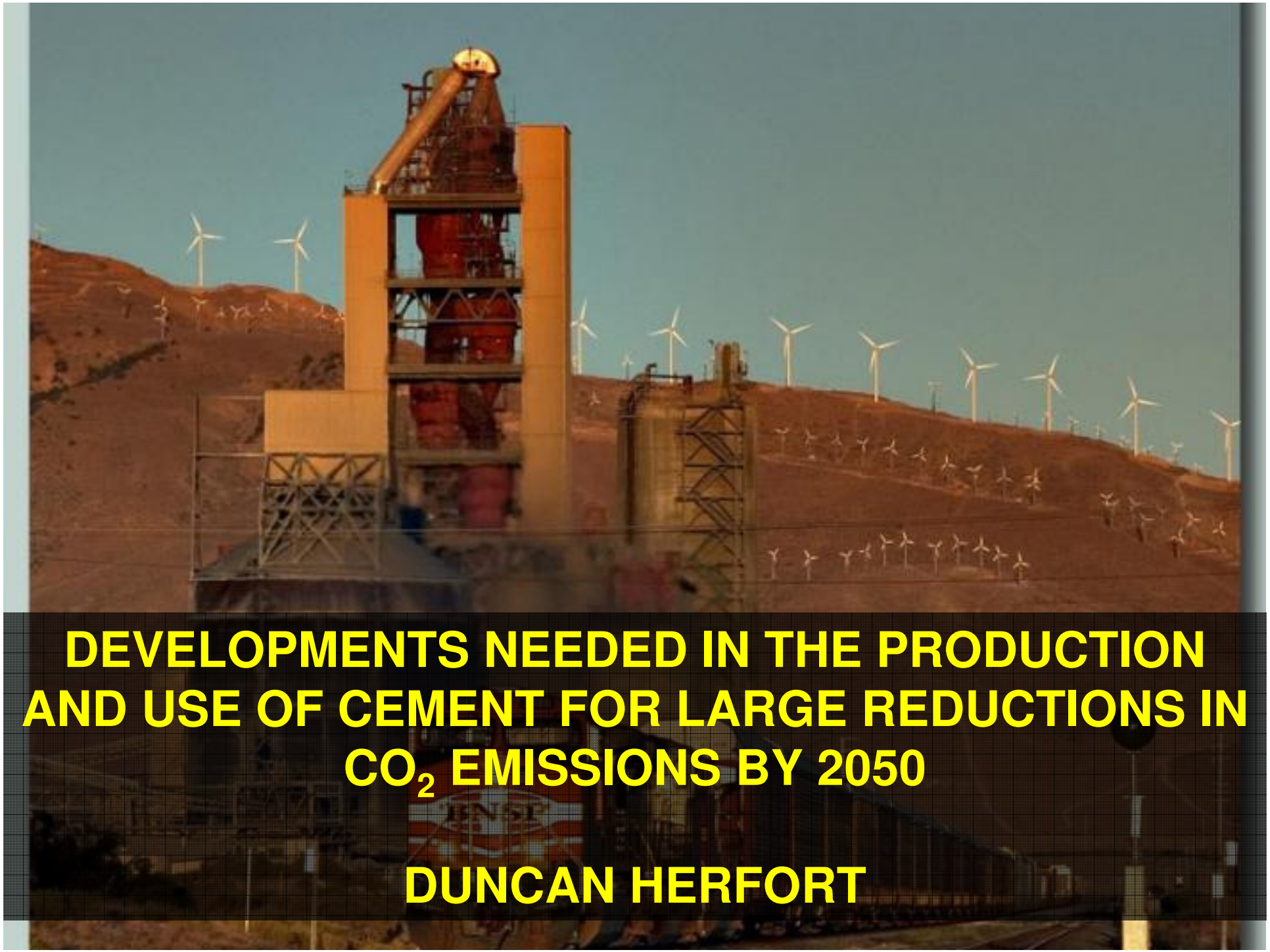
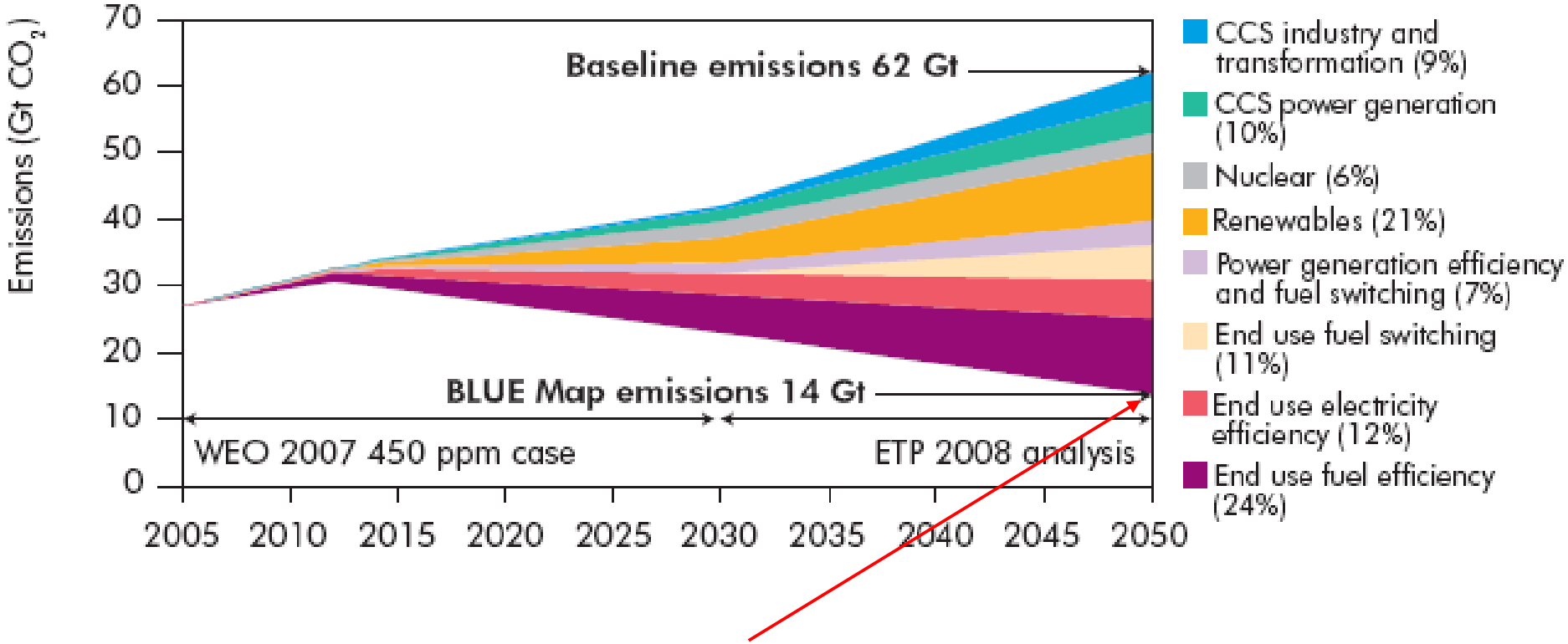


DEVELOPMENTS NEEDED IN THE PRODUCTION AND USE OF CEMENT FOR LARGE REDUCTIONS IN CO_2 EMISSIONS BY 2050

DUNCAN HERFORT



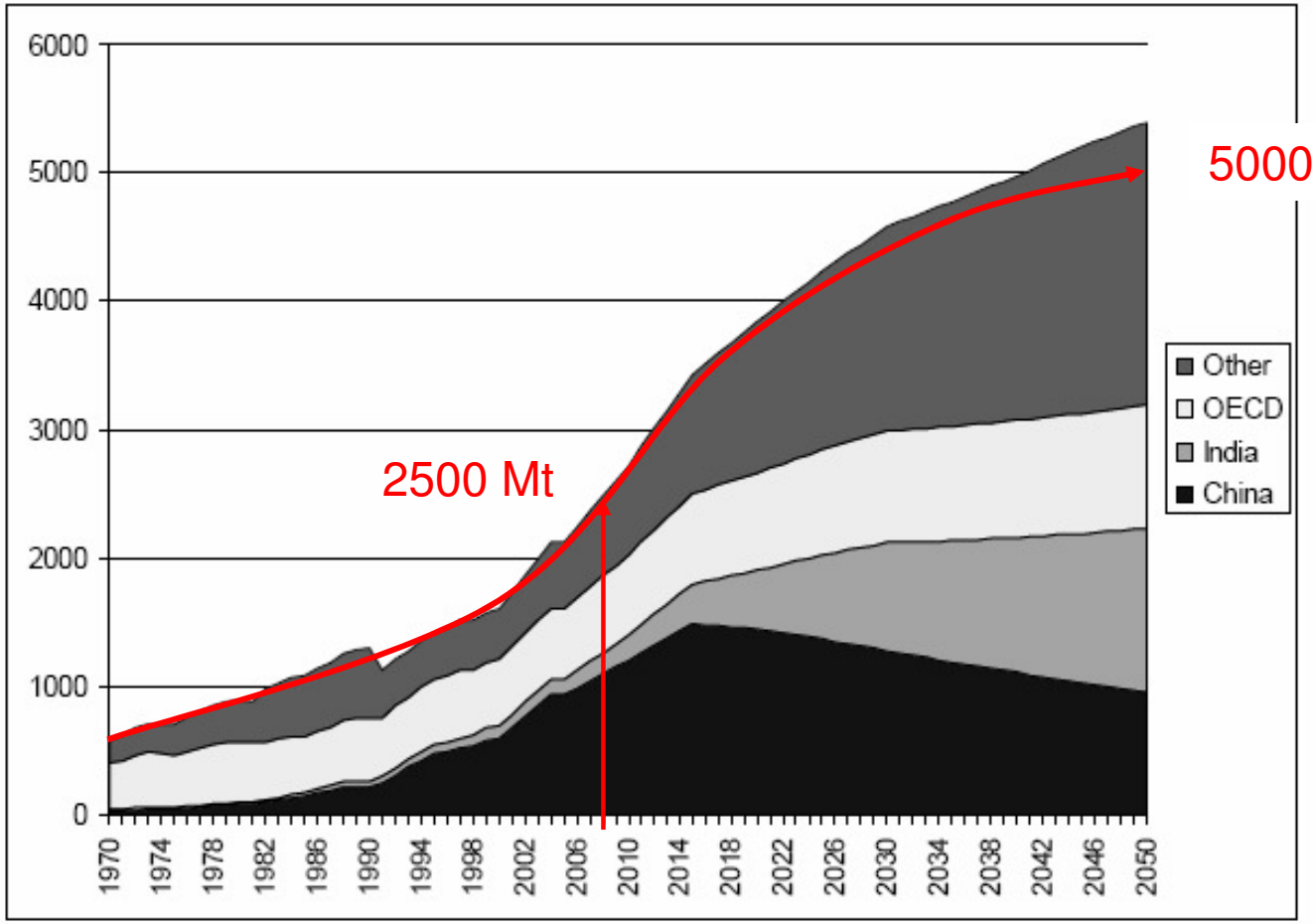
Corresponds to stabilization of CO_2 concentrations at c. 500 ppm and temperature increase of 2.4°C, and acidification of ocean above solubility product for aragonite.

From the IEA: "Four approaches can be applied to increase the energy efficiency and reduce CO_2 emissions in the cement industry:

(1) increase the process energy efficiency,
(2) use coal fuel substitutes,
(3) capture and store CO_2
(4) develop new cement types that reduce the use of cement clinker."

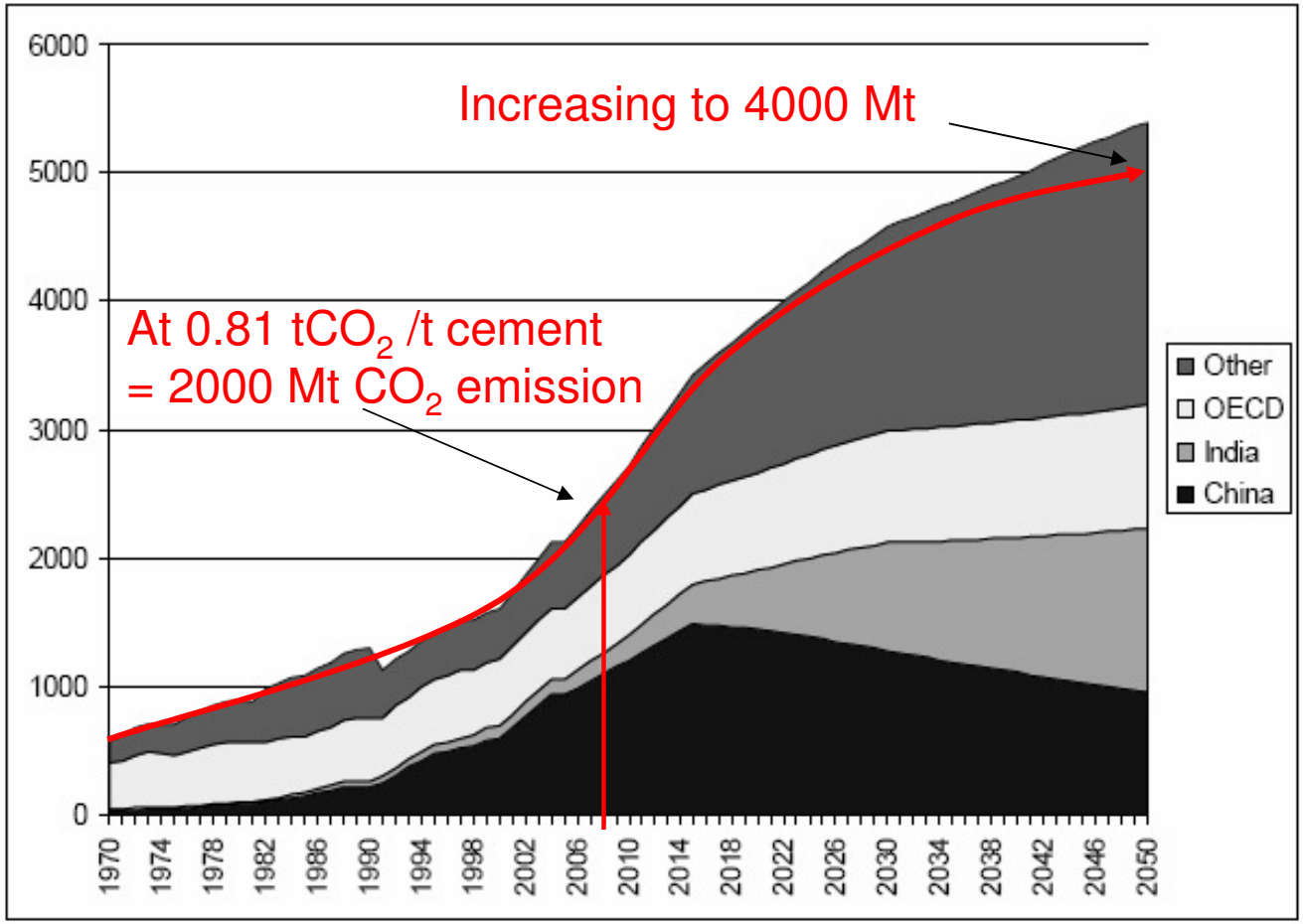
Vælg og zoom

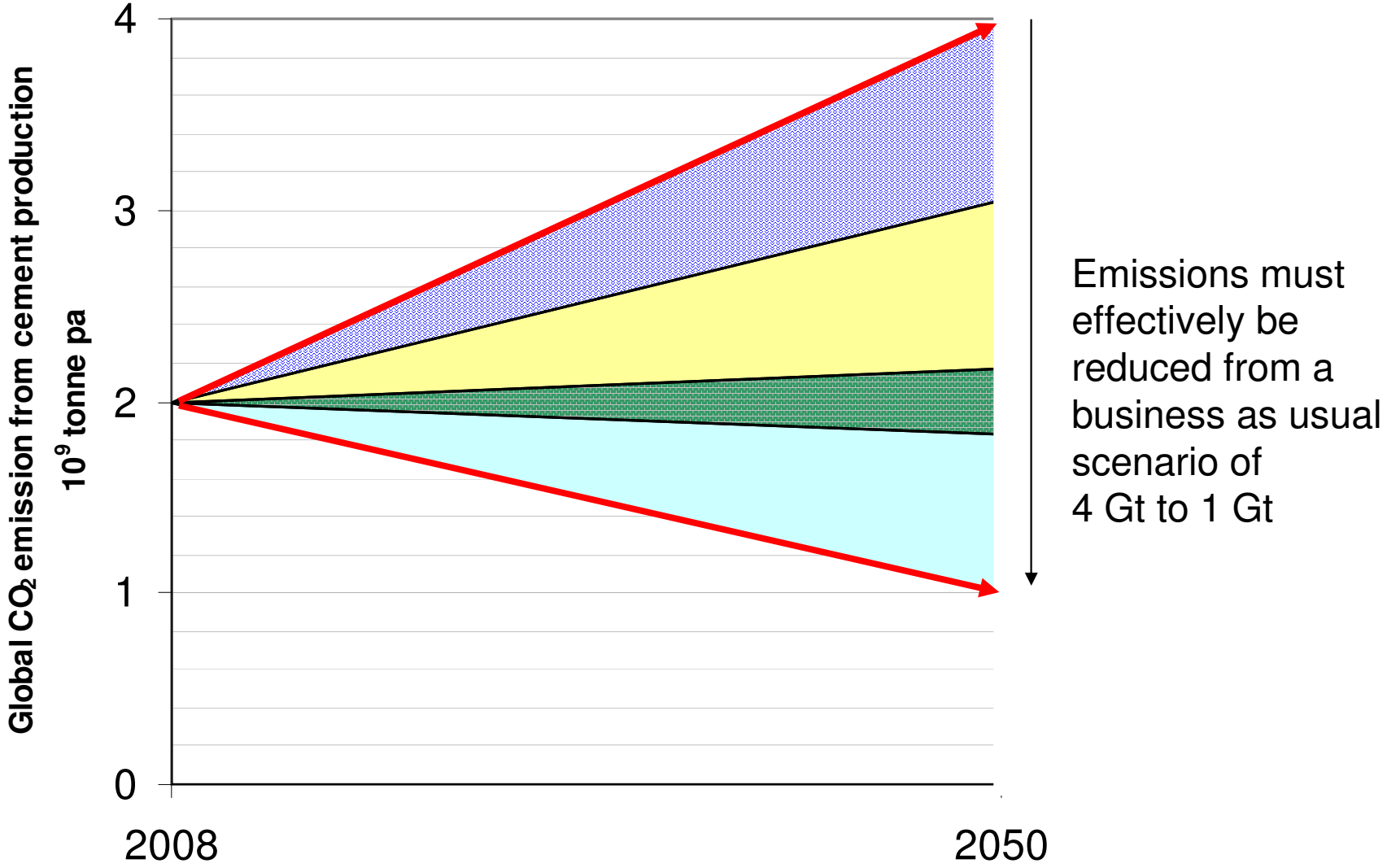
Global Cement Production 1970-2050



Vælg og zoom

Global Cement Production 1970-2050

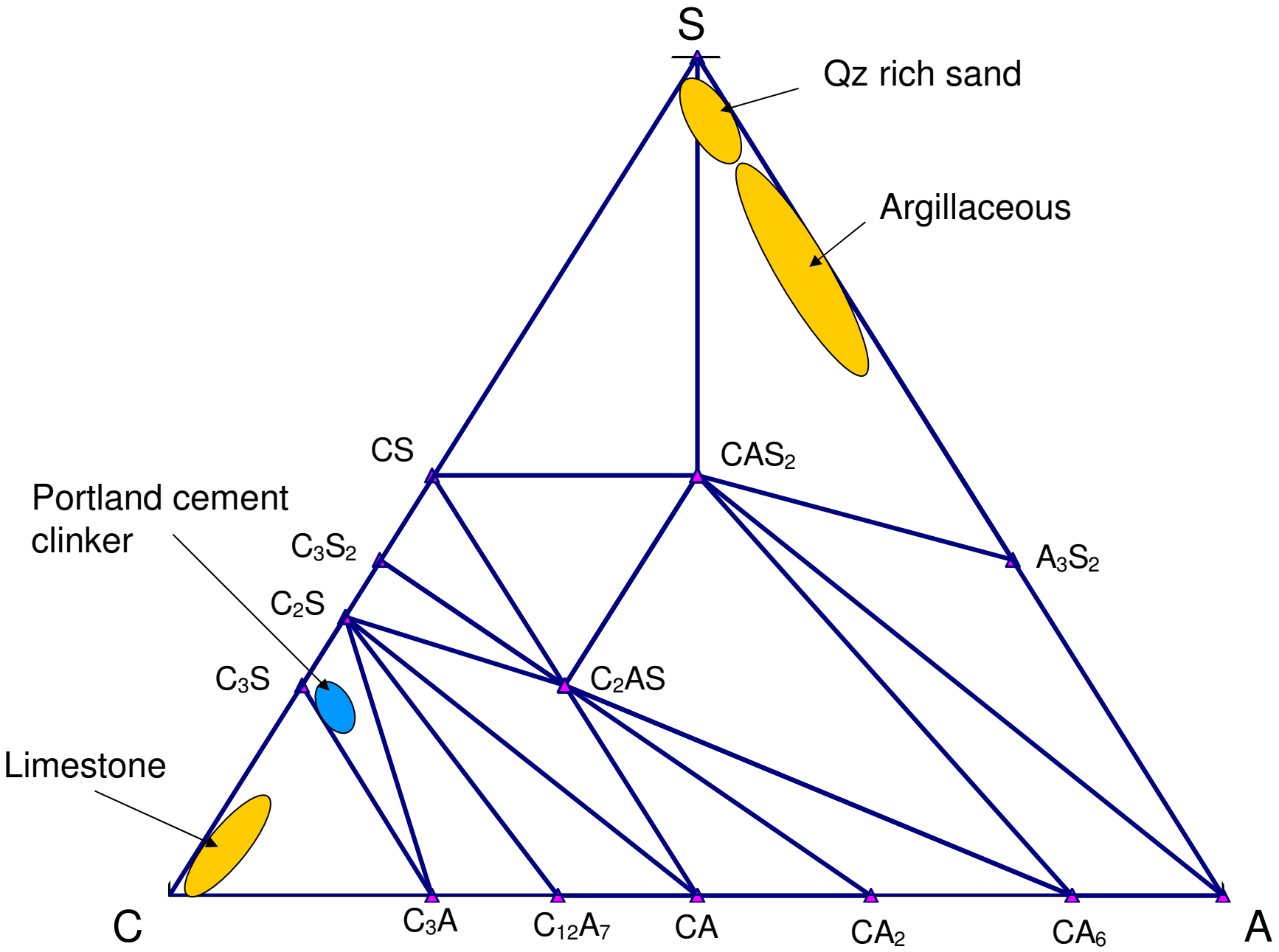



Global CO_2 emission from cement production
10^9 tonne pa
4
3
2
1
0
2008
2050
Emissions must effectively be reduced from a business as usual scenario of 4 Gt to 1 Gt


CO_2 EMISSIONS FROM CLINKER PRODUCTION
SCMS
CONCRETE CARBONATION
CARBON CAPTURE & STORAGE
ALKALI ACTIVATED ALUMINO SILICATES

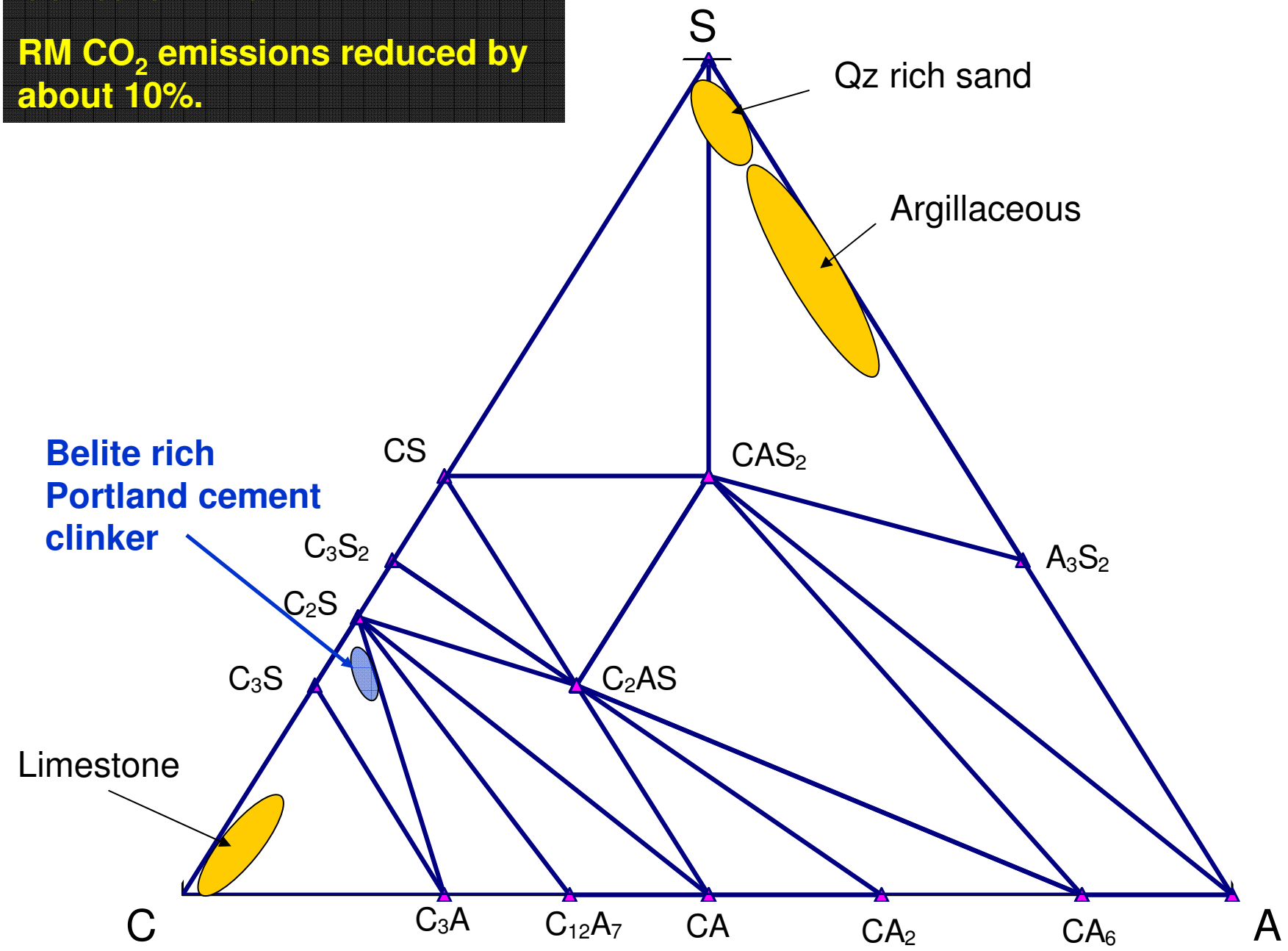

CO_2 EMISSIONS FROM CLINKER PRODCUTION
•RAW MATERIALS
•KILN EFFICIENCY
•LOW CARBON FUELS
SCMS
CONCRETE CARBONATION
CARBON CAPTURE & STORAGE
ALKALI ACTIVATED ALUMINO SILICATES


raw materials

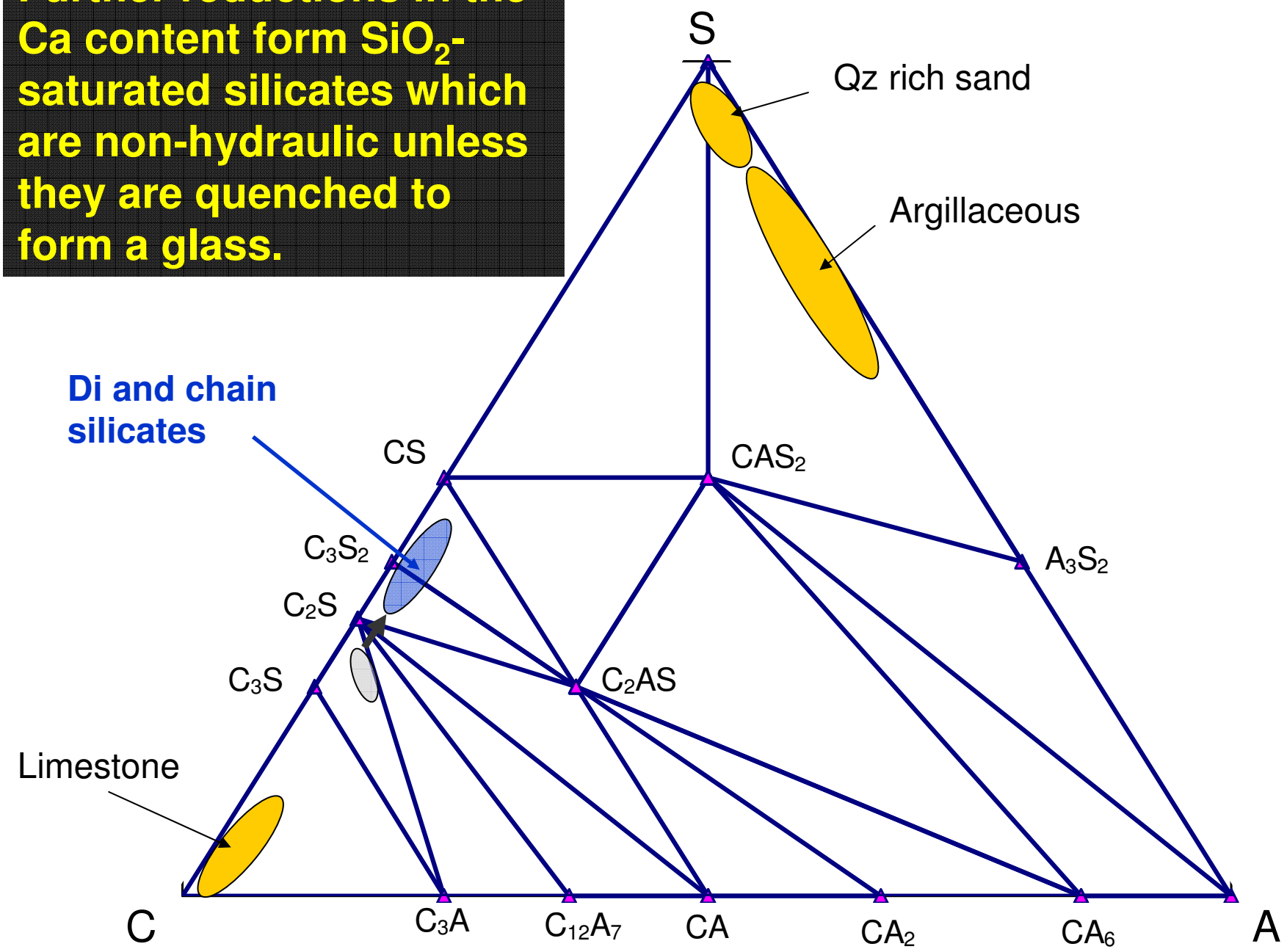

S
Qz rich sand
Argillaceous
CS
CAS2
Portland cement
clinker
C3S2
A3S2
C2S
C3S
C2AS
Limestone
C
C3A
C12A7
CA
CA2
CA6
A

belite clinker

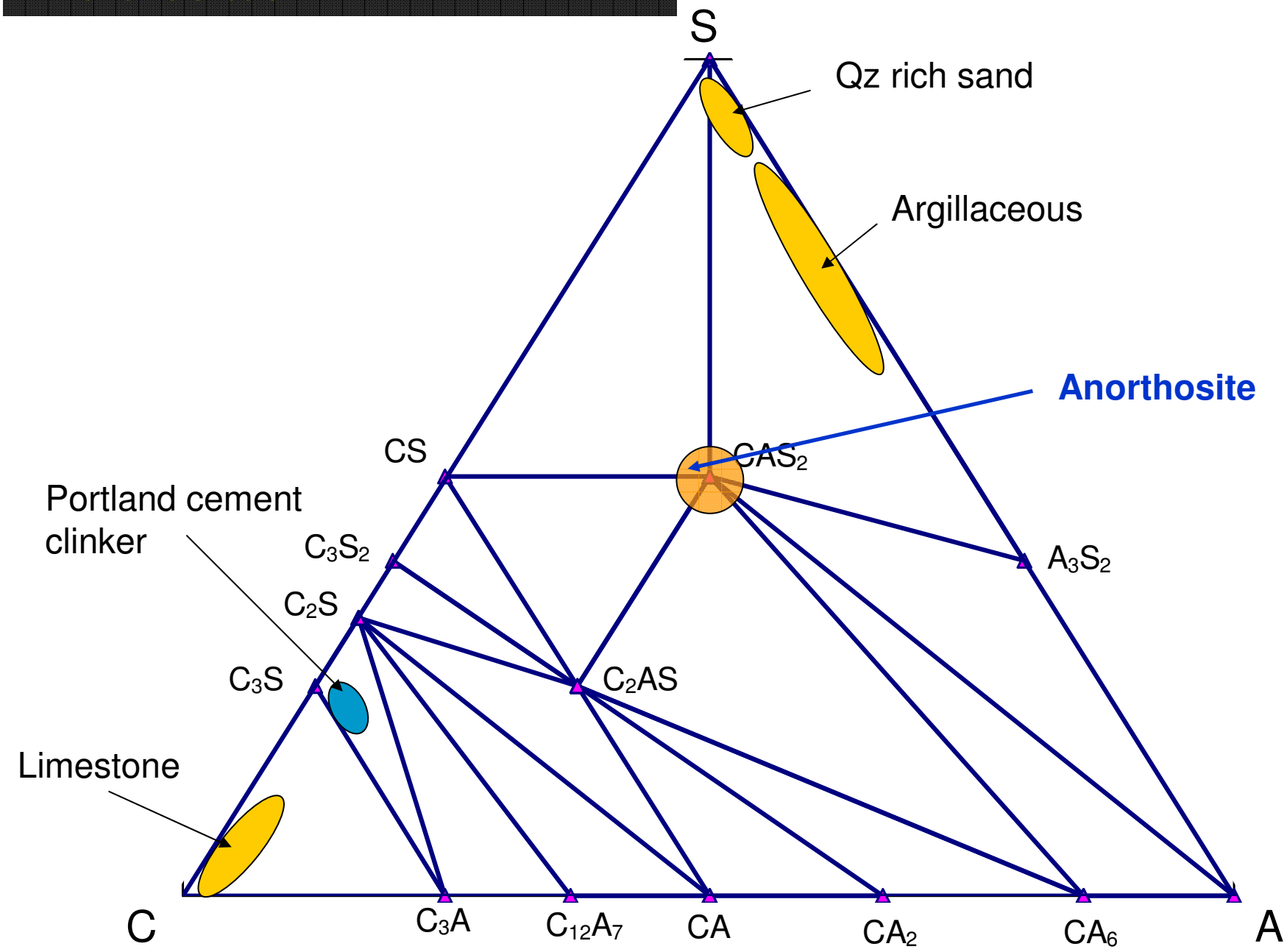
RM CO_2 emissions reduced by about 10%.



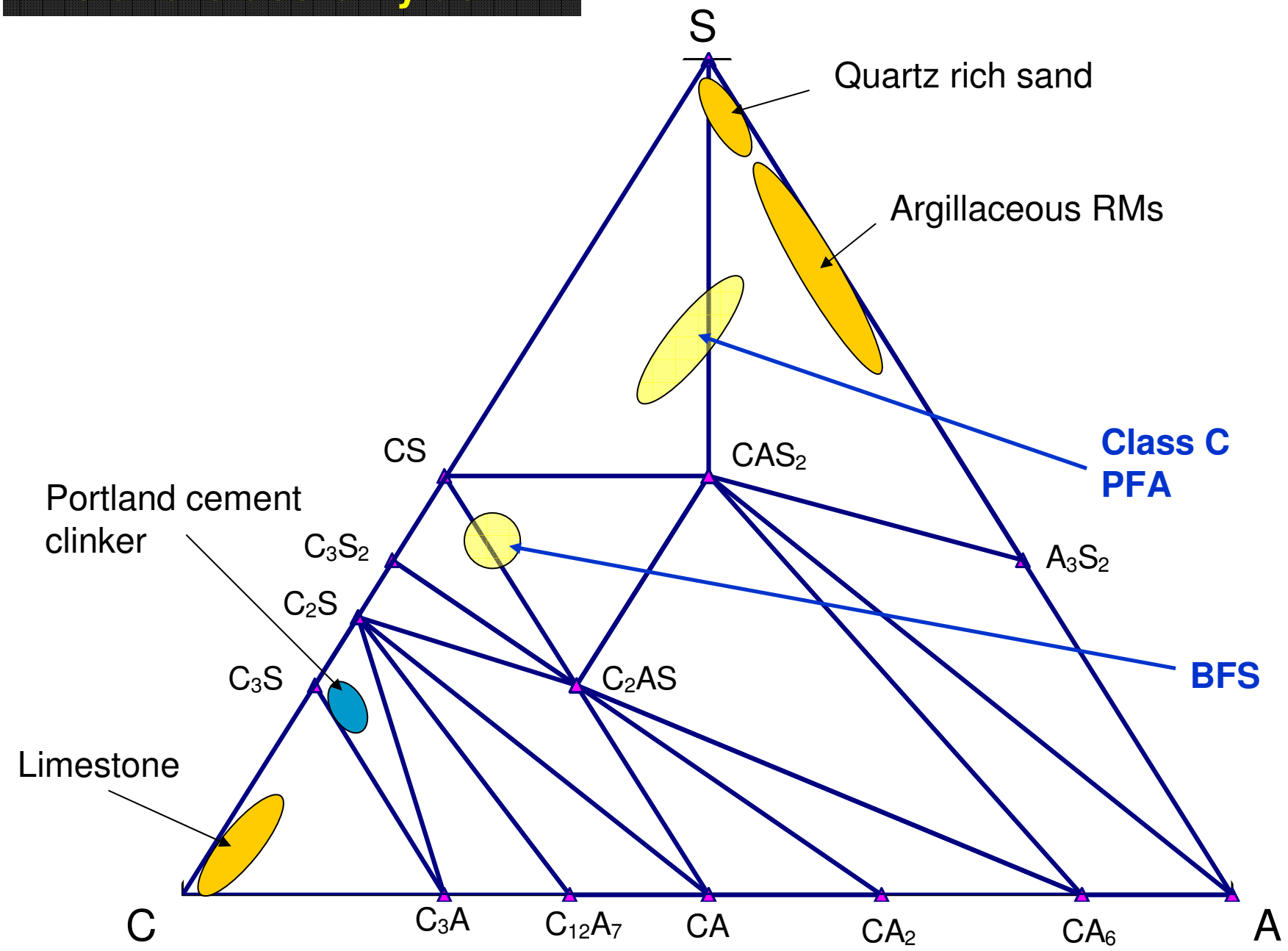
Further reductions in the Ca content form SiO_2-saturated silicates which are non-hydraulic unless they are quenched to form a glass.



Anorthosites

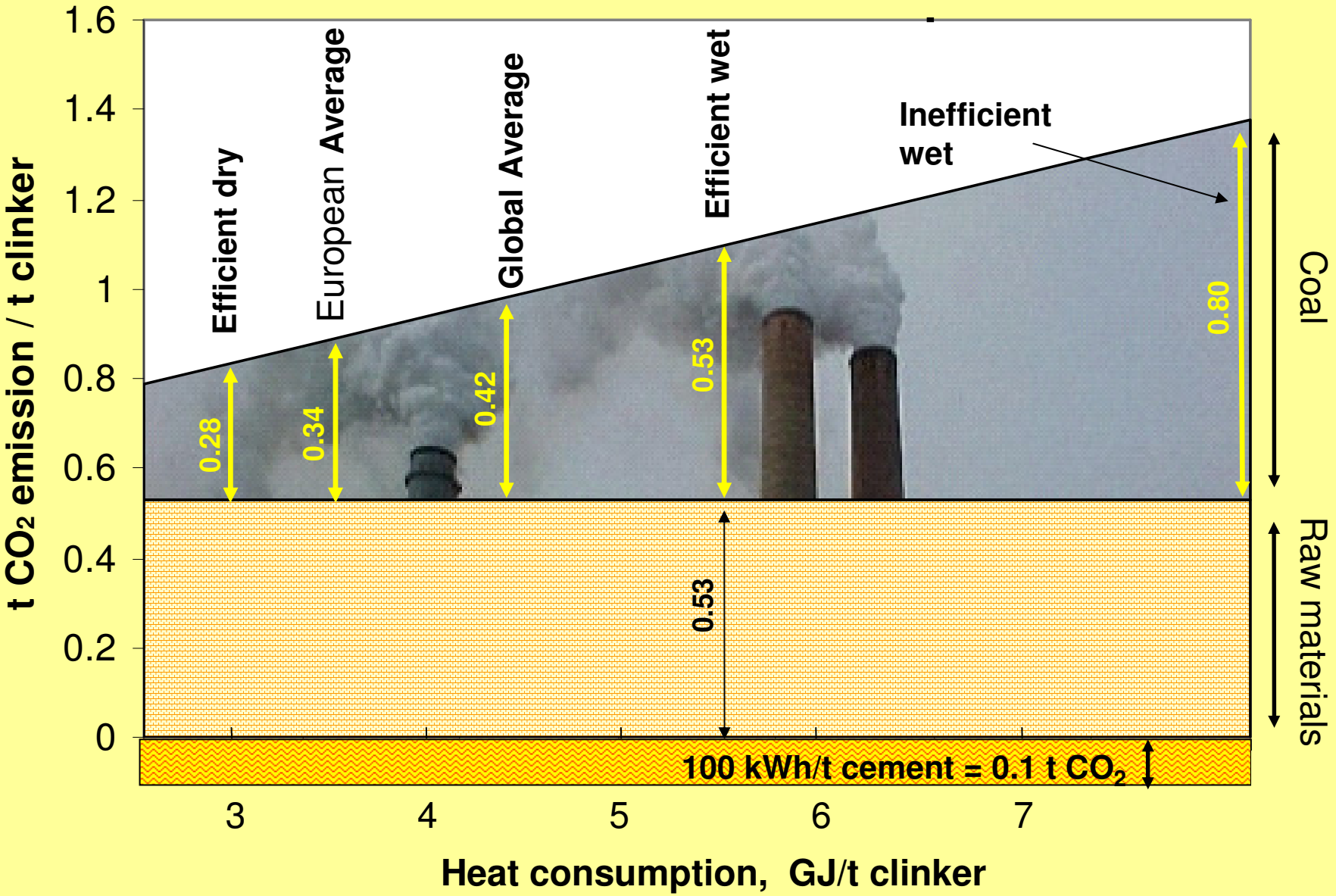


BFS and Class C fly ash




LOW CARBON FUELS
AND KILN EFFICIENCY

CO_2 emissions from clinker production as a function of kiln efficiency



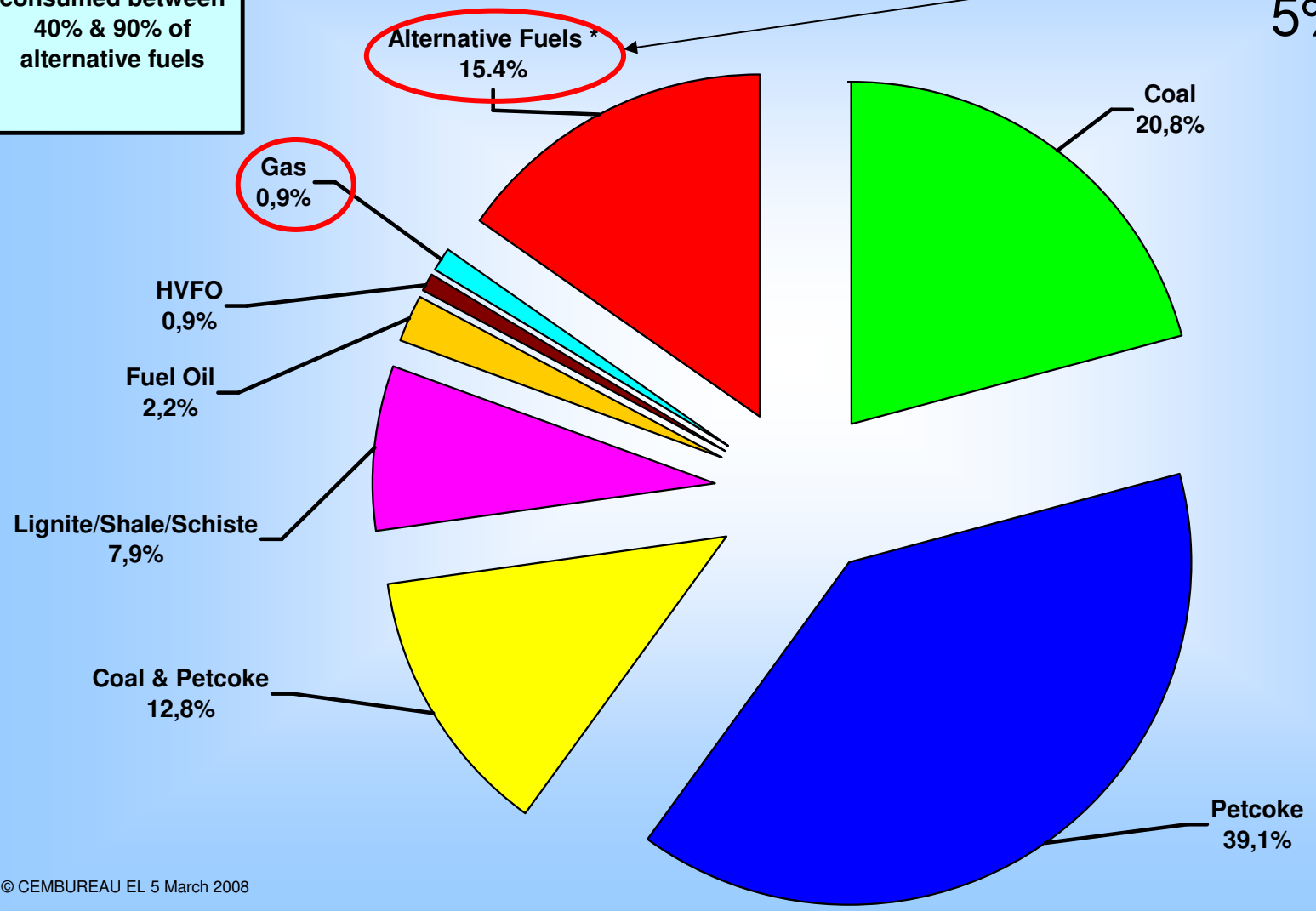
Total consumption
TJ= 821 409

*six countries consumed between 40% & 90% of alternative fuels

Energy Consumption - 2006 -

(Average CEMBUREAU)

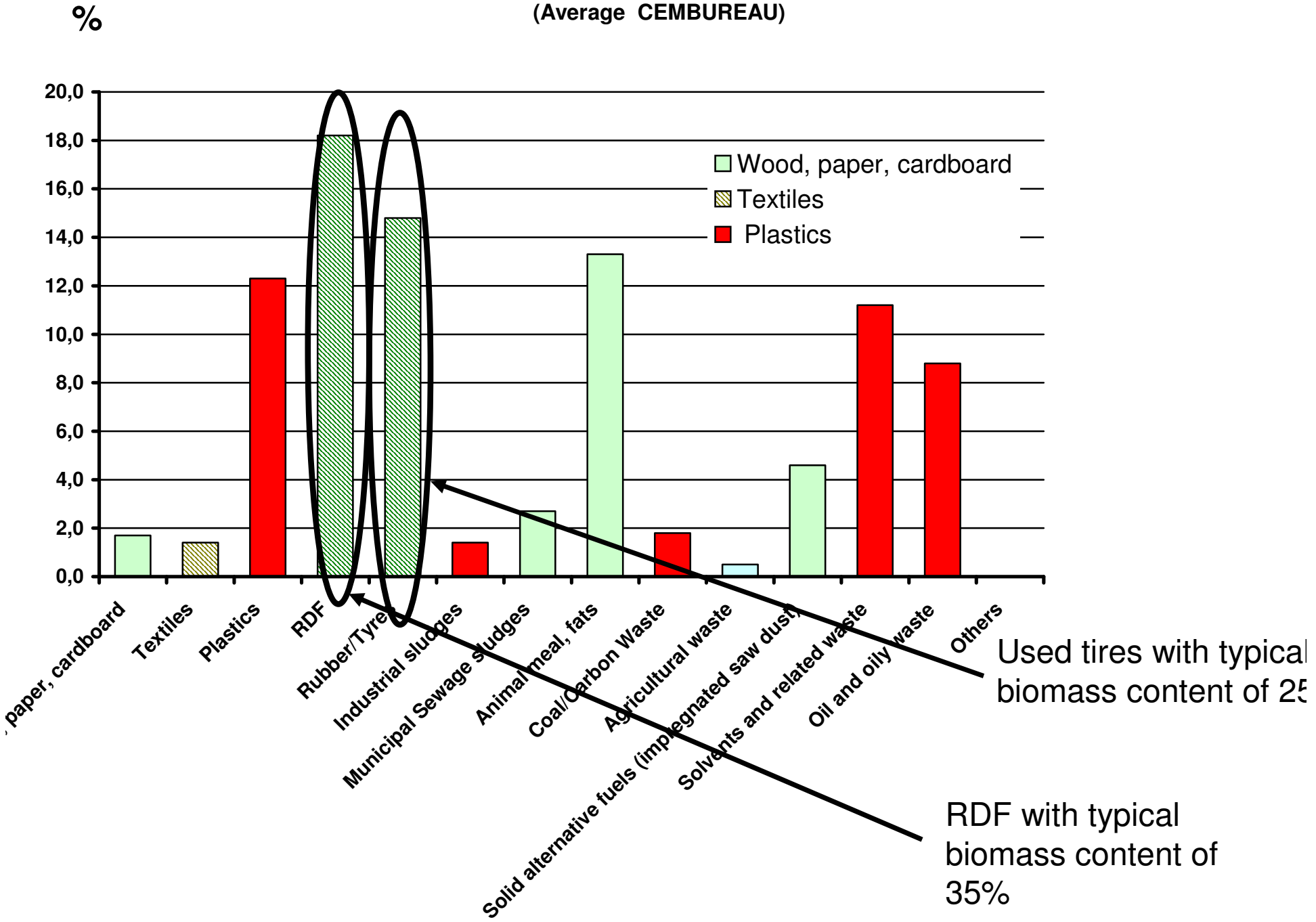
Global average of 5% AF



CEMBUREAU

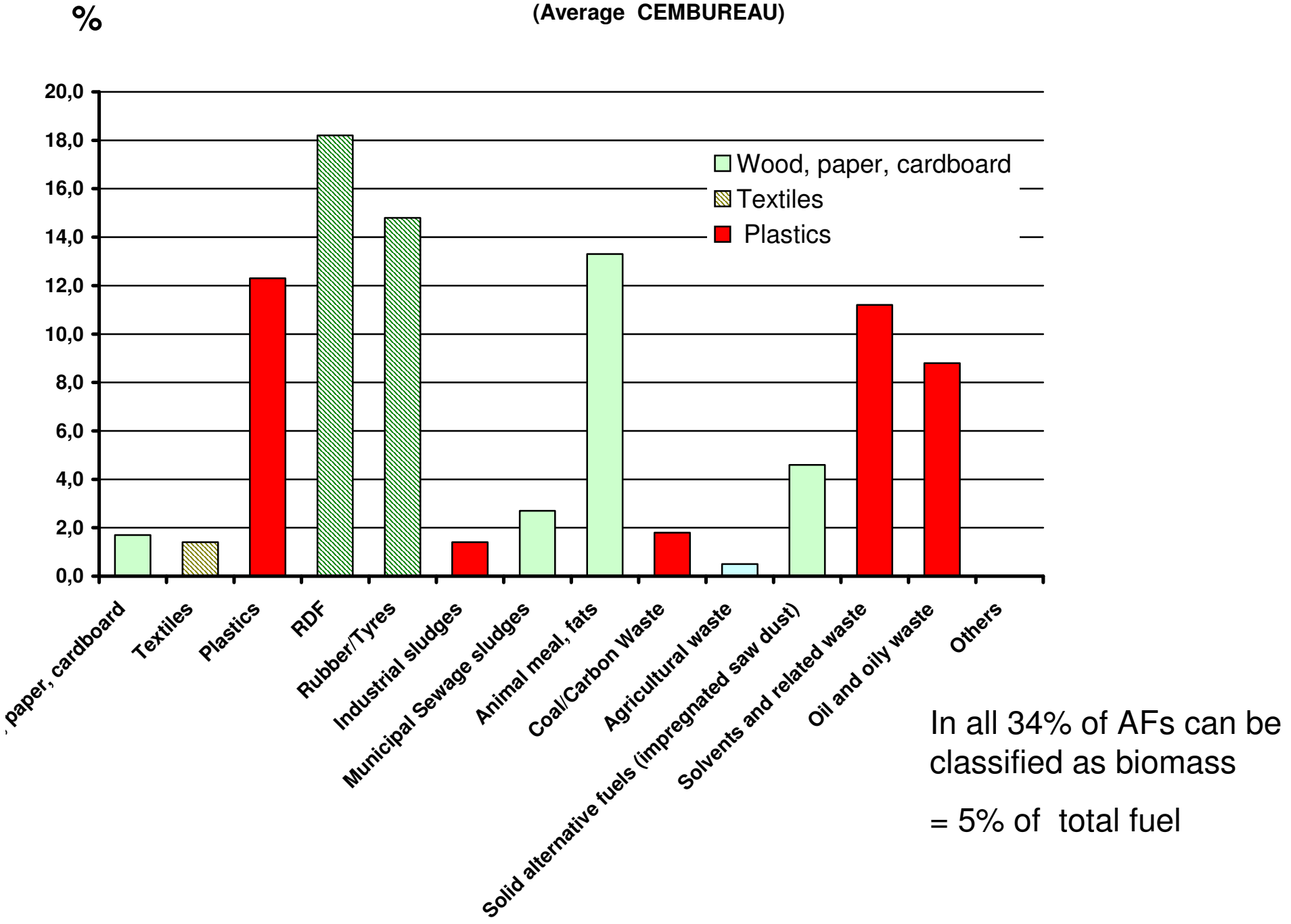
Alternative fuels used in cement kilns - 2006-

(Average CEMBUREAU)



Alternative fuels used in cement kilns - 2006-

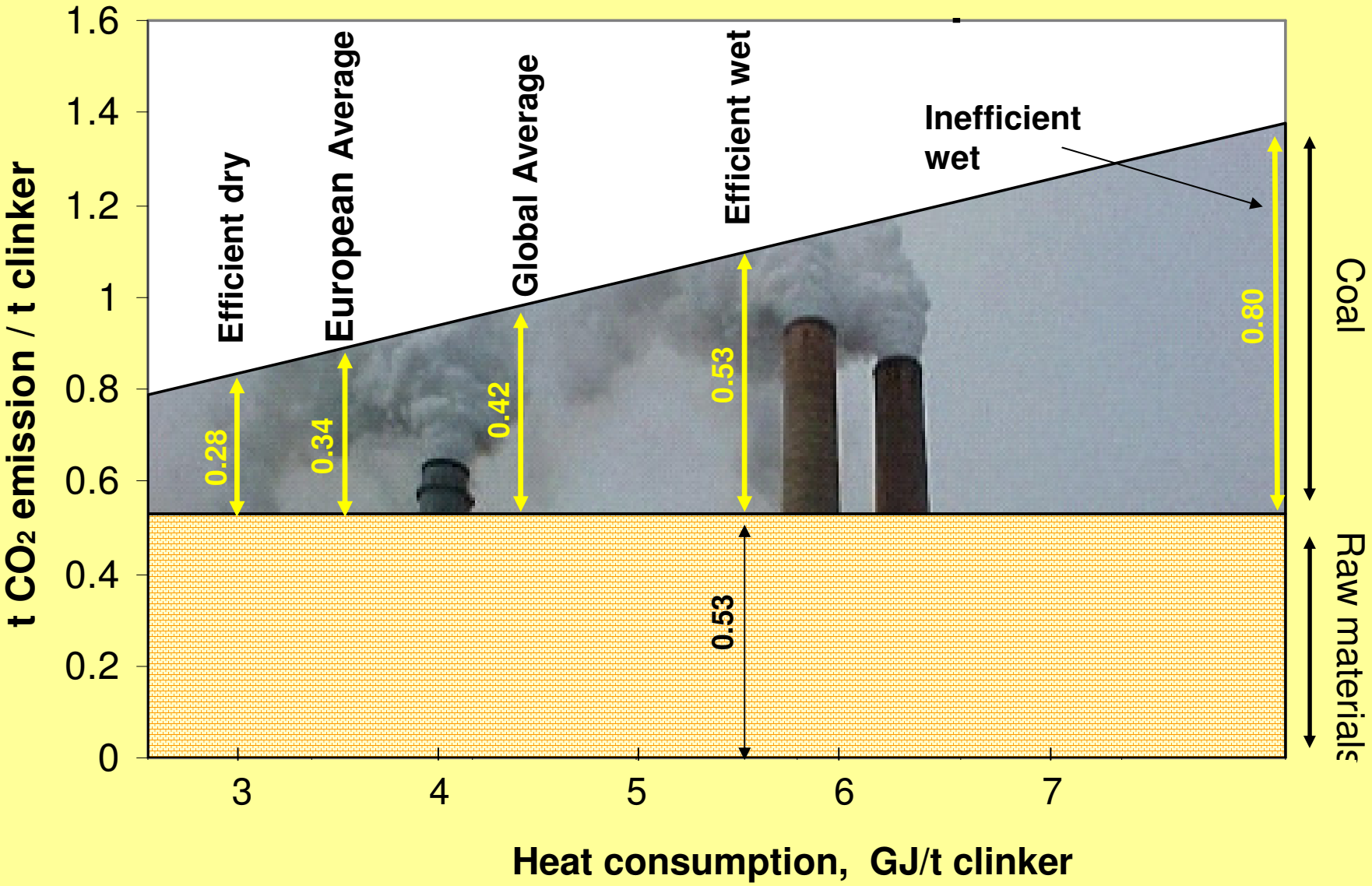
(Average CEMBUREAU)



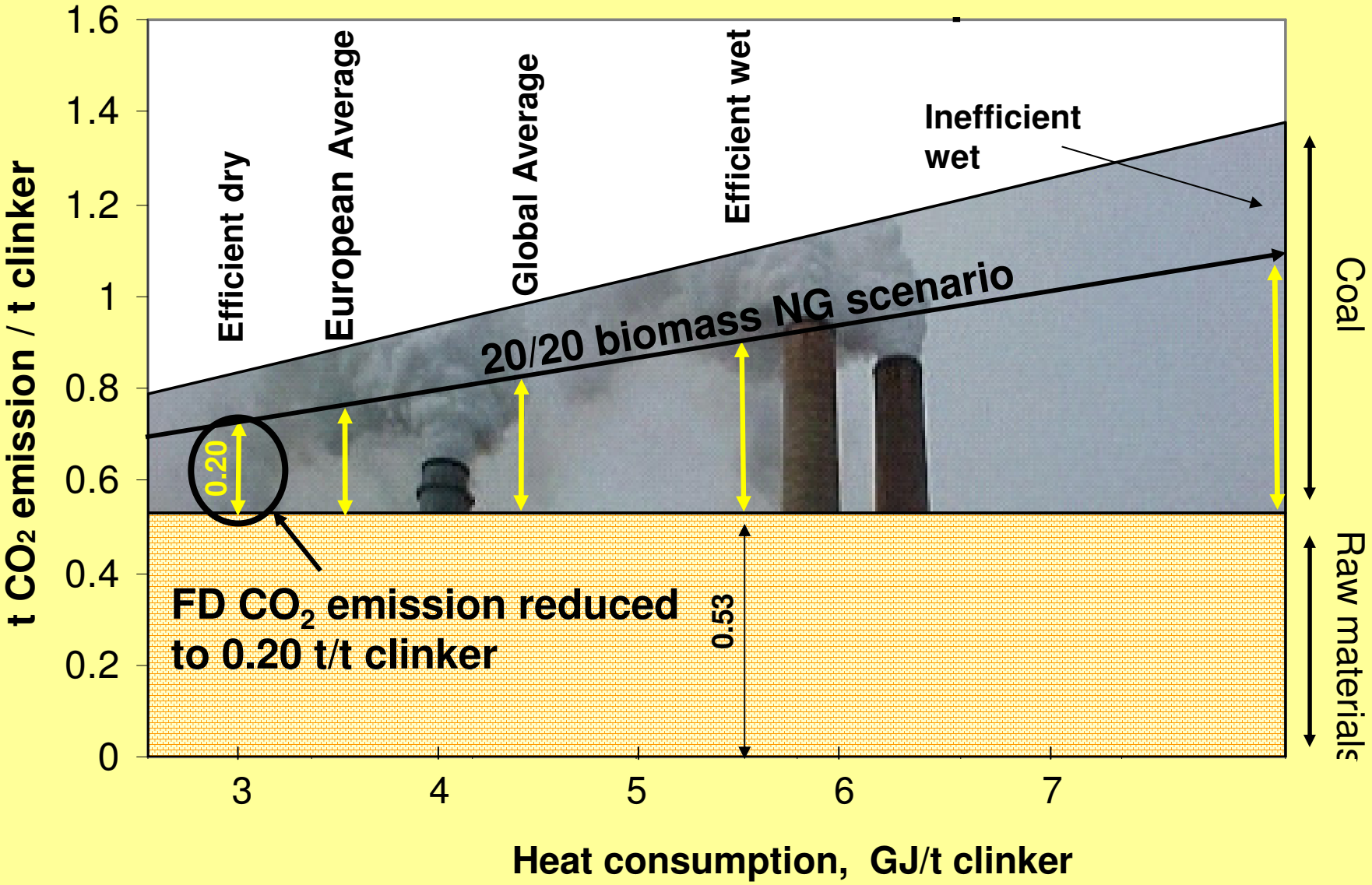
In all 34% of AFs can be classified as biomass

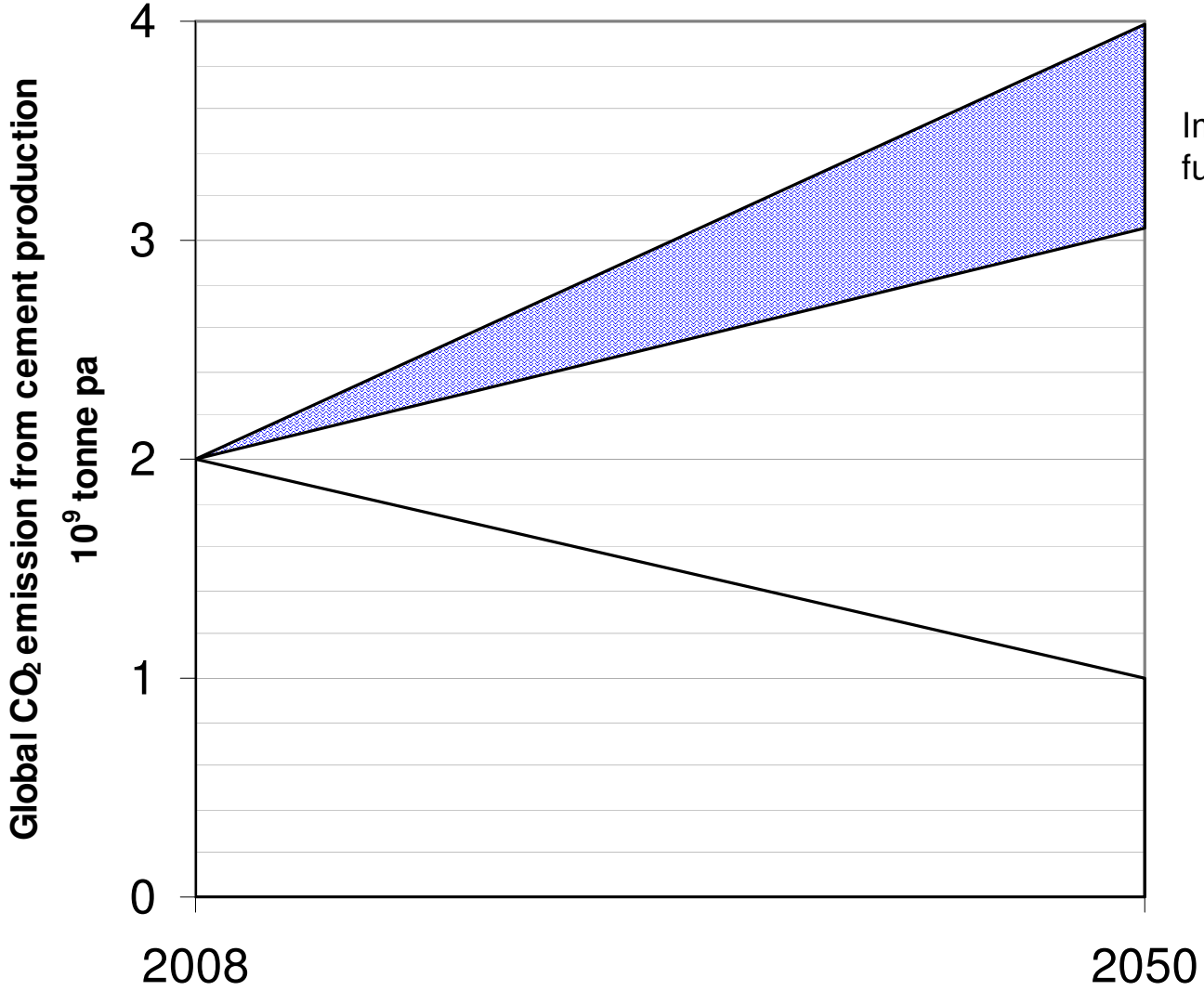
= 5% of total fuel

CO_2 emissions from clinker production as a function of kiln efficiency

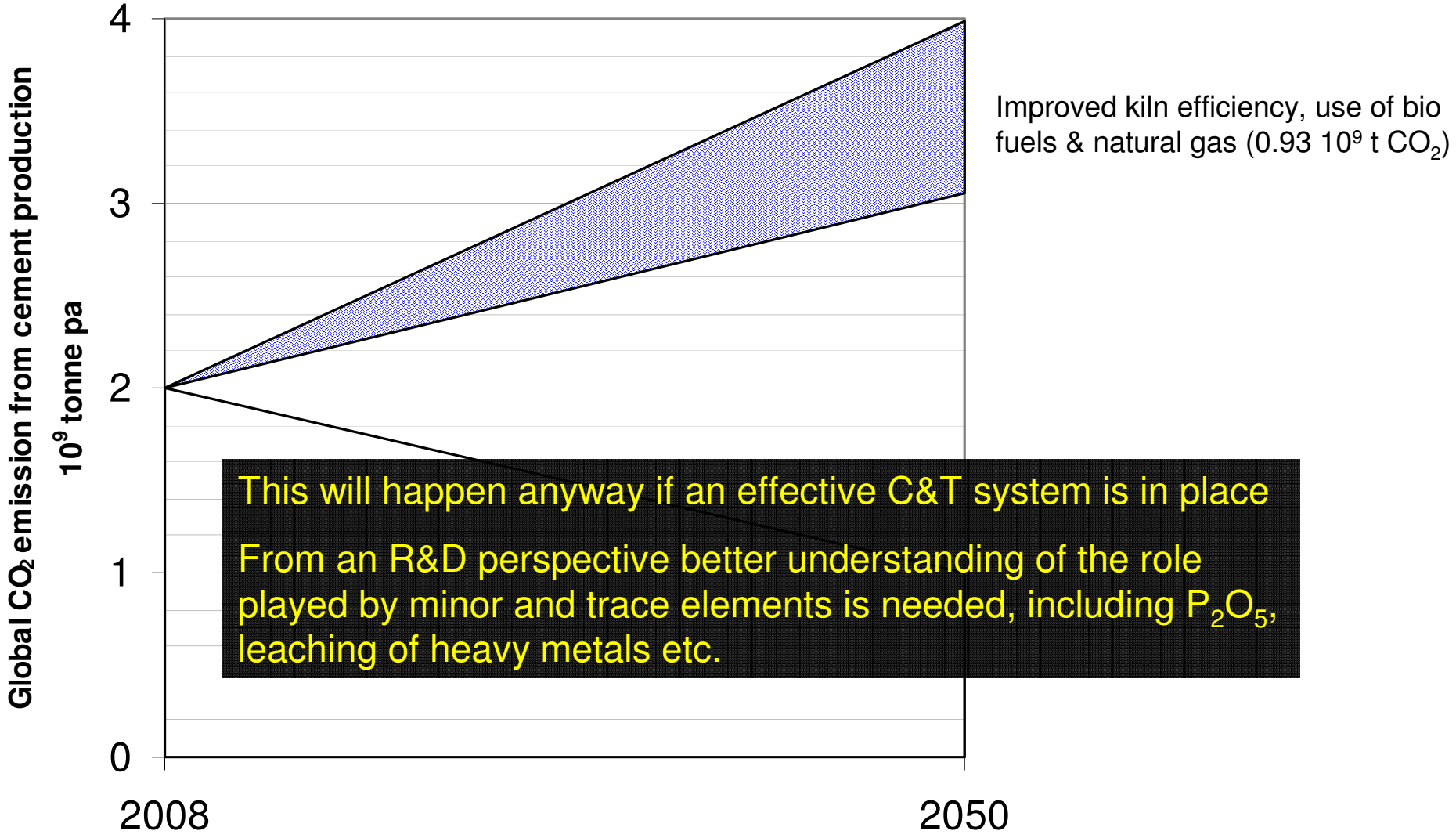


CO_2 emissions from clinker production as a function of kiln efficiency



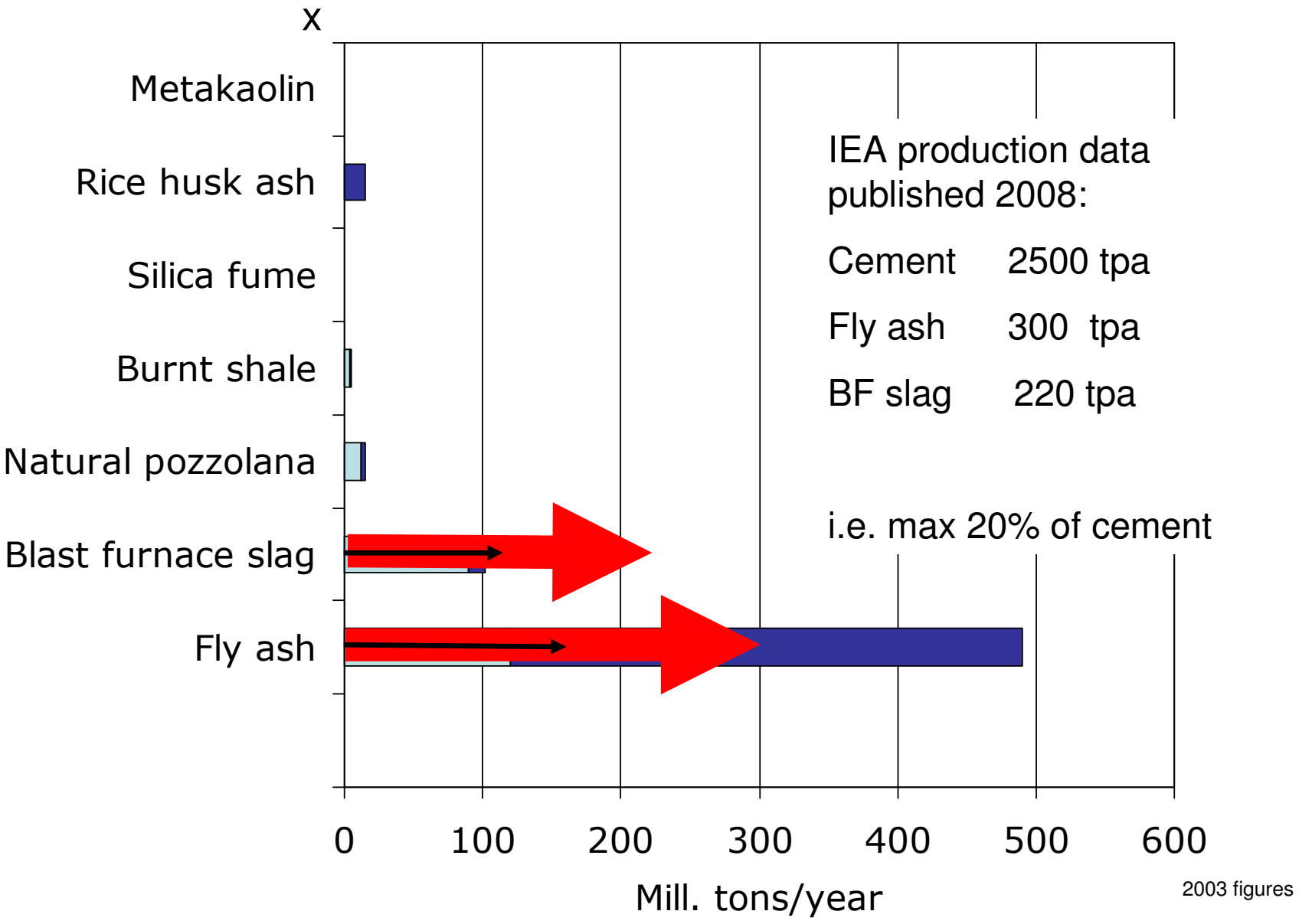


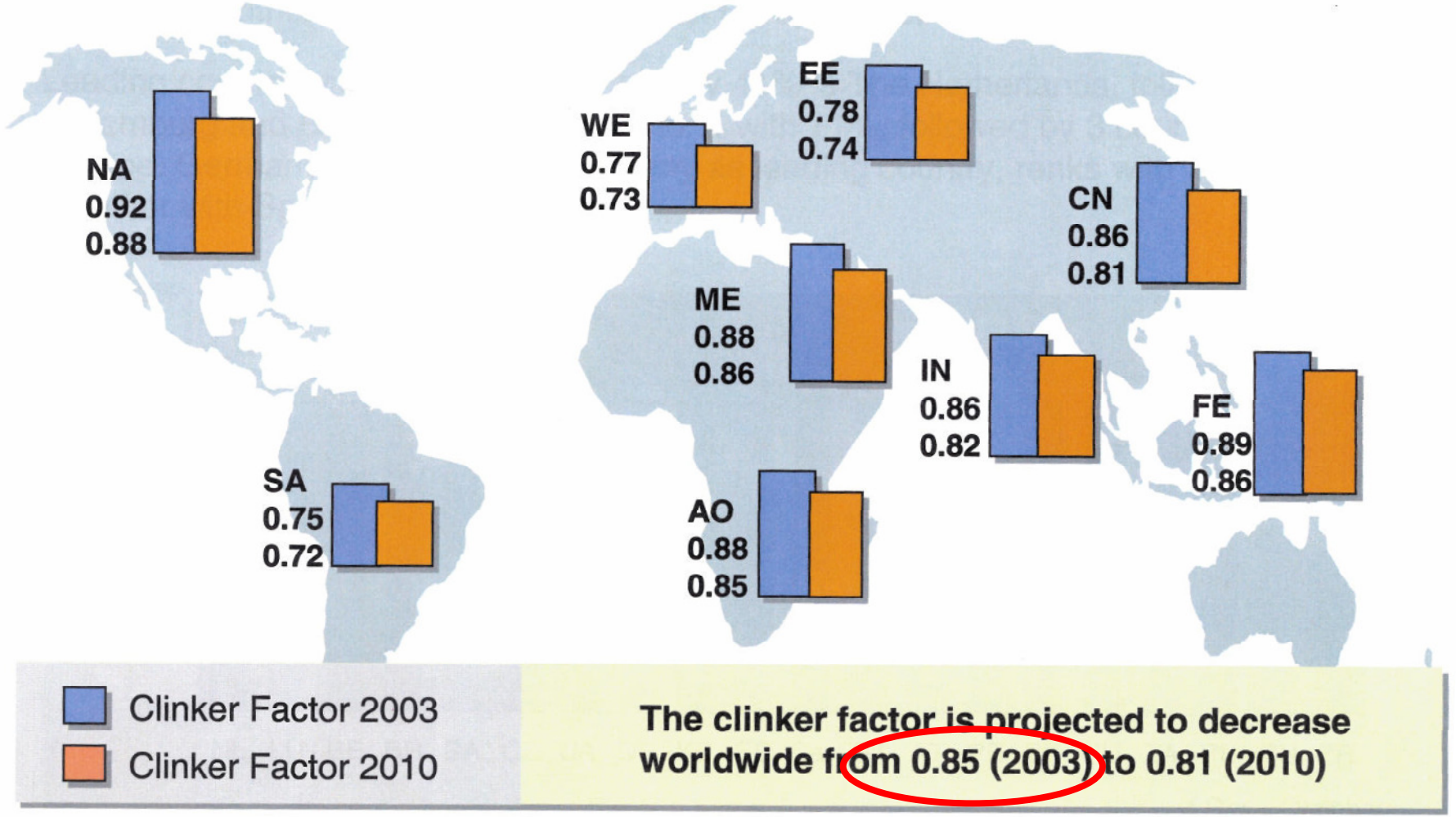
Improved kiln efficiency, use of bio fuels & natural gas (0.93 10^9 t CO_2)

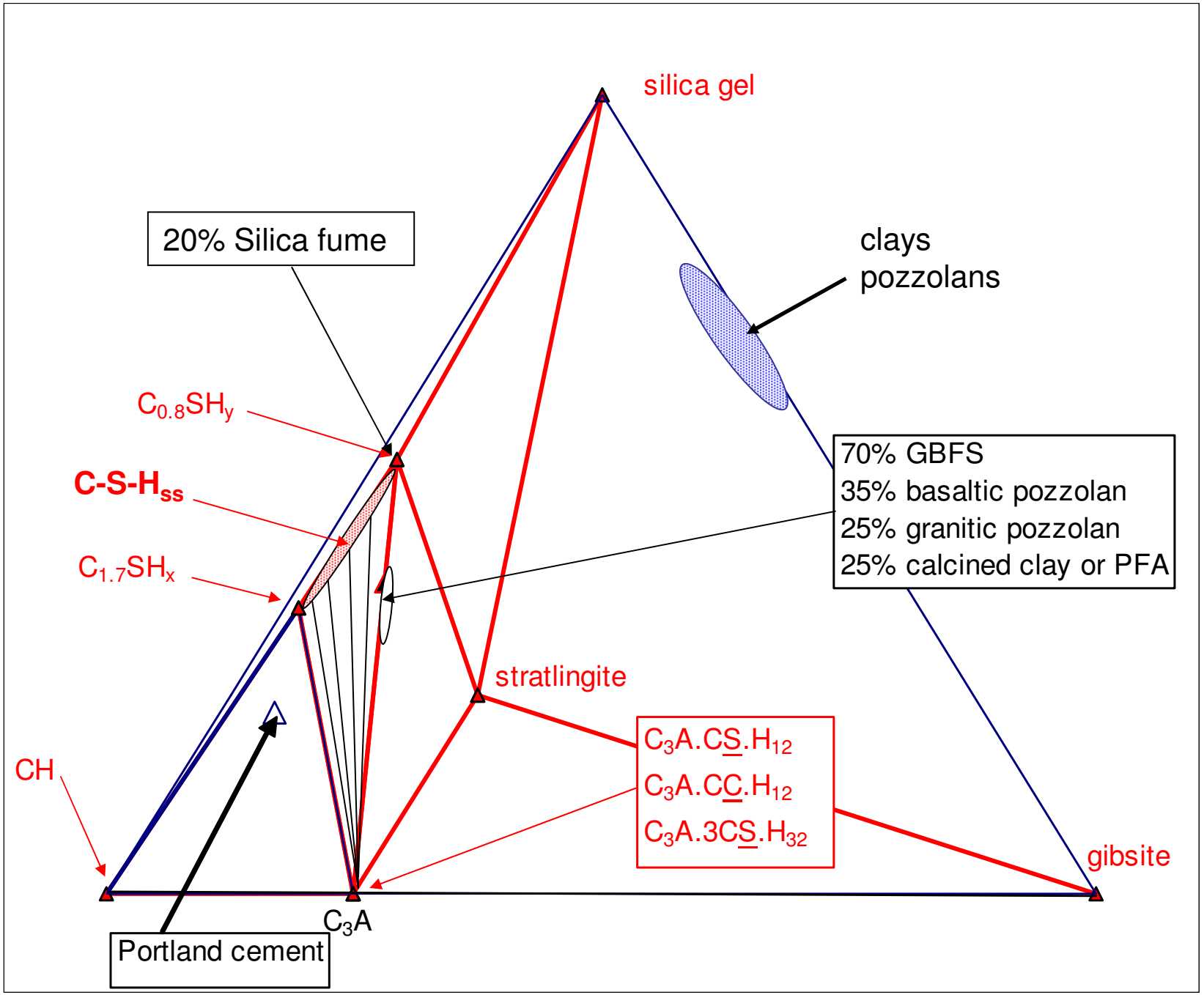

Global CO_2 emission from cement production
10^9 tonne pa
4
3
2
1
0
2008
2050
Improved kiln efficiency, use of bio fuels & natural gas (0.93 10^9 t CO_2)
This will happen anyway if an effective C&T system is in place
From an R&D perspective better understanding of the role played by minor and trace elements is needed, including P_2O_5, leaching of heavy metals etc.

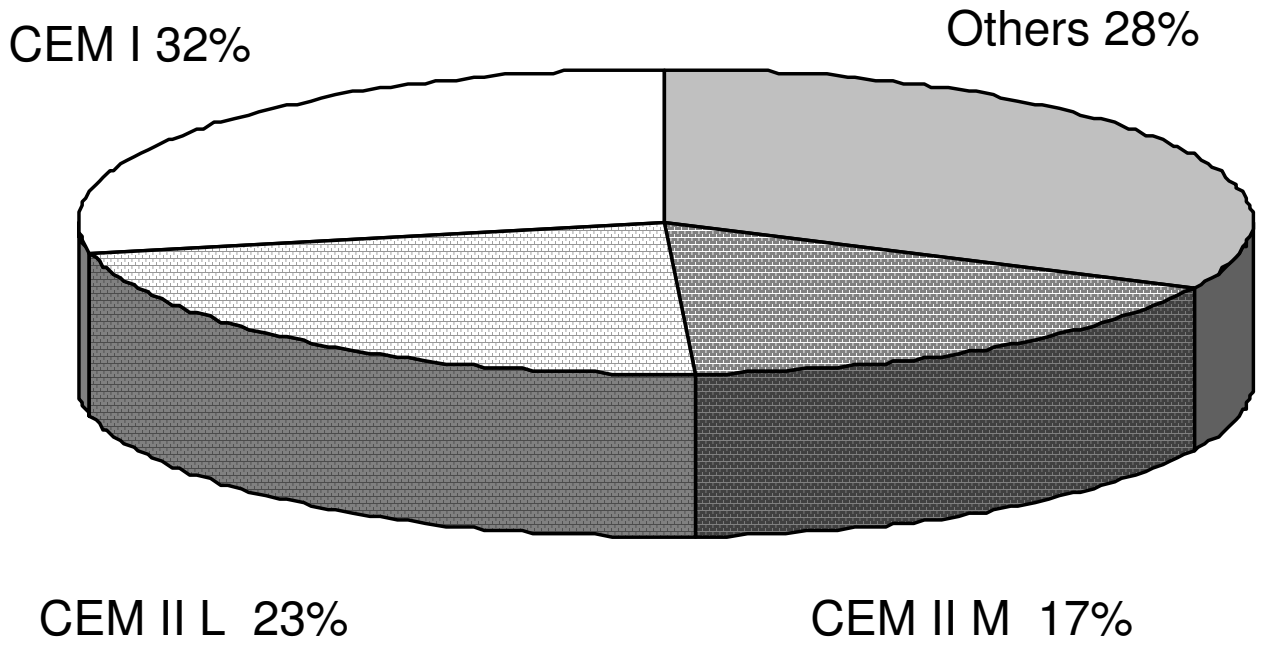

CO_2 EMISSIONS FROM CLINKER PRODCUTION
•RAW MATERIALS
•KILN EFFICIENCY
•LOW CARBON FUELS
SCMS
CONCRETE CARBONATION
CARBON CAPTURE & STORAGE
ALKALI ACTIVATED ALUMINO SILICATES

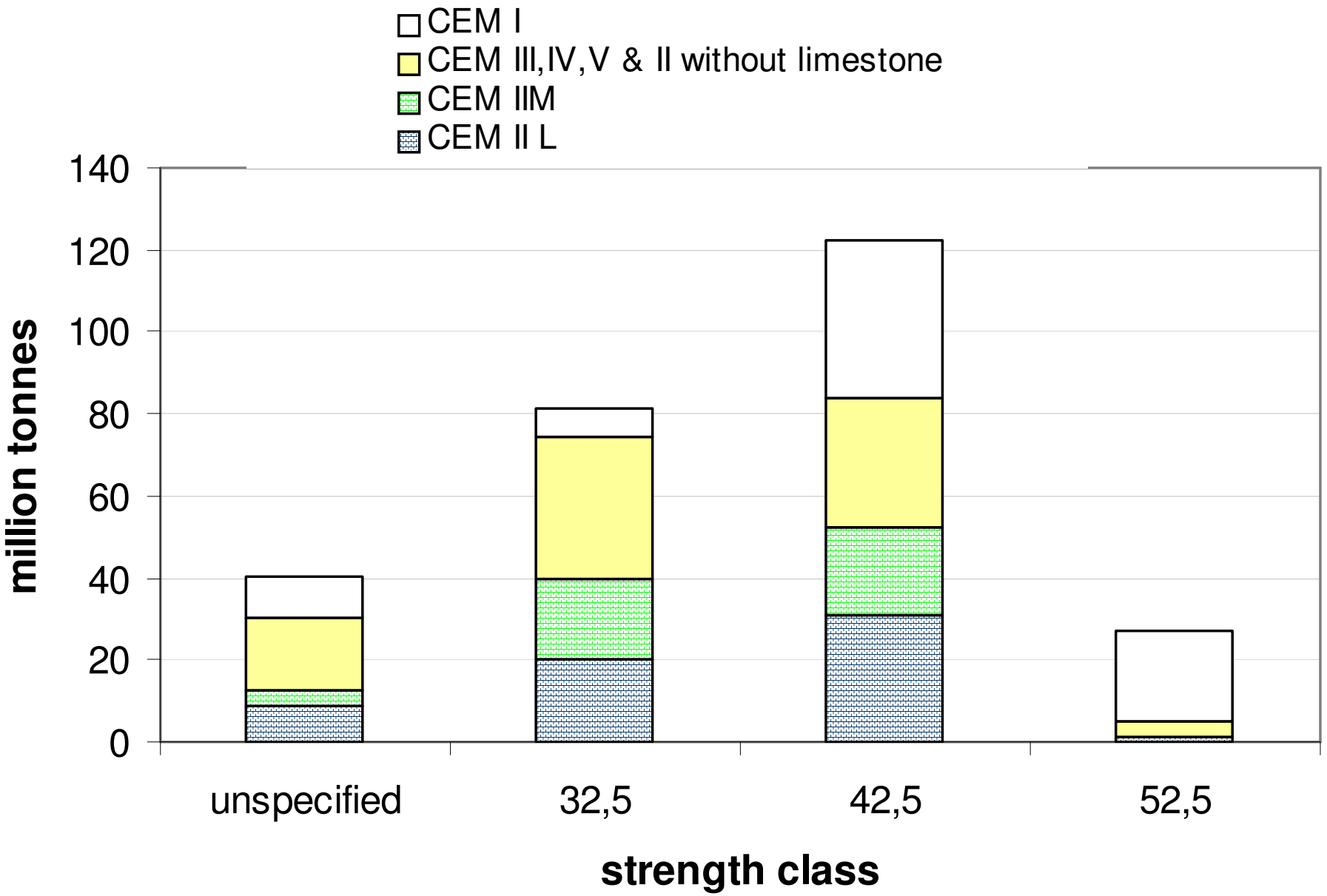
Availability of supplementary cementitious materials

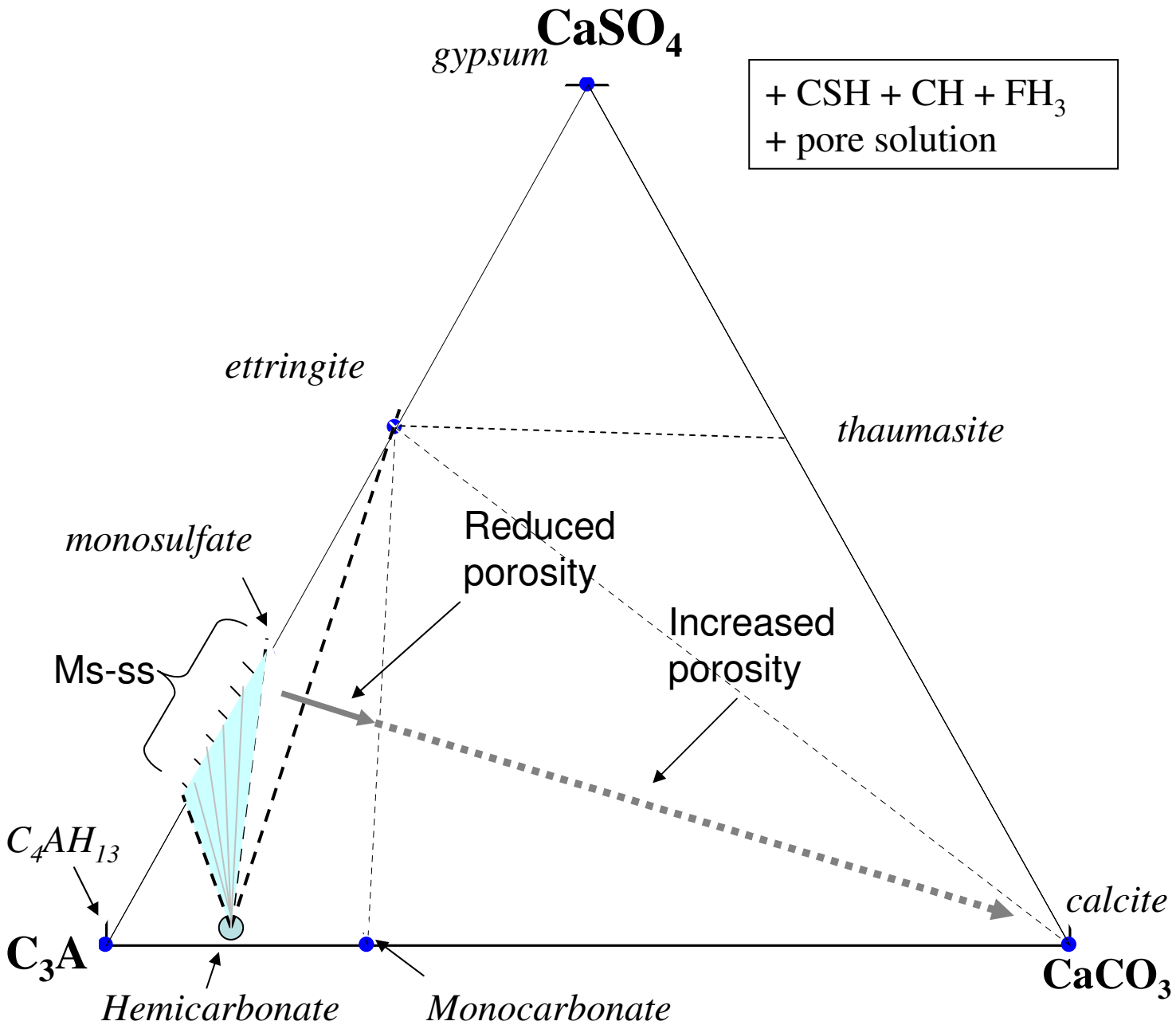



NA
0.92
0.88
SA
0.75
0.72
WE
0.77
0.73
EE
0.78
0.74
CN
0.86
0.81
ME
0.88
0.86
IN
0.86
0.82
FE
0.89
0.86
AO
0.88
0.85
Clinker Factor 2003
Clinker Factor 2010
The clinker factor is projected to decrease worldwide from 0.85 (2003) to 0.81 (2010)

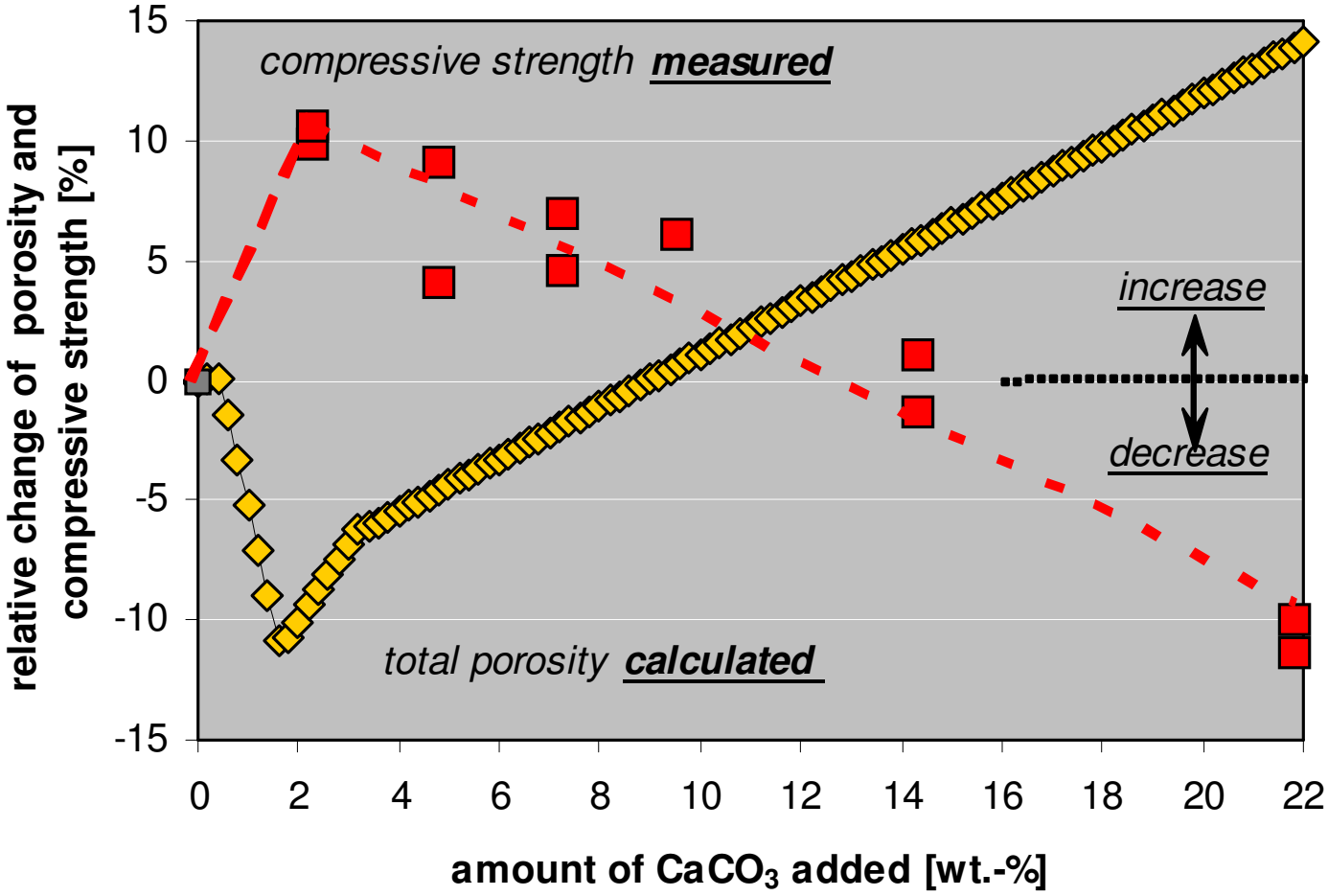

silica gel
20% Silica fume
clays
pozzolans
$C_{0.8}SH_y$
C-S-H$_{ss}$
$C_{1.7}SH_x$
70% GBFS
35% basaltic pozzolan
25% granitic pozzolan
25% calcined clay or PFA
stratlingite
$C_3A.C\underline{S}.H_{12}$
$C_3A.C\underline{C}.H_{12}$
$C_3A.3C\underline{S}.H_{32}$
CH
gibsite
C_3A
Portland cement


CEM I 32%
Others 28%
CEM II L 23%
CEM II M 17%

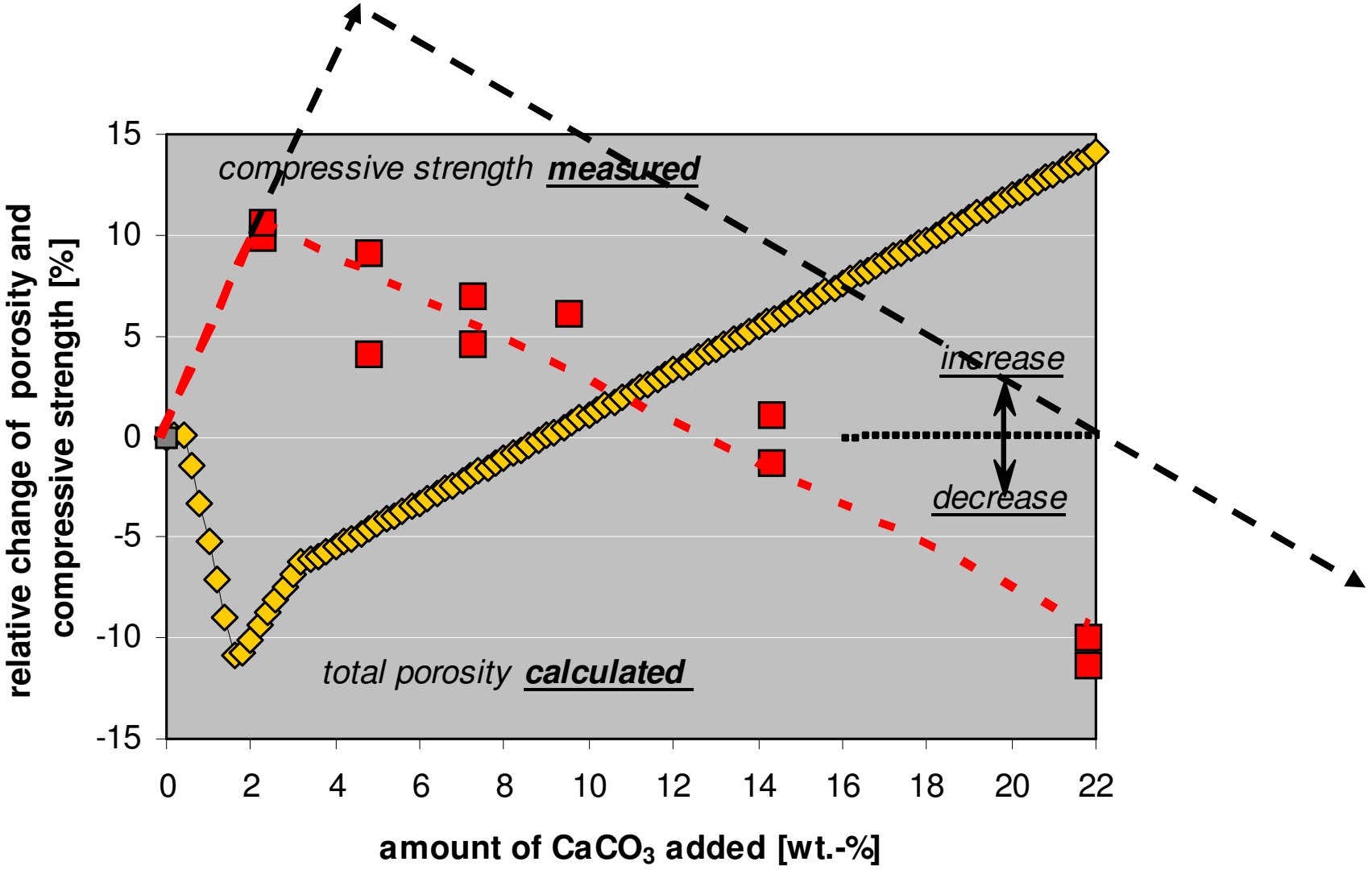

CEM I
CEM III,IV,V & II without limestone
CEM IIM
CEM II L
140
120
100
80
60
40
20
0
million tonnes
unspecified
32,5
42,5
52,5
strength class


CaSO4
gypsum
+ CSH + CH + FH3
+ pore solution
ettringite
thaumasite
monosulfate
Reduced
porosity
Increased
porosity
Ms-ss
C4AH13
calcite
C3A
CaCO3
Hemicarbonate
Monocarbonate

Correlation: Porosity – Compressive Strength (exp. Data by D. Herfort, Aalborg cement)



Very good correlation between predicted changes of relative porosity and measured compressive strength



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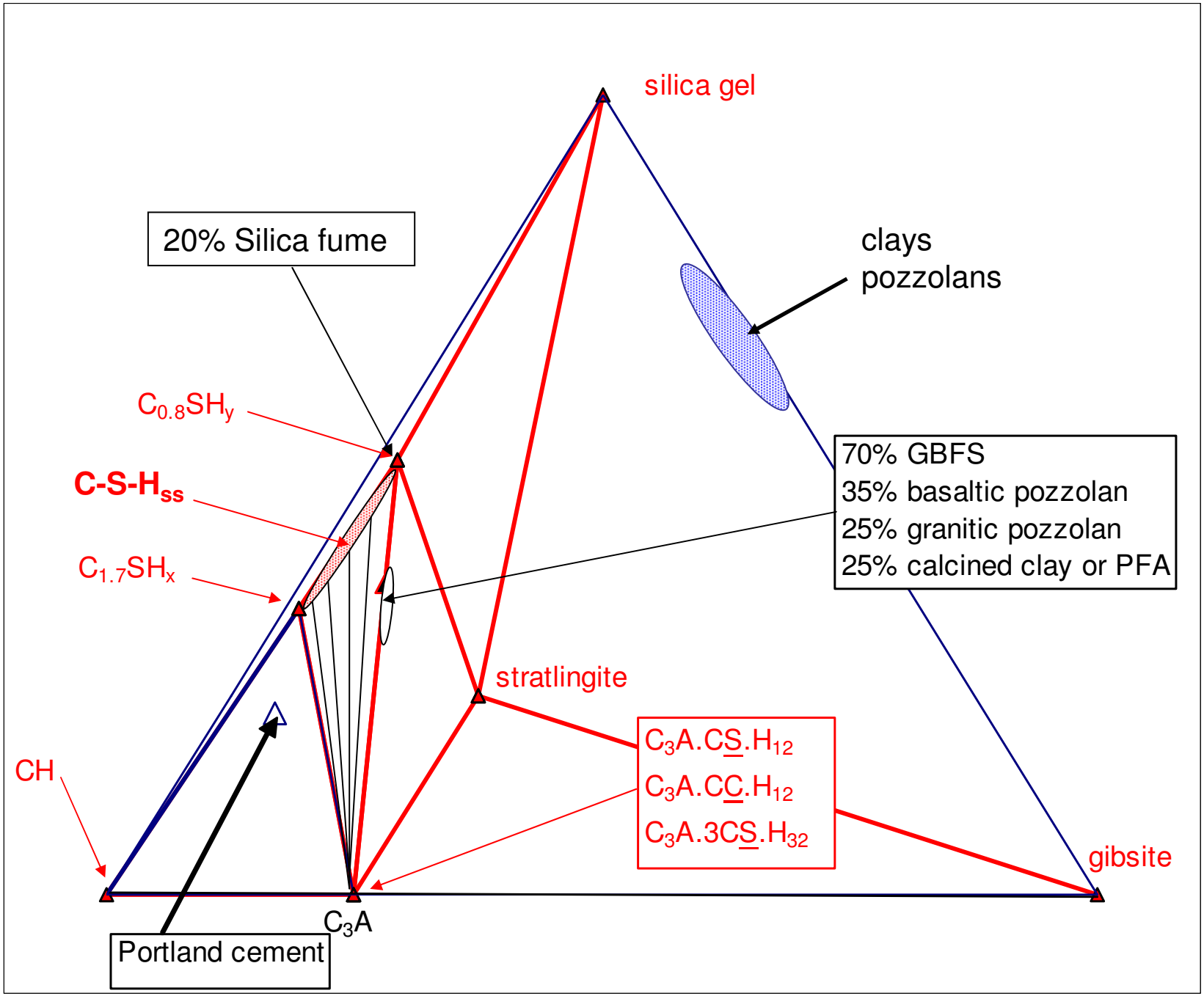
silica gel
20% Silica fume
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$C_{0.8}SH_y$
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70% GBFS
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stratlingite
$C_3A.C\underline{S}.H_{12}$
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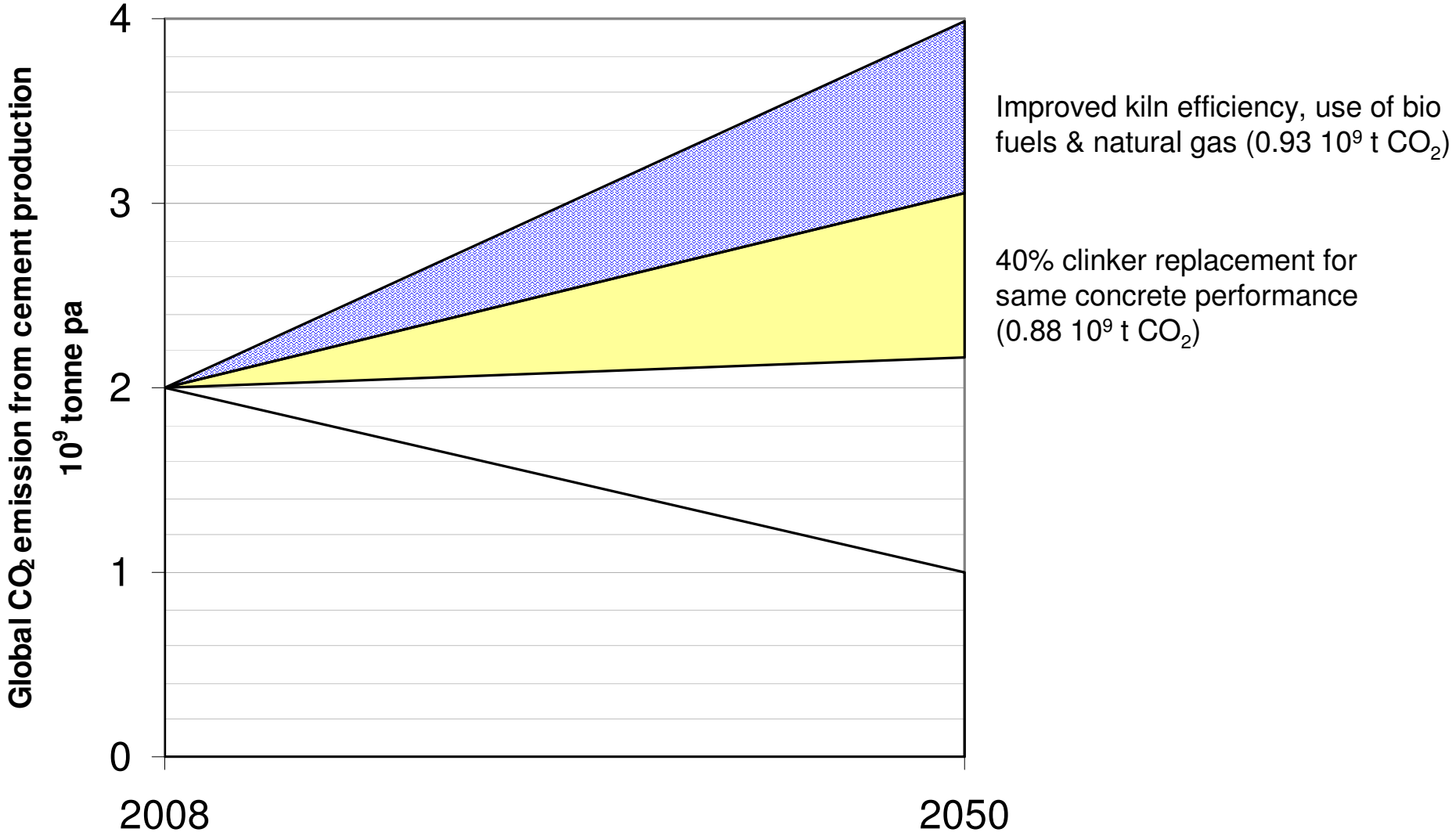
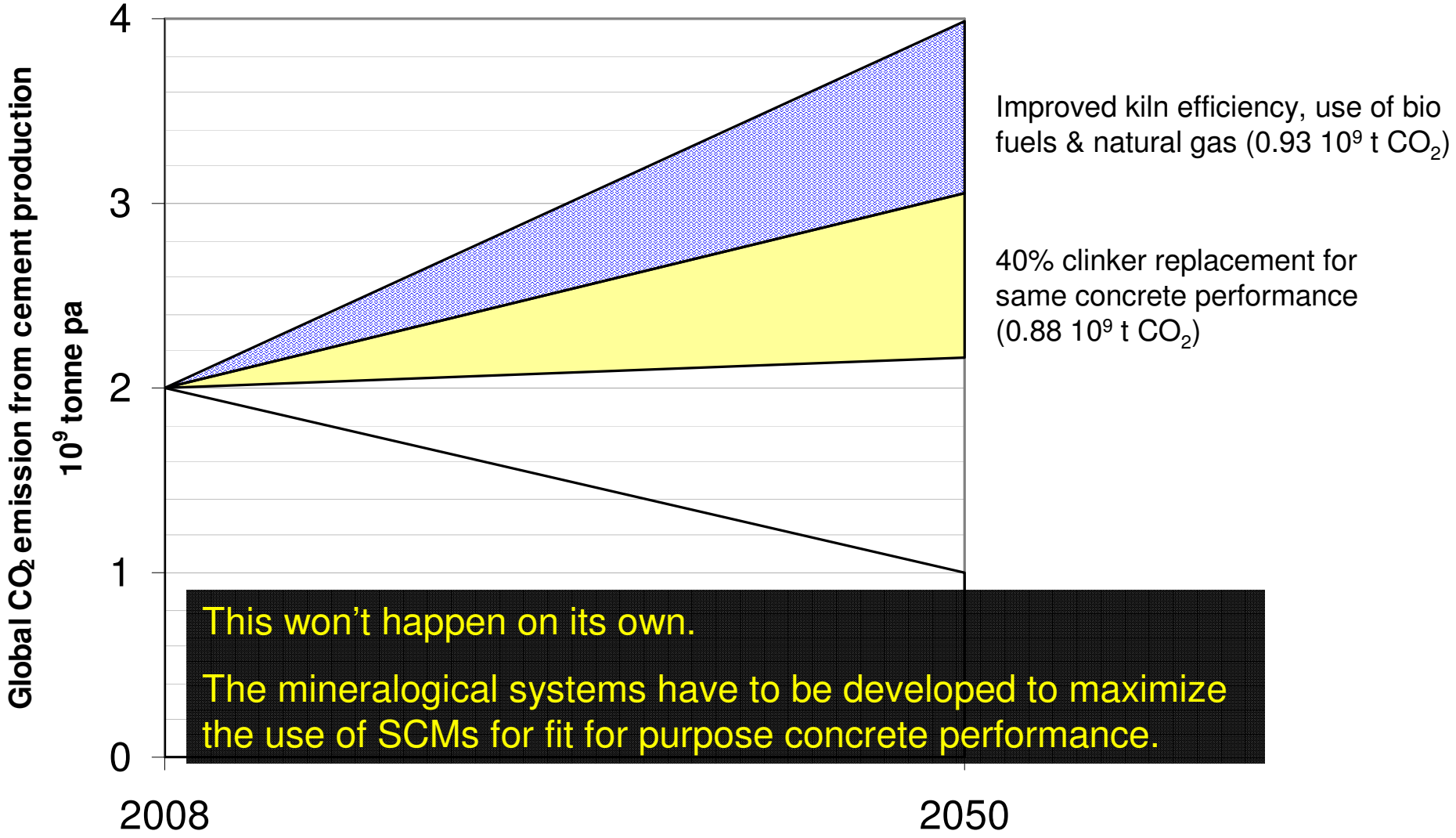
CH
gibsite
C_3A
Portland cement


Global CO_2 emission from cement production
10^9 tonne pa
4
3
2
1
0
2008
2050
Improved kiln efficiency, use of bio fuels & natural gas (0.93 10^9 t CO_2)
40% clinker replacement for same concrete performance (0.88 10^9 t CO_2)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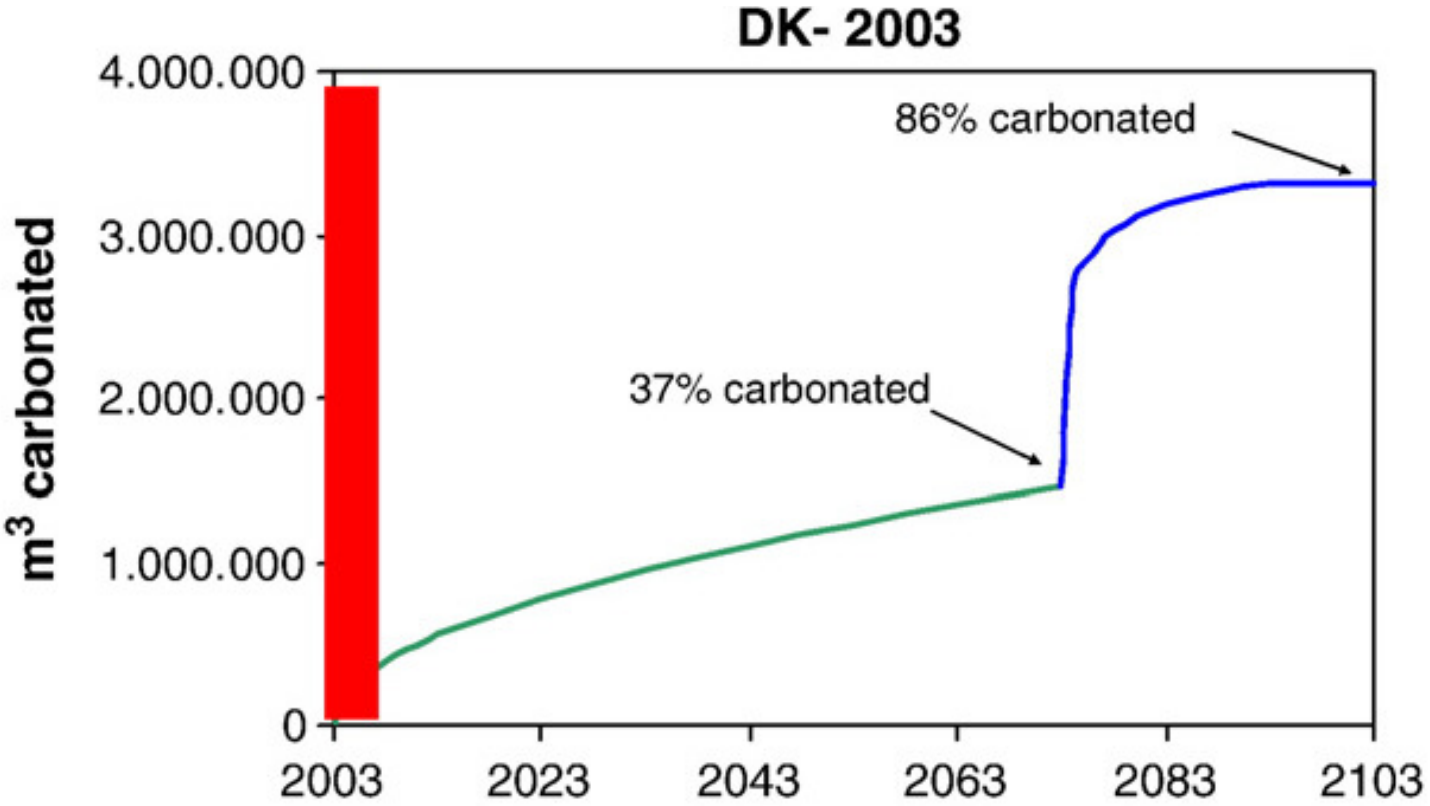
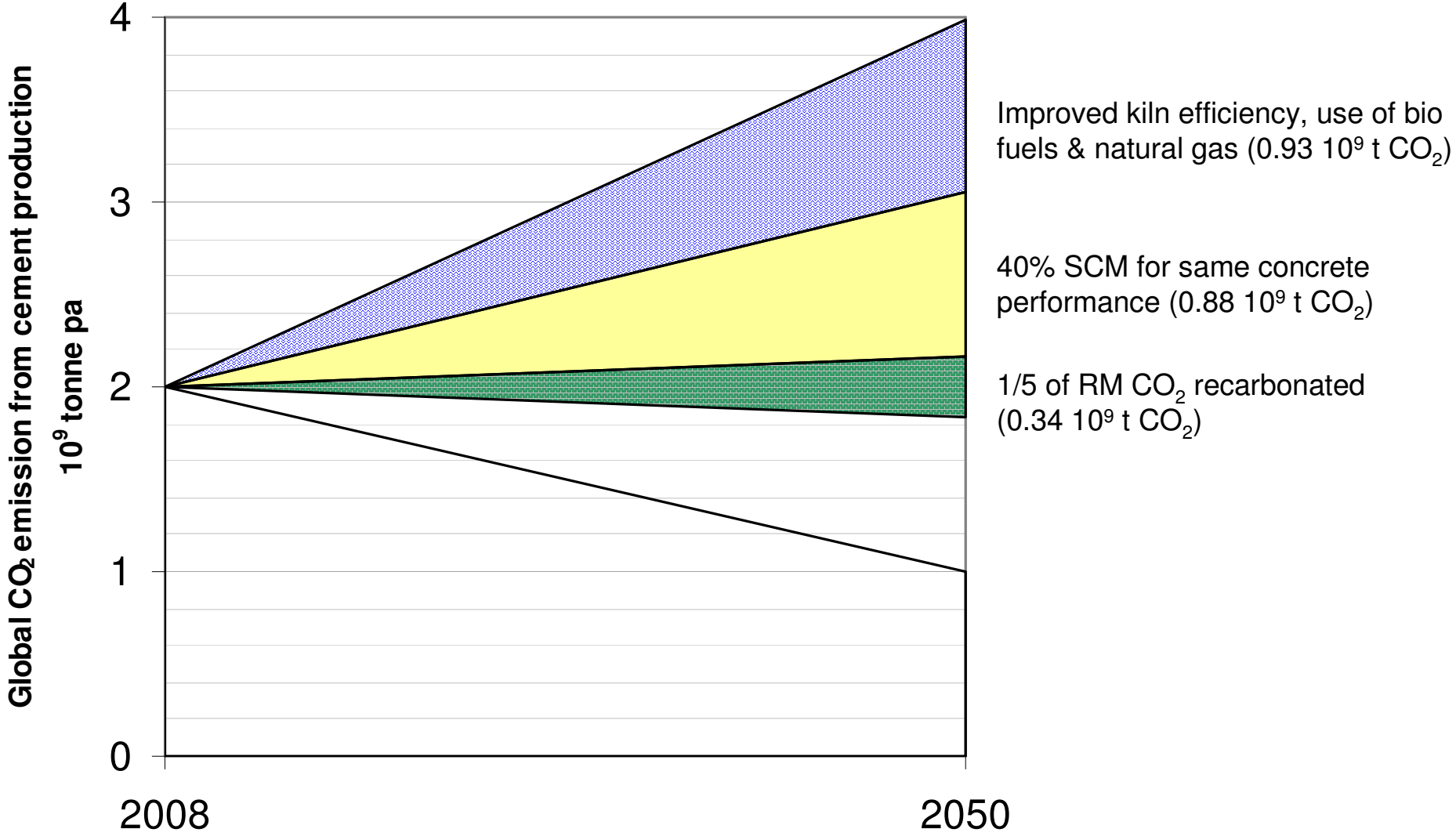
Improved kiln efficiency, use of bio fuels & natural gas (0.93 10^9 t CO_2)
40% clinker replacement for same concrete performance (0.88 10^9 t CO_2)
This won't happen on its own.
The mineralogical systems have to be developed to maximize the use of SCMs for fit for purpose concrete performance.


CO_2 EMISSIONS FROM CLINKER PRODCUTION
•RAW MATERIALS
•KILN EFFICIENCY
•LOW CARBON FUELS
SCMS
CONCRETE CARBONATION
CARBON CAPTURE & STORAGE
ALKALI ACTIVATED ALUMINO SILICATES


CONCRETE
CARBONATION


DK- 2003
4.000.000
3.000.000
2.000.000
1.000.000
0
m3 carbonated
86% carbonated
37% carbonated
2003
2023
2043
2063
2083
2103


Actual recycled aggregate, stockpiled 1 year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2008
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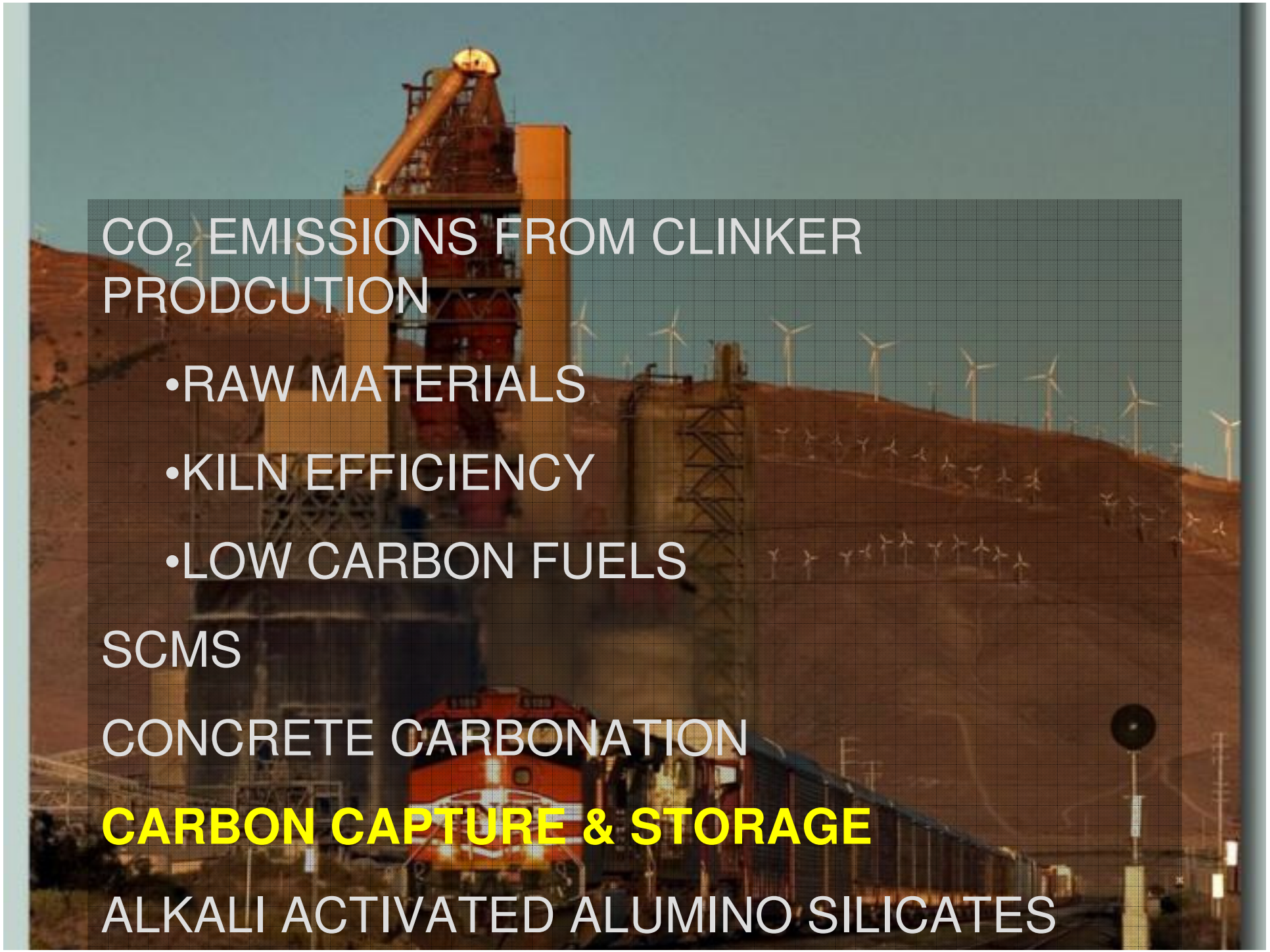
Improved kiln efficiency, use of bio fuels & natural gas (0.93 10^9 t CO_2)
40% SCM for same concrete performance (0.88 10^9 t CO_2)
1/5 of RM CO_2 recarbonated (0.34 10^9 t CO_2)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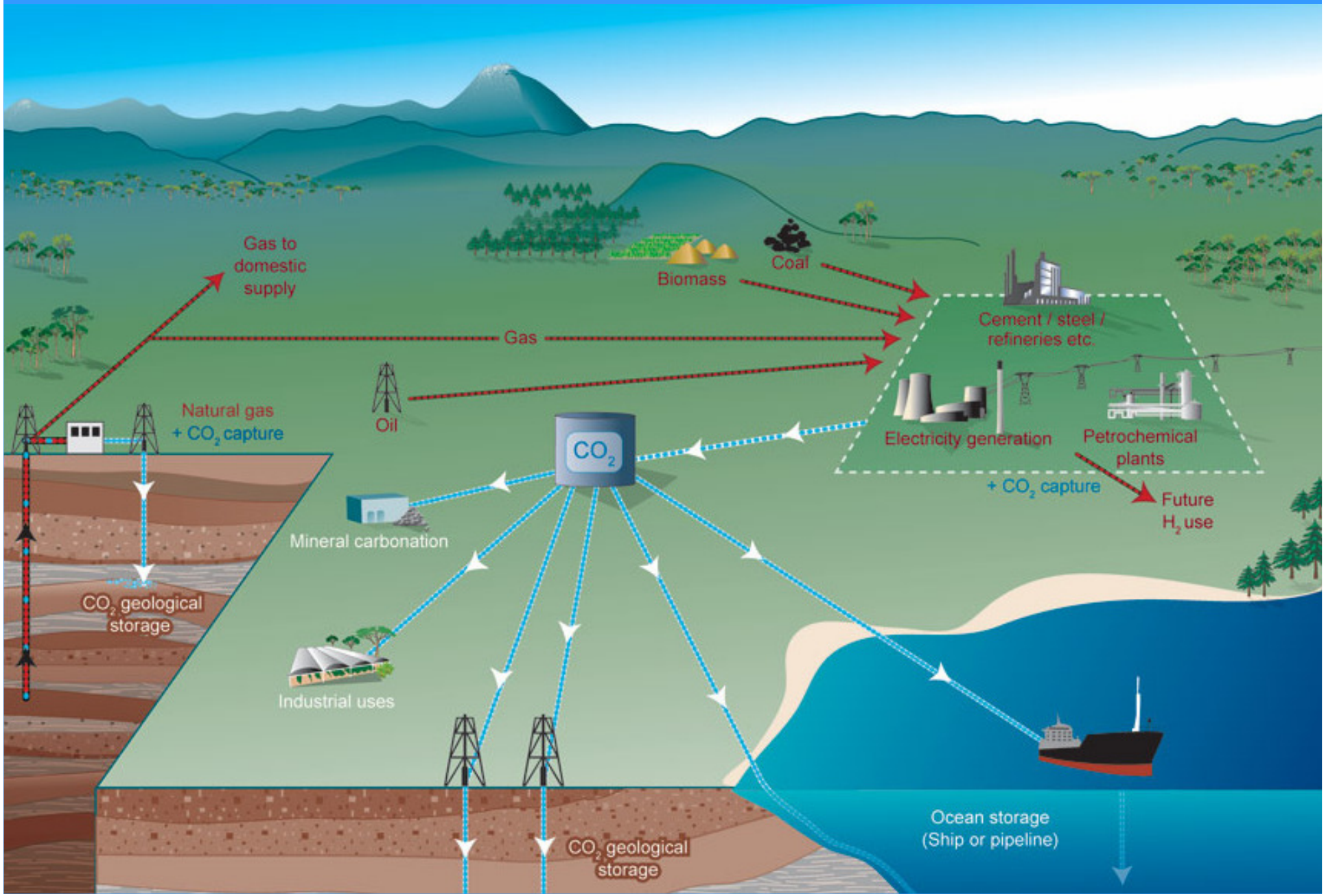
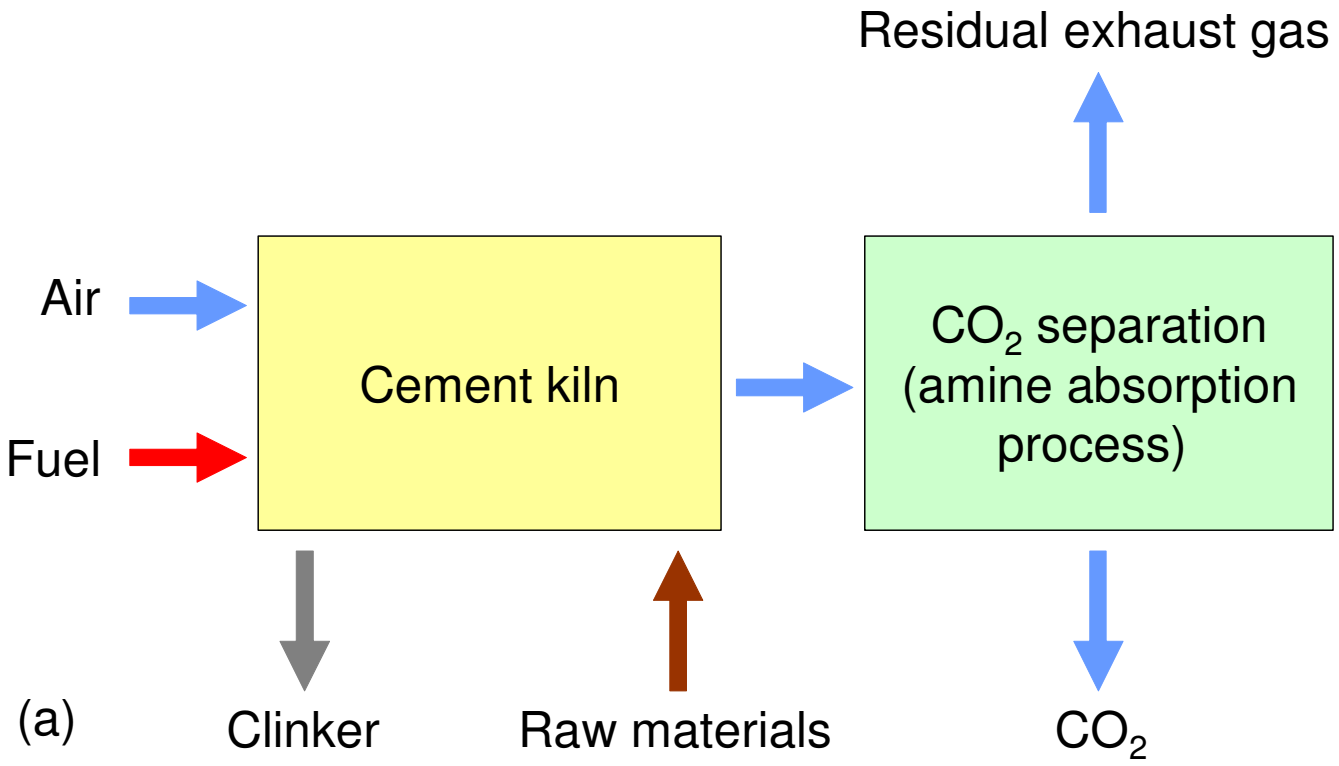
CARBON CAPTURE AND STORAGE

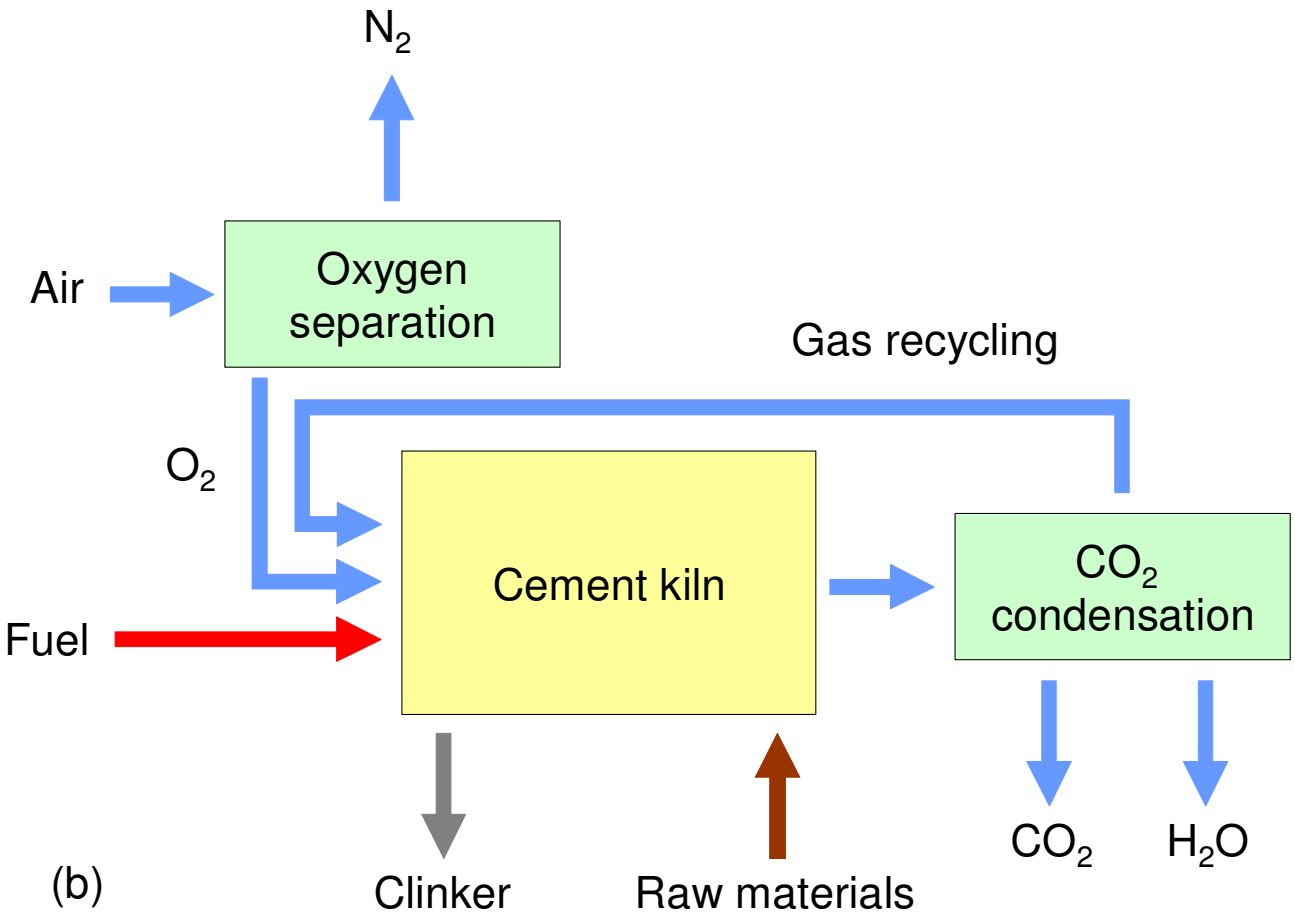


POST COMBUSTION

Adds $50 to $100/t CO_2 avoided to cost of production

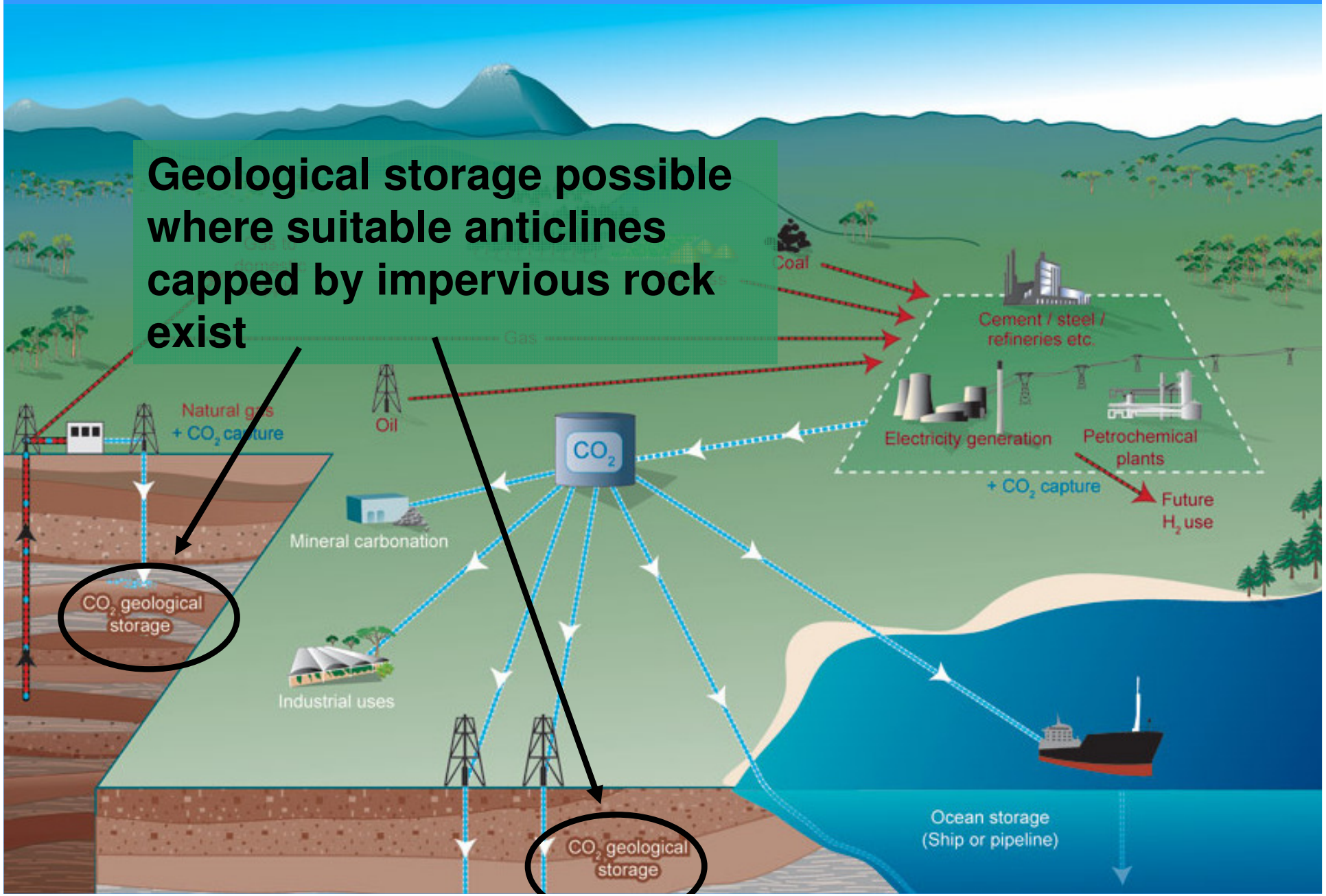


OXYFUEL

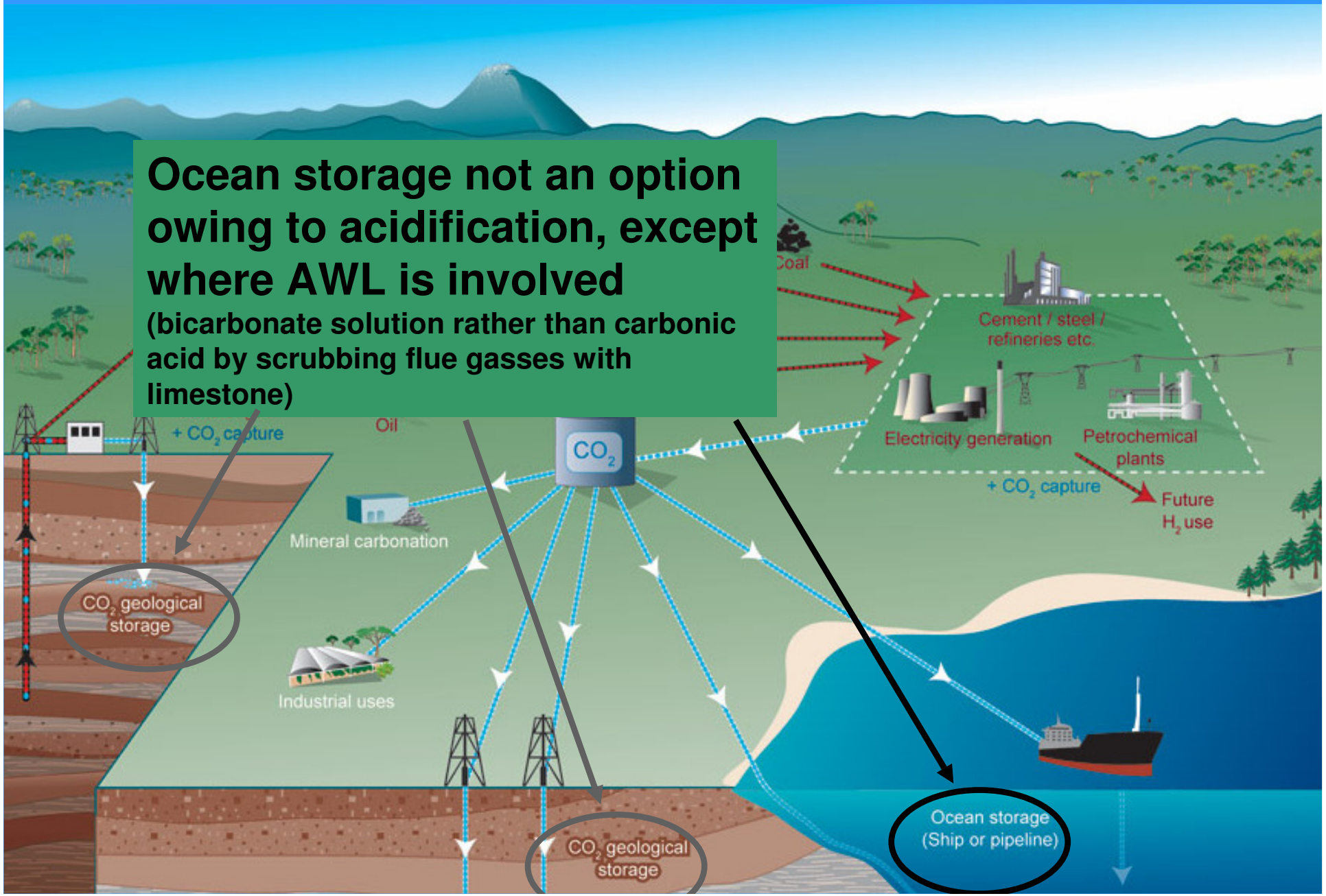

N_2
Air
Oxygen separation
Gas recycling
O_2
Cement kiln
CO_2 condensation
Fuel
Clinker
Raw materials
CO_2
H_2O

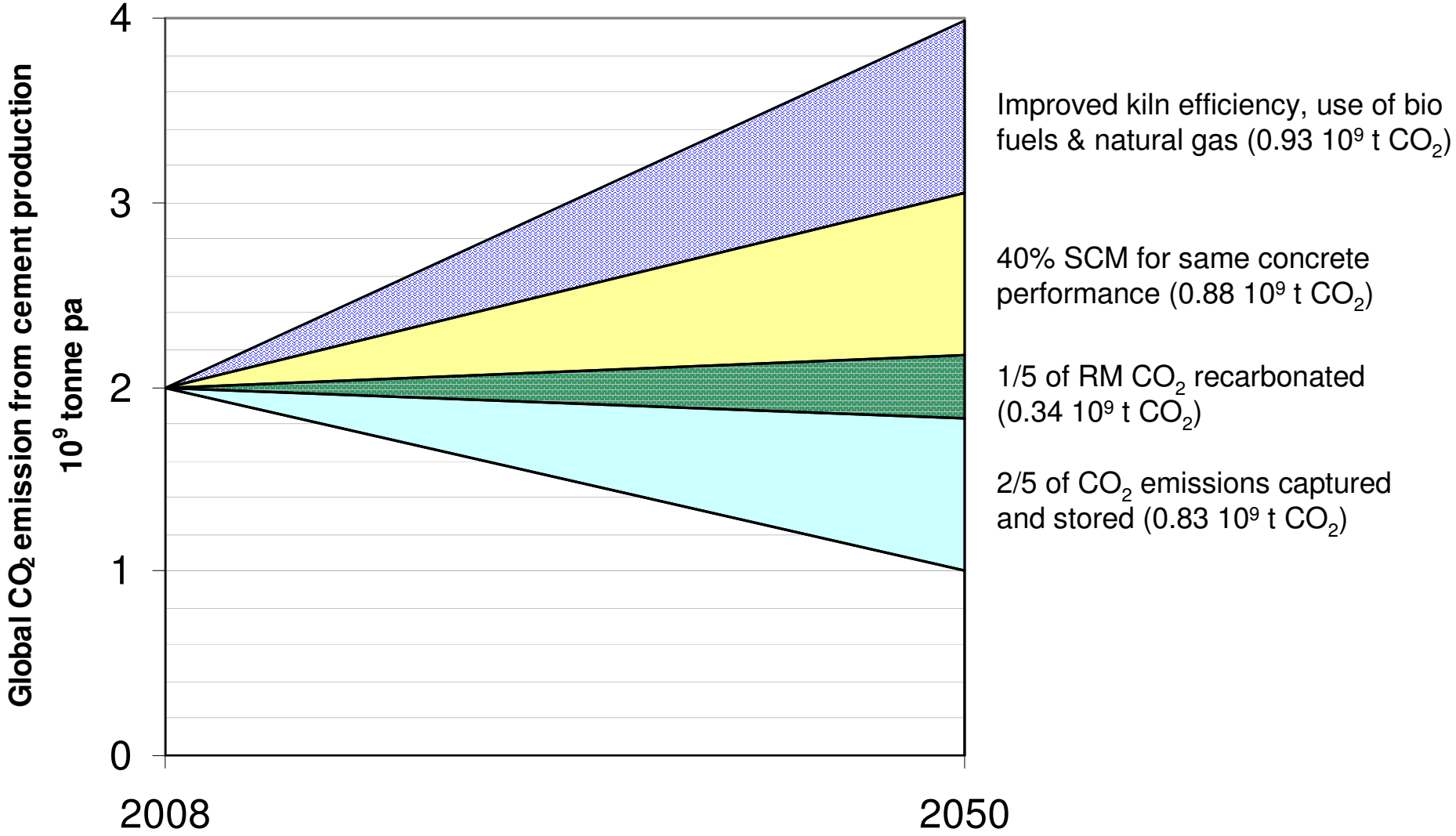
(b)

CARBON CAPTURE AND STORAGE



CARBON CAPTURE AND STORAGE

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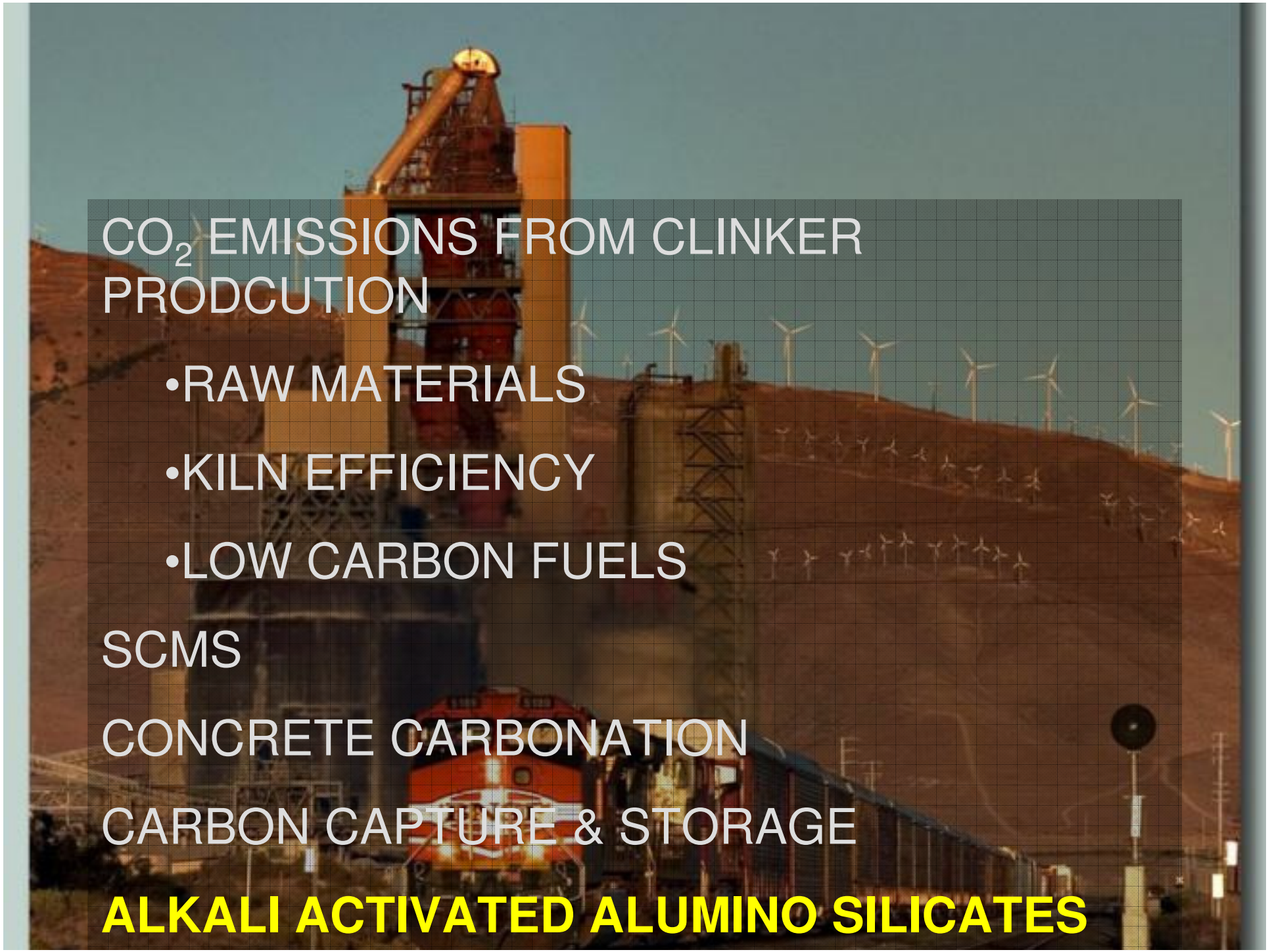
1/5 of RM CO_2 recarbonated (0.34 10^9 t CO_2)
2/5 of CO_2 emissions captured and stored (0.83 10^9 t CO_2)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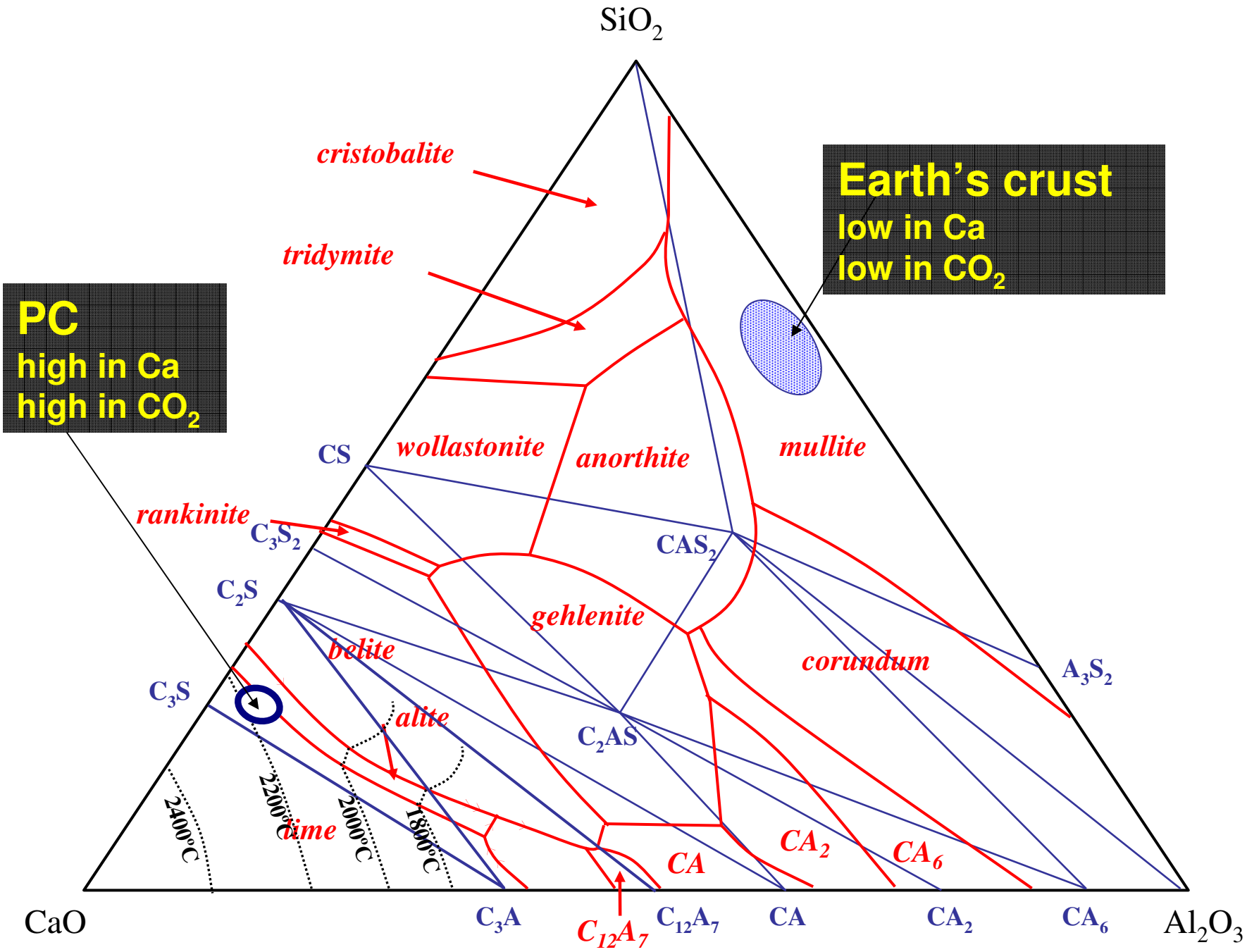
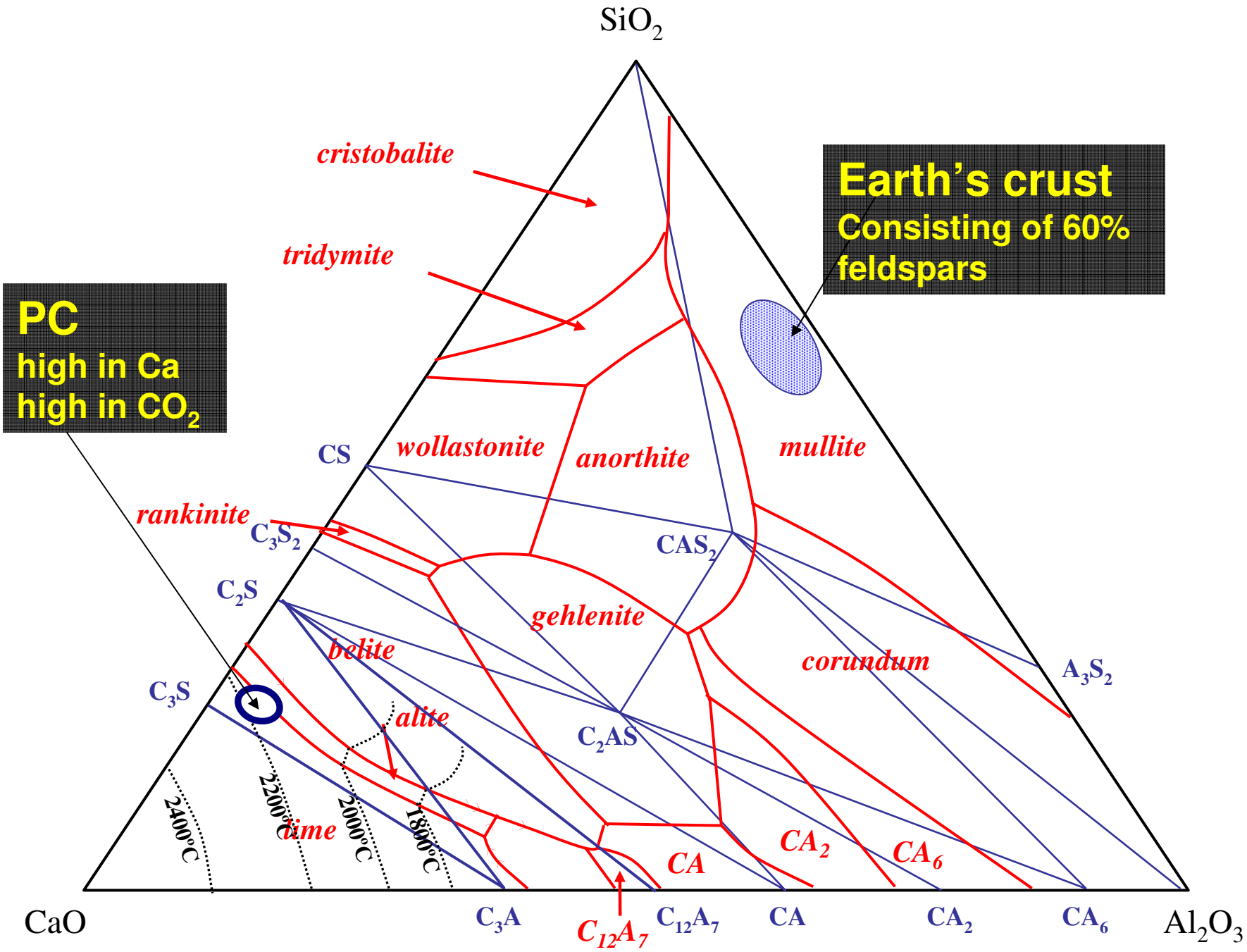
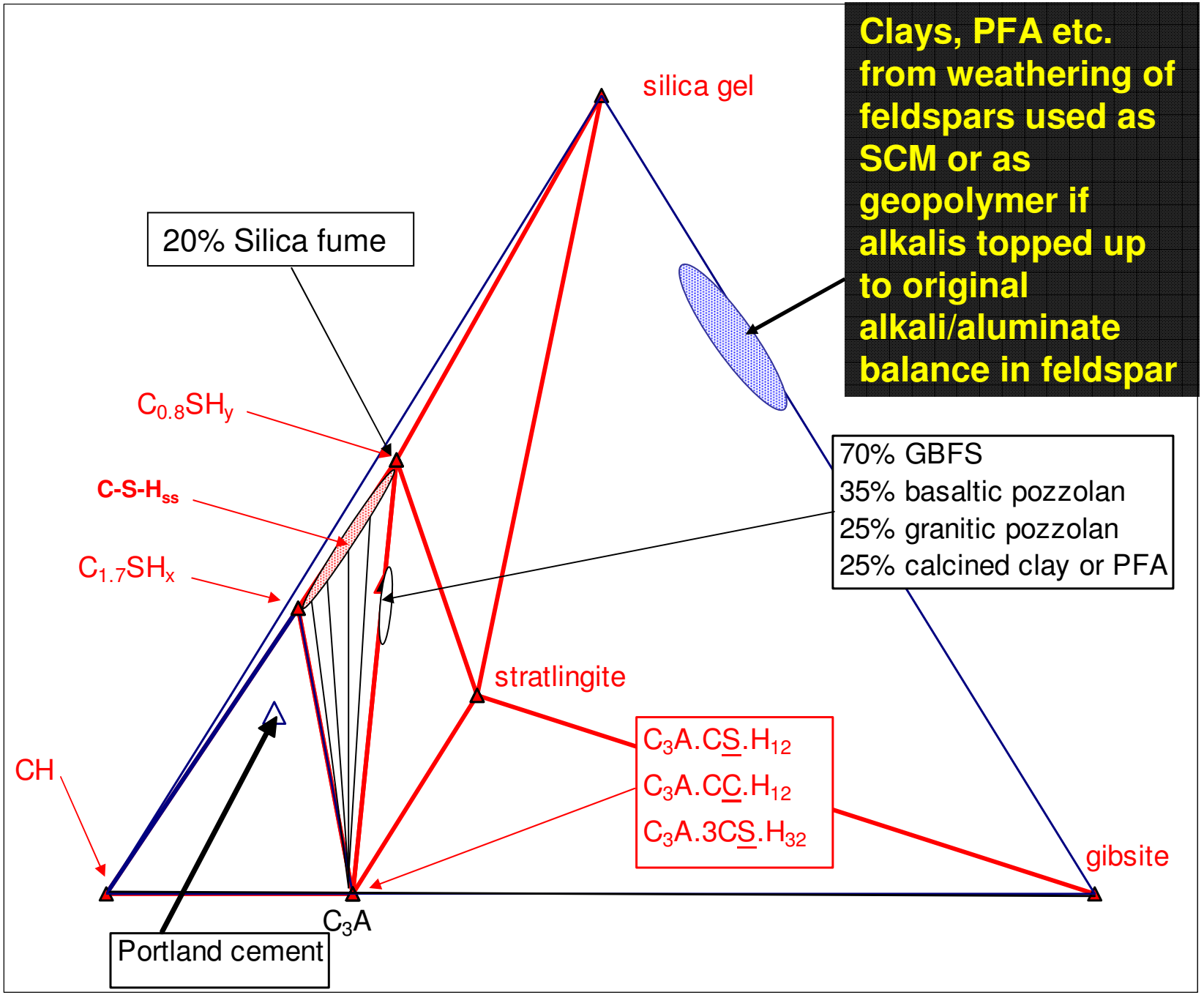
ALKALI ACTIVATED ALUMINO-SILICATE CEMENTS

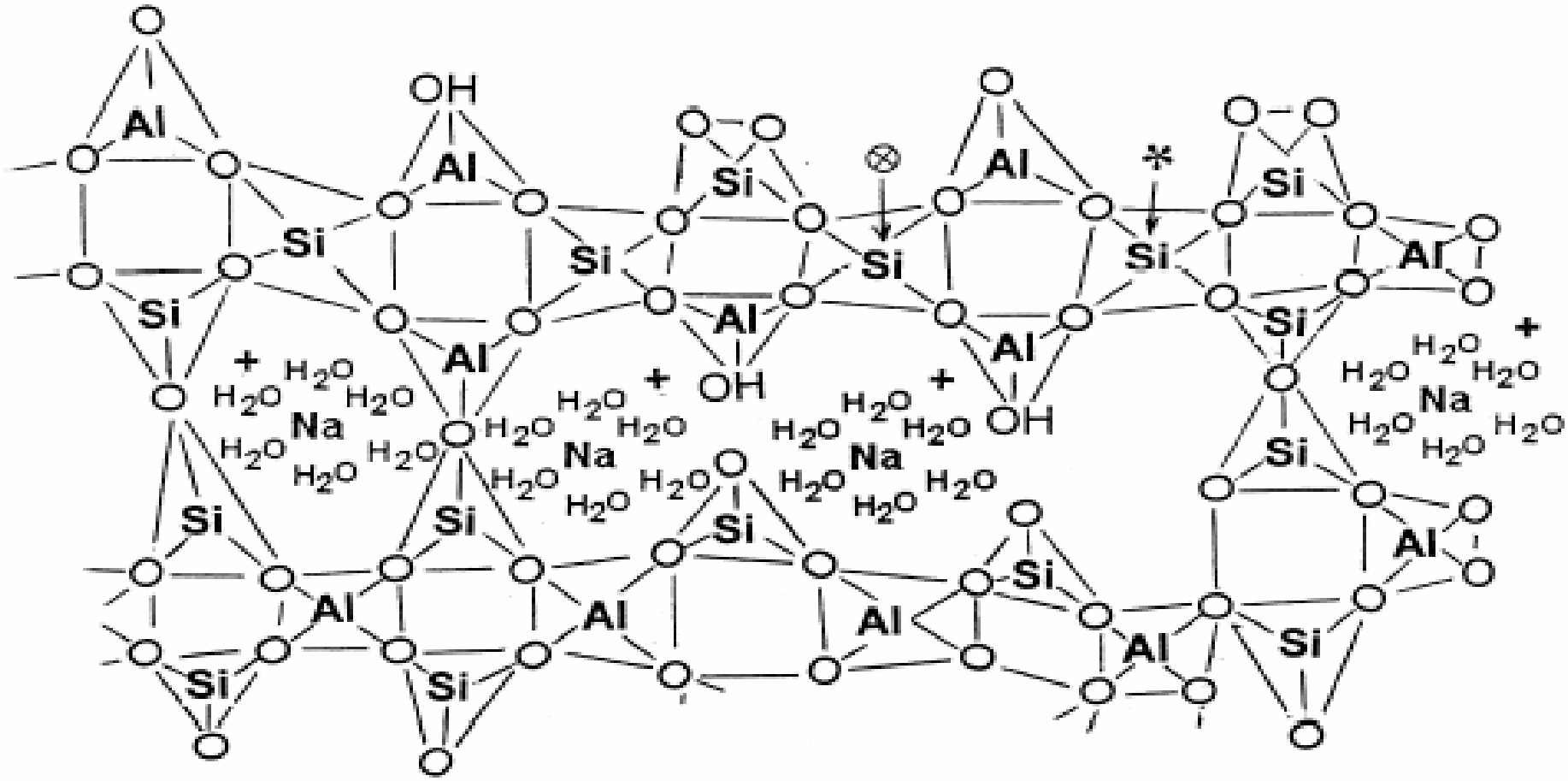
•alkali-activated systems are claimed to require 60% less energy to produce than PC and to reduce CO_2 emissions by 80%


SiO2
cristobalite
tridymite
Earth's crust
low in Ca
low in CO2
PC
high in Ca
high in CO2
CS
wollastonite
anorthite
mullite
rankinite
C3S2
CAS2
C2S
gehlenite
belite
corundum
A3S2
C3S
alite
C2AS
2400°C
2200°C
time
2000°C
1800°C
CA
CA2
CA6
CaO
C3A
C12A7
CA
CA2
CA6
Al2O3

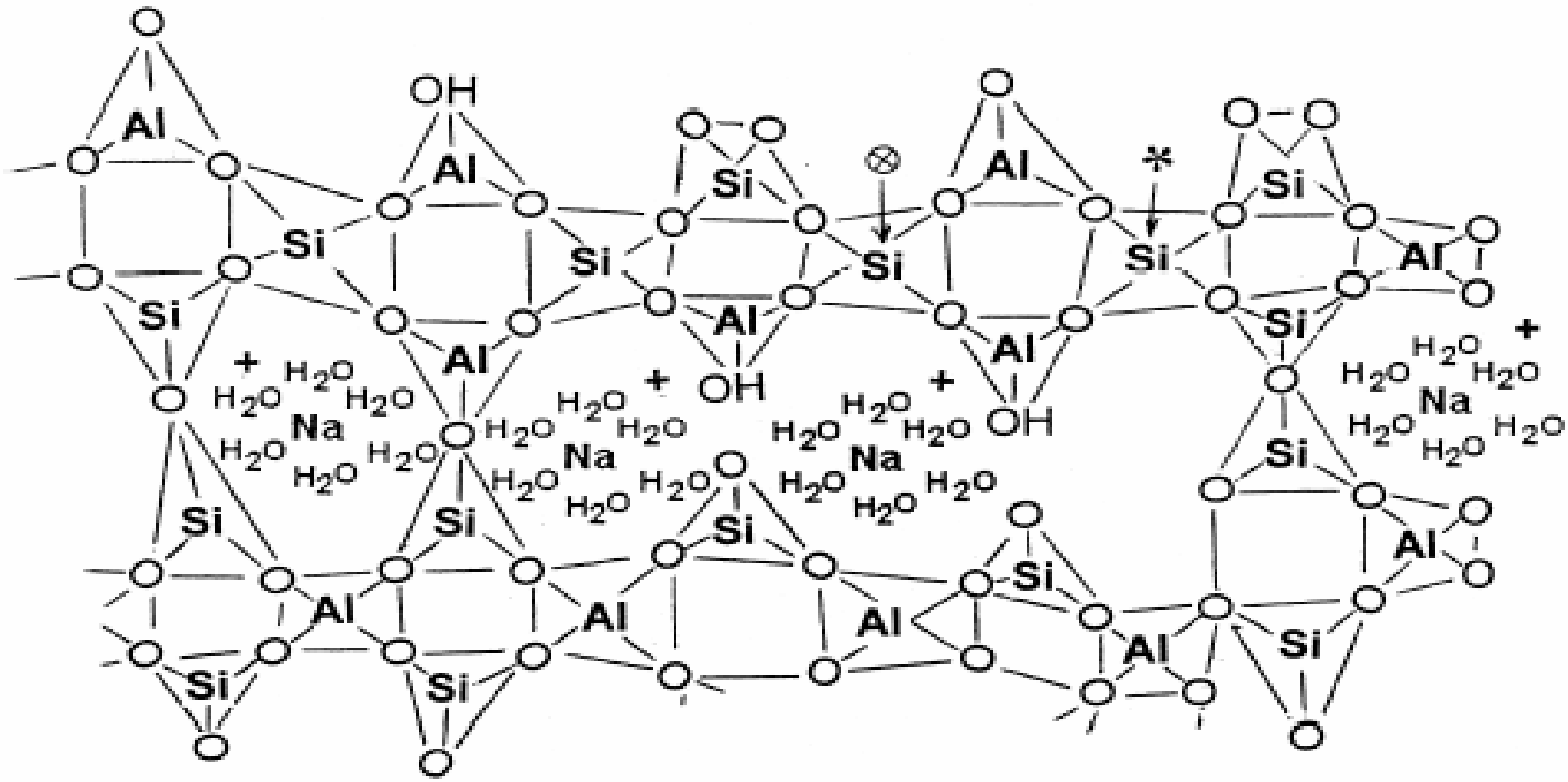

SiO2
cristobalite
tridymite
Earth's crust
Consisting of 60% feldspars
PC
high in Ca
high in CO2
CS
wollastonite
anorthite
mullite
rankinite
C3S2
CAS2
C2S
gehlenite
belite
corundum
A3S2
C3S
alite
C2AS
2400°C
2200°C
2000°C
1800°C
time
CA
CA2
CA6
CaO
C3A
C12A7
CA
CA2
CA6
Al2O3

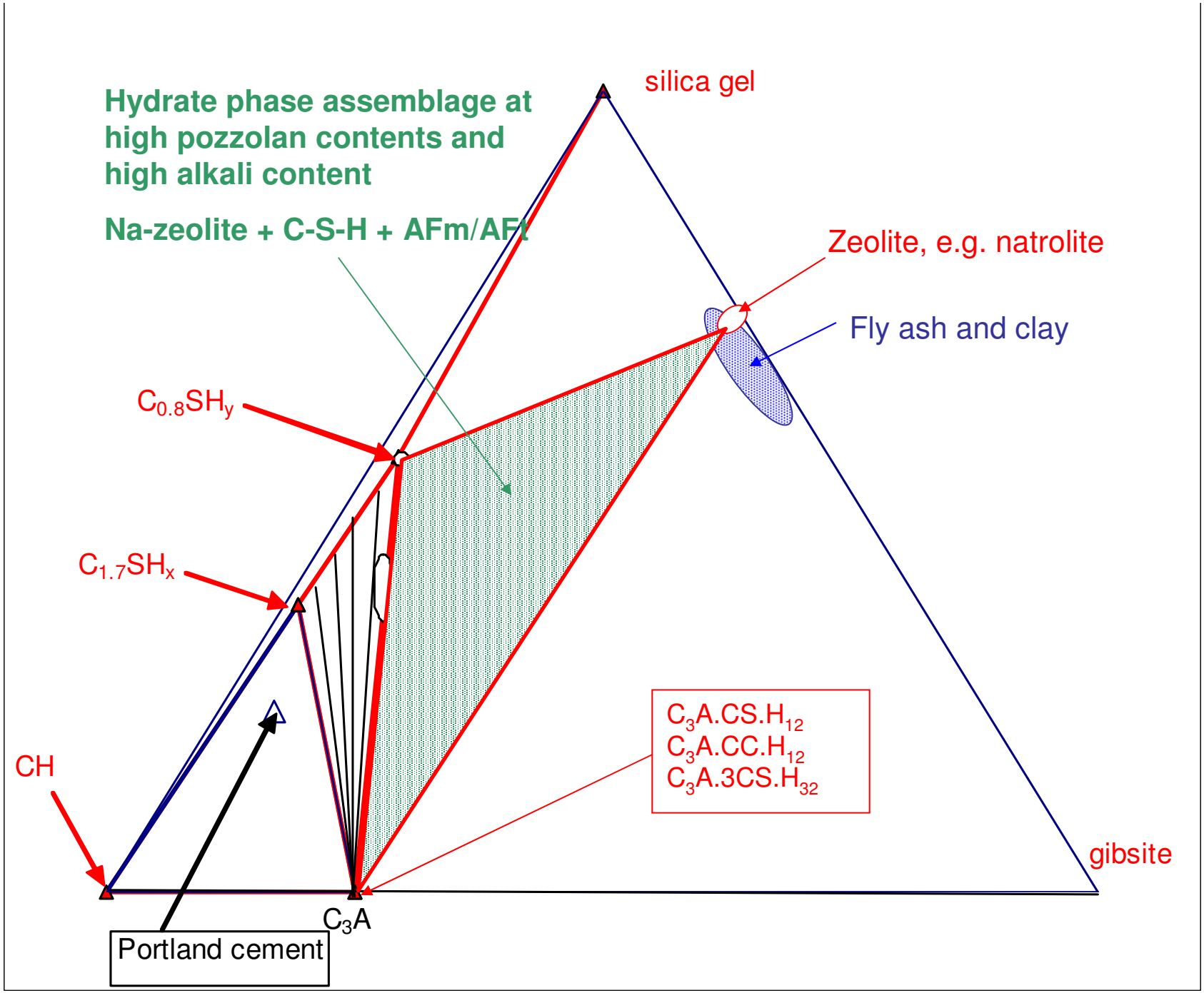

Clays, PFA etc. from weathering of feldspars used as SCM or as geopolymer if alkalis topped up to original alkali/aluminate balance in feldspar
silica gel
20% Silica fume
$C_{0.8}SH_y$
C-S-H_{ss}
$C_{1.7}SH_x$
70% GBFS
35% basaltic pozzolan
25% granitic pozzolan
25% calcined clay or PFA
stratlingite
$C_3A.C\underline{S}.H_{12}$
$C_3A.C\underline{C}.H_{12}$
$C_3A.3C\underline{S}.H_{32}$
gibsite
CH
C_3A
Portland cement

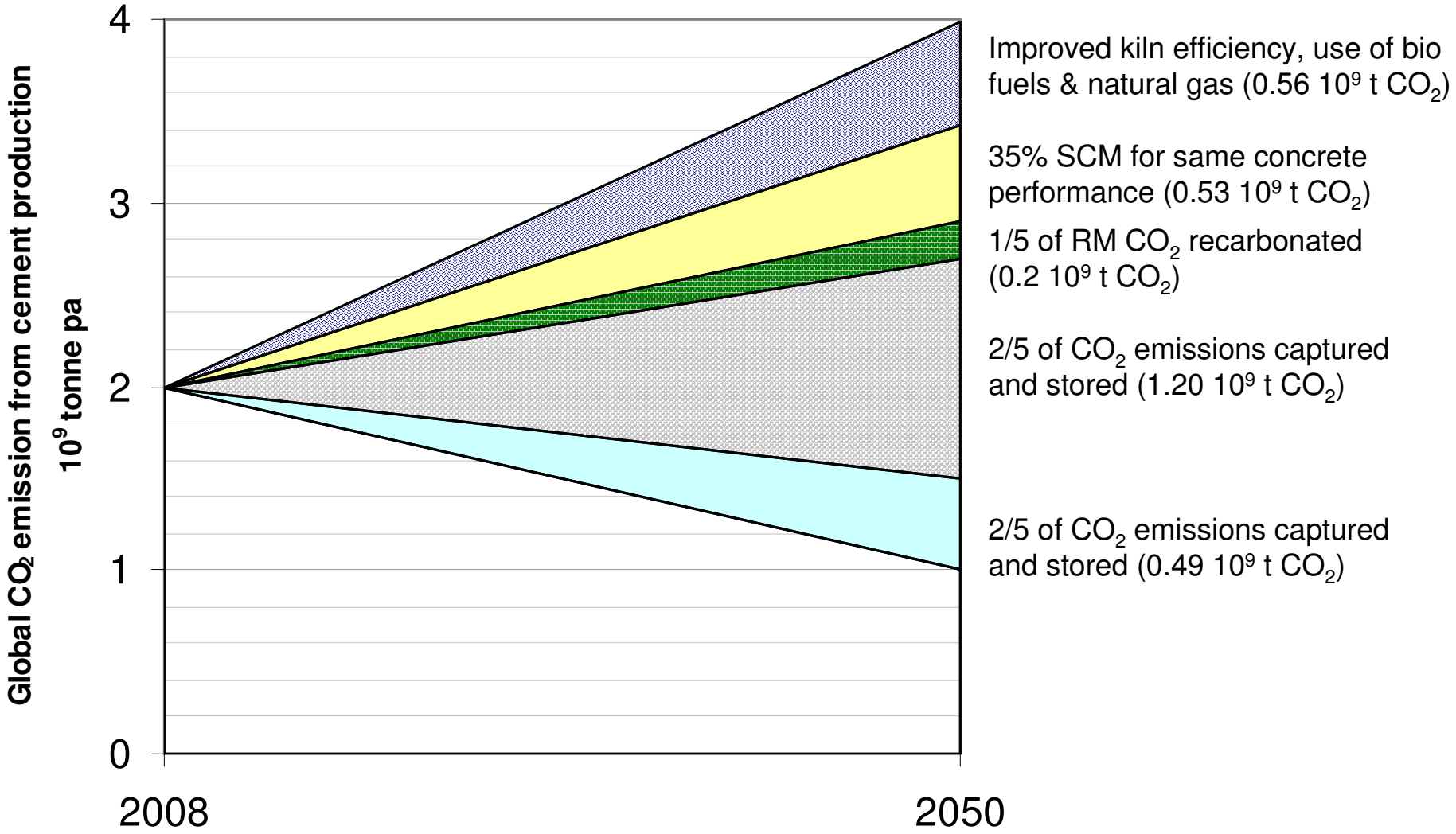
Instead of feldspars which are only stable at high temperature low T, much more open framework silicates, are formed which are closely related to the zeolites.



Despite the high alkali content, the alkalis are tied up in the silicates and a high pH pore solution cannot be maintained for protection of steel reinforcement against corrosion, which makes hybrid PC-alkali activated AS interesting.




Hydrate phase assemblage at high pozzolan contents and high alkali content
Na-zeolite + C-S-H + AFm/AFt
silica gel
Zeolite, e.g. natrolite
Fly ash and clay
$C_{0.8}SH_y$
$C_{1.7}SH_x$
CH
$C_3A.CS.H_{12}$
$C_3A.CC.H_{12}$
$C_3A.3CS.H_{32}$
gibsite
C_3A
Portland cement


Global CO_2 emission from cement production
10^9 tonne pa
4
3
2
1
0
2008
2050
Improved kiln efficiency, use of bio fuels & natural gas (0.56 10^9 t CO_2)
35% SCM for same concrete performance (0.53 10^9 t CO_2)
1/5 of RM CO_2 recarbonated (0.2 10^9 t CO_2)
2/5 of CO_2 emissions captured and stored (1.20 10^9 t CO_2)
2/5 of CO_2 emissions captured and stored (0.49 10^9 t CO_2)

CONCLUDING COMMENTS

In order to achieve these reductions, the efforts must be global.

In some areas CCS may be more economical than maximum use of SCMs or biofuels and visa versa.

Alkali activated alumino-silicates can in theory replace up to 40% of Portland cement, but in regions where CCS is already required, would not provide additional CO_2 avoidance.

Realistically these solutions can only take place within a global and transparent cap and trade system that does not distort competition.