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Avoiding major climate change in a cleaner fossil fuels world - *challenges and opportunities*

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University of Bath, I-SEE Seminar
7th February 2017

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Imperial College London

100 years of living science

Lecture Outline

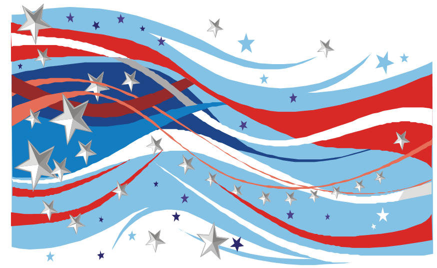
Why are fossil fuels key to achieving a sustainable energy future?

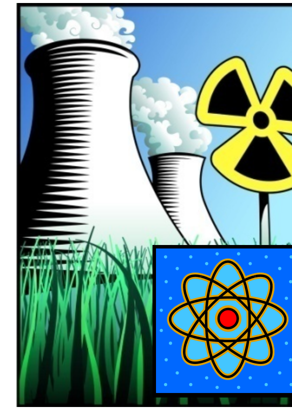
- The energy landscape
- The energy transition
- Fossil fuels – the elephant in the room
- Managing the elephant
- Imperial research
- Engineering the Journey –
  the key role of (Chemical) Engineers
- What can you do?

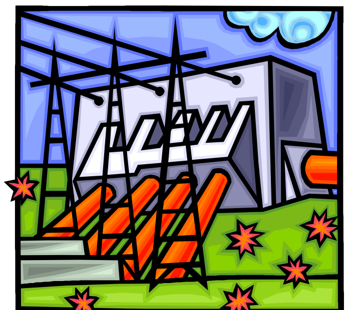
The Energy Landscape

Current world consumption 15 TW

Hydroelectric: 4.6 TW gross, 1.6 TW feasible technically, 0.6 TW installed capacity



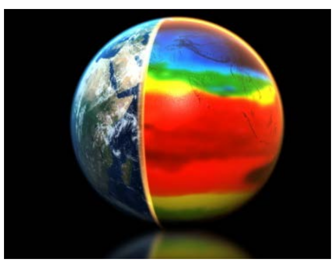




Tidal/Wave/Ocean Currents: 2 TW gross

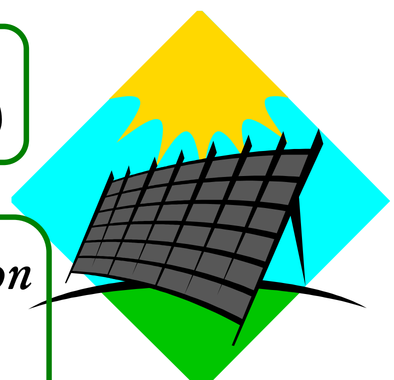
Nuclear: Current 1TW

Fossil Fuels: Current 12.5 TW Potential 25 TW



Geothermal: 9.7 TW gross (small % technically feasible)

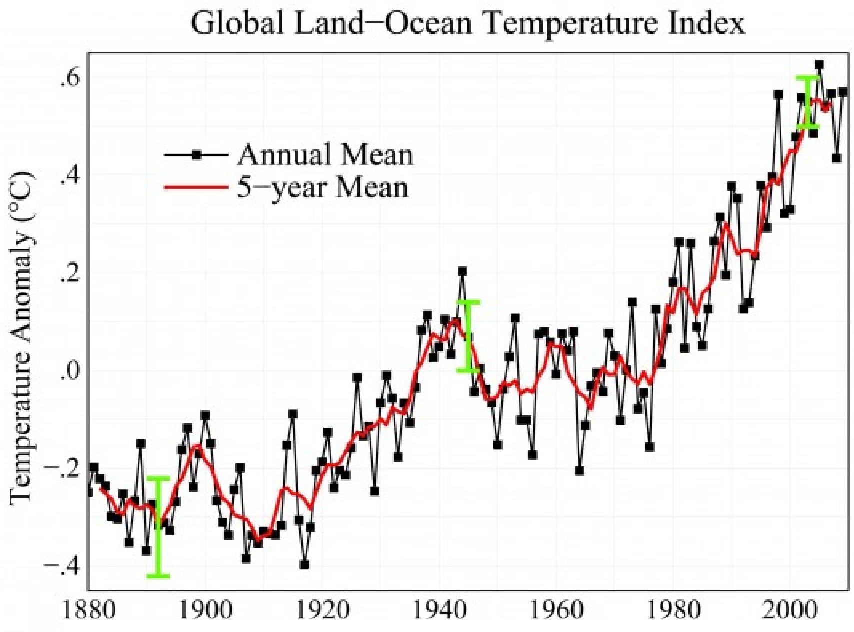
Wind 2-4 TW extractable

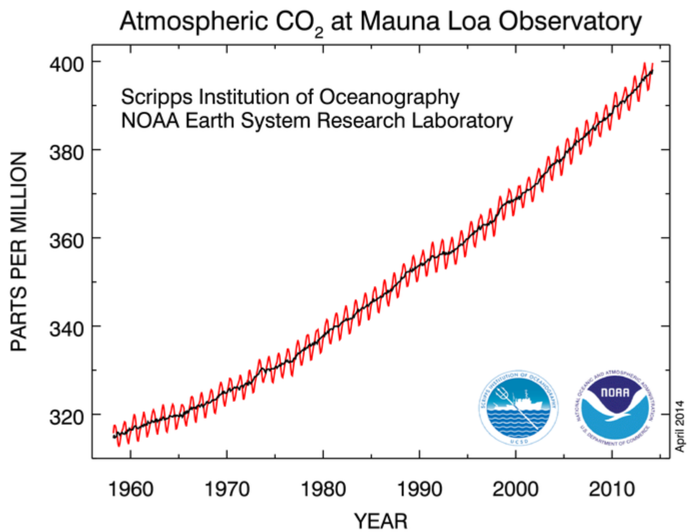


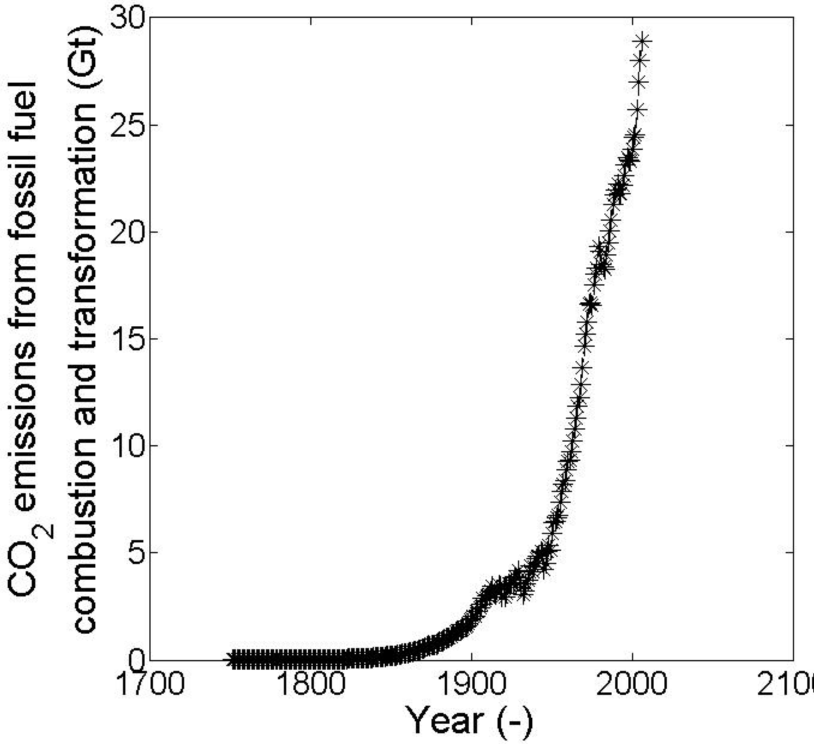
Solar: 1.2×10^5 TW on earth's surface, 36,000 TW on land

Biomass/fuels: 5-7 TW, 0.3% efficiency for non-food cultivatable land

The Driver for Carbon Mitigation







CO_2 emissions from the combustion of fossil fuels, excluding use in cement industry

Boden T, Marland G, Andres RJ. Carbon Dioxide Information Analysis Centre Oak Ridge National Laboratory, Oak Ridge, Tennessee

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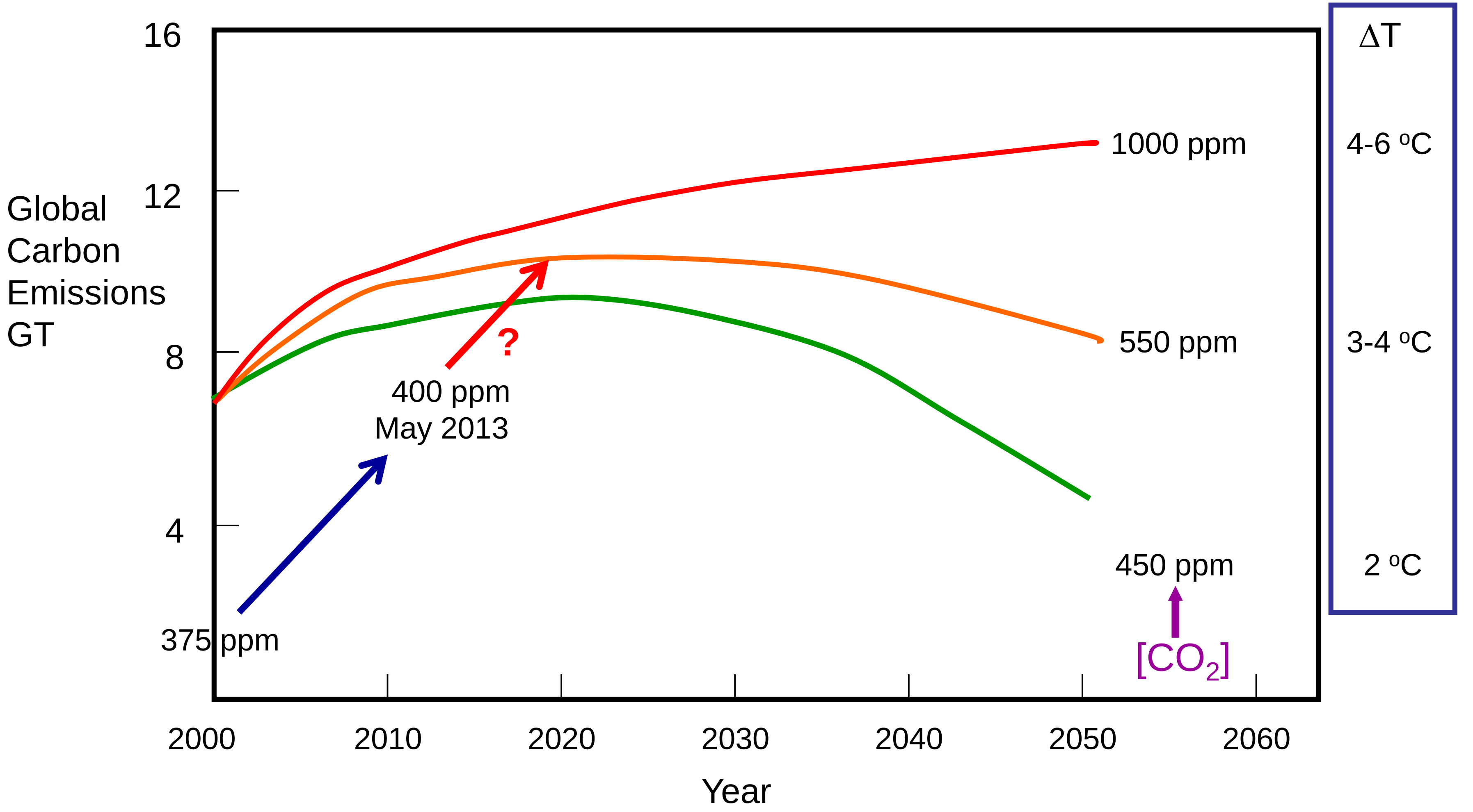
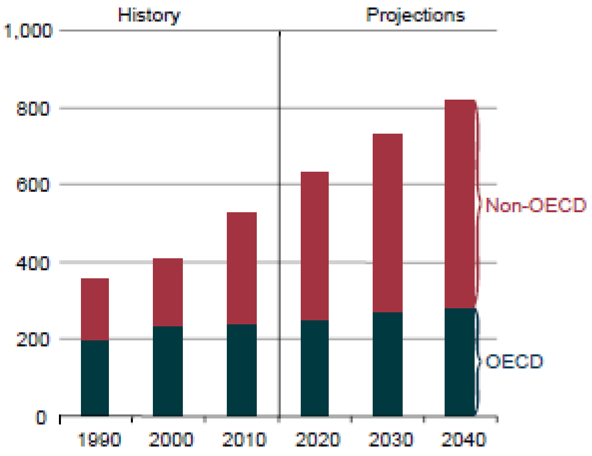
CO_2 Emissions Scenarios



UK – each individual generates ~ 10 te CO_2 per annum

Major Future Energy Demand Drivers

Figure 1. World energy consumption, 1990-2040 (quadrillion Btu)



- World population:
  - ~7bn 2014
  - Growth ~ 1.2% pa
  - Projections:
    - 8bn by 2030, 9bn by 2050

- Major economic expansion of BRIC, non-OECD countries

- World energy demand to double by 2050

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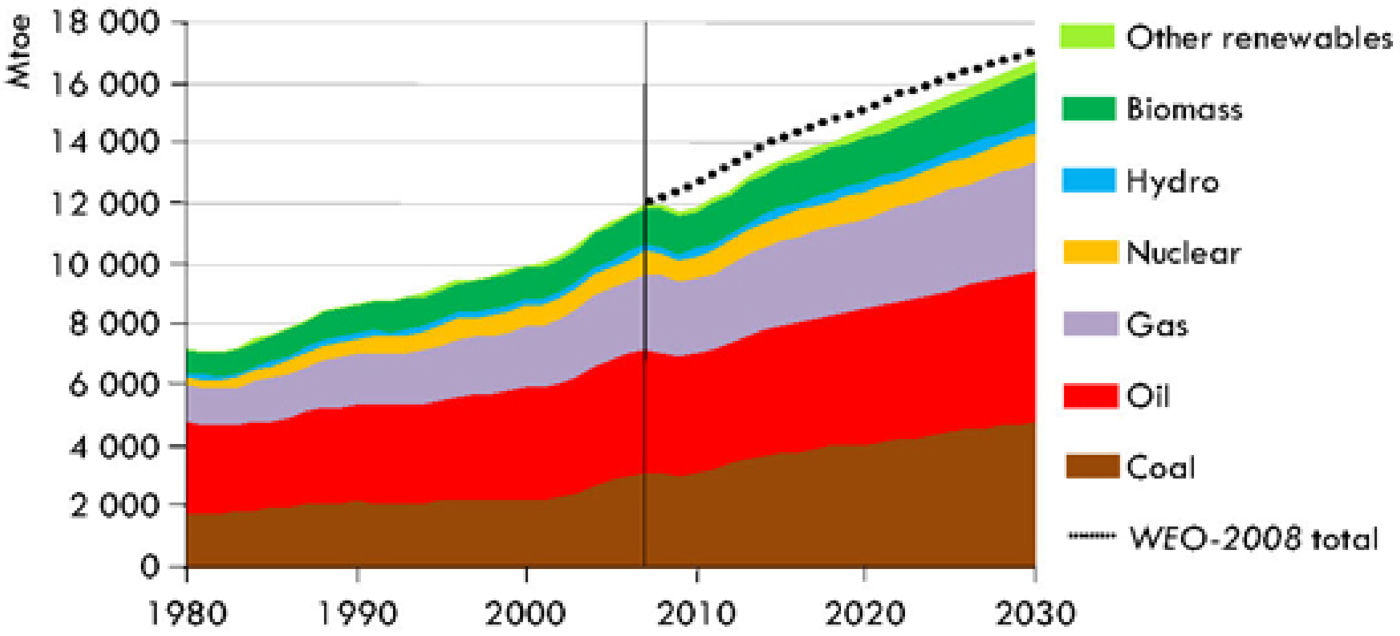
Future Energy Mix…

the growth of renewables but the continued importance of hydrocarbons



Source: International Energy Agency World Energy Outlook 2009

Global demand grows by 40% between 2007 and 2030, with coal use rising most in absolute terms

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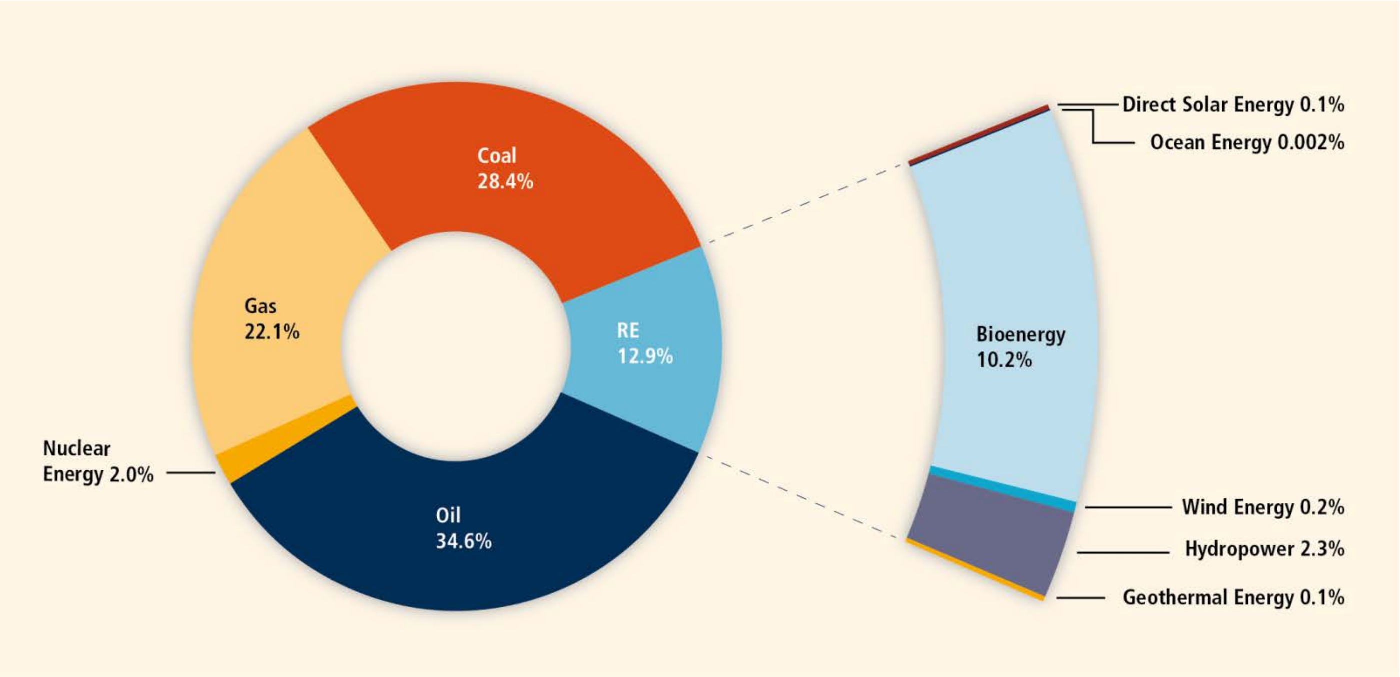
Current Energy Mix

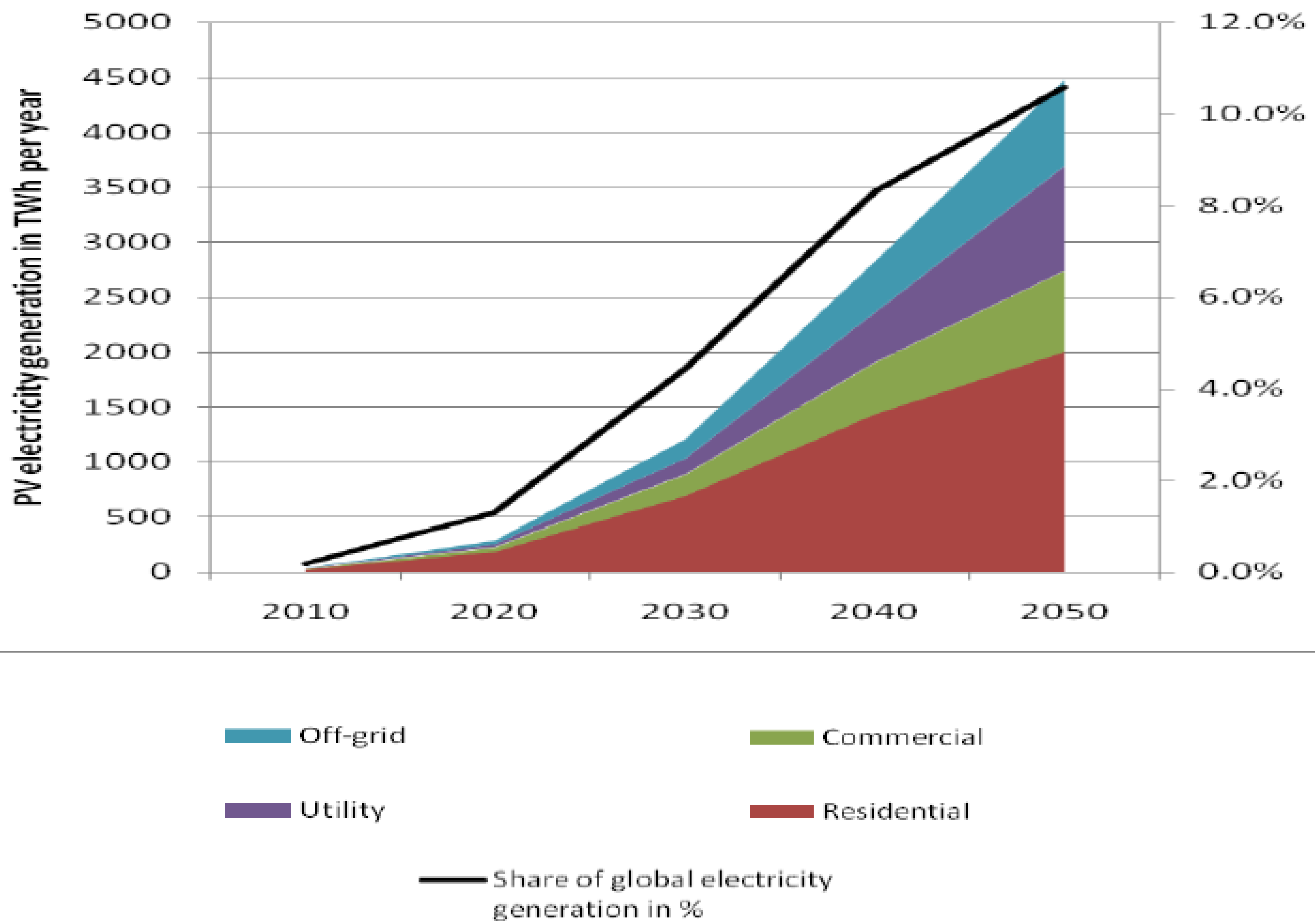


IEA Energy Technology Perspectives 2010

Factors limiting rapid growth of Alternative Energy Routes

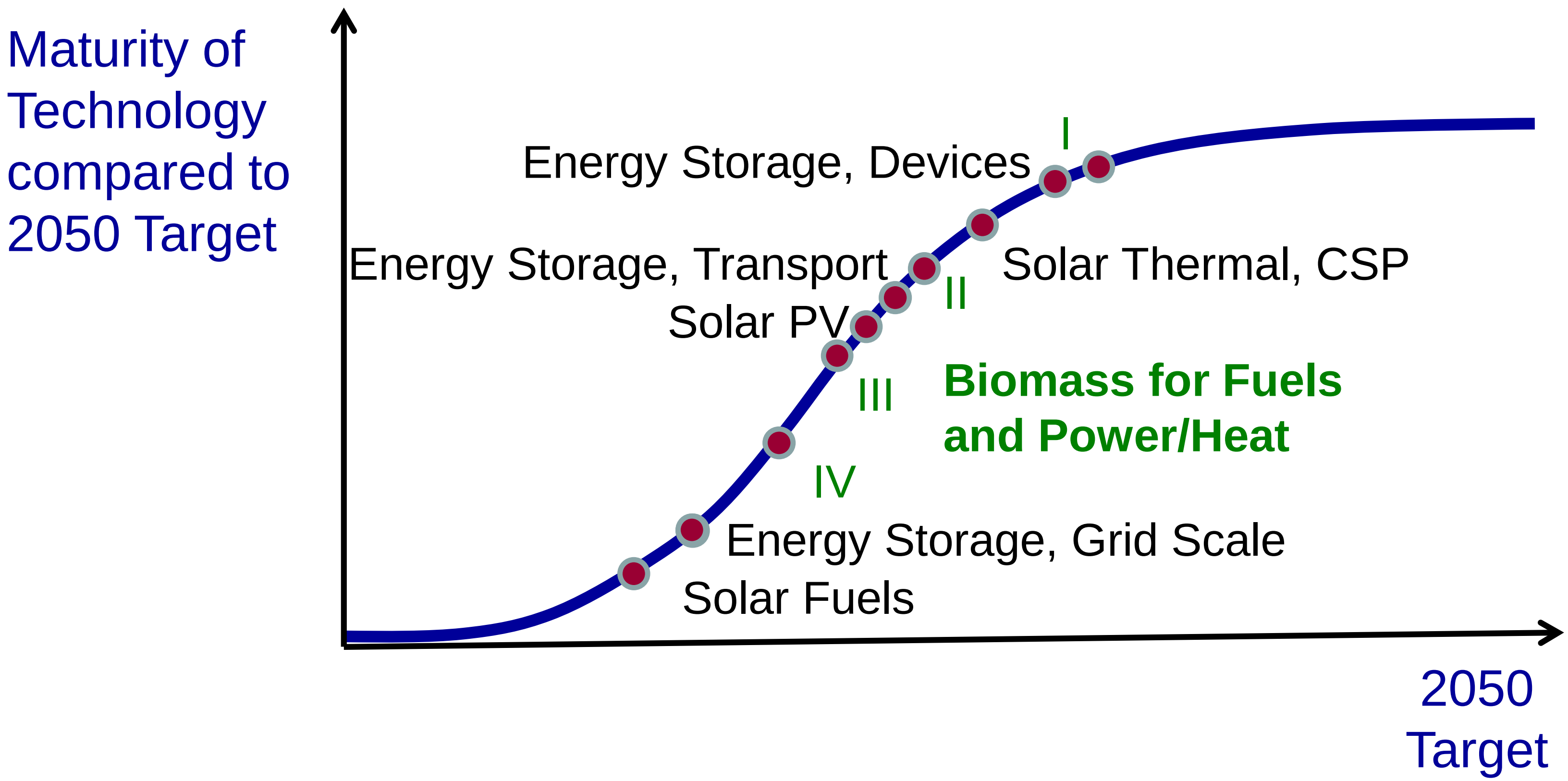
- Slow rate of developing technology, improving energy efficiency
- Bringing costs down – comparability with fossil fuels (+ CCS)
- Availability – delivering sufficient capacity
  - eg landmass limitations
- Coping with intermittency – energy storage
- Nuclear
  - Safety – Fukushima, March 2011
  - Waste disposal and legacy
  - Proliferation…military use, terrorism…

Solar PV Roadmap Targets

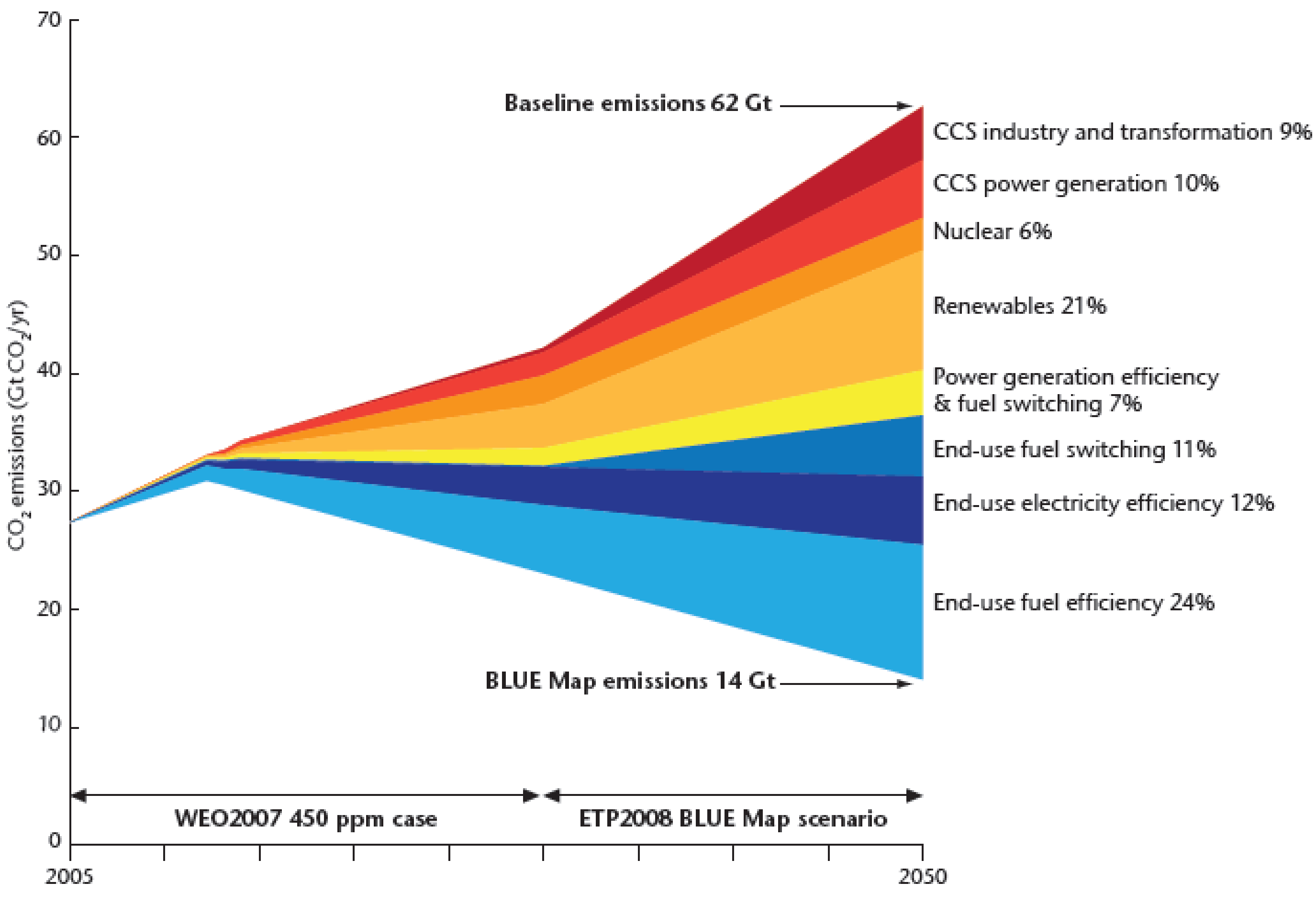


If sound policies are put in place, PV can provide 5% of global electricity generation in 2030, 11% in 2050

Maturity of Renewable Energy Technologies



World abatement of energy-related CO_2 emissions in the 450 ppm Scenario

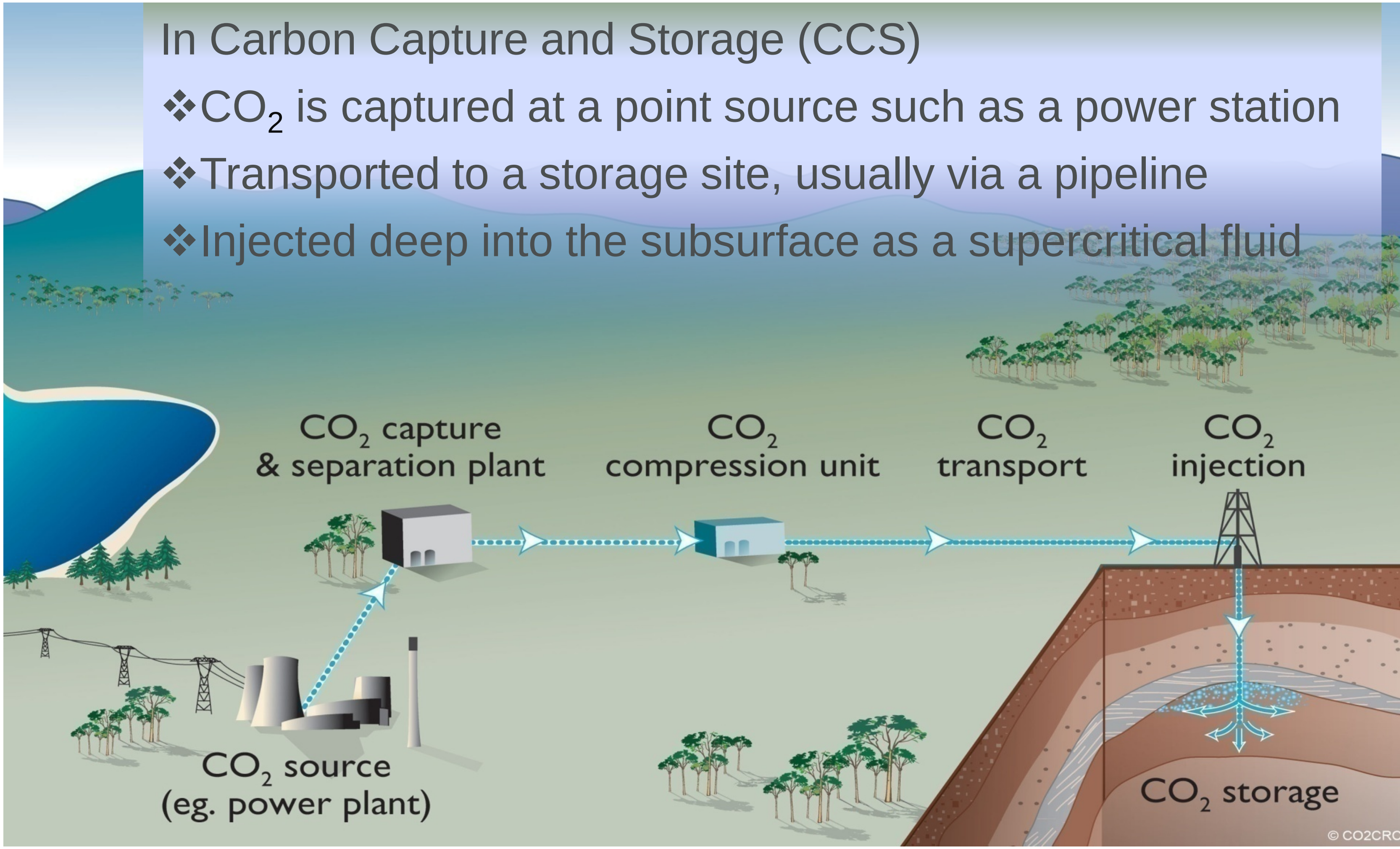


Source: IEA, *Energy Technology Perspectives* (2008a).

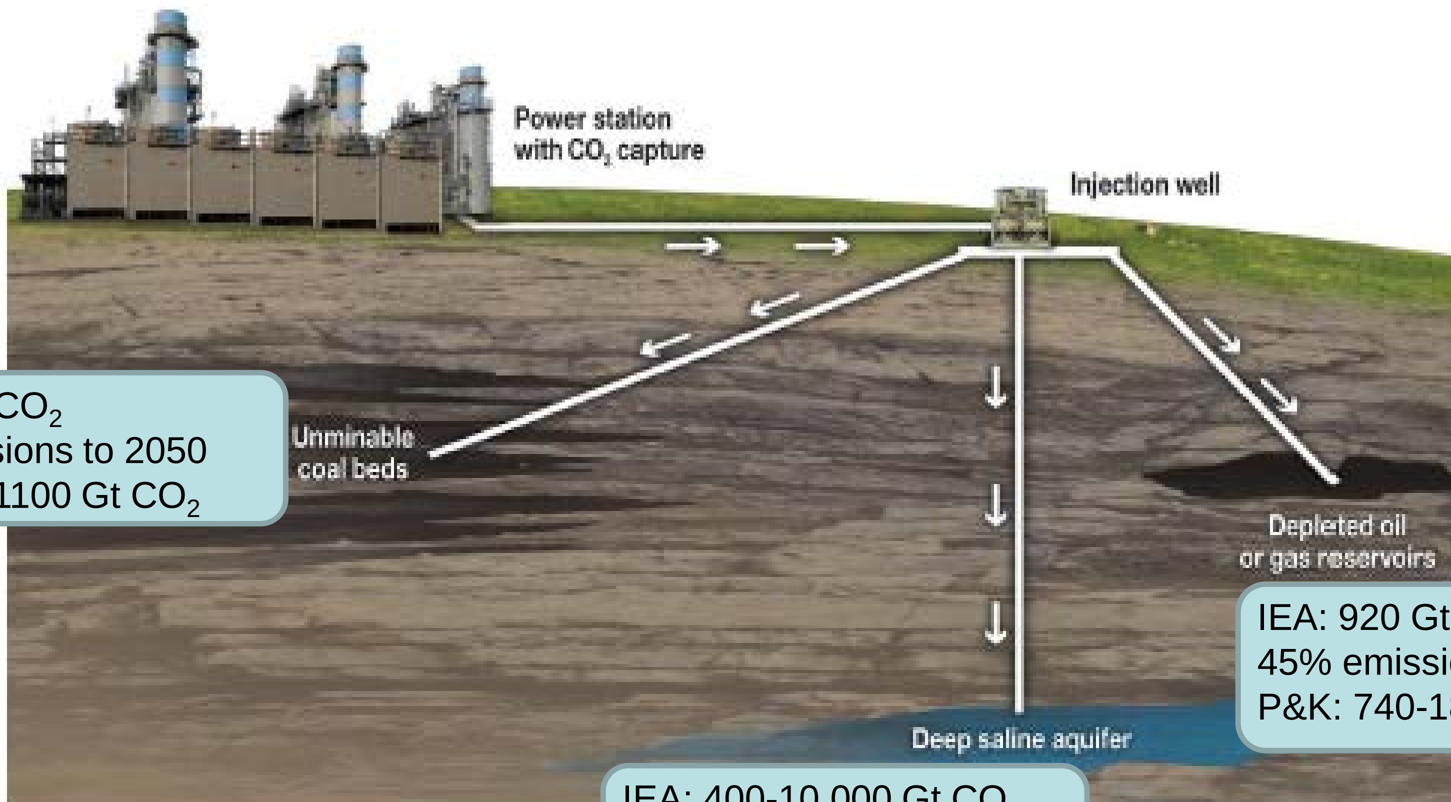
Carbon capture and storage must play a role...

In Carbon Capture and Storage (CCS)

- CO_2 is captured at a point source such as a power station
- Transported to a storage site, usually via a pipeline
- Injected deep into the subsurface as a supercritical fluid



Carbon Capture and Storage – the main options



IEA: 40Gt CO_2
<2% emissions to 2050
P&K: 370-1100 Gt CO_2

IEA: 920 Gt CO_2
45% emissions to 2050
P&K: 740-1850 Gt CO_2

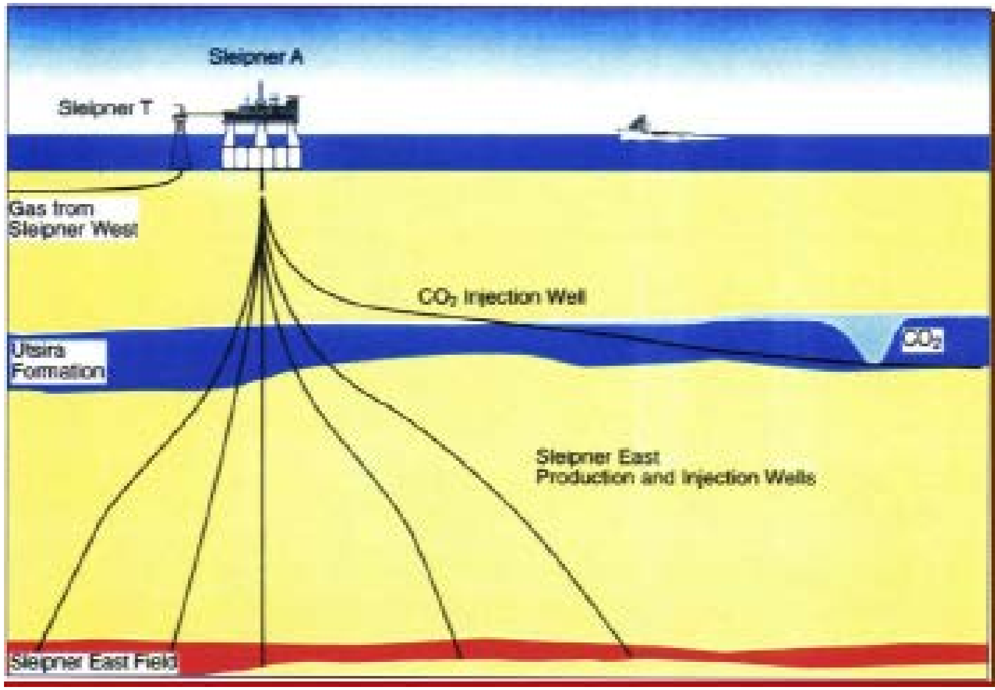
IEA: 400-10,000 Gt CO_2
20-500% emissions to 2050
P&K: 370-3700 Gt CO_2

Estimated worldwide geological storage capacity > 2000 Gte CO_2

IEA: Freund, Comparative potentials at storage costs up to \$20/t CO_2 P&K: Parson and Keith, Science 282, 1053-1054, 1998

Sleipner CO_2 Injection Project

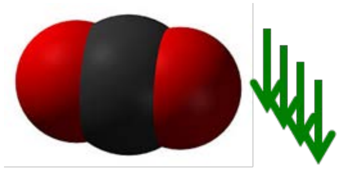
- 1 million tonnes CO_2 injected per year
- CO_2 separated from produced gas
- Avoids Norwegian CO_2 tax (~$55 per te)
- Gravity segregation and flow under shale layers controls CO_2 movement



SaskPower Boundary Dam Integrated CCS Project

- (World's 1st) Commercial CCS Project
- Coal-fired, post-combustion capture
- Estevan, Saskatchewan, Canada
- 110 MW power
- 1Mt CO_2 stored pa
- Equivalent to removing ~ 250,000 cars
- CO2 used for EOR in nearby depleted oil reservoirs
- Remainder stored in 3.4km deep Deadwood saline aquifer – Aquistore Project

How do we achieve this low carbon fossil fuels future?



- Use less energy
  - Energy Efficiency

- Use more gas
  - A Future 'Gas Economy'

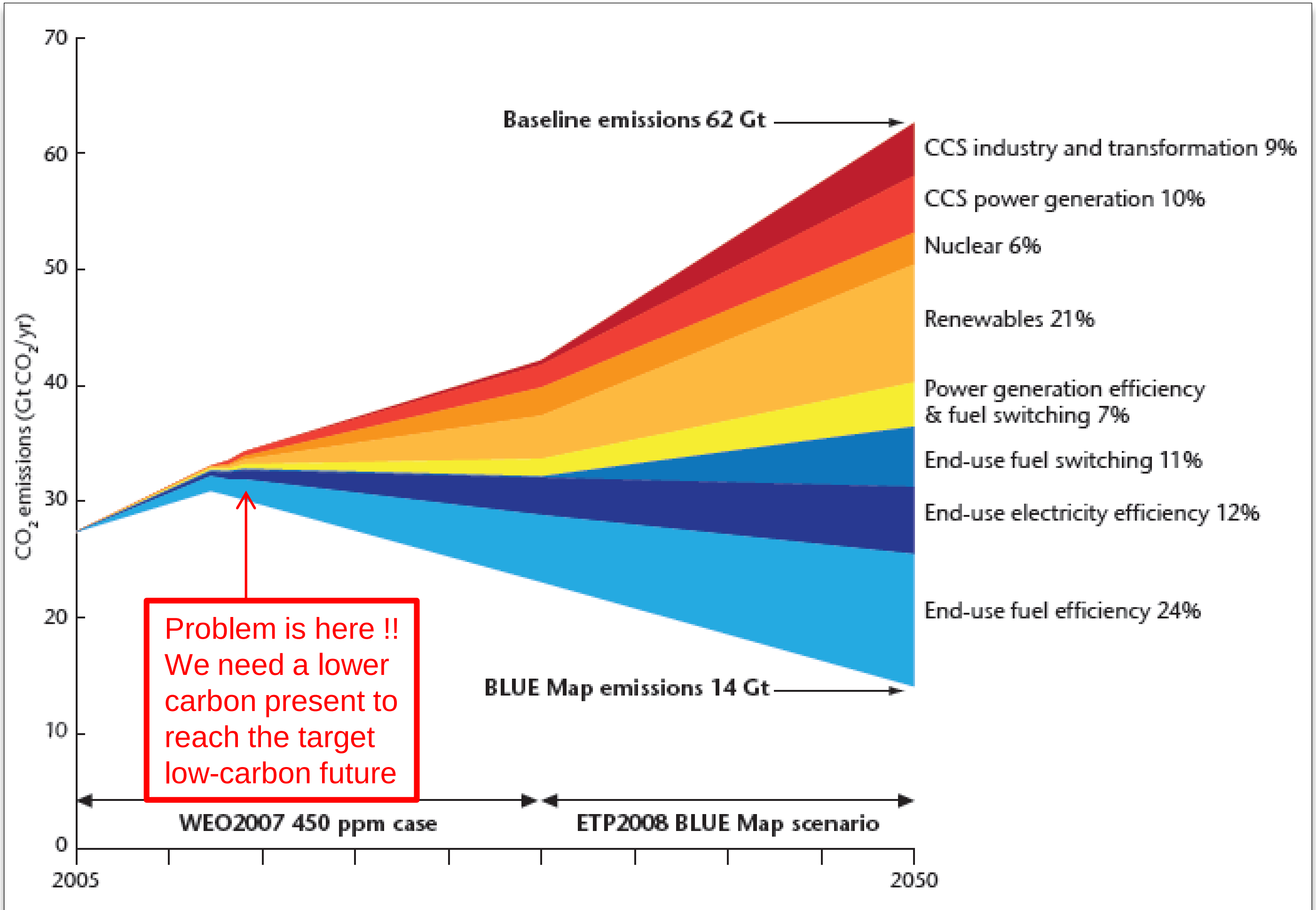
- Capture as much CO_2 as possible
  - From gas as well as coal and oil

- Increase nuclear
  - Not a rapid solution

- Fossil fuels → portfolio of renewables asap
  - but >50 years…very country specific – natural resources + policies

- To drive all this, we need effective carbon pricing
  - Key lever to manage the Energy Transition to 2050 and beyond

World abatement of energy-related CO_2 emissions in the 450 ppm Scenario



Source: IEA, *Energy Technology Perspectives* (2008a).

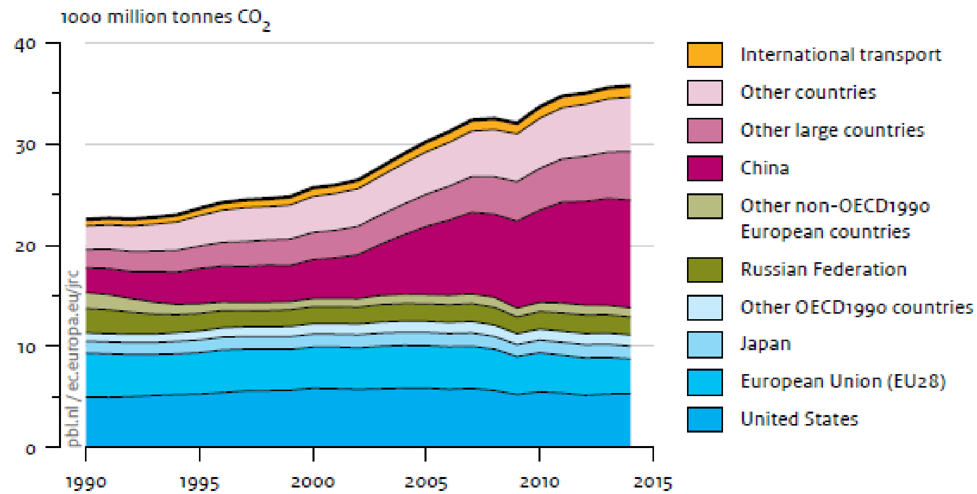
How are we doing on reducing carbon emissions?

- 1990 – 2.39 t CO_2 per toe
- 2010 – 2.37 t CO_2 per toe
- But…since US shale gas took off, atmospheric CO_2 levels increasing by 1.1% pa, *cf* ~3% pa previously
  - A foretaste of the benefits of a ‘golden age of gas’…is gas a destination, rather than a transition, fuel?
- Nevertheless…CO_2 levels from FFs are not stabilising in a non-CCS world

However, there is a chink of light!

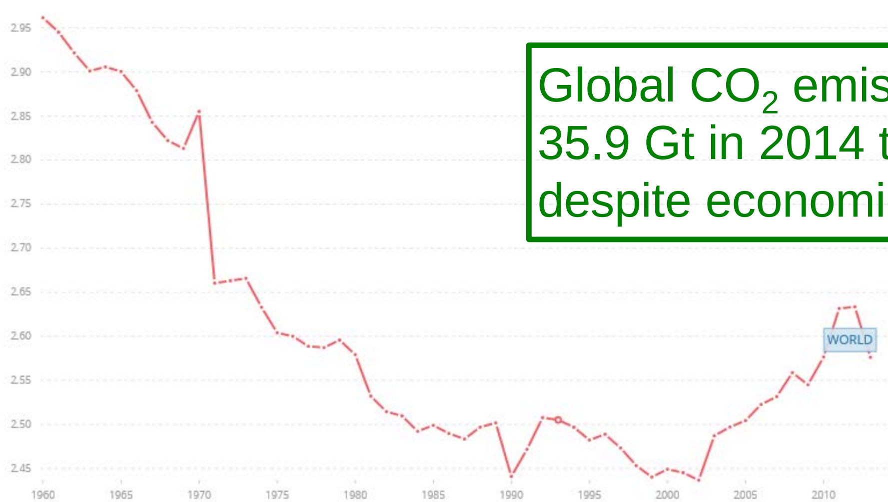
Figure 2.1

Global CO_2 emissions per region from fossil-fuel use and cement production



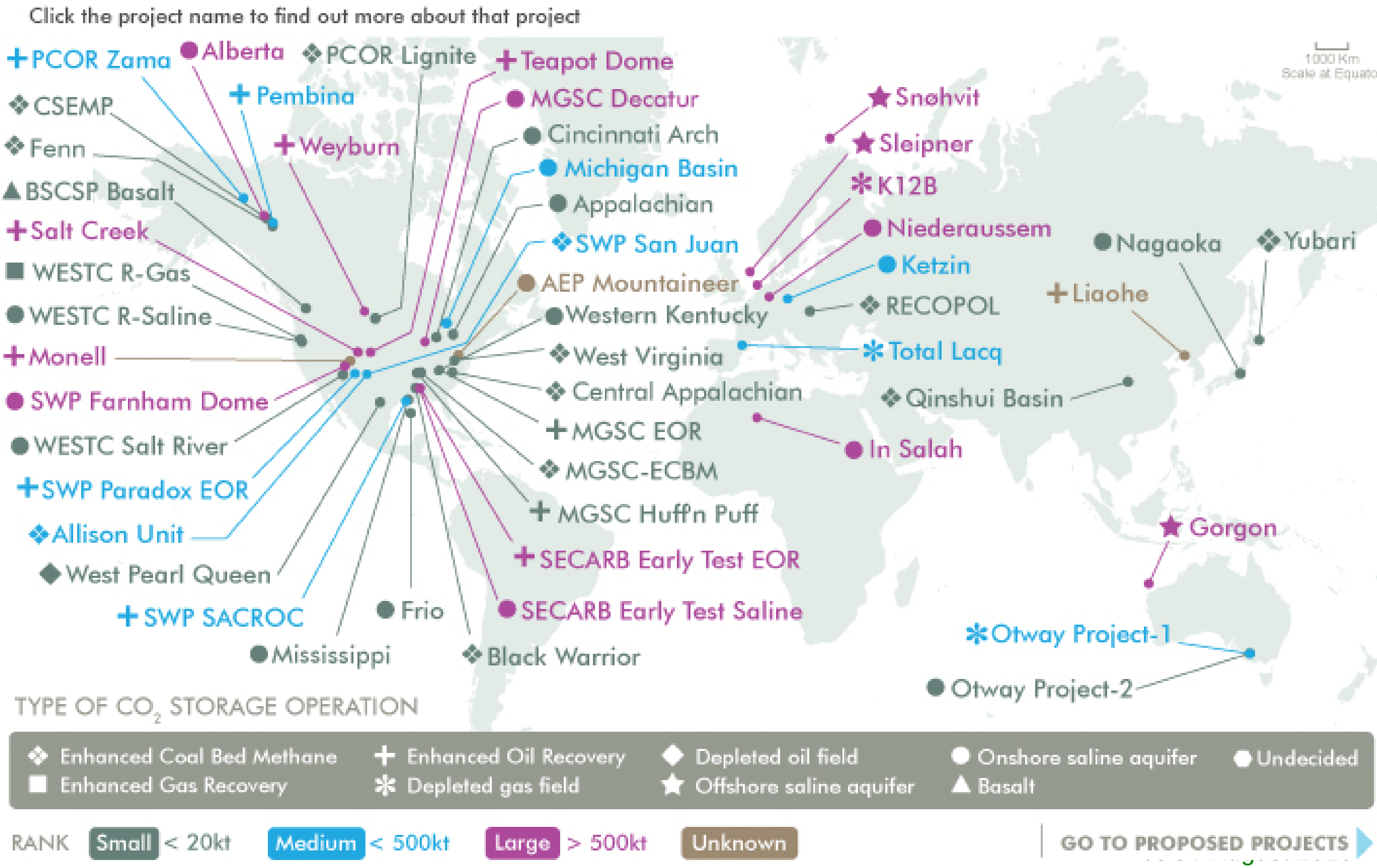
Source: EDGAR 4.3 (JRC/PBL, 2015) (1970-2012; notably IEA 2014 and NBS 2015); EDGAR 4.3FT2014 (2013-2014): BP 2015; GGFR 2015; USGS 2015; WSA 2015

Global CO_2 emissions, t CO_2 per toe



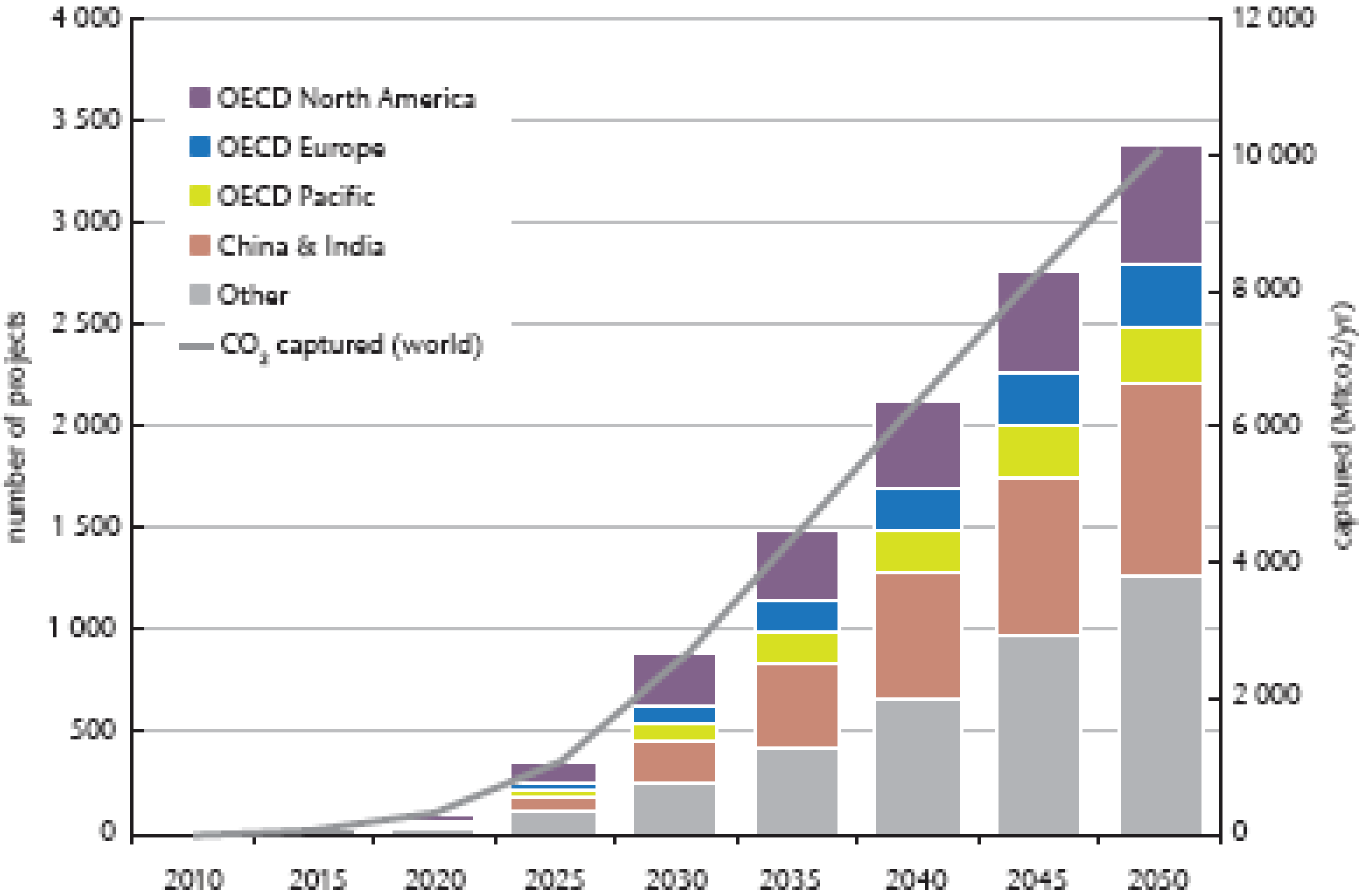
Global CO_2 emissions went down from 35.9 Gt in 2014 to 35.7 Gt in 2015, despite economic growth of 3.1%

Current CCS projects – planned or underway



http://www.co2crc.com.au/demo/worldprojects.html

Global deployment of CCS...?

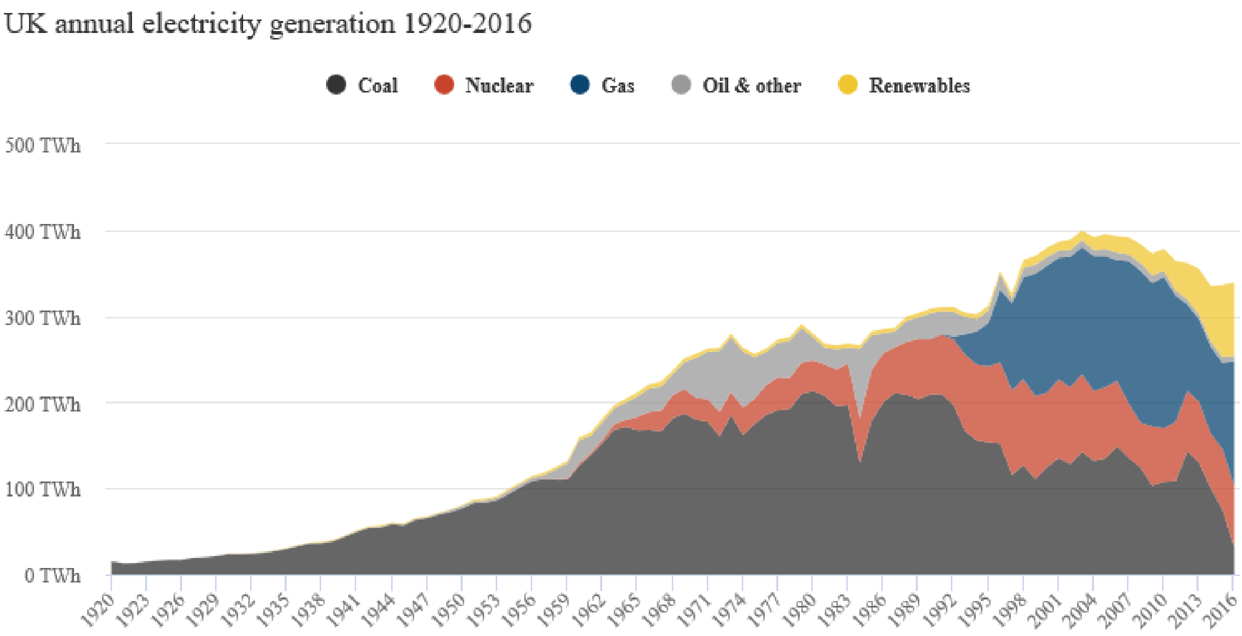


IEA, Technology Roadmap, CCS, 2010

A lot of progress has to be made very quickly… av. 100 projects per year after 2020

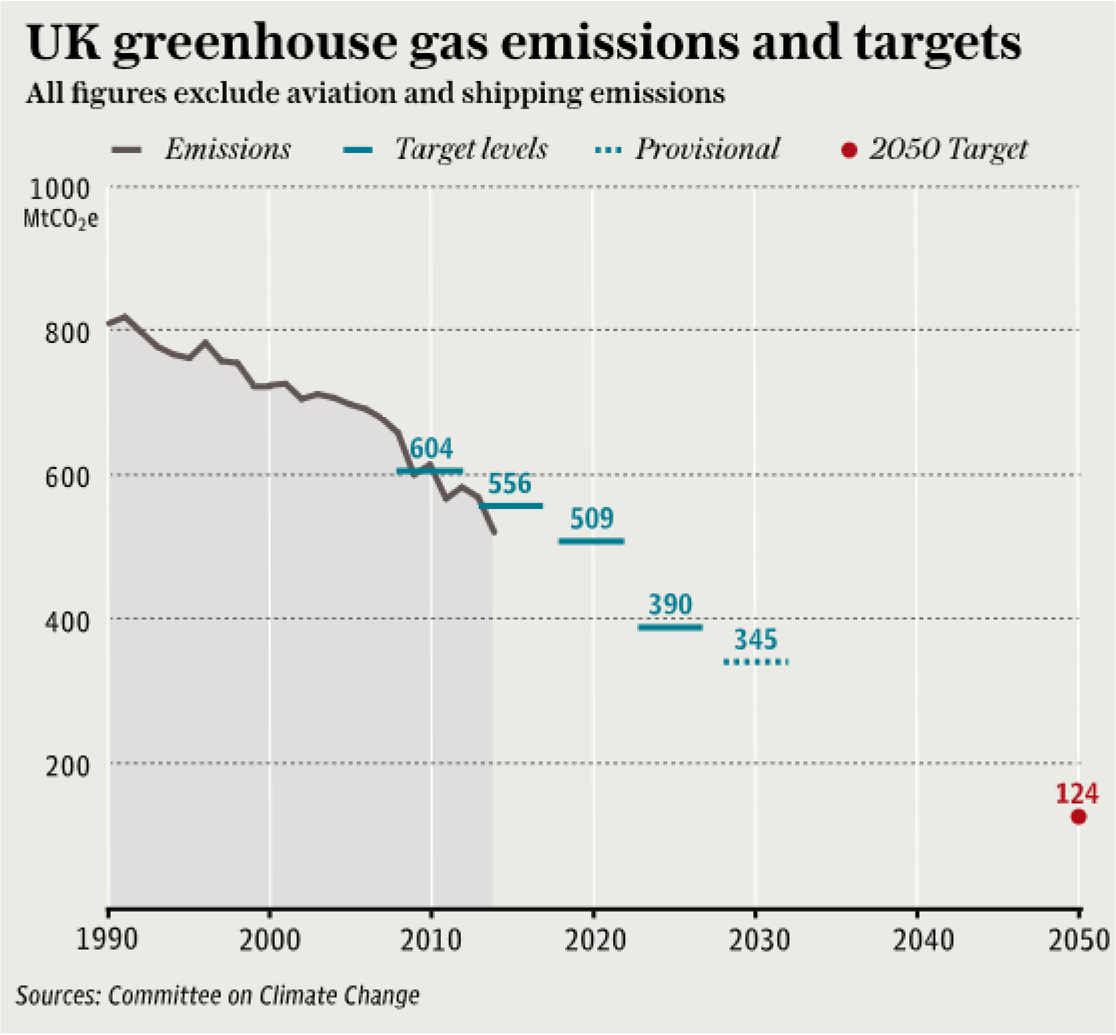
The changing face of the UK's Electricity Mix

UK Electricity Generation 2016:
Gas 45%, Wind 11.5%, Coal 9.2%
Coal + Gas down 38% since 2010



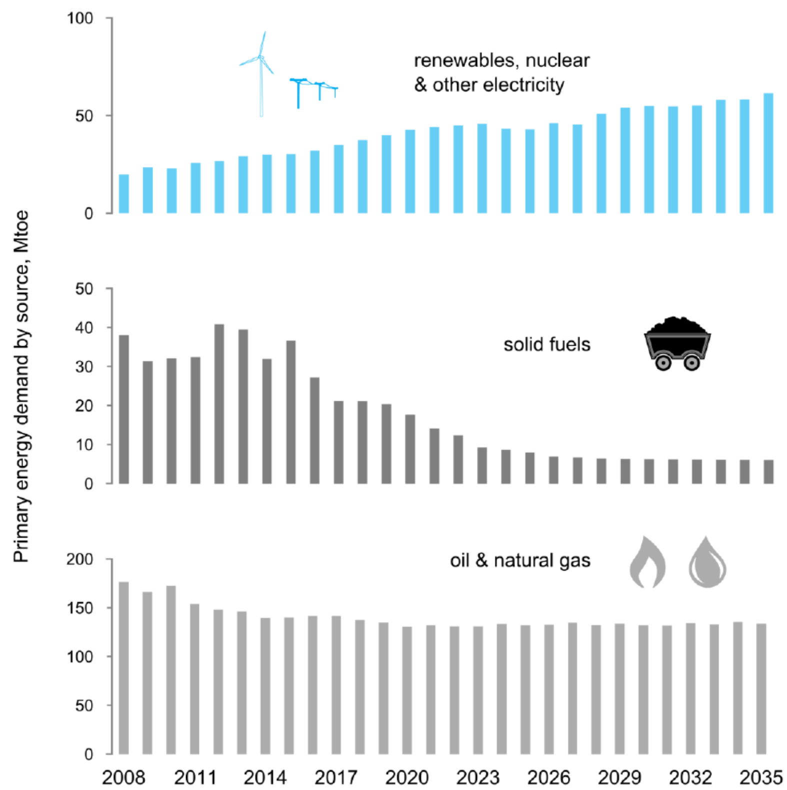
UK Carbon Budgets

Climate Change Act 2008



UK Primary Energy Demand Projection 2015

Figure 4.1: Primary energy demand by fuel



The figure shows that primary energy demand for oil and gas stays relatively static over the projection period. Demand for renewables, nuclear electricity and other electricity grows steadily whilst demand for solid fossil fuels like anthracite declines rapidly.

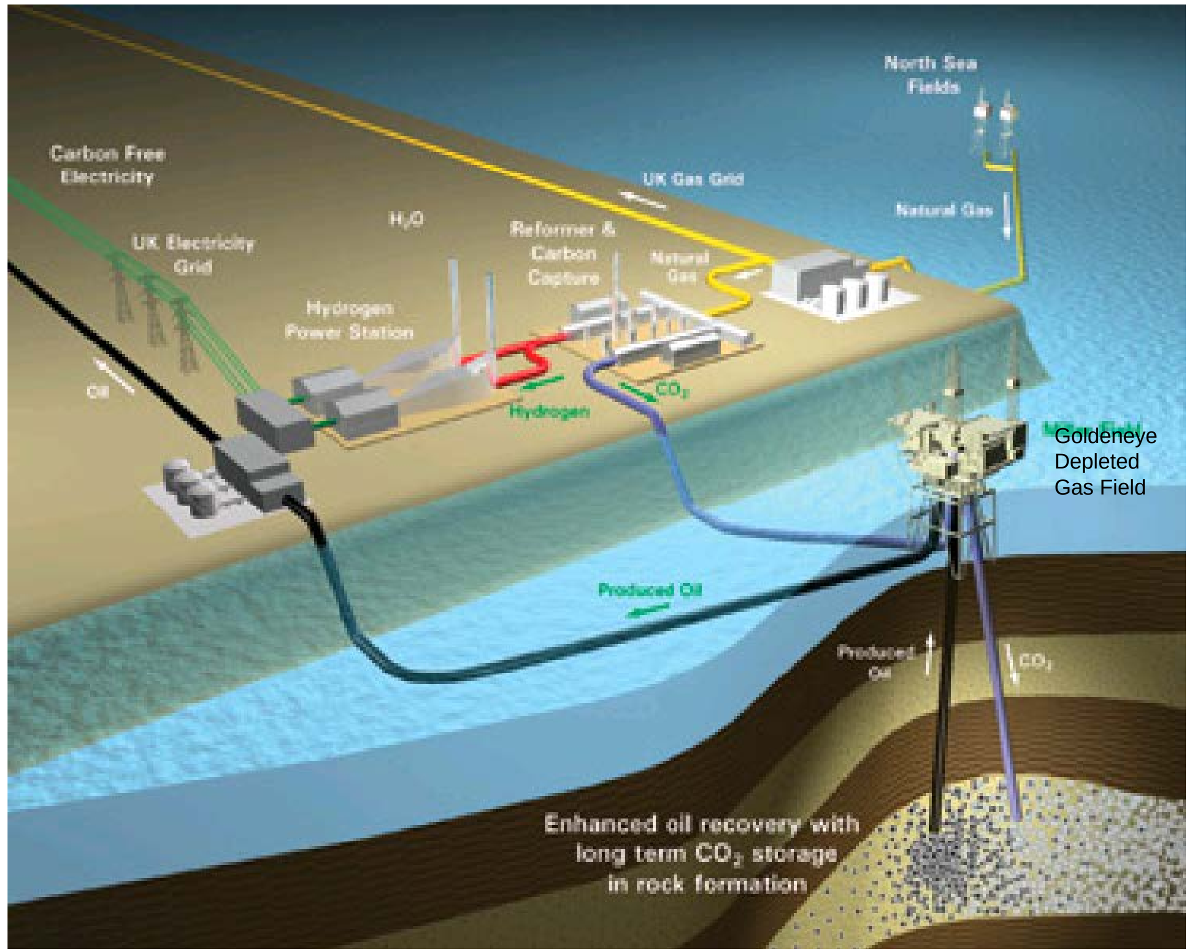
UKCCS Commercialisation Competition: Shell, SSE Peterhead Project

Also White Rose Project

- Alstom
- Drax Power
- BOC
- National Grid

• Coal-fired power station

• Storage in saline aquifer in southern North Sea



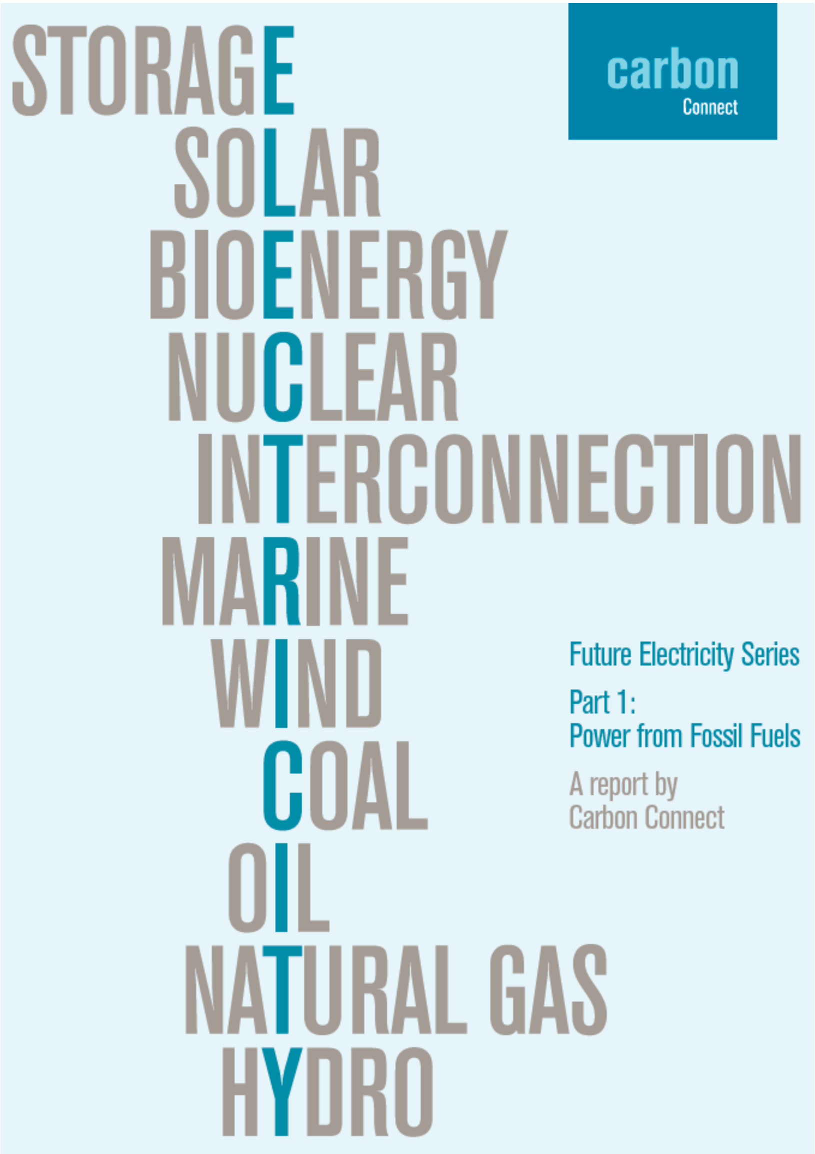
Projects cancelled November 2015 Autumn Statement

The costs of not implementing CCS

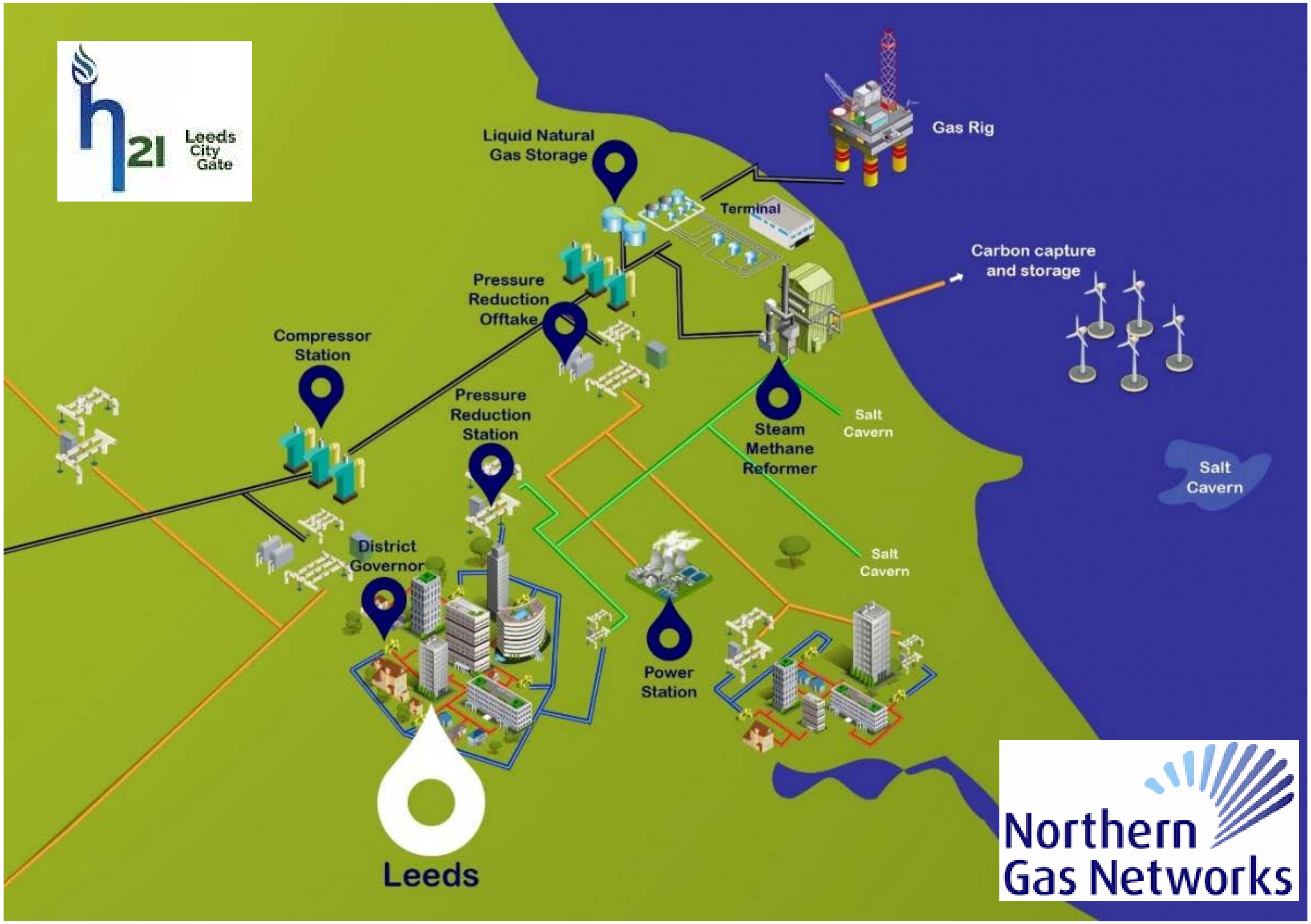
Costs of not deploying CCS in UK, quickly enough:
£30-40bn pa by 2050

- Need to use more costly renewables prematurely
- Failure to reduce industrial emissions

US Study (EPRI 2009):
Electricity in 2050:
+210% without CCS
+ 80% with CCS

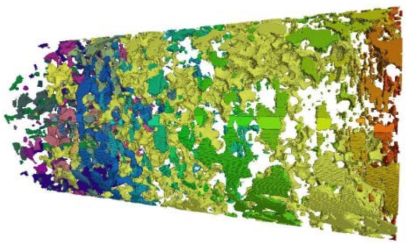


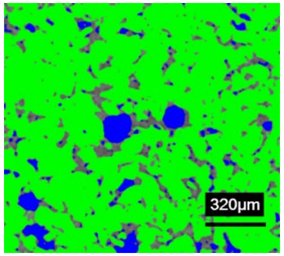
Hydrogen for Heating



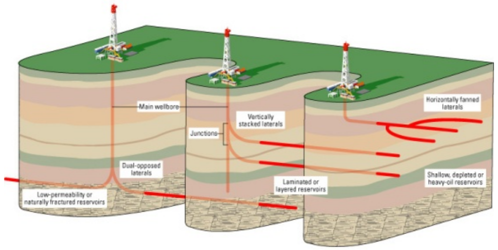
GCM Research – across the energy landscape

- Carbon Capture and Storage – QCCSRC

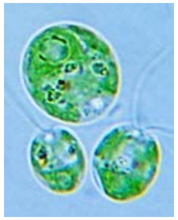


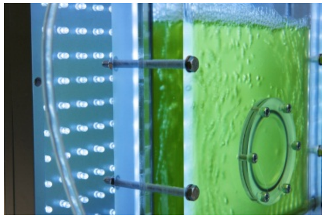


- Underground gasification of (heavy) hydrocarbons with *in situ* CCS



- Fuels and chemicals from green algae and cyanobacteria





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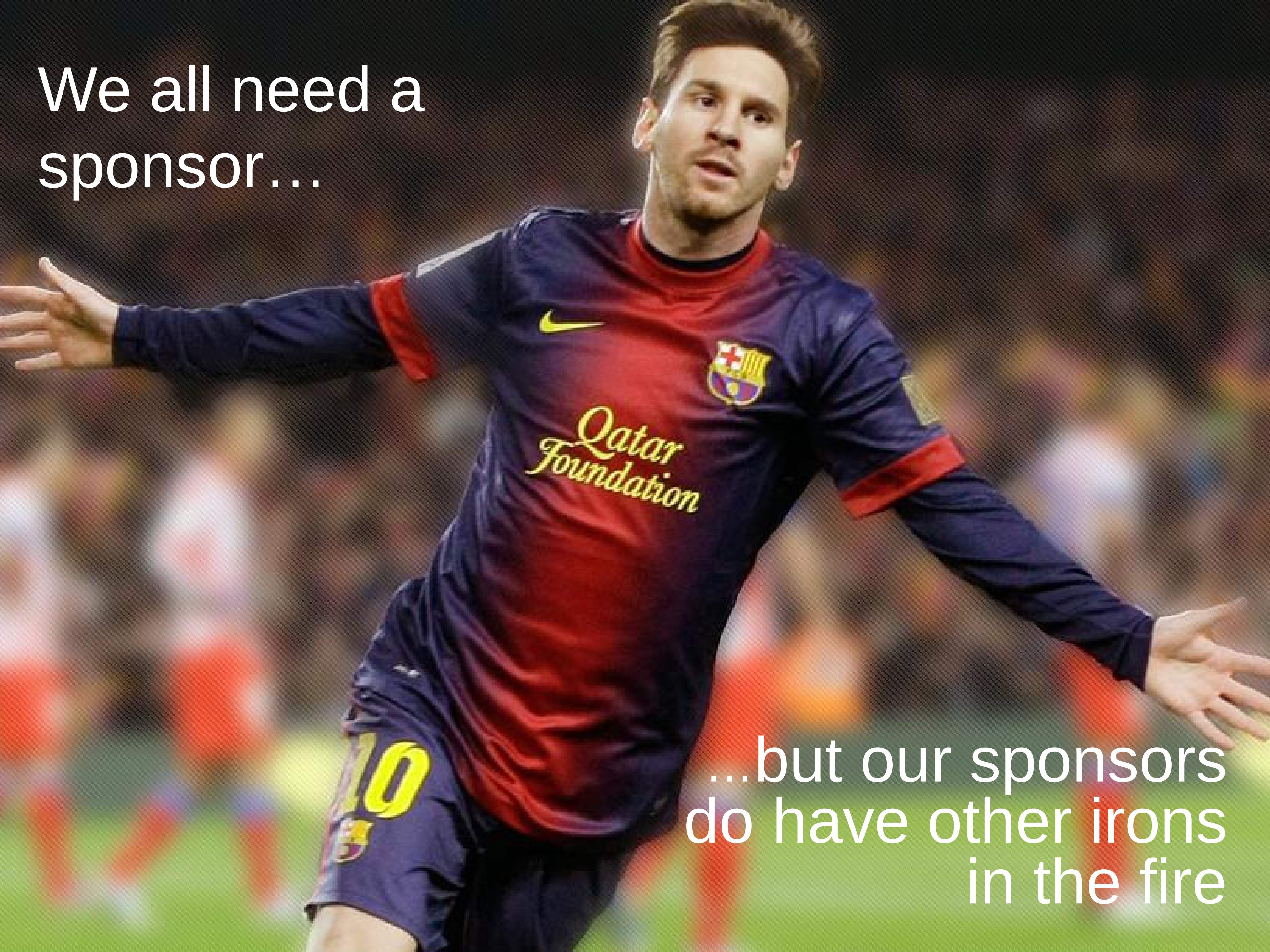
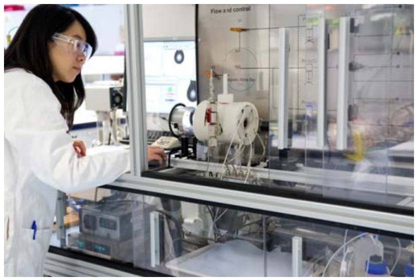

We all need a sponsor…
Qatar Foundation
…but our sponsors do have other irons in the fire

Qatar Carbonates and Carbon Storage Research Centre

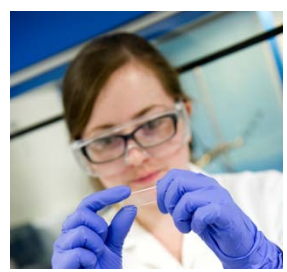
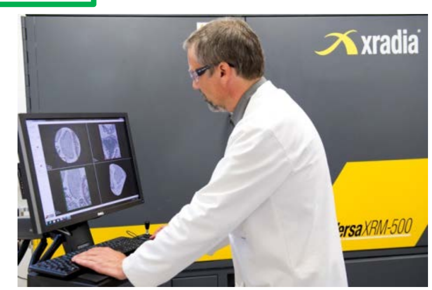
- A 10 year (2008-18), $70m programme to provide the science and engineering underpinning the cost-effective, safe, permanent storage of CO_2 in carbonate reservoirs
- Also addresses CO_2 EOR
- Sponsored by
  - Qatar Petroleum
  - Shell
  - Qatar Science and Technology Park (Qatar Foundation)

Qatar Carbonates and Carbon Storage Research Centre

A 10 year, $70m programme
“Putting CO2 in its place”



- 17 Academic Staff
- 3 QCCSRC Lecturers
- 16 Postdoctoral Researchers
- 32 + 4 + 14 PhD Students
- 5 Technical Support Staff

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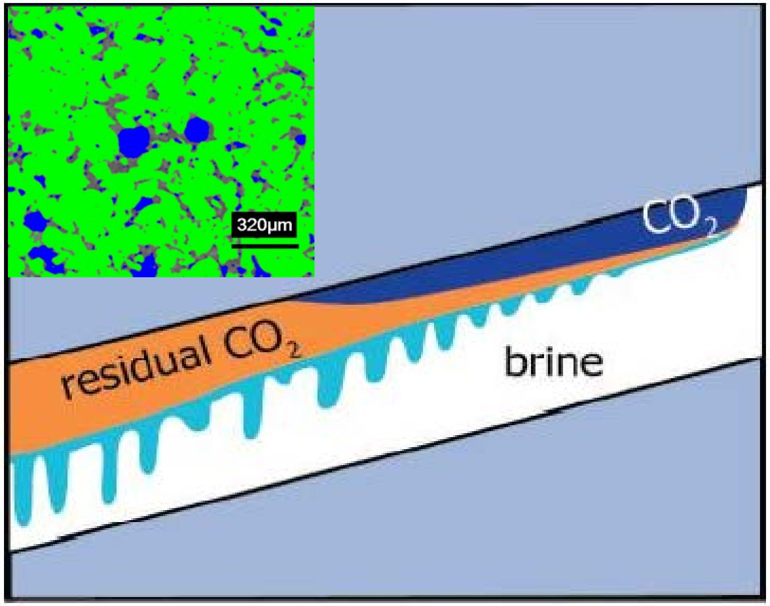
Qatar Petroleum

QATAR SCIENCE & TECHNOLOGY PARK

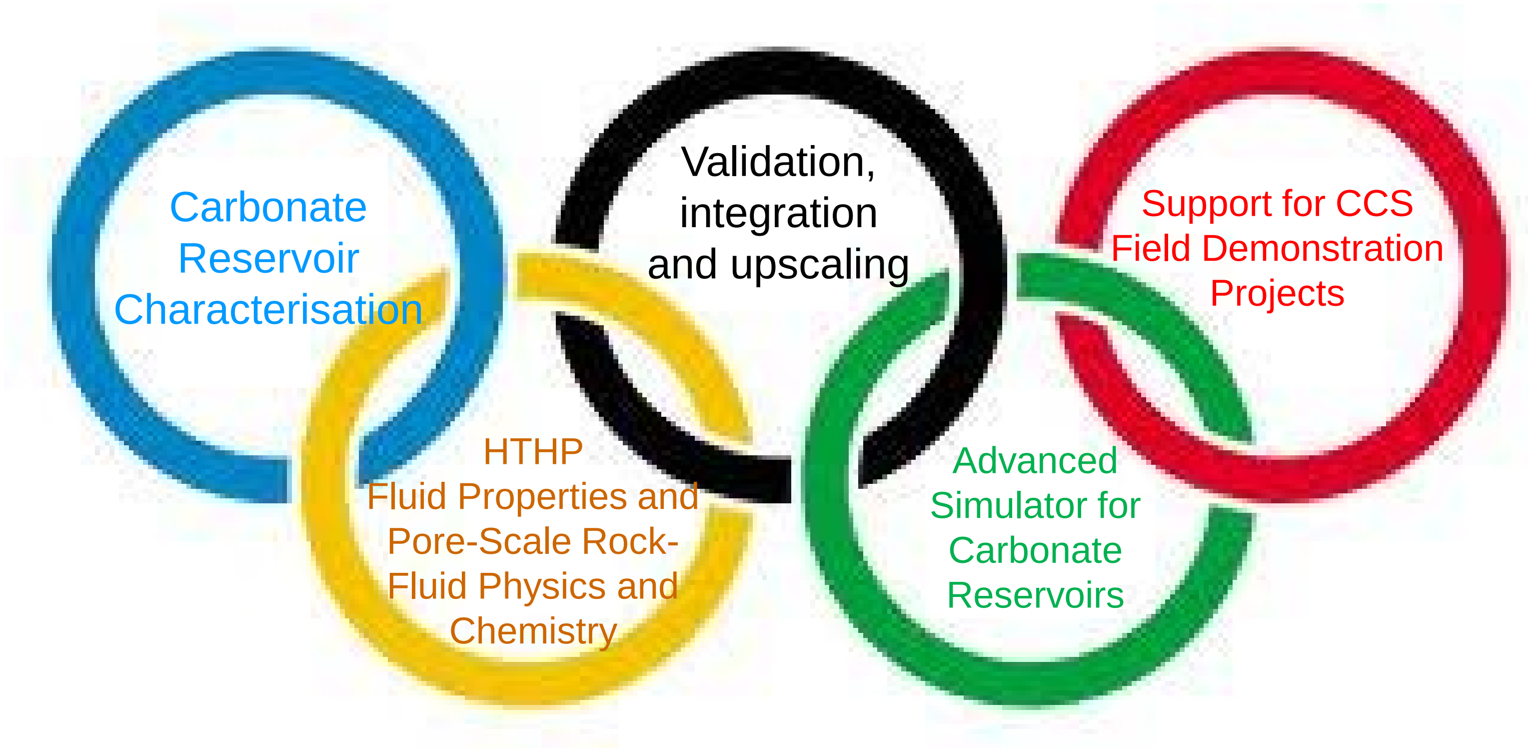
Long-term fate of ‘buried’ CO_2

How can we be sure that the CO_2 stays underground?

- Caprock seals
- Capillary Trapping
  - rapid (decades): CO_2 as pore-scale
  - bubbles surrounded by water
  - we can design this process
- Dissolution
  - CO_2 dissolves in water – 10^3 years
- Chemical reaction - mineralisation
  - forming acid
  - carbonate precipitation – 10^3–10^9 years



The five projects of QCCSRC



Fluid Properties at HTHP Reservoir Conditions

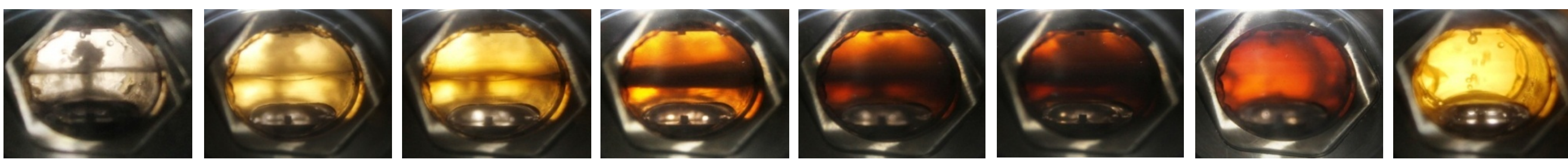
Professor Martin Trusler
GCM
Professors George Jackson, Amparo Galindo, Claire Adjiman

Phase Behaviour of CO_2 + Hydrocarbons

Dr Saif Al Ghafri
PhD Student
Research Fellow, UWA

Dr Esther Forte
former PhD Student, now
Research Fellow

Dr Shuxin Hou
Postdoc, now with
Statoil



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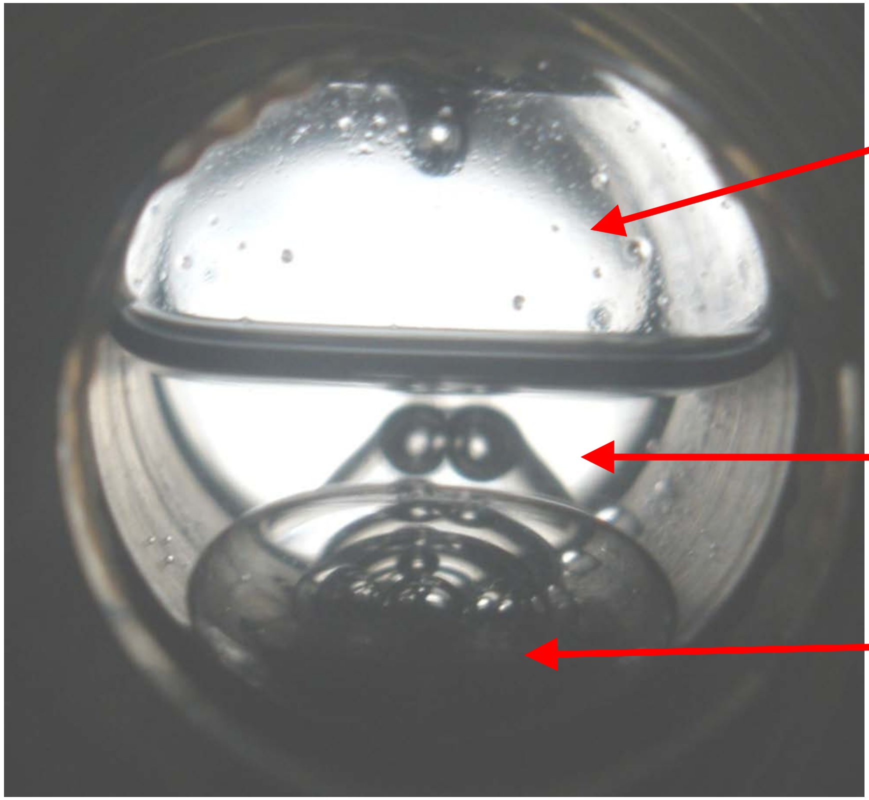
Complex Phase Behaviour of CO_2-hydrocarbons-water/brines



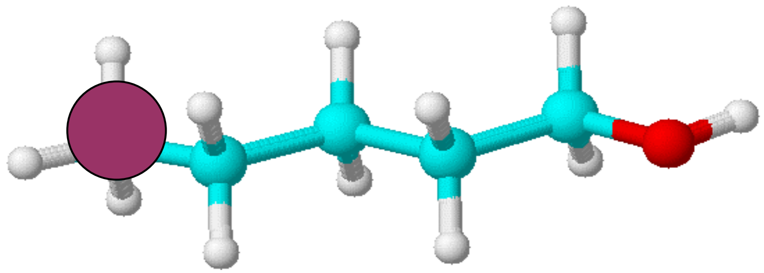
CO_2-rich gas phase

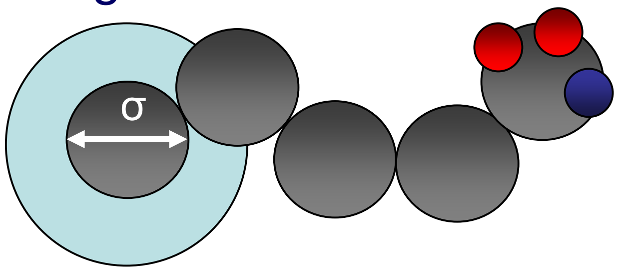
Hydrocarbon -rich liquid phase

Water-rich liquid phase

SAFT-VR Equation of State

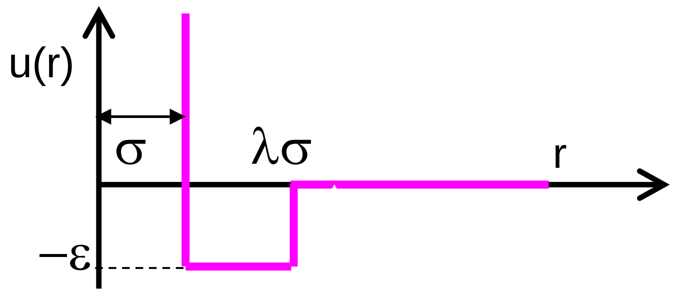
Molecules described by tangent spherical segments





m spherical segments

Interaction between segments = Square-Well potential



$$u(r) = \begin{cases} \infty & \text{if} \quad r < \sigma \\ -\varepsilon & \text{if} \quad \sigma < r < \lambda\sigma \\ 0 & \text{if} \quad \lambda\sigma < r \end{cases}$$

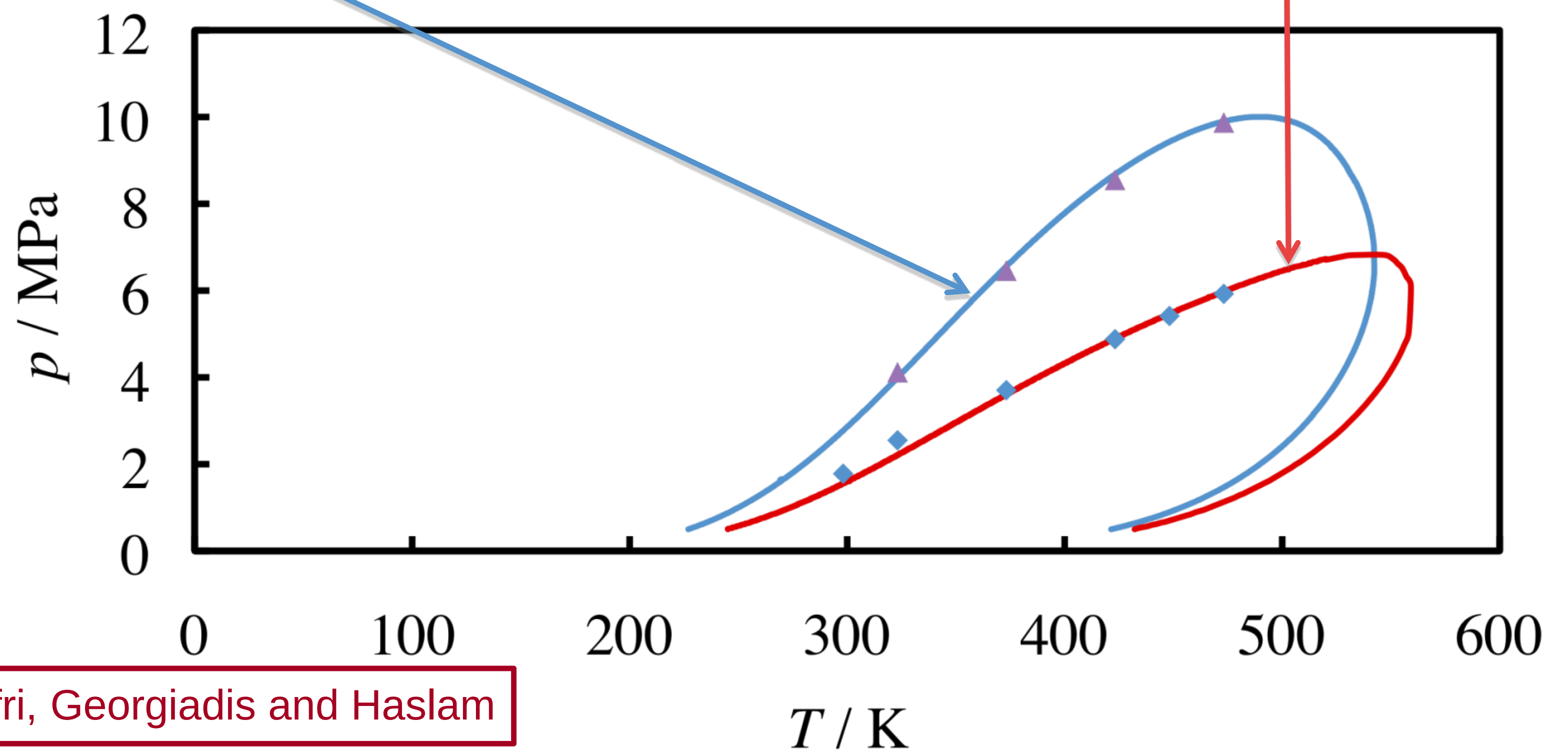
Each component is described by 4 parameters: m, σ, ε, λ

CO_2 + *n*-heptane + toluene

- Fixed-composition, p-T space

36% CO_2 + 21% *n*-heptane + 42% toluene

20% CO_2 + 27% *n*-heptane + 53% toluene



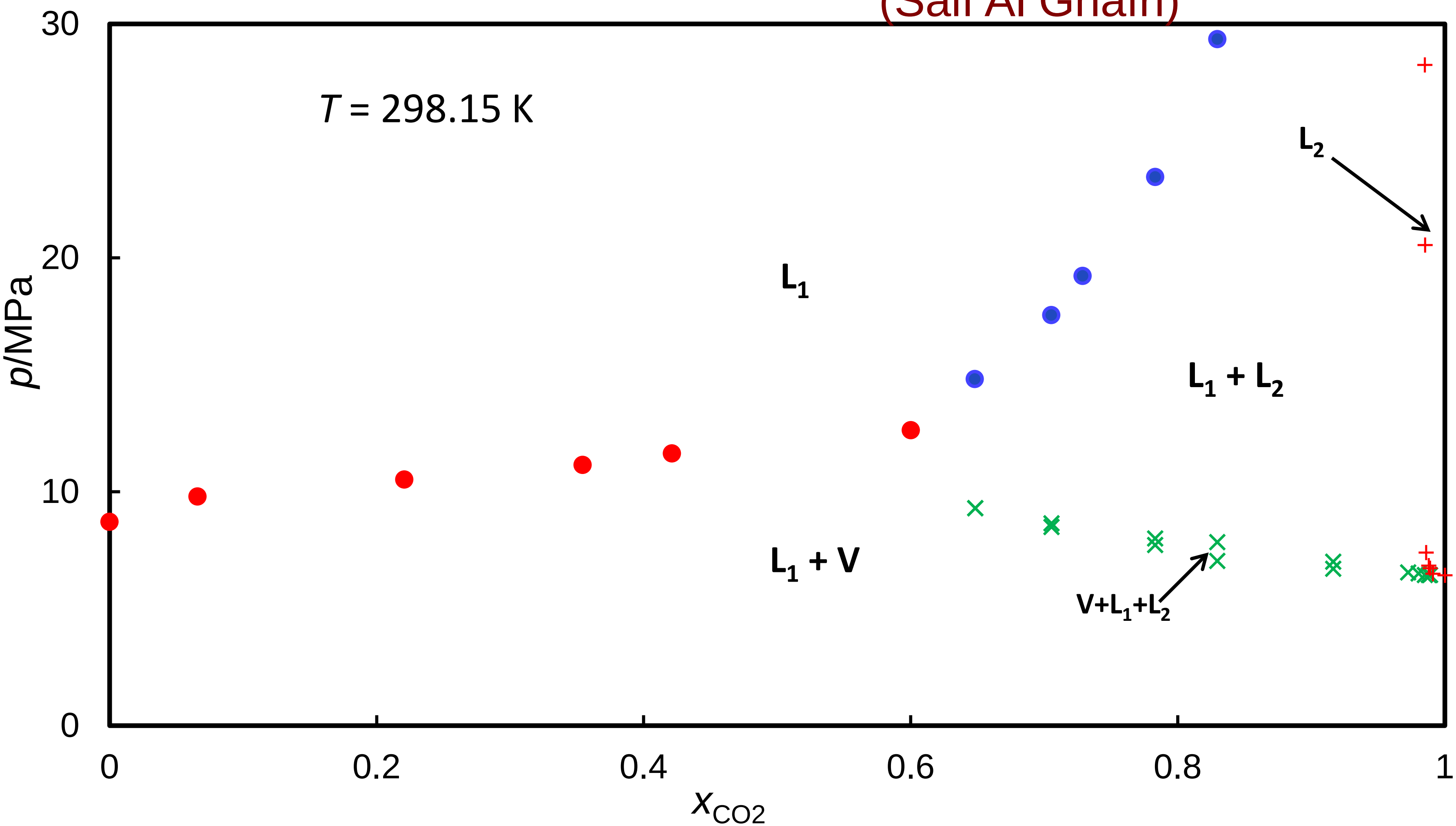
Al Ghafri, Georgiadis and Haslam

(Symbols represent experiments; curves represent SAFT-γ-Mie predictions)

Bubble & Dew Curves

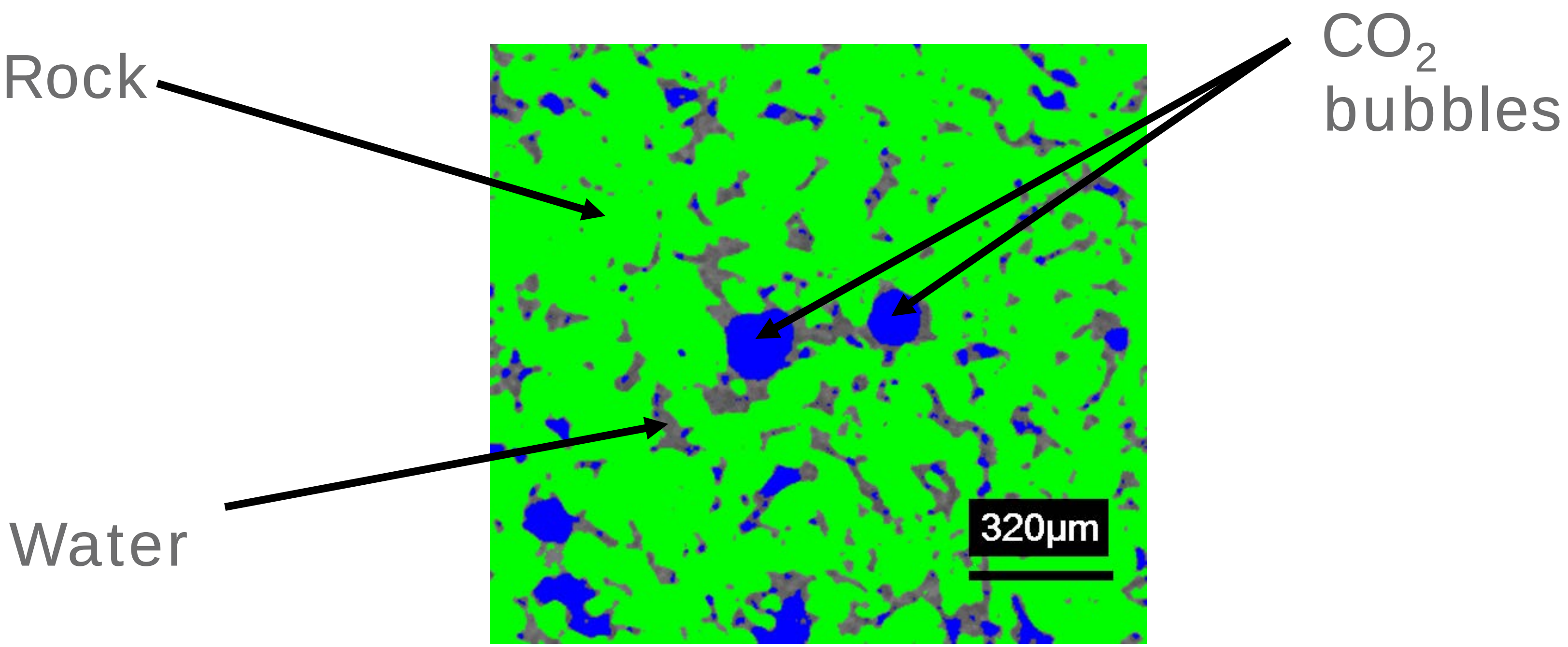
20 component synthetic live oil + CO_2

(Saif Al Ghafri)



CO_2 trapping

- As CO_2 migrates through the rock, it can be displaced by water, trapped in pore-scale bubbles and cannot move further

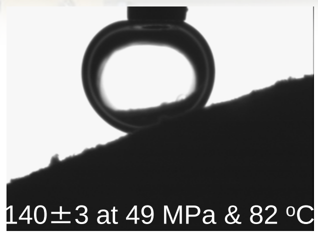


Dong, 2007

Qatar Carbonates and Carbon Storage Research Centre

HPHT Interfacial Tension of CO_2-Hydrocarbon-Brine Systems

Dr Apostolos Giorgiadis
PhD 2011



Dr Xuesong Li
PhD 2013

Imperial College London

قطر للبترول
Qatar Petroleum

QATAR SCIENCE & TECHNOLOGY PARK

Interfacial Tension: n-decane-CO_2

Experiments compared with SAFT-DFT

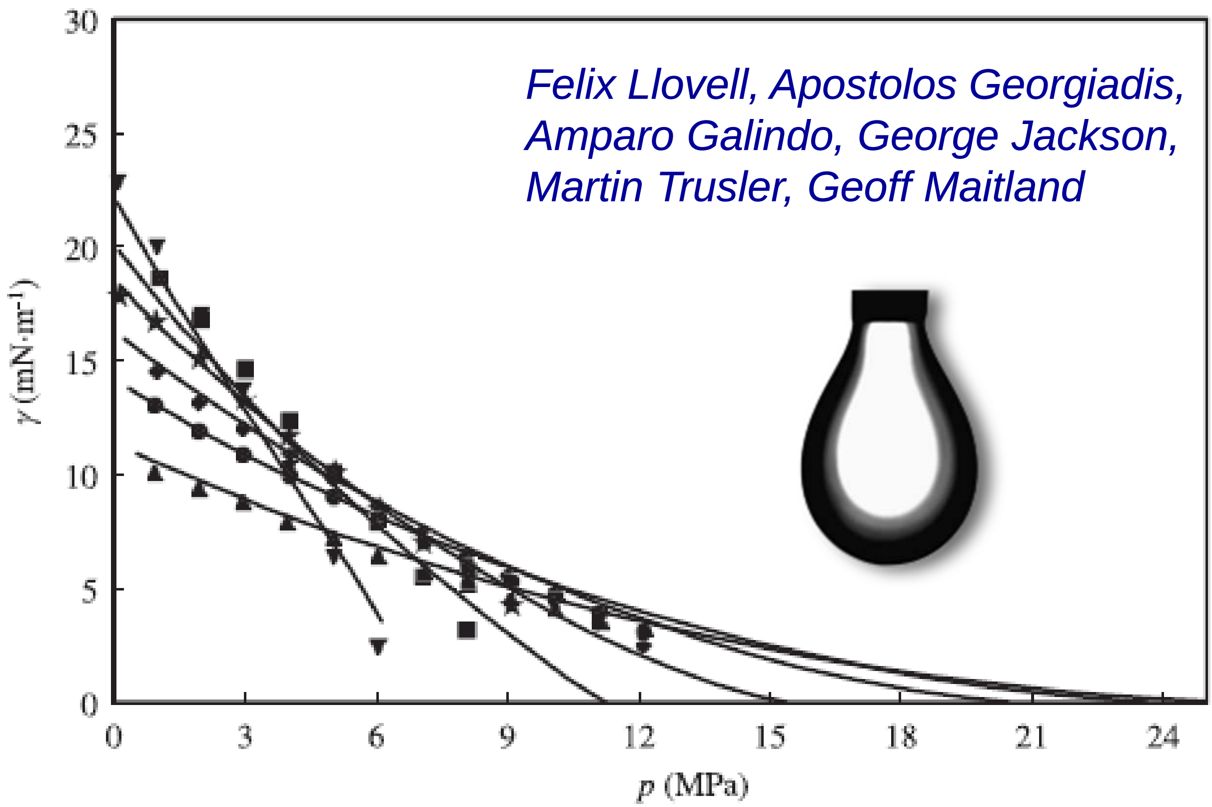
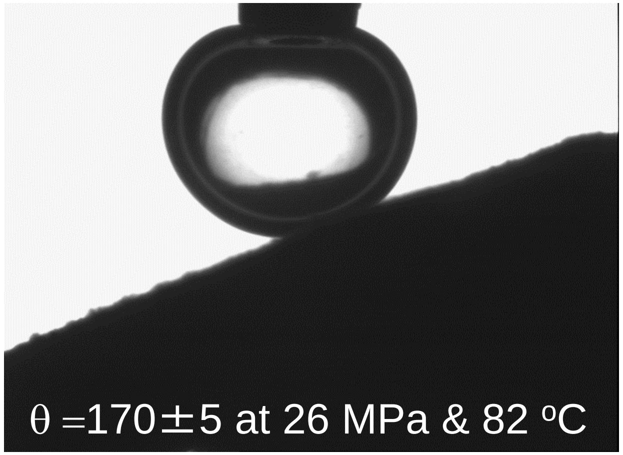
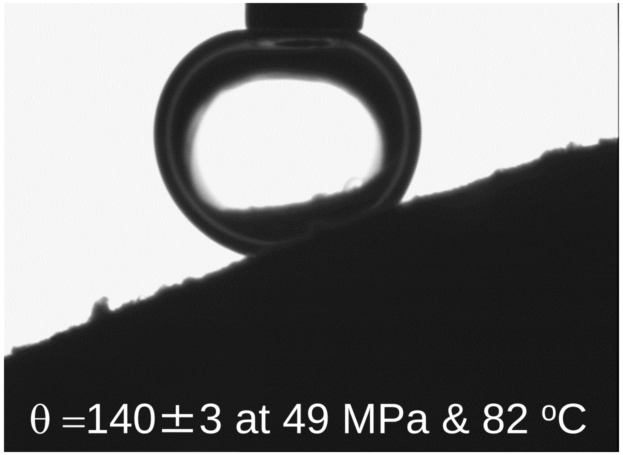


Fig. 3. Interfacial tension modelling and measurements of the (n-decane + CO_2) system as a function of pressure for different isotherms: (▼) at 298.0 K; (■) at 323.4 K; (★) at 343.6 K; (◆) at 373.5 K; (●) at 403.1 K; (▲) at 443.1 K. Continuous curves (–) correspond to the SAFT-VR-DFT predictions (cf. Section 3.1).

Contact Angle vs Pressure: Al_2SiO_5 Ceramic + H_2O + CO_2

contact angle CO_2-substrate (degrees)	pressure [MPa]
170 ± 5	26.6
148 ± 2	29.7
150 ± 2	32.0
150 ± 2	39.5
141 ± 2	47.0
140 ± 3	48.9





Fluid flow in porous and fractured (carbonate) rocks

Revolution in core analysis

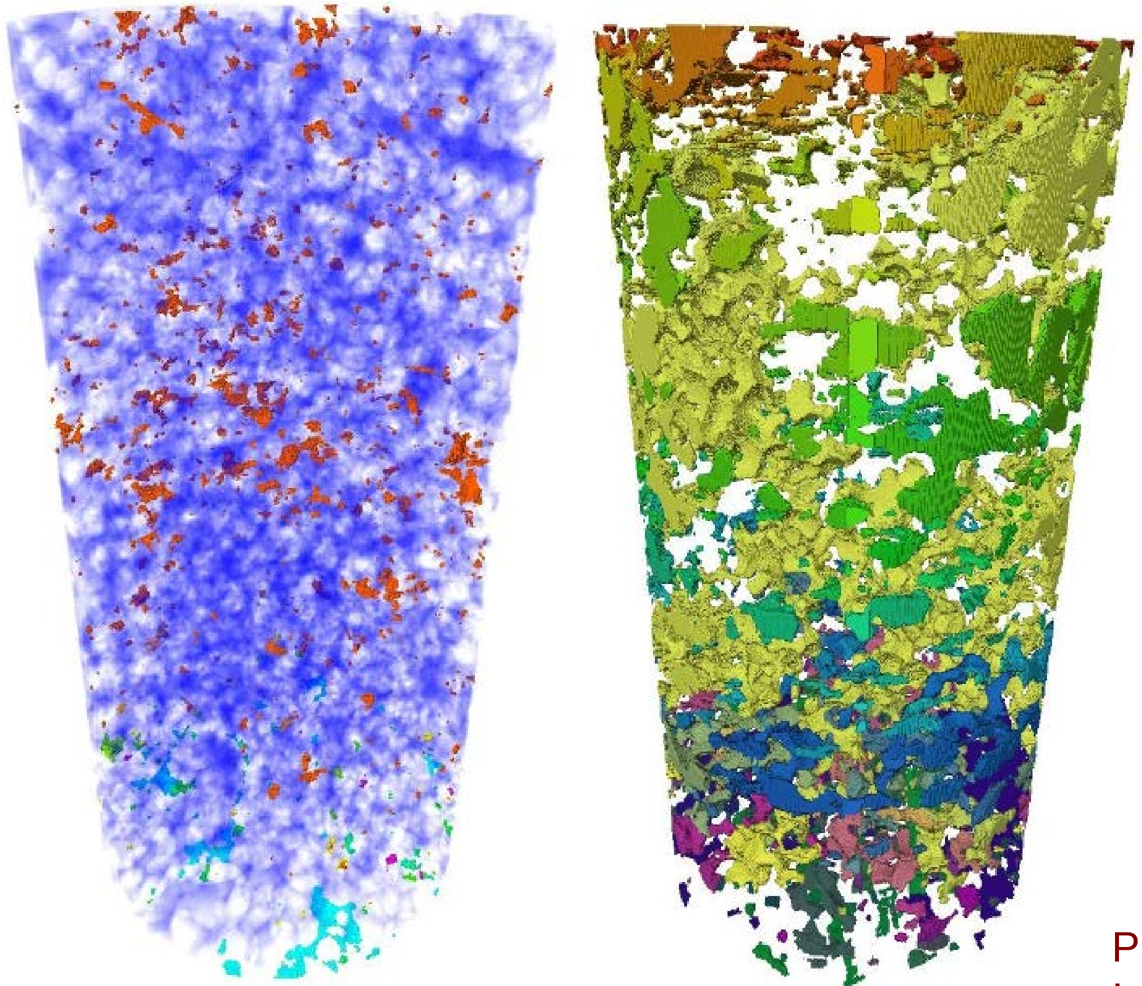
- Ability to image rocks and fluids at the pore scale,
- Coupled with novel predictive computational methods.


HD-350E

Pore-scale trapping and contact angle measurements in carbonate rocks

Matthew Andrew
Martin Blunt and Branko Bijeljic

Capillary trapping in Ketton Limestone



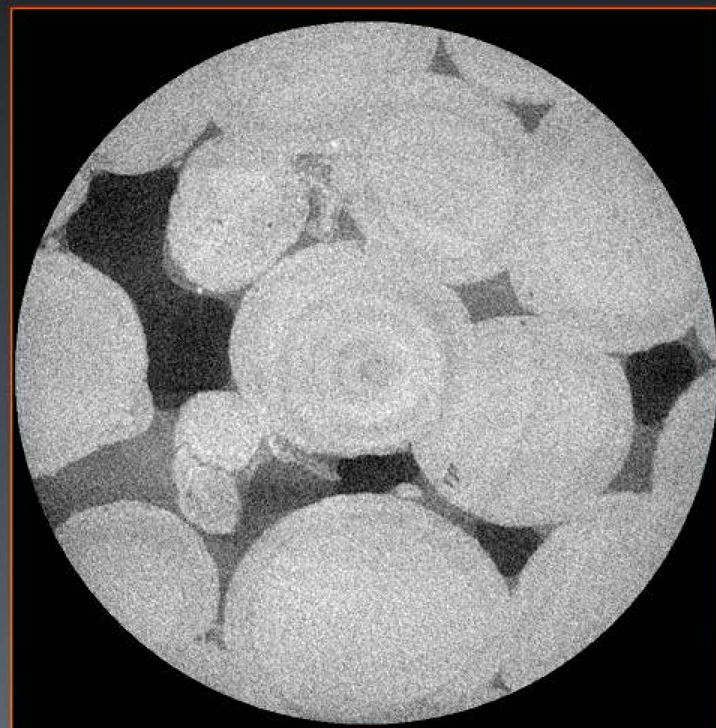
(Left) Non-wetting CO_2 after primary drainage. Pale blue is one large cluster: other colours are smaller clusters.

(Right) CO_2 ganglia after brine flooding. The colours indicate cluster size. Significant contribution of large clusters.

Core has diameter 6.5 mm and resolution of around 6 μm.

Pioneering *in situ* reservoir-condition Imaging (only lab to do this successfully)

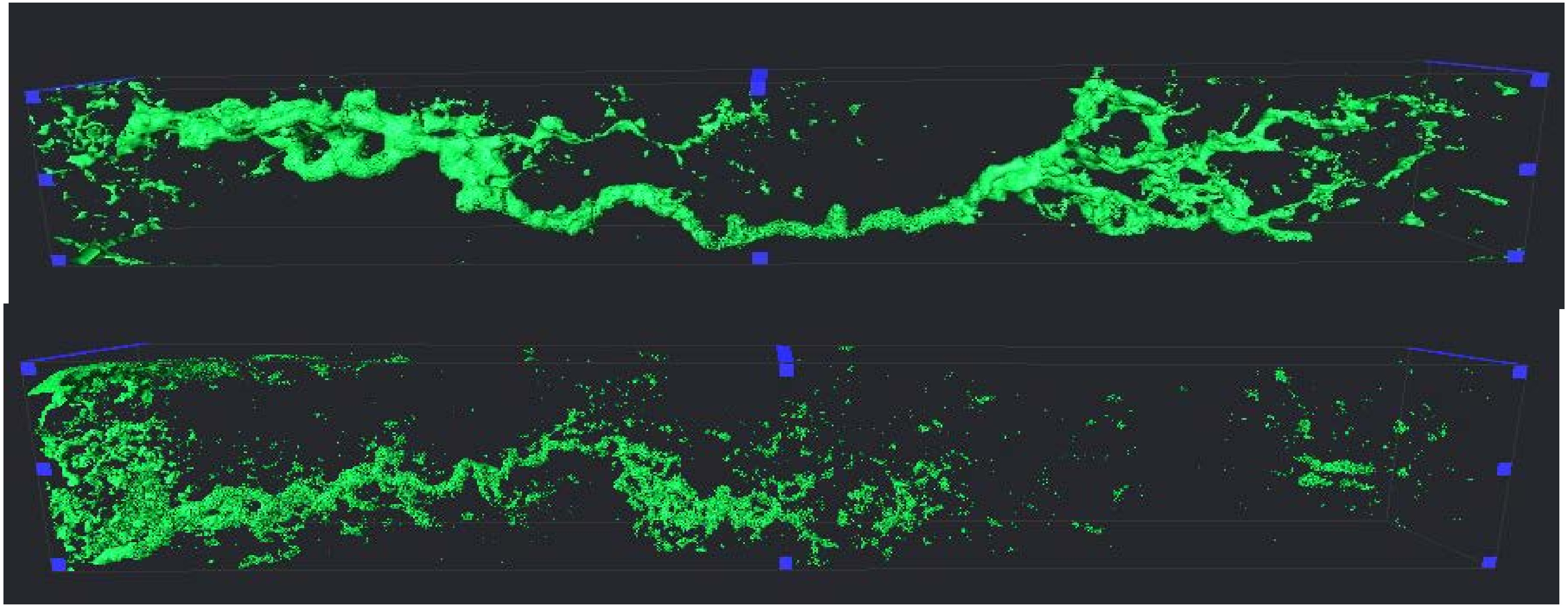
μ-CT Study of CO_2 trapping and wetting



Pore-scale dissolution of Portland Limestone by supercritical CO_2

Observe dissolution patterns in Portland at high and lower reaction rates. Further work to analyze the results, perform *in situ* experiments, showing the dynamic evolution of the pore fabric, and pore-by-pore modelling and validation.

$Da_1 > Da_2$



The essence of QCCSRC's Research: Fluids Moving and Reacting in Carbonate Rocks

QCCSRC PIs:

Geology and Geochemistry – Dr Cedric John, Prof John Cosgrove

Thermophysical Properties – Professors Martin Trusler, Geoff Maitland, George Jackson, Amparo Galindo and Velisa Vesovic, Dr Andrew Haslam, Dr Nico Riesco

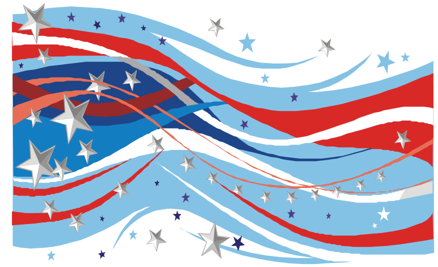
Flow in Porous Media – Professor Martin Blunt, Dr Sam Krevor, Dr Edo Boek, Dr Branko Bijeljic, Dr John Crawshaw

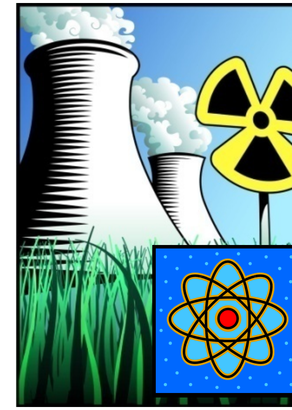
Reservoir Modelling – Professors Matt Jackson, Peter King, Martin Blunt

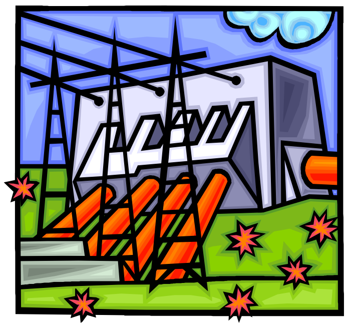
The Energy Landscape

Current world consumption 15 TW

Hydroelectric: 4.6 TW gross, 1.6 TW feasible technically, 0.6 TW installed capacity



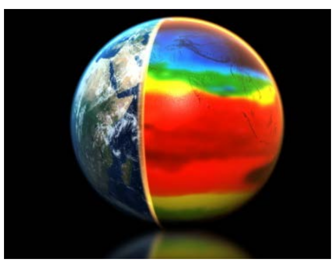


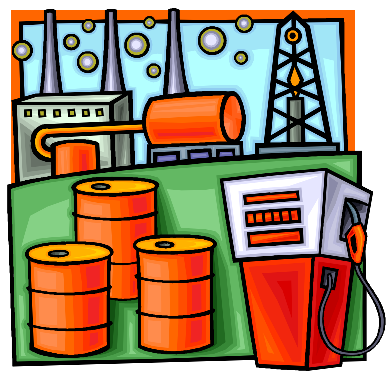


Tidal/Wave/Ocean Currents: 2 TW gross

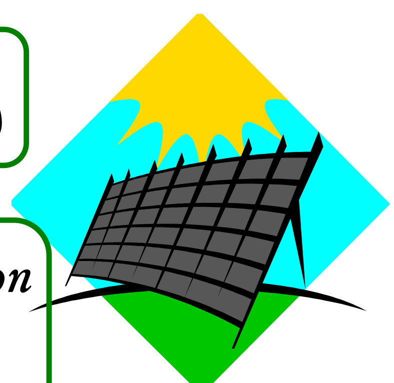
Nuclear: Current 1TW

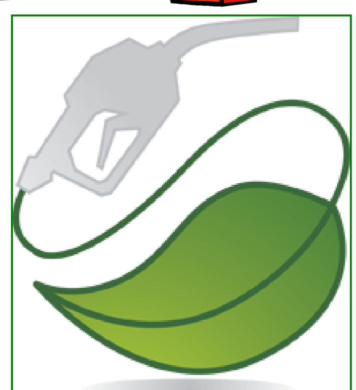
Fossil Fuels: Current 12.5 TW Potential 25 TW





Geothermal: 9.7 TW gross (small % technically feasible)





Wind 2-4 TW extractable

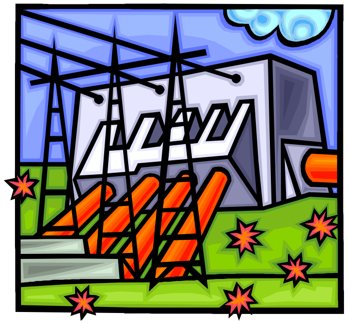
Solar: 1.2 x 10^5 TW on earth's surface, 36,000 TW on land

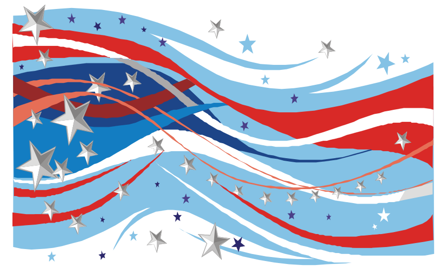
Biomass/fuels: 5-7 TW, 0.3% efficiency for non-food cultivatable land

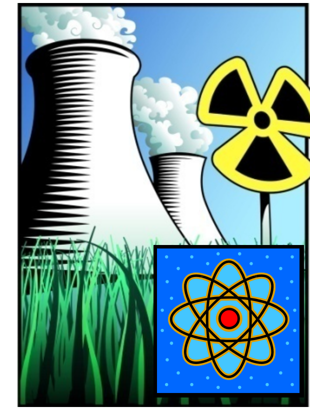
Future Energy Landscape?

2075 world consumption 35 TW

Hydroelectric: 1.5 TW



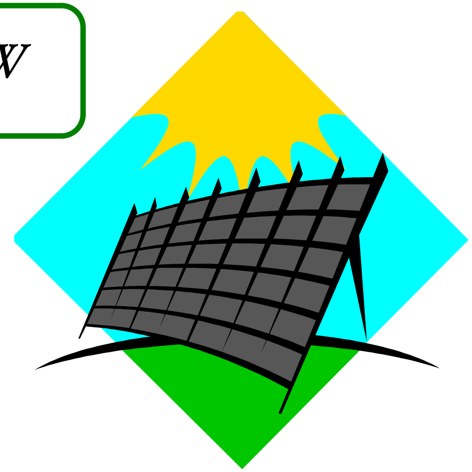


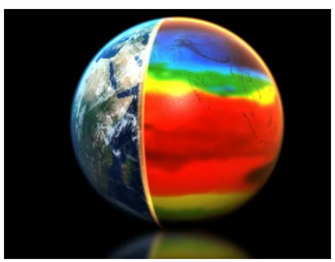


Tidal/Wave/Ocean Currents: 2 TW gross

Nuclear: Current 5 TW

Solar: 20 TW





Geothermal: 1 TW gross)

Wind 4 TW

Fossil Fuels + CCS: 5 TW

Biomass/fuels: 5 TW

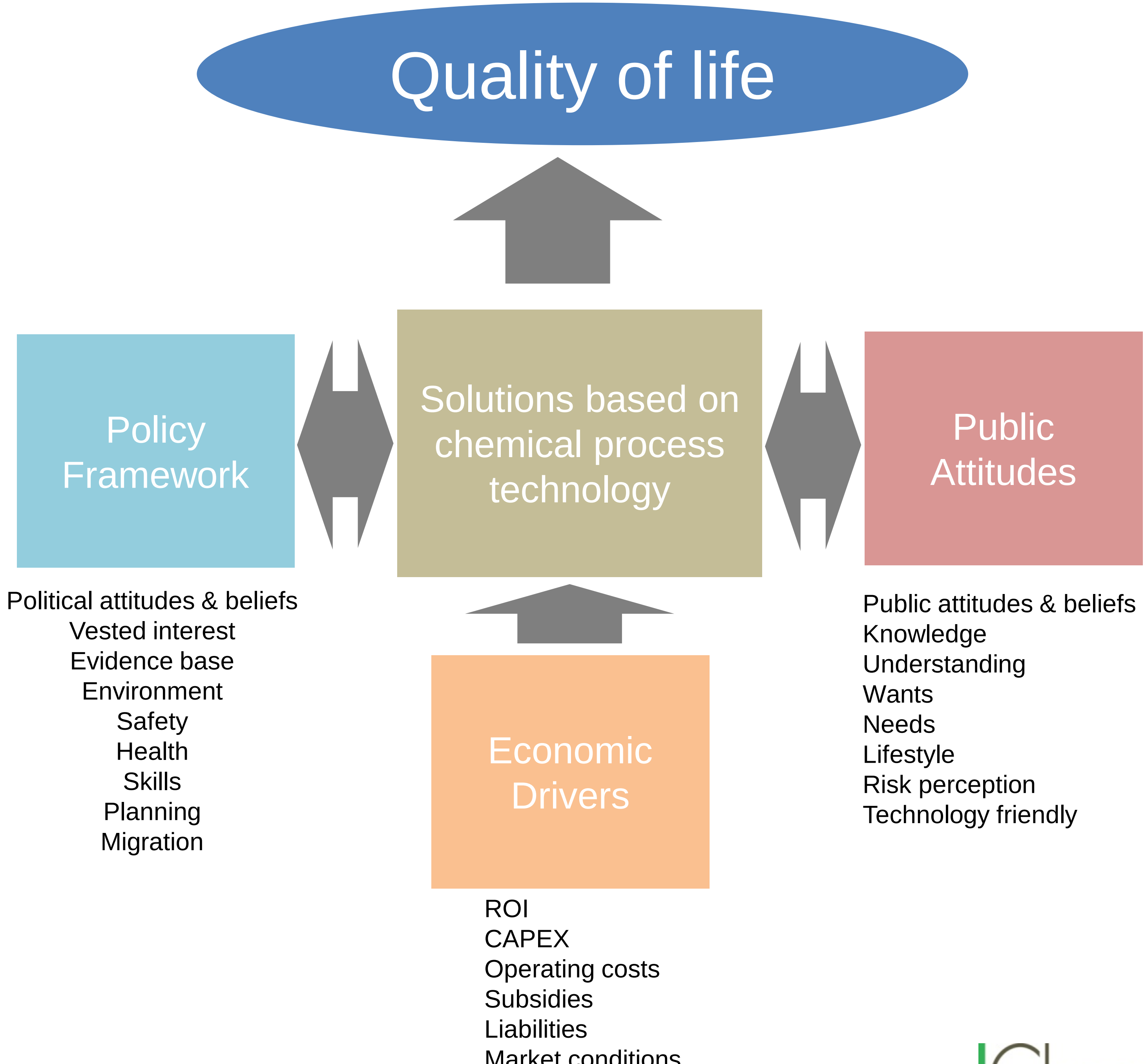
IChemE ADVANCING CHEMICAL ENGINEERING WORLDWIDE

What can Chemical Engineers do?

Provide innovative low cost, low carbon technical solutions

- An integrated and holistic approach to moving across the energy landscape
  - A process systems engineering approach
- Lower the cost of carbon capture by 50%
- Keep low-value, environmentally damaging components of FFs underground
  - Sub-surface processing → eg H_2, CH_4, MeOH, DME, syngas, heat
- Step-change in grid-scale energy storage devices
- Robust solutions to solar thermal desert sand and heat exchange fluid issues
- Algae at scale for biofuels, chemicals and CO_2 capture
- Use nuclear plant heat to improve efficiency of CCGT
- Innovative solutions for energy efficiency in manufacturing, buildings and homes

IChemE ADVANCING CHEMICAL ENGINEERING WORLDWIDE

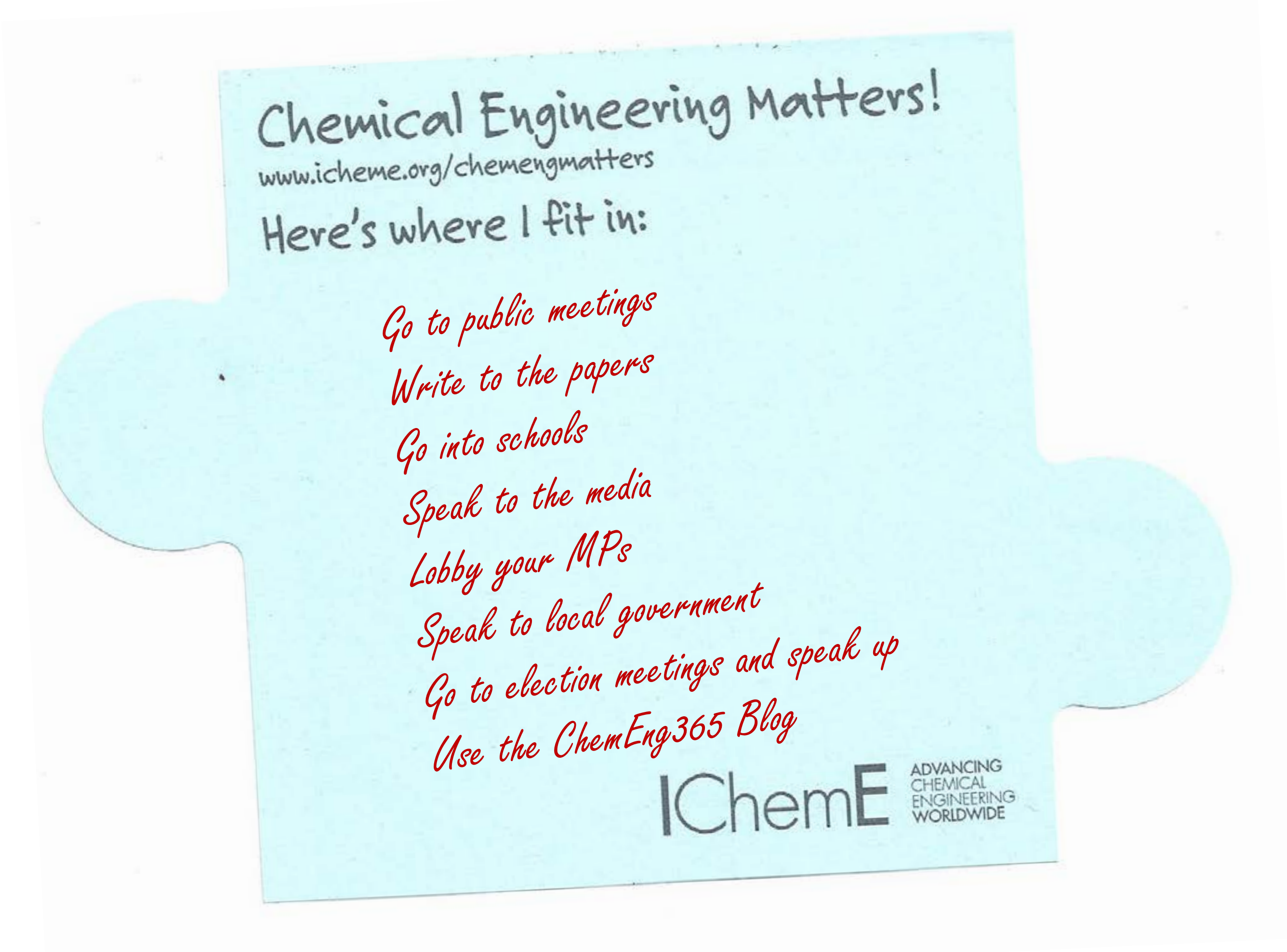


IChemE ADVANCING CHEMICAL ENGINEERING WORLDWIDE

Every individual has a role to play

It’s up to us all to tell the world that urgent action on Climate Change Mitigation is needed
– and to recognise/accept that there is no free lunch!

Ways to make your voice heard…



"Let's speak to the outside world, not just to ourselves"

IChemE ADVANCING CHEMICAL ENGINEERING WORLDWIDE

What can I do?

- Engage in the energy debate
- The IChemE Energy Centre
- Play your part in Energy Efficiency
  - Try to save 80% of your 10te CO_2 pa
  - Use carbon calculator tools eg DECC
    - http://www.globalcalculator.org/
    - http://my2050.decc.gov.uk/
- Encourage local energy projects
- Persuade others and lead by example

So…the future of energy is a mix of different sources for the rest of this century

…no easy choices

…and no free lunches

…Clean Energy costs more

Fossil Fuels and avoiding climate change

…are they compatible?

They must be…we have no choice

But we have to act quickly to achieve this

…The time for talking is over!