Imperial College London

60 YEARS OF CHEMICAL ENGINEERING
THE UNIVERSITY of EDINBURGH School of Engineering

Avoiding major climate change in a cleaner fossil fuels world - *the challenges and opportunities for (chemical) engineers and governments*

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Immediate Past President IChemE

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Imperial College London

Edinburgh Chemical Engineering Diamond Jubilee Keynote Lecture 15th October 2015

IChemE ADVANCING CHEMICAL ENGINEERING WORLDWIDE

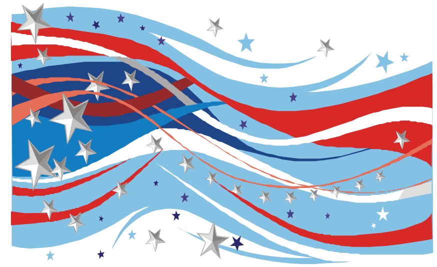
Overview

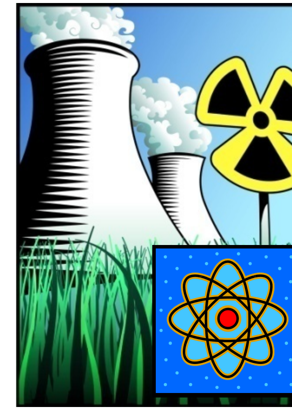
- The energy landscape
- The energy transition
- Fossil fuels – the elephant in the room
- Managing the elephant
- Engineering the Journey –
  ‘Chemical Engineering Matters’
- The key role of Chemical Engineers
- The role of IChemE and its groups
  …working together…and you!

The Energy Landscape

Current world consumption 15 TW

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

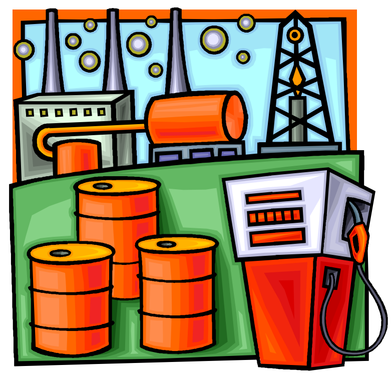


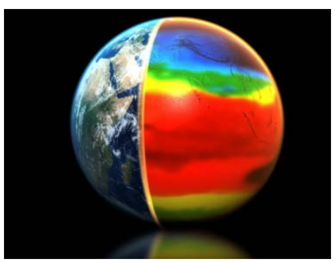


Tidal/Wave/Ocean Currents: 2 TW gross

Nuclear: Current 1TW

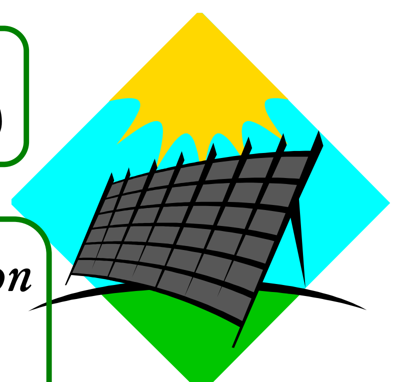
Fossil Fuels: Current 12.5 TW Potential 25 TW





Geothermal: 9.7 TW gross (small % technically feasible)

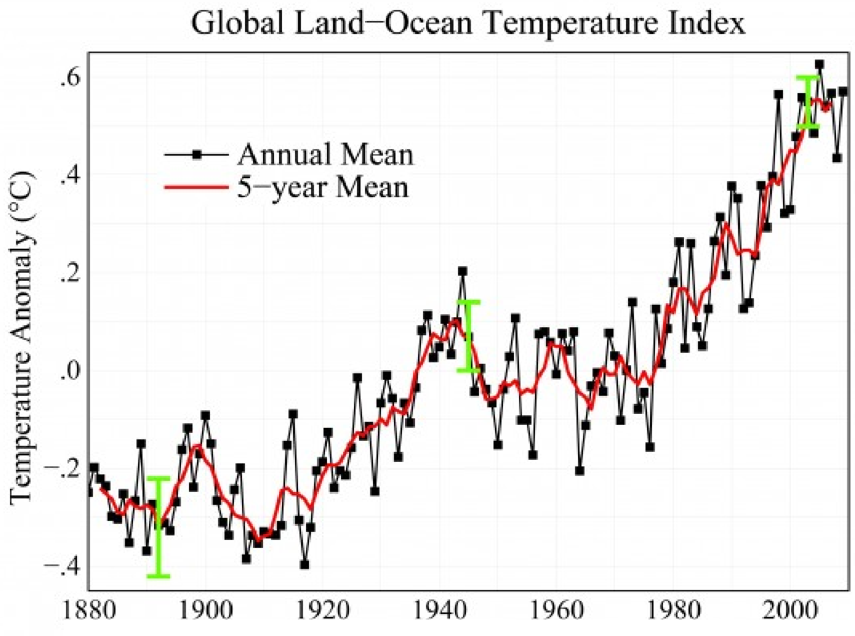
Wind 2-4 TW extractable

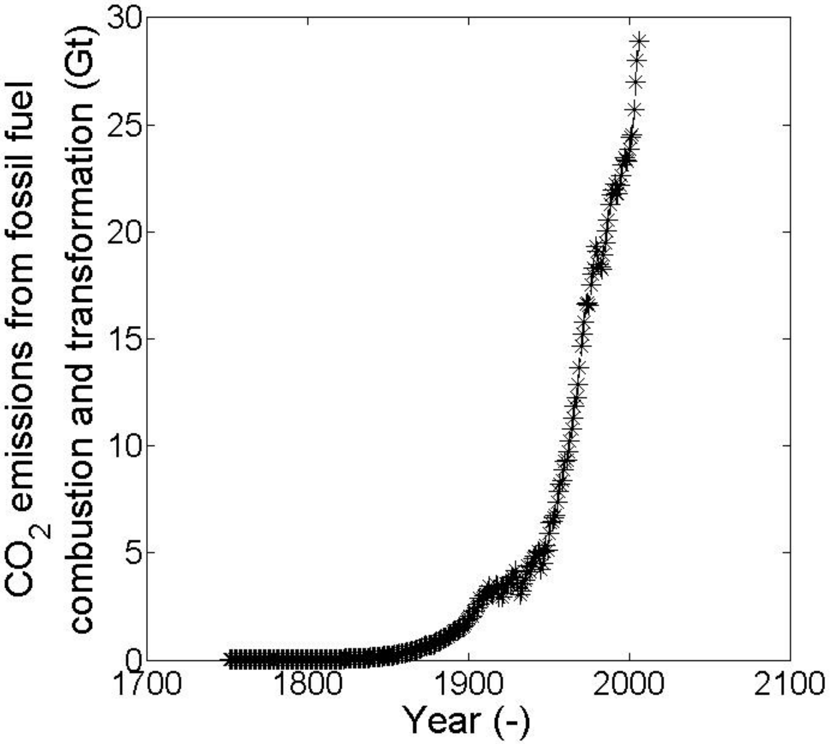


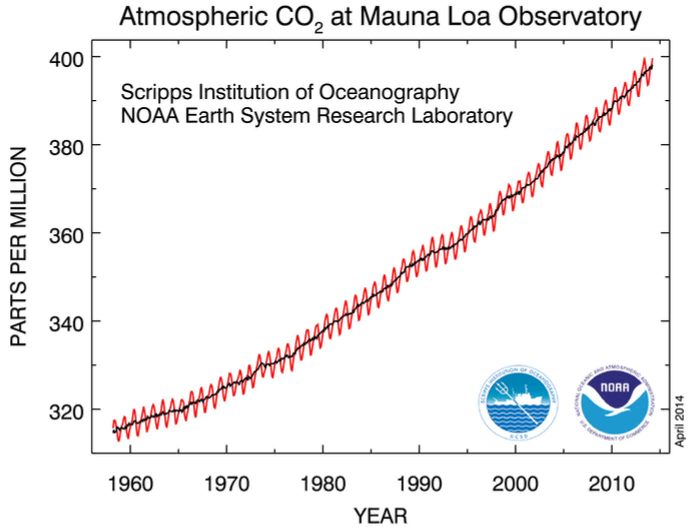
Solar: 1.2×10^5 TW on earth's surface, 36,000 TW on land

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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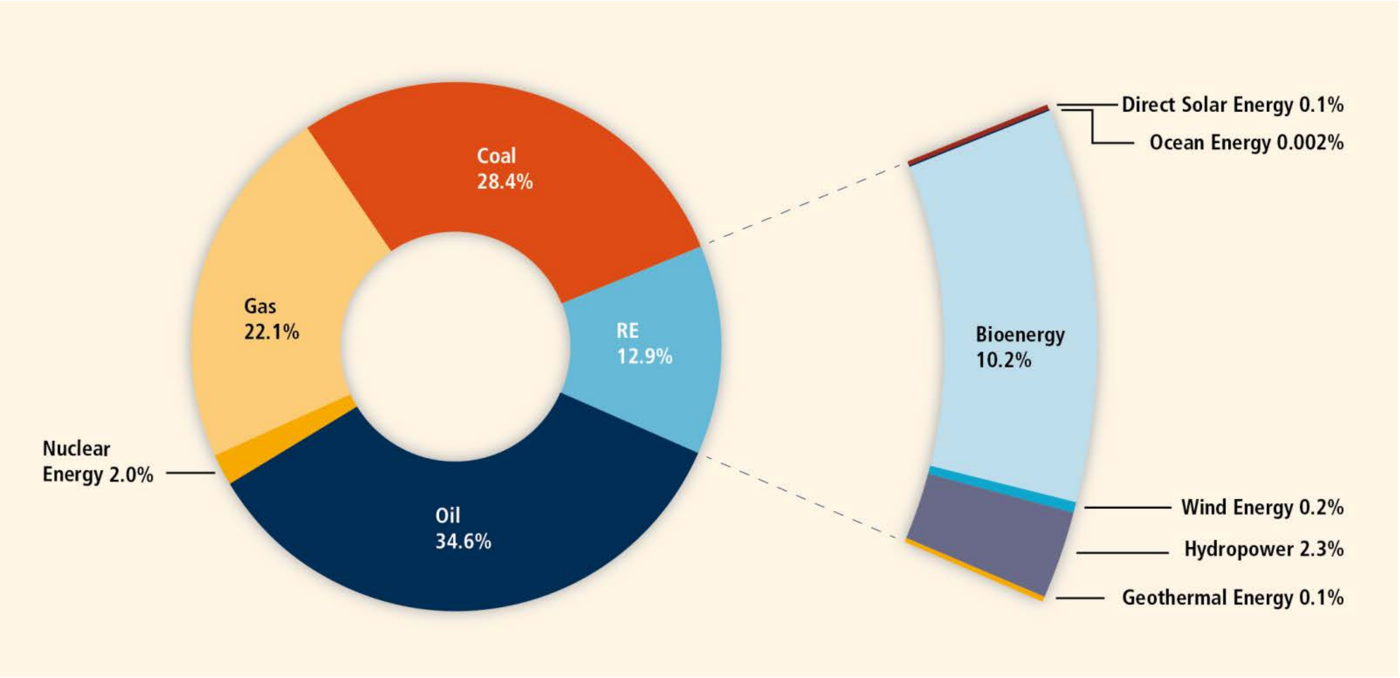
Current Energy Mix



IEA Energy Technology Perspectives 2010

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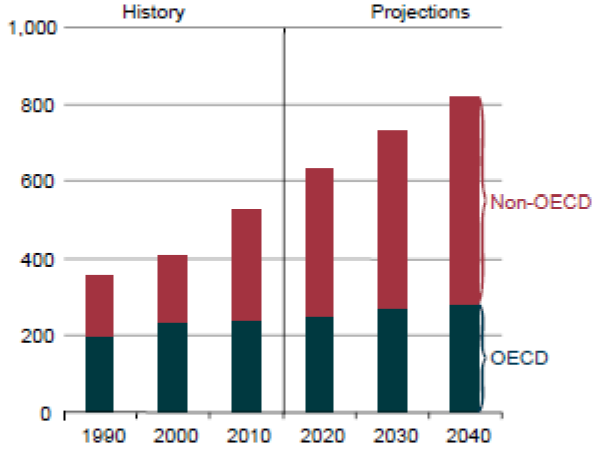
Major Future Energy Demand Drivers

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



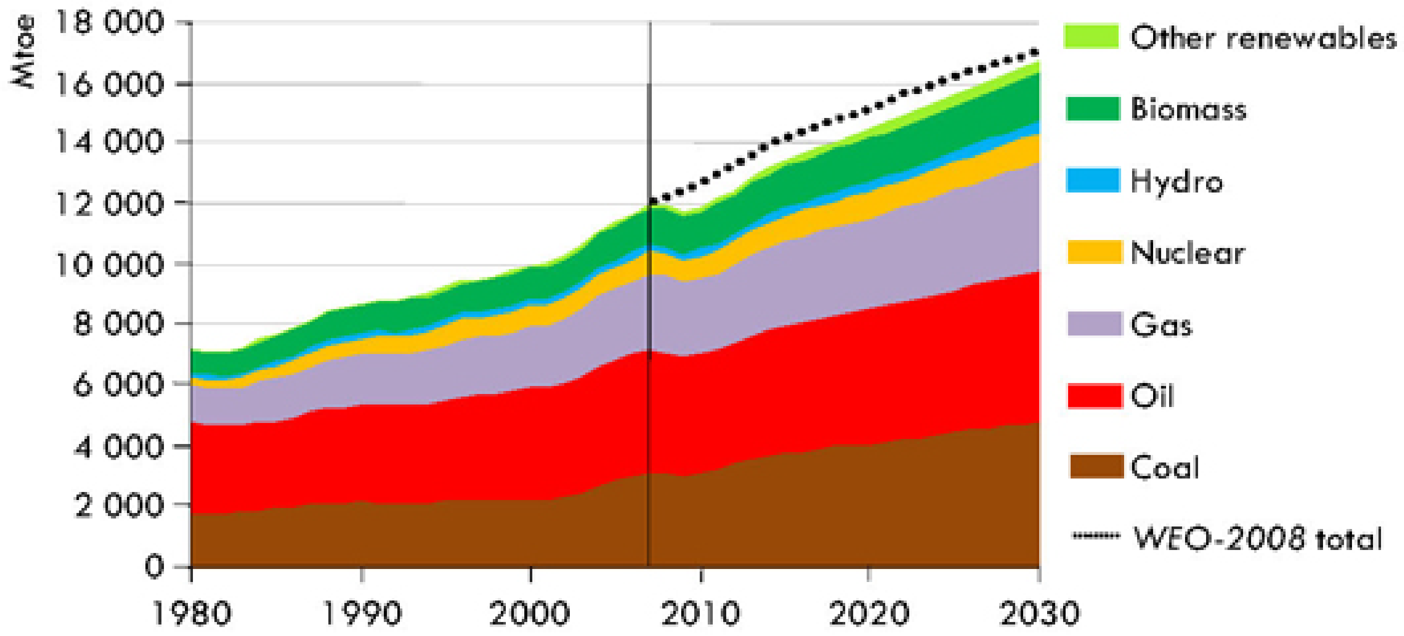
- World population:
  - ~7bn 2014
  - Growth ~ 1.2% pa
  - Projections:
    - 8bn by 2030, 9bn by 2050

- Major economic expansion of BRIC, non-OECD countries

- World energy demand to double by 2050

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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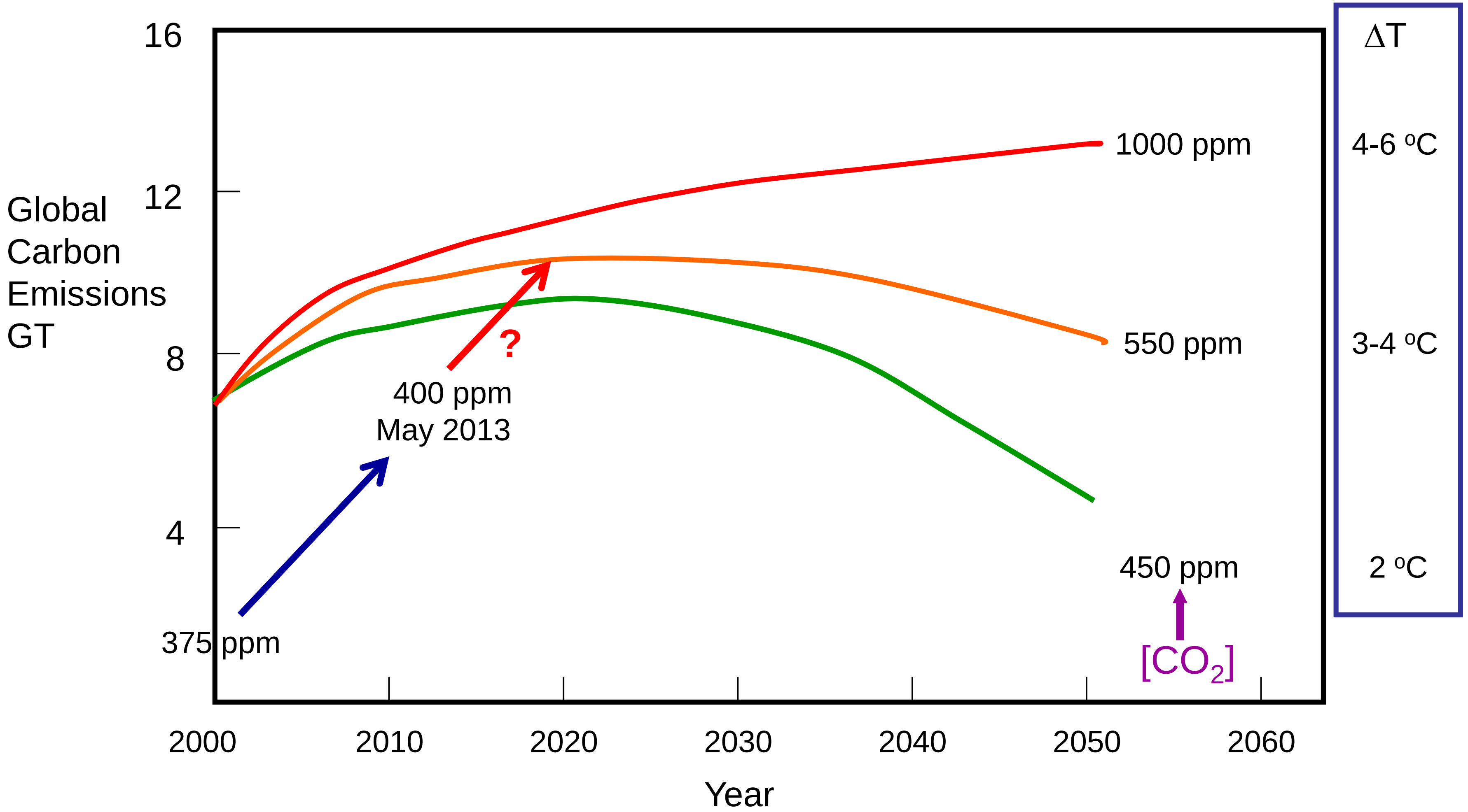
CO_2 Emissions Scenarios

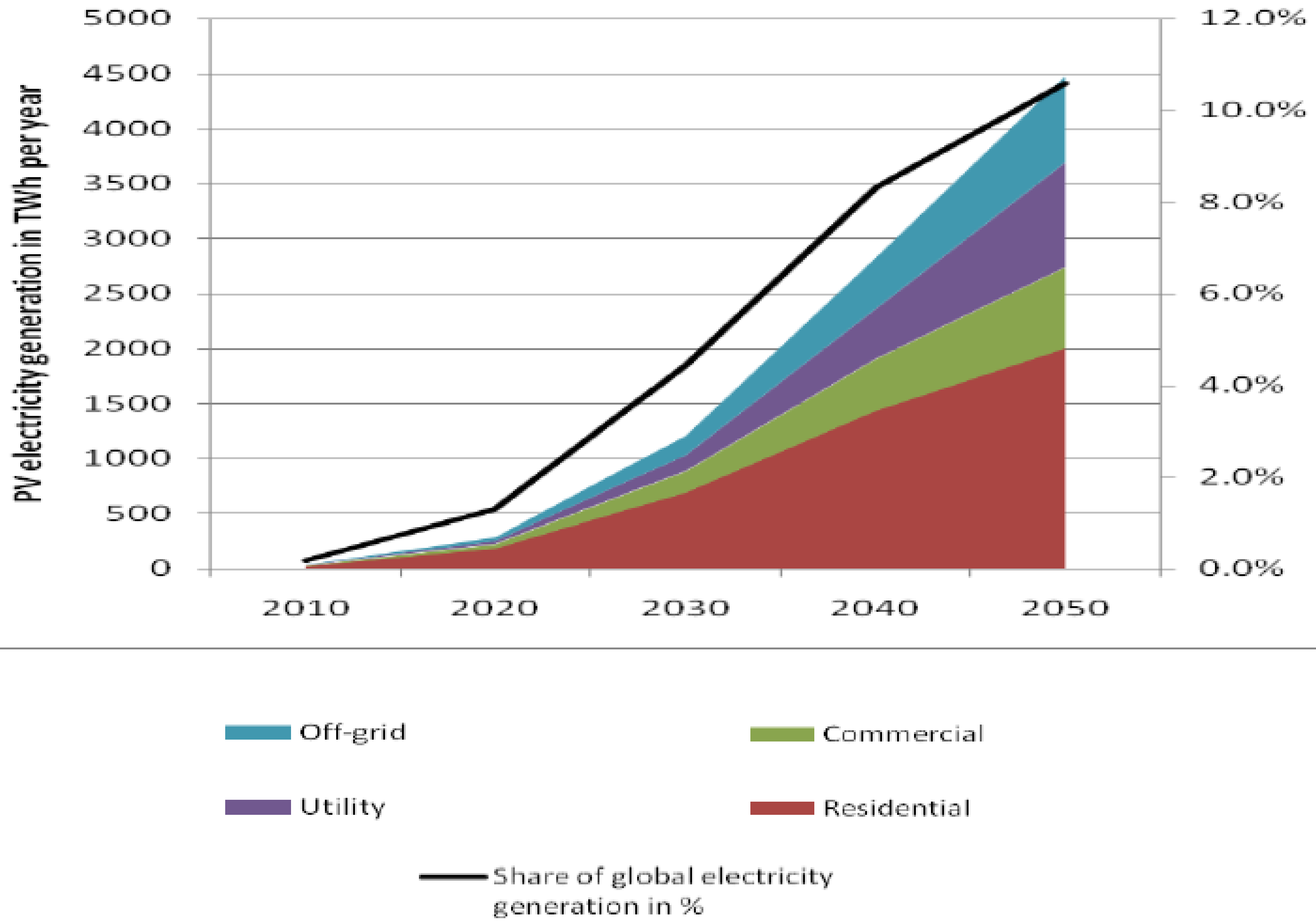


UK – each individual generates ~ 10 te CO_2 per annum

Factors limiting rapid growth of Alternative Energy Routes

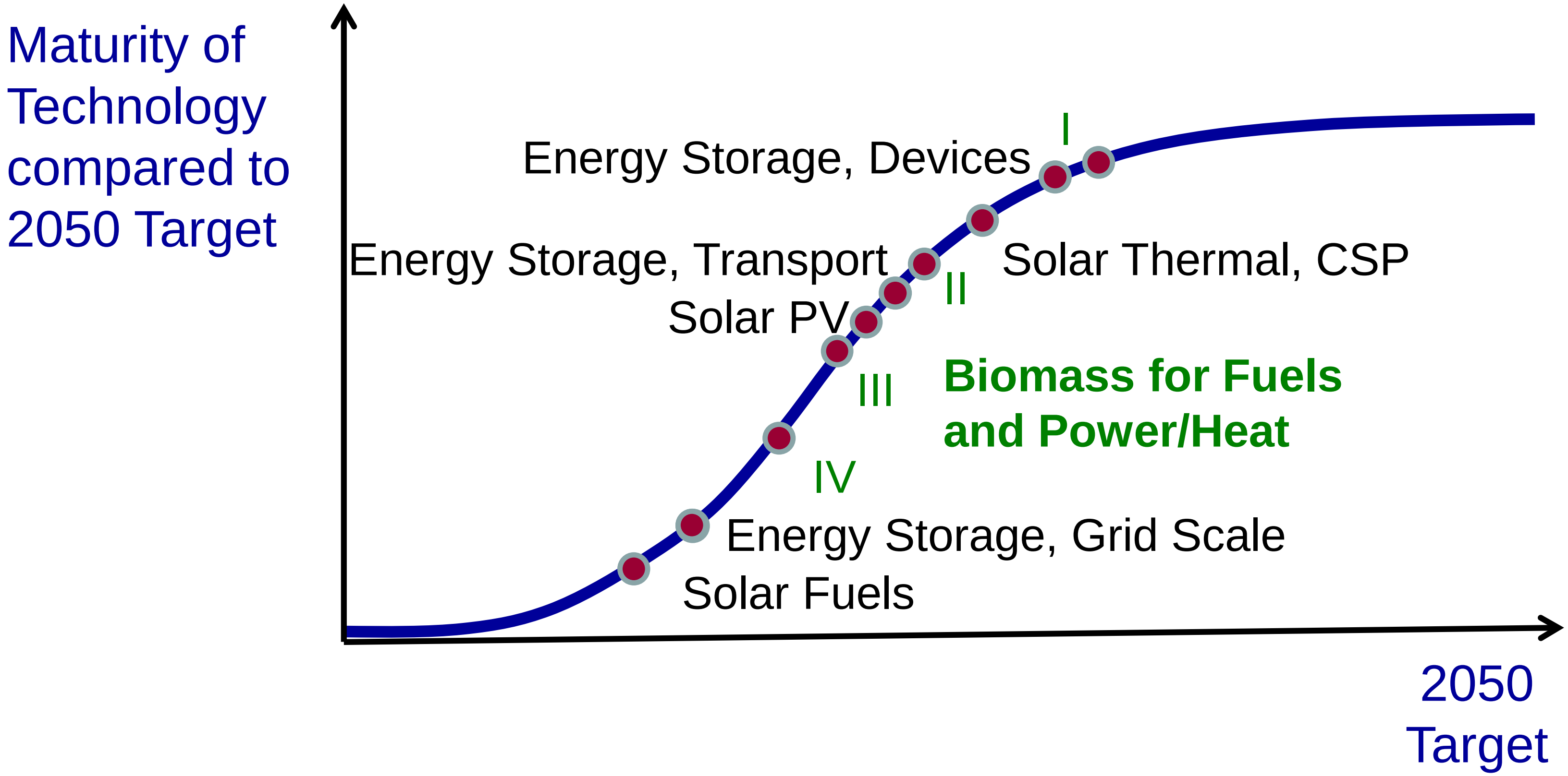
- Slow rate of developing technology, improving energy efficiency
- Bringing costs down – comparability with fossil fuels (+ CCS)
- Availability – delivering sufficient capacity
  - eg landmass limitations
- Coping with intermittency – energy storage
- Nuclear
  - Safety – Fukushima, March 2011
  - Waste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



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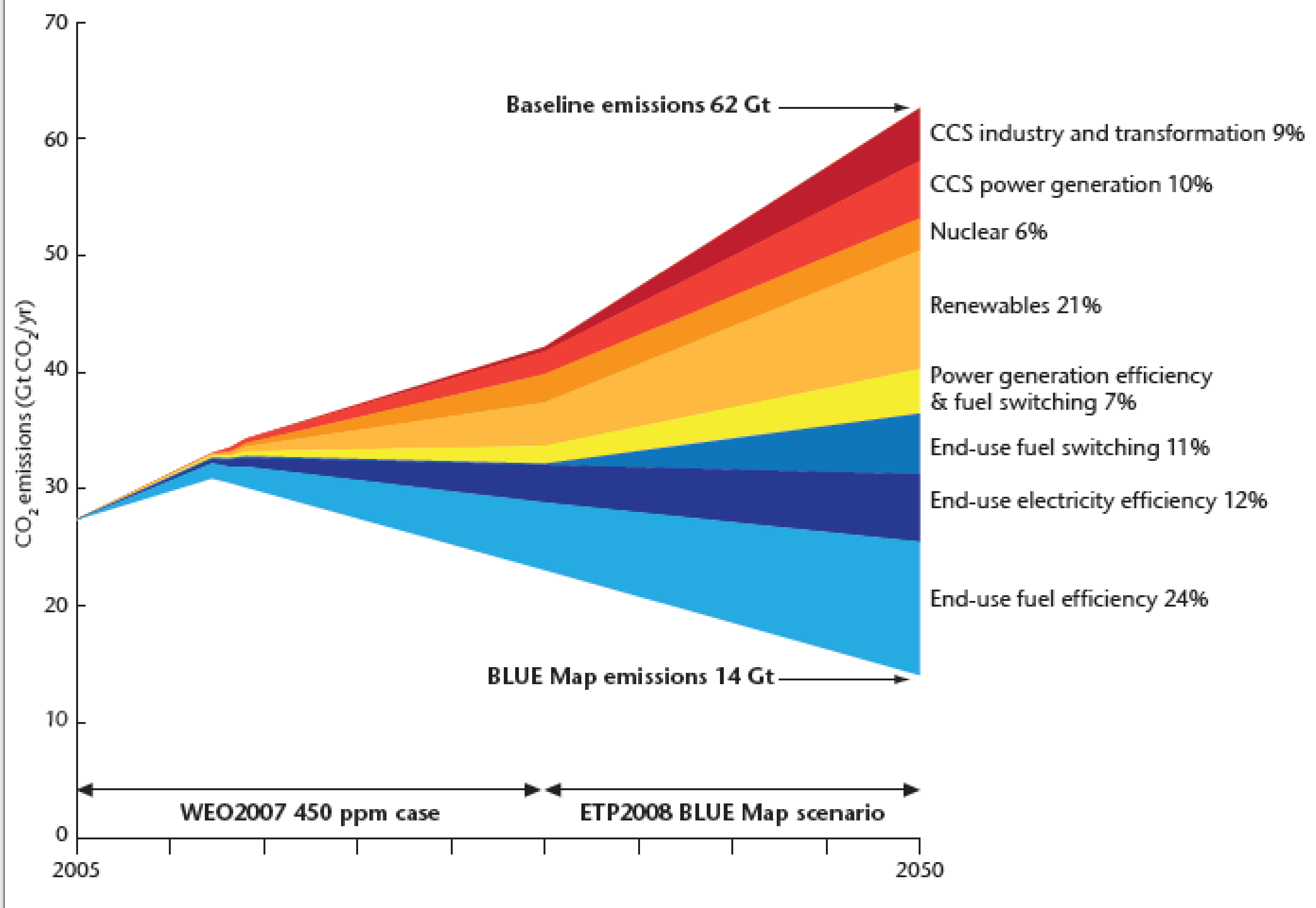
World abatement of energy-related CO_2 emissions in the 450 ppm Scenario

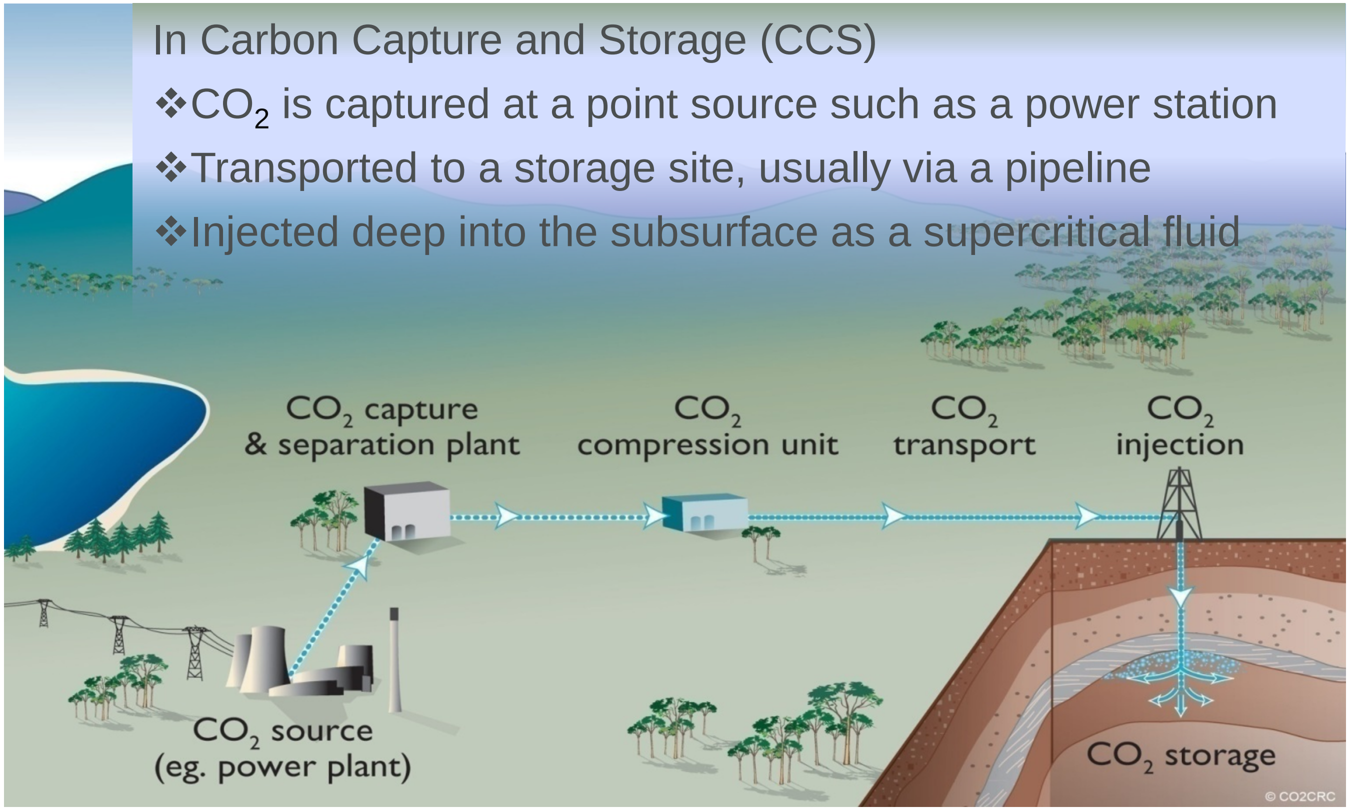


Source: IEA, *Energy Technology Perspectives* (2008a).

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



- But there is a cost…energy/electricity prices could increase by up to 25% by using Fossil Fuels + CCS – no free lunch!
- However electricity prices will rise anyway as we switch to unsubsidised renewal energy sources – the days of cheap energy are over

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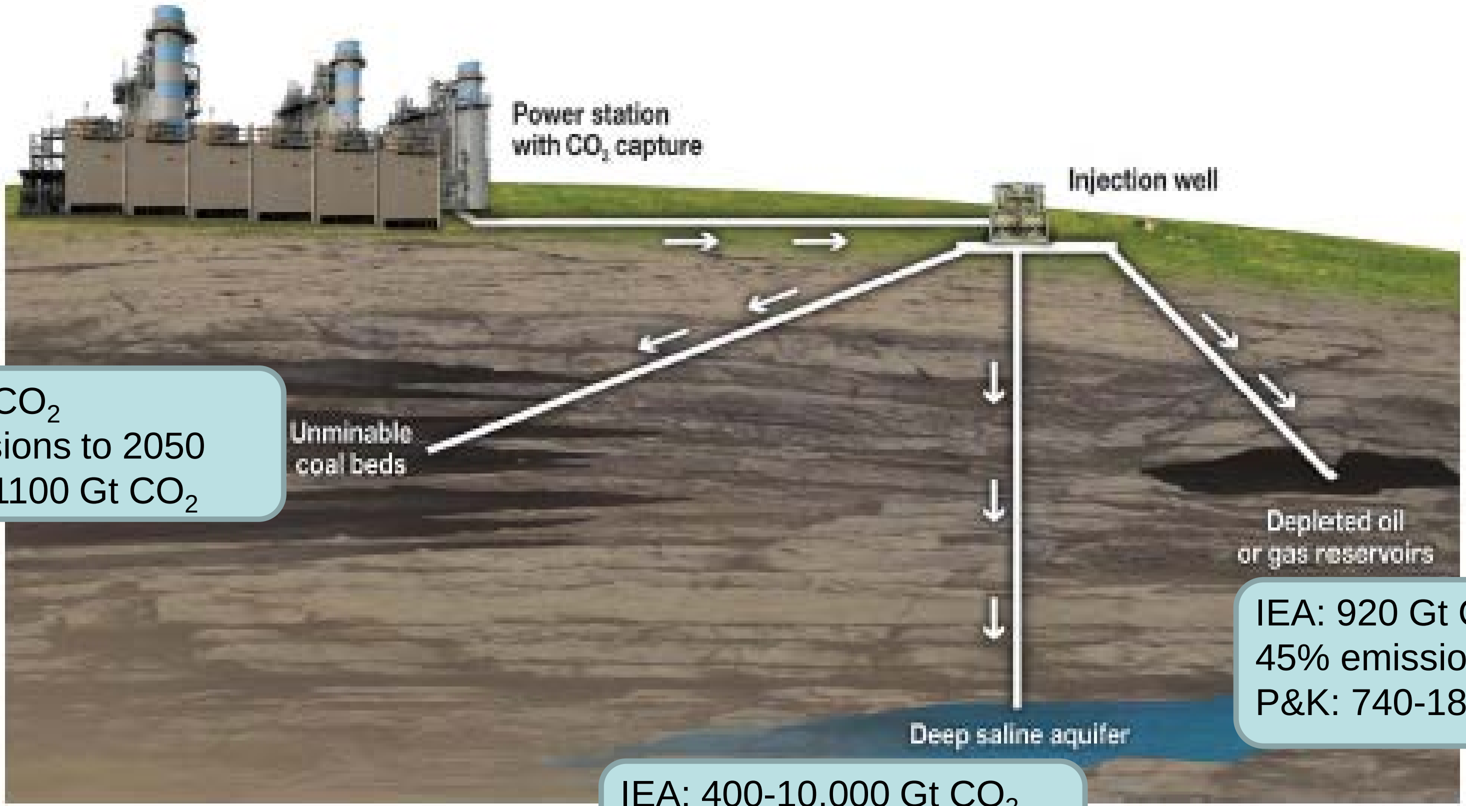
Carbon Capture and Storage – the main options



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

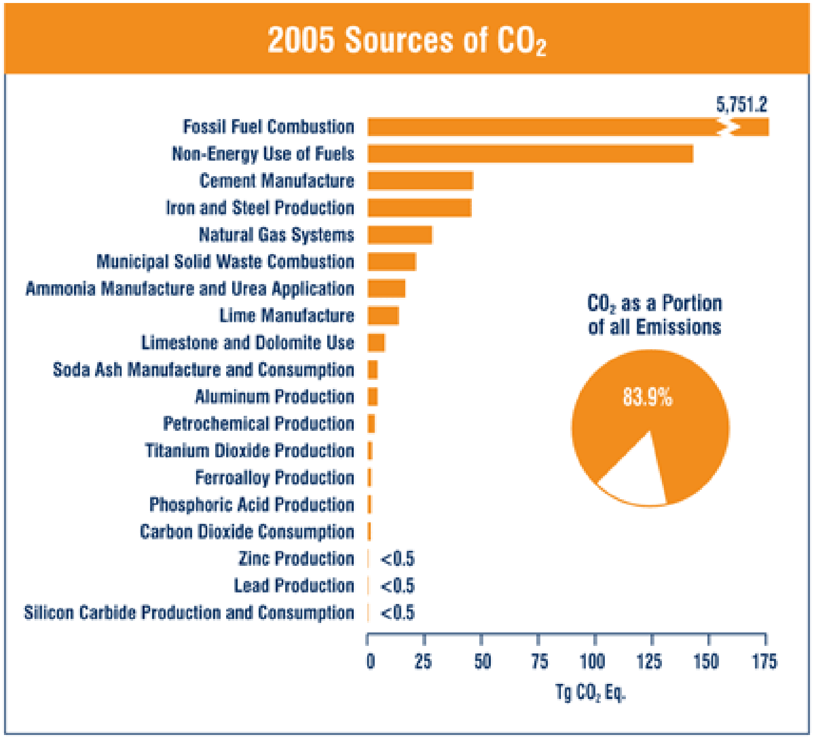
IEA: 400-10,000 Gt CO_2
20-500% emissions to 2050
P&K: 370-3700 Gt CO_2

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

Not forgetting…fossil fuels (and CO_2 emissions) as a key part of manufacturing

- Fuel for energy intensive industries e.g.
  - cement manufacturing
  - iron and steel
  - ammonia and urea



CCS is the only way to decarbonise large-scale manufacturing

- Feedstock for chemicals, plastics and other materials which dominate the world we live in
  - Long-term switch to renewable biofeedstocks?
  - A major challenge for chemical engineers

How do we achieve this low carbon fossil fuels future?

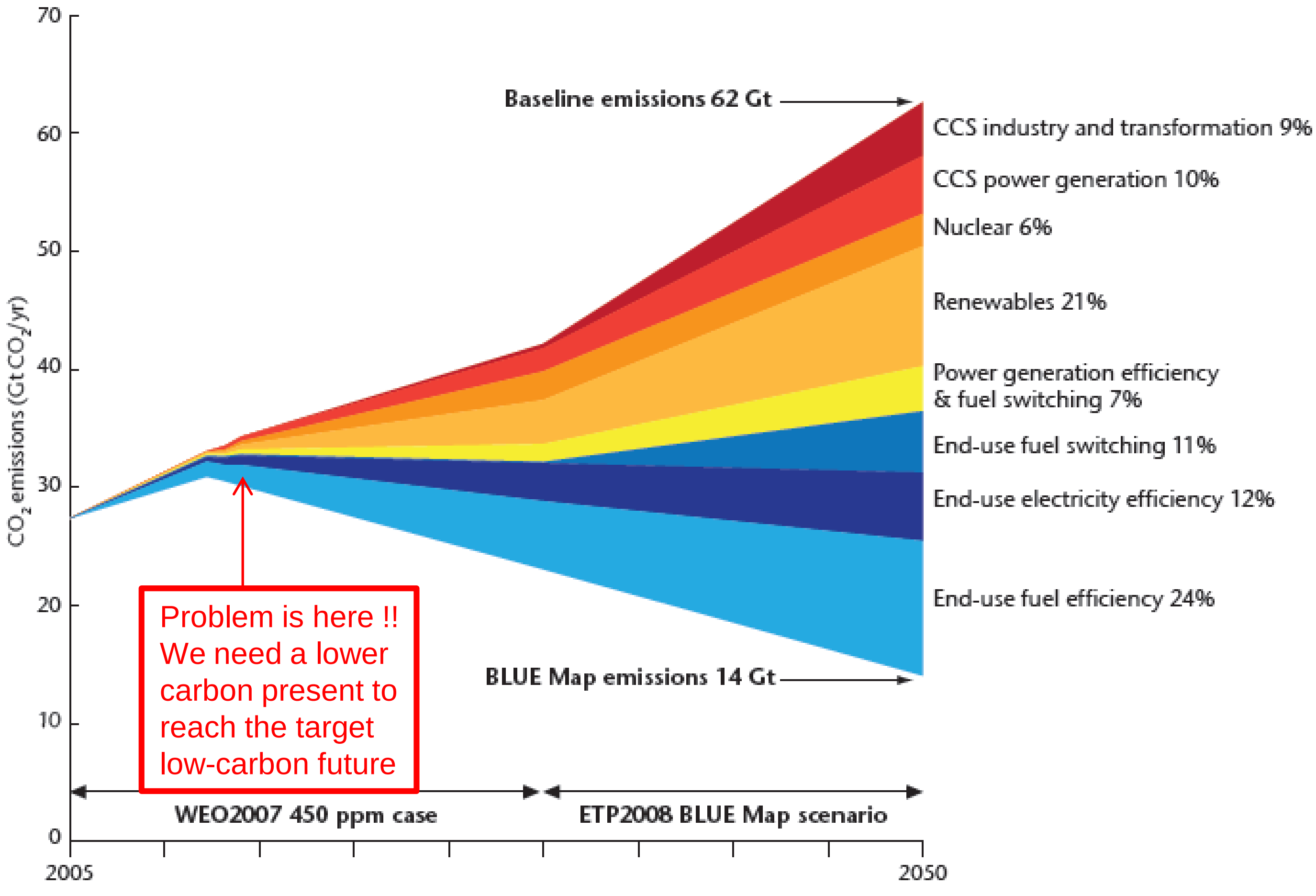
- Use less energy
  - Energy Efficiency

- Use more gas
  - A Future 'Gas Economy'

- Capture as much CO_2 as possible
- Increase nuclear
  - Not a rapid solution

- Fossil fuels → renewables asap
  - but >50 years…very country specific – natural resources + policies
- Meanwhile
  - Deplete as slowly as possible
  - Feedstocks: Naptha → Gas → Renewables
  - Exploit unconventionals as necessary…shale gas, tar sands, gas hydrates…

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

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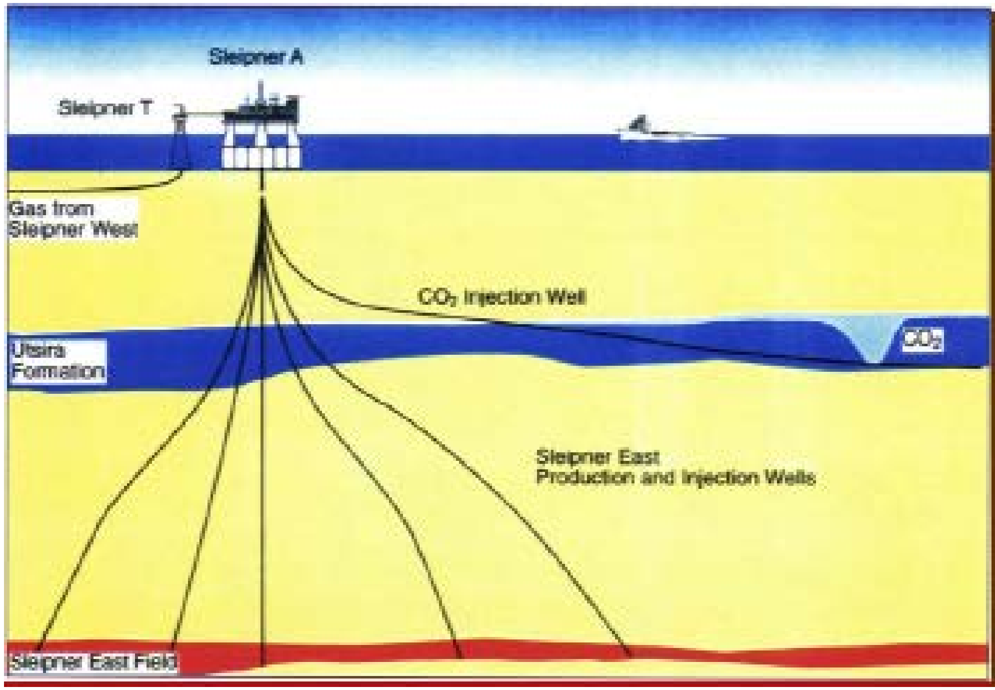
Sleipner CO_2 Injection Project

- 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

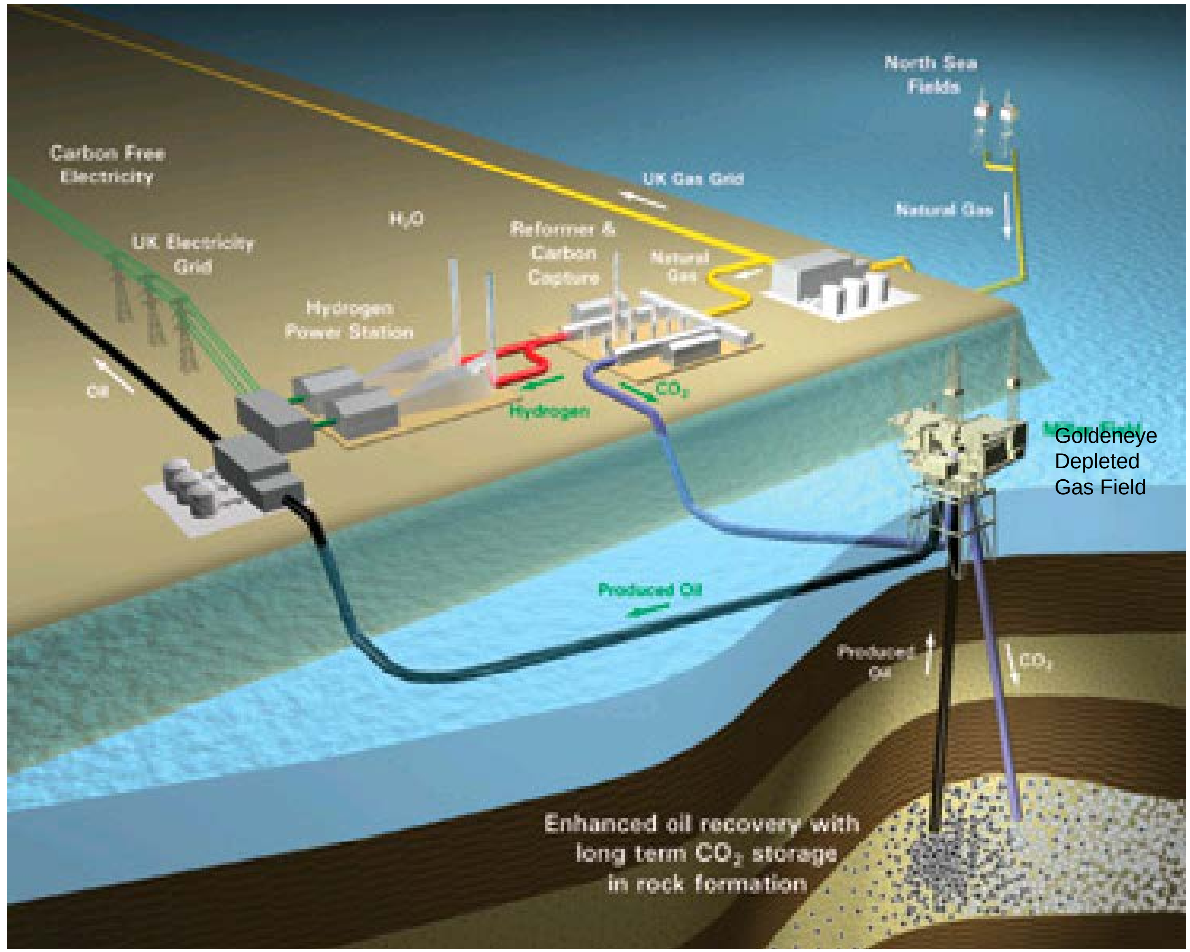
- (World's 1st) Commercial CCS Project
- Coal-fired, post-combustion capture
- Estevan, Saskatchewan, Canada
- 110 MW power
- 1Mt CO_2 stored pa
- Equivalent to removing ~ 250,000 cars
- CO_2 used for EOR in nearby depleted oil reservoirs
- Remainder stored in 3.4km deep Deadwood saline aquifer – Aquistore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

UKCCS Commercialisation Competition: Shell, SSE Peterhead Project

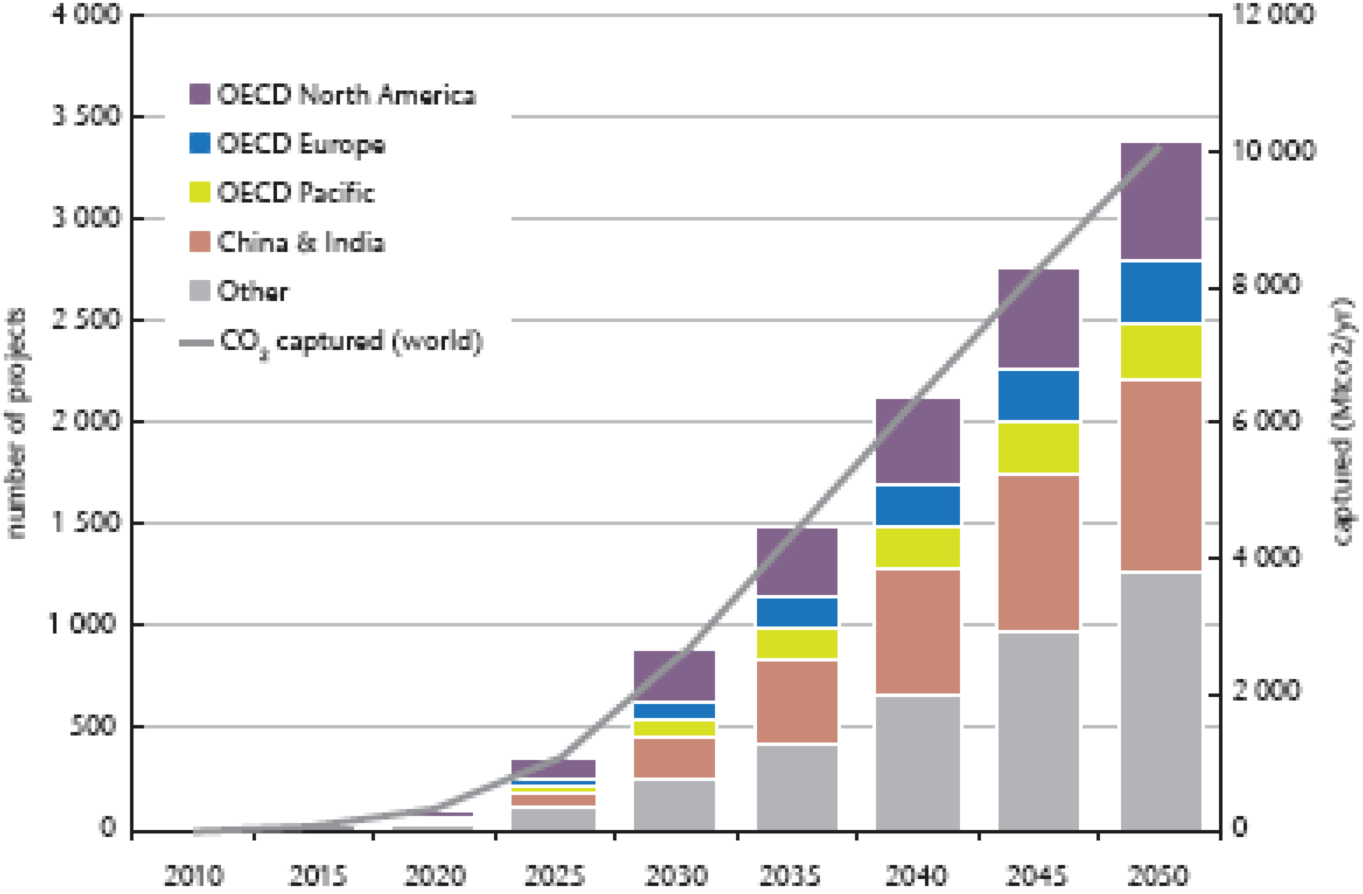
Also White Rose Project
- Alstom
- Drax Power
- BOC
- National Grid

• Coal-fired power station

• Storage in saline aquifer in southern North Sea



Global deployment of CCS...?



IEA, Technology Roadmap, CCS, 2010

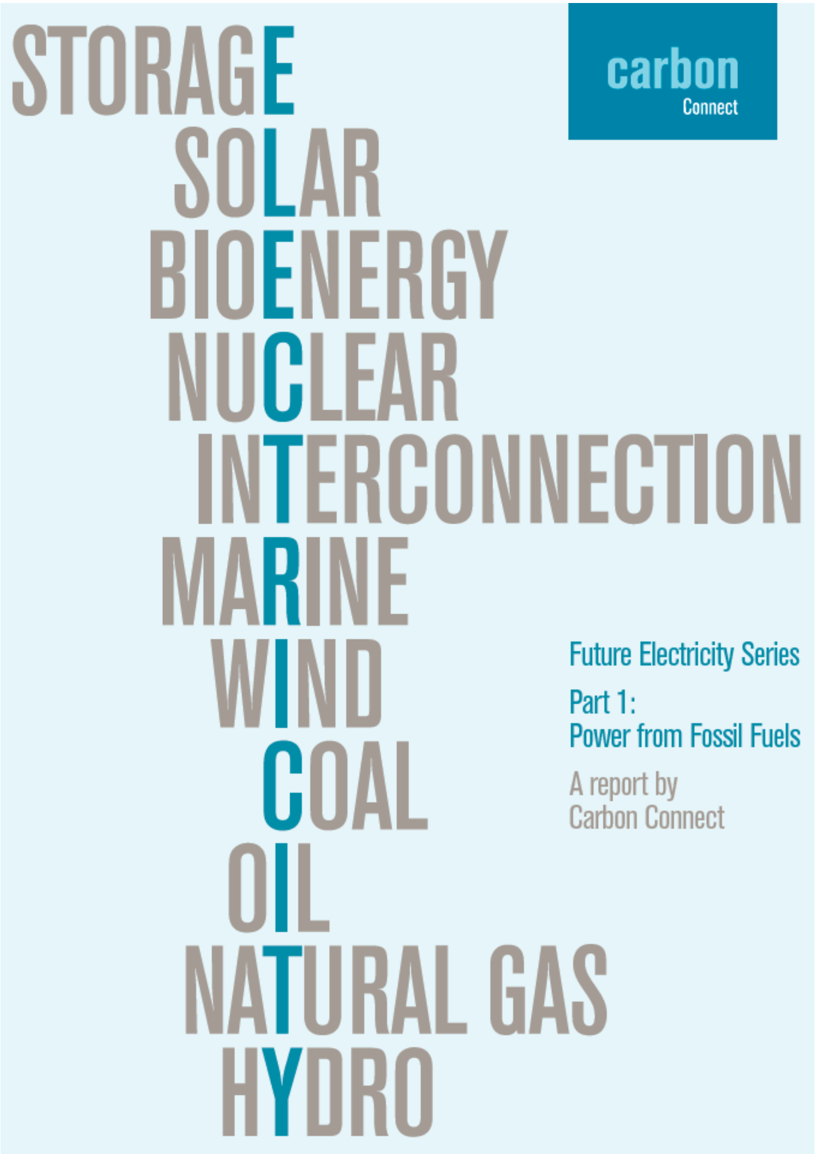
A lot of progress has to be made very quickly… av. 100 projects per year after 2020

The costs of not implementing CCS

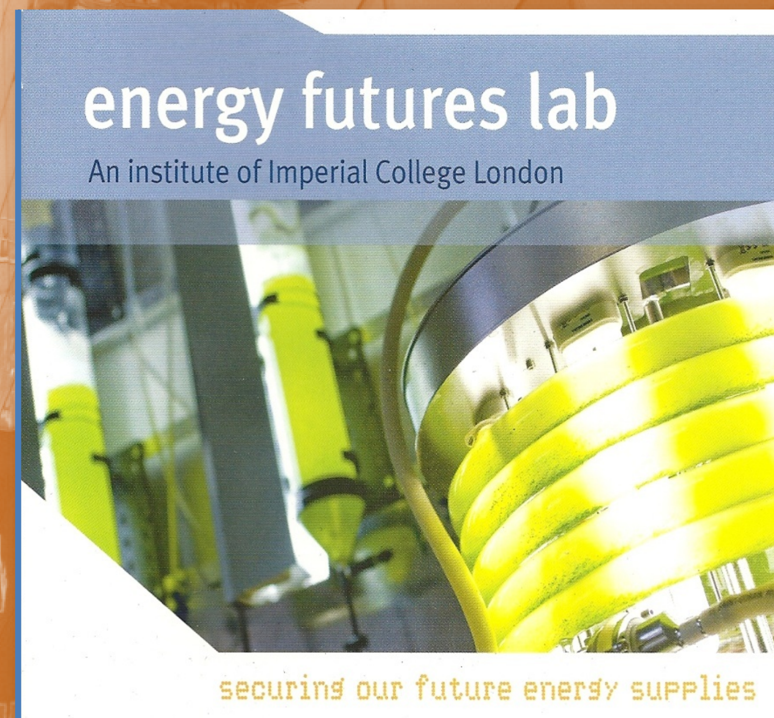
Costs of not deploying CCS in UK, quickly enough:
£30-40bn pa by 2050

- 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



Back to the future



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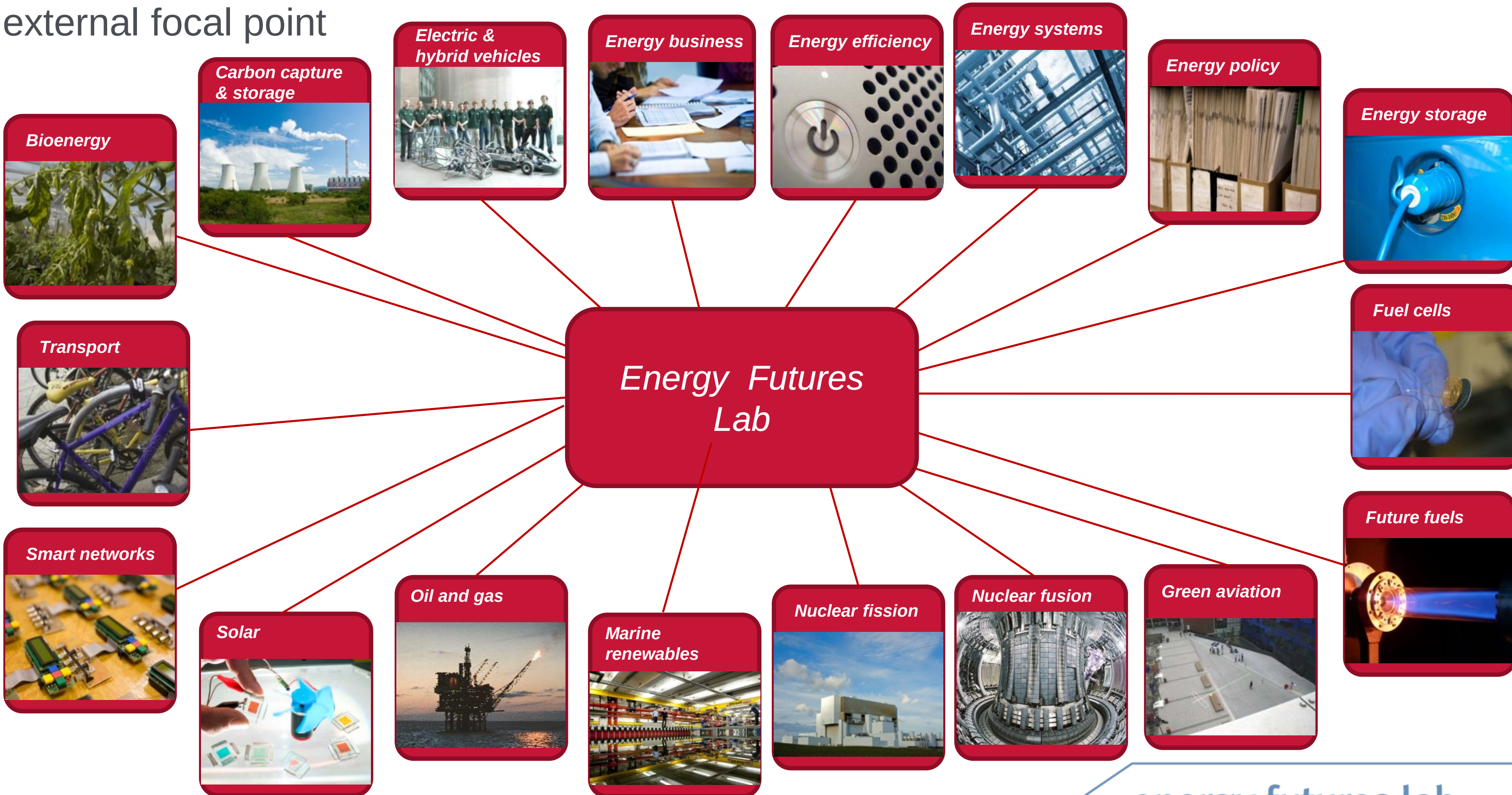
Energy Futures Lab - Research Networks

18 research networks to enable internal cross-departmental communication and provide external focal point



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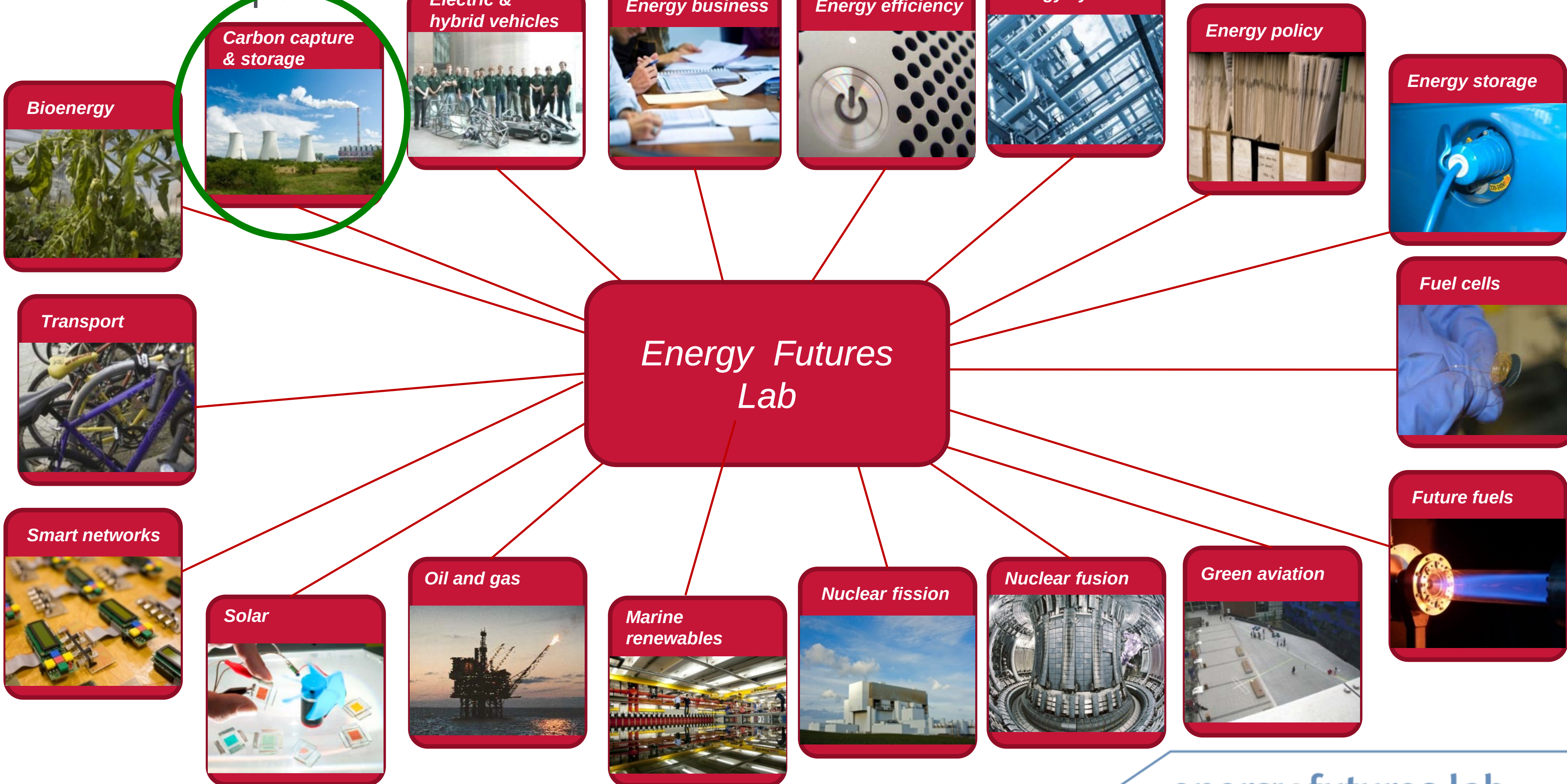
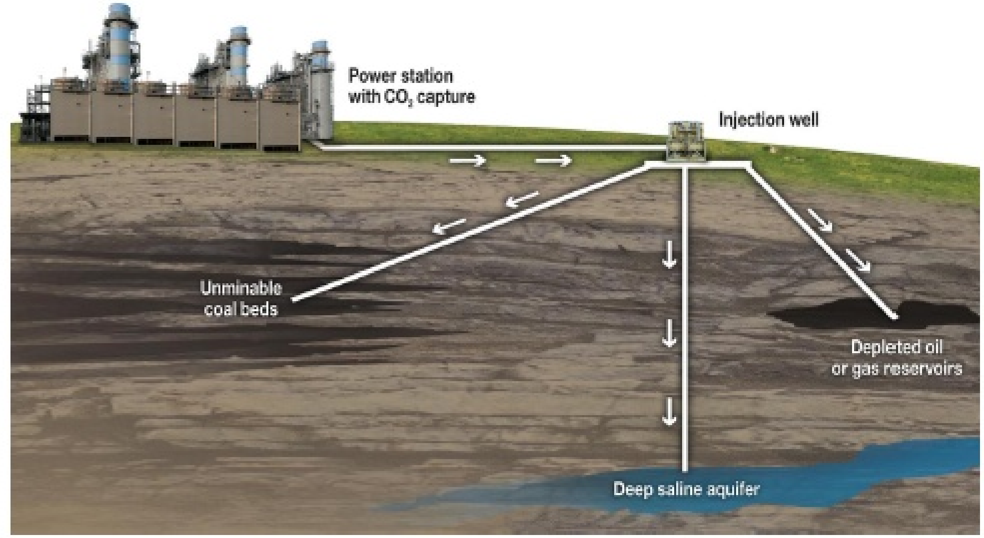


A Vision for Clean Fossil Fuels

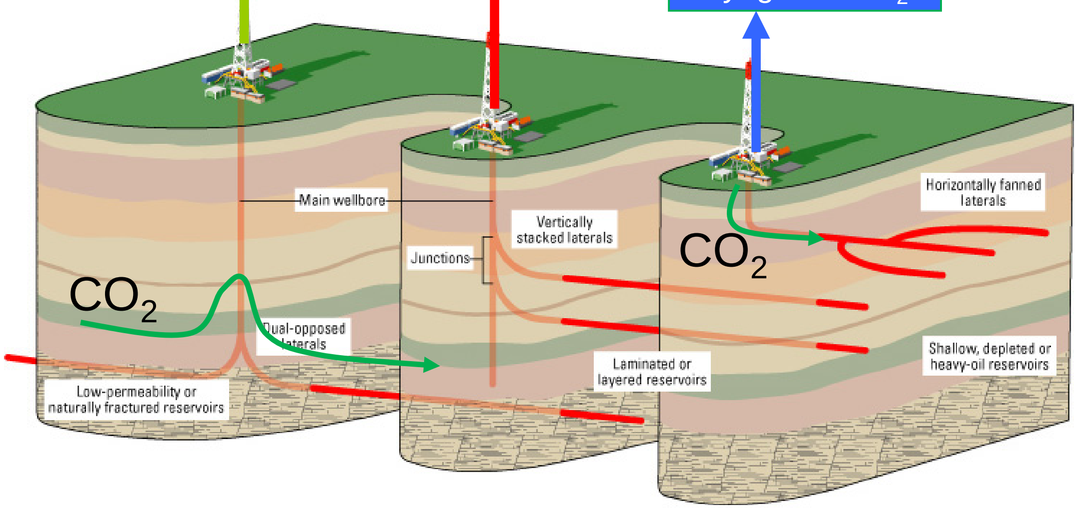
Short Term : CCS



Low C Fuel - H_2, CH_4, MeOH…

Electricity Heat

Chemicals, Feedstocks, Syngas CO/H_2



Long Term: Sub-surface processing + in situ CCS

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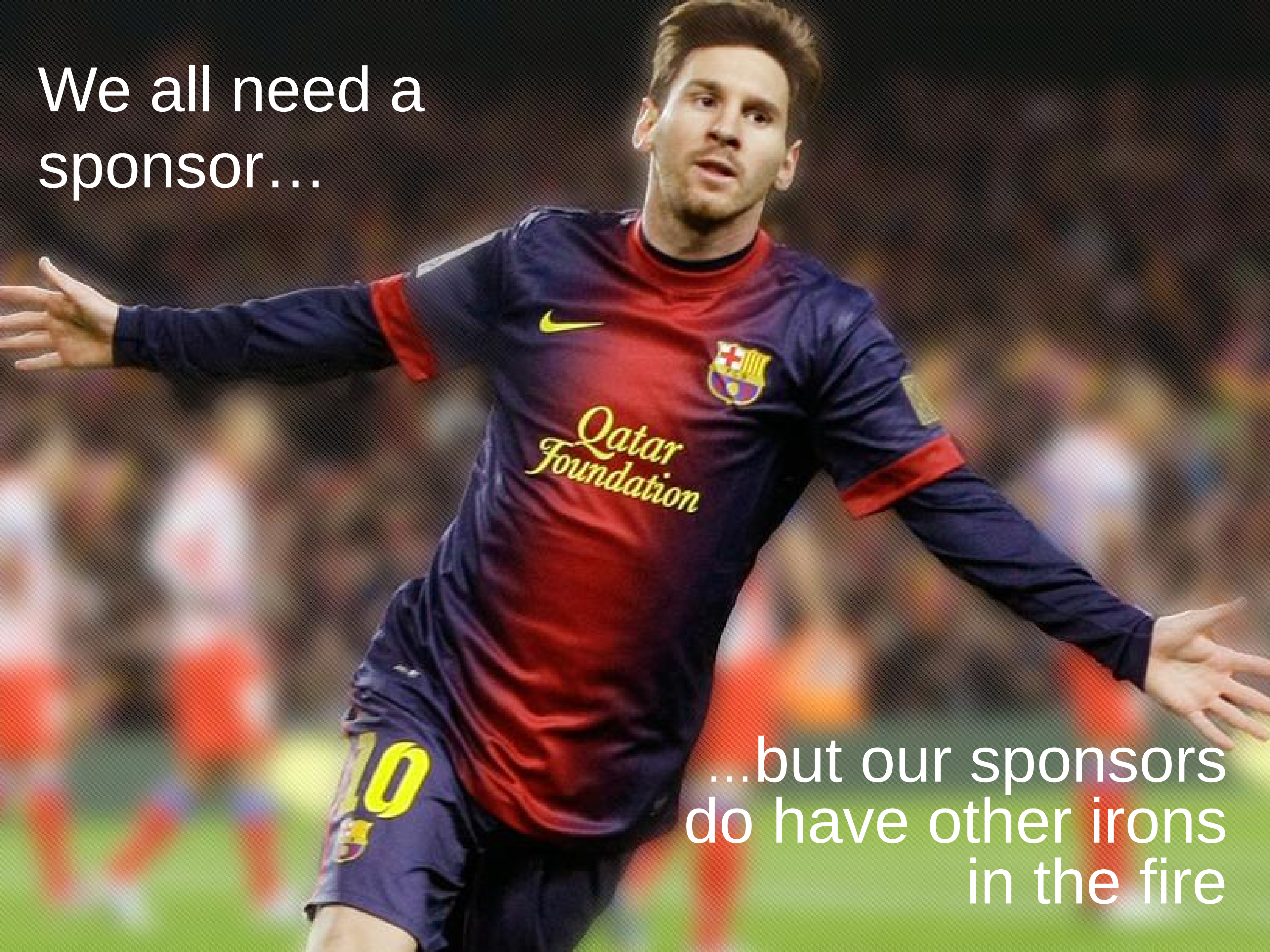
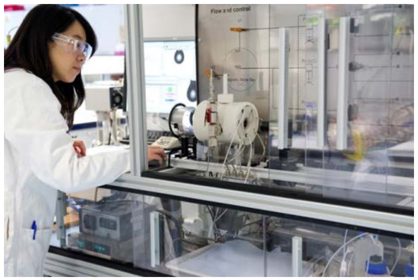

We all need a sponsor…
Qatar Foundation
…but our sponsors do have other irons in the fire

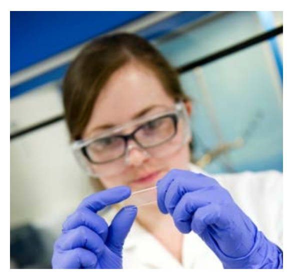
Qatar Carbonates and Carbon Storage Research Centre

A 10 year, \$70m programme
“Putting CO_2 in its place”




- 17 Academic Staff
- 3 QCCSRC Lecturers
- 10 Postdoctoral Researchers
- 34 PhD Students
- 5 Technical Support Staff



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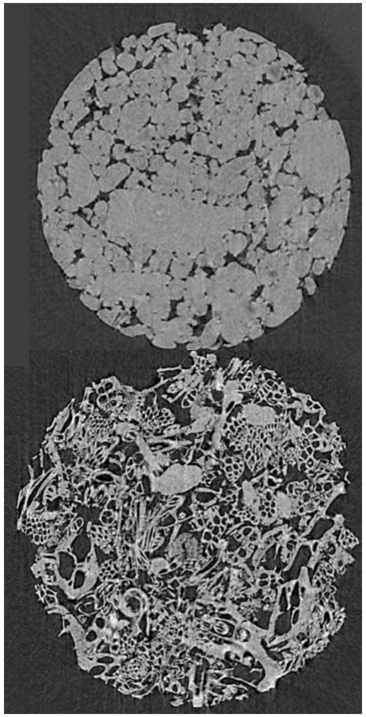
قطر للبترول
Qatar Petroleum

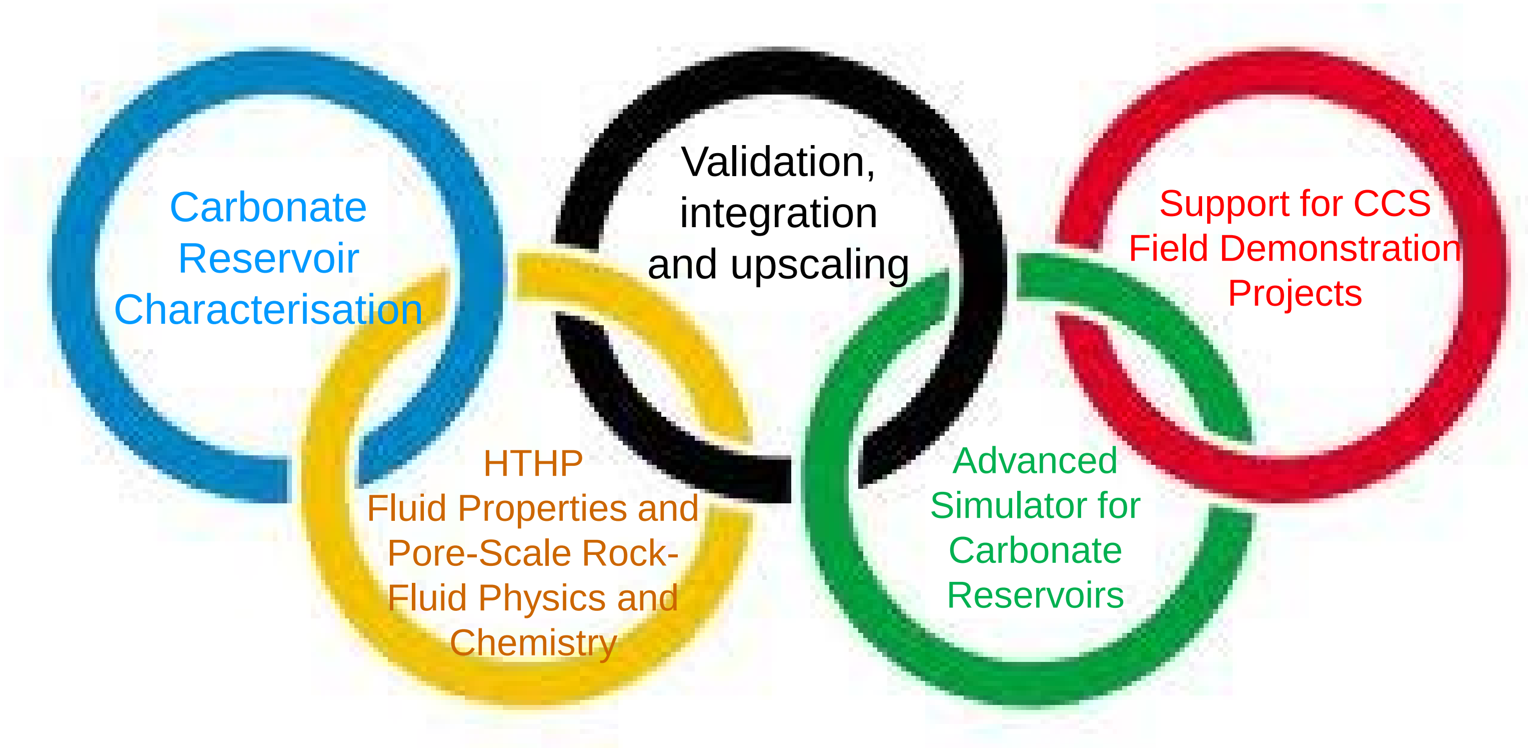
QATAR SCIENCE & TECHNOLOGY PARK

What's different about Carbonate Reservoirs?

- Structure
  - Broader pore size distribution
  - Natural fractures
- Chemical reaction
  - Reactive flow changes pore space
  - Dissolution-Precipitation



The five projects of QCCSRC



Qatar Carbonates and Carbon Storage Research Centre

Fluid Properties at HTHP Reservoir Conditions

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

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Qatar Petroleum

QATAR SCIENCE & TECHNOLOGY PARK

HTHP Thermophysical Properties are key...

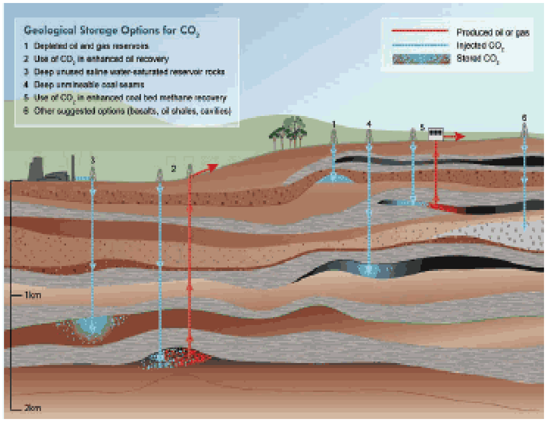
- Enhanced (Heavy) Oil Recovery using supercritical CO_2 (scEOR), and
- CO_2 Capture and Storage (CCS)

both require

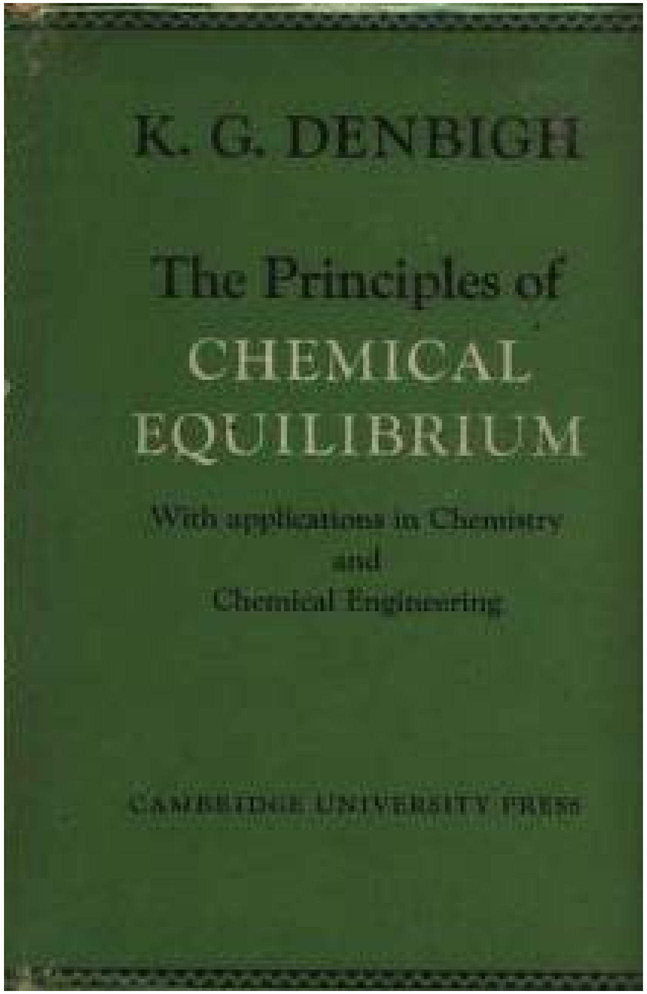
- Phase behaviour
- Interfacial tension
- Viscosity/Density

of CO_2/hydrocarbon/brine systems

at capture or reservoir storage HTHP conditions



Thermodynamics Demystified!



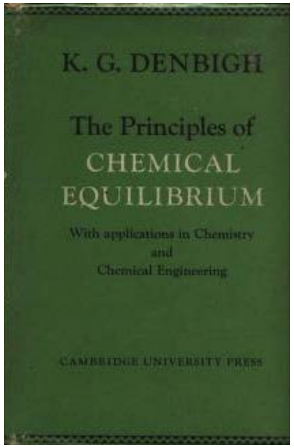
Kenneth Denbigh

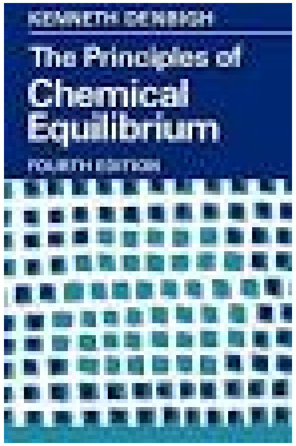
- 1955-1960 Head of Department of Chemical Engineering, Edinburgh University and Heriot Watt College

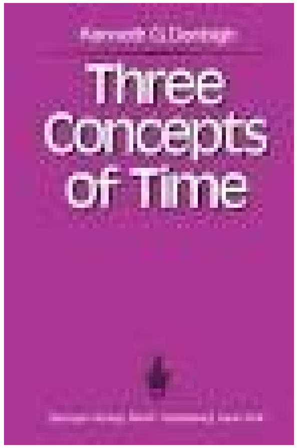
- 1960-66 Courtaulds Professor of Chemical Engineering, Imperial College London
- 1966-77 Principal, Queen Elizabeth College London

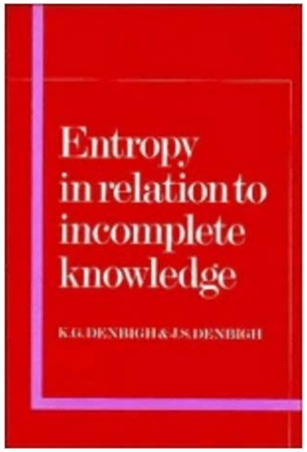
Kenneth Denbigh

- Prolific Author









- Director, Council for Science and Society 1977-83
- ‘Chemical Engineer and Philosopher of Science’
- “Few scientists or engineers tackle as wide a range of intellectually challenging problems as Denbigh did. His books are clear, well argued and a delight to read. They are a lasting legacy of a man who thought deeply about some of the hardest problems of our time and who showed always kindness and courtesy in his discussion of them with his colleagues.” Obituary Independent February 2004

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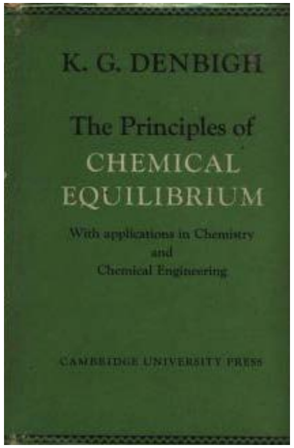

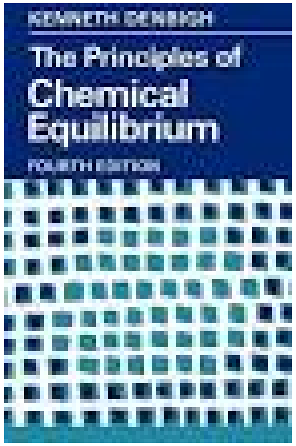

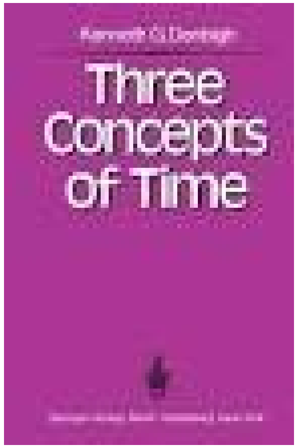

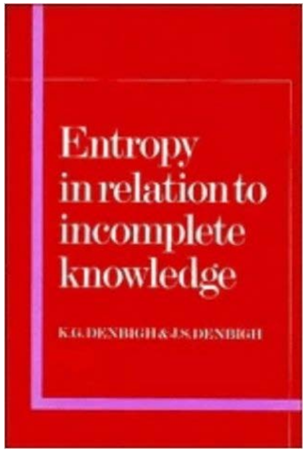

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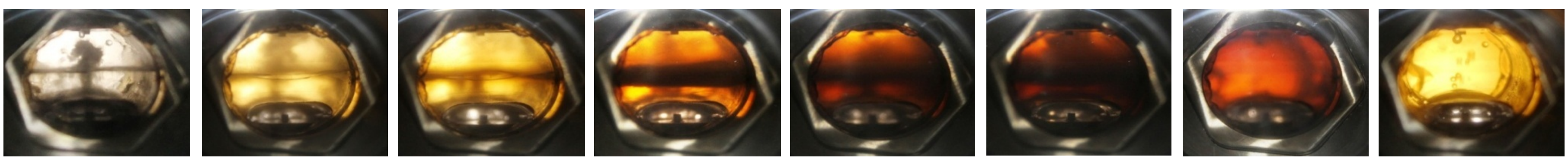
Phase Behaviour of CO_2 + Hydrocarbons

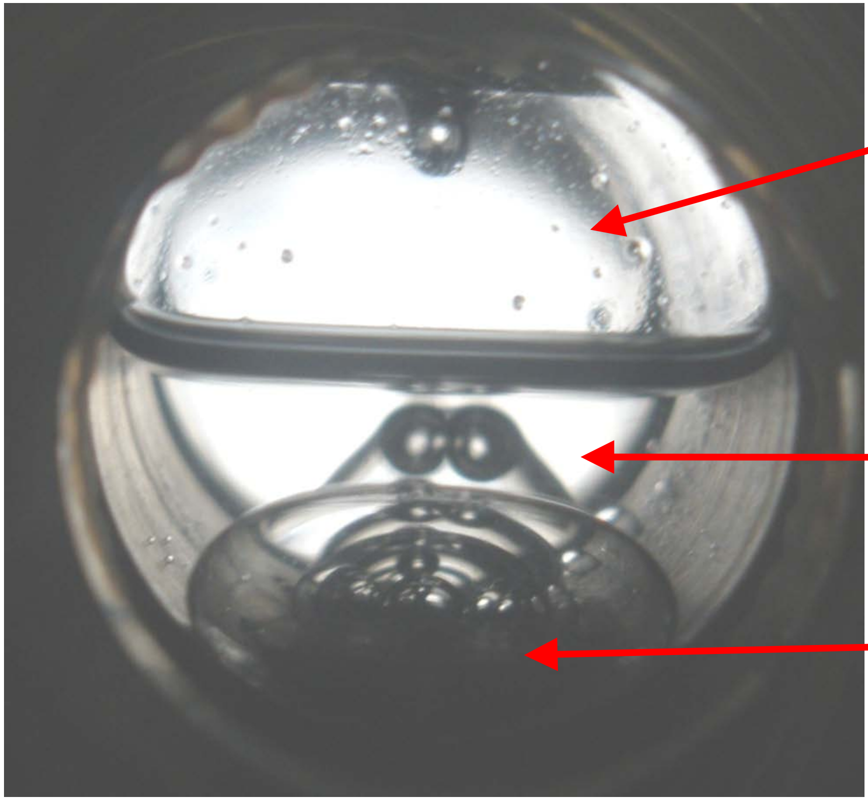
Dr Saif Al Ghafri
PhD Student
Now Research Fellow

Dr Esther Forte
former PhD Student, now
Universität Kaiserslautern

Dr Shuxin Hou
Postdoc, now with
Statoil



Complex Phase Behaviour of CO_2-hydrocarbons-water/brines



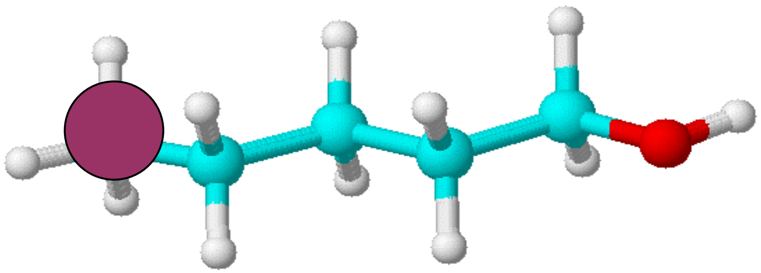
CO_2-rich gas phase

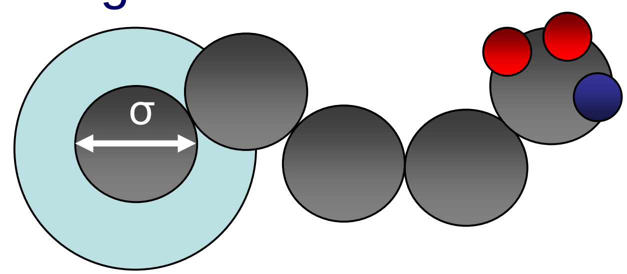
Hydrocarbon -rich liquid phase

Water-rich liquid phase

SAFT-VR Equation of State

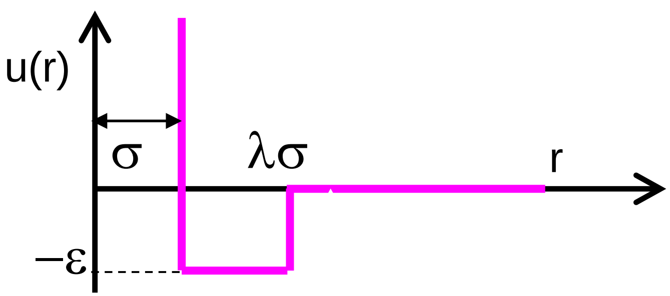
Molecules described by tangent spherical segments





m spherical segments

Interaction between segments = Square-Well potential



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

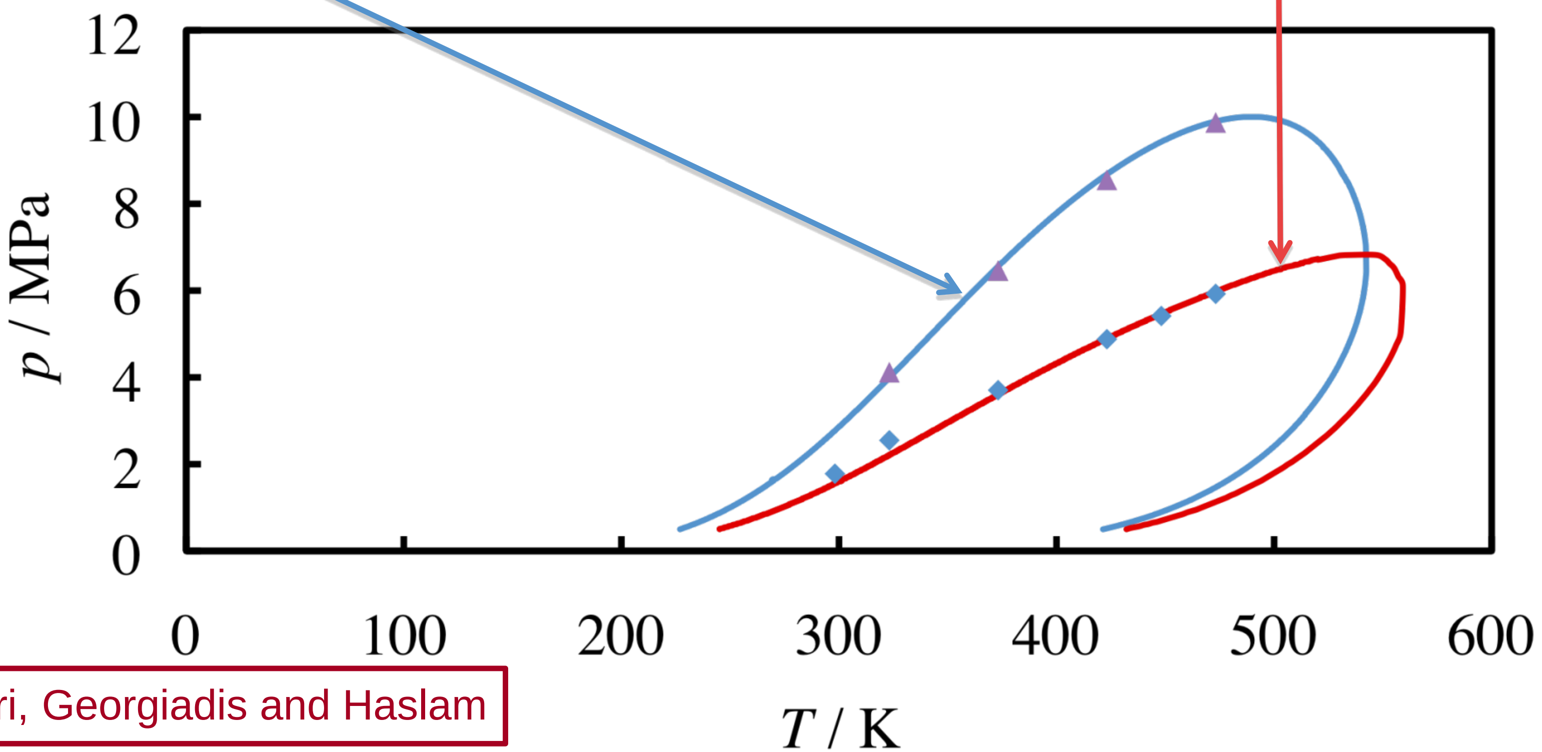
Each component is described by 4 parameters: m, σ, ε, λ

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

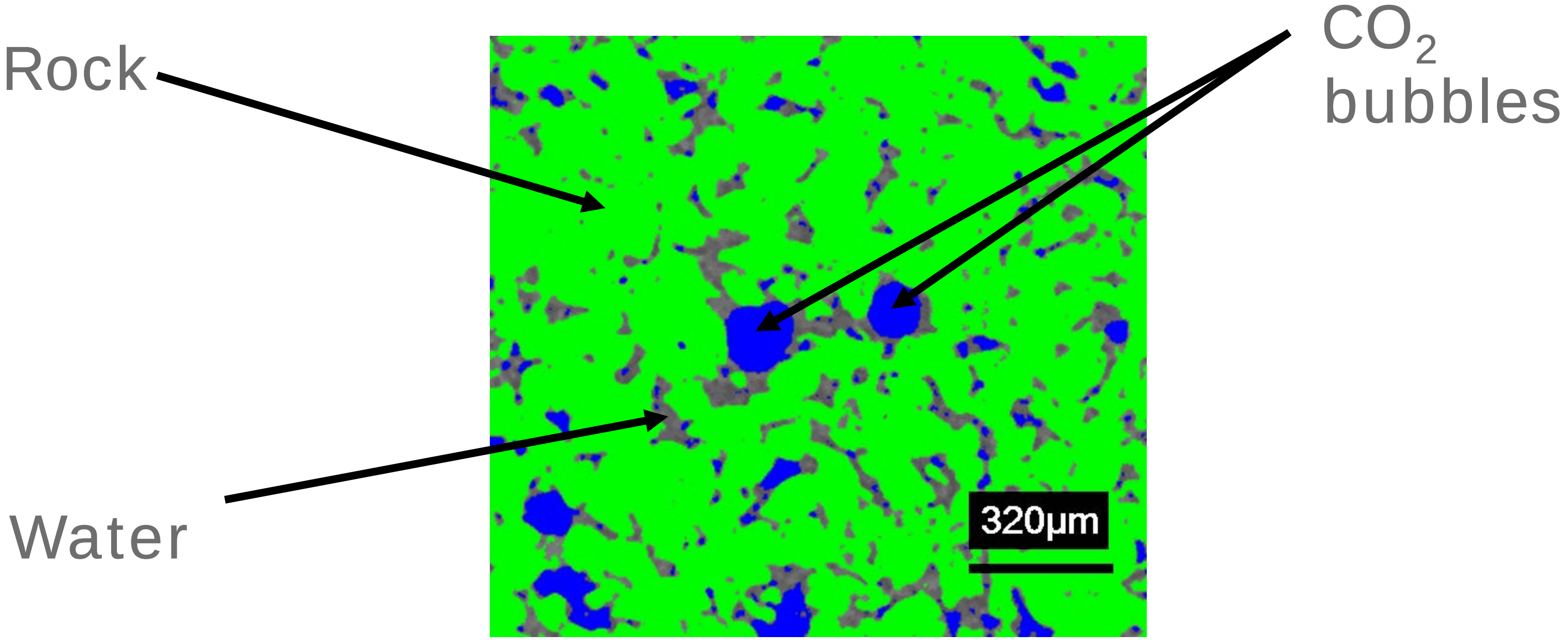


Al Ghafri, Georgiadis and Haslam

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

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

HPHT Interfacial Tension of CO_2-Hydrocarbon-Brine Systems

Dr Apostolos Giorgiadis
PhD 2011

Dr Xuesong Li
PhD 2013

Interfacial Tension: n-decane-CO_2

Experiments compared with SAFT-DFT

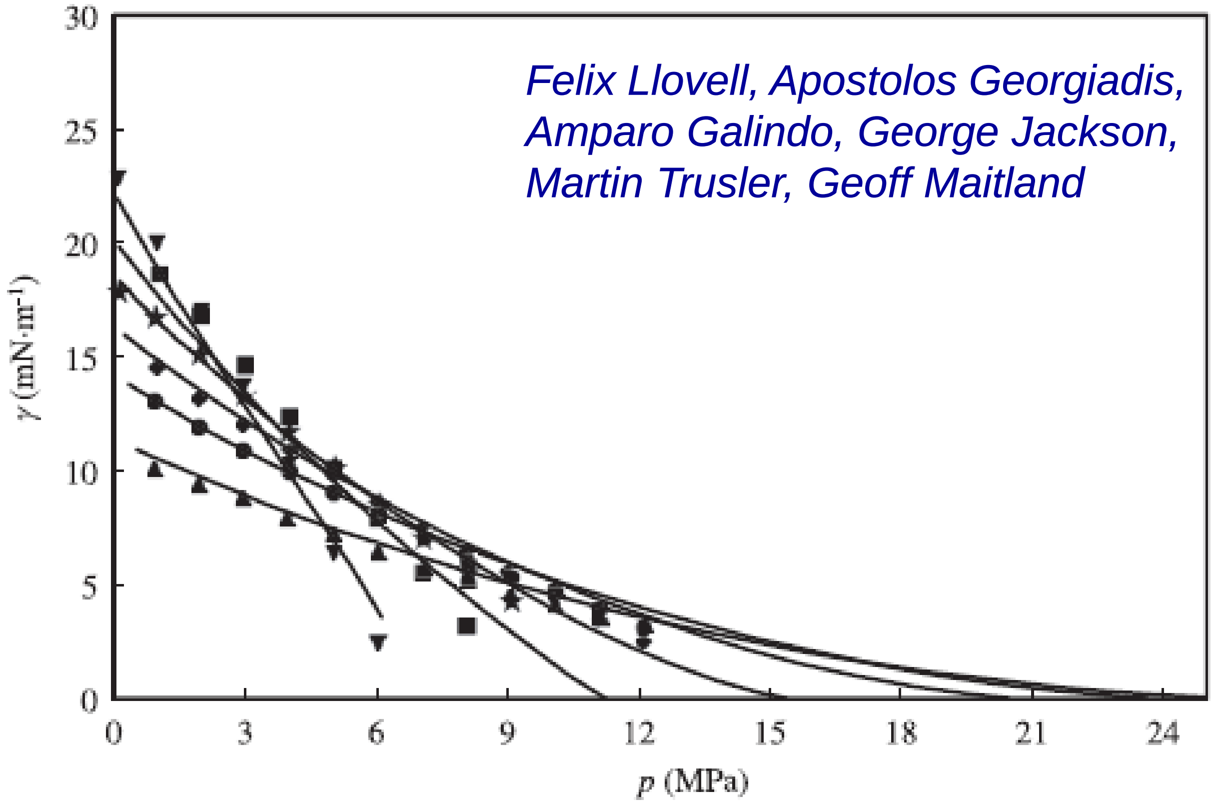


Fig. 3. Interfacial tension modelling and measurements of the (n-decane + CO_2) system as a function of pressure for different isotherms: (▼) at 298.0 K; (■) at 323.4 K; (★) at 343.6 K; (♦) at 373.5 K; (•) at 403.1 K; (▲) at 443.1 K. Continuous curves (–) correspond to the SAFT-VR-DFT predictions (cf.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

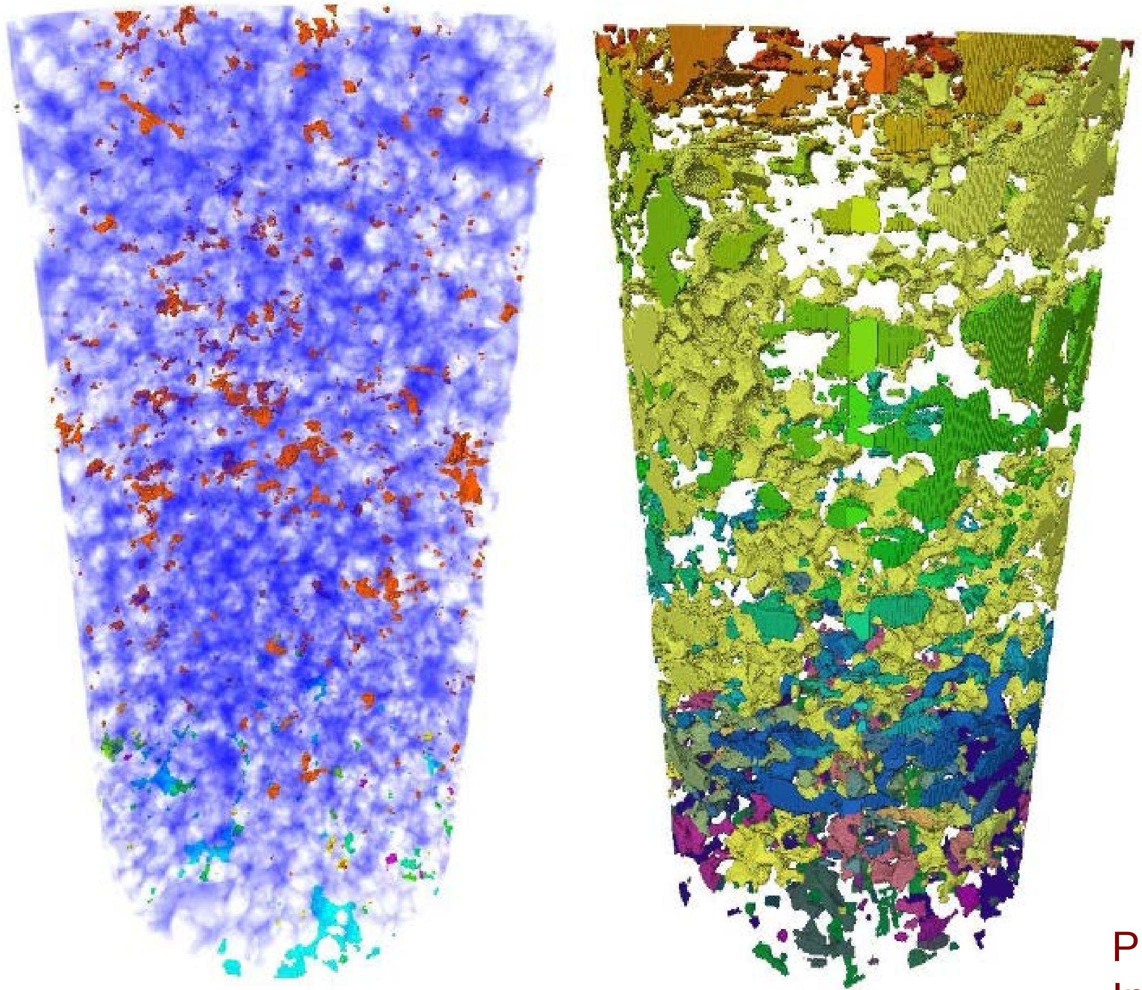
Imaging fluid flow in porous and fractured (carbonate) rocks

Revolution in core analysis

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


HD-350E

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.

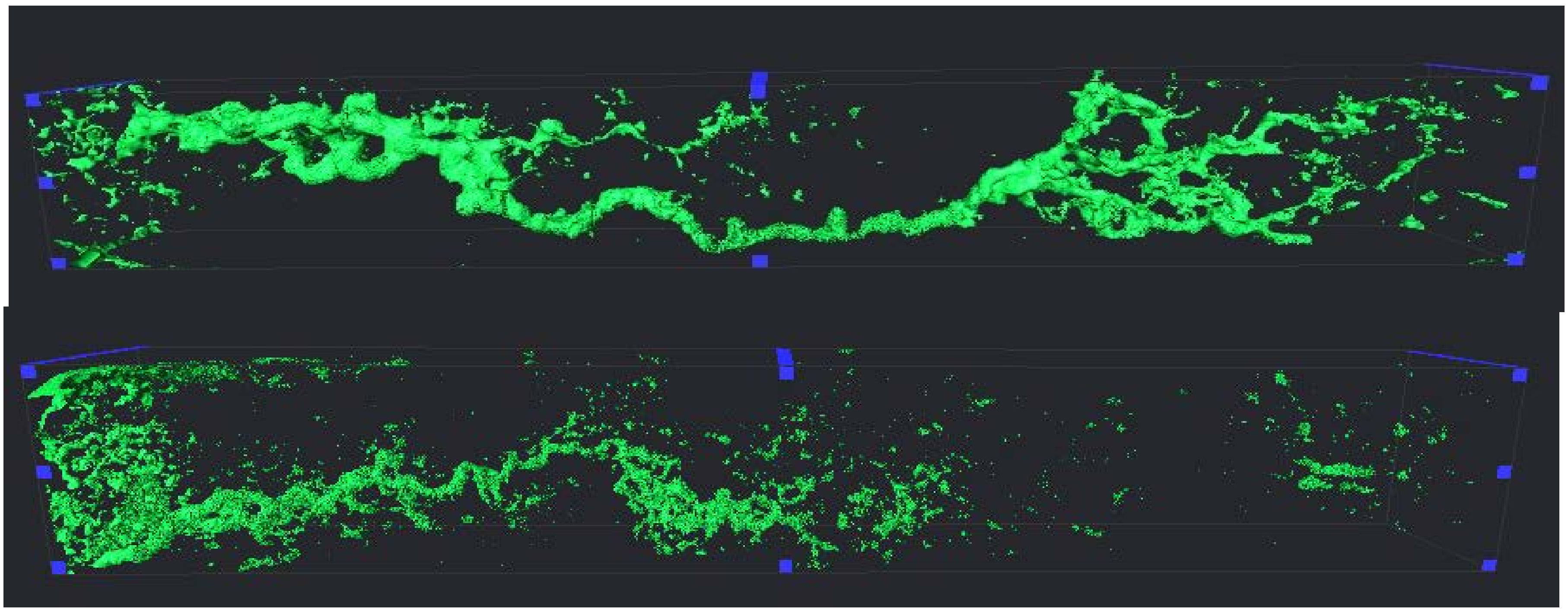
Core has diameter 6.5 mm and resolution of around 6 μm.

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

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.

$Da_1 > Da_2$



Qatar Carbonates and Carbon Storage Research Centre

Pore-scale trapping and contact angle measurements in carbonate rocks

Matthew Andrew
Martin Blunt and Branko Bijeljic

Imperial College London
Qatar Petroleum
QATAR SCIENCE & TECHNOLOGY PARK

μ-CT Study of CO_2 trapping and wetting

Qatar Carbonates and Carbon Storage Research Centre

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

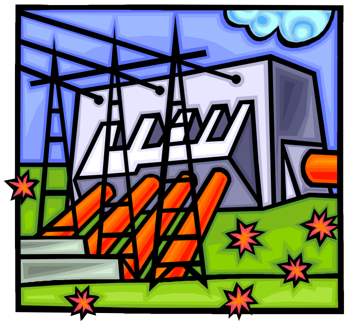
Flow in Porous Media – Professor Martin Blunt, Dr Sam Krevor, Dr Edo Boek, Dr Branko Bijeljic, Dr John Crawshaw

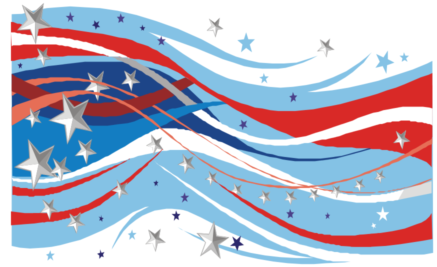
Reservoir Modelling – Professors Matt Jackson, Peter King, Martin Blunt

The Energy Landscape

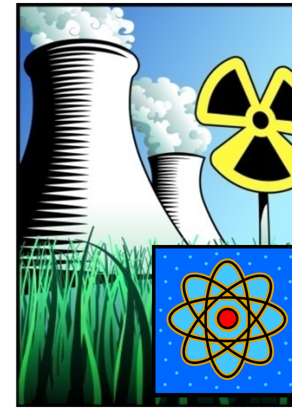
Current world consumption 15 TW

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

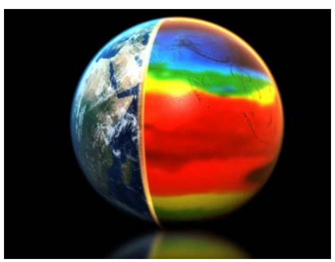




Tidal/Wave/Ocean Currents: 2 TW gross

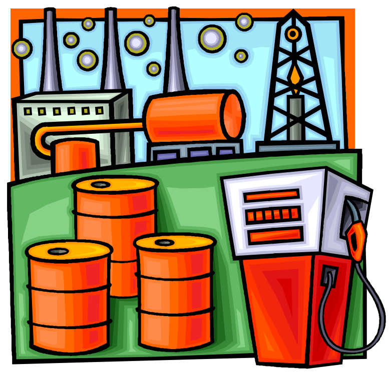


Nuclear: Current 1TW

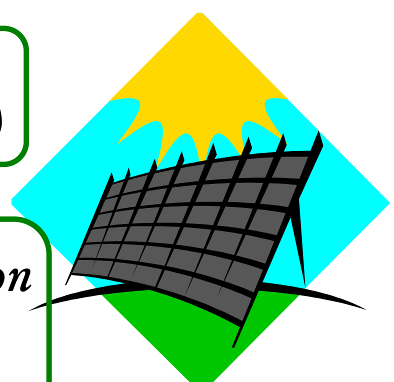


Geothermal: 9.7 TW gross (small % technically feasible)

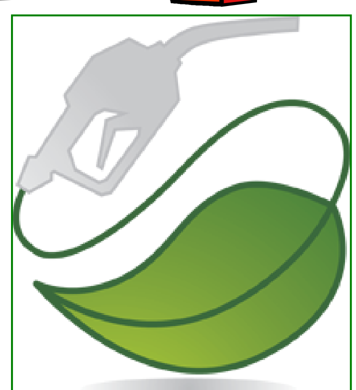
Fossil Fuels: Current 12.5 TW Potential 25 TW



Wind 2-4 TW extractable



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

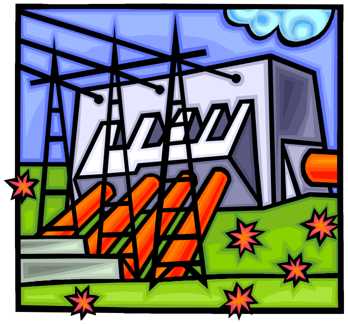


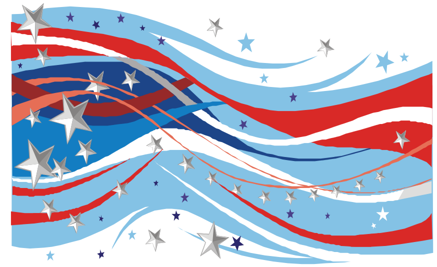
Biomass/fuels: 5-7 TW, 0.3% efficiency for non-food cultivatable land

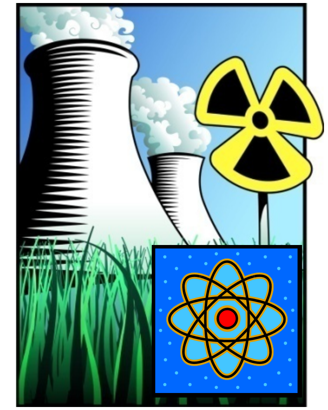
Future Energy Landscape?

2075 world consumption 35 TW

Hydroelectric: 1.5 TW



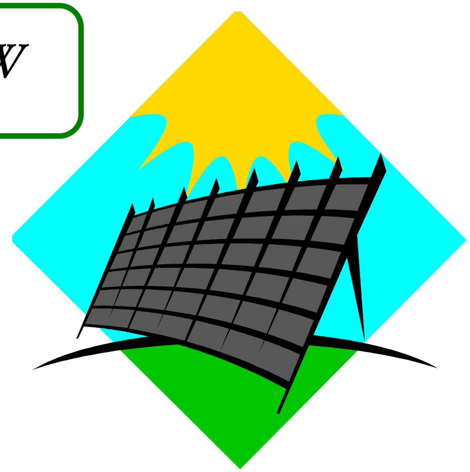


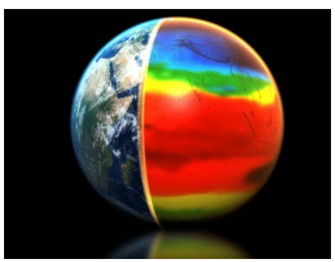


Tidal/Wave/Ocean Currents: 2 TW gross

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

How do we (Chemical) Engineer the Journey?

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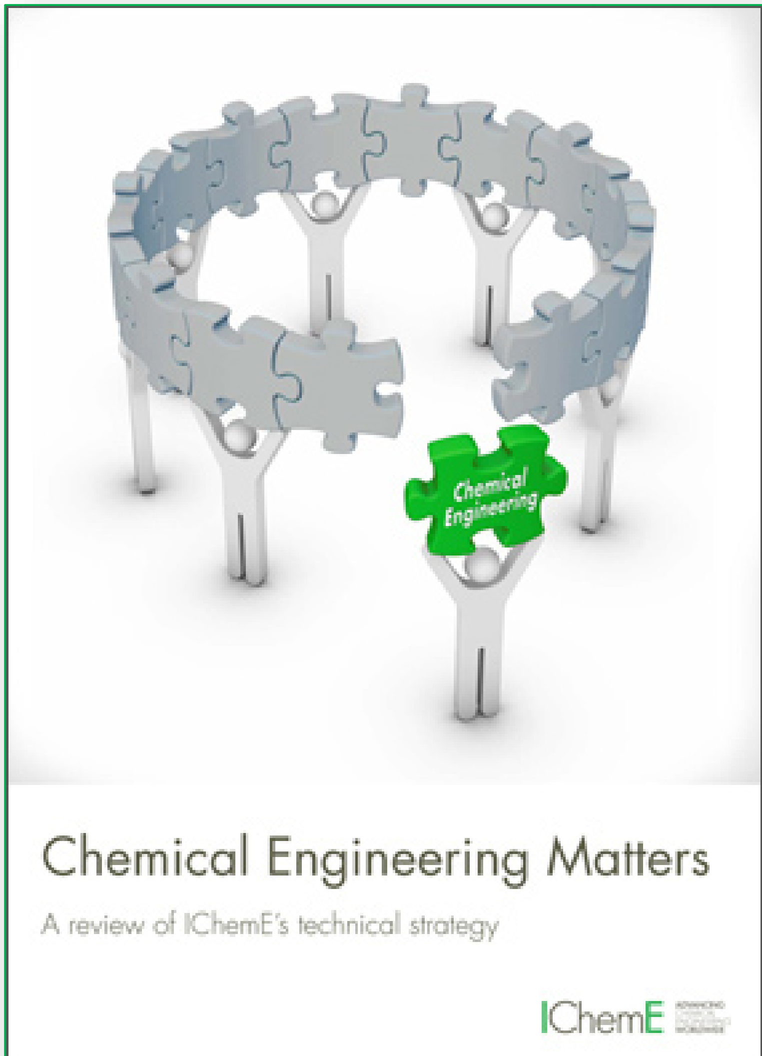
We link in to Chemical Engineering Matters



Four vistas:

- Energy
- Water
- Food & nutrition
- Health & wellbeing

Safety & risk
Sustainability
Education & training
Research

Economics, politics and public attitudes

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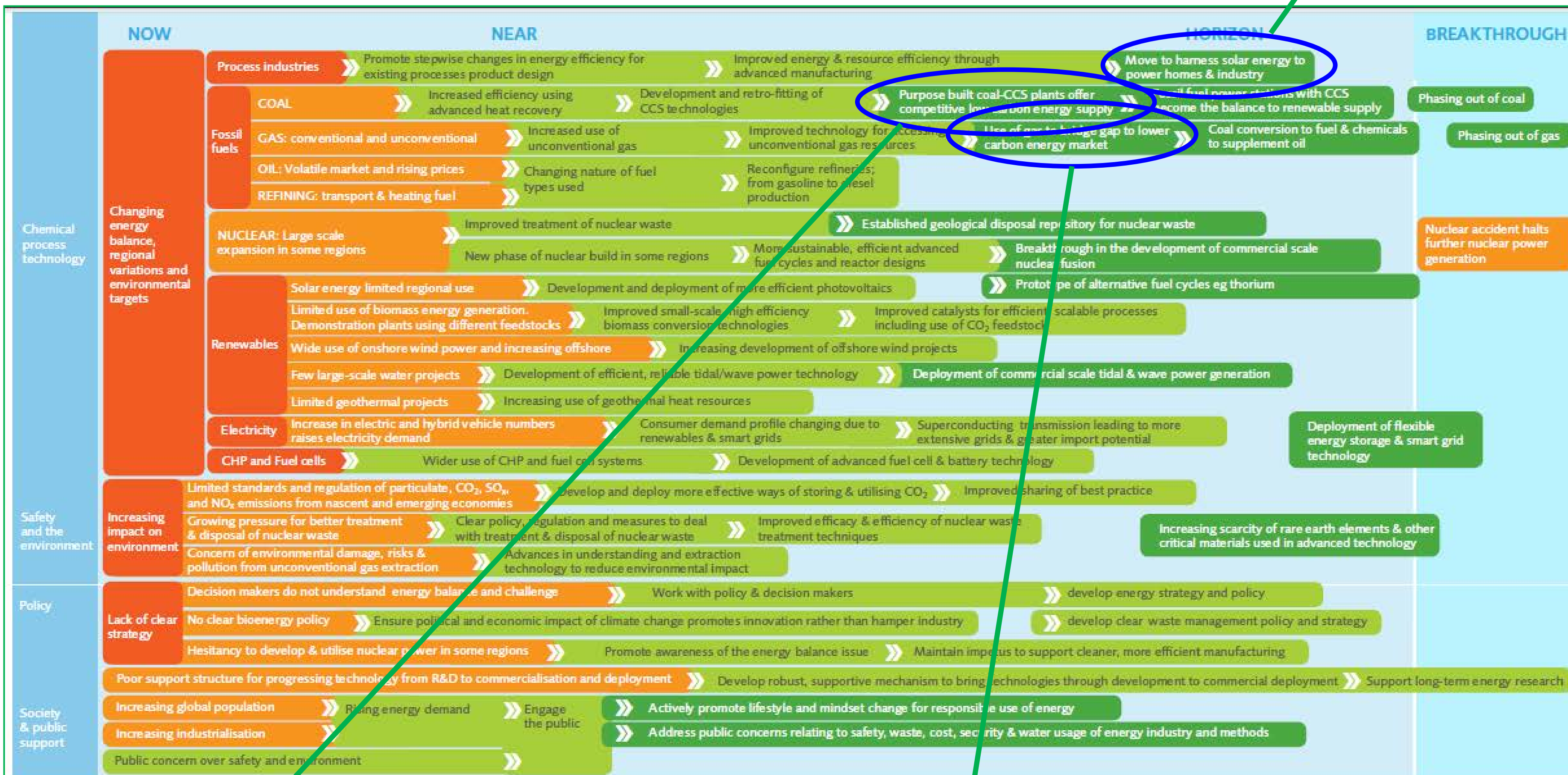
The energy vista

Move to harness solar energy to power homes and industry



Fossil fuel power stations with CCS become the balance to renewable supply

Use of gas to bridge the gap to a lower carbon energy market

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Engineering the Journey – Avoiding Catastrophic Climate Change

- Engineers, not governments, are the key
  - – Chemical Engineers in particular

Three stages to this journey:

- Planning the journey
  - – Route options; benefit, value and risk analyses
  - – A process systems engineering approach
- Providing the innovative technical solutions that will enable and accelerate this journey
  - – Managing the transition
- Public and Government engagement
  - – Influencing Public Opinion and Policy

What can Chemical Engineers do?

Provide innovative low cost, low carbon technical solutions

- Lower the cost of carbon capture by 50%
- Promote CCS for decarbonising chemical manufacturing
- Keep low-value, environmentally damaging components of FFs underground
  - Sub-surface processing → eg H_2, CH_4, MeOH, DME, syngas, heat
  - Leave CO_2, SO_x, NO_x, asphaltenes etc underground
  - Use FF as sacrificial fuel → energy and carbon neutral process
- 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 effectiveness of CCGT
- Innovative solutions for energy efficiency in manufacturing, buildings and homes

IChemE ADVANCING CHEMICAL ENGINEERING WORLDWIDE

Mind your language!!!

- We have to get better at communicating with the public…and with governments
- Convey effectively what we do
  - Simplify without patronising
  - Demystify without removing key messages
  - But keep evidence-based arguments for government and some media
  - Find ways to explain better risk and uncertainty…that they cannot be eliminated – our role is to manage them
- "We are sleep-walking into a catastrophic climate change future"
- We need more ChemEng role models…to stand up and be counted

Every individual has a role to play

It's up to you to tell the world that chemical engineering matters

IChemE President's Blog

2014/15

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Making food last longer (Day 78)

Globalisation has created opportunities for many industries, but the growth of some fast moving consumer goods (FMCG) – especially fresh foods – continue to be limited
...
cap on their exporting potenti...
with burgeoning ...
resh' food import...
n' food supplies.

Combating sewer corrosion (Day 96)

Sewer management is a difficult business; it depends on a careful balance of chemical and civil engineering.

Sewer infrastructure maintenance is a costly business, e.g. in America the federal government has required cities to invest more than $15 billion in new pipes since 2007.

The concrete foundations of sewers are often corroded due to additives used in the processing of drinking water. In Australia some concrete pipes are being corroded by up to 90 per cent.

It's not just the polar bears at risk (Day 163)

A common image of mankind's influence on our planet is to show its impact on nature and wildlife.

In relation to climate change, the plight of the polar bear is often highlighted. But should that image now include humans?

By the end of the century it may be a reality – certainly the Intergovernmental Panel on Climate Change (IPCC) think so.

In my role as a professor of energy engineering and my previous stern warnings about our dangerously low rate of progress in reducing carbon emissions, you can imagine that I had been eagerly anticipating last Sunday's release of the IPCC's Synthesis Report.

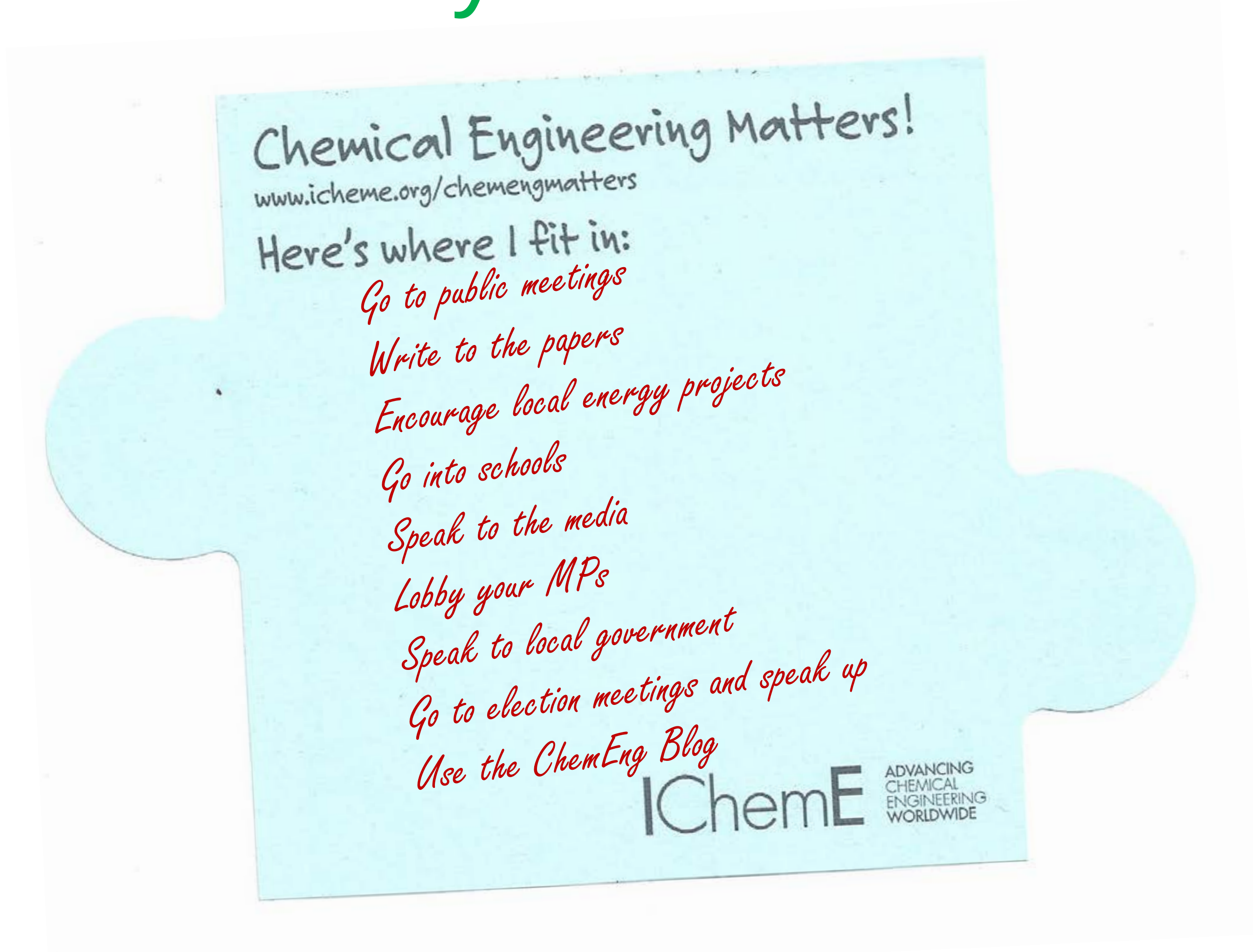
ChemEng 365

http://ichemepresident.wordpress.com/

The IChemE Energy Centre

- Outward facing, influential forum
- Bringing together the energy-related SIGs Joint SIG workshops and debates
- Internally: develop a coherent mixed-energy route to the future
- Externally: speak in a more unified and convincing way to a very confused public…and governments
- Position IChemE more effectively to interface with
  - Engineering the Future
  - Government consultation
  - Influencing public opinion
    - Public engagement in the Energy Sector
    - Chemical Engineering role models

Ways to make your voice heard…



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

IChemE ADVANCING CHEMICAL ENGINEERING WORLDWIDE

Imperial College London

60 YEARS OF CHEMICAL ENGINEERING
THE UNIVERSITY of EDINBURGH School of Engineering

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

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!

Congratulations Edinburgh Chemical Engineering on your Diamond Jubilee

…and to help mark the occasion…