Two Lectures on

The Outlook for Energy Supply and Demand

+ a Colloquium

Can Future Energy Needs be Met Sustainably?

Given at CERN, September 2015 by

Chris Llewellyn Smith

Director of Energy Research Oxford, President SESAME Council

Rev 1 13/10/15: 2015 data added to slide 36; slide 40 added, illustrating slide 39; mistake corrected on slide 76

Rev 2 9/11/15: slide 80 – revised/corrected

Introduction to These Slides

In this folder I have merged the Lectures and the Colloquium, in the order in which they were given (Lecture 1 - 14 September, Colloquium - 15 September, Lecture 2 – 16 September).

The contents are listed on the next slide. Because the Colloquium was sandwiched between the Lectures, the overall sequence of topics is not ideal. The Colloquium was designed to be accessible to people who did not attend the Lectures, so inevitably there is some overlap.

Since I gave the lectures, I have corrected a few minor mistakes, updated some information, included some cross-references, and added some explanations to help readers who did not hear the talks.

If you notice any remaining mistakes, please let me know (by email to c.llewellyn-smith@physics.ox.ac.uk) and I will correct them and post a corrected version.

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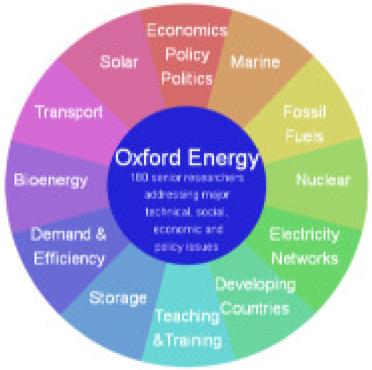

The Outlook for Energy Supply and Demand

Lecture 1

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Introduction

- **The challenge**
- **Drivers of policy**
- **Environmental impacts –** see Colloquium, slides 33-36

The Challenge

- **The biggest challenge of the 21st century**

  - provide sufficient food, water, and energy to allow everyone on the planet to live decent lives in decent environments, in the face of rising and increasingly urbanised population, the threat of climate change, and (in the long term) declining fossil fuels*

  * Today 7 billion, over 50% living in big cities
  Later in the century 9 to 10 billion, 80% in big cities

- **Energy is a necessary** (but not sufficient) **means to meet this challenge** – which must be tackled holistically

  - providing the additional energy needed to lift billions out of poverty while decarbonising the world's energy system (to reduce pollution, climate change…) will be extremely difficult

Drivers of Energy Policy

1. Security

Is there enough to meet needs? Will the lights stay on?

Are there queues at petrol pumps?

2. Cost

Is energy affordable? Do energy prices foster industrial competiveness and development?

3. Clean Environment

Does the system minimise pollution, health and climate impacts?

Trade-offs are required → highly political, economic, and social as well as technical issue. In practice security and costs are mainly driving what’s happening in most countries (with a few exceptions: China, Germany,...)

Primary Energy

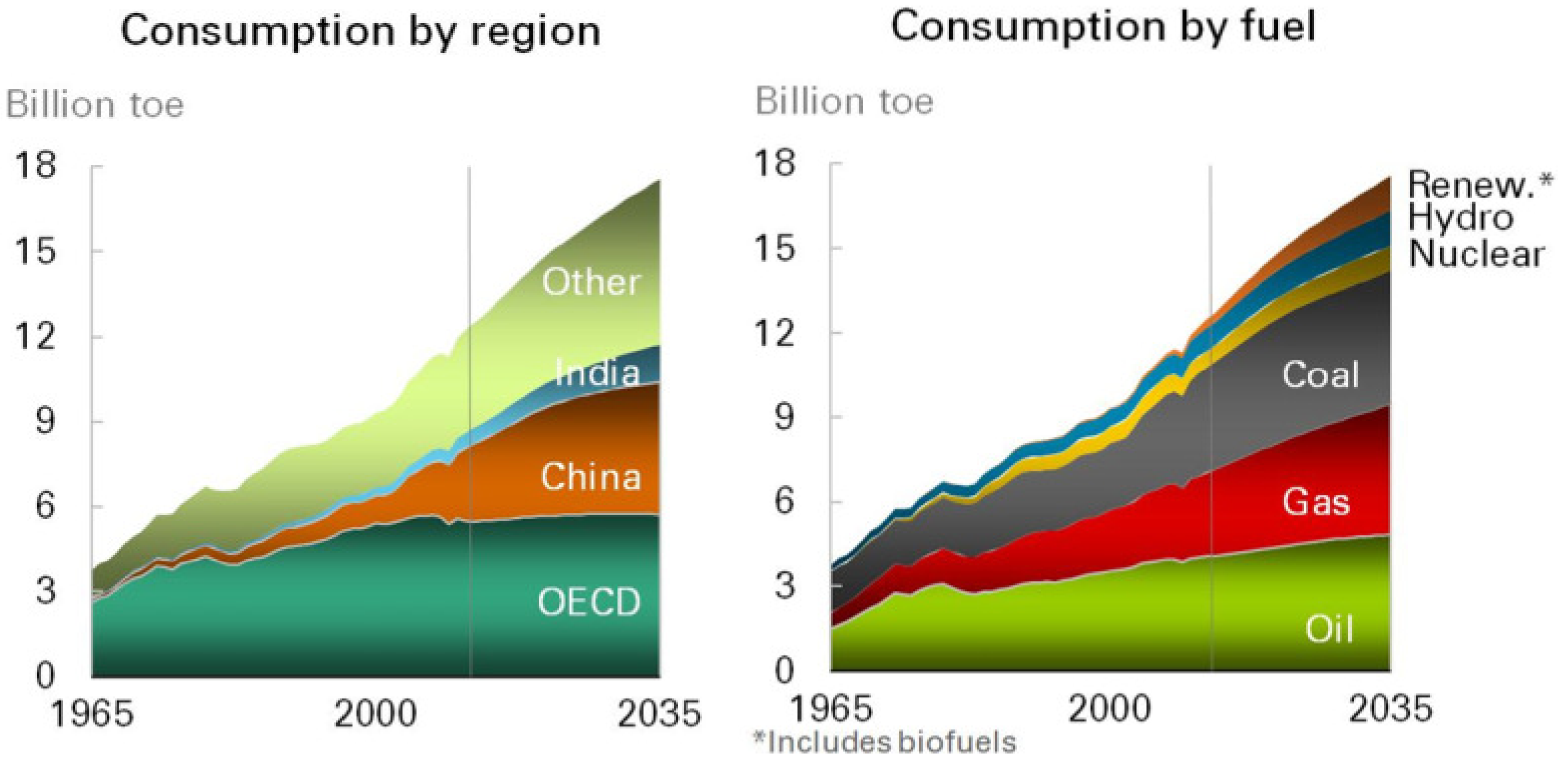
- **Overview**
- **Interlude:** sources of data, units, definitions,
- **OECD/non-OECD differences**
- **Sources of energy**

Will use ‘thermal equivalent’ primary energy – see slide 15

How Much Primary Energy

The world is using the same amount of energy as would be provided by burning 14.2 billion tonnes of oil per year. This corresponds to 2.0 ‘tonnes of oil equivalent’ (toe) for every man, woman and child on the planet

- How fast is energy use increasing?
- Who is using it?
- What are the main sources?



BP Past data + Projections

Based on “most likely” assessment of future policy trends. Not included: 10% from biomass *(apart from biofuels which contribute ~ 0.5%)* and waste. Includes ~ 6% oil & gas → non-energy uses.

- Energy use growing rapidly - growth from Non-OECD countries where 1.3 billion still lack electricity, 2.7 billion lack clean cooking facilities, and more energy needed. Per capita energy use in the USA = 7 x Egypt = 32 x Bangladesh
- Fossil fuels set to continue to dominate. Role of renewables expected to remain relatively small, despite rapid growth in percentage terms

Note Added

As I explained in the lecture, and in response to a question after the Colloquium, the reliability of the projections above and below can be assessed by:

1) Noting that past projections for the ‘big picture’ worked reasonably well – the main deviations arose from under or over estimates of future economic growth.
2) Varying the assumptions – see next slide.
3) Comparing estimates made by different authors – see next slide.

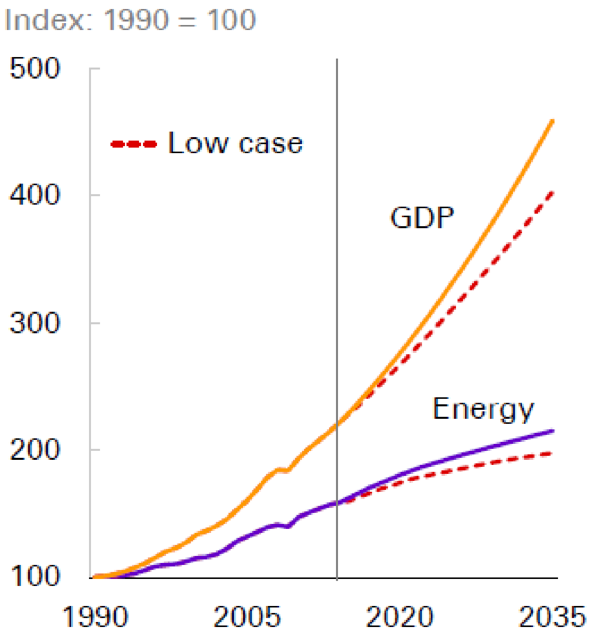
Past projections were of course not borne out exactly in all details, and some of the assumptions were badly wrong, e.g. for the prices of fossil fuels – see slides 91-93 – although use of these fuels proved to be relatively insensitive to the prices.

Projections depend on assumptions (sensitive to GDP growth) **and authors – but big picture is clear**

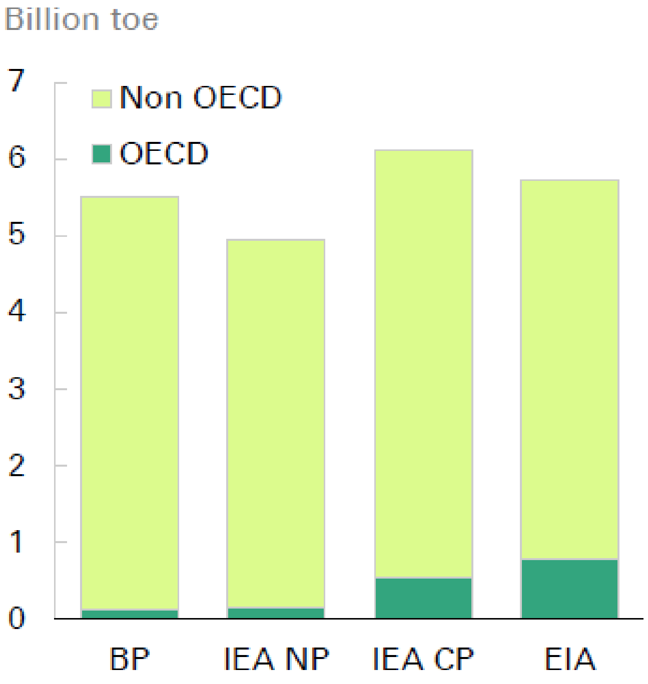
BP Projection with lower growth →

13% less GDP growth (23% less in non-OECD Asia)
→ Energy growth 8% less (16% less in non-OECD Asia)
→ Projected emissions growth (2015 to 2035) falls from 25% to 14 %

GDP and energy demand in base and low case



Changing 2035 Chinese electricity consumption by +/-20% → +/- 2.7% in global energy use



← **Different projections for *increment* in energy consumption 2015-2035.**

Variations in the projected increments should be judged in relation to the 2013 BP data: OECD/non-OECD - 5.5/7.6 btoe

Sources of Data

- **BP** - see BP web site. Traded fuels only.

  2015 ‘Energy Outlook 2035’

  Statistical Review of World Energy 2015 + spread-sheet with details

- **International Energy agency (IEA) -** see IEA web site.

  Extensive data (including estimates for non-traded biomass & waste)

  Partial summary in Key World Energy Statistics 2014

  Annual World Energy Outlook - lots of information and scenarios (2014 and 2013 editions not yet available free)

- Many others, e.g. the US **Energy Information Administration (EIA)** provides data and outlooks for the US

Units

- **Energy** - generally use tonnes of oil equivalent (toe) or kWh
- **Power** – use Watts (W)

  (also of course mtoe, btoe, MW, TW, TWh,…..)

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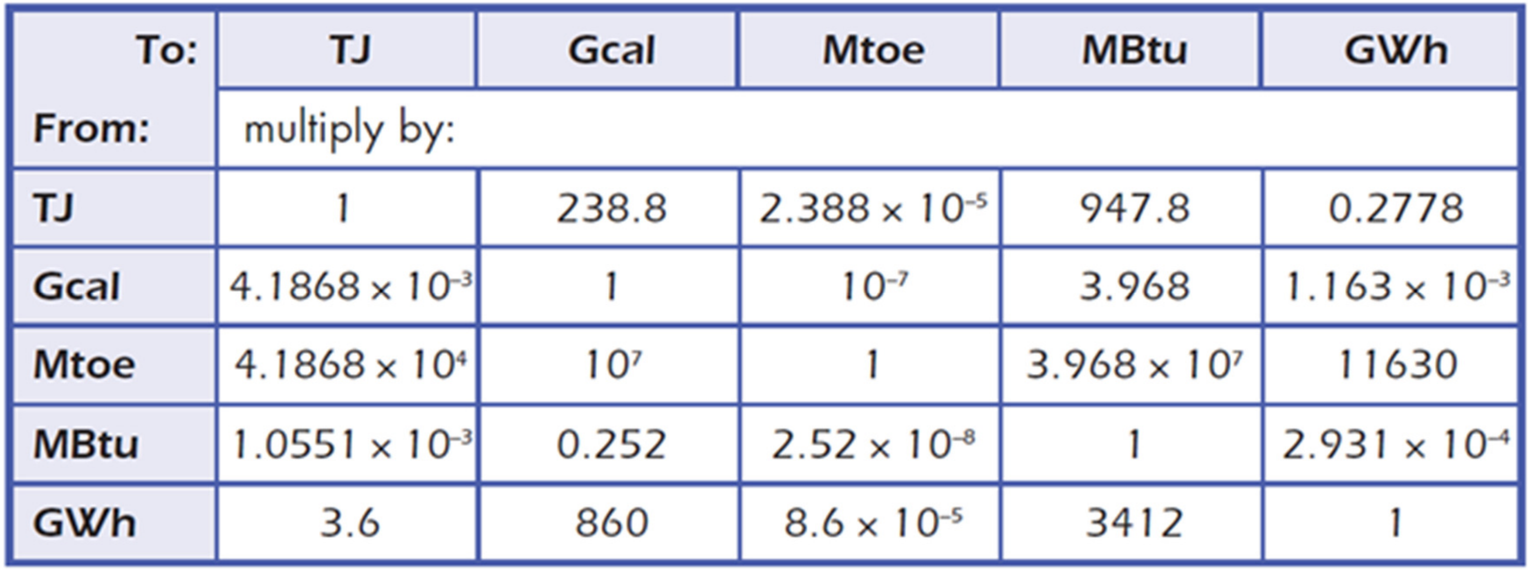
Conversion Factors for Energy



To:	TJ	Gcal	Mtoe	MBtu	GWh
From:	multiply by:				
TJ	1	238.8	2.388×10^{-5}	947.8	0.2778
Gcal	4.1868×10^{-3}	1	10^{-7}	3.968	1.163×10^{-3}
Mtoe	4.1868×10^{4}	10^{7}	1	3.968×10^{7}	11630
MBtu	1.0551×10^{-3}	0.252	2.52×10^{-8}	1	2.931×10^{-4}
GWh	3.6	860	8.6×10^{-5}	3412	1

- The calorific value of coal, oil and gas varies, but roughly

  1 tonne of oil ~ 1.5/3.0 tonnes of hard coal/lignite ~ 1,100 m^3 of natural gas ~ 12 MWh ~ 42 MJ

- I barrel (bbl) of oil = 159 litres = 0.136 m^3 = 0.136 tonnes

Different Definitions of Primary Energy

For (e.g.) 2011 IEA report:

	'Primary Energy'	**Electricity produced**		
	mtoe p.a.	TWh p.a.		mtoe p.a.
Nuclear	**670**	**2,650**	**=**	**230**
Hydro	**300**	**3,510**	**=**	**300**

The IEA Primary Energy data seem to suggest that nuclear is more important than hydro, which is wrong. Explanation: IEA defines primary energy

- For nuclear as the heat produced by burning nuclei, calculated from the electrical output assuming 34% average efficiency and converted to mtoe
- For hydro as the electrical energy produced, converted to mtoe

BP use '**thermal equivalent energy**' **=** electrical output of sources that produce electricity directly and nuclear divided by 0.38 (38% is the typical efficiency of a modern thermal power plan). Thermal output is used for coal, gas, oil.

This puts all sources on the same footing and *approximately* represents their relative importance

Here thermal equivalent primary energy is widely used, with waste and biomass contributions (as reported by IEA) **that are omitted by BP included**

Variations in Per Capita Energy Use

Energy use per capita in non-OECD countries is growing rapidly:

BP 2035 (2014) projection/2012	Population	Energy	CO_2
Non-OECD	+ 28%	+ 69%	+ 54%
OECD	+ 11%	+ 5%	- 9%

But the non- OECD average per capita (1.2 toe) is still well below the OECD average (4.4 toe), and the average hides huge variations:

Per capita energy use in 2012 in selected countries (toe)				
USA	UK	China	India	Bangladesh
7.2	3.2	2.2	0.64	0.23

Note that subtracting the difference between energy embodied in manufactured exports and imports changes the picture to (e.g.):

USA - 7.8 toe, UK - 3.7 toe, China - 1.7 toe.

Sources of Primary Energy

Global Figures:

Thermal equivalent primary energy 2014	
Fossil	78.7% Oil 29.7% Coal 27.4% Gas 21.6%
Biomass + waste	9.6%
Hydro	6.2%
Nuclear	4.0%
Rest	1.5% →

Wind → 1.1% 2012 to 2014 + 34%
Solar → 0.3% + 92%
Geo → 0.1% Total primary +3%

There are big variations e.g.:

2012	**China**	**India**
Oil	15%	29%
Coal	65%	43%
Gas	4%	7%
Biomass & waste	7%	25%

Final Energy

- Use and trends by
  - Purpose: variations
  - Fuel
  - Form
- Use of electricity

Final Energy Use by Purpose

<table>
<tr><th colspan="6">World final energy use (excluding non-energy uses of fossil fuels)</th></tr>
<tr><td>Industry</td><td>Transport</td><td>Residential</td><td>Commerce & public service</td><td>Agriculture, forestry & fisheries</td><td>Not specified</td></tr>
<tr><td>31%</td><td>31%</td><td>25%</td><td>9%</td><td>2.4%</td><td>1.6%</td></tr>
<tr><th colspan="6">There are substantial variations from these averages, e.g.:</th></tr>
<tr><th colspan="6">China</th></tr>
<tr><td>51.7%</td><td>15.3%</td><td>23.7%</td><td>3.8%</td><td>2.2%</td><td>3.45</td></tr>
<tr><th colspan="6">India</th></tr>
<tr><td>35.3%</td><td>11.5%</td><td>38.2%</td><td>4.0%</td><td>4.8%</td><td>2.3%</td></tr>
</table>

Final Energy Use by Fuel:

Final energy use by fuel					
Oil	Electricity	Gas	Biomass, waste & biofuels	Coal	Heat: CHP +… geothermal
40.6%	18.1%	15.2%	12.4%	10.1%	3.5%

Final Energy Use by Form:

Heat - 52%, Transport - 30%, Electricity - 19%

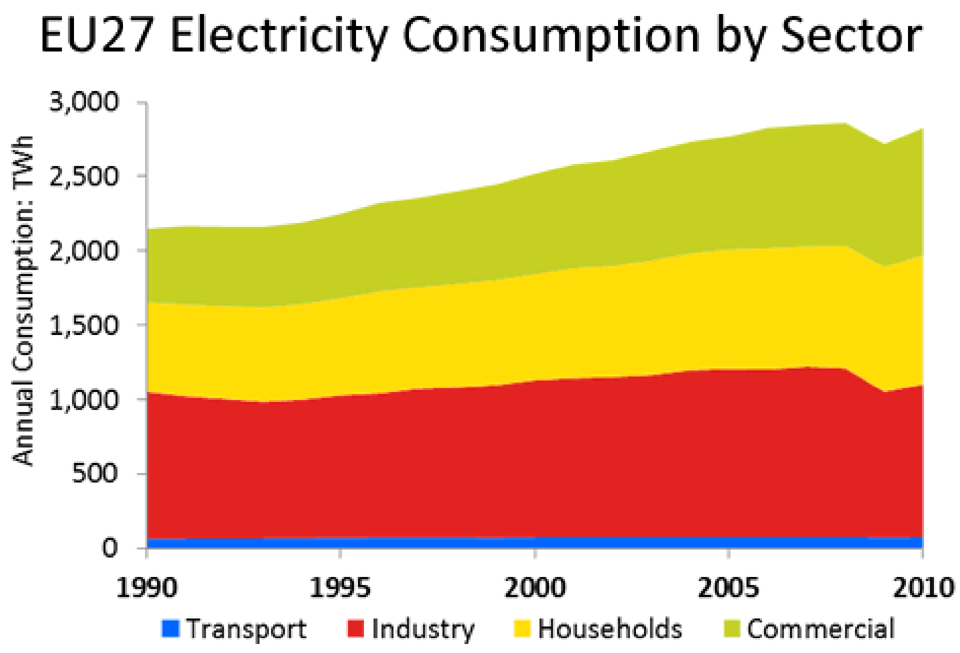
Allowing for losses in transforming primary energy to final energy the calls on primary energy are approximately:

Heat ≈ Electricity ≈ 40%, Transport ≈ 20%

Role of electricity is increasing (see later)

Uses of Electricity

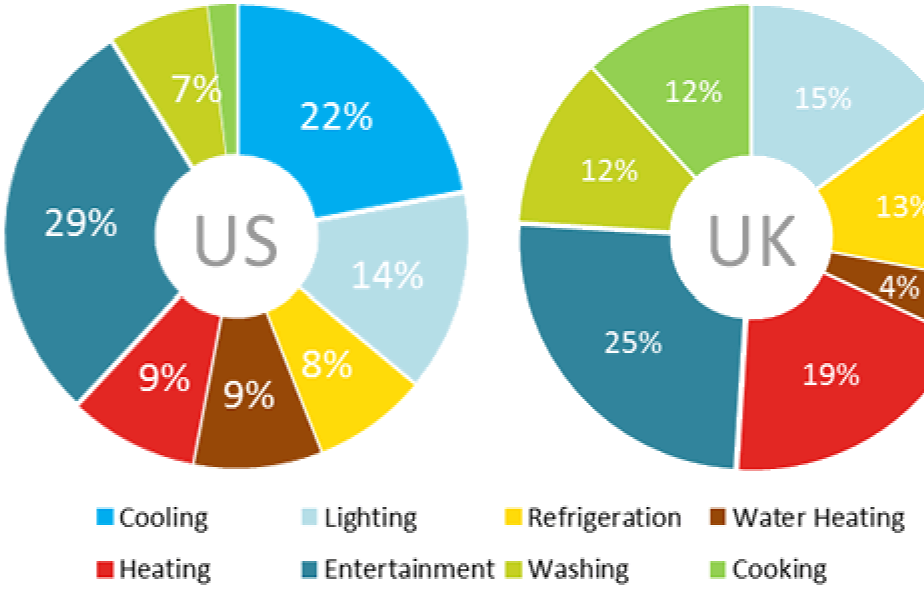
EU breakdown →



USA: much bigger % in buildings (residential, commercial) and less in industry

2012: commercial 36.9%, residential 38.4%, industry 23.6%,..

Household Use →

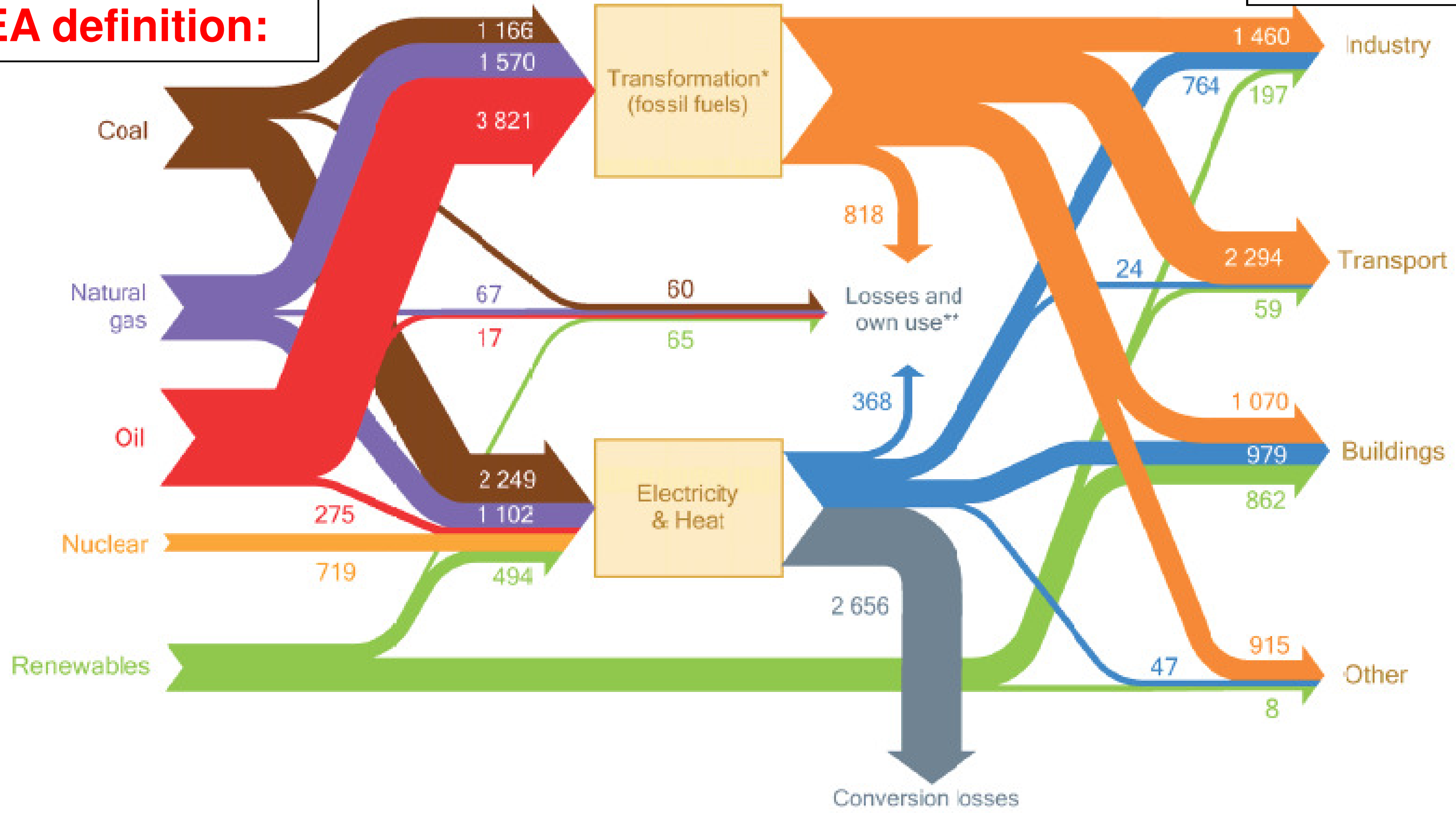


US homes use 2.5 times as much as UK homes, in different ways:

The Global Energy System (IEA 2010)

Primary Energy IEA definition:

Final Energy:



Correcting for losses in electricity generation (but not for other losses), by dividing by 0.38, the 2010 contributions of primary energy ~ Industry 31%, Transport 21%, Buildings 39%, Other 9%

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Reducing Demand & Increasing Efficiency

- Demand Reduction
- Energy intensity trends
- Opportunities for greater efficiency
- Barriers
- Role of regulation

Demand Reduction

	Demand Reduction	**Efficiency Gains**
Lighting	Use natural light	Better light bulbs
Cars	Use other means	Improve engines

Many opportunities to reduce demand:

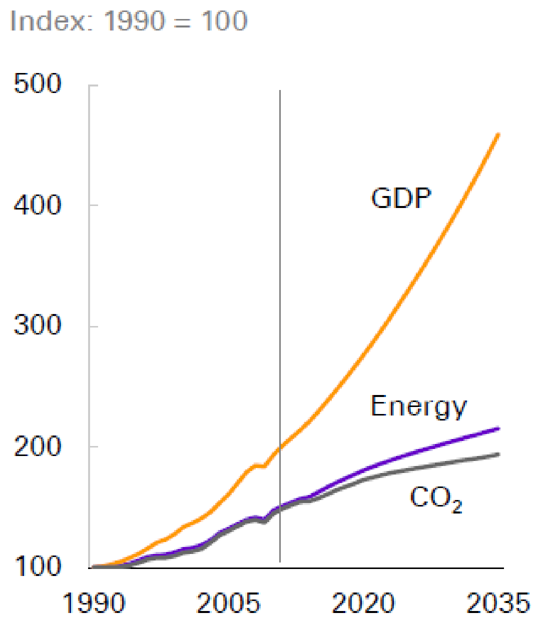
- **Change life-styles** e.g. bicycle to work, become vegetarians
- **Better planning and design**
  - Design buildings → use natural light and ventilation, better insulation
  - Plan cities and transport systems → encourage walking, bicycling, use of public transport. Major opportunities in rapidly developing/urbanising countries – adopt low-energy/carbon development paths early.

Note: energy consumption in cities set to rise from ~ 66% to ~ 85% of total. Planning/procurement by cities & communities → important drivers of demand and efficiency

Demand management is vital even if unlikely to mitigate expected rise in demand very significantly (time management of electricity demand also vital)

Efficiency - "Low Hanging Fruit"?

- Energy intensity = consumption/GDP is falling - fall is expected to accelerate, and carbon intensity = CO2/energy is also expected to fall:
- Energy intensities in different countries are converging. Carbon intensities are expected to fall everywhere but are not converging – different fuel mixes (China & India expected to remain relatively high)



Source: BP 2015

- **Technically could do *much* better**

IEA claims *energy use in 2035 could be reduced by 14 % relative to New Policy Scenario solely by adopting measures that save both energy and money*

Where would this come from?

If it's true, why's it not happening?

Possible Energy Savings

IEA WEO 2012

2035 Savings mtoe	**Current → New Polices** (NPS)	**New Polices → Efficient World**
Power	35	200
Industry	335	545
Buildings	240	970
Transport	290	485
Total	**900** (7% of 2012)	**2200 + 150** from other sectors (agriculture,…)

14% less energy in 2035 than in NPS

Likely to happen

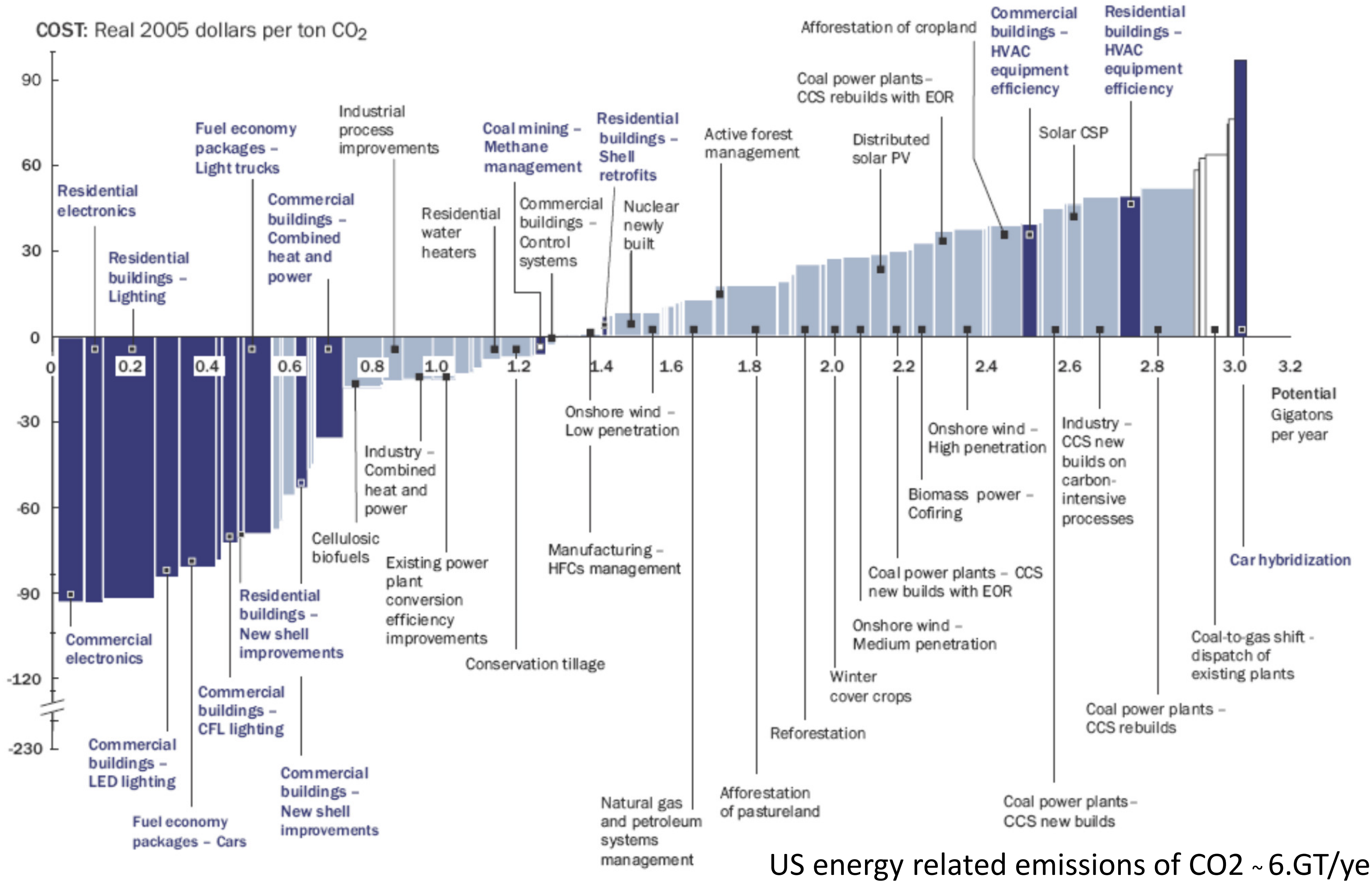
Claim all measures save money and energy

Many studies of reducing CO2 emissions while saving money

U.S. mid-range abatement curve - 2030

Carbon dioxide abatement: estimated removal cost per ton of CO_2 in 2005 dollars and removal potential in gigatons/yr for various strategies.

▨ Abatement costs <$50 per ton



US energy related emissions of CO2 ~ 6.GT/year when this study was made

Source: *Reducing U.S. Greenhouse Gas Emissions: How Much at What Cost?*, Executive Report, McKinsey & Company, December 2007

Barriers to Energy Efficiency

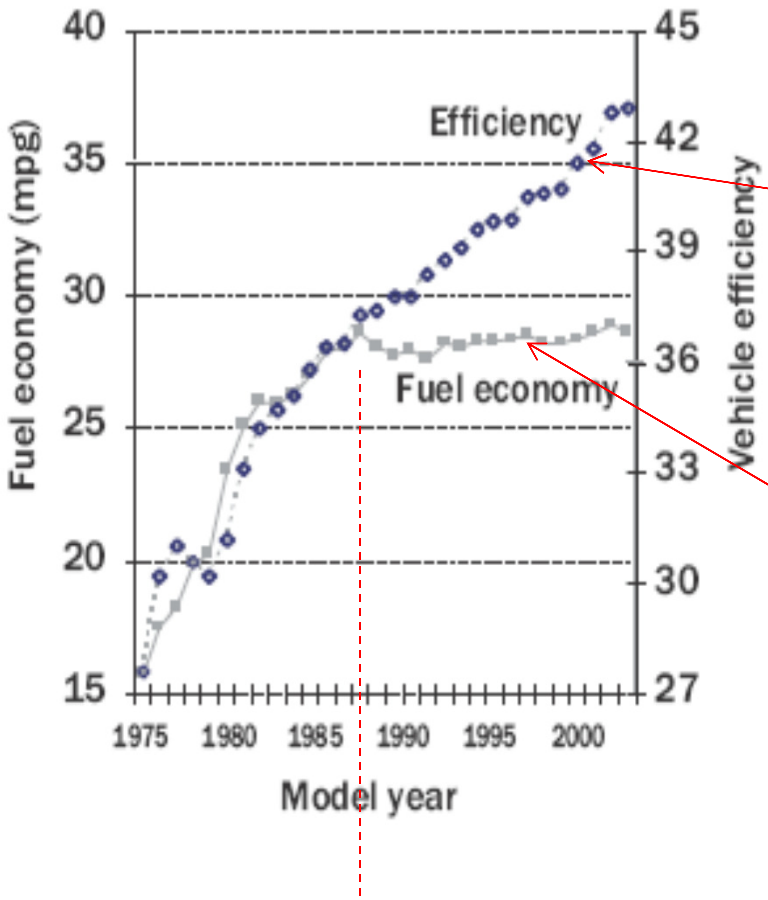
Technically, large improvements (40% or more?) look possible, **but** they are not happening

- Appraisal optimism and neglect of transaction costs
- Direct and (more importantly) indirect rebound effect
- No incentives for the affluent to make small savings, which collectively can be large, e.g. electric lighting, uses 20% of electricity
- Poor lack capital

Need regulation - cars, buildings, light-bulbs, appliances…

Effect of Regulation

US Passenger Vehicles



Efficiency - Ton-miles per US gallon

Economy - Miles per US gallon

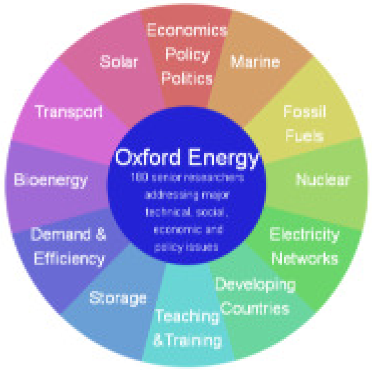
Current standards for new vehicles:

35.5 mpg by 2016

54.5 mpg by 2025

End of mandatory **C**orporate **A**verage **F**uel **E**conomy standards

Conversion factor: 30 miles/US gallon is equivalent to 7.85 litres/100 km



Can Future Energy Needs be Met Sustainably?

Colloquium

Chris Llewellyn Smith

Director of Energy Research, Oxford University

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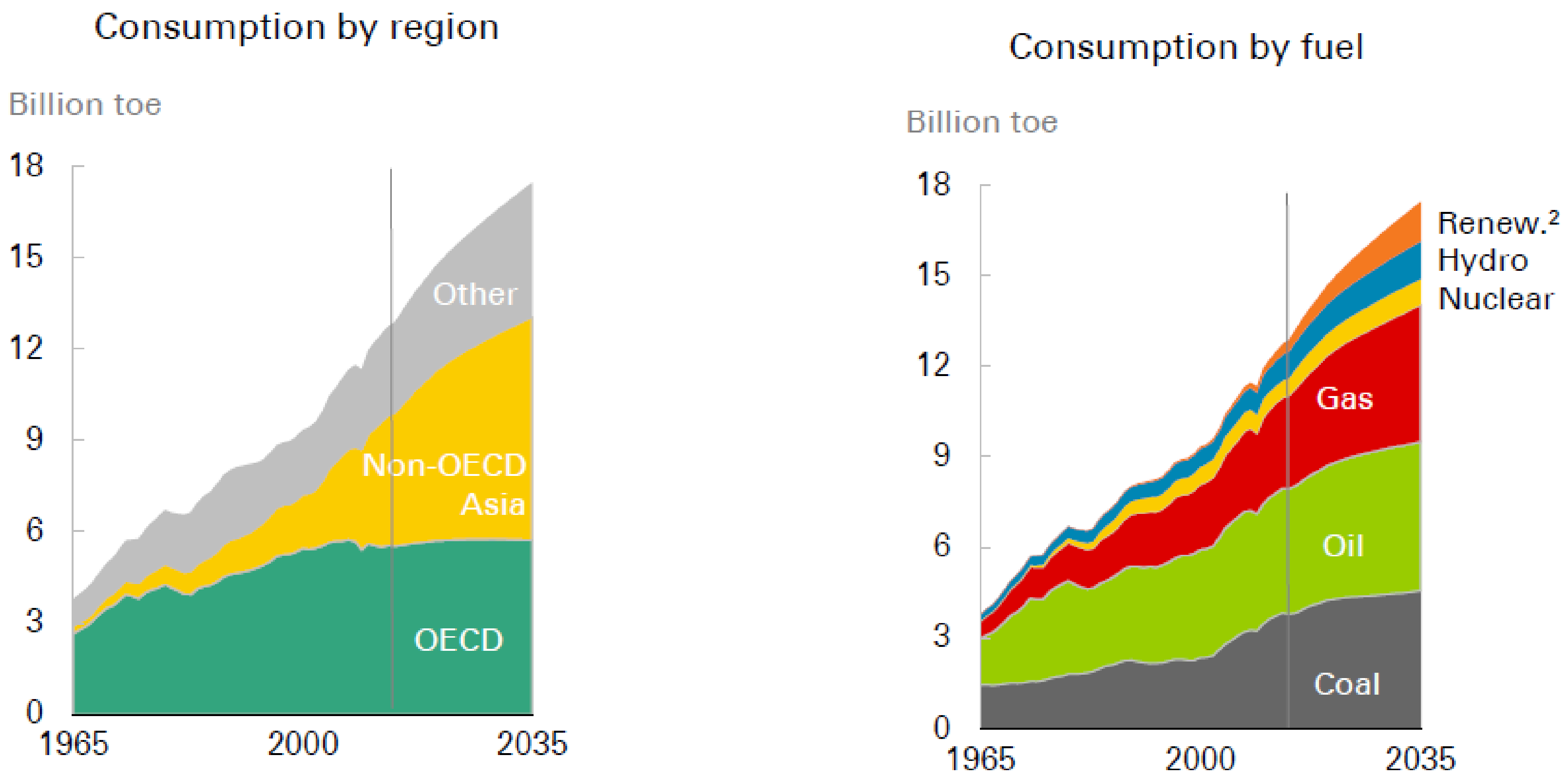
Some Basic Facts

The world is using the same amount of energy as would be provided by burning 14.2 billion tonnes of oil per year. This corresponds to 2.0 ‘tonnes of oil equivalent’ (toe) for every man, woman and child on the planet

- How fast is energy use increasing?
- Who is using it?
- What are the main sources?

Note: the reliability of the projections on the following pages is discussed in Lecture 1, slides 11-12


Consumption by region

Consumption by fuel

BP Past data + Projections

Based on “most likely” assessment of future policy trends. Not included: 10% from biomass *(apart from biofuels which contribute ~ 0.5%)* and waste. Includes ~ 6% oil & gas → non-energy uses.

- Rapid growth from Non-OECD countries where 1.3 billion still lack electricity, 2.7 billion lack clean cooking facilities, and more energy is needed. Per capita energy use in the USA = 7 x Egypt = 32 x Bangladesh.
- Fossil fuels set to continue to dominate. Role of renewables expected to remain relatively small, despite rapid growth in percentage terms.

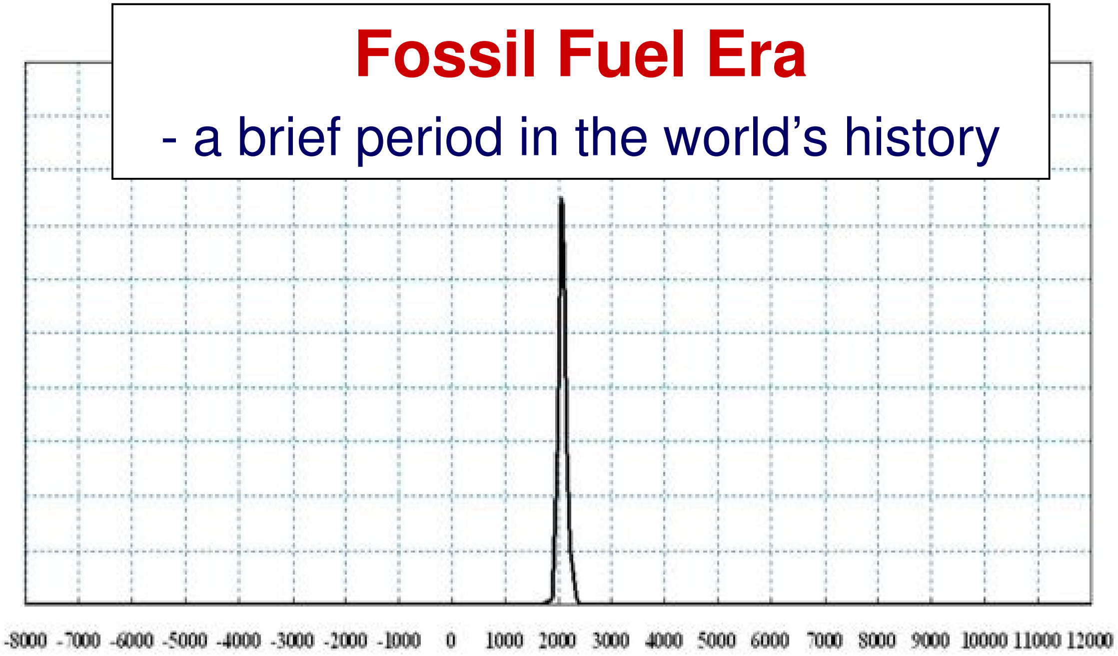
Use of Fossil Fuels is Unsustainable

Long-term: :

They will eventually become increasingly scarce and expensive, but not for*

- *many hundreds of years for coal*
- *at least 50 years for oil and gas (scarcity towards the end of the century?)*

- *see slides 88-89*



Fossil Fuel Era

- a brief period in the world’s history

Short/medium term: **producing**

- Climate change
- Dangerous pollution

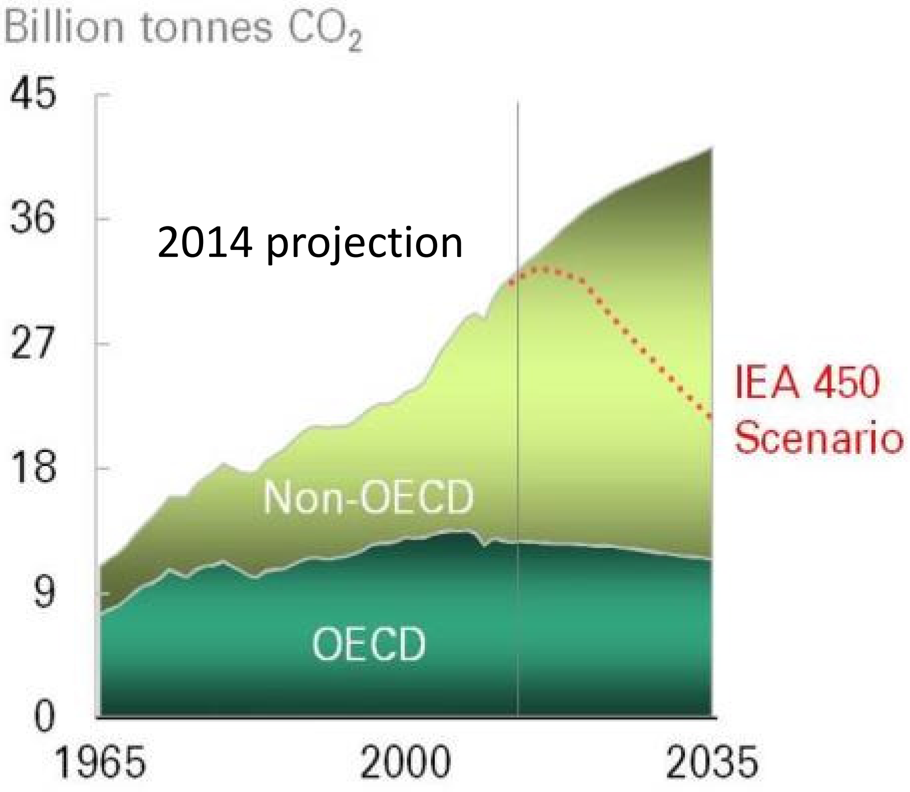
Next three slides

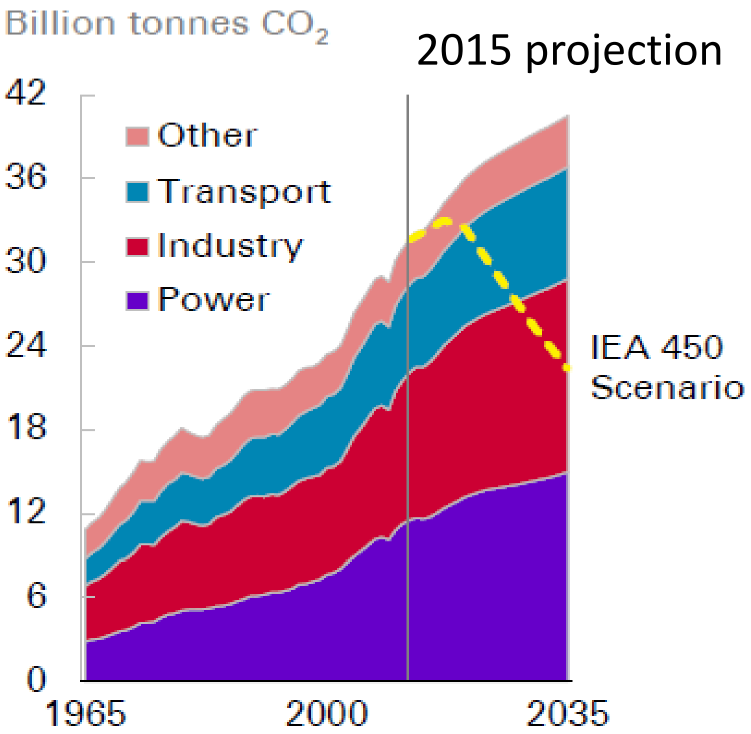
Moving away from fossil fuels will also improve security of supply in countries without large reserves + re-balance global politics

Added Note

On the next slide, the IEA 450 Scenario is one in which atmospheric CO2 remains below 450 ppm. The link between CO2 levels and temperature rise is uncertain, but this is the level at which atmospheric scientists say there is a 50% chance of global average temperature rise remaining below 2C. CO2 accumulates in the atmosphere (see slide 96), so to keep below 450 ppm, integrated future emissions will have to be less than the integral under the dashed curve. If they continue beyond 2035 on the trajectory projected by BP up to 2035, this would require emissions to drop precipitously to zero around 2045.

BP Projections of Energy Related CO_2 Emissions





2035 projections won’t be right in detail, but different models all foresee similar large increases in energy and the projected trajectory of emissions/energy is unlikely to be very badly wrong – infrastructure mostly in place

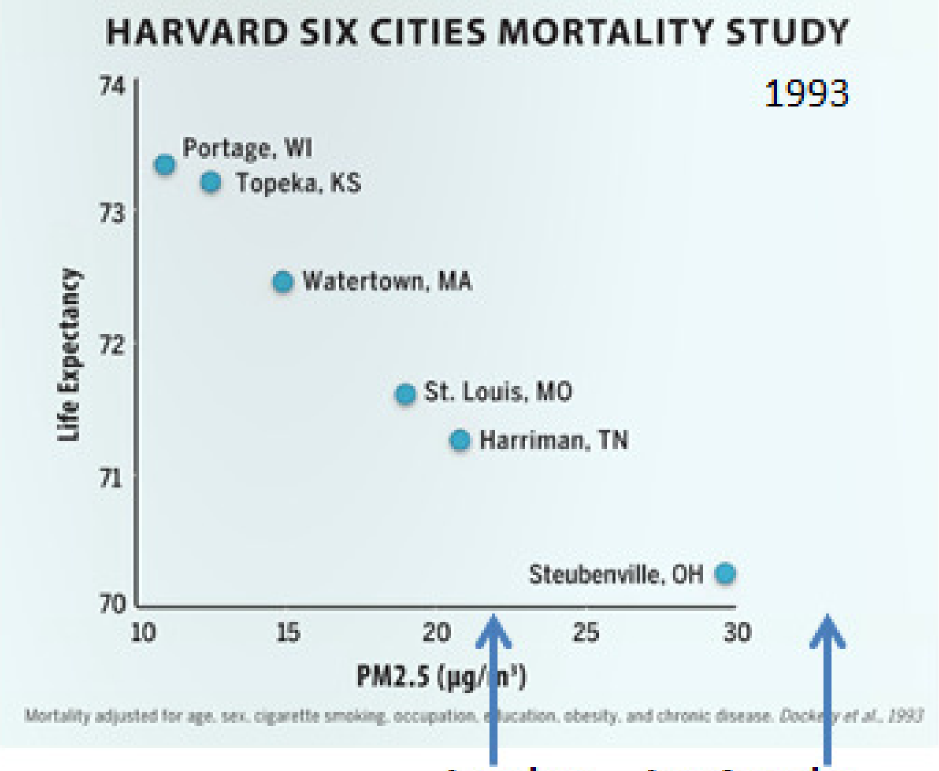
Low economic growth scenario: 37% increase in energy reduced to 25%
25% increase in CO2 reduced to 14%

Air Pollution

- **Globally** (WHO 2014) 7 million premature (typically 10 years loss of useful life) deaths p.a. (out of 56 million p.a. total)

- **US** (2013 MIT study) 210 k p.a. from burning fossil fuels (out of 2.5 million total) of which 200 k from particulates including : 58 k road transport, 54 k power generation, 43 k industry – main culprit is coal

Numbers very uncertain but undoubtedly a single large coal power station is far more lethal than Chernobyl



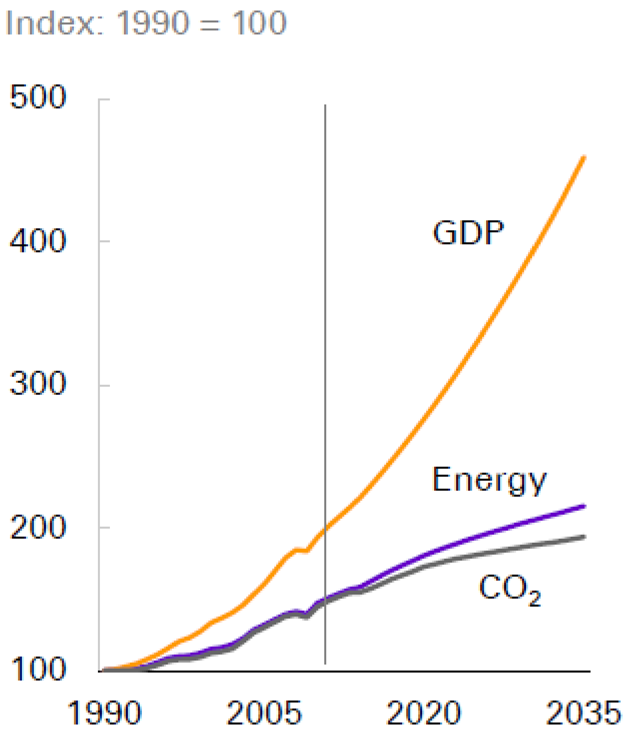
HARVARD SIX CITIES MORTALITY STUDY

Mortality adjusted for age, sex, cigarette smoking, occupation, education, obesity, and chronic disease. *Dockery et al., 1993*

Could we use less, more efficiently?

Yes : energy Intensity (= energy use/GDP) **and carbon intensity** (= CO2/energy) **are decreasing, but not fast enough:**

GDP, energy and emissions



Source: BP 2015

Technically could do much better, **but…**

Meeting rising demand while decarbonising

- **Curb energy use.** Could do much better, **but**… *see slides 23-29*
- **Move to low carbon sources**

Sufficient abundance? Yes

Can the cost compete with fossil fuels (would solve the problem)?

Generation cost for: wind - now the lowest
solar - decreasing rapidly

But cost ≠ value for intermittent sources, and cost of integrating wind and solar will increase when their contributions increase

Need to drive down costs and learn how to integrate large-scale wind & solar + meanwhile replace coal with gas when possible and improve efficiency of the use of fossil fuels

Low Carbon Energy Resources

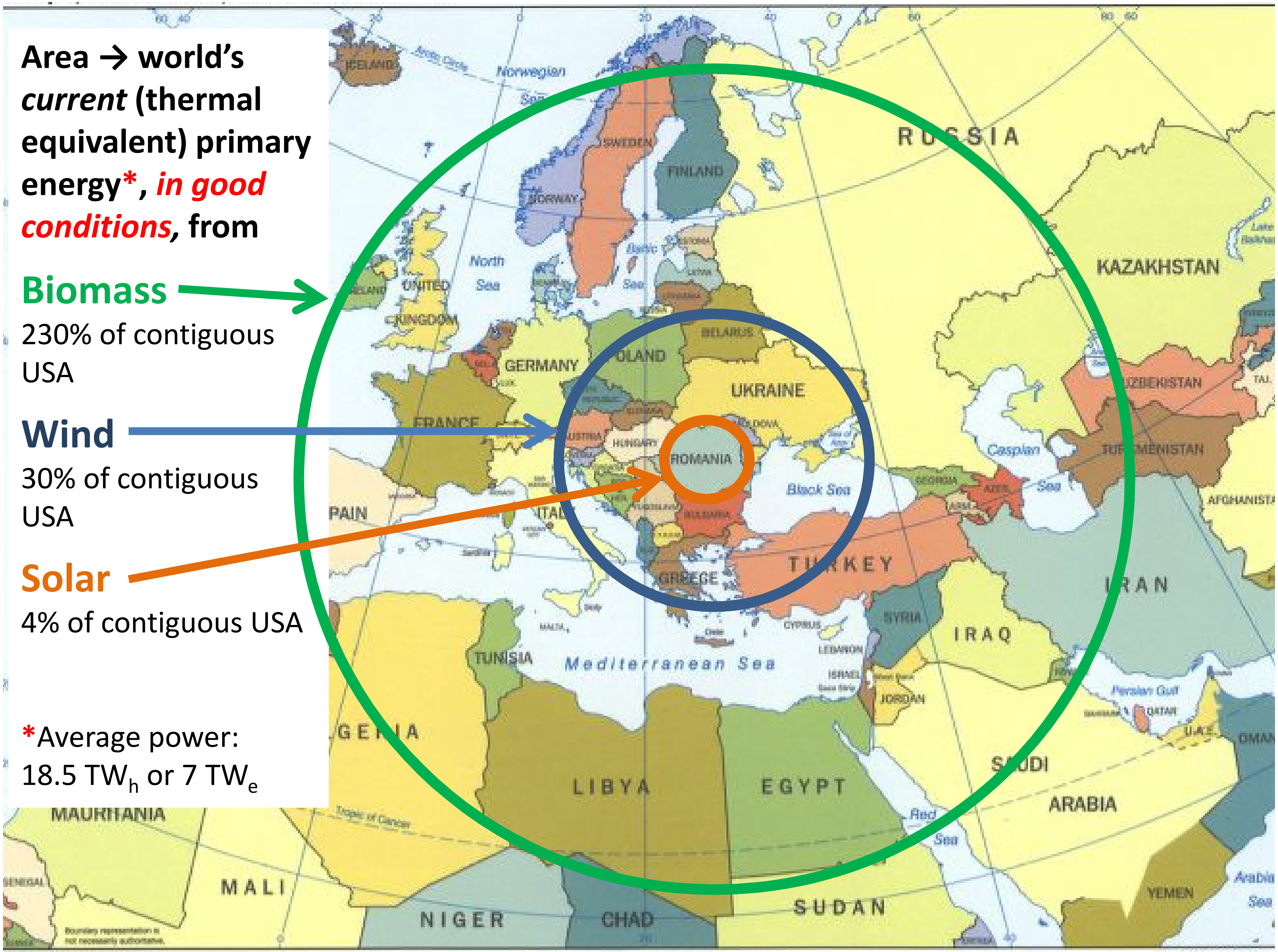
Target (T). If all energy from **Heat: $T_h \approx 18.5$ TW_h**
Electricity: $T_e \sim 8$ TW_e (??)

+ 35% in 2035?

	Today % of T	**Potential – note T = T for world here**	**Issues**
Bio	9.4%	Area = 230% of contiguous US to meet T_h in OK conditions*	Land & water use + carbon footprint
Hydro	5.5%	15% of T_e	Environmental
Nuclear	3.6%	Almost unlimited?	Cost; public perception
Wind	1.0%	Area = 30% of contiguous US to meet T_e in OK conditions*	Integration cost NIMBYism
Solar	0.27%	Area = 4% of contiguous US to meet T_e in OK conditions*	Integration cost

Geothermal & Marine - can be important locally but not globally

*** The areas A are illustrated on the next slide,** added 13/10/15



Area → world's *current* (thermal equivalent) primary energy*, *in good conditions*, from

Biomass

230% of contiguous USA

Wind

30% of contiguous USA

Solar

4% of contiguous USA

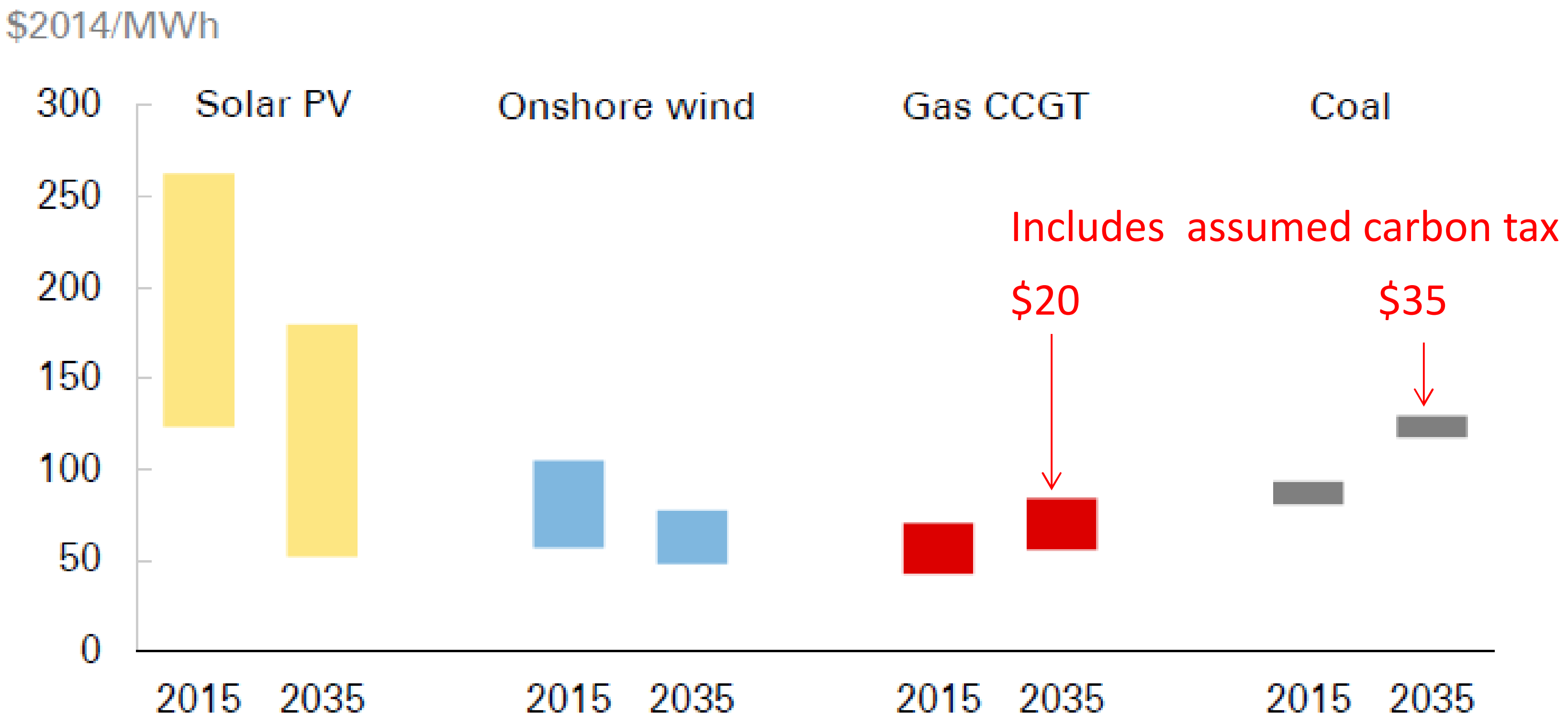
*Average power: 18.5 TW_h or 7 TW_e

US EIA estimates (June 2015) for Levelized Cost Of Electricity generation for sources coming on line in USA 2020 – geographical averages

Dispatchable Sources	**$/MWhr**	
Coal: Conventional	95	
Advanced	116	
Advanced with CCS	144	
Gas: Conventional C Cycle	75	With US gas price . With European cost 73 (e.g.) → over 100
Advanced C Cycle	73	
Advanced C Cycle with CCS	100	
Advanced nuclear	95	UK Government willing to pay £90
Biomass	100	
Non-dispatchable sources – *should not compare with LCOE for dispatchable sources*		
Wind	74	
Wind off-shore	197	
Solar PV	125	Best 100, worst 187
Solar thermal	240	Best 180. worst 361
Hydro	83	

Crystal gazing further ahead:

Cost* of new grid-scale power generation, North America example



* Levelized cost per MWh of building and operating a plant over it's lifetime. Solar and wind costs exclude the cost of grid integration, and exclude any subsidies or tax incentives. Gas and coal costs in 2035 include the cost of carbon at an assumed price of $40/tonne.

Now look at low carbon electricity sources except hydro

…in order of decreasing current importance

Bioenergy

(not just liquid bio-fuels)

Big increase would require crops that

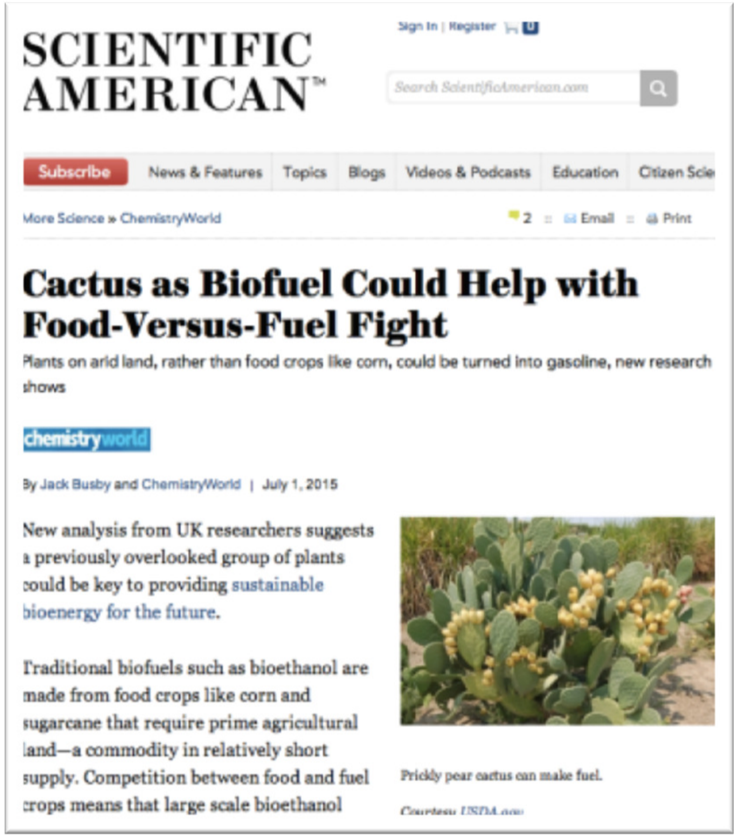
- Don’t displace food production, use little water, and/or photosynthesise much more efficiently
- Small carbon foot
- Low cost exploitation

Oxford colleagues investigating:

Crassulacean **A**cid **M**etabolism (CAM) plants and their exploitation using improved **A**naerobic **D**igestion Find:

4% to 15% of the 2.5 bn ha of potentially available semi-arid would → 5 PW_eh

~ 20 % of current electricity



Cactus as Biofuel Could Help with Food-Versus-Fuel Fight

Plants on arid land, rather than food crops like corn, could be turned into gasoline, new research shows

By Jack Busby and ChemistryWorld | July 1, 2015

New analysis from UK researchers suggests a previously overlooked group of plants could be key to providing sustainable bioenergy for the future.

Traditional biofuels such as bioethanol are made from food crops like corn and sugarcane that require prime agricultural land—a commodity in relatively short supply. Competition between food and fuel crops means that large scale bioethanol

Prickly pear cactus can make fuel.

Courtesy USDA.gov

www.scientificamerican.com/article/cactus-as-biofuel-could-help-with-food-versus-fuel-fight/ and gizmodo.com/this-humble-cactus-could-help-power-our-drought-stricke-1715966241

Large Scale Anaerobic Digestion of CAM Plants & Agricultural Waste?

A huge resource

Crop waste + dry-land CAM plants that you could add a vast amount

Electricity as cheap as coal?

By learning from cows, hope to reduce biogas plant sizes by a factor of 20 → big cost savings

Better than batteries

Biogas (easy to store)+ solar perfect for mini-grids

Valuable co-products

Biogas plant waste can supply charcoal, fish and fertiliser

FissION

See slide 114 and following + appendix for more on fission + fusion

- **Could play a much bigger role. Possible barriers:**
  - **Uranium?** Plenty – see slides 89 & 123 (then thorium, fast breeders)
  - **Public perceptions**
  - **Cost + financing are the real barriers**
- **Capital cost/kW$_e$ expected to *decrease* with size, but data *suggest an increase*** (power 0 to 0.10) - time over runs,…

  Doubling number of units has decreased cost in most cases, but by < 10% (new labour force; design modifications; new regulations;…)

→ Could Small Modular Reactors cut cost significantly?

- Design simplification
- Multiple units one site
- Production learning
- Standardisation
- Short build schedule
- Finance savings

Future Steps for Fission

Near term

- Larger reactors – focus on bringing down costs of PWRs and ABWRs

- SMRs – build some to see if they really are cheaper/kW$_e$. Funding? Regulation?

Longer term:

- Study/develop fast-breeders*, thorium*, molten salts, high temperature reactors – Generation IV consortium is studying six options: need to reduce number and start building proto-types before long

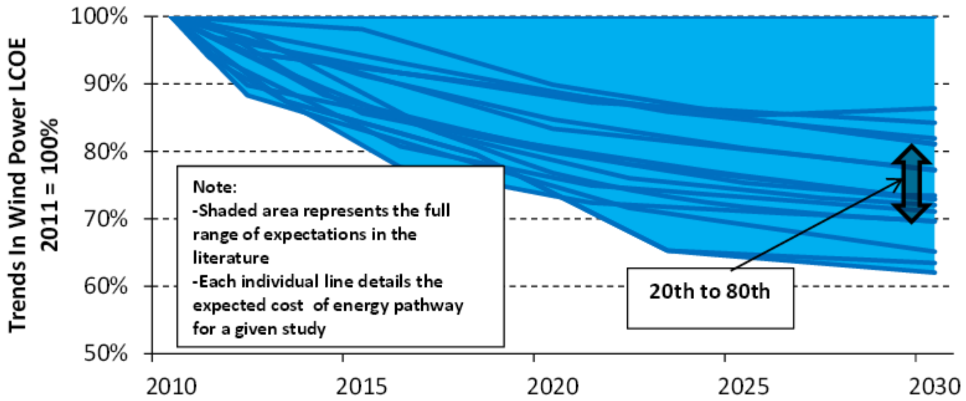
* will be needed (and/or fusion) if nuclear is to play a role in long-term: long lead time to develop/deploy, need to get moving in case a major expansion of nuclear power shortens life-time of uranium supplies

Cost Reductions for On-shore Wind?

Evolution:

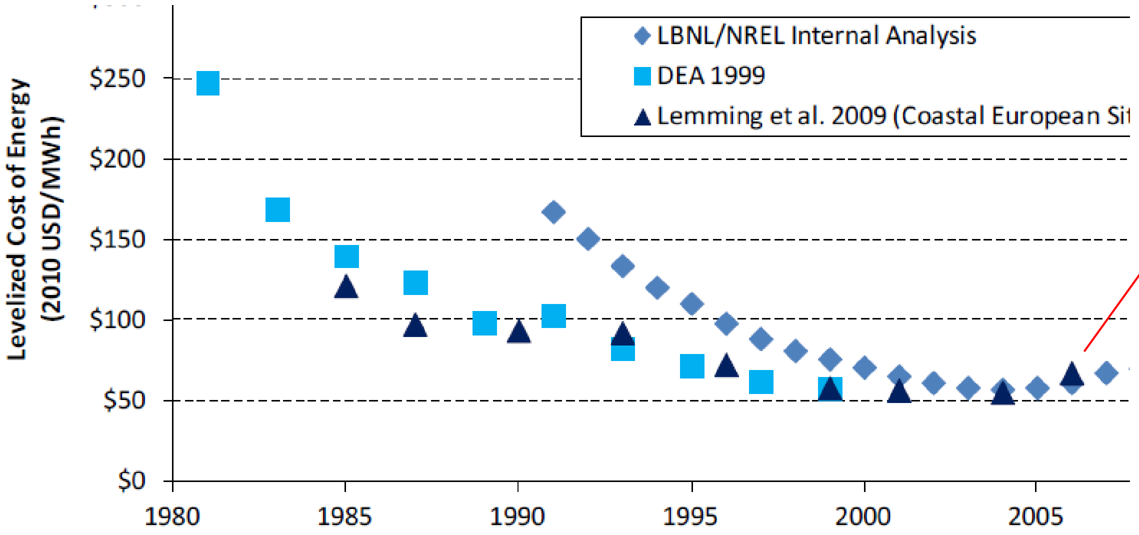
Anticipate improvements :

(IEA Wind Task 26)



LCOE Projections in 18 scenarios

Past trend:



Rising commodity prices

Revolution? Kites?? www.google.com/makani www.kitepowersolutions.com

Cost Reductions for PV?

Evolution

Module costs are falling rapidly

t

But:

Module now less than half the total

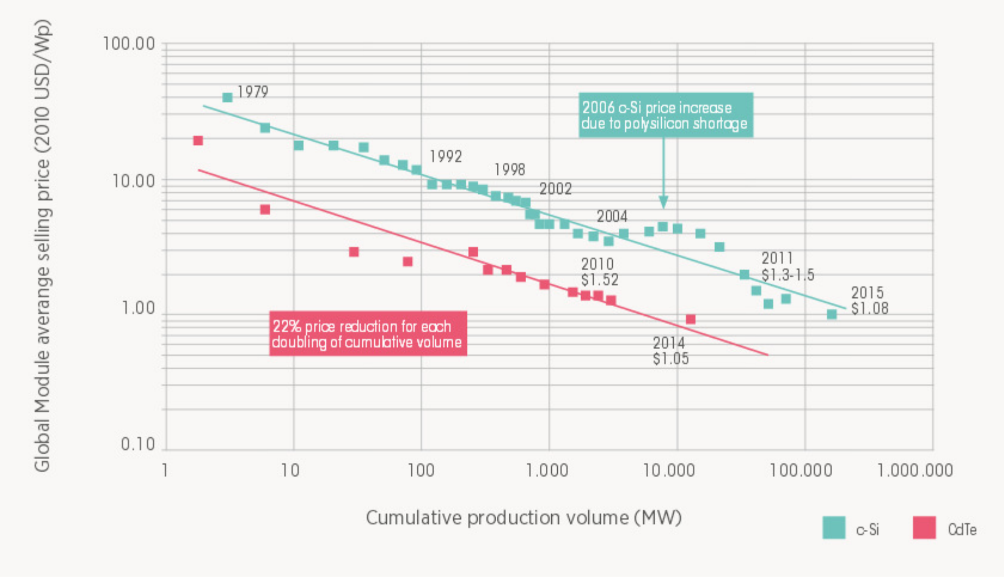


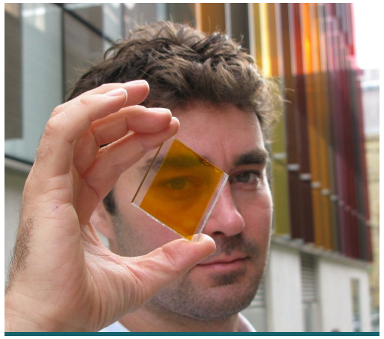
FIGURE 4.1 THE GLOBAL PV MODULE PRICE LEARNING CURVE FOR C-SI WAFER-BASED AND CDTE MODULES, 1979 TO 2015

Need to drive down cost of balance of plant (land, labour, inverters,…)
depends on location and system
German domestic costs (Q1 2006)/(Q3 2014) = 0.26 total, 0.19 modules, 0.43 balance of plant

Revolution? Perovskites, pioneered in Oxford

Solar Cells Based on Perovskites

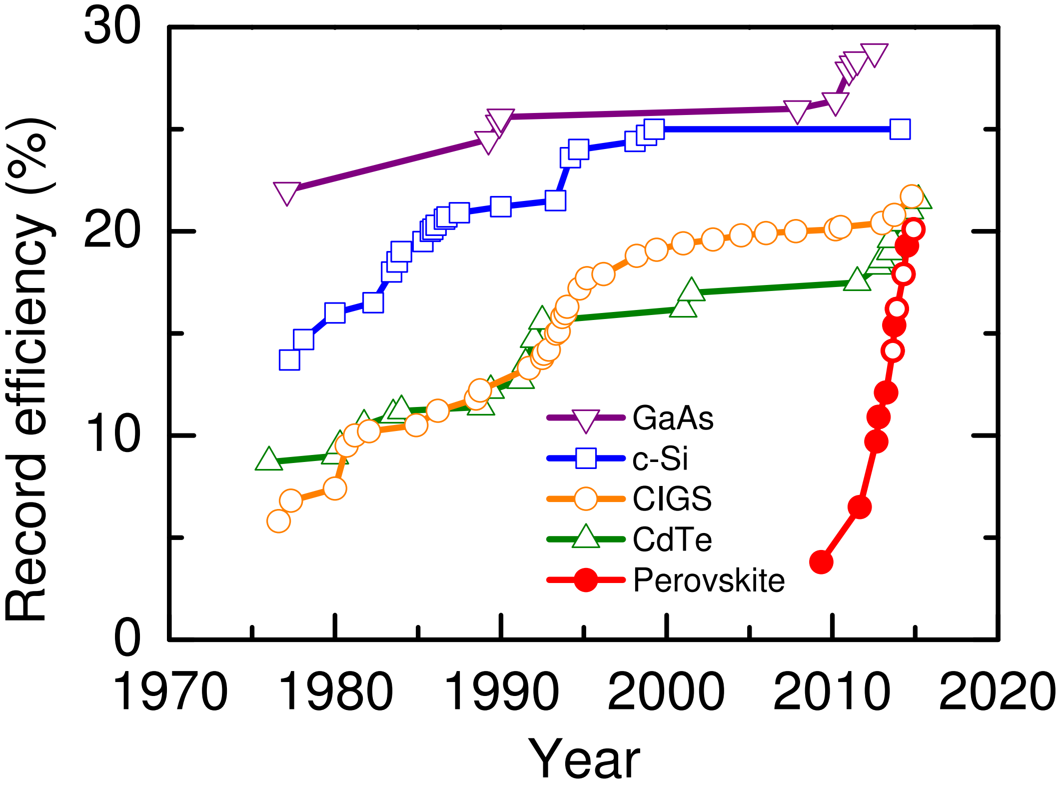
Pioneered by Henry Snaith
One of '10 people who matter'
according to Nature, Dec. 2013



Meteoric rise in efficiency:

Over 30% by 2016?

Looks as if they will be much cheaper than Silicon – but the target is moving



Conclusions on low carbon sources

- **Good news**
  - Generating costs for solar and wind falling rapidly
  - Bio may have a bigger potential than thought
  - Jury out on whether SMRs can lower cost of fission

BUT

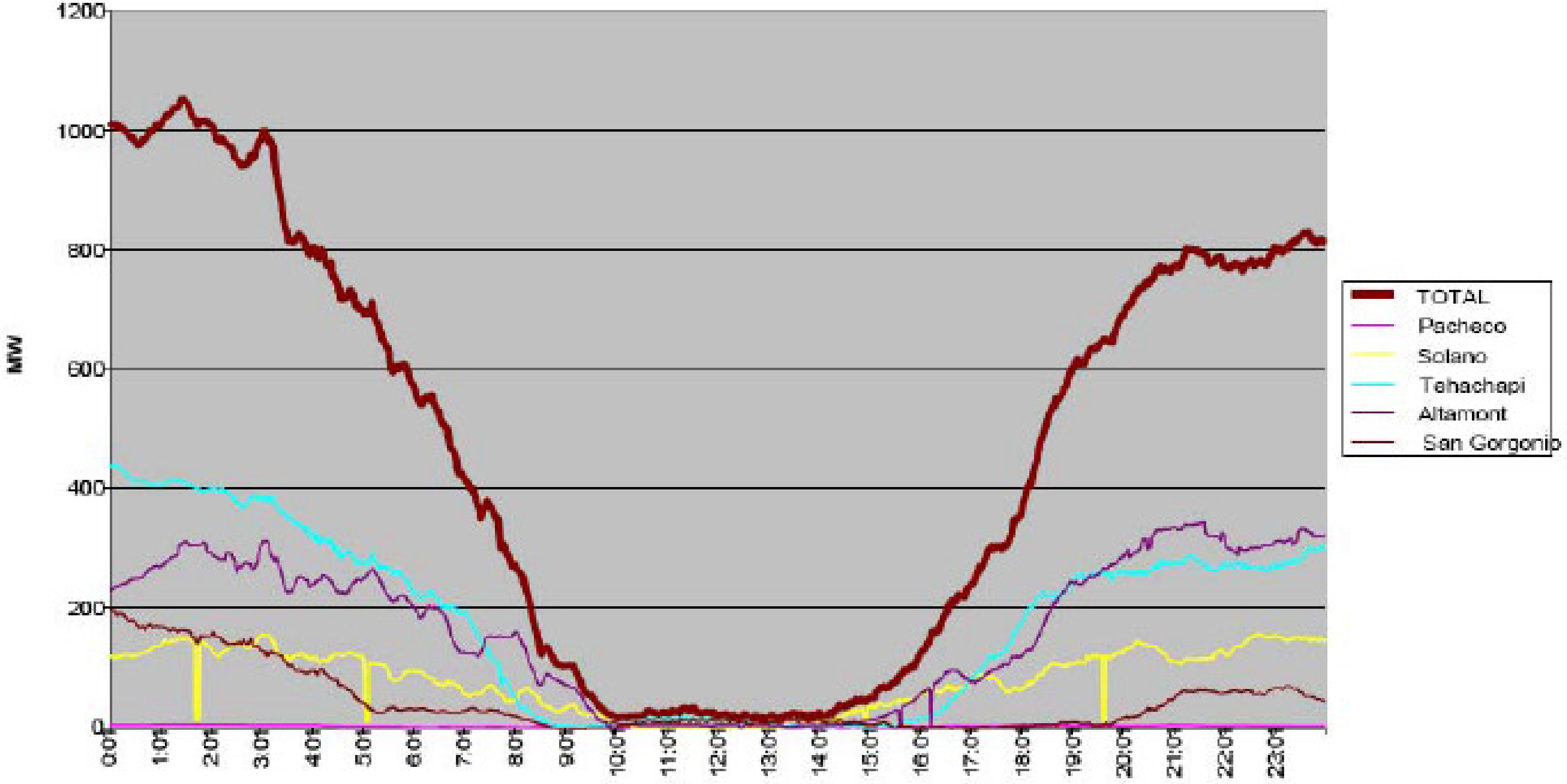
- Generating cost ≠ value for non-dispatchable/intermittent sources
- Cost of integrating solar & wind* will rise as their contributions increase ***needs strengthened/smarter grid; new ways to store energy; aggressive demand management*
- Electricity markets will have to be re-designed to deliver optimal solution

Now consider **Integrating Renewables** (issues ~ intermittency, studies of Germany with 100% renewables, storage, markets)

Intermittency: Wind In California

blows mainly in late afternoon and at night – when prices low

Extreme case (zero in middle of day!). Note: fluctuations smoothed in total:

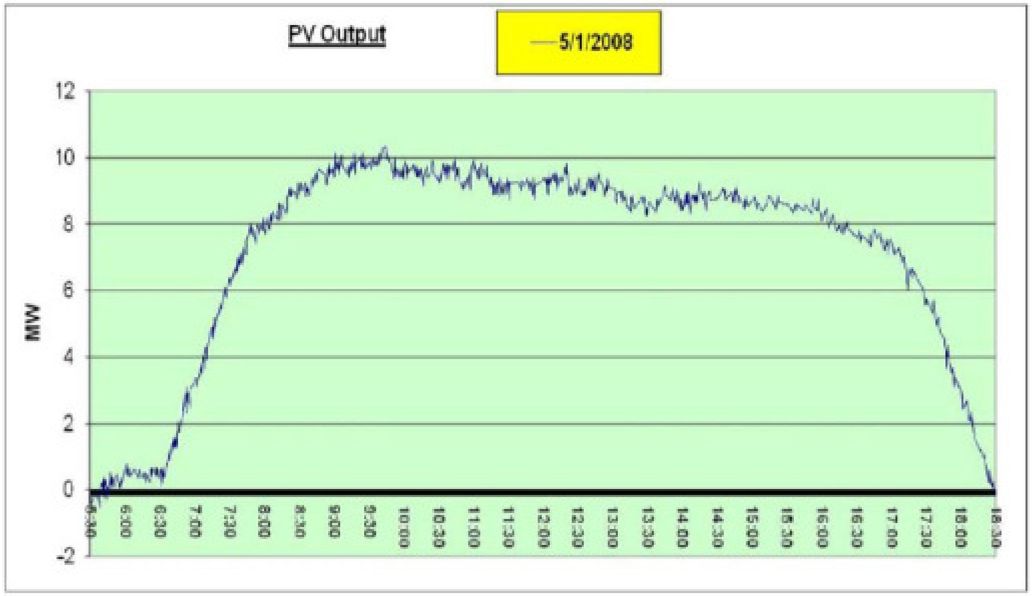


Source: NERC (2009), p.16

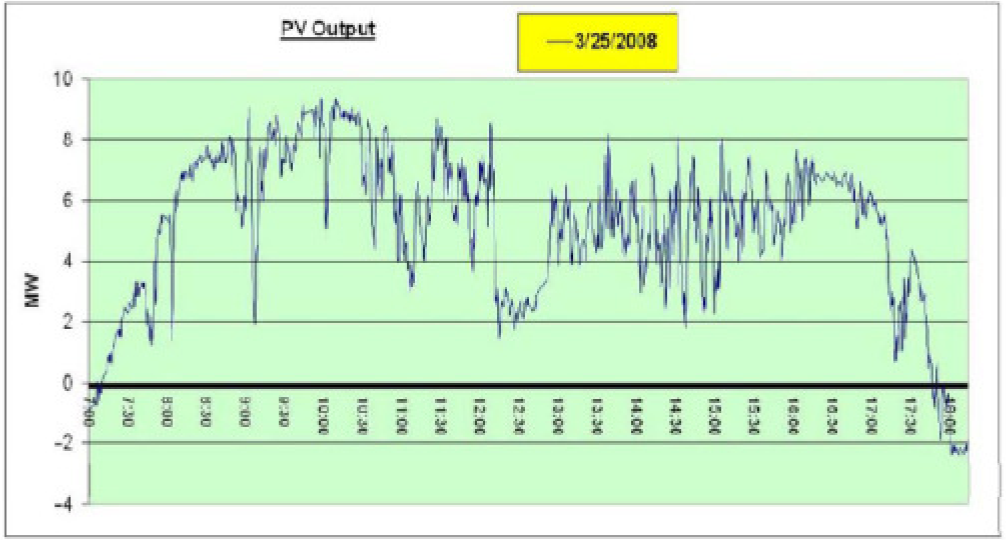
Solar PV in California

Well correlated with demand (especially air-conditioning). Can smooth for systems on the grid, but domestic systems need own storage (batteries)

PV plant output on a sunny day (Sampling time 10 seconds)



PV Plant output on a partly-cloudy day (Sampling time 10 seconds)



Source: NERC (2009), page 28

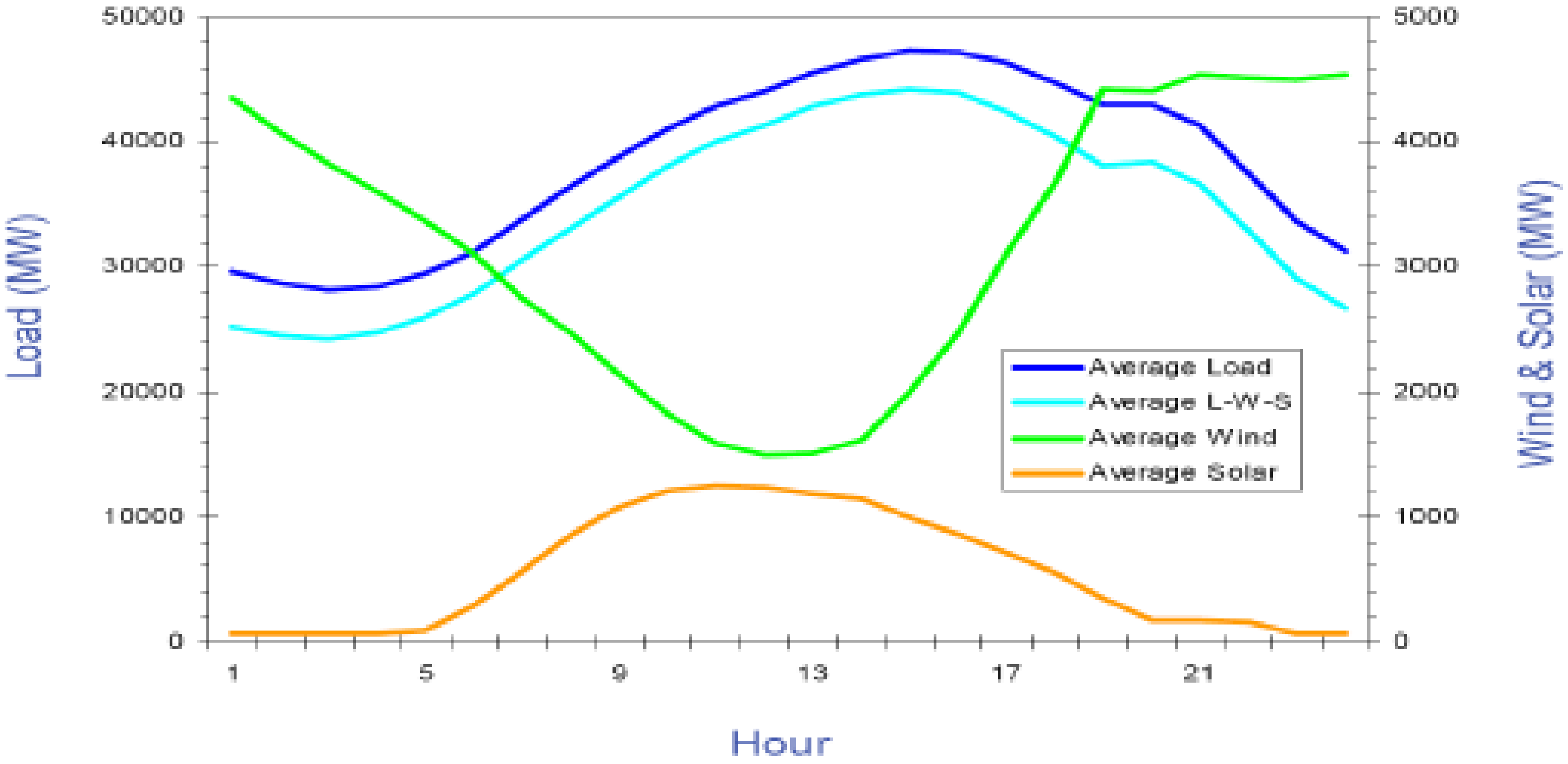
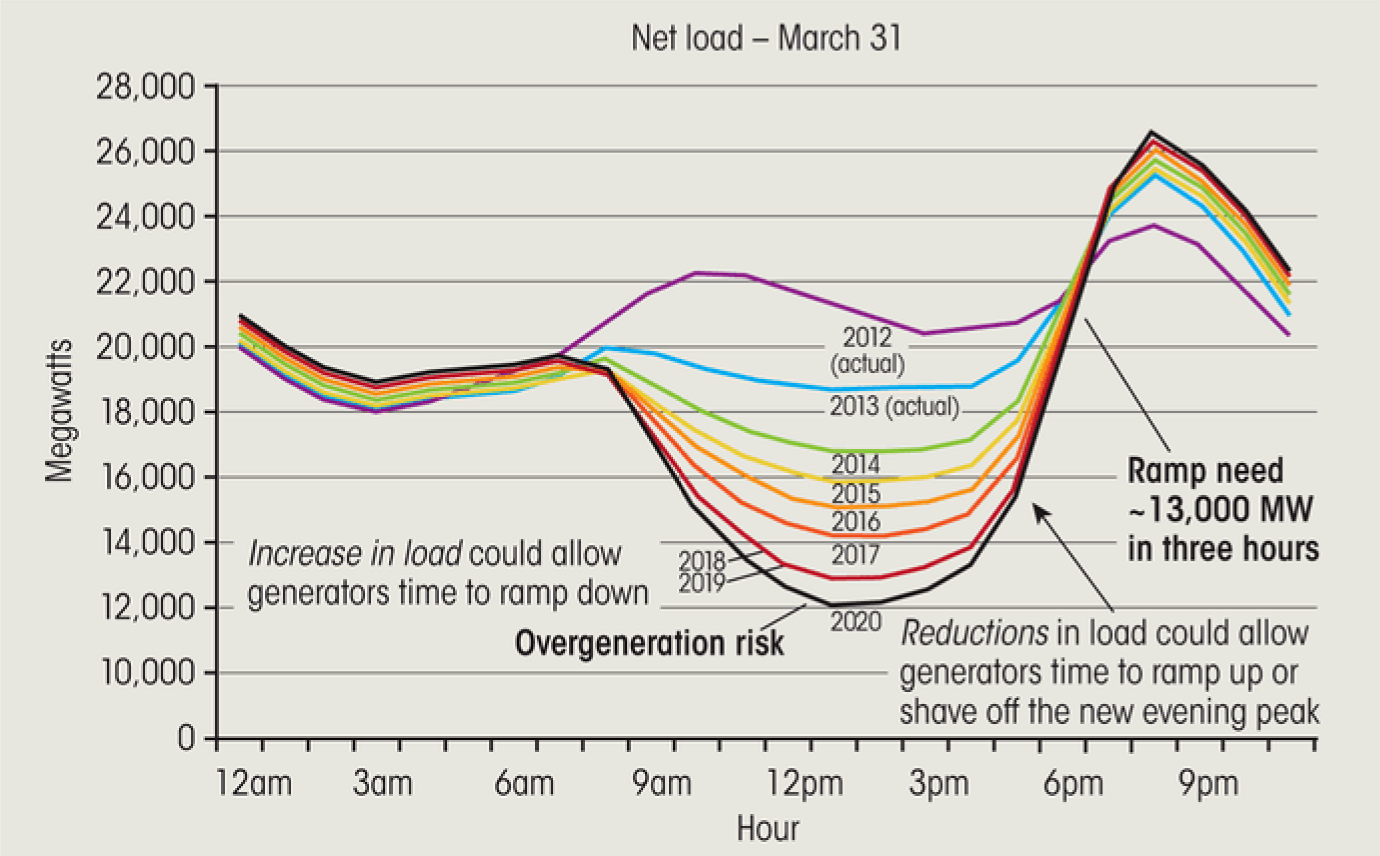


Figure 2.8: California average wind and solar output, along with net demand, July 2003.

Note: different scales

Solar and wind complementary, but solar is growing fast and the outlook today does looks more challenging →

California's Future Load Shape and Opportunities for DR = Demand Response



Increase in load could allow generators time to ramp down

Overgeneration risk

Ramp need ~13,000 MW in three hours

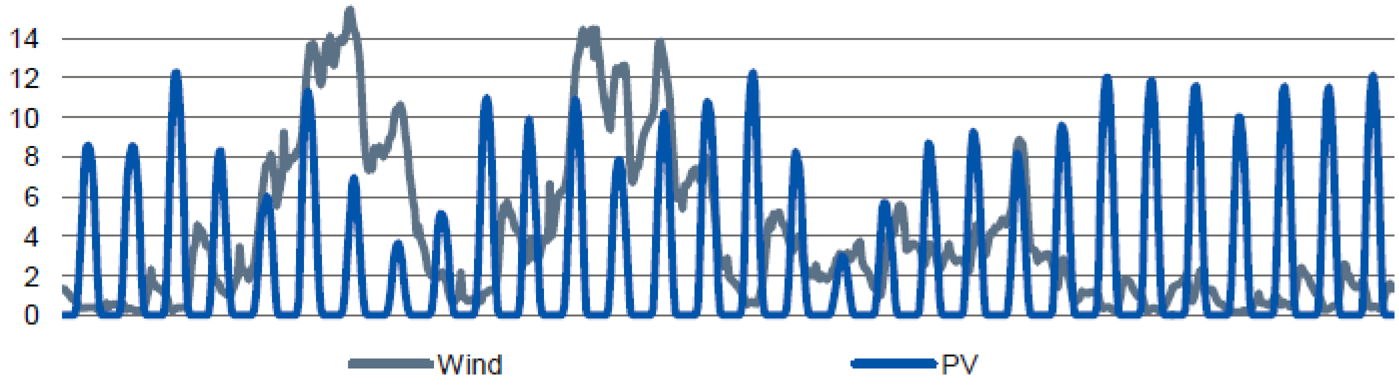
Reductions in load could allow generators time to ramp up or shave off the new evening peak

Increasing customer-sited solar generation is starting to produce a mid-day dip

Fluctuations in Wind and Solar in Germany

Fluctuations in wind and solar-generated electricity

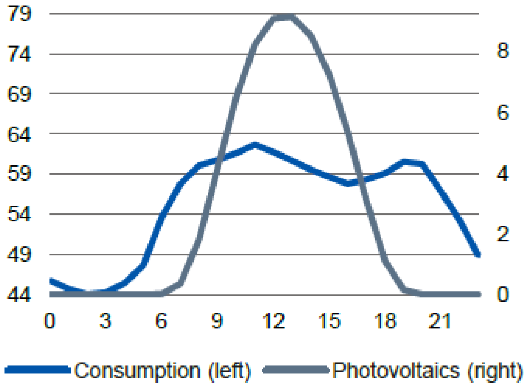
Hourly feed-in values (GW), Germany, September 2011



Source: ENTSO-E

Fluctuations in consumption and PV electricity over the day 5

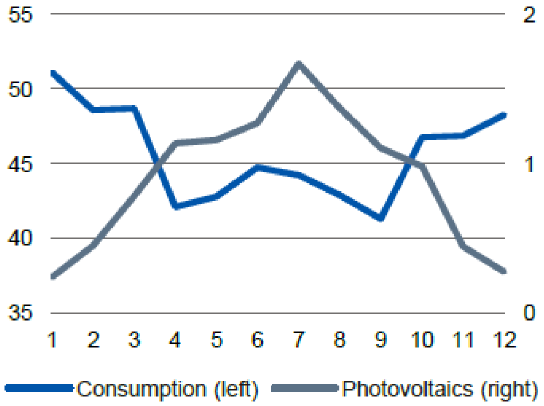
Daily averages (GW), Germany, September 2011



Sources: EEG/KWK-G, ENTSO-E

PV electricity generation over the year vs. consumption 3

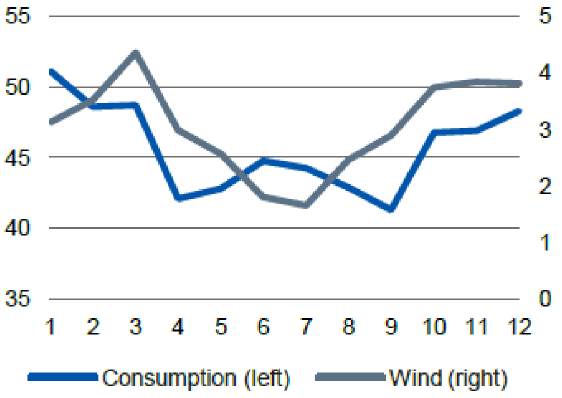
Monthly data 2010, Germany (TWh)



Source: ENTSO-E

Wind electricity generation over the year vs. consumption 4

Monthly data 2010, Germany (TWh)

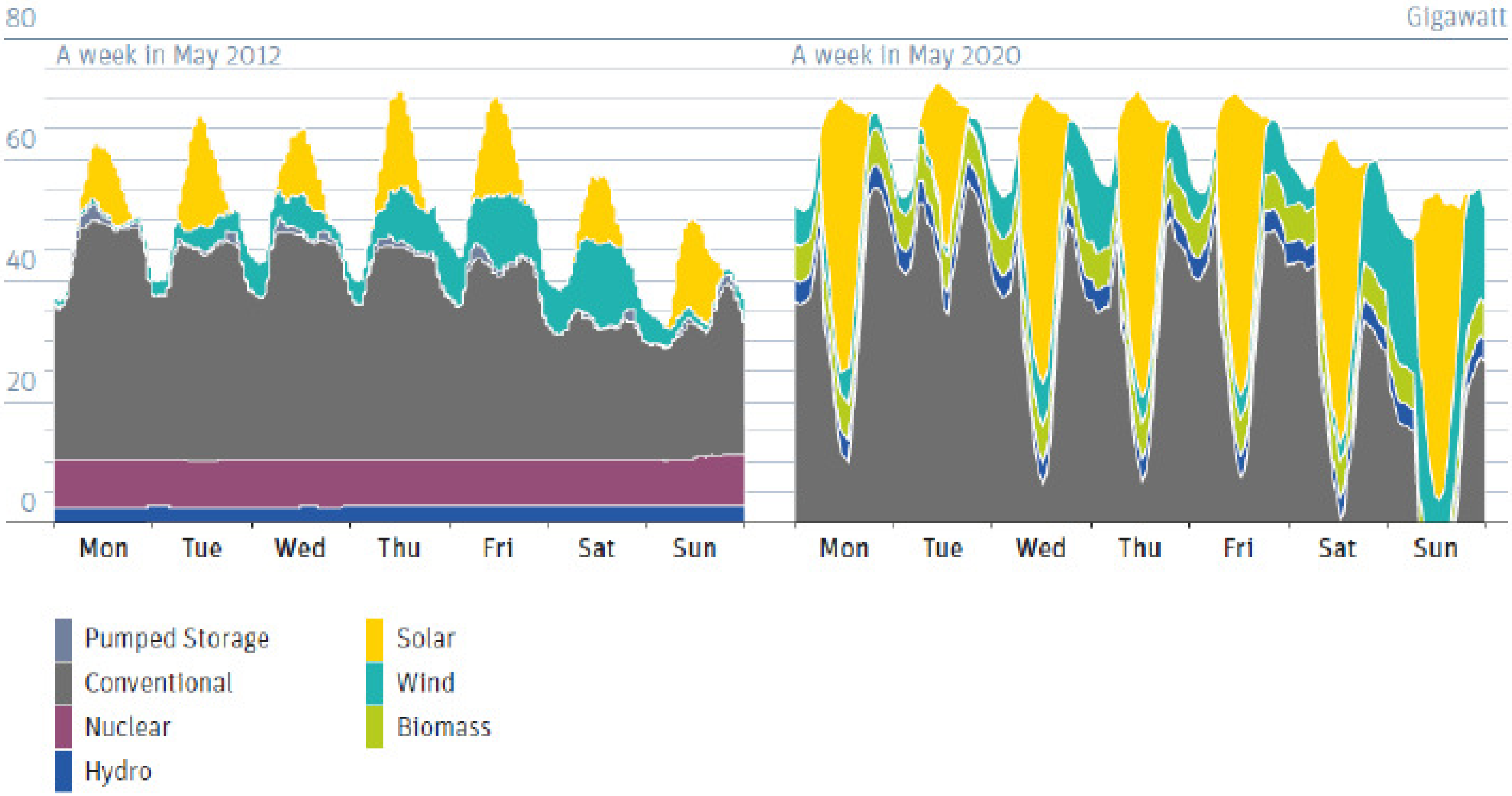


Source: ENTSO-E

Renewables need flexible backup, not baseload

Estimated power demand over a week in 2012 and 2020, Germany

Source: Volker Quaschning, HTW Berlin



Problems with Large-scale Wind & Solar

Illustration: two studies of powering Germany with 100% renewables (F Wagner and 'Kombikraftwerk' – Agency for renewable Power + partners, Frauenhofer, Siemens,…)

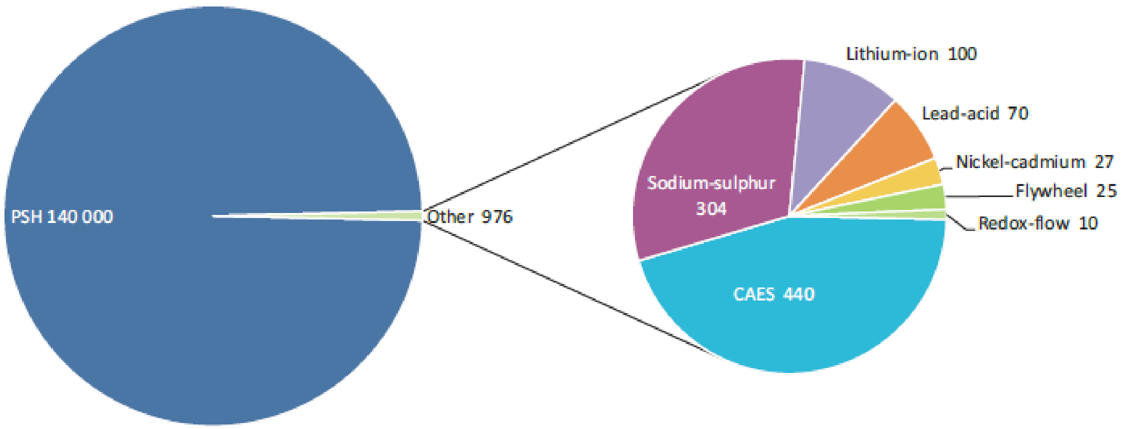
- Both Studies use usual actual data for demand, wind and solar in 2012
- Both Studies ~ 80% wind + solar; huge surplus (Wagner: 131 TWh in 2012, 27% of consumption); *require* ***lots of storage*** (Wagner: 33 TWh capacity ~ 600 x German pumped hydro, which is 5 x UK) *which* ***needs to be developed***
- Times when sun and wind do not blow: need ***very large, flexible****, not much used,* ***back-up*** (Kombikraftwerk assume huge amounts of bio-gas with large storage)
- ***Need much stronger/smarter grid***
- ***Aggressive demand management*** *very helpful*
- *Imports/exports* (**European super-grid**) *very helpful (but surplus too large and volatile for 100% export)*

It can be done in principle, but very difficult, very expensive + need market reform to make it happen

Storage 1

- **Want grid-scale storage on a time scale from m-seconds to months**
  - balance fluctuations; compensate for failures, *note: inflexible supply (nuclear, tidal,…) also creates a demand for storage*
  - absorb excess from wind and solar
  - reduce need for back-up (wasted capital when not operating; many systems inefficient if ramped)
  - …

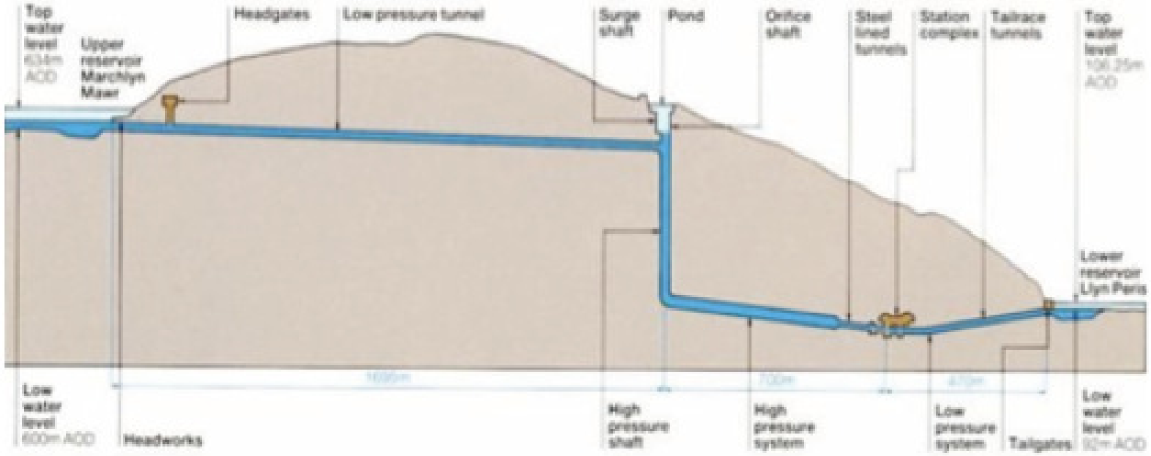
Figure 4: Current global installed grid-connected electricity storage capacity (MW)



140 GW pumped-hydro, capacity = 5% of average world load but would only last a few hours

Dinorwig (N Wales) Pumped Hydro

1.7 GW/8 GWh ~ 4% of average UK load for 5 hours. 16 seconds to reach full power



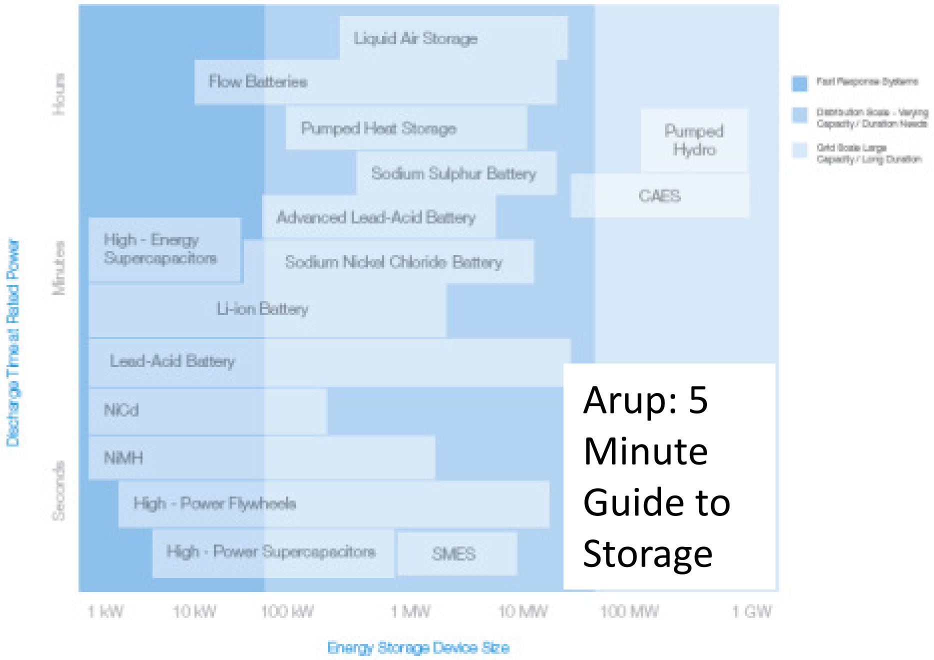
Source:
First Hydro, Dinorwig

Storage 2: Technologies

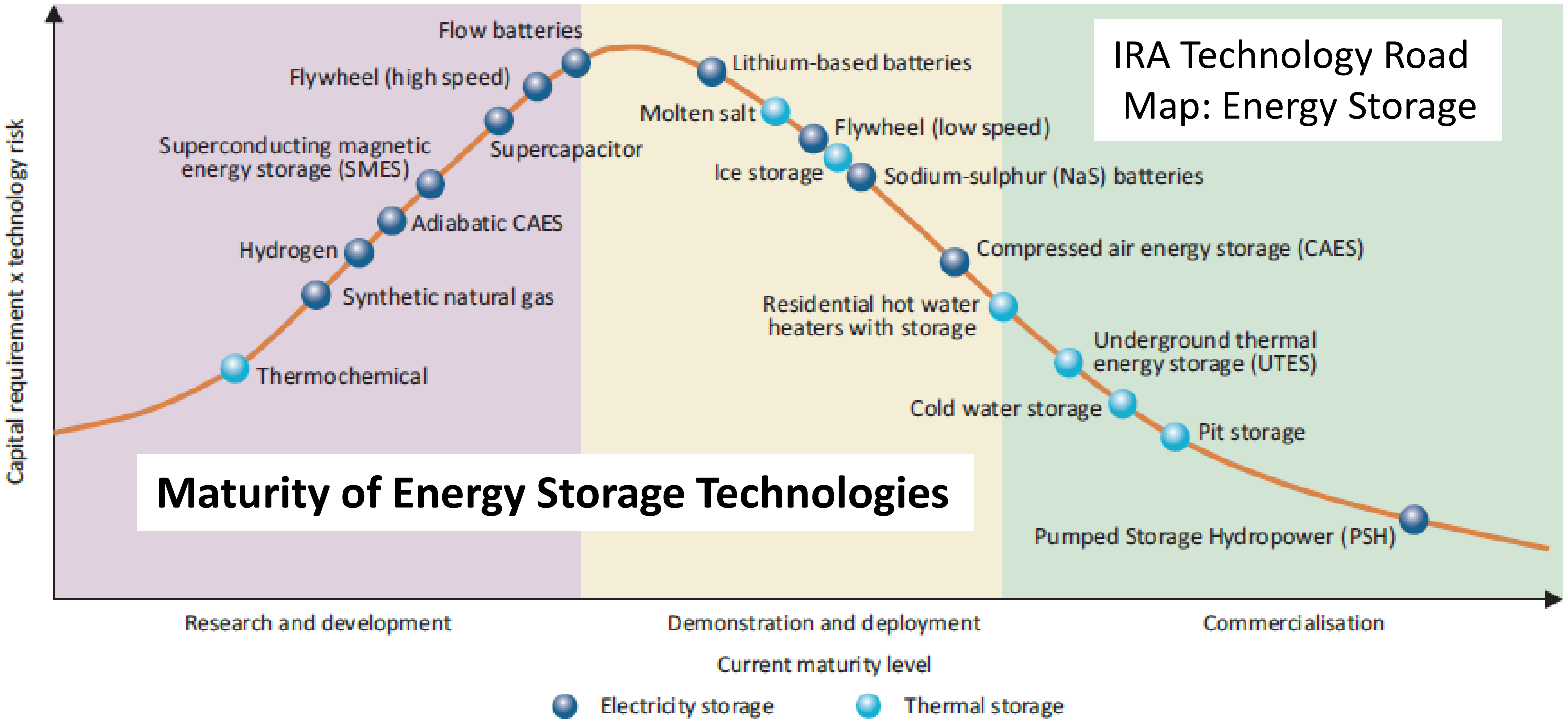
Need to consider:

Role; Scalability; Central vs. local; Energy vs. power; Cost; Efficiency;…

Comments on: Use of electric vehicles, hot water tanks; Power to gas (hydrogen, ammonia,…); Hot/cold pebbles; Synthesising hydro carbons.



Arup: 5 Minute Guide to Storage



IRA Technology Road Map: Energy Storage

Maturity of Energy Storage Technologies

Added Note

Here are the comments alluded to on the previous slide (which I did not have to make in the talk):

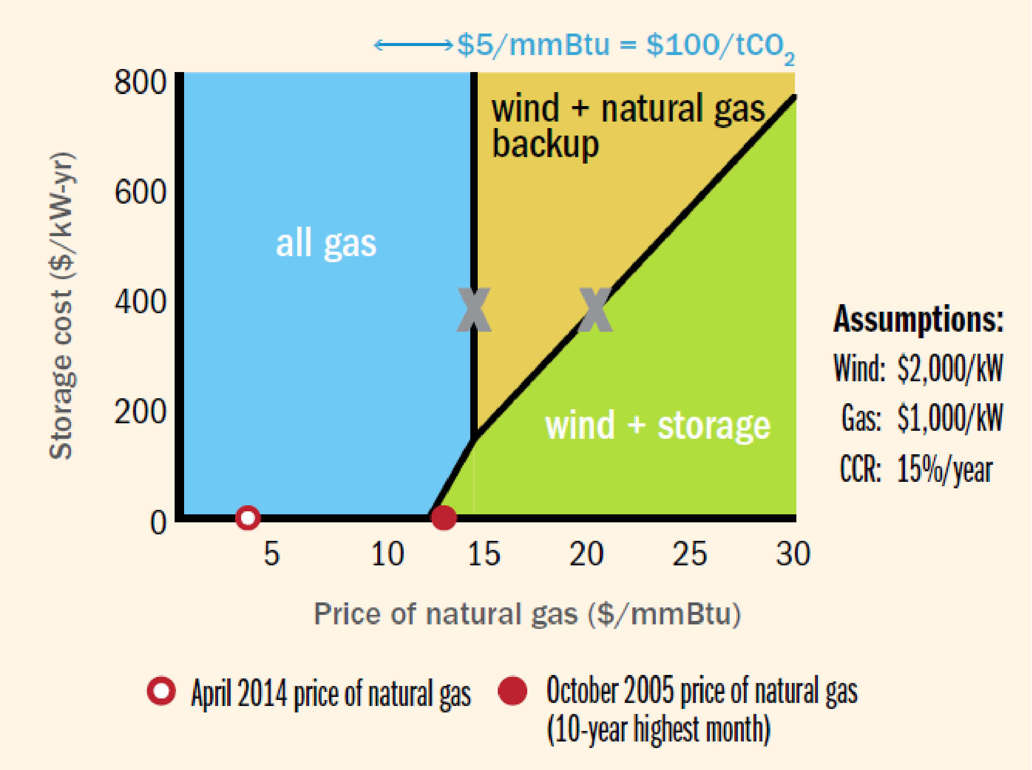
- **E**lectric **V**ehicles could be used for storage – although they tend to be used at times when additional power is needed, and their capacity won't be large for decades (see slides 75-76)
- Hot water tanks could absorb a lot of off-peak/surplus power: in the UK they store four times as much energy as Dinorwig (slide 59)
- Power can be turned to gas, and then back to power or used to power vehicles (which however would require wide deployment of fuelling infrastructure).   Most attention has been on hydrogen, but ammonia is attracting increasing interest – see www.stfc.ac.uk/news/hydrogen-breakthrough-could-be-a-game-changer-for-the-future-of-car-fuels/ for a new way of turning it into hydrogen
- For an example of interesting ideas on hot/cold pebbles see *www.**isentropic**.co.uk/*
- A lot of work has been done on synthesising hydrocarbons from CO2 - it would require a large source of CO2 close to a source of low-C energy, and at best be almost carbon neutral over the life-cycle, but the infrastructure for distributing hydrocarbons is of course in place

Storage 3

Economic Issues:

Competitiveness: highly simplified model with not unreasonable assumptions (Socolow et al) → (depending on gas price) need CO2 price to make storage viable:

Costs are annualized capital costs; the Xs correspond to $390/KW/yr for storage



- How to value? Must consider full benefits (less back-up, use all wind & solar, possibility of arbitrage,…)
- How to charge beneficiaries (part of generation or transmission?)?
- How to incentivise provision?

Issues for Electricity Markets

Underlying problems: i) supply and demand must match instantaneously, ii) ensuring security of supply considered a public good

Minimising cost while ensuring security of supply and meeting climate targets involves decisions on:

- Investment (in generation & transmission): requires model of future (variation in) demand (taking account of increase in electric cars etc.) + changes in supply (more local, with homes exporting as well as importing)
- Design of tariffs & regulations that will spread the load
- Operation: requires anticipating demand from minutes to days

Hard in a fully integrated nationalised model: much harder in a competitive market* - players must anticipate each others' behaviour

* no competition in transmission = a natural monopoly

Market competition claimed to lower prices (it seemed to do so in the UK initially: generators sweated assets, but did not invest properly for the future)

- but successful design of markets has to address many difficult questions (different - often incoherent – fixes introduced in different countries)

Questions for Electricity Market Design

- How to ensure investments → generation mix that meets climate targets?
- How to ensure sufficient capacity to meet maximum demand (last kWh = by far the most expensive)?
- How to ensure sufficient conventional generation - being displaced by zero marginal cost renewables when the wind blows/sun shines, undermining business case (German utilities facing bankruptcy)?
- How to ensure homes which generate their own power (and export surplus) pay a fair share for the grid (at the moment they are subsidised by those who buy all their power)?
- How to asses who benefits, and how they should pay, for strengthening the grid, storage?
- Who should provide storage (generators, distributors, others), and how should provision be incentivized?
- How to implement demand management, and integrate/balance with storage and stronger grid?
- ….

Towards Conclusions

Can the world's (growing) energy needs be met:

- **With fossil fuels?** *Yes for at least 50 years*
- **Without fossil fuels?** *With existing technology - incredibly difficult: impossible at a price society would be prepared to pay*

To meet future energy needs sustainably

technological advances are needed - *soon* since making large scale changes in energy infrastructure will take decades

- Now consider
  - Necessary technical actions
  - Necessary public policy actions

Necessary Actions - Technical

- Until at least mid-century fossil fuels will continue to play a major role, so *while developing CCS and alternatives,* it is **very important to**
  - **Replace coal with gas** as far as possible (pollution, CO2)
  - **Improve efficiency of use of fossil fuels**
- **To have a serious chance of decarbonising will need many or all of the following:**
  - Large scale affordable Carbon Capture and Storage
  - Radical reduction in use of oil in transport and wide deployment of heat pumps (both → more electricity)
  - Lower costs for solar and wind (happening) and learn how to handle them on a large scale (storage to be developed, super-grids, demand management, reformed markets)
  - Large scale biomass → electricity + biofuels (for flight)
  - Lower costs for nuclear
  - Big improvements in efficiency
  - Things we have not thought of
  - Devise economic and policy tools to make this happen

Ways to Save 1 billion tonnes CO2

Approximate

Power generation

- Switch 2,600 TWh coal* to gas (2012: coal 40.3% of power → 28.9%; gas 22.4% → 33.8%)
- Install 80% efficient CCS on 1,420 TWh coal (2012: 13% of all coal generation)
- Replace 1,150 TWh from coal* with nuclear (2012: 10.8% → 15.9%)
- Replace 1,150 TWh from coal* with renewables (2012: hydro 16.5% → 21.6% ***or*** increase other renewables 5.0% → 10.1%)
- Increase average efficiency of coal* power generation from 33% (2012) to 38%

Efficiency in End Use

- 22% improvement in efficiency in 2012 road transport
- 11% improvement in energy effiency in 2012 industry

But the 450 ppm target requires saving 18 bn t in 2035 relative to a scenario that already includes a lot of these measures

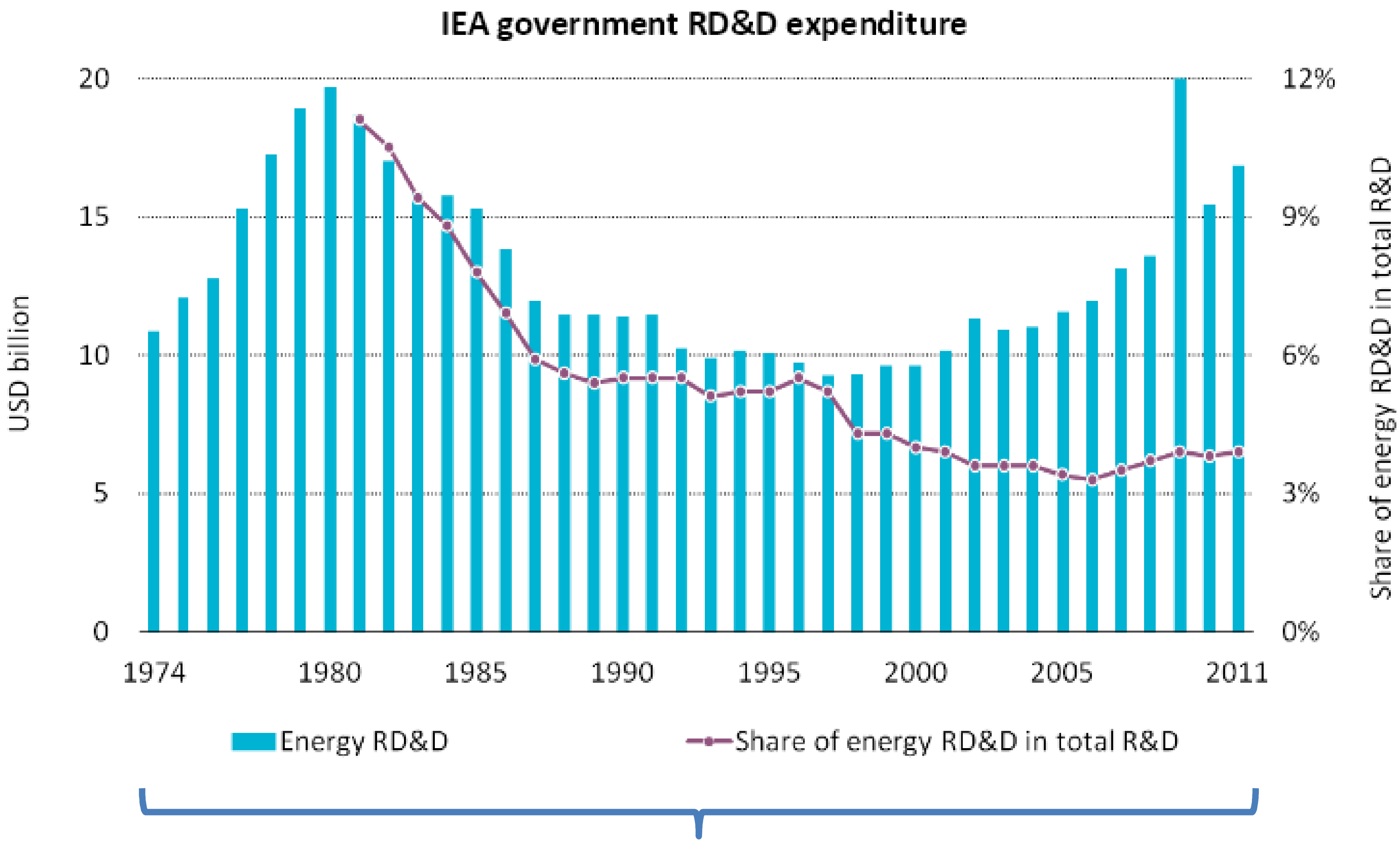
(IEA NPS: coal → 36.4% efficient; gas generation + 3,600 TWh, but coal + 2,500 TWh; hydro + 60%; nuclear + 77%; renewables in power generation x 4)

* *Reduction in coal use also reduces methane emissions in mining*

Necessary Actions - Policy

- **Better planning to reduce demand –** *especially in growing cites/developing countries*
- **Stronger regulations,** vehicles, performance of appliances, buildings…
- **Phase out $550 billion/year of subsidies for consumption of fossil fuels** (only 8% benefits world's 20% poorest people)
- **Carbon tax** (provides more certainty than cap and trade) + in the absence of global agreement: **B**order **C**arbon **A**djustments

  (or regulate power plants)
- **Increase the $120 billion/year subsidies to launch* new not yet cost-effective energy sources and efficiency measures**
  *then phase out
- **Adopt policies** (what?) **that stimulate innovation, and increase long-term publicly funded R&D**
- **Reform electricity markets**

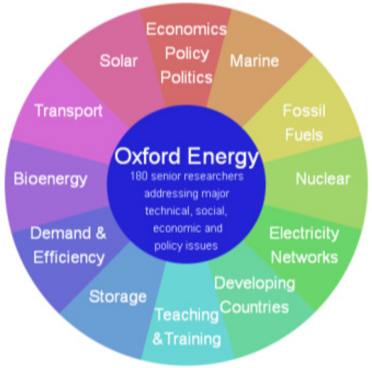


In this period world energy use increased 113%

Concluding Remarks

- To allow everyone on the planet to lead decent lives, much more energy will be needed
- We can meet the need with fossil fuels for (at least) 50 years - but we should be decarbonising
- No real progress with decarbonisation
- Decarbonisation is possible, but will require developing and implementing new technologies and new policies
- Large scale changes in energy infrastructure take decades – so action is needed now

Malthusian “solution” if we fail?



The Outlook for Energy Supply and Demand

Lecture 2

Chris Llewellyn Smith

Director of Energy Research, Oxford University

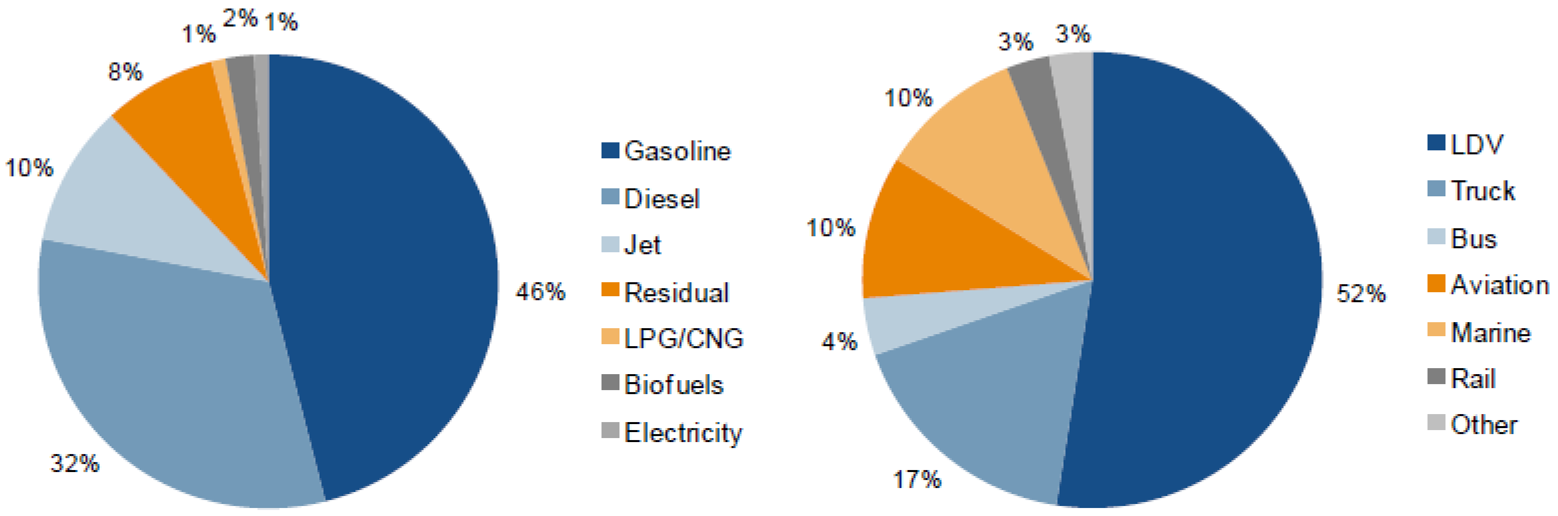
President SESAME Council

www.energy.ox.ac.uk

Transport

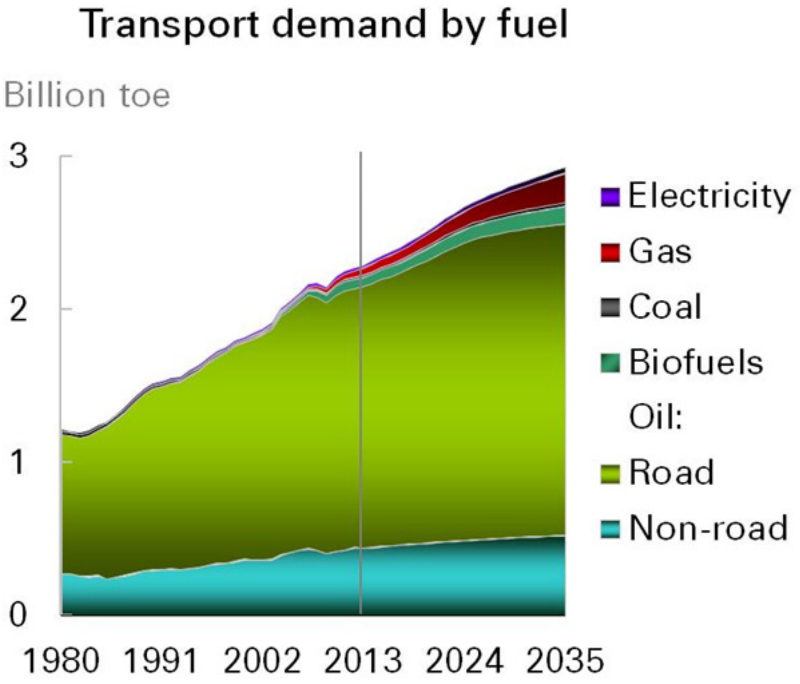
- Uses
- Fuels & trends
- Vehicle ownership
- Vehicle trends – efficiency, types

Transport Uses & Fuels



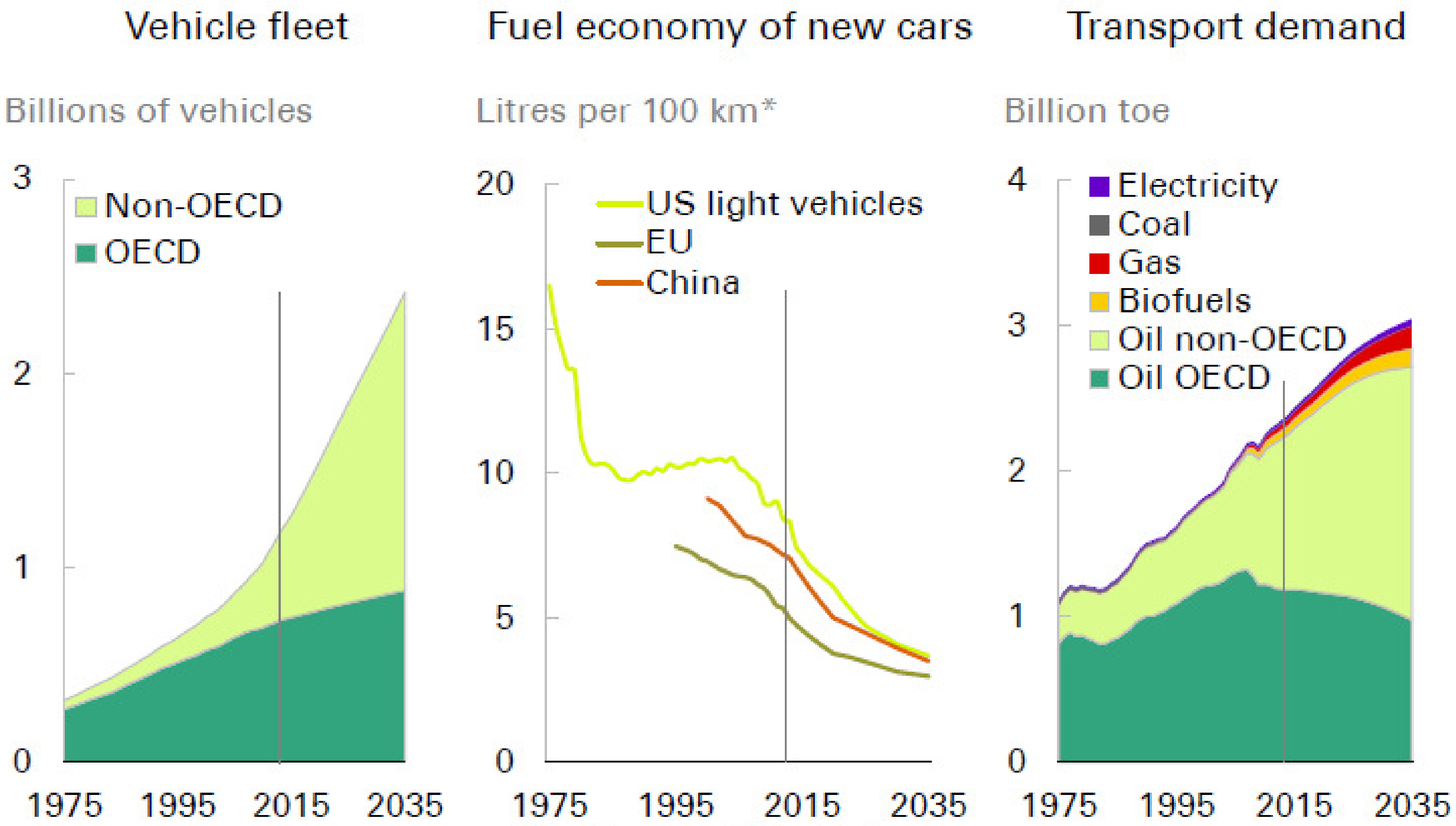
2010 Snapshot (WEF)

BP Projection:



Vehicle Ownership and Energy Demand

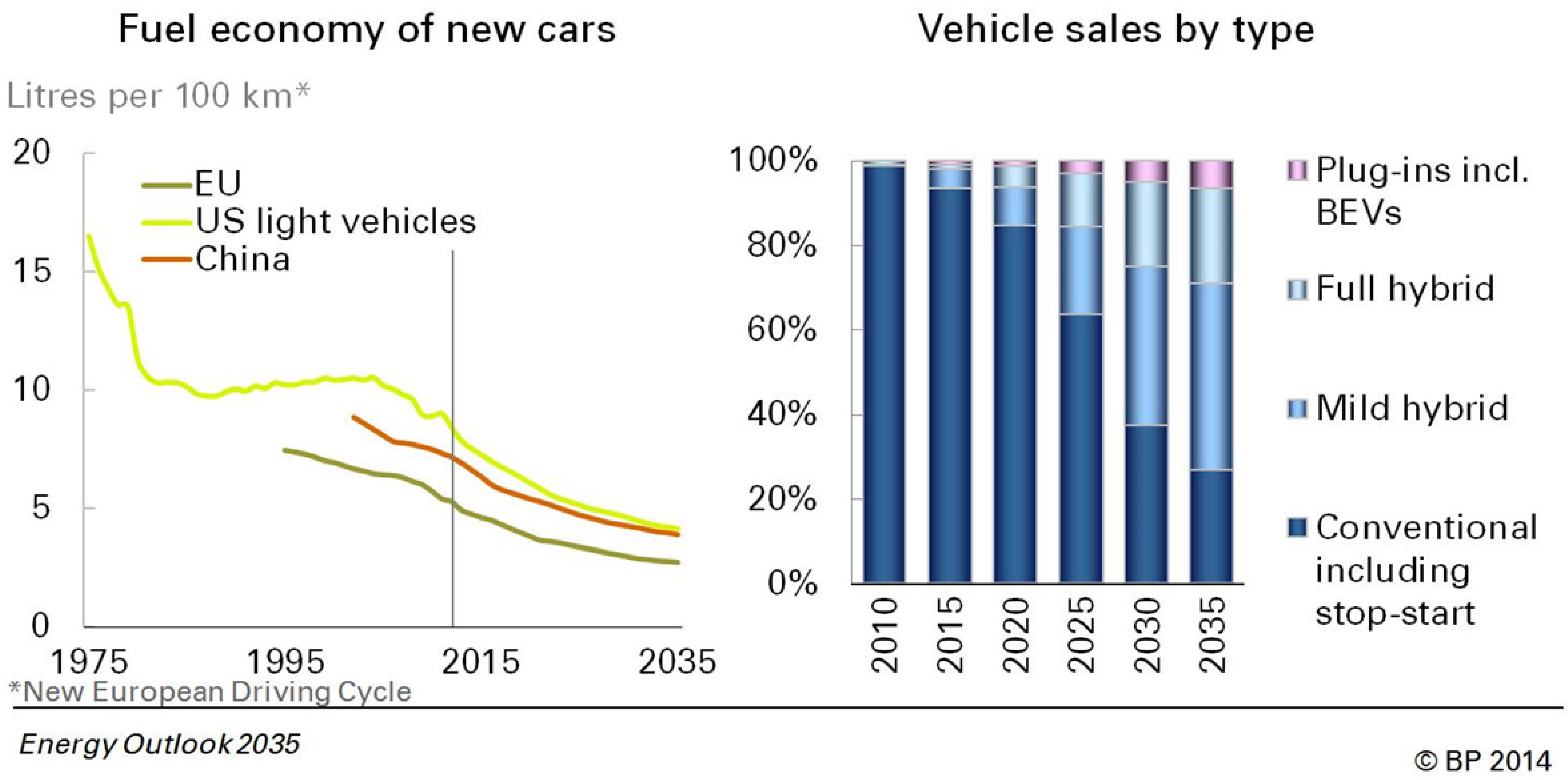
Vehicle numbers are likely to grow rapidly…



*New European Driving Cycle

Energy Outlook 2035

Increase in effiency makes conventional cars a moving target for electric cars, which BP thinks will come in slowly:



Fuel economy of new cars

Vehicle sales by type

Energy Outlook 2035

© BP 2014

Electric Cars

CO2 and Electricity demand

- **To save CO2 need relatively decarbonised power supply:**

  Compare 5,000 kms in

  - petrol powered car @ 5 litres/100 km → 0.6 t CO2
  - electric car → 1 MWh →

    0.8 t CO2 if electricity all from coal

    0.5 t CO2 if electricity all from natural gas

- **Move to electric cars (which is likely to be slow?) will → large but not sensational increase in electricity demand:**

  If *all* UK's 30 million cars → electric, would increase total electrity demand by ~ 15%

Heat

- Challenge of Decarbonisation
- Heat pumps

Heat

Although the calls on primary energy are *approximately*:

Heat ≈ Electricity ≈ 40%, Transport ≈ 20%

heat gets relatively little attention, presumably because

Very hard to decarbonise heat: use less (better insulation), Combined Heat & Power*, heat pumps – need low carbon electricity *(next slide)*

Transport → more efficient/hybrid/electric cars

Low carbon electricity is key

***CHP** can turn ~ 80% of primary energy into electricity + useful heat

Currently → 10% of world electricity from CHP

Heat Pumps

refrigerator = best know example

Coefficient **O**f **P**erformance = (heat pumped)/(work done in pumping)

= (Heat from electrical energy via heat pump)/ (Heat from same electrical energy directly)

Depends on temperature difference [Carnot maximum = $T_H/(T_H-T_C)$]

UK's Heat Pump Association quotes typical COP for Ground [Air] Source Heat Pump of 3.2 [2.9]

Advantages?

Cost: assuming electricity price = 3 x gas price, and (gas → heat) is 90% efficient, then operating a heat pump costs less than using gas to heat house provided COP > 2.7 – *although the capital cost of heat pump >> boiler*

CO2: assuming 37.5% electricity generation efficiency and 90% boiler efficiency

Gas → Electricity → Heat Pump with COP = 3.2 [2.9] → Heat generates 25% [18%] less CO2 than Gas → Heat

With current UK generation mix, heat pumps provide very little CO2 gain

Heat Pumps and Electricity Supply

Move to heat pumps (likely to be slow) will → large increase in electricity demand, especially peak demand, e.g.

In UK:

Providing all domestic and commercial space and water heating (now supplied by fossil fuels + resistive electrical heating) with heat pumps would **increase**

- **average electrity load by ~ 15 GW**, c/f current average of 40 GW
- **peak load by a factor of order two!!** (current peak ~ 60 GW)

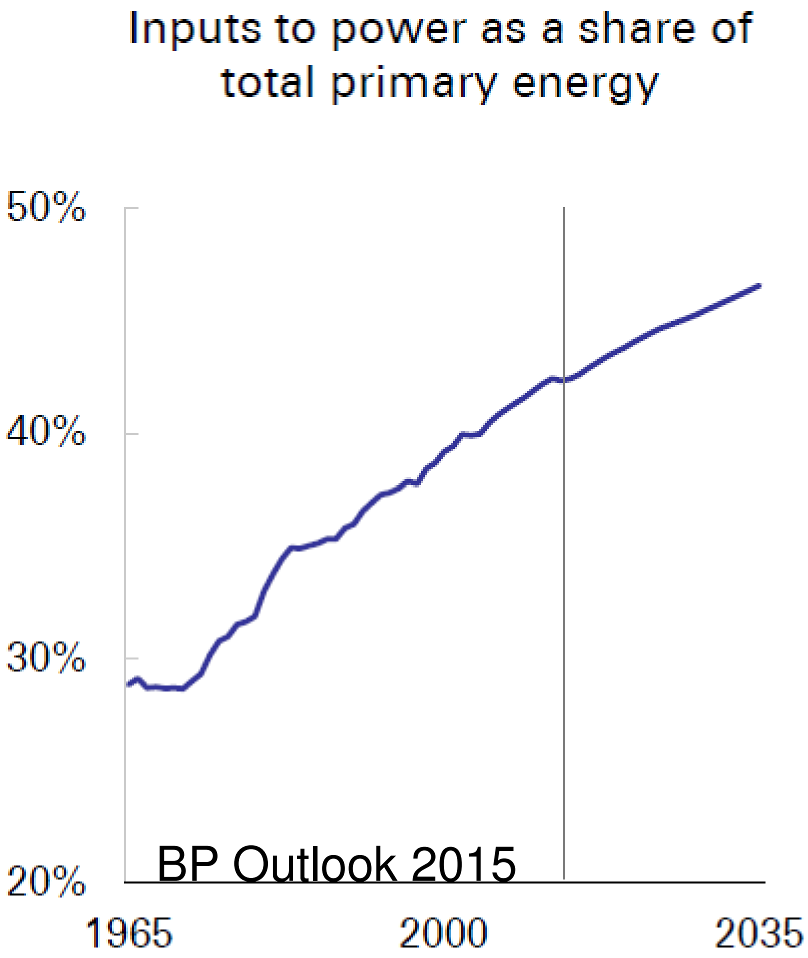
In 2014 **industry used ~ 210 TWh of fossil energy** (not including that used to provide ~ 100 TWh of electricity , c/f total UK electricity use ~ 350 TWh)

- ***this will be extremely hard to de-carbonise***

Electricity

- **Sources & trends**
- Generations costs – see Colloquium slides 40, 41 and following
- **The grid & smart grid**
- Problems with intermittent renewables – see Colloquium slides 50-57
- Energy Storage – see Colloquium slides 58 - 62
- Markets – see Colloquium slides 63-64

Share of Primary Energy → Power Generation



Growth is mainly from non-OECD Countries:

2012	IEA Data & Definition mtoe	
	Primary energy	Primary energy to power
OECD	5351	2198 = 41% of PE
Non-OECD	7760	2893 = 37% of PE
2035 NPS Projection		
OECD	+ 3%	+7.5% → 43% of PE
Non-OECD	+ 50%	+ 84% → 46% of PE

The small difference between BP and IEA's (primary energy to power)/(primary power) ratios is due to i) BP's omission of most waste and biomass, and ii) differences in the definition of primary energy

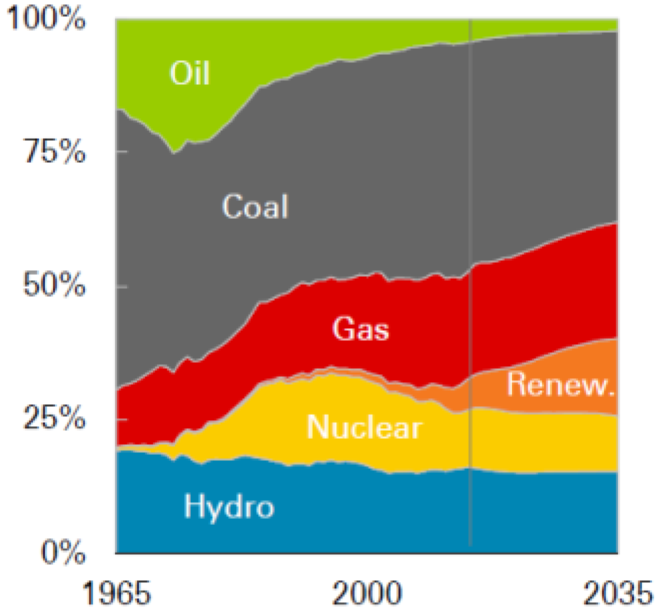
Electricity Generation

Source

	IEA 2012
Total TWh	**22752**
Fossil	**67.7%** Coal 40.3% Gas 22.4% Oil 5.0%
Hydro	**16.5%**
Nuclear	**10.8%**
Wind	**2.3%**
Biomass	**1.5%**
Solar	**0.45%**
Waste	**0.42%**
Geo	**0.31%**
Marine	**0.0022%**
Σ Renewables	**21.5%**

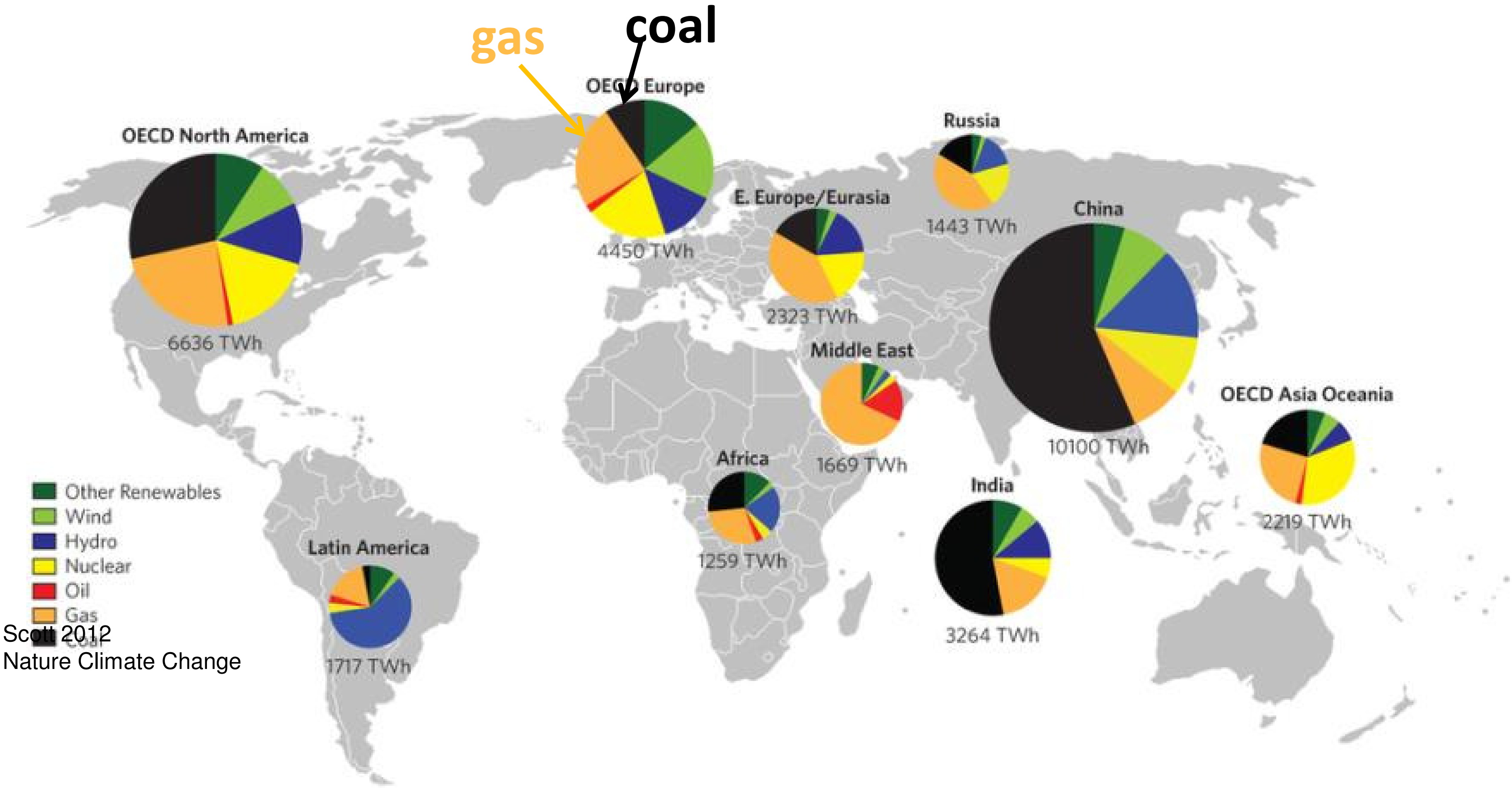
Trends

Electricity	**Increase 2008 - 2013**	**% in 2013**
Total	15%	100%
Hydro	18%	16%
Wind	190%	2.7%
Bio + Waste	66%	1.8%
Solar	1000%	0.54%
Geo	1%	0.30%



Expected electricity Sources in 2030 (IEA NPS 2011)

Note major differences in different countries



Scott 2012
Nature Climate Change

More recent projection for 2030:

4% less **Coal**, but still 22% more than in 2012

7% more **Gas**, 54% more than in 2012

The Grid

	Generation →	Long distance transmission →	Intermediate/ local →	Industry… → Households
Voltage	2-30 kV	120-1000 kV	3-130 kV	240 V (UK)
Losses ~ $1/V^2$	**UK:**	~ **2%**	~ **6%**	

Long-distance transmission DC vs. AC

DC has larger fixed cost (AC-DC conversion) but lower cost/km (AC: higher peak voltage → thicker cables for given power, but stepping voltage up/down easy)

High voltage DC: better than AC above ~ 900 km for 1 GW (500 km for 500 MW) + underwater above ~ 10 km (?), e.g. under English channel

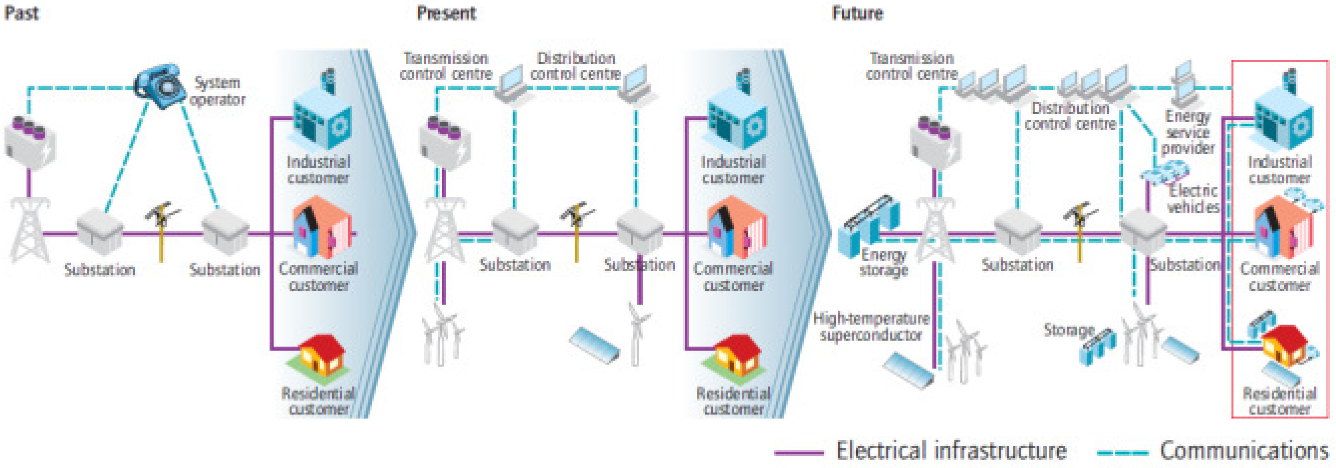
[Superconducting? Conceivably, but not soon - unlikely (?) without higher temperature sc]

Super-grids: benefits/cost sharing needs analysis

The flexibility provided by a very large grid would help accommodate local fluctuations in supply and demand

Smart Grid

with multiple connections between diverse sources & users, bidirectional flows, feed-back between suppliers, users & the grid operator, …



is needed to minimise cost, maximise reliability, optimally integrate intermittent renewables & accommodate new users (electric vehicles,…) and provide

- real time information to operators on demand, power quality & supply to allow them to monitor, manage constraints, integrate
- information to consumers enabling real-time pricing & incentives to adjust use

→ efficiently balance supply and demand + lower peak load

Questions for Markets: incentivise provision of last kWh and upgrading grid; deal with big changes in supply (inflexible renewables with low marginal costs) & demand,…

Fossil Fuels

- Resources
- Environmental impacts
- Prices
- Coal
- Oil
- Gas
- Shale and fracking

Saudi saying: “My father rode a camel. I drive a car. My son flies a plane. His son will ride a camel”. **Is this true? I think not**

- Production of **conventional oil** in conventional places likely to peak soon, **but**

  Plenty of other oil: altogether IEA thinks enough for 170 years at current rate of use, although a lot of it is *(currently)* relatively expensive to extract

- **IEA thinks enough gas/coal for 240 years/2,900 years years at current rate of use**

- **Fossil fuels able/likely* to continue to play a dominant role for a long time**. Don’t be surprised by increasing oil prices as use of unconventionals in remote places increases, but don’t bet on it

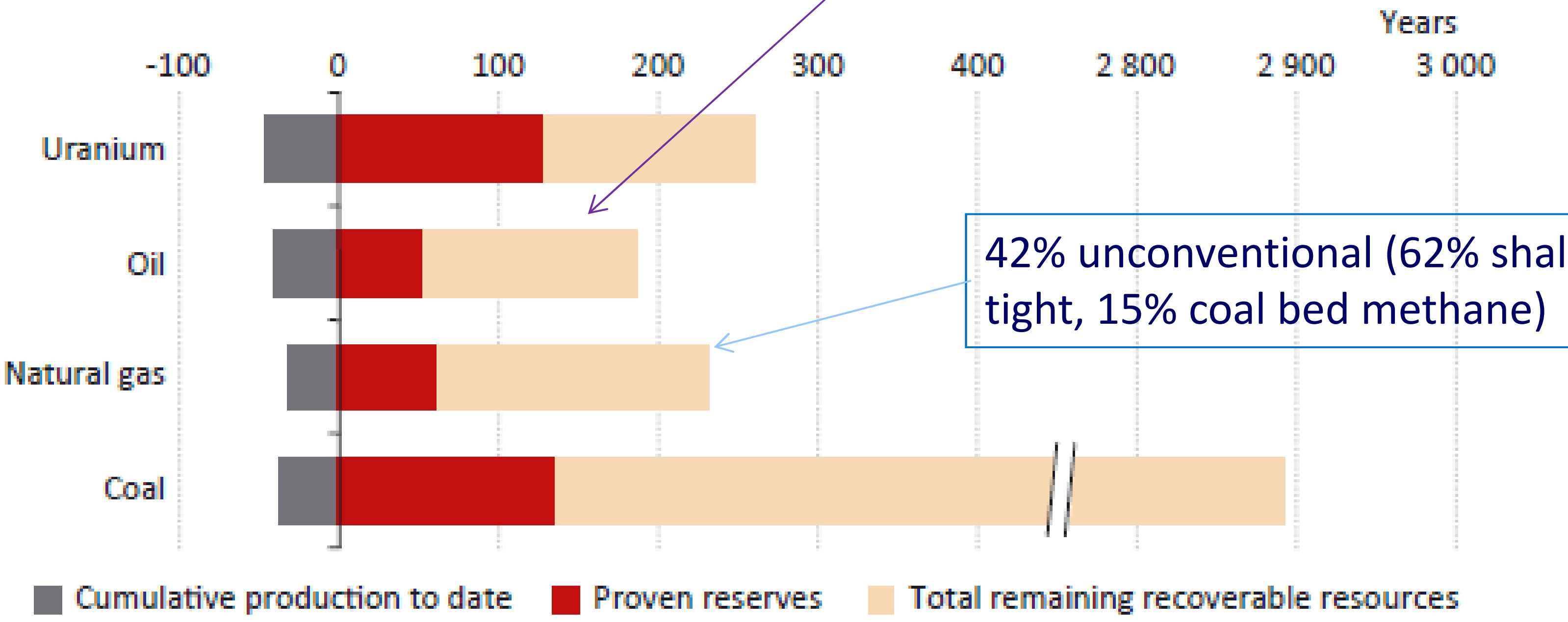
  **in which case CCS or other NETs will be essential to mitigate climate change*

But in the (very) long run they will become increasingly scare and expensive

Fuel Resources (IEA WEO 2014)

- remaining years at current rate of use

45% conventional (37% of-shore > 1/3 deep water)
55% unconventional (57% EHOB, 33% Kerogen, 10% tight)



42% unconventional (62% shale, 24% tight, 15% coal bed methane)

* Expressed as number of years of produced and remaining resources based on estimated production rates in 2013. For uranium, proven reserves include reasonably assured and inferred resources (see Chapter 11 for more details).

Oil and gas expected to be revised upwards as technology improves

Coal is the Major Problem for the Environment

- Comparison of fossil fuels using IEA numbers for world average efficiencies (in detail depends on quality of coal…):

	Coal	Oil	Gas
CO2/thermal energy	1	0.7	0.6
Efficiency of power generation*	33%	32%	37%
CO2/electrical energy	1	0.7	0.54
* Japan	42%	44%	47%

- Should move away from coal (CO2, pollution, mining deaths) and improve efficiency of power generation
- Replacing all coal with gas would reduce CO2 emissions from energy by over 20%

Fossil Fuel Prices

- Can talk of a world price for coal and oil but not for gas as the cost of liquefaction and re-gasification is high*
- **Mugs game to try to predict price of oil and gas**. Cost assumptions used in past projections badly wrong, although use has proved relatively insensitive to these assumptions – see next two slides which compare past assumptions with what happened
- **Coal is currently cheapest/mtoe**, although in USA gas is a cheaper source of electricity as generation efficiency is higher

*Liquefaction + shipping (US to Europe) would add ~ $4/MBtu (regasification would add another $70c). Prices are volatile (for historical prices see next slide but one).

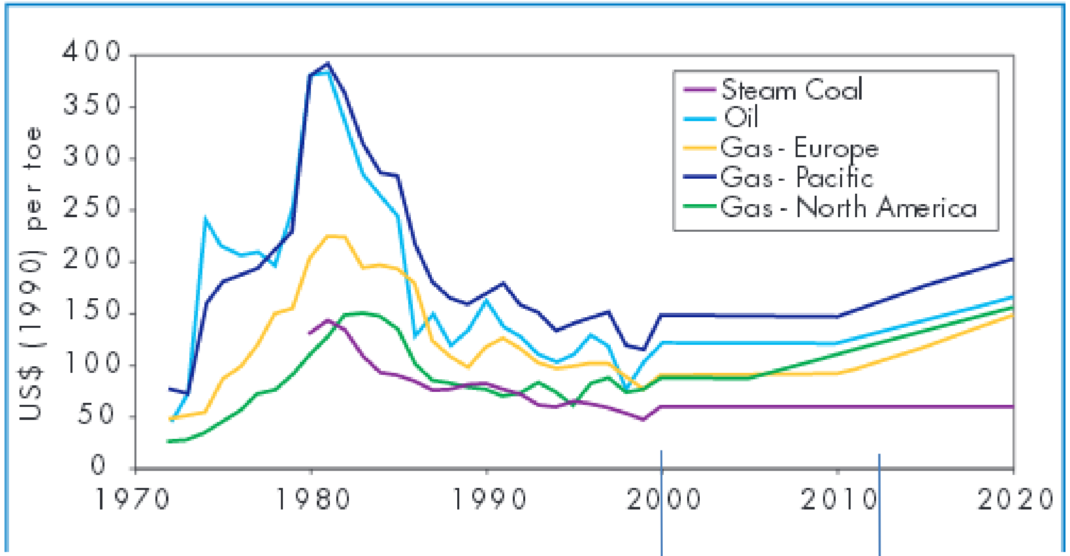
The US (Henry Hub) spot price in mid Sept. 2015 was $2.7/Mbtu (down from an average of $4.4 in 2014)

The EU natural gas import price averaged $6.9/Mbtu in July 2015 (down from $9.8 in Dec. 2014)

The Japanese LNG import price averaged $8.5/MBtu (down from $15.6 in Dec. 2014)

IEA
WEO
2000

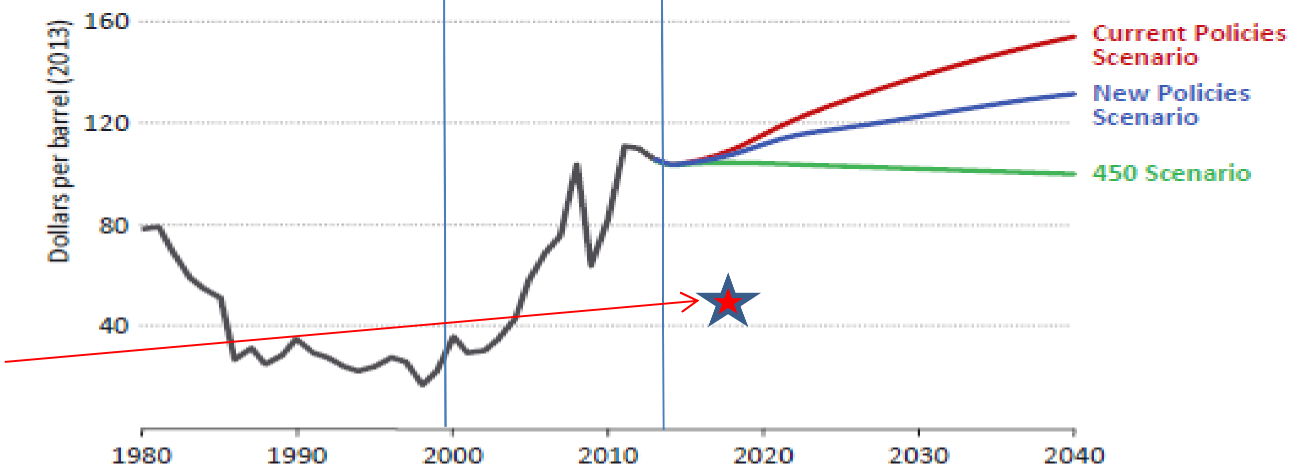
Figure 1.4: **Assumptions for World Fossil Fuel Prices**



Note: different units in top and bottom slides

IEA
WEO
2014

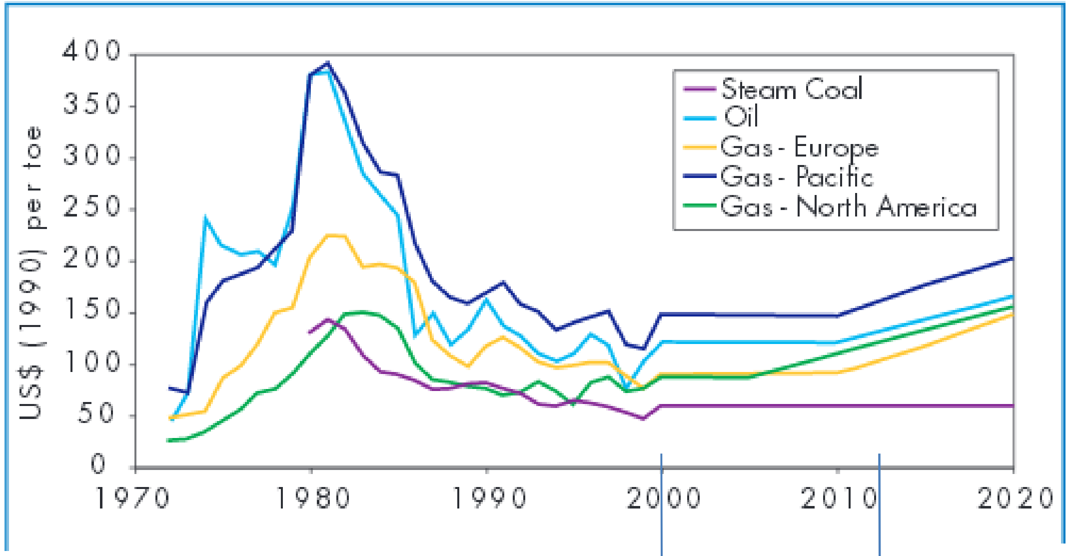
Figure 1.2 ▻ Average IEA crude oil import price by scenario



6/9/15
$47

IEA WEO 2000

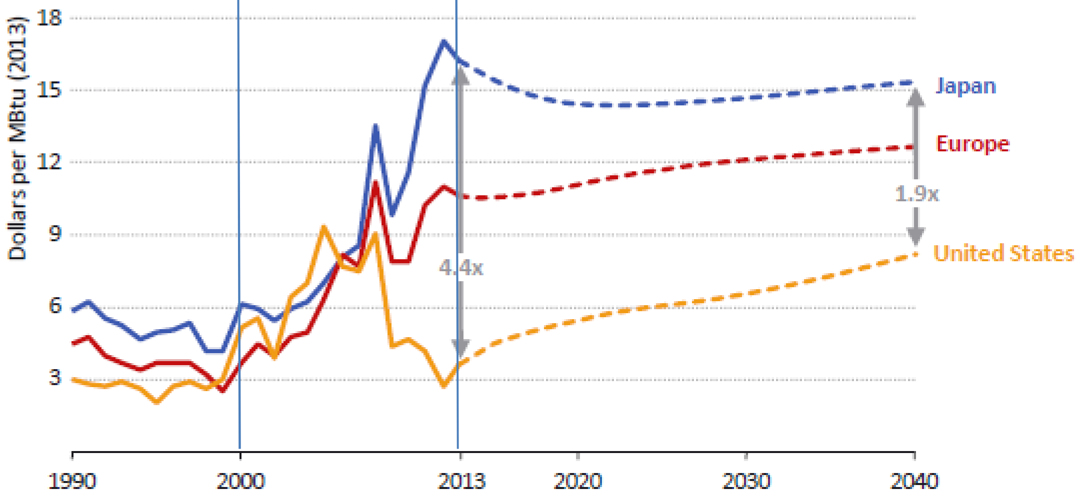
Figure 1.4: **Assumptions for World Fossil Fuel Prices**



Note: different units in top and bottom slides

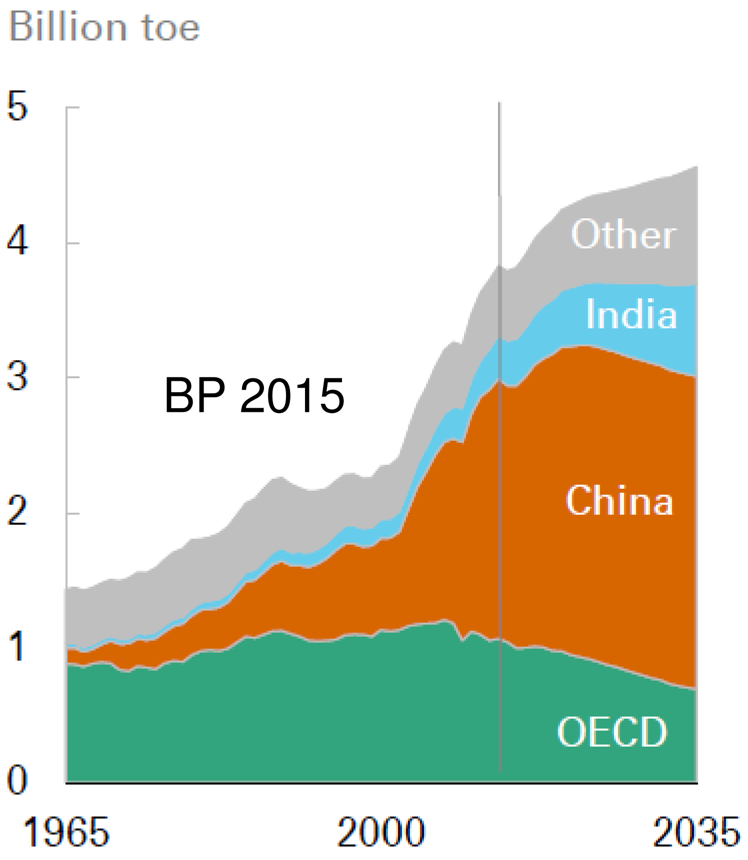
IEA WEO 2014

Figure 1.3 ▷ Natural gas price by region in the New Policies Scenario

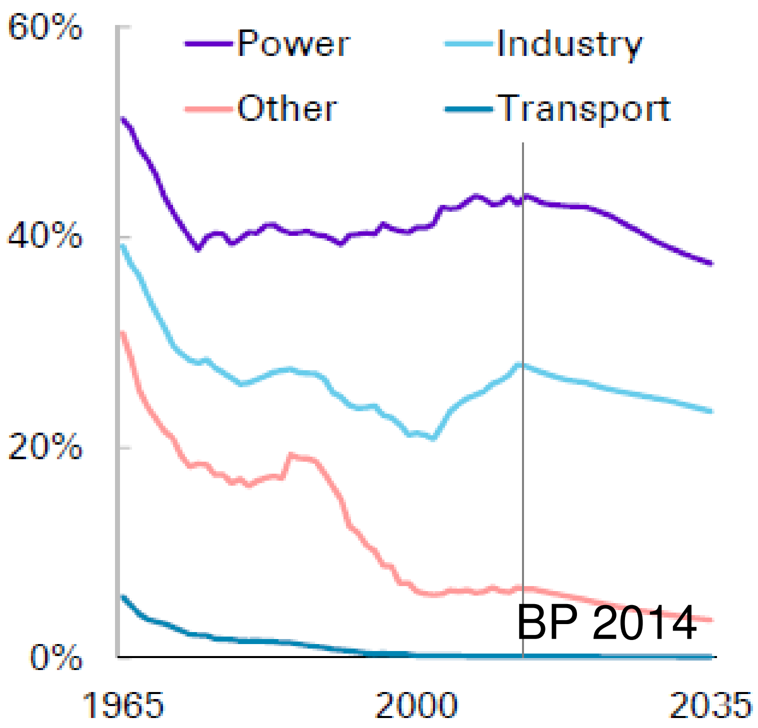


Coal

Falling in OECD
Growth slowing in non-OECD



Relative Importance
expected to fall in all sectors



Cleaner Coal: Impact of Efficiency

China	2012	2040 IEA NPS Scenario	**Dream****
Power from coal - TWh	3812	5545 + 45%	5545
Efficiency	31.9%	36.5%	48%***
Coal used → power - Mtoe	1027*	1301 + 27%	989 - 4%

*26.5% of all World's 2012 coal production

**Increasing the average efficiency is of course a slow business

***the state-of-the-art efficiency

For comparison: wind + solar in China:

2012: 102 TWh

2040: NPS scenario 1233 TWh

Increase saves 290 mtoe coal assuming 36.5% efficiency

(c/f total UK consumption 347 TWh in 2012)

Carbon Capture and Storage 1

If CO_2 emissions stop, level in atmosphere drops very slowly

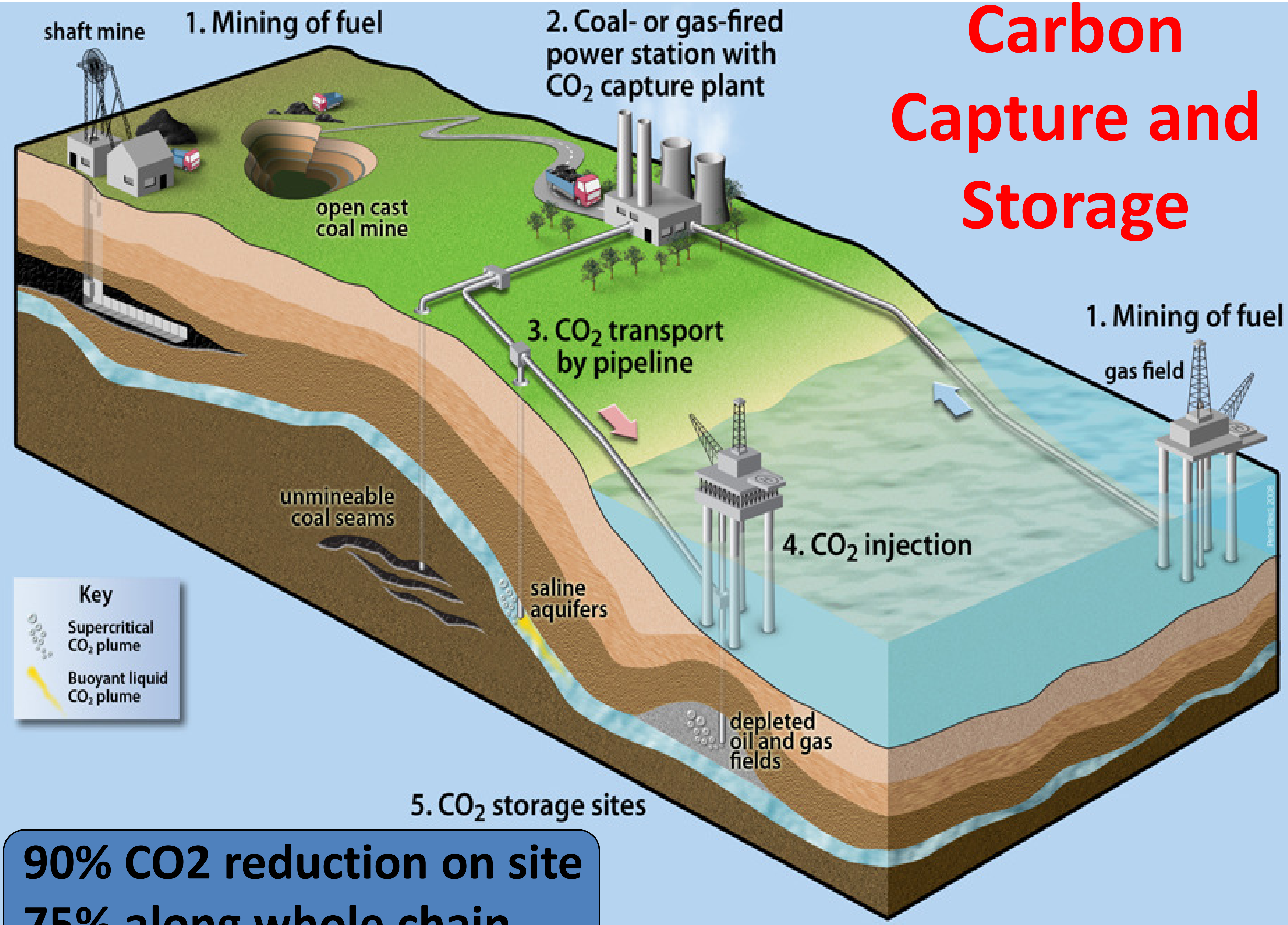
- new ocean/atmosphere equilibrium at 20%-35% of peak (relative to pre-industrial level) after 2-20 centuries (then uptake as calcium carbonate - thousands of years, and finally by igneous rock - hundreds of thousands)

→ **Slowing use of fossil fuels is no help in the long run,** except by buying time to develop cost competitive alternatives

→ **Carbon Capture** (from power stations *and large industrial plants*) **and Storage would help,** provided it stays buried for thousands of years!

[Even better (in principle) pull carbon-dioxide out of the atmosphere using: enhanced weathering of olivine, artificial trees and other **N**egative **E**mission **T**echnologies – such ideas deserve study, but many have undesirable side effects and all currently look expensive, as does CCS]

Carbon Capture and Storage



90% CO2 reduction on site
75% along whole chain

Carbon Capture and Storage 2

- **Expected to work and be safe, but will**
  - only capture some 80%
  - be expensive: EIA estimate for plant coming on line 2020:

    Advanced Coal: CCS adds $28/MWh → order $50/tCO2

    But others quote bigger numbers (e.g. $100/tCO2) initially
- **Lots of storage** capacity (albeit not everywhere e.g. India) **-** UK N Sea could store 60-80 bn t CO2 (vs. 10 bn t/year globally from coal power generation)
- **Lots of plans – but little action. Now changing?**
- **Should be trialled to establish cost, and *if* looking competitive rolled out on a large scale – *meanwhile worrying that many low carbon scenarios rely heavily on CCS***

Full-scale full chain CCS projects


Boundary Dam, Sask.

110MW, 1Mt/yr, 2nd Oct 2014


Texas Clean Energy Project, Tx.

245MW, 2-3Mt/yr, by 2018

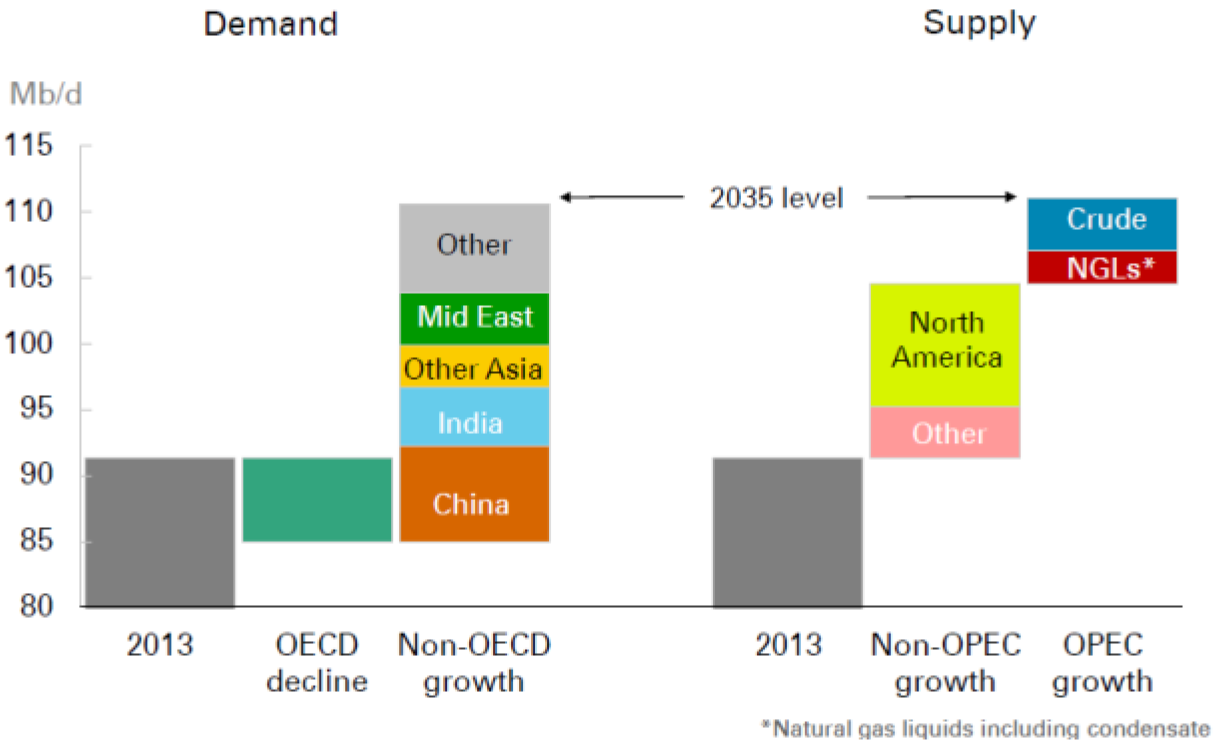

Kemper County, Miss.

582 MW, 3.5 Mt/yr, May 2015


QUEST, Alb.

~1.1Mt/yr, Mid 2015

Oil: Shifts in Demand and Production



*Natural gas liquids including condensate

Rise of USA:

Due to tight/shale oil, and **N**on-**G**as **L**iquids associated with shale gas

Oil production mtoe	2004	2014
Saudi Arabia	500	543
USA	325	520
Canada	149	210
Russia	463	534
China	174	211

Oil Price: recent dramatic fall:

albeit to level from 1985-2005

Why? Thought to be a combination of

Falling demand

US Shale (more on this later)

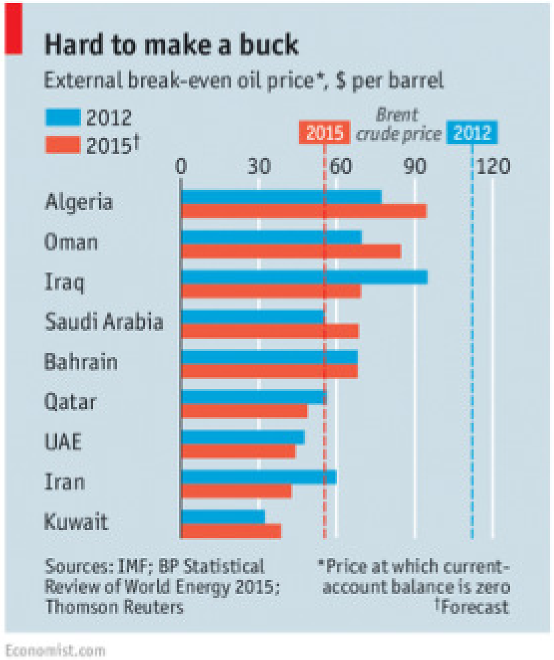
Saudi Arabia not cutting back to maintain price, in order to undermine US shale (many think it’s happening, but as technology improves minimal viable price is falling)

What are the consequences?

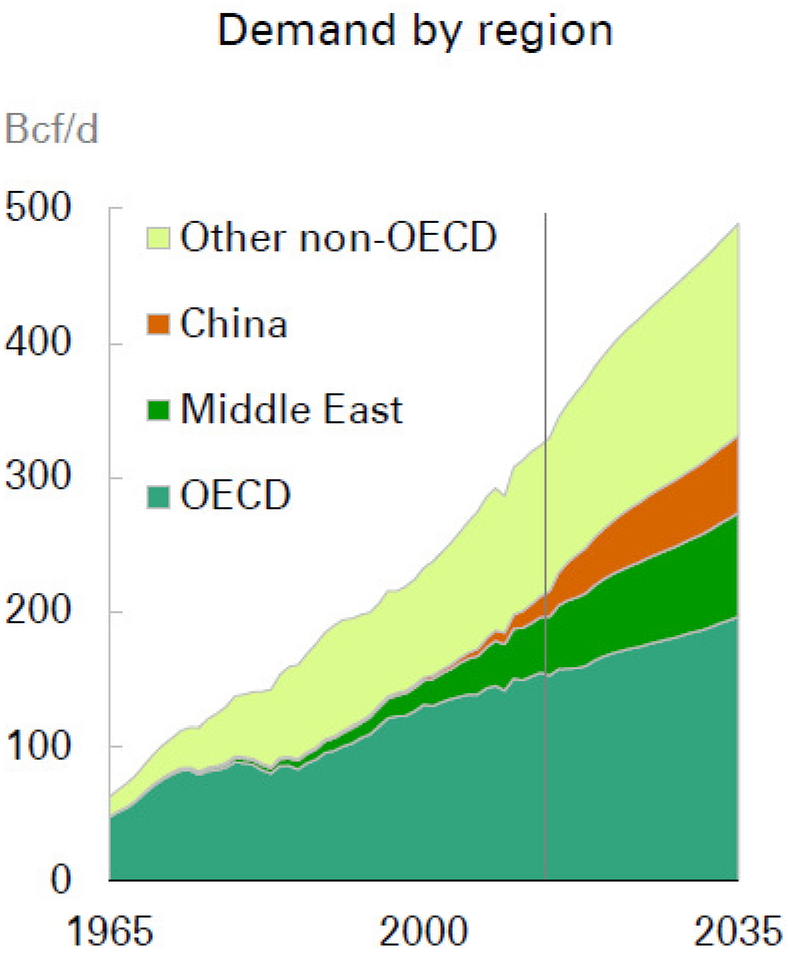
Good news for importing countries

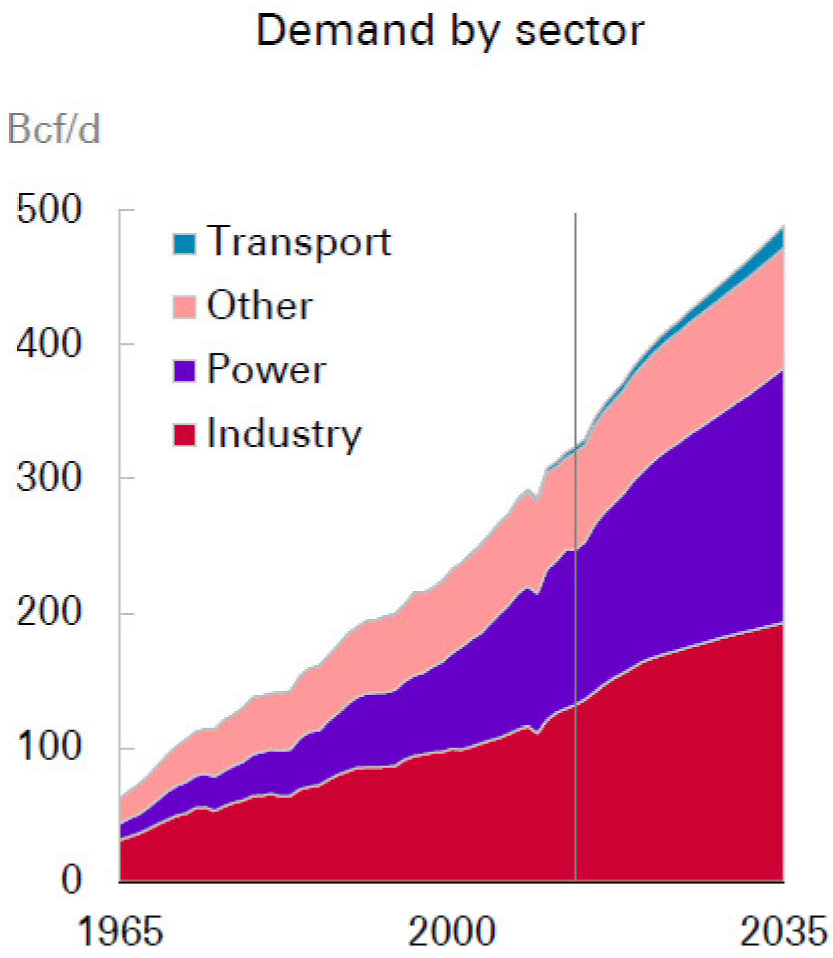
But a huge problem for countries that need a high price to balance the budget

Russia needs ~ $80/barrel



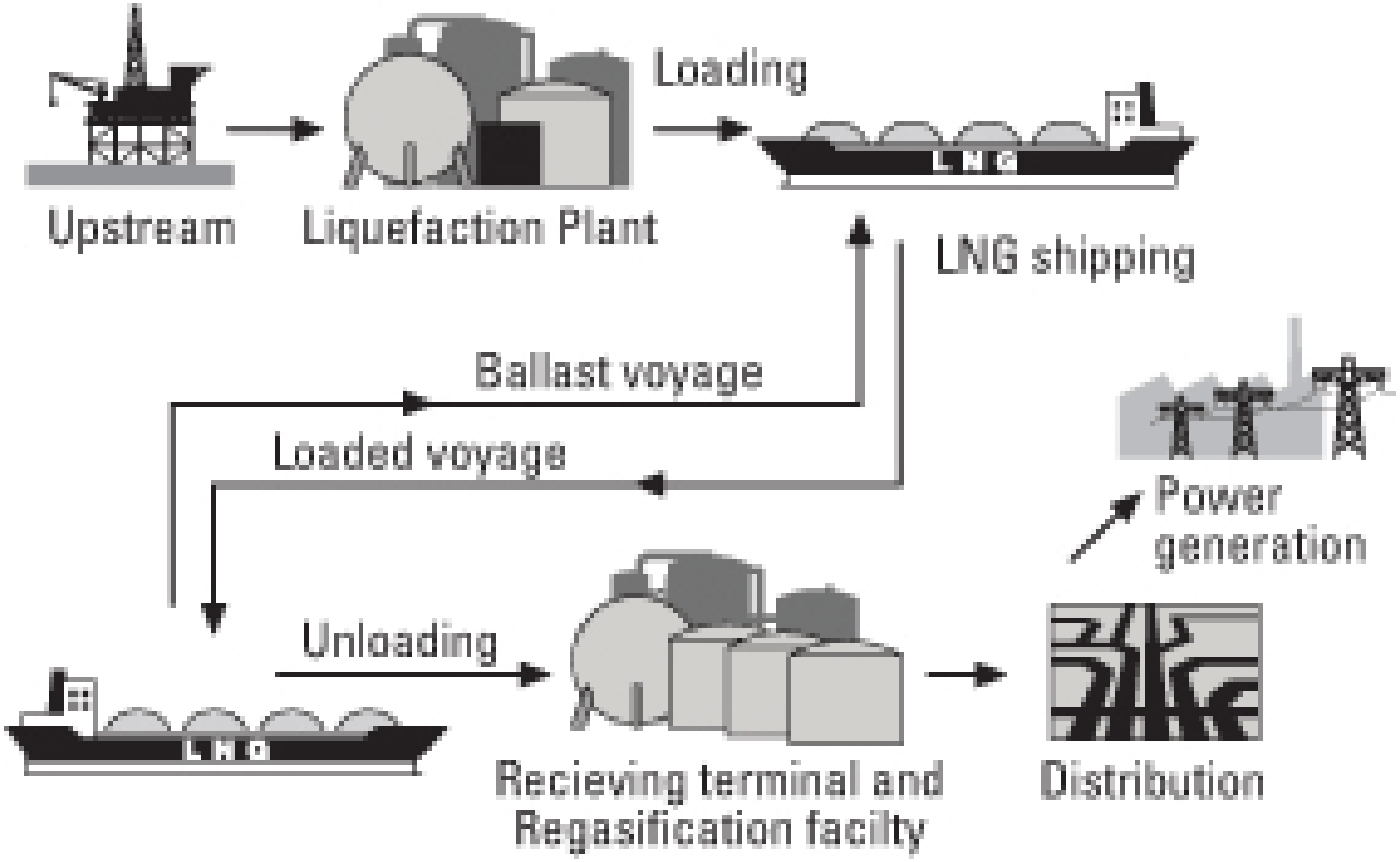
Gas Demand





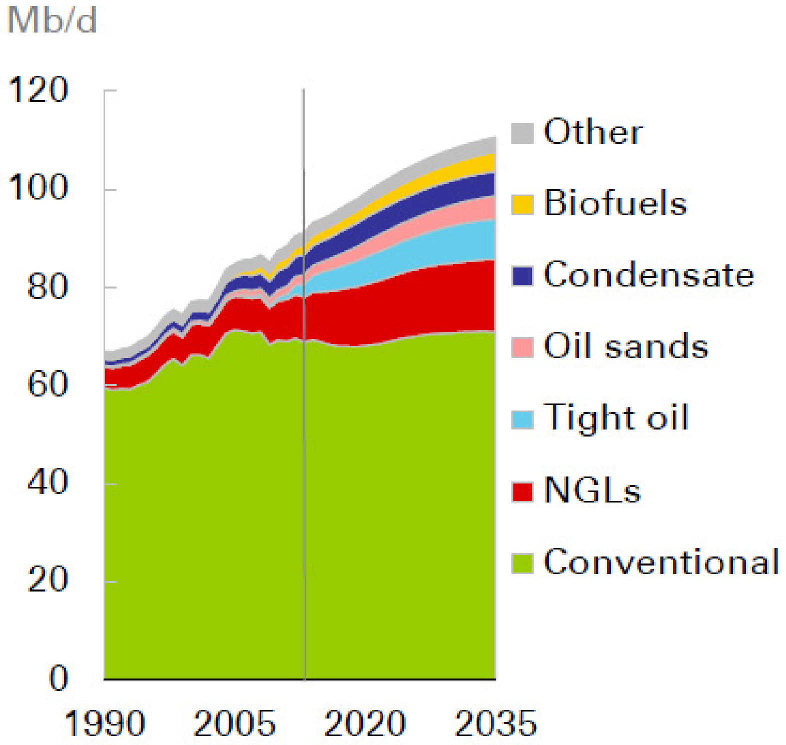
Some 33% of gas is traded internationally: 22% pipeline, 11% LNG
Anticipated that some 33% (of rising total) will remain traded in 2035, approximately equally by pipeline and as LNG

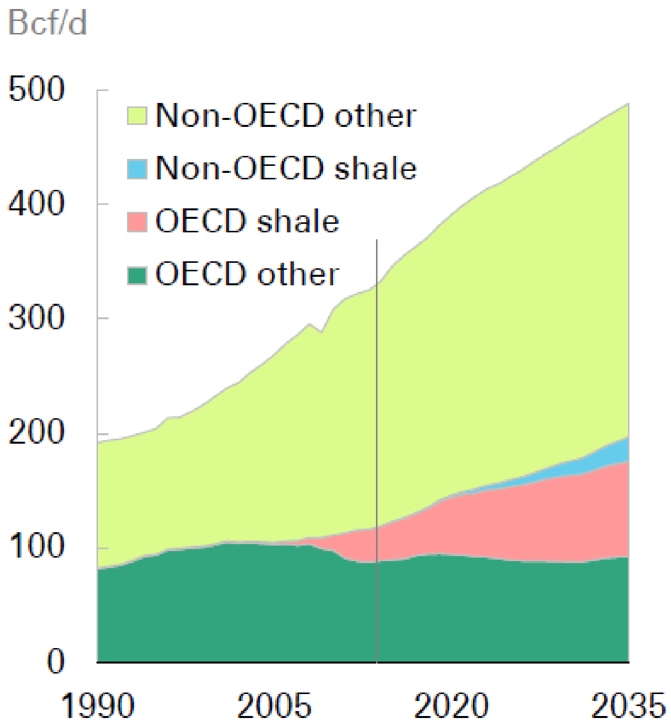
LNG Supply Chain



South Hook LNG Import Terminal, Pembroke

Rise of Shale in Oil and Gas


Liquids supply by type


Gas production by type and region

- **Consequences of US shale revolution**
- **What is fracking? Is it safe? Local impact?**
- **Where is there shale oil/gas? How much?**

Consequences of US Gas and Oil Fracking Revolution

Unlikely that US experience (shale became largest source of US gas, at over 40%, at end of 2013) **will be repeated elsewhere, but:**

- Gas from Qatar* → Far East, UK,… (rather than USA as originally planned)
- Very low US gas price → competitive advantage
- Perhaps the USA will lead the world in decarbonisation as coal → gas, gas powered trucks, and cheap electricity → more electric vehicles?
- US coal not staying in the ground: it is being exported, helping to drive down the cost of coal - which is much cheaper than gas elsewhere:

  10 GW additional fossil generating capacity in Germany planned to replace nuclear: was hoped gas, but recently added 2.2 GW lignite!
- US energy independence? Chinese aircraft carriers in the Gulf?

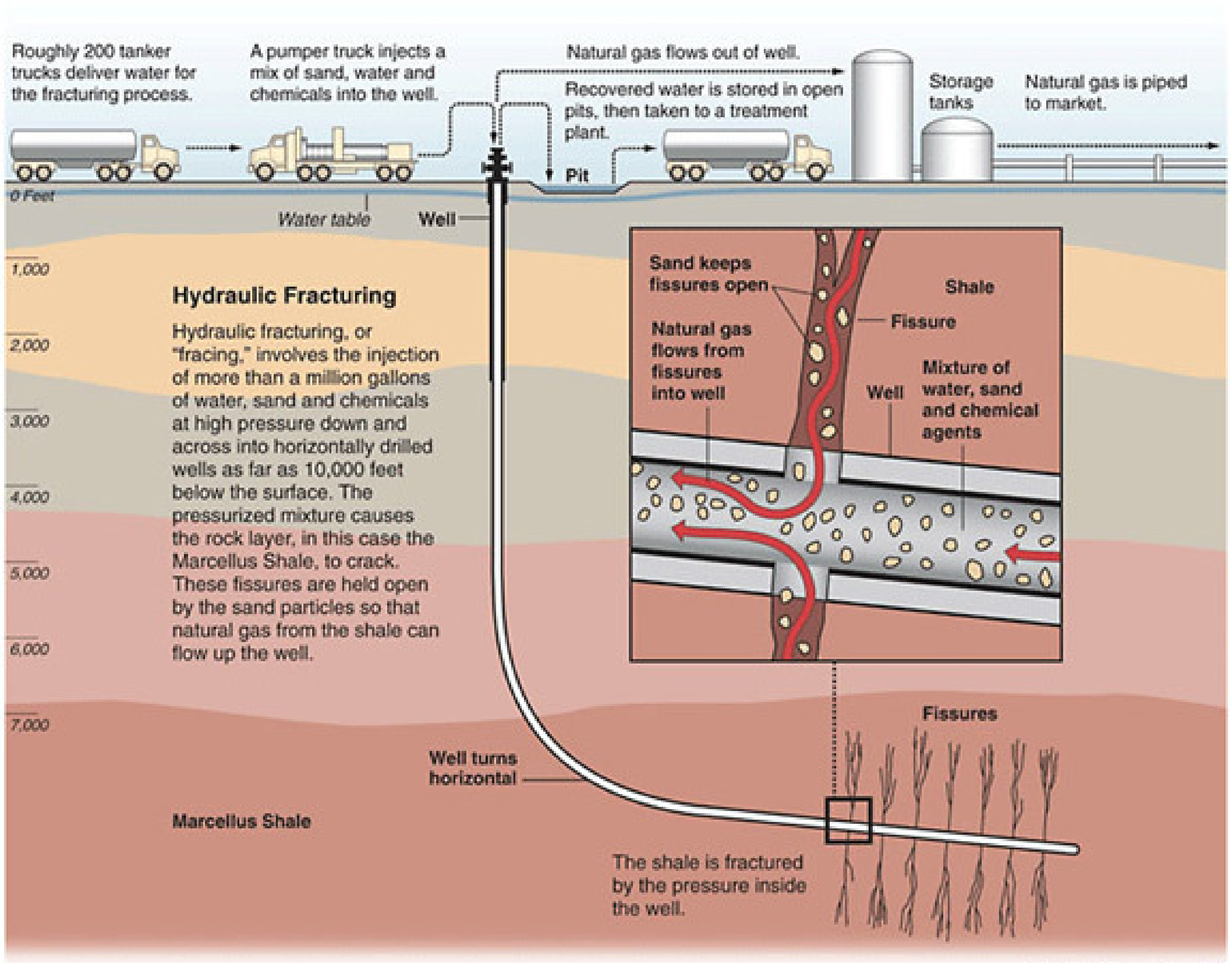
* In 2014 22% of all gas produced was imported/exported in pipelines; 11% as Liquefied Natural Gas (LNG). The 3.0% of world production exported by Qatar is small globally but important for Japan (21% of Qatari exports → 19% of all Japanese gas consumption), India (16% → 32%), S Korea (17% → 37%), UK (10% → 16%)

Fracking: What is it?

Shale is a common type of sedimentary rock formed from deposits of mud, silt, clay and organic matter. Shale gas mainly consists of methane trapped in shale with very low permeability.

Explosive charges perforate sections of the well.

Pressure of injected fluids (95% water, 5% sand, 0.2% additives) opens fractures (new & existing), extending a few hundred metres, which are propped open by the sand.



Roughly 200 tanker trucks deliver water for the fracturing process.

A pumper truck injects a mix of sand, water and chemicals into the well.

Natural gas flows out of well.

Recovered water is stored in open pits, then taken to a treatment plant.

Natural gas is piped to market.

The shale is fractured by the pressure inside the well.

Hydraulic Fracturing

Hydraulic fracturing, or "fracing," involves the injection of more than a million gallons of water, sand and chemicals at high pressure down and across into horizontally drilled wells as far as 10,000 feet below the surface. The pressurized mixture causes the rock layer, in this case the Marcellus Shale, to crack. These fissures are held open by the sand particles so that natural gas from the shale can flow up the well.

Graphic by Al Granberg

Fracturing fluid flows back to the surface but now also contains saline water & dissolved minerals from the shale formation

Is it Safe?

If done properly: I think yes (IEA best practice guidelines would add 7% to cost)

Environmentally no worse than many other forms of power production

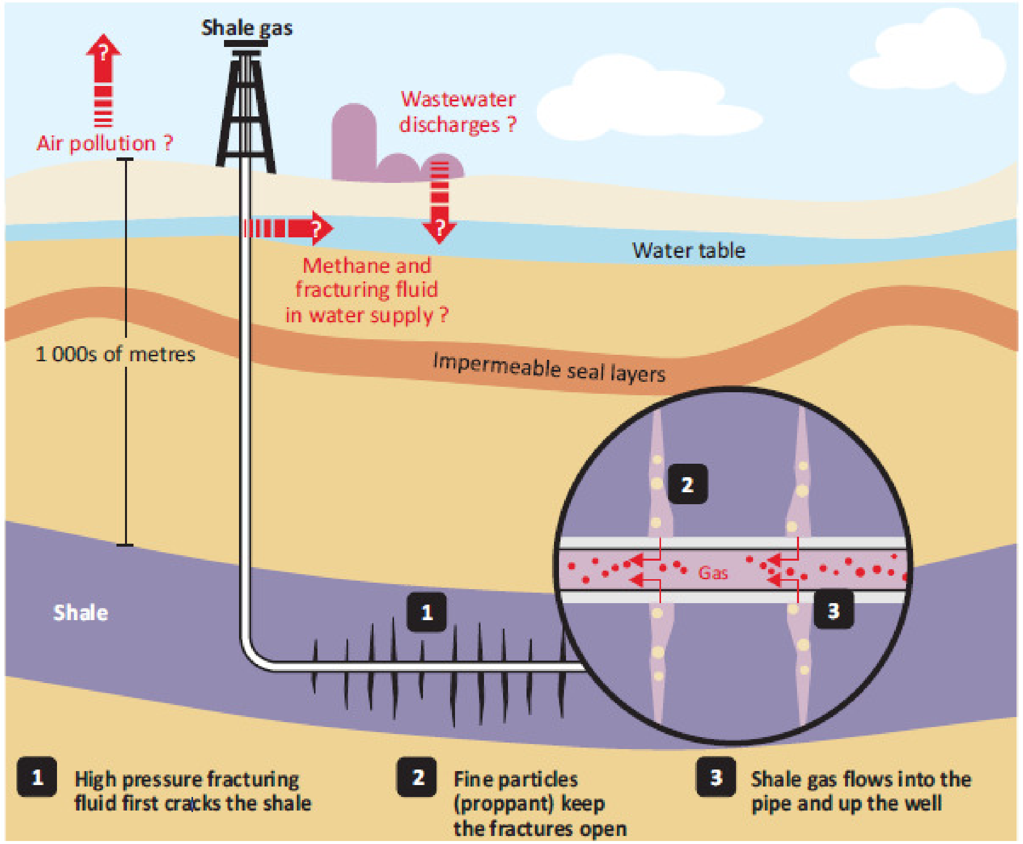
Earthquakes a much smaller hazard than for coal mining + much less pollution than coal

Biggest problems: large surface foot-print when drilling (see following slides) + trucking in sand

Concerns about use of water & effect on its quality largely misplaced

Lack of incentive for landowners + high population density will hinder development in Europe

Figure 1.3 ▷ Shale gas production techniques and possible environmental hazards



West Virginia Shale Gas Pad – Drilling Phase ..

Production Phase – Same Location

How Much?

Technically recoverable (with existing technology) resources – *not necessarily economic*. For comparison: in 2014 world consumed 33.6 bn bl oil, 120 trcf gas

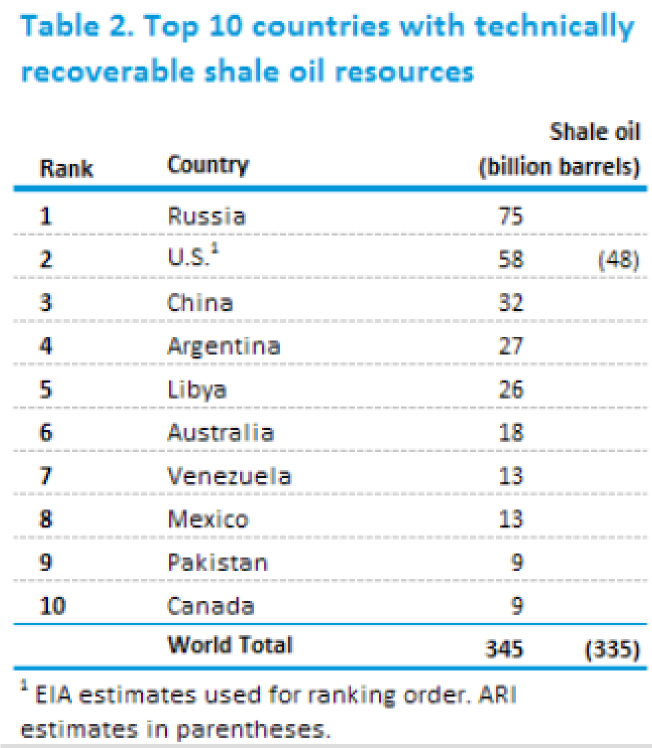


Table 2. Top 10 countries with technically recoverable shale oil resources

Rank	Country	Shale oil (billion barrels)	
1	Russia	75	
2	U.S.[1]	58	(48)
3	China	32	
4	Argentina	27	
5	Libya	26	
6	Australia	18	
7	Venezuela	13	
8	Mexico	13	
9	Pakistan	9	
10	Canada	9	
	World Total	**345**	**(335)**

[1] EIA estimates used for ranking order. ARI estimates in parentheses.

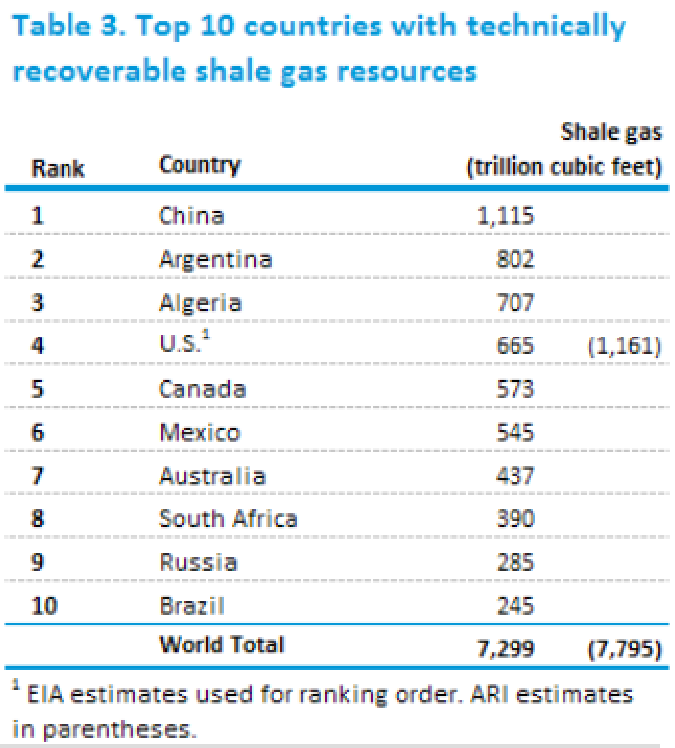


Table 3. Top 10 countries with technically recoverable shale gas resources

Rank	Country	Shale gas (trillion cubic feet)	
1	China	1,115	
2	Argentina	802	
3	Algeria	707	
4	U.S.[1]	665	(1,161)
5	Canada	573	
6	Mexico	545	
7	Australia	437	
8	South Africa	390	
9	Russia	285	
10	Brazil	245	
	World Total	**7,299**	**(7,795)**

[1] EIA estimates used for ranking order. ARI estimates in parentheses.

Europe (ARI), top ten gas

	Gas tcf	Oil bn bl
EU consumption 2014	13.7	4.6
Poland	148	3.3
France	137	47
Ukraine	128	1.1
Romania	51	0.3
Denmark	32	0
UK	28	0.7
NL	26	2.9
Bulgaria	17	0.2
Germany	17	0.7
Sweden	10	0

These (2013) estimates are **very uncertain**
No estimates for some major basins in China, SE Europe, India

Very Dependent on Local Conditions, e.g. US vs. UK

US: better outcrops, geology better understood….

UK: need better geological background knowledge (strategic coring programme, pilot fracking test)

Eagle Ford, West Texas

Bowland Shale, N. England

Given geology + environmental regulation - unlikely that UK shale gas will be particularly cheap

Given likely size of resource (and constraints from population density and mineral rights) very unlikely that shale will become a major source of UK gas

Don’t expect UK shale to have a significant impact on UK gas prices

Conclusions on Shale Gas & Oil

- The world has lots of shale gas and oil – but how much can/will be extracted is unclear
- Shale has been a game changer for US production and has already impacted other regional markets by re-directing LNG

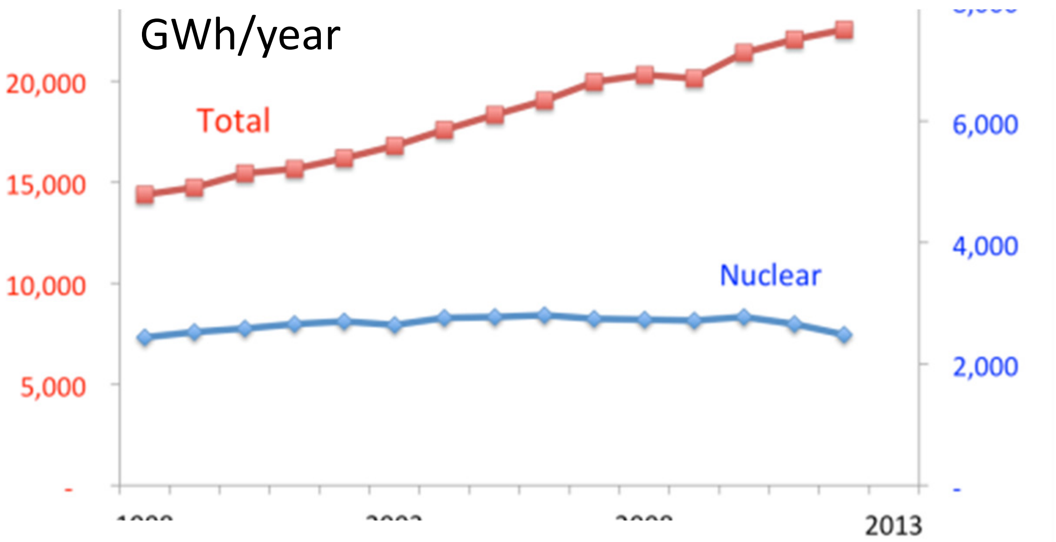
although sustainability of US shale growth unclear

- Shale development possible in Europe, South America, India and China – could be significant, but conditions are very different in different places
- Still early days (watch this space) but it does not look like a game changer except in the USA

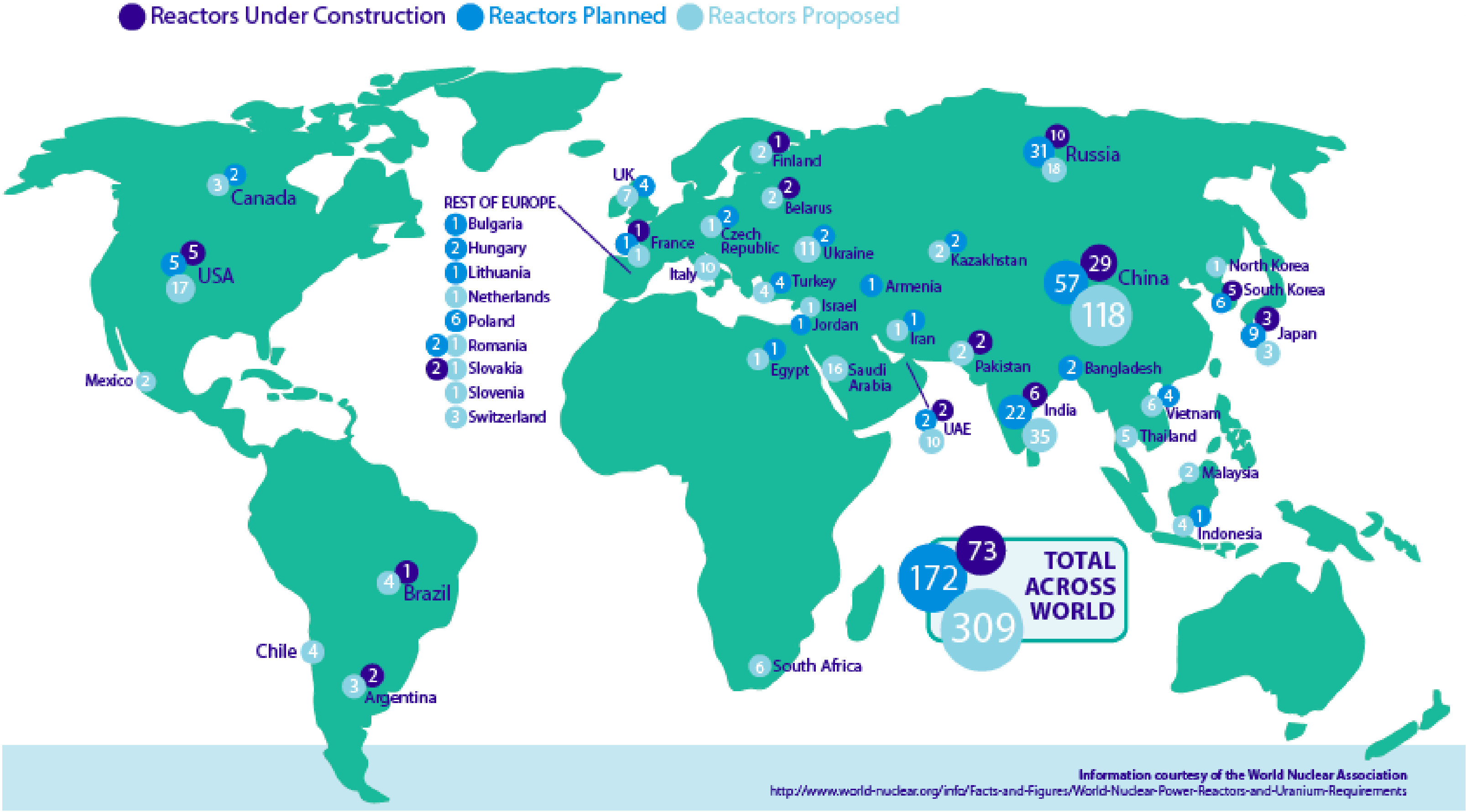
Nuclear

- **Current situation and plans**
- **Barriers to expansion?** (partly covered in Colloquium)
- **Costs – small modular reactors?** (partly covered in Colloquium)
- **Future steps for fission** (also covered in Colloquim)
- **Fusion**

Nuclear has stalled:



Although there are plans for expansion:



Information courtesy of the World Nuclear Association
http://www.world-nuclear.org/info/Facts-and-Figures/World-Nuclear-Power-Reactors-and-Uranium-Requirements

Barriers to Expansion

Still second largest source of low carbon energy and could play a much bigger role. Possible barriers:

- **Uranium?** Plenty – probably enough for over 250 years with current use, then thorium, fast breeders or perhaps fusion –see slides 89 & 123 - 126
- **Public perceptions**
- **Cost + Financing are the real barriers**

EIA estimates LCOE of US plants entering service in 2019 will be $96/MWh

but cost is the big issue in the UK where the government will pay EDF $140/MWh (EPR!)

→ Could **S**mall **M**odular **R**eactors cut cost significantly?

Fission Cost vs. Size

- Capital cost/kW$_e$ expected to *decrease* with size, but data *suggest an increase* (power 0 to 0.10) - time over runs, complexity,…
- Doubling number of units has decreased cost in most case, but not by more than 10% (new labour force; design modifications; new regulations;…)
- Small Modular Reactors (SMRs) could bring down cost, even if cost/kW$_e$ increases in going down from say 1000 MW$_e$ to 100 or 200 MW$_e$
  - Design simplification
  - Multiple units one site
  - Production learning
  - Standardisation
  - Short build schedule
  - Finance savings

Future Steps for Fission

Near term:

- Larger reactors – focus on bringing down costs of PWRs and ABWRs

- SMRs – build some to see if they really are cheaper/kW$_e$. Funding? Regulation?

Longer term:

- Study/develop fast-breeders*, thorium*, molten salts, high temperature reactors – Generation IV consortium is studying six options: need to reduce number and start building proto-types before long. *See Appendix for additional material*

* will be needed (and/or fusion) if nuclear is to play a role in long-term: long lead time to develop/deploy, need to get moving in case a major expansion of nuclear power shortens life-time of uranium supplies

Fusion - see appendix for additional material

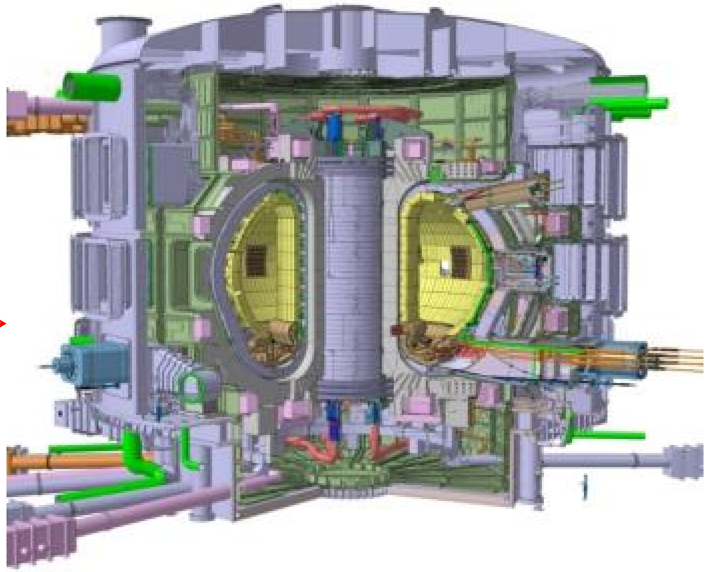
- **It works** - powers the sun, Joint European torus at Culham near Oxford ET has – briefly – produced 16 MW of fusion power

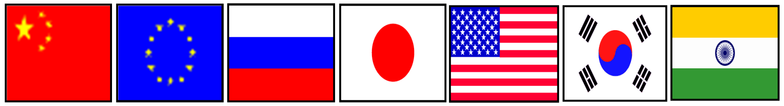
  and has many attractive features - essentially unlimited fuel, intrinsic safety, no long lived nuclear waste…

- **Should develop vigorously**

- **Big questions:** *can it be made to work competitively (with what?) and reliably on the scale of a power station?*
  If so, when?

- **Next major step –** complete ITER →
  - first device which will produce power station conditions in a plasma
  - *see how well it works*
  - *understand why it cost so much*





Future of Fusion

- **Magnetic Confinement**

  ITER cost over-run due to a mixture of

  - first-of-a-kind
  - sub-optimal structure
  - bad management
  - intrinsic

  After ITER works there should be a major review to decide how much is intrinsic before deciding to build a proto-type (meanwhile development of materials and technologies should continue in in parallel to ITER)

- **Other routes to fusion** – inertial confinement is generations behind magnetic confinement: none of the alternatives that keep popping up look credible

Concluding Remarks

For detailed conclusions see Colloquium – slides 63-69

- To allow everyone on the planet to lead decent lives, much more energy will be needed
- We can meet the need with fossil fuels for (at least) 50 years - but we should be decarbonising
- No real progress with decarbonisation
- Decarbonisation is possible, but will require developing and implementing new technologies and new policies
- Large scale changes in energy infrastructure take decades – so action is needed now

Malthusian “solution” if we fail?

Appendix

Contains additional material that was not covered in the lectures on: uranium resources, different nuclear fuel cycles, fast breeder and thorium reactors, and fusion

Uranium Resources

Main Messages

- The cost of uranium (pre conversion, enrichment etc.) contributes only $0.3c/kWh to the cost of nuclear electricity at today’s price: nuclear power could accommodate a large price increase
- There’s lots of uranium (the amount available depends on the price – a higher price will stimulate exploration): shortages of uranium are not going to hold back nuclear power in the near future

In detail/for the record:

- The ‘world average’ reactor uses 280 tonnes/GW-year of uranium oxide: the current price is ≈ $85/kg
- The world’s nuclear industry currently uses 85 k-t of uranium oxide/year
- WNO quotes resources at a cost below $130/kg that are enough for 150 years at the current rate of use: uranium phosphates would add 105 to 260 years
- An MIT study of lifetime of resources at current rate of use with different cost finds:

  Probability of 100 years: 50% at < $120/kg, 85% at < $170/kg
  500 years: 50% at < $140/kg, 85% at < $220/kg
  1000 years: 50% at < $160/kg, 85% at < $300/kg

Different Nuclear Fuel Cycles

- **Recycle** in conventional reactors – can get up to 30% more energy/kg + reduce waste volume by factor 2 or 3 (note: slightly increased proliferation risk + short-term risk from waste streams)
- **Higher temperature/pressure** → more energy/kg of fuel
- **Fast Breeder Reactors**
- **Thorium Reactors**
- **And then there's fusion…..**

A mixed economy has attractions:

Conventional reactors + burn waste in

- some Fast Breeder reactors, or
- Accelerator Driven waste burners

Plutonium Fast Breeders

- In natural uranium, only ^{235}U (0.7%) is fissile, but fast neutrons can turn the other 99.3% into fissile Plutonium:

$$^{238}U + n \rightarrow {}^{239}Np \rightarrow {}^{239}Pu$$

fertile *fissile*

⇨ **order 60 times more energy/kg of U**

⇨ far less waste, *and* can burn waste from conventional reactors because fast neutron destroy transuranics

Potential problems

- more expensive
- not quite so safe
- large plutonium inventory/potential for proliferation
- slow ramp up (1 reactor→ 2 takes ~ 12 years)

Thorium

- **Can burn 100% of thorium,** which is much more abundant than ^{235}Uranium*, and generates much less waste, using

$$^{232}\mathrm{Th} + n \rightarrow {}^{233}\mathrm{Th} \rightarrow {}^{232}\mathrm{Pa} \rightarrow {}^{233}\mathrm{U}$$

fertile *fissile*

* Thorium abundance in the earth's crust ~ 3xurnaium. The accessible ^{232}Th resource not well studied but 5.4 mt are said to have been identified, vs. 0.25 Mt for ^{235}U (including the upper estimate for phosphates)

- Breeding ratio too small for one reactor to fuel itself and provide enough extra ^{233}U to fuel a second reactor

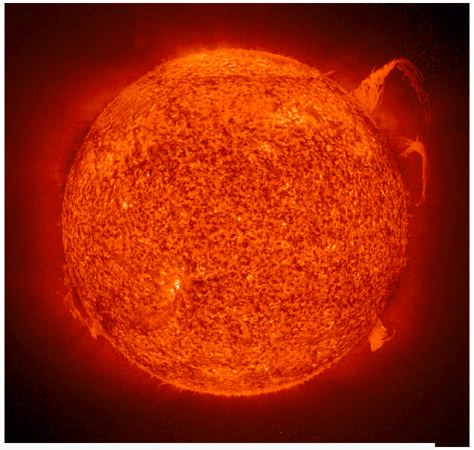
  To get started: need Pu or highly enriched U core

  or neutrons from **A**ccelerator **D**riven spallation source**

- Fuel handling much more complex that in conventional reactors - this is one factor that could outweigh the claimed advantages. **Need more development** to find out

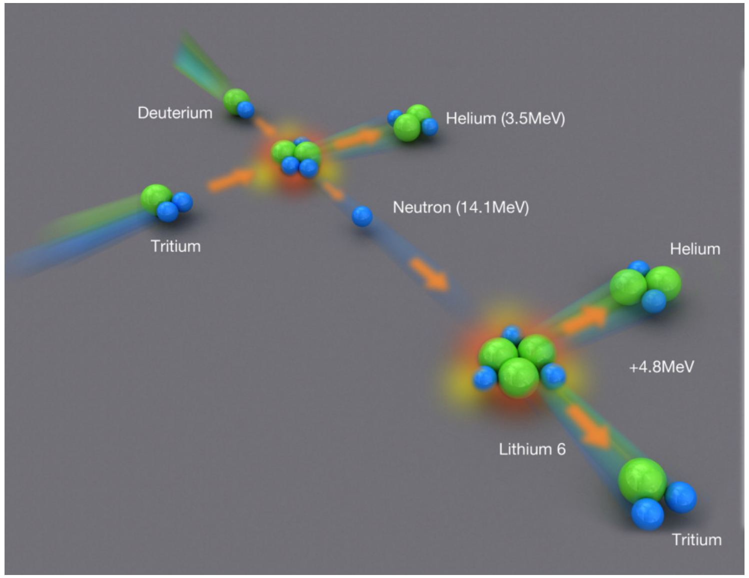
** *avoids having a near critical system, but economics suggest AD system's best potential is for actinide burning*

FUSION powers the sun and stars



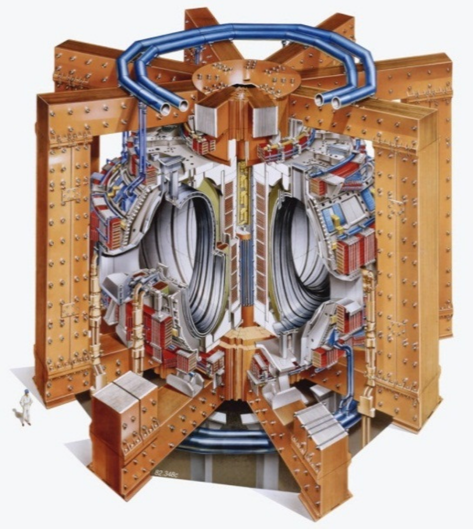
In fusion, energy is released when two light nuclei merge

The most promising fusion reaction for producing energy on earth is:



A controlled ‘magnetic confinement’ fusion experiment at the **J**oint **E**uropean **T**orus (JET in the UK) has (briefly) produced 16 MW of fusion power from the D-T reaction

so **it works**



Big question: when can it be made to work reliably and economically, on the scale of a power station?

Problem: it’s technically very challenging: need to heat ≥ 2000 m^3 of dilute gas to > 150 million ^{0}C and keep it from touching the walls for weeks (JET ~ 80 m^3, seconds) and cannot be demonstrated on a small scale

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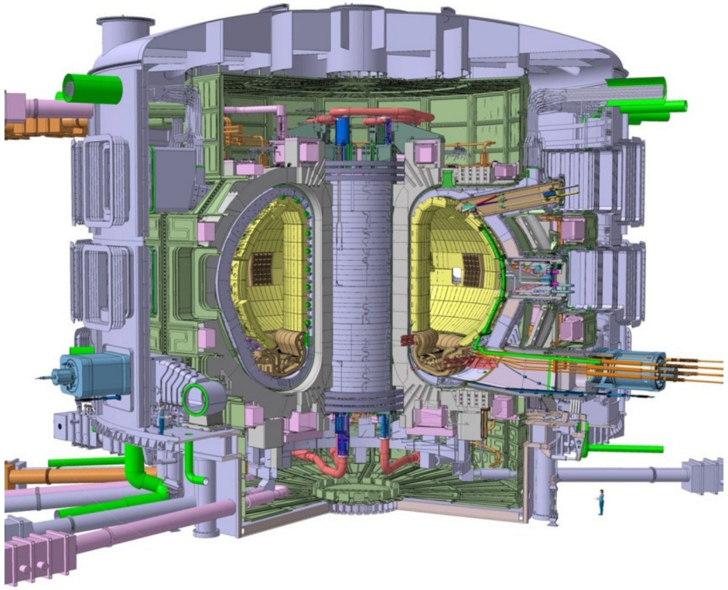
Why bother?

Lithium in one laptop battery + 40 litres of water would provide 200,000 kW-hours = per capita electricity production in the EU for 30 years – with no CO_2 and no long-lived waste

Enough raw fuels (lithium and water) for millions/billions of years

Next Steps



Build a device with 3xvolume of JET to create power station conditions. This (ITER) is being done by the EU, Japan, Russia, USA, China, Korea & India

Once ITER is built (8 years) and has run for 10 years it will be possible to start building a Demonstrator Power Plant, *provided* meanwhile better fusion technology can be developed (not being adequately funded)

Conclusions

It should be possible to make a fusion power station, ***although*** not clear when/whether it will be possible to make it reliable and competitive (with what?)

I am *absolutely certain* that the world must pursue fusion development as rapidly and effectively as reasonably possible (no point doing it badly)

- the potential is enormous

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