

The Energy Challenge and The Case for Fusion

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Energy Facts

■ The world uses a lot of energy, very unevenly

- at a rate of 16 TW. Per person in kW

World – 2.4, USA -10.3, UK - 5.1, China - 2.0, Bangladesh - 0.21

*Note: electricity production only accounts for ~ 1/3 of primary energy use, **but** this fraction can/will rise*

and produces lot of CO₂. Tonnes per person/year:

World - 4.4, USA - 19, UK - 8.6, China - 4.6, Bangladesh - 0.25

■ World energy use expected to increase ~ 40% by 2030

Increase needed to lift billions out of poverty in the developing world

■ 80% of the world's primary energy is generated by burning fossil fuels (oil, coal, gas) *which is*

- causing potentially catastrophic climate change, and horrendous pollution

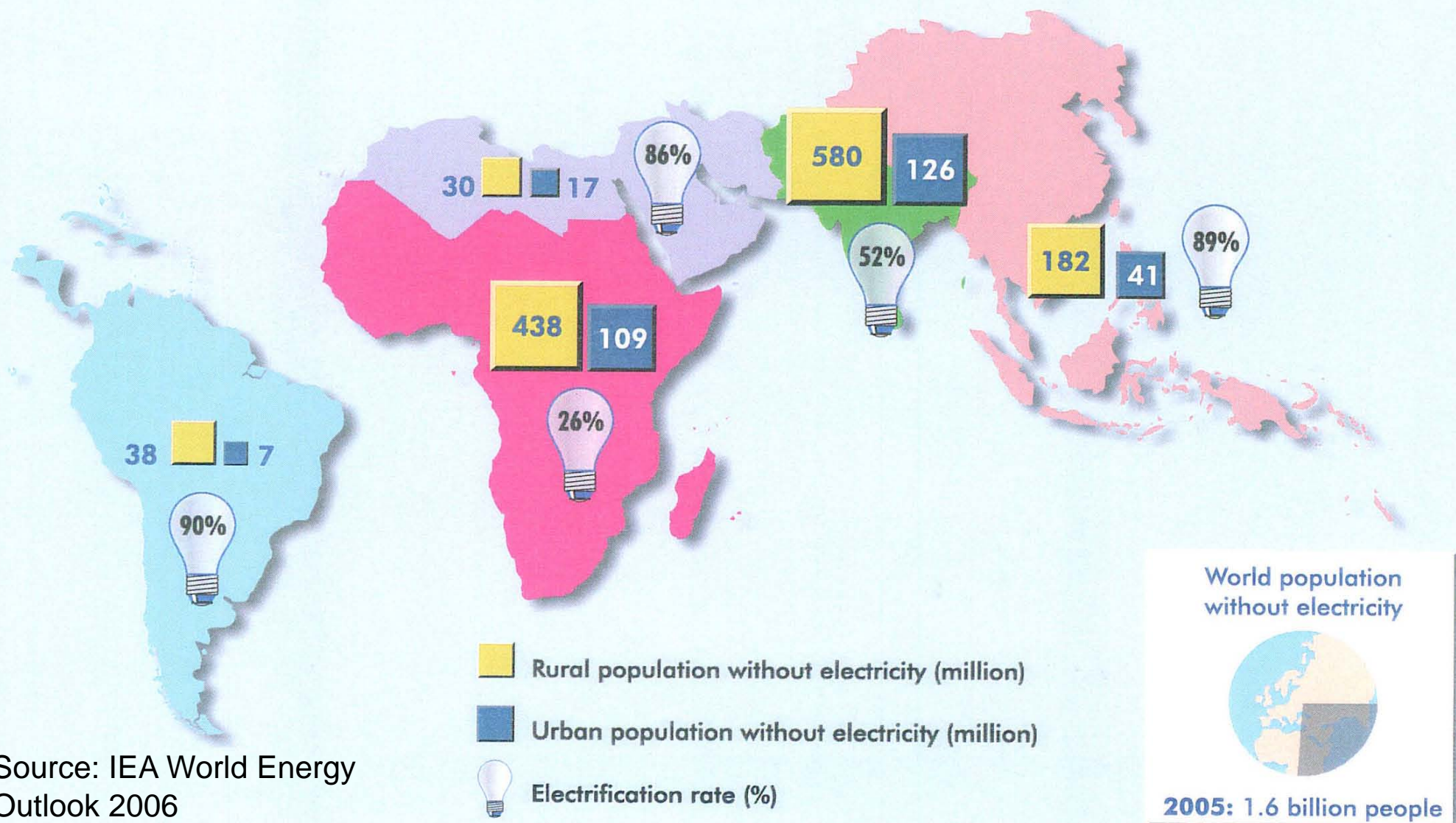
- unsustainable as they won't last forever

Will elaborate on developing world and sources of energy, then ask:

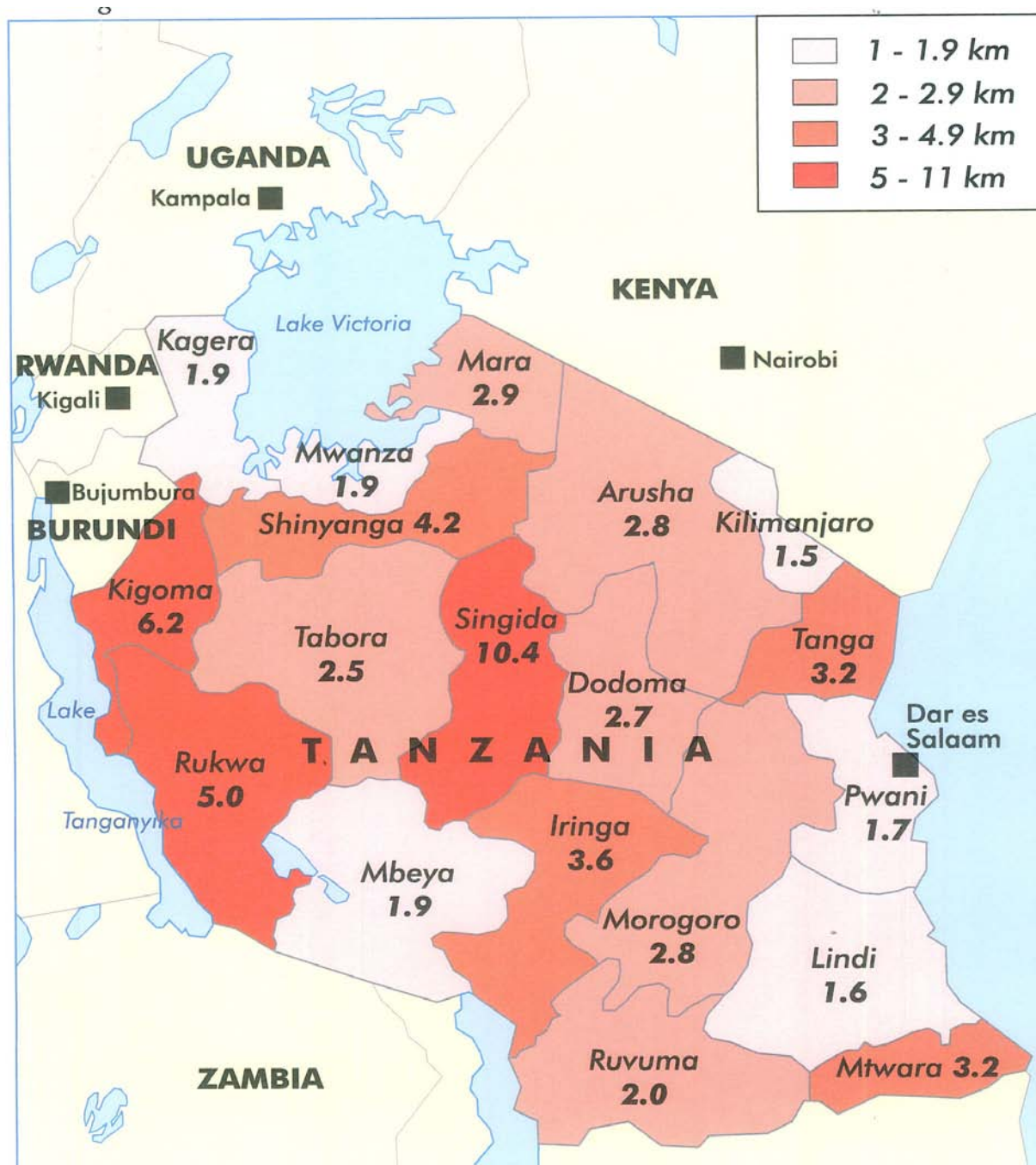
What are the time scales to prepare for the end of fossil fuels, and for actions to avoid climate change?

What actions can/should we take?

1.6 billion people (~ 25% of the world's population) lack electricity:



Source: IEA World Energy Outlook 2006



Distances travelled to collect fuel for cooking in rural Tanzania; the average load is around 20 kg

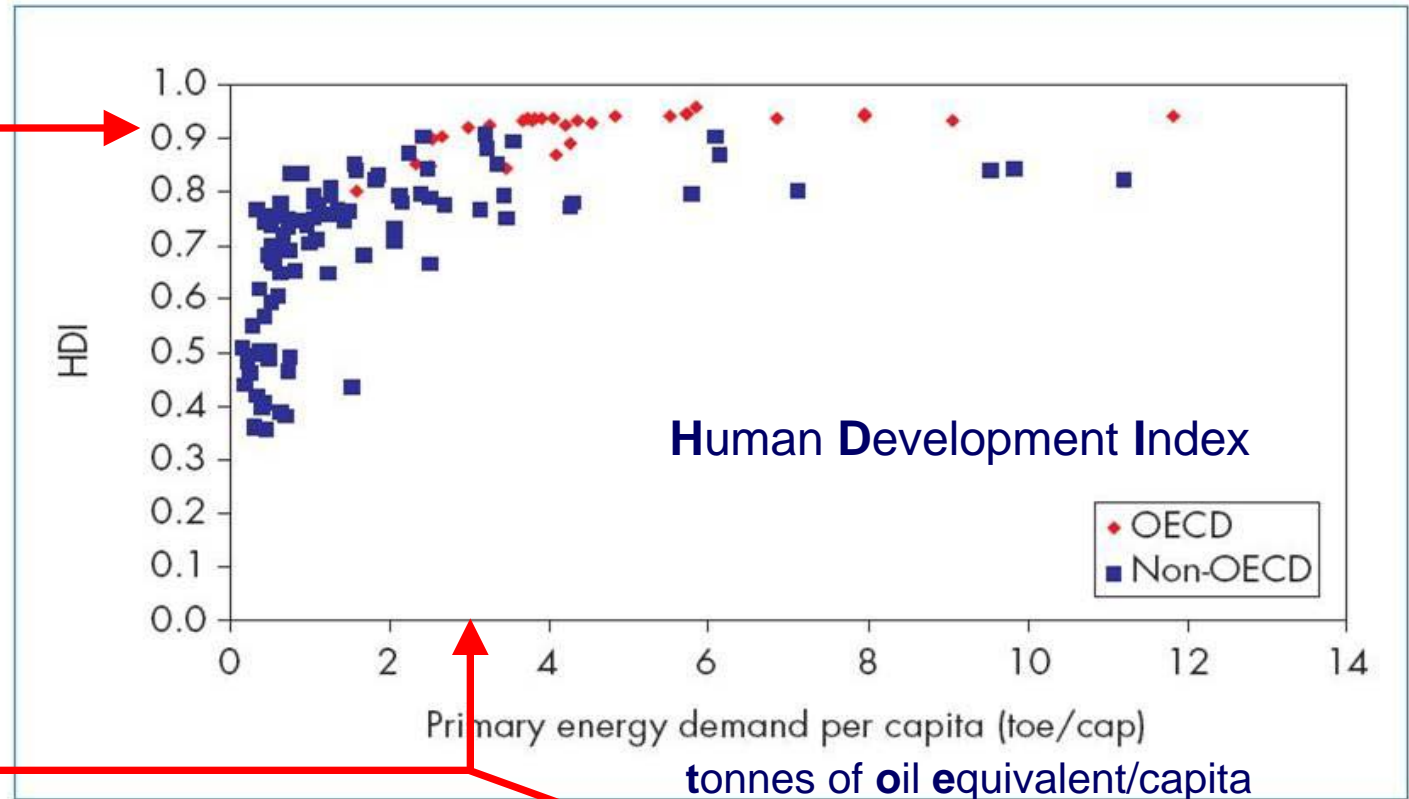
Source: IEA World Energy Outlook 2006

Note further

- i) Annual deaths from indoor cooking ~ 1.5 M (malaria 1.2 M, TB 1.6 M)
- ii) Climate change will have worst effects in developing world

HDI (~ life expectancy at birth + adult literacy & school enrolment + GNP per person at PPP) and Primary Energy Demand per person, 2002

Goal (?) →



To reach this goal seems need

Sources: IEA analysis; UNDP (2004).

For all developing countries to reach this point, would need world energy use to double with today's population, or increase 2.6 fold with the 8.1 billion expected in 2030

If also all developed countries came down to this point the factors would be 1.8 today, 2.4 in 2030

Sources of Energy

■ World's primary energy supply (*rounded*):

Approximate thermal equivalent:

81.4 % - *fossil fuels	77.5%
9.8% - combustible renewables and waste	9.3%
5.9% - nuclear	5.6%
2.2% - hydro	6.3%
0.7% - geothermal, solar, wind, .	1.3%

* 42% oil, 33% coal, 26% natural gas

Note: energy mix very varied

e.g. in China: Coal → 64% of primary energy; gas – only 3%

This is (part of) the explanation for the very large number of deaths premature deaths caused by air pollution in China. Annual figures (WHO 2007):

Globally - 2 million deaths, China 650,000, India - 530,000, USA - 41,000

and explains why CO₂ per capita is above world average

Timescale for the end of fossil fuels

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? Maybe

- **Oil** will be largely exhausted in 50 years

Recent UKERC review of all work on Peak Oil concludes that peak in **conventional oil** is likely to occur before 2030, and there is a significant risk that it will occur before 2020. Production will then fall ~ 3% (?) p.a.

Lots more ‘Unconventional’ oil (Venezuela ~ 1.2 tr barrels; Canada ~ 1.8 tr barrels) – how much can/should be used?

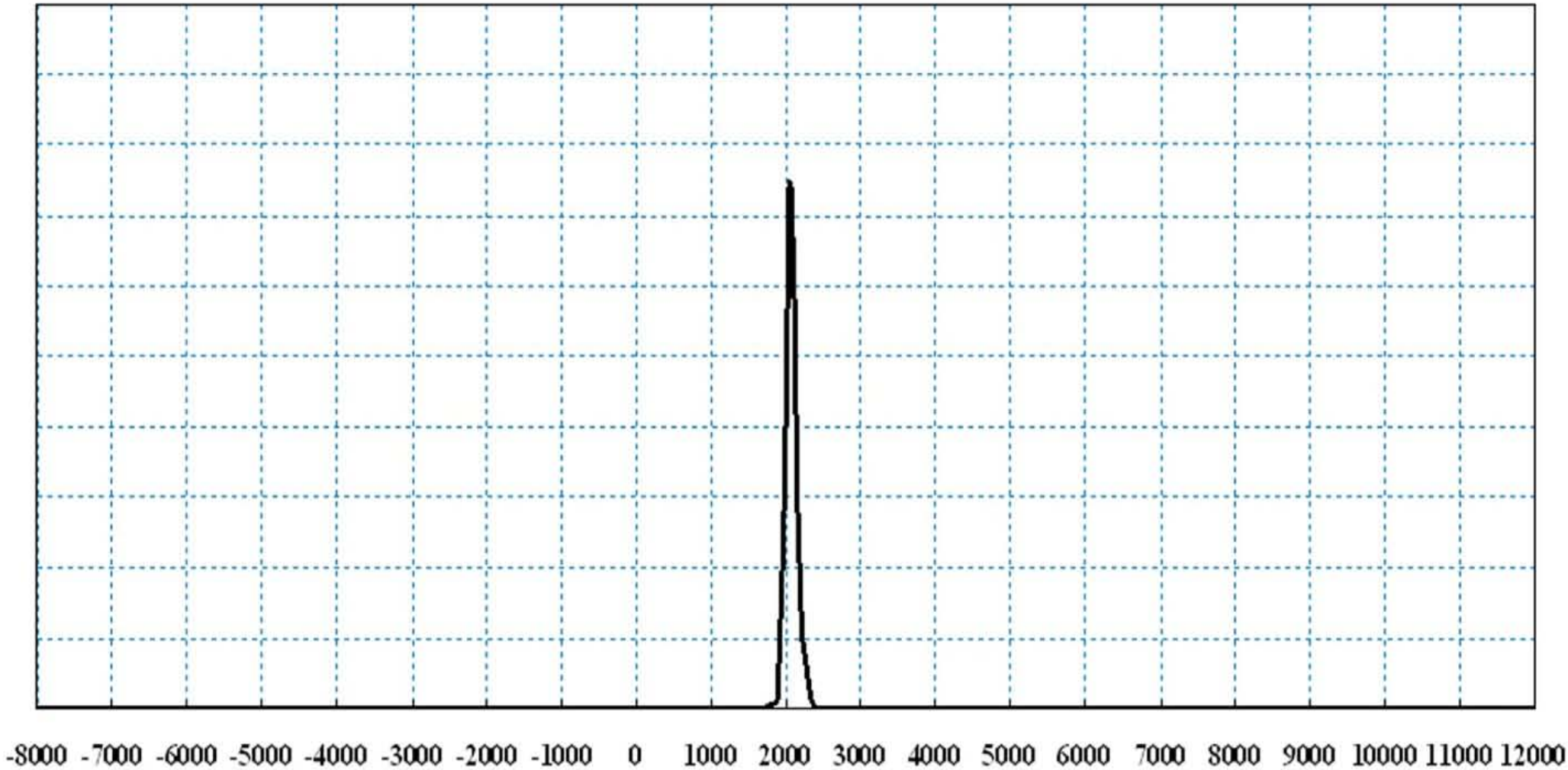
- **Gas** – conventional gas estimated to last ~ 130 years with current use (73 years with [IEA] 1.5% growth), **but** recent huge expansion in prospects for unconventional gas adds ~ 130 years (not including methyl hydrates)

- **Coal:** often said that there is enough for over 200 years (true?) - but that is with current use; with 1.9% p.a. growth [IEA] this becomes ~ 115 years

***Note:** growth in gas and coal will increase as oil become scarce*

We need to start preparing for the post oil era now and thinking about the post fossil fuel era





Fossil Fuel Use

- a brief episode in the world's history

Timescale to avoid climate change

- CO₂ stays in the atmosphere for hundreds of years

We should have taken action yesterday!

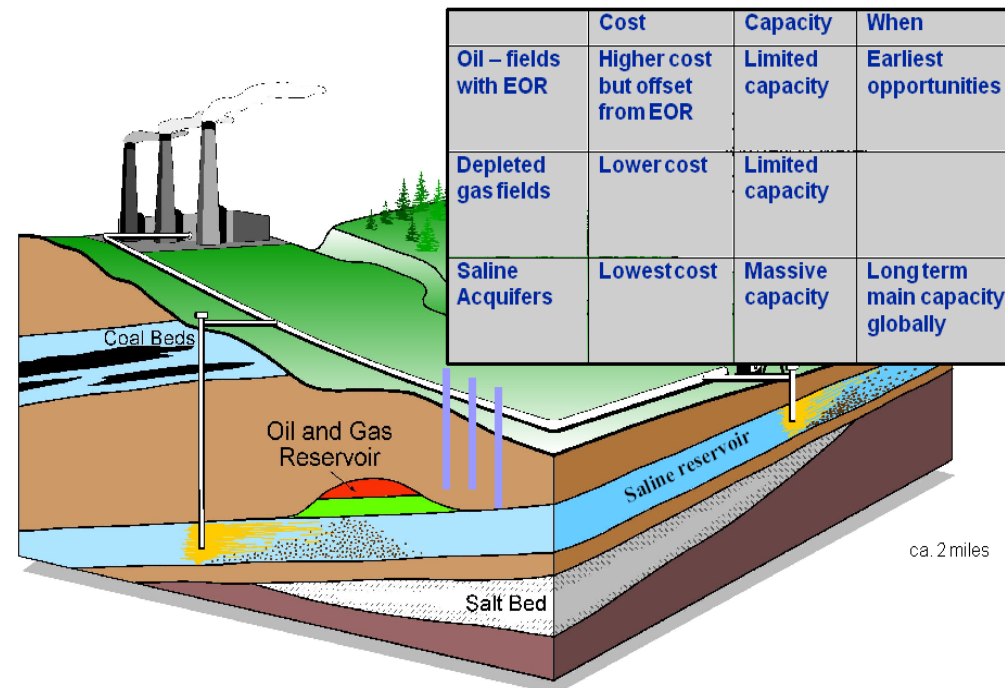
Likely that most of the remaining fossil fuels will be burned in ~ 100 years, in which case the only action that can help is

- **Carbon Capture and Storage***

*capture and burial of CO₂ from power stations and large industrial plants

which should be developed as a matter of urgency and (if feasible) rolled out on the largest possible scale *(easy to say, but harder to do as it will put up the cost)*

CO₂ storage options



Necessary Actions in Preparation for the End of the Fossil Fuel Era

■ Reduction of energy use/efficiency

- can reduce the growth in world energy use, and save a lot of money, **but** unlikely to reduce total use, unless living standards in the developed world drop dramatically, or do not rise in the developing world

■ Develop and expand low carbon energy sources

- need all, but only solar and nuclear (fission and/or fusion) have the *potential* to take over a large fraction of the role currently played by fossil fuels

■ Devise economic tools and ensure the political will to make this happen

These steps also crucial for tackling climate change, for which carbon capture and storage is *also* vital

Use of Energy

End Use (rounded)

≈ 25% industry

≈ 25% transport

≈ 50% built environment
(private, industrial, commercial) } ≈ 30% domestic in UK

Energy Efficiency

One slide on buildings, although huge gains also to be made in **transport** and there are substantial gains possible elsewhere, e.g. raise world average thermal power plant efficiency from ~ 30% to 45% (state of the art), smart/interactive grid

Huge scope but demand is rising faster

Note: Energy intensity (= energy/gpd) fell 1.6% pa 1990-2004

Efficiency is a key component of the solution, but cannot meet the energy challenge on its own

The Built Environment

Consumes ~ 50% of energy

Improvements in design could have a big impact

e.g. could cut energy used to heat homes by up to factor of three (**but** turn-over of housing stock ~ 100 years)

Lighting ~ 19% of all electricity world-wide

Better use of natural light; reduce 'over-lighting'; more efficient bulbs:

- traditional incandescent bulbs ~ 5% efficient
- compact fluorescent lights ~ 20% efficient
- in longer term : LEDs (up to 50% efficient)

Detailed US study: upgrading residential incandescent bulbs and ballasts and lamps in commercial buildings could save = 3% of all electricity use

Tools: better information, regulation, financial instruments



Source: Foster and Partners. Swiss Re Tower uses 50% less energy than a conventional office building (natural ventilation & lighting...)

Low Carbon Energy Sources

■ What can replace the 13TW (and growing) from fossil fuels?

Maximum practical additional potentials (*thermal equivalent*):

Wind 3TW*, geothermal 100GW, hydro 2TW, bio 1TW, marine 100GW

which **add up to less than 7 TW**

** claim can in principle get 72TW_e*

We should expand them as much as we reasonably can (easy to say, but harder to do as it will put up the cost), but the world will need something else, which can only be:

Solar and/or Nuclear (fission or fusion)

[Conclusions are very location dependent: geothermal is a major player in Iceland, Kenya,...; the UK has 40% of Europe's wind potential and is well placed for tidal and waves; the US south west is much better than the UK for solar; there is big hydro potential in the Congo;...]



?

Not

Enough

Solar Potential

- **Average flux reaching earth's surface is 170 Wm^{-2}**

220 Wm^{-2} at equator, 110 Wm^{-2} at 50 degrees north

- **170 Wm^{-2} on 0.5% of the world's land surface (50% occupied) would, with 15% efficiency, provide 19 TW** (*equivalent to much more primary energy*)

- **Photovoltaics are readily available with 15% efficiency or more, and concentrated solar power can be significantly more efficient**

Photosynthesis:

- **Natural:** *even sugar cane is only 1% efficient at producing energy: wood ~ 1/6th efficiency of sugar cane*

With 0.5% efficiency, need 15% of world's land surface to give 19 TW

Bio-fuels (2005) used 1% of agricultural land → 1% of road transport

- **Artificial:** exciting possibility of mimicking photosynthesis in an artificial catalytic system to produce hydrogen (to power fuel cells), with efficiency of possibly 10% (and no: wasted water, fertiliser, harvesting) – should be developed

Solar (non-bio)

- **Photovoltaics** (hydrogen storage?)

 - cost needs to come down

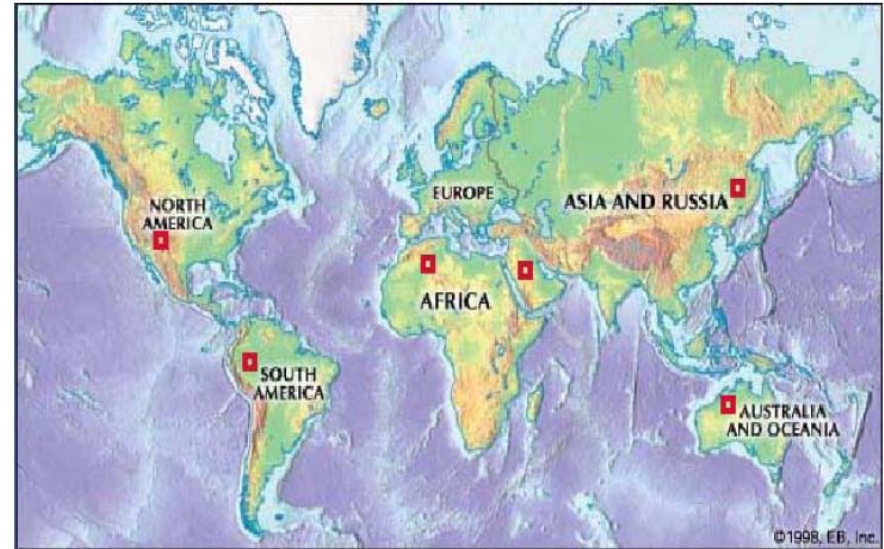
- **Concentration** (parabolic troughs, heliostats, towers)

 - turbines (storage: molten salts,....)

 - High T → improved electrolysis (or even 'thermal cracking' of water to hydrogen?)

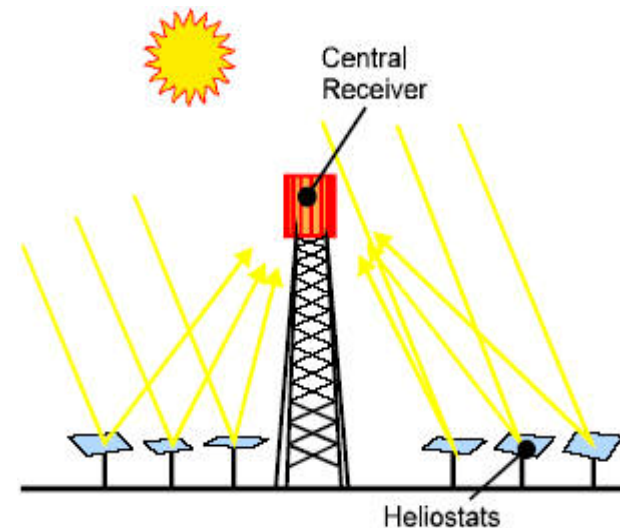
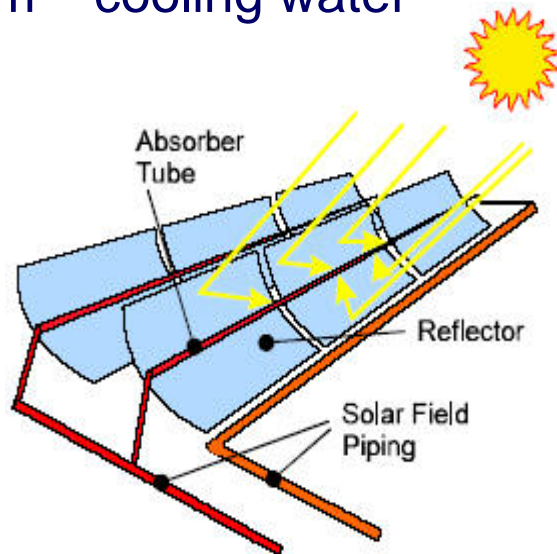
 - Challenges: new materials, fatigue...

 - Problem – cooling water



6 boxes sized to produce 3.3TW of power each (20TW total – 630EJ)

Source: Lewis et al 2003c



Nuclear

Should be expanded dramatically now

- **New generation of reactors**
 - Fewer components, passive safety, less waste, more proliferation resistant, lower down time and lower costs
 - On large scale: several options - AP1000, EPR, CANDU, ESBWR,...
 - On smaller scale (slightly farther ahead): PBR
- **Looking to the future, need to consider**
 - Problems and limitations (snails pace of planning permission in some countries, safety, waste, proliferation, uranium resources)
 - Options (Different fuel cycles, Uranium/plutonium fast breeders, Thorium reactors, Fusion)

Problems and limitations

- **Safety** – biggest problem is perception

Modern 1 GW coal power station with W European population density causes ~ 300 premature deaths (~ 10 years loss of life) per year → 9,000 in 30 years: more than Chernobyl

- **Waste** – problem is volume for long term disposal

US figures:

Existing fleet will → 100,000 tonnes (c/f legislated capacity of Yucca mountain = 70,000 tonnes)

If fleet expanded by 1.8% p.a. → 1,400,000 tonnes at end of century

- **Proliferation** – need to limit availability of enrichment technology, and burn or contaminate fissile products

Uranium Resources

■ Two categories:

- ‘Conventional’ - **up to 16 Mt** (3.1Mt identified + estimates of undiscovered)

- Unconventional – huge amounts in phosphates, sandstone, sea water

*Thought that 22 Mt in phosphates may be economically recoverable
a by-product that of producing phosphoric acid → **16 + 22 = 38 Mt***

NB energy cost of extraction must be less than energy content,

but + \$100/lb only → + 0.1\$c/kw-hr

With Fast Breeder Reactors, which produce ~ 60 times more energy/kg, much more would be economic (even U in sea water?)

- 16 Mt [**38 Mt**] in (current) conventional reactors at present rate of use would last 200 years [**475 years**]

If nuclear increased six fold (to ~100% of current world electricity production)
16 Mt [**38 Mt**] is enough for 33 years [**80 years**]

- **Conclusion:** if there is a big expansion of fission, will have to develop fast breeder reactors seriously (noting that for 1 FBR to make enough fuel for a second takes 12 years), or turn to thorium (doubling time ~30 years)
– but this is not urgent

Different Fuel Cycles/Fuel

■ Goals

- Reduce waste needing long-term disposal (destroy: [99.5+%?] of transuranics, and heat producing fission products [caesium, strontium])
- Destroy or 'contaminate' weapons-usable material
- Get more energy/(kg of uranium)

■ Options (some gains possible from improved burn-up in once through reactors; as in all thermal power plants, higher temperature → more energy/kg of fuel)

- **Recycle** in conventional reactors – can get ~2 times energy/kg + reduce waste volume by factor 2 or 3 (note: increased proliferation risk + short-term risk from waste streams)
- **Fast breeders** – turn ^{238}U (99.3%) into fissile ^{239}Pu , **but** more expensive, not quite so safe or proliferation resistant, 1 reactor → 2 takes ~ 12 years
- **Thorium**. Accessible ^{232}Th (can all be burnt) resource seems (??) to be over 4 Mt, vs. 0.1 Mt for ^{235}U (if total accessible U resource is 16 Mt), **but** need development, very long doubling time
- **Mixed economy**: conventional reactors + burn waste by having some FBRs or accelerator based waste burners

FUSION

powers the sun and stars

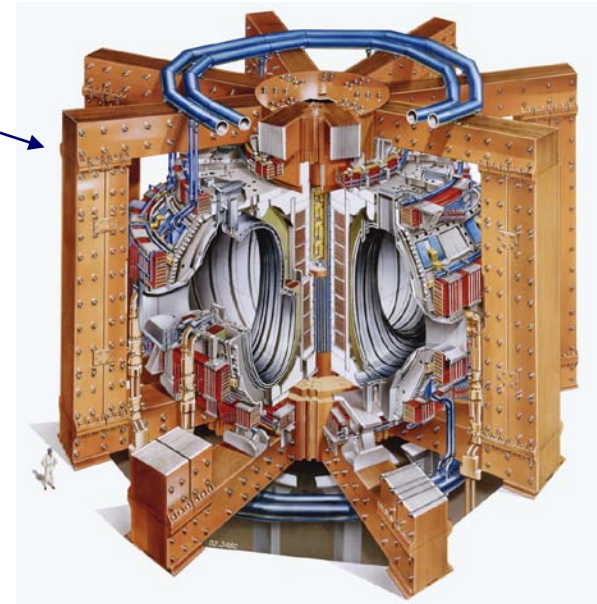
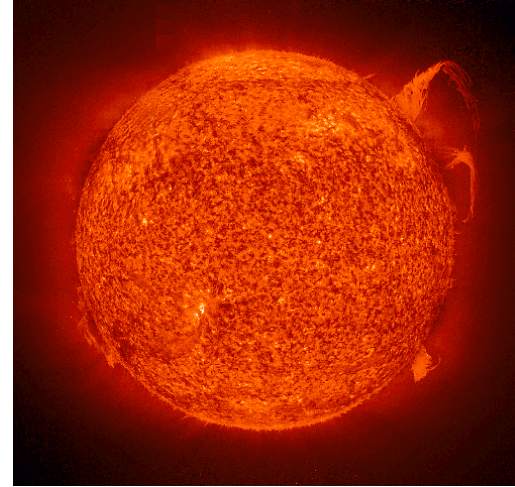
and a controlled 'magnetic confinement' fusion experiment at the **J**oint **E**uropean **T**orus (**JET**) (in the UK) has produced 16 MW of fusion power

so it works

The big question is

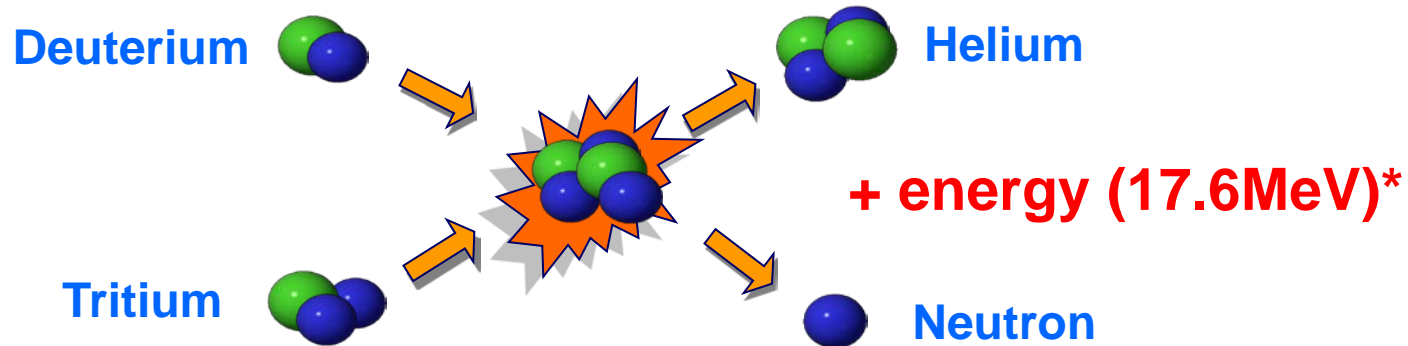
- when will it work reliably and economically, on the scale of a power station?

First: What is it? Why bother? Why is it taking so long?



WHAT IS FUSION ?

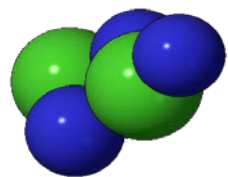
Most effective fusion process involves deuterium (heavy hydrogen) and tritium (super heavy hydrogen) heated to above **100 million °C** :

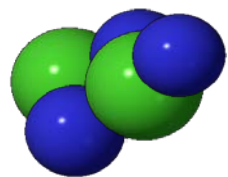


A “magnetic bottle” called a **tokamak** keeps the hot gas away from the wall

Challenges: make an effective “magnetic bottle” (now done ?) a robust container, and a reliable system

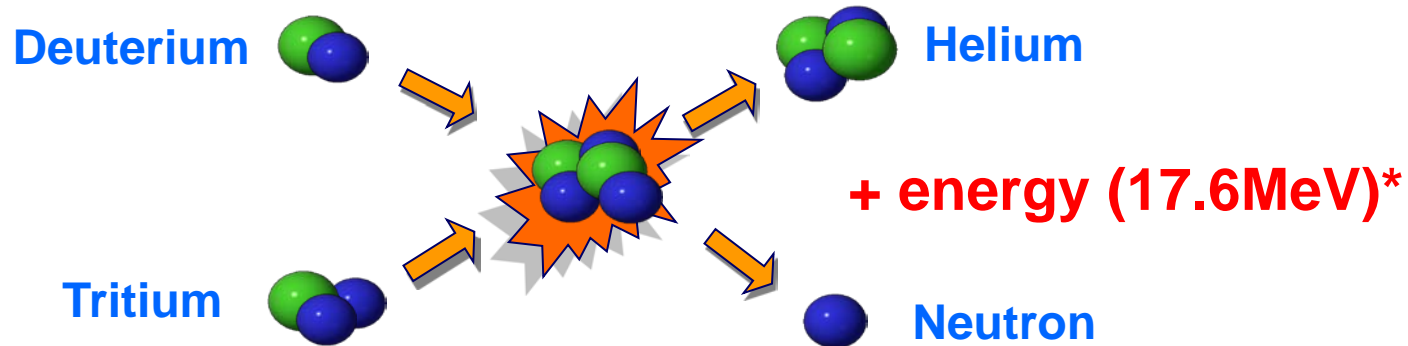
* ten million times more than in chemical reactions, e.g. in burning fossil fuels
⇒ while a 1 GW coal power station would use 10,000 tonnes of coal a day, a fusion power station would only use 1 Kg of D + T





WHAT IS FUSION ?

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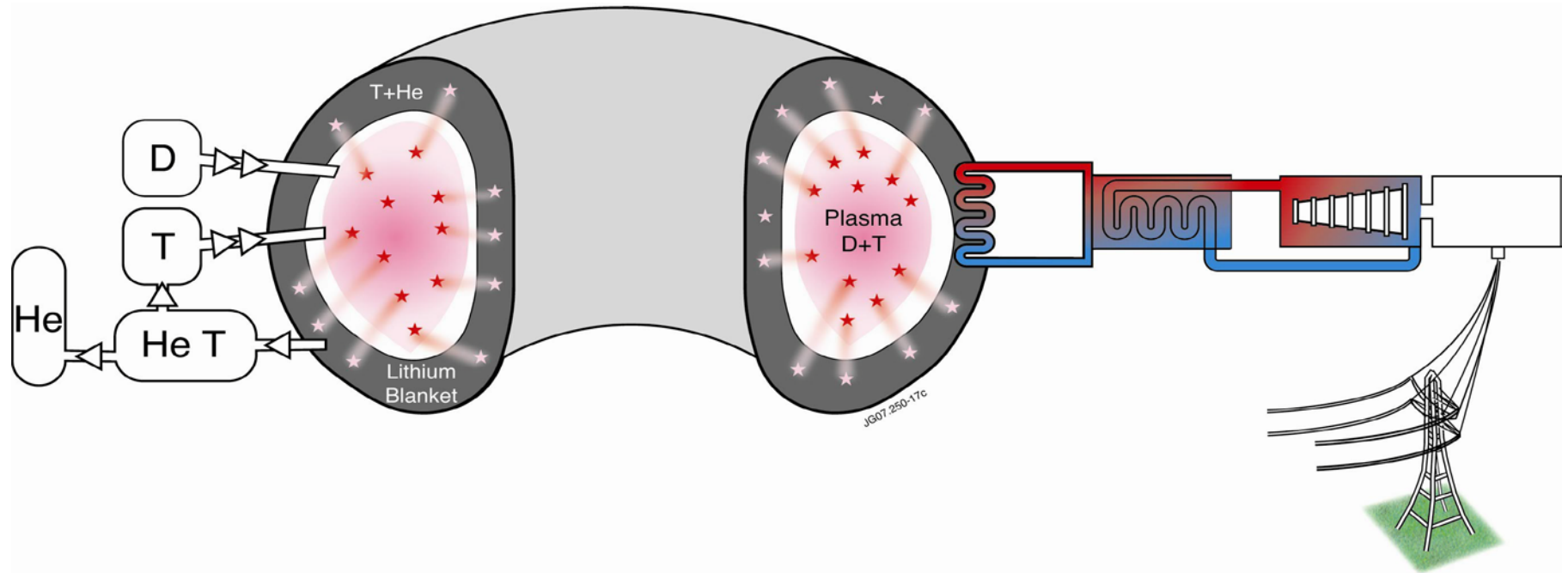


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A Fusion Power plant would be like a conventional one, but with a different fuel and furnace



The blanket captures **energetic neutrons** produced in the fusion process, which:

- react with lithium in the blanket to **produce Tritium** (\Rightarrow fuel the reactor)
- deposit **their energy** \Rightarrow **heat** which is extracted through a cooling circuit and used to boil water and produce steam to drive a generator

Why bother?

Lithium in one laptop battery (\Rightarrow *tritium* from the reaction:

neutron (from fusion) + lithium \rightarrow tritium + helium)

+ 40 litres of water (from which 'heavy water'/deuterium can easily be extracted), used to fuel a fusion power station, would provide 200,000 kW-hours =

US/EU per capita electricity production for 15/30 years, in an intrinsically safe manner with no CO₂



**N.B Lithium
very abundant**

Unless/until we find a barrier, this is sufficient reason to develop fusion power

FUSION ADVANTAGES

- unlimited fuel
- no CO₂ or air pollution
- intrinsic safety
- no radioactive “ash” and no long-lived radioactive waste
- competitive* electricity generation cost, *if* reasonable availability (e.g 75%) can be achieved

*compared to most other carbon free electricity sources

FUSION DISADVANTAGES

■ The blankets will become radioactive

but can choose materials so that half lives ~ 10 years, and all components could be recycled ⇒ new fusion power plant within 100 years **(no waste for permanent repository disposal: no long-term burden on future generations)**

■ More research and development needed

Fusion power stations will need plasma volumes of at least 1000 m³ (ten times JET), so small scale demonstration impossible (hence - relatively slow - step by step progress)

Why so long?

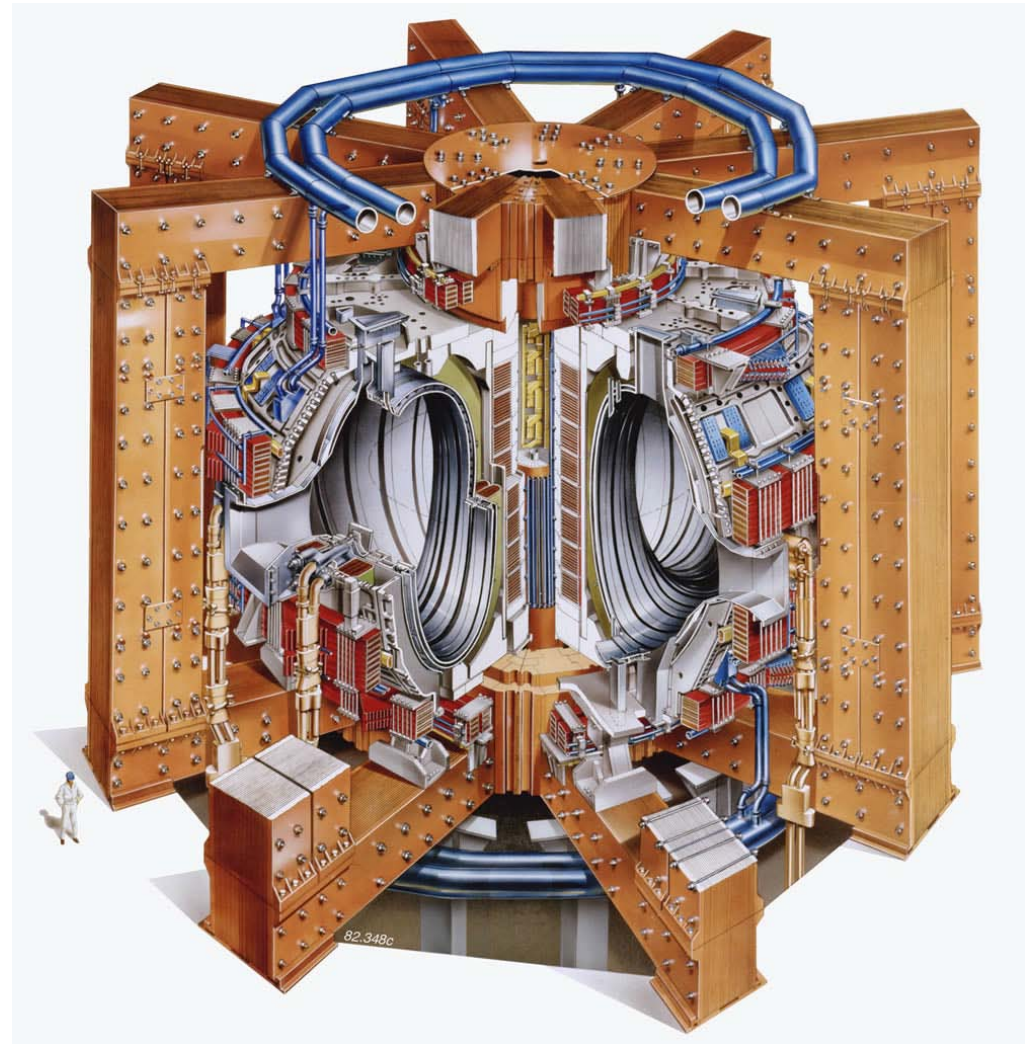
- **Cannot demonstrate on a small scale:** (power out)/(power to operate) grows faster than (size of fusion device)² – need GW scale to be viable
- **Not funded with any urgency** – otherwise from agreement on basic geometry in 1969, could have reached today's position 15 years ago
- **It is very challenging**
 - need to heat ~ 2000 m³ of gas to over 100 M °C, without it touching the walls
 - find robust materials with which to make the walls (able to withstand intense neutron bombardment and heat loads)
 - ensure reliability of very complex system

Nevertheless huge progress: from T3 to JET and from JET to ITER (later)

Progress in Fusion has been enormous, but even **JET** (currently the world's leading fusion research facility) is not large enough to be a (net) source of power



T3: Volume $\sim 1 \text{ m}^3$
Temperature $\sim 3 \text{ M } ^\circ\text{C}$
Established tokamak as best configuration (1969)

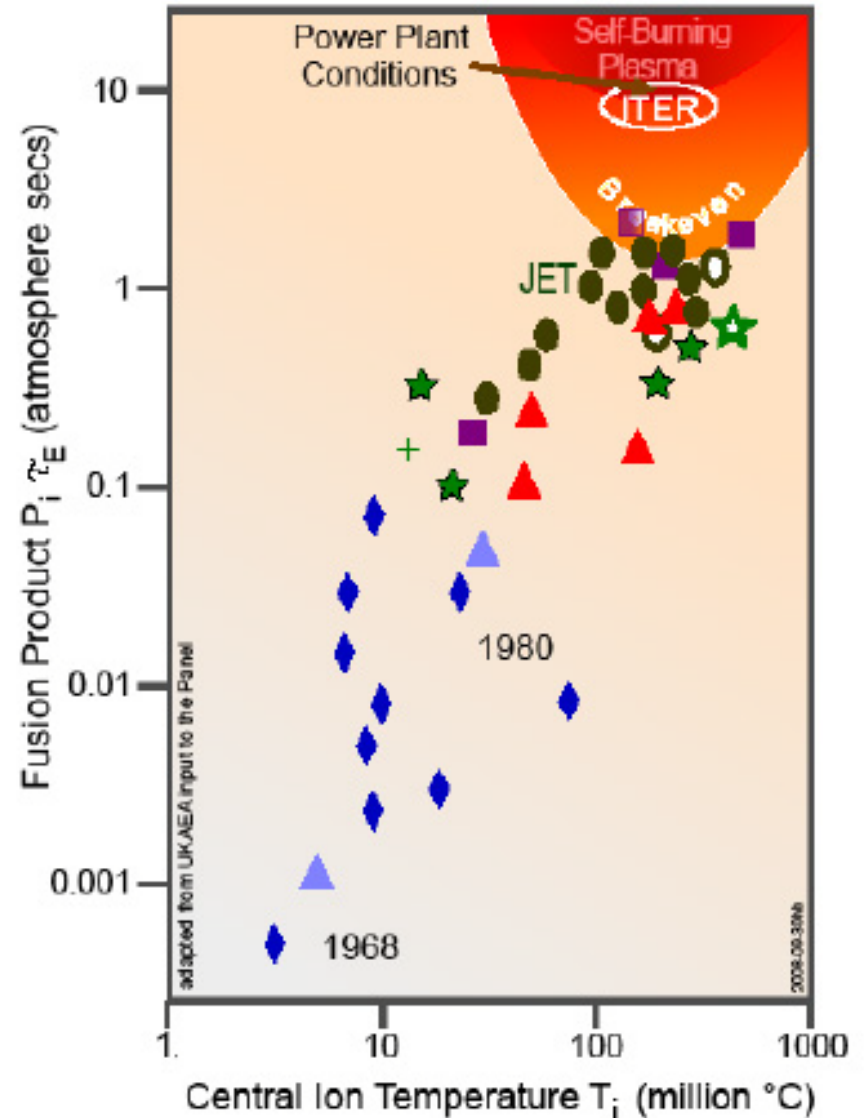


JET: Volume $\sim 100 \text{ m}^3$
Temperature $\sim 150 \text{ M } ^\circ\text{C}$
World record (16 MW) for fusion power (1997)

Progress

- Huge strides in physics, engineering, technology
- **JET**: 16 MW of fusion power ~ equal to heating power
- Ready to build a Giga Watt-scale tokamak: **ITER** – expected to produce 10 x power needed to heat the plasma

P_i = pressure in plasma;
 τ_E = (energy in plasma)/(power supplied to keep it hot)



NEXT STEPS FOR FUSION

- **Construct ITER (International Tokamak Experimental Reactor)**

- ⇒ energy out = 10× energy in

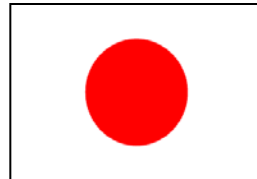
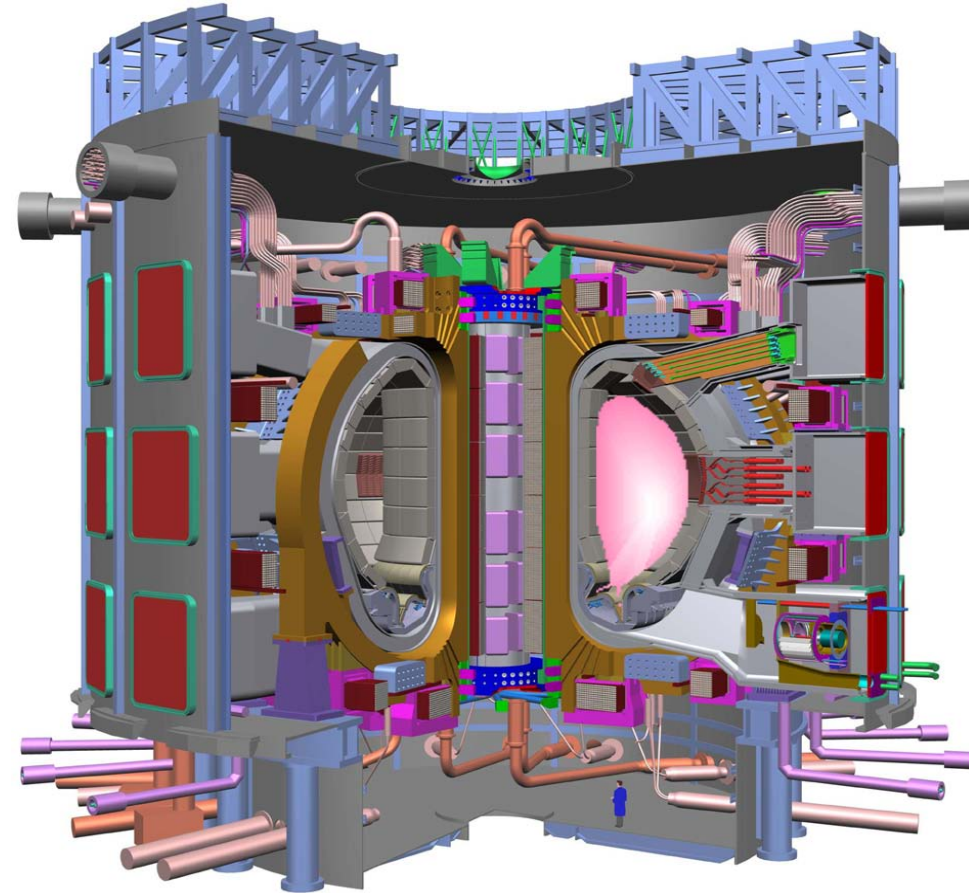
- ⇒ “burning” plasma

During construction: further improve tokamak performance in experiments at JET, DIII-D, ASDEX-U, JT- 60..., and **continue work on alternative configurations** [Spherical Tokamaks (pioneered in UK), Stellarators]

- **Intensified R&D on i) materials for plasma facing and structural components** and tests of materials at the proposed **International Fusion Materials Irradiation Facility (IFMIF)**, and **ii) fusion technologies** (remote handling, heating systems, blanket, fuel cycle, magnets,...)

ITER

- Aim - demonstrate integrated physics and engineering on the scale of a power station
- Key ITER technologies fabricated and tested by industry
- Construction beginning at Cadarache in southern France. Over 5 Billion Euros construction cost
- Partners house over half the world's population



European Power Plant Conceptual Study

- Encouraging range for the expected cost of fusion generated electricity: 9 €-cents/kW-hour for early near-term (water cooled steel) model; 5 €-cents/kW-hour for early advanced (Li-Pb cooled Si-C composites) model

Note

- Economics favours large fusion power plants → major centres of population (complementary to renewables)
- Capital intensive; very low operating cost – lots of cheap off peak power → hydrogen?

Results of this study used as input to Culham 'Fast Track' study

FUSION 'FAST TRACK'

Time table for building first Demonstrator/Prototype Power Plant ('DEMO'), *assuming adequate funding, and no major adverse surprises:*

- **Build ITER ~ 10 years**
- **Operate and gain sufficient experience from ITER ~ 10 years**
- **In parallel: intensified materials work** (*approve and build IFMIF as soon as possible*) and **development of fusion technologies** (magnets, remote handling, heating systems, fuel cycle, safety,...), and **design work on DEMO**

→ Start building DEMO in ~ 20 years

→ Power from DEMO to the grid in ~ 30 years

→ 'Commercial' fusion power ~ middle of the century

A compact 'Component Test Facility' would also be desirable (necessary?). A more aggressive approach (justified in my opinion) would involve building a low performance DEMO much sooner.

Could what is available add up to a solution?

■ Known technologies could *in principle* meet needs with constrained CO₂ until around the middle of the century, ***but it will be much much harder than implied by:***

IEA '450' scenario developed as input to Copenhagen in which

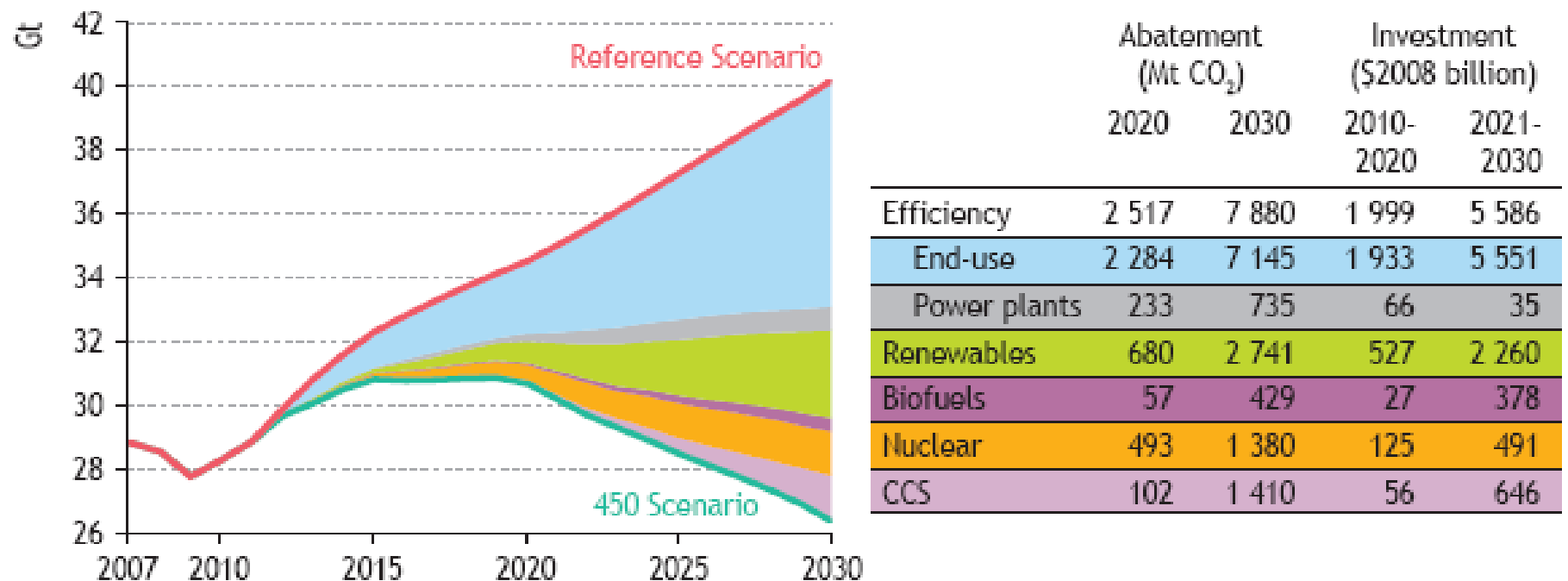
- CO₂ rises to 510 ppm 2035–2045, then declines very slowly to 450 ppm
- Measures in 2010-30 technically possible but near limit of believable
- No suggestion for how CO₂ production will continue to decline beyond 2030 (with world population still rising)
- Fossil fuels still play a very big role – what as they diminish?
- No head room for greater equity (per capita energy use: in EU assumed to decrease from 3.5 toe to 3.3, in China assumed to rise from 1.5 toe to 2.0 toe, but in India the rise is only from 0.5 toe to 0.8 toe)

Overall, the report gives a very misleadingly optimistic impression

IEA Reference Scenario assumes government policies adopted and enacted, although many not yet fully implemented

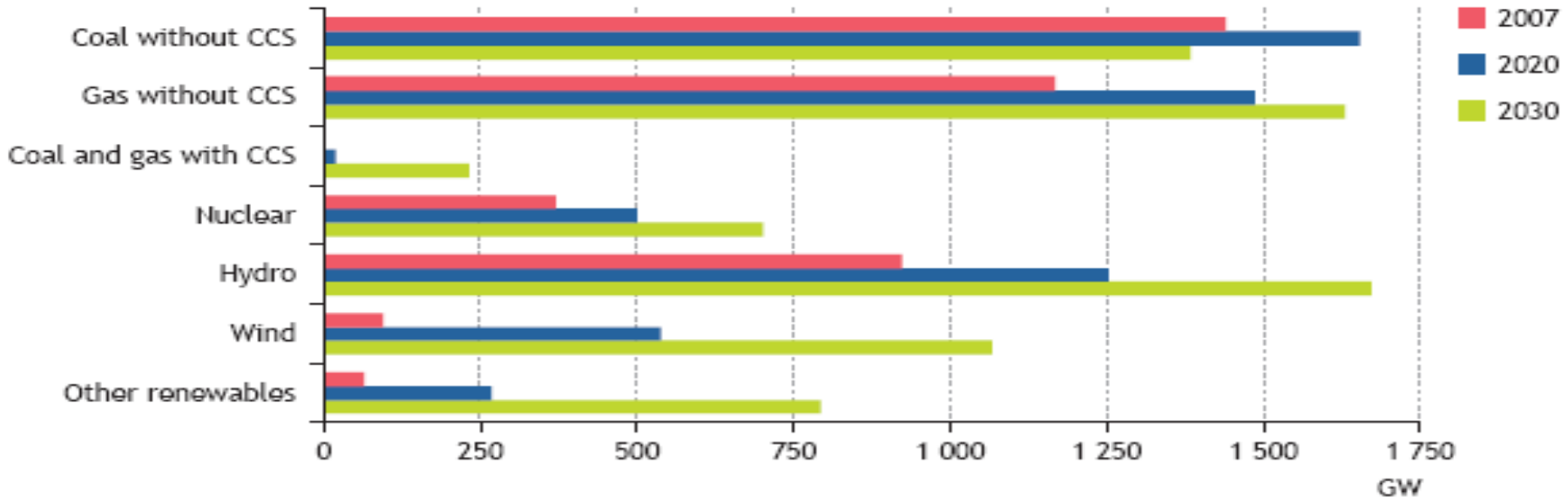
'450 Scenario' goes much further

Figure 3: World energy-related CO₂ emissions abatement



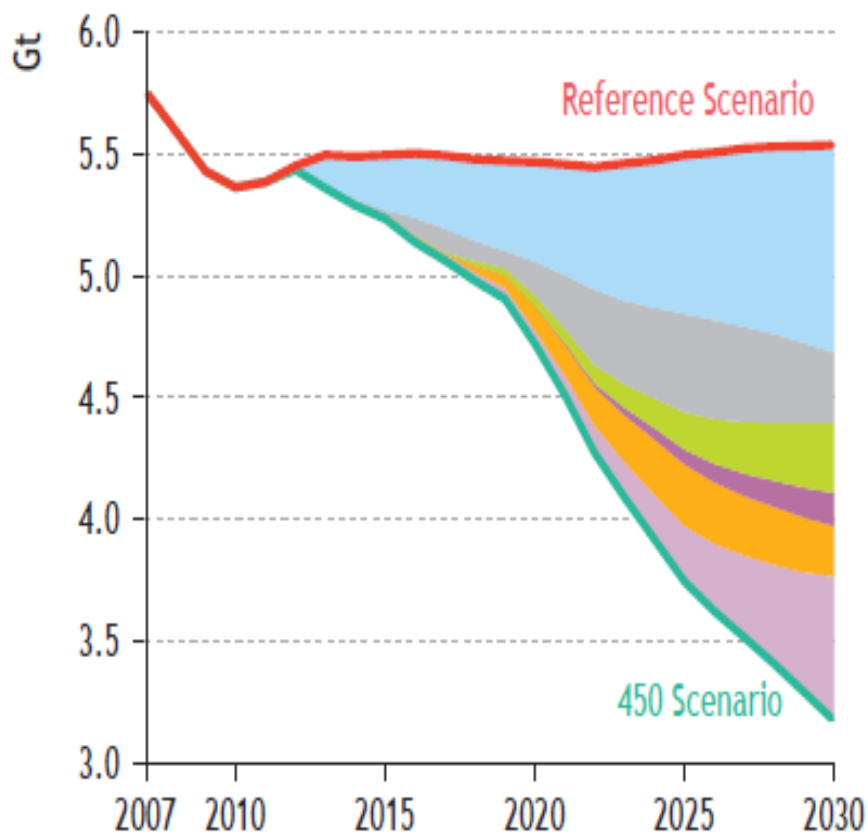
- 2030 emissions still 25% more than 1990 (population up 55 %)
- 450 curve must continue downwards to bring CO₂ from ~ 510 ppm in 2045 to 450 ppm eventually: how?

Figure 4: World power generation capacity in the 450 Scenario



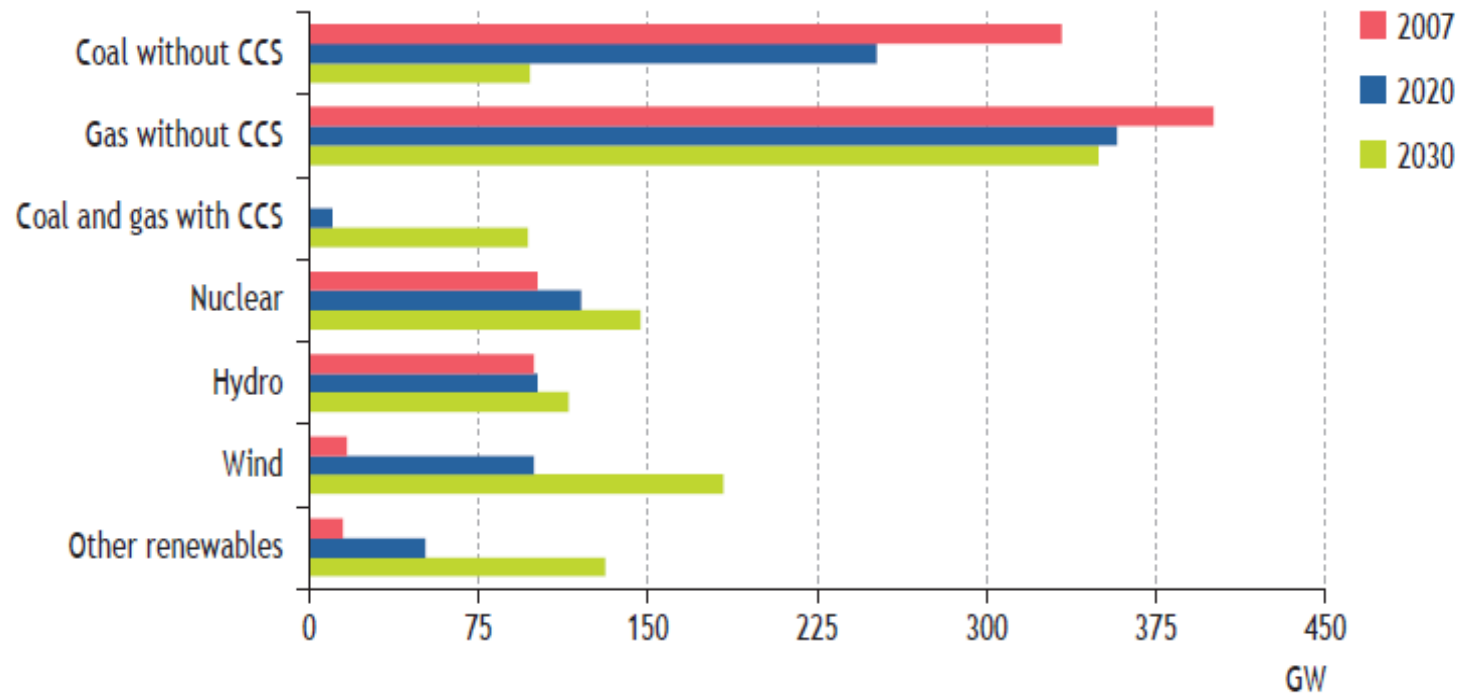
Note: Nuclear x 2.0 → average output 634 GW
Hydro x 1.8 → average output 646 GW
Wind x 16 (NB Figure gives capacity, not output, but the figure does not seem consistent with the tables) → average output 228 GW
on-shore, 88 off-shore
Still lots of coal and gas, CCS assumed to work
Solar PV x 130 → average output 525 GW
Solar concentrated x 325 → average output 325 GW

Figure 13: United States energy-related CO₂ emissions abatement



	Abatement (Mt CO ₂)		Investment (\$2008 billion)	
	2020	2030	2010- 2020	2021- 2030
Efficiency	548	1 141	475	955
End-use	411	855	443	949
Power plants	137	286	32	5
Renewables	43	288	36	330
Biofuels	0	136	0	127
Nuclear	101	206	62	77
CCS	57	593	33	300

Figure 14: United States power generation capacity in the 450 Scenario



Coal x0.5

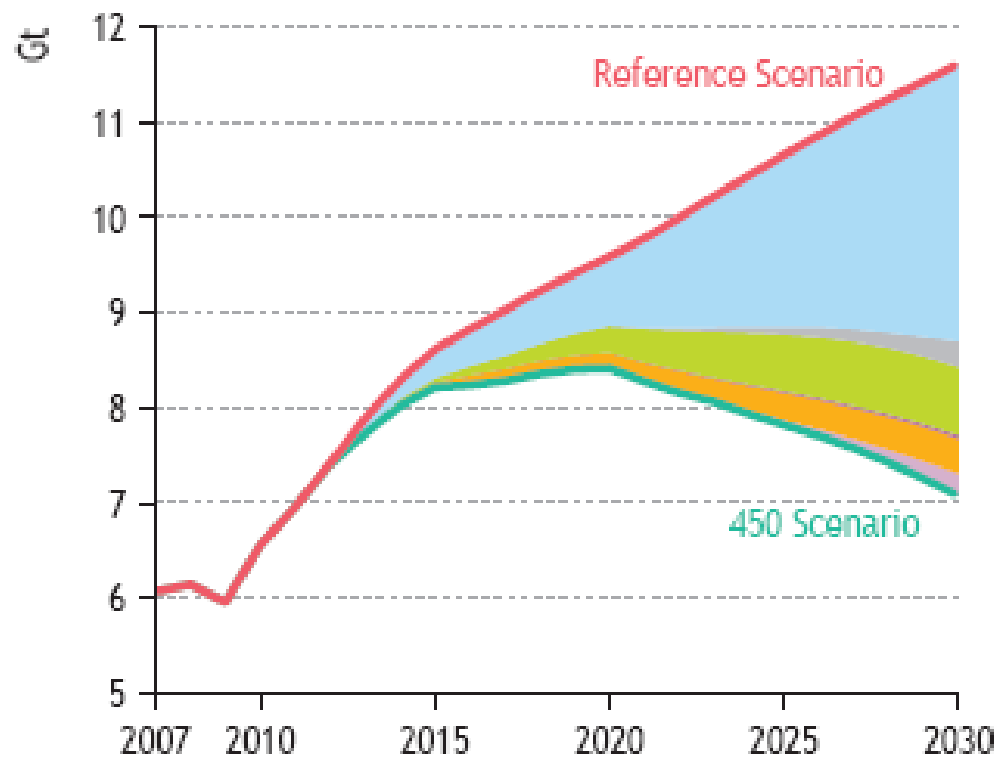
Nuclear x1.45 (→ 140 GW_e)

Hydrox1.3

Windx14 (→ 60 GWe)

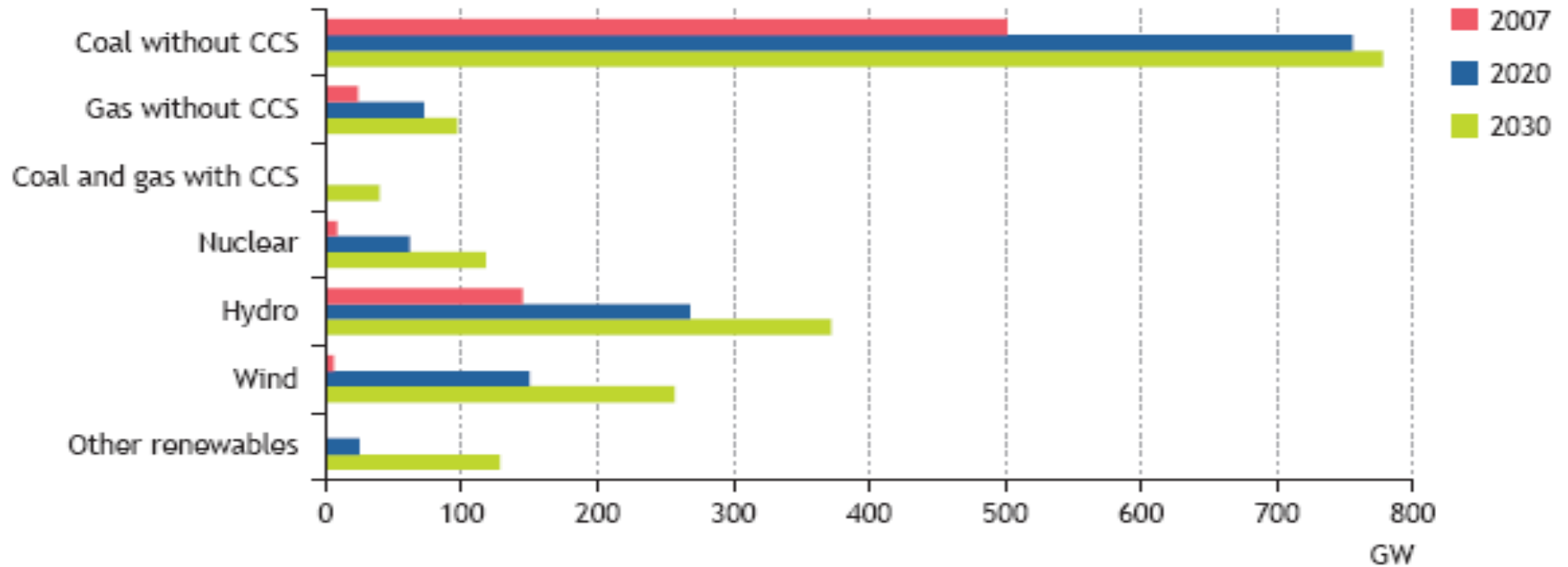
Other renewables x 4.6 (→ 50 GWe)

Figure 38: China energy-related CO₂ emissions abatement



	Abatement (Mt CO ₂)		Investment (\$2008 billion)	
	2020	2030	2010- 2020	2021- 2030
Efficiency	728	3 195	266	1 210
End-use	728	2 923	257	1 205
Power plants	0	272	8	5
Renewables	279	715	208	485
Biofuels	0	35	1	28
Nuclear	168	366	63	107
CCS	3	243	1	68

Figure 39: China power generation capacity in the 450 Scenario



Coal x1.3

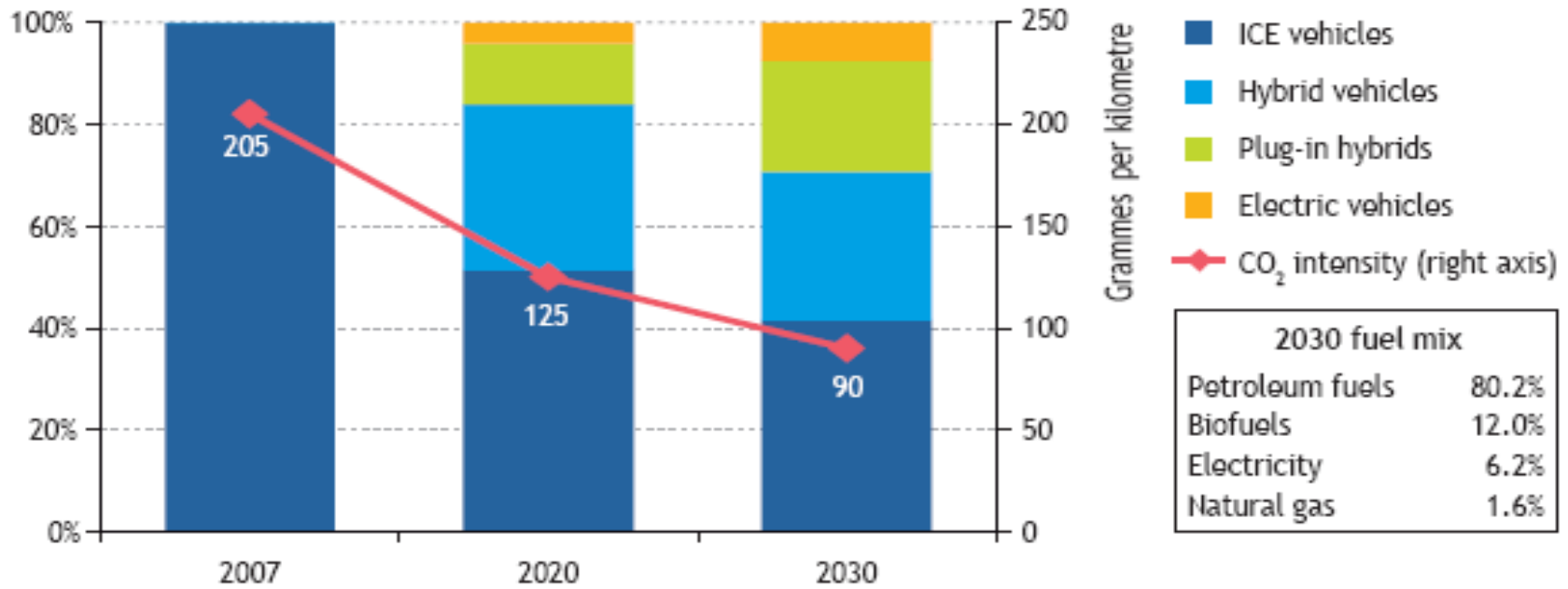
Nuclear x15 (\rightarrow 100 GW_e)

Hydrox2.2

Windx70 (\rightarrow 70 GWe)

Other renewables x 230 (\rightarrow 50 GWe)

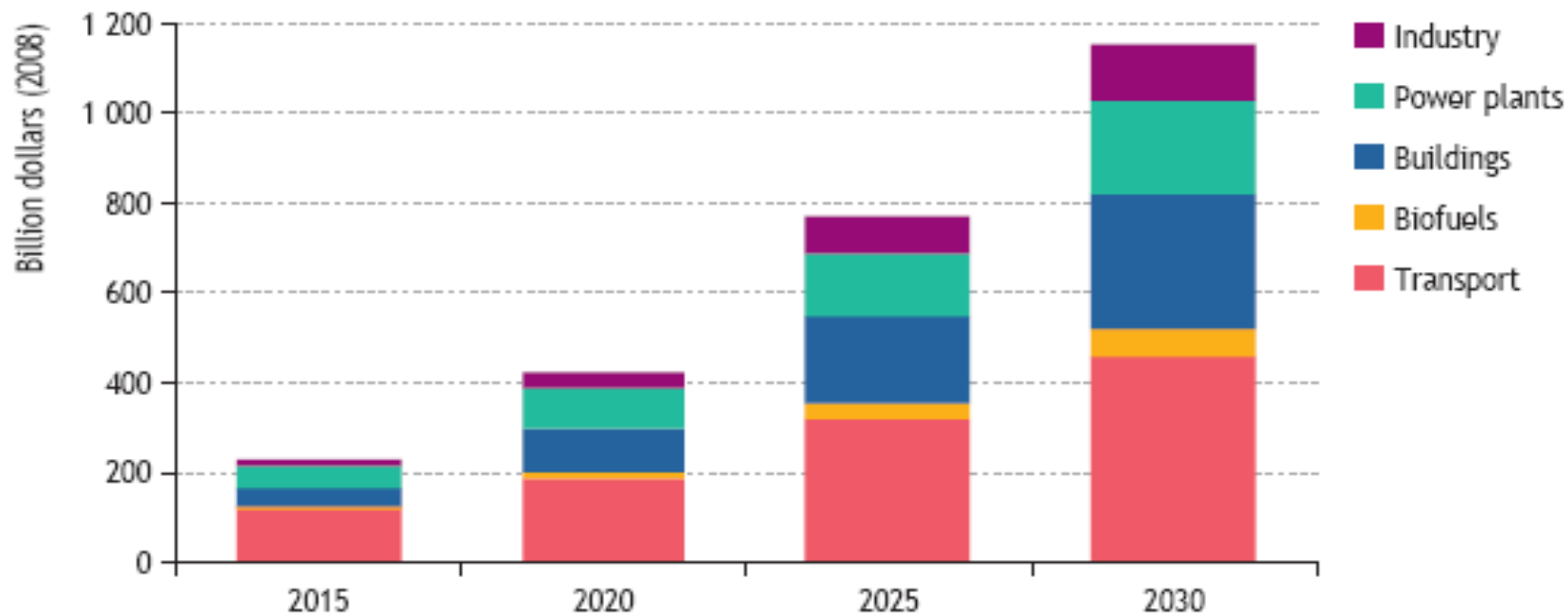
Figure 5: World share of passenger vehicle sales by technology and average new vehicle on-road CO₂ intensity in the 450 Scenario



Assumptions on Buildings

- Energy consumption 2752 Mtoe (2007) → 3232 Mtoe (2030)
- CO₂: 2754 Mt (2007) → 2743 Mt (2030)
i.e. 15% average decrease in CO₂/energy
or all new housing → zero carbon

Figure 6: World additional investment in the 450 Scenario relative to the Reference Scenario



Total additional investment cost (relative to reference scenario) is \$10.1 trillion – 0.5% of gdp in 2020 rising to 1.1% in 2030

\$6.6 trillion in low C power generation (72% renewables, 19% nuclear, 9% CCS)

Savings on fuel \$8.6 trillion

Local air pollution cost down by \$40 billion in 2020, \$100 billion in 2030

The IEA's failure to point out that the 450 scenario has is very very challenging has led to complacency, not least because some influential commentators have not read the report carefully:

e.g. Bill Emmott (Editor of the Economist 1993-2006) wrote an article in the London Times (on 29 October 2009) claiming that CO₂ reduction is taking care of itself

... in a section of its annual World Energy Outlook, released early to inform the climate debate, it said that if China carries out its stated programme for energy efficiency and emissions reduction, its annual output of carbon dioxide in 2030 will be about 7 gigatonnes instead of the 11.1 gigatonnes previously predicted — and not because China is expected somehow to give up getting richer.

In fact 11.1 gigatonnes assumes that China carries out its stated programme; *7 gigatonnes is in the incredibly challenging 450 scenario*

Could what is available add up to a ‘solution’?

Known technologies could *in principle* meet demand with constrained CO₂ (*but > 500 ppm inevitable?*) until the middle of the century

but only with

- technology development, e.g. for carbon capture and storage - *essential*
- increased efficiency: *most obvious steps save money*

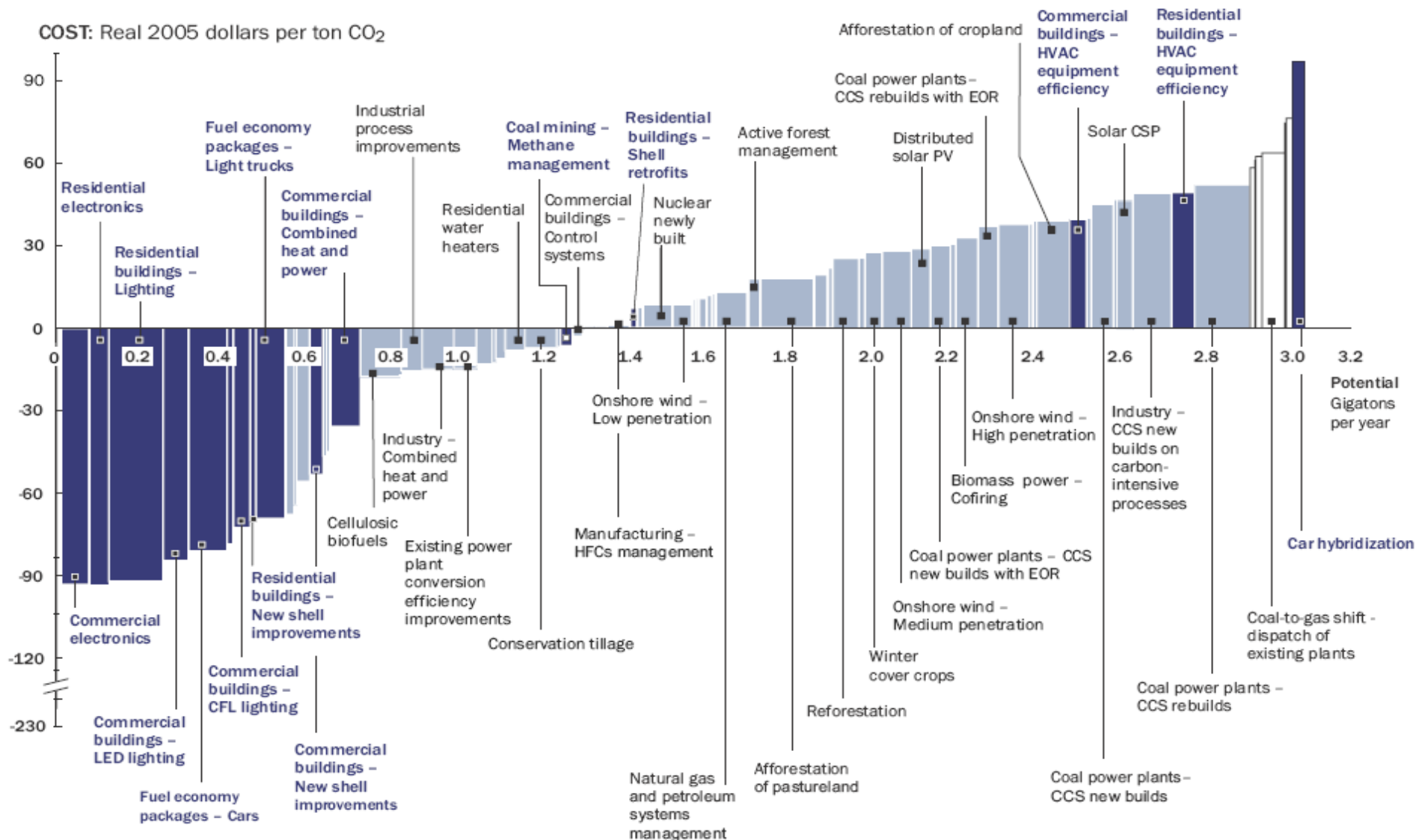
why's it not happening?

- all known low carbon sources pushed to the limit (*including much more nuclear*)
- **public willingness to pay more *before* the lights to out** in order to reduce CO₂ and prevent lights going out, **and/or political will *globally* to force the public to do so** → cost up through Carbon tax (best) or credits (more likely) + strong regulations

U.S. mid-range abatement curve - 2030

Carbon dioxide abatement: estimated removal cost per ton of CO₂ in 2005 dollars and removal potential in gigatons/yr for various strategies.

Abatement costs < \$50 per ton



Final Conclusions

- Huge increase in energy use expected; large increase needed to lift world out of poverty
- Challenge of meeting demand in an environmentally responsible manner is enormous
- No silver bullet - need a portfolio approach
Need all sensible measures: more wind, hydro, biofuels, marine, and **particularly: CCS** (essential to reduce climate change) and **increased efficiency**, and in longer term: more **solar** and **nuclear fission**, and **fusion** [we hope]
- Huge R&D agenda - needs more resources (to be judged on the ~ \$5 trillion p.a. scale of the world energy market)
- Need fiscal incentives - carbon price, regulation
- **Political will (globally)** - targets no use on their own

The time for action is now

Malthusian solution if we fail?

Plasma Physics Issues

Major positive developments (1980s and 90s)

- 'Bootstrap' plasma current (predicted at Culham) → much less external power needed than previously thought
- High confinement mode (serendipitous discovery at Garching) → higher pressure + more fusion power with given magnetic field

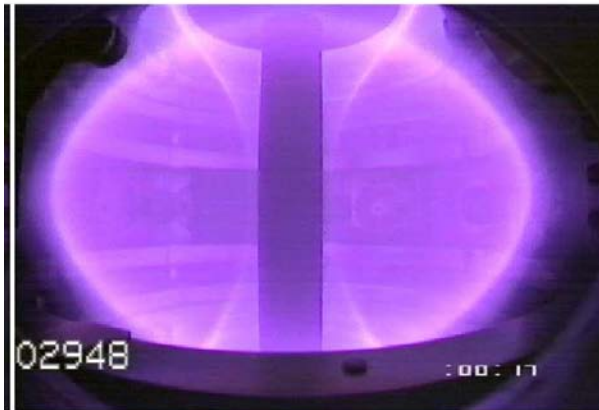
Potential Problems

- New instabilities in burning plasmas?
- Steady state operation in power station conditions (looks possible with help of bootstrap current: if not, could → pulsed machine, or stellarator)

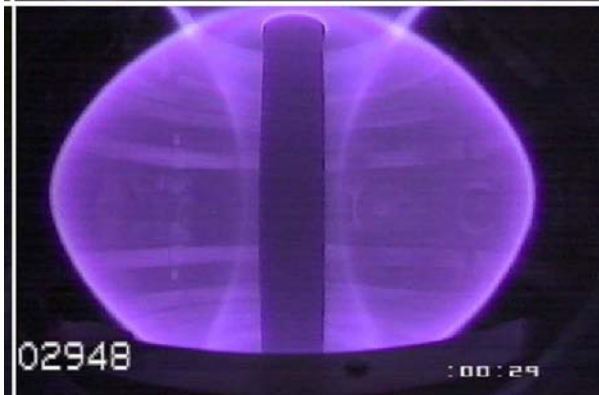
Potential improvement

- Better control of potential instabilities to allow higher pressure

Transition to 'High confinement mode' in MAST (at Culham, UK)



Before: the edge of the plasma is fuzzy and energy containment is poor



After: The edge of the plasma is very sharp and energy containment improves and the plasma pressure that can be maintained is bigger

MATERIALS

- **Structural materials** – subjected to bombardment of 2 MW/m² from 14 MeV neutrons
- **Plasma facing materials subjected to an additional 500 kW/m² from hot particles and electromagnetic radiation** (much more on ‘divertor’)
- **Various materials have been considered, and there are good candidates that may survive in these conditions, BUT:**
- Further modelling + ***experiments essential:***

Only a dedicated (~ €1 billion) accelerator-based test facility - the **International Fusion Materials Irradiation Facility (IFMIF)** - can reproduce reactor conditions: *results from IFMIF will be needed before a prototype commercial reactor can be licensed and built*

Materials Issues

Major positive development (1990s)

- Body-centred cubic low activation steels seem (?) able to withstand neutron damage

Potential problems

- Effect of helium generation in the materials
- Heat on 'divertor' (can be reduced by compromising design)

Potential improvement

- Development of advanced materials (SiC ceramics,...) for much higher temperature operation