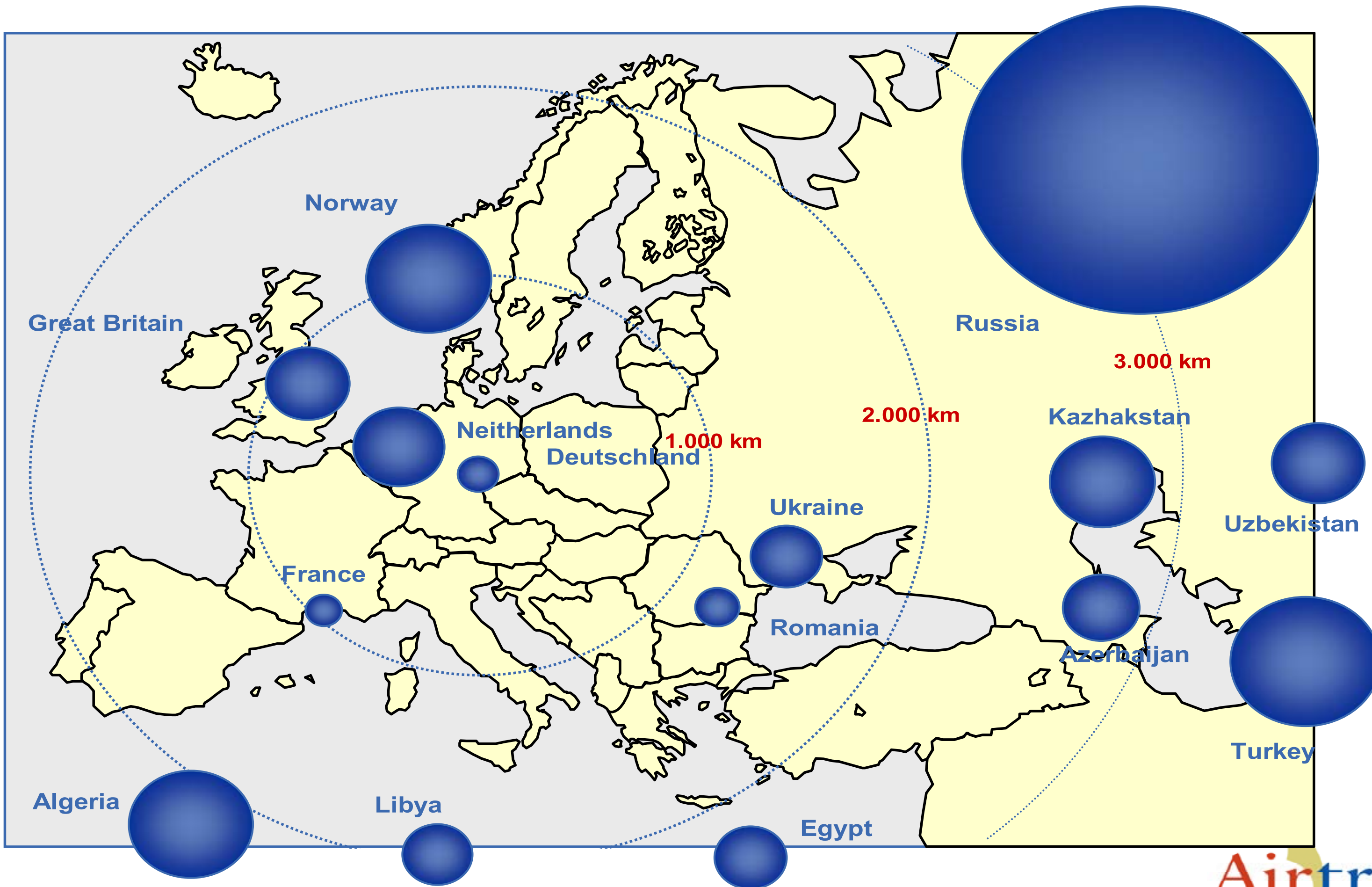
Energy, Sustainability and Development

Chris Llewellyn Smith

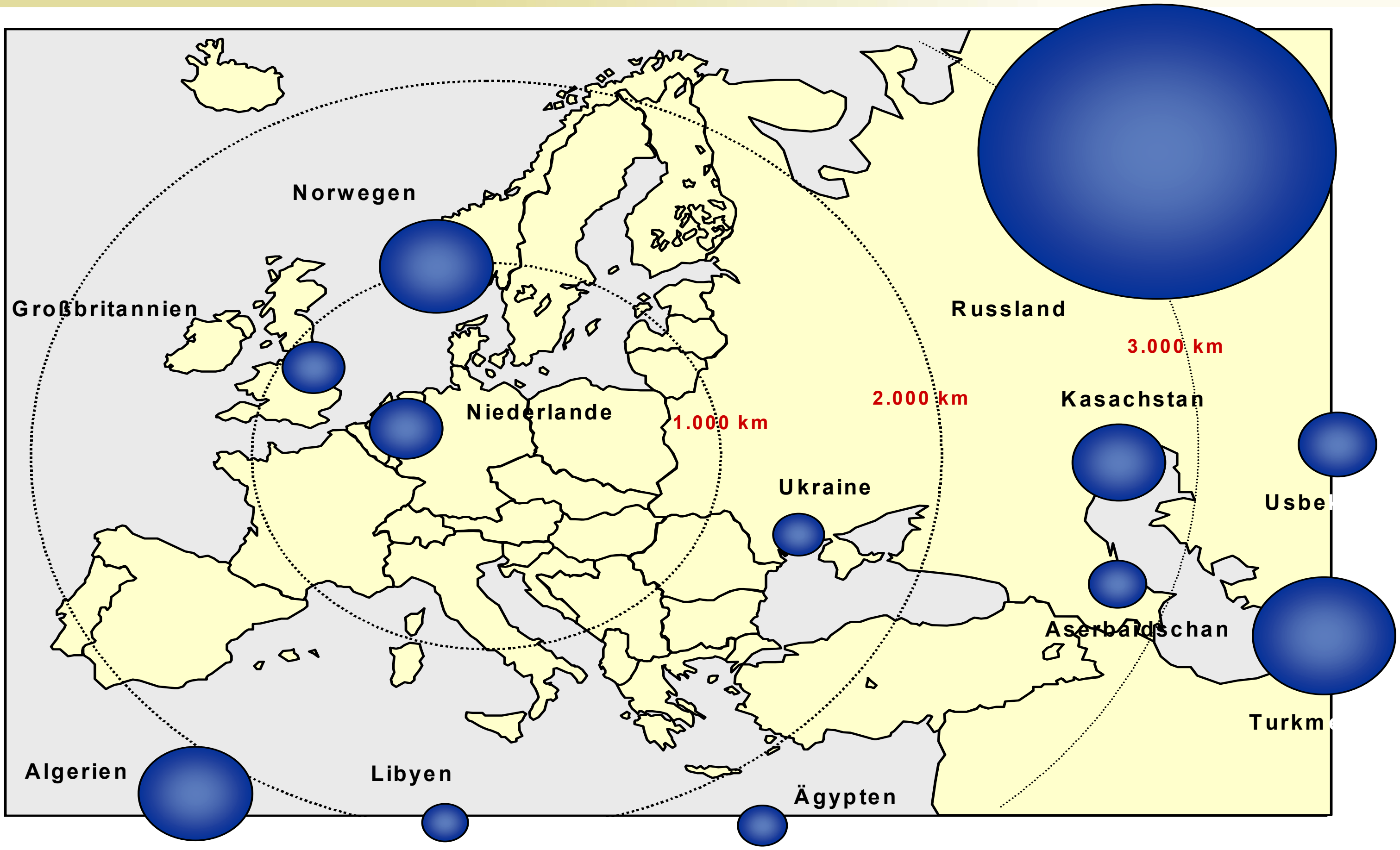
- The energy challenge
- Technical means to meet the challenge
- Can they provide a solution?
- Economic instruments and the political challenge

Sources of Natural Gas 1999

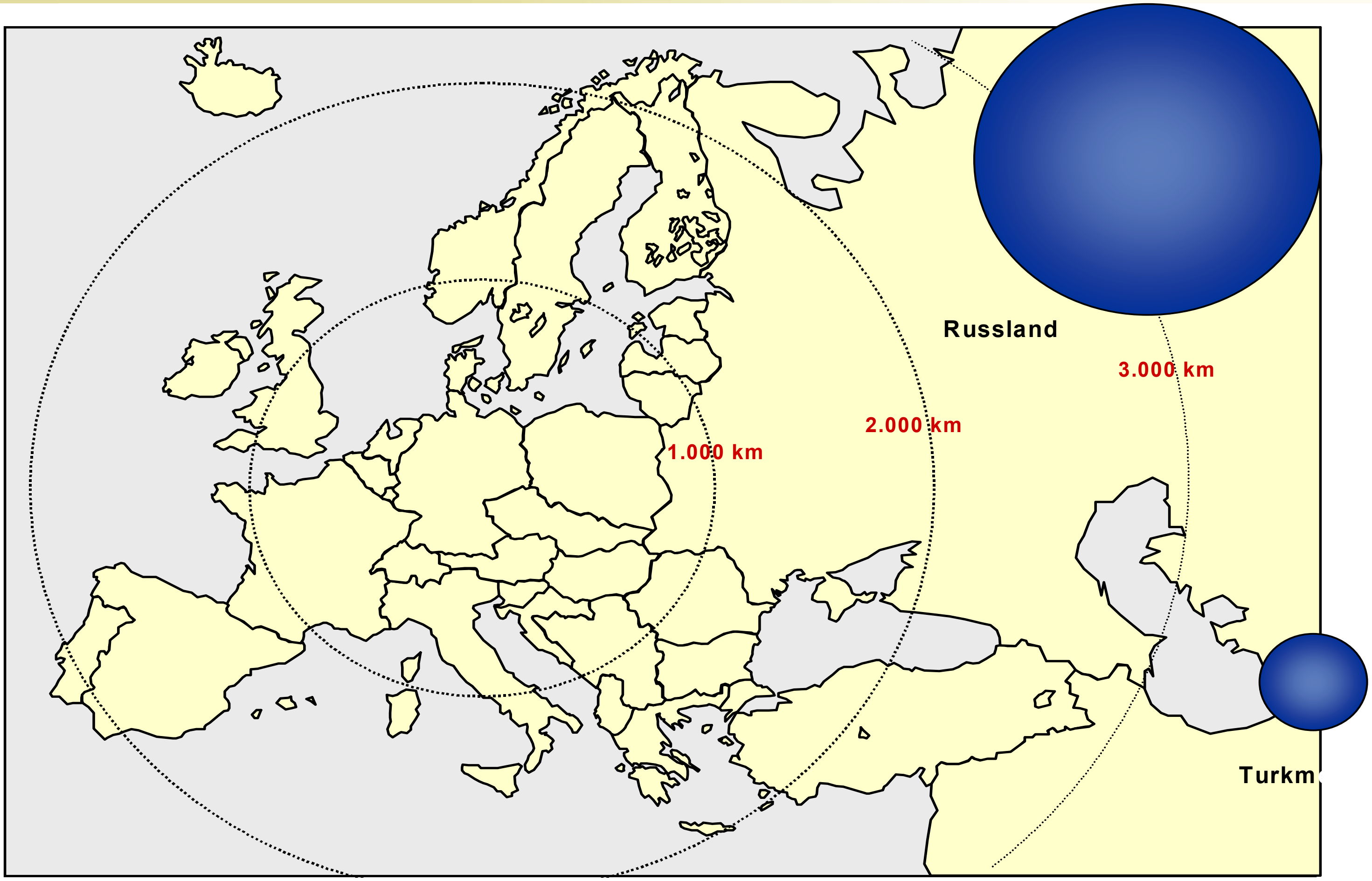
EU gets 24% of its primary energy from gas (55% imported) - growing at 5% pa



Sources Natural Gas 2010



Sources Natural Gas 2025



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Basic Energy Facts

1) **The world uses a lot of energy** – average power consumption is 2,350 Watts per person

(world energy [electricity] market ~ $4.5 trillion [$1.5 trillion] pa)

- **very unevenly** (use per person in USA = 50x Bangladesh)

2) **World energy use is expected to grow 50% by 2030**

- growth necessary in developing countries to lift billions of people out of poverty

3) **80% is generated by burning fossil fuels**

→ *climate change & debilitating pollution*

- *which won't last for ever*

Need more efficient use of energy (and possibly a change of life style) **and major new sources of clean energy - this will require fiscal measures, regulation and new technology**

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- **The world uses a lot of energy**
  - 11,220 million tonnes of oil equivalent (Mtoe) each year

  (2004 data; IEA 2006)

  Average power consumption per person = 2,350 Watts

- **Use is very unevenly distributed**

  Average consumption per person:

USA	-	10,500 Watts
California	-	7,300 Watts
UK	-	5,200 Watts
China	-	1,650 Watts (growing 10% pa)
India	-	700 Watts
Bangladesh	-	210 Watts

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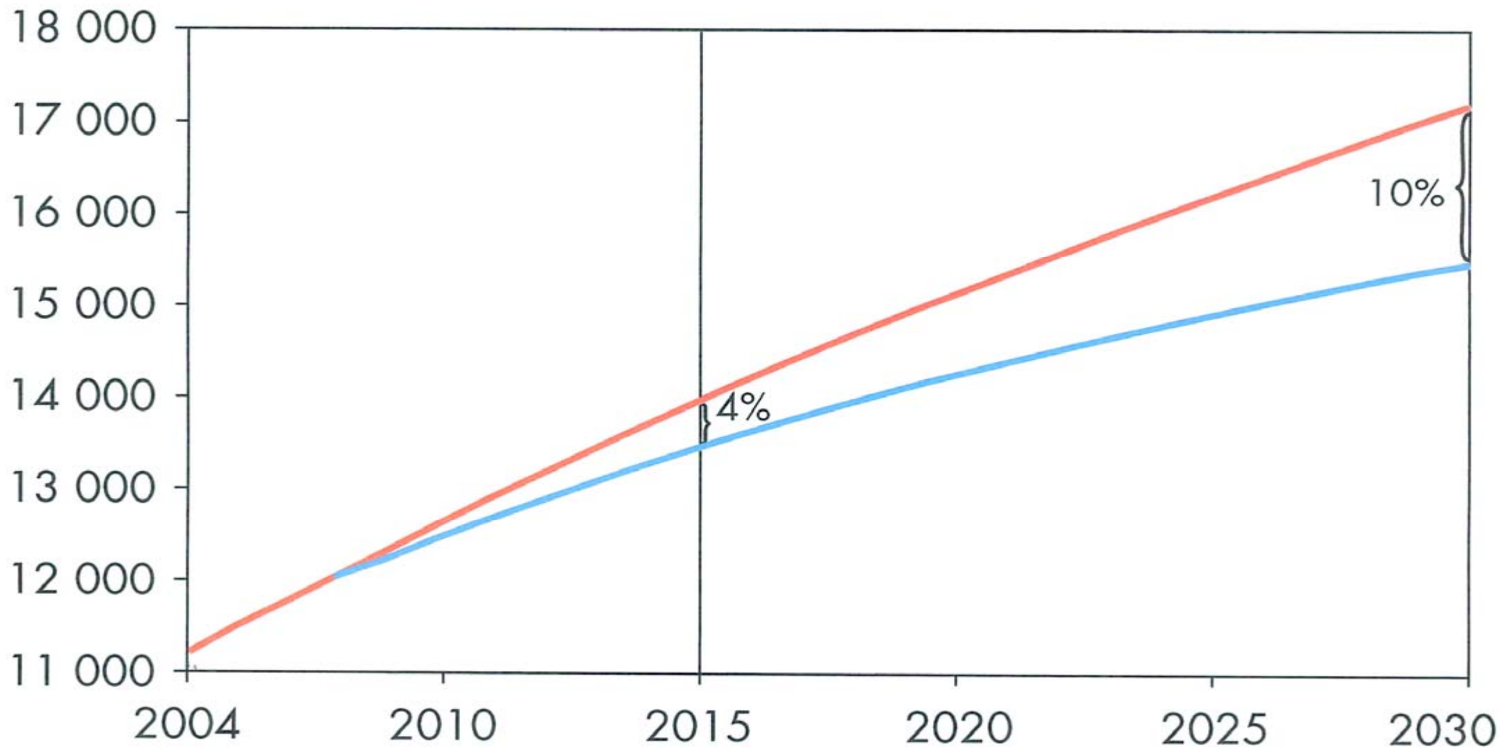
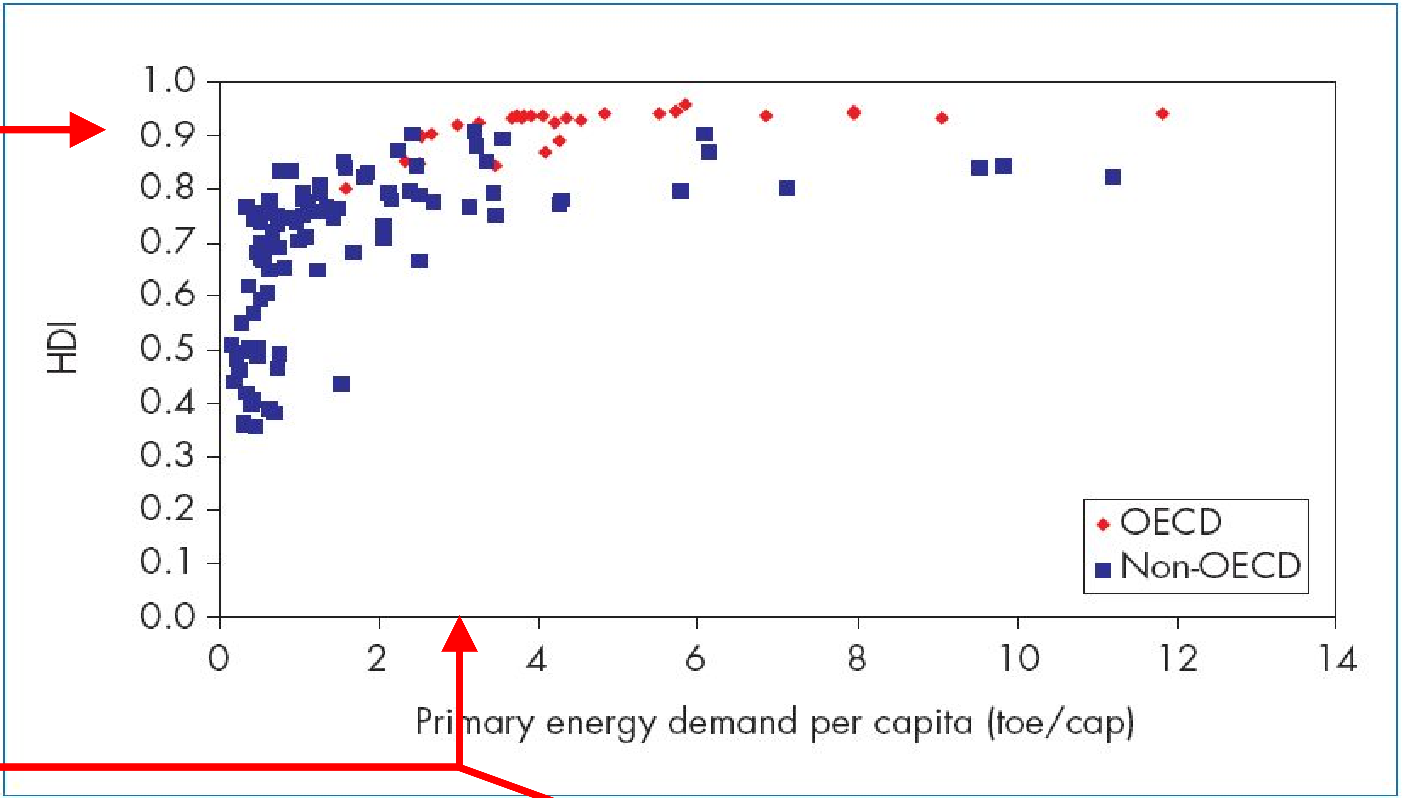
World Primary Energy Demand (Mtoe) in the IEA's 2006 reference and alternative scenarios
Note world population 6.4 billion (2004) ⇨ 8.1 billion 2030



CO_2 emissions increase 55%/30% by 2030 in the reference/alternative scenarios (note: scenarios very sensitive to assumptions about China). **NB:** even if CO_2 emissions frozen immediately at today's level, atmospheric CO_2 would rise ~100 ppm in next 50 years.

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

Implications

of the fact that reaching 3 toe per capita everywhere seems almost impossible* (completely impossible* to accomplish while reducing CO_2 emissions):

*****_at least without a large reduction in population: there could be a Malthusian solution_

Changes of life style in the developed world are needed to enable changes in the standard of living in the developing world, where conditions are dire (see next four slides) **and climate change will hit hardest** (see following slide)

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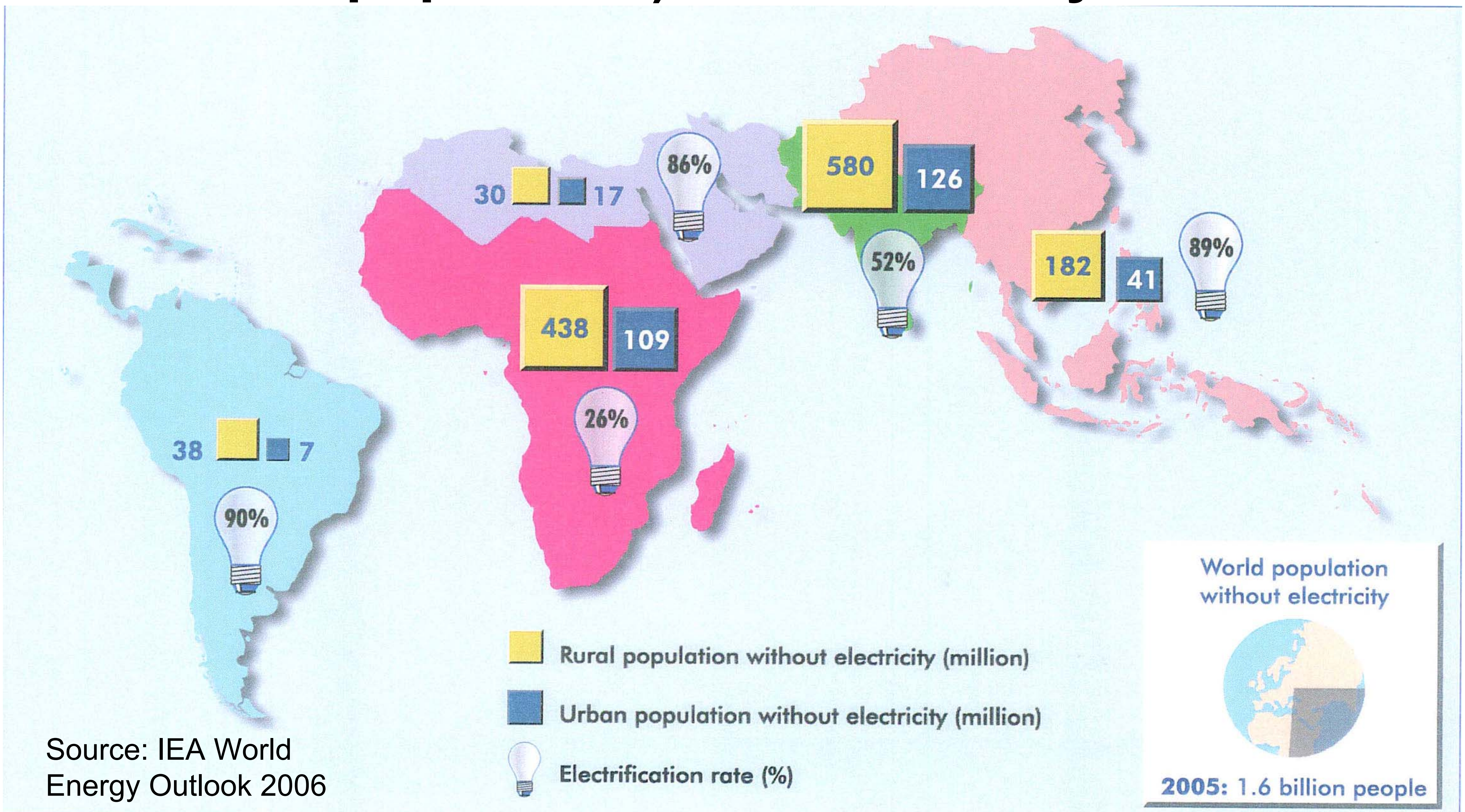
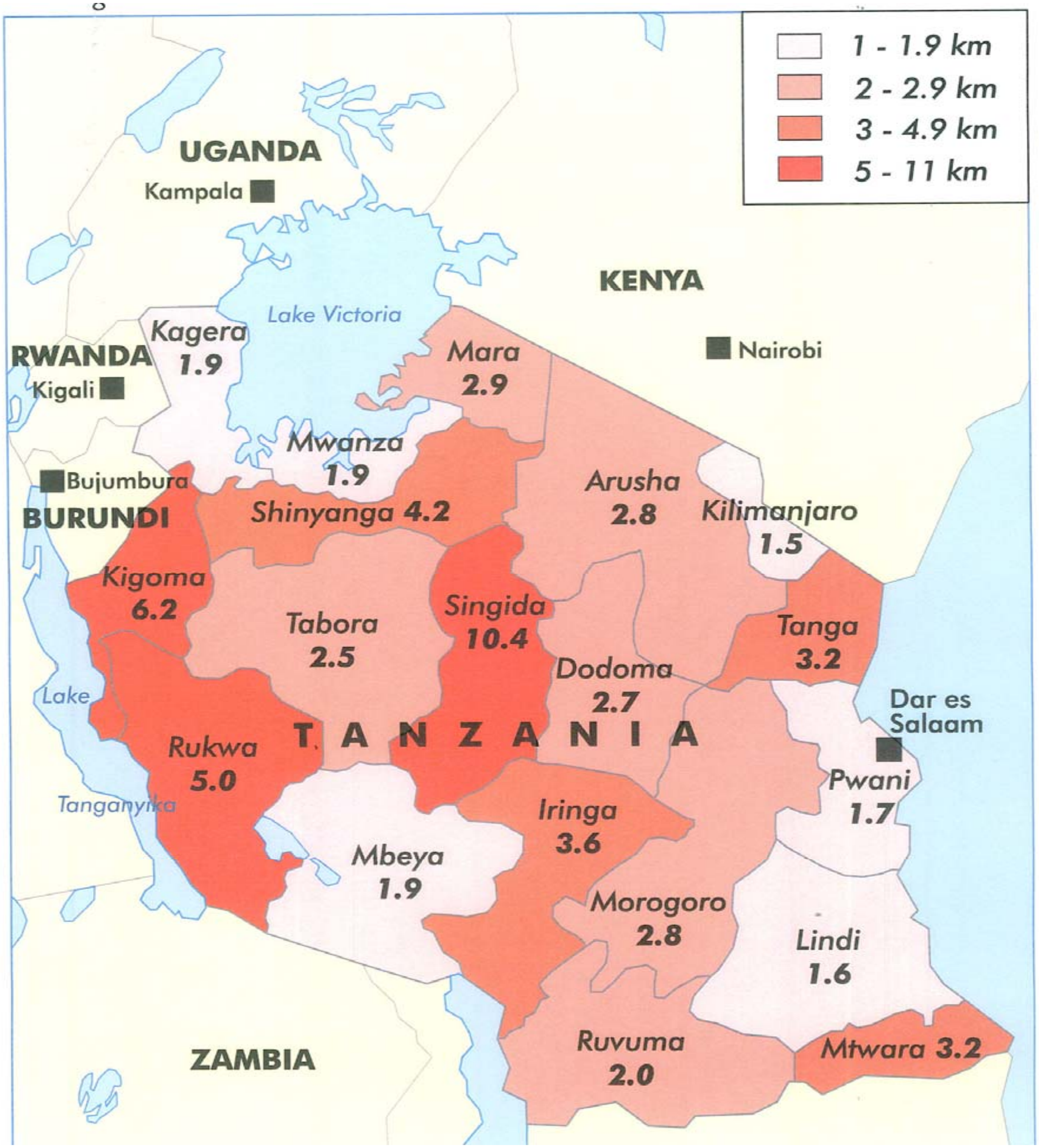
1.6 billion people (over 25% of the world's population) lack electricity:



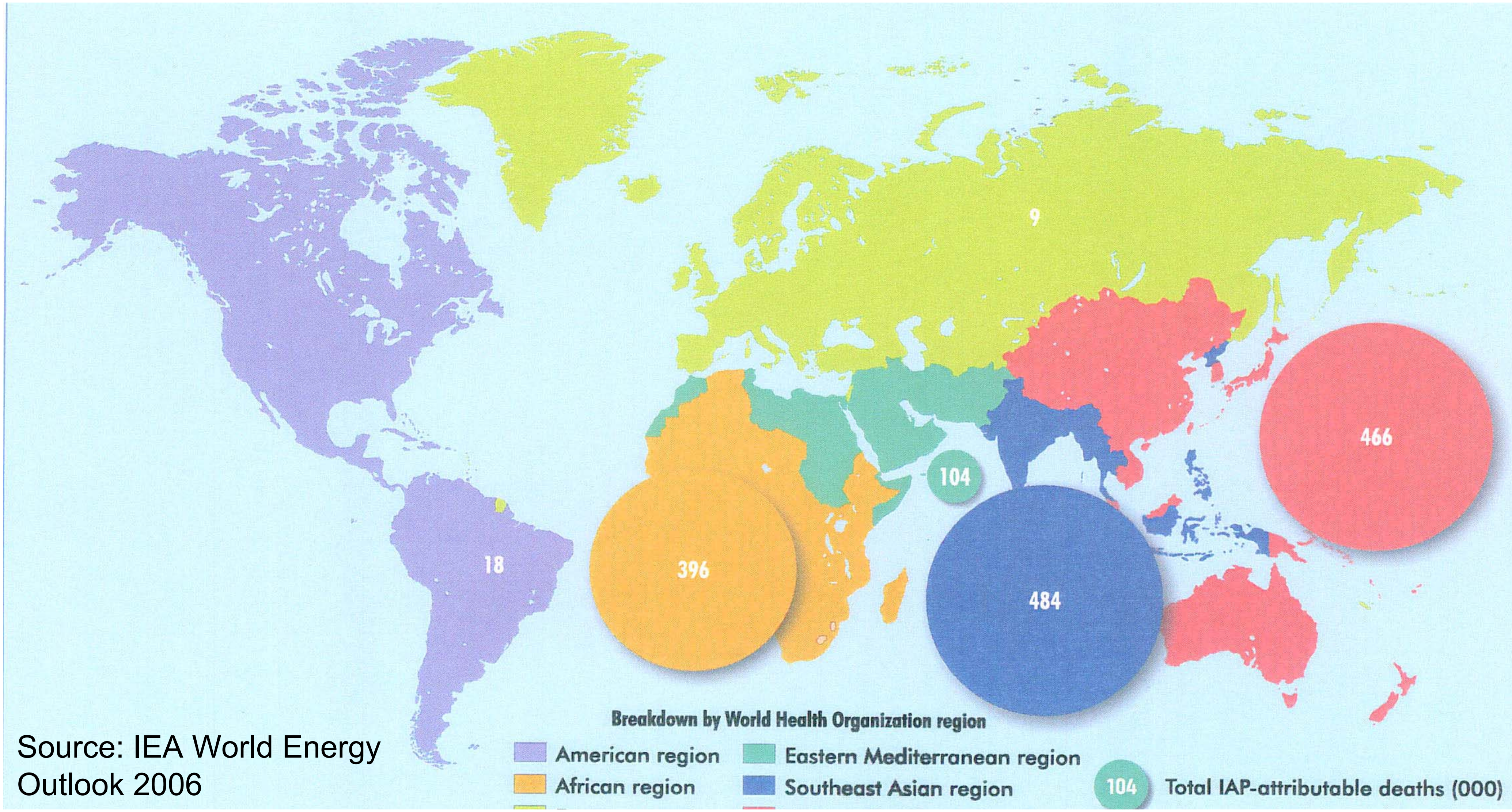
Source: IEA World Energy Outlook 2006



Distances travelled to collect fuelwood in rural Tanzania; the average load is around 20 kg

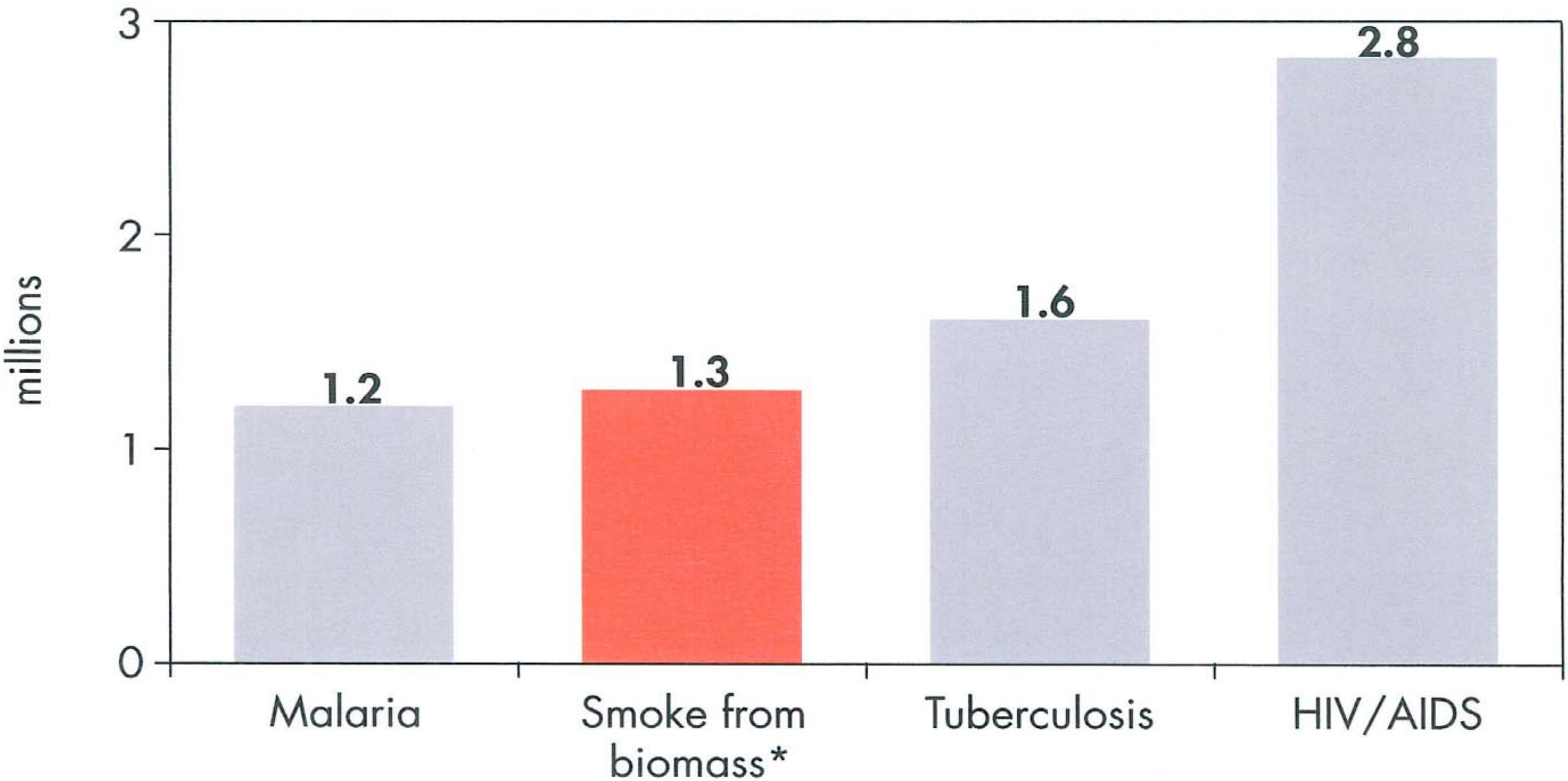
Source: IEA World Energy Outlook 2006

Deaths per year (1000s) caused by indoor air pollution (biomass 85% + coal 15%); total is 1.5 million – over half children under five



Source: IEA World Energy Outlook 2006

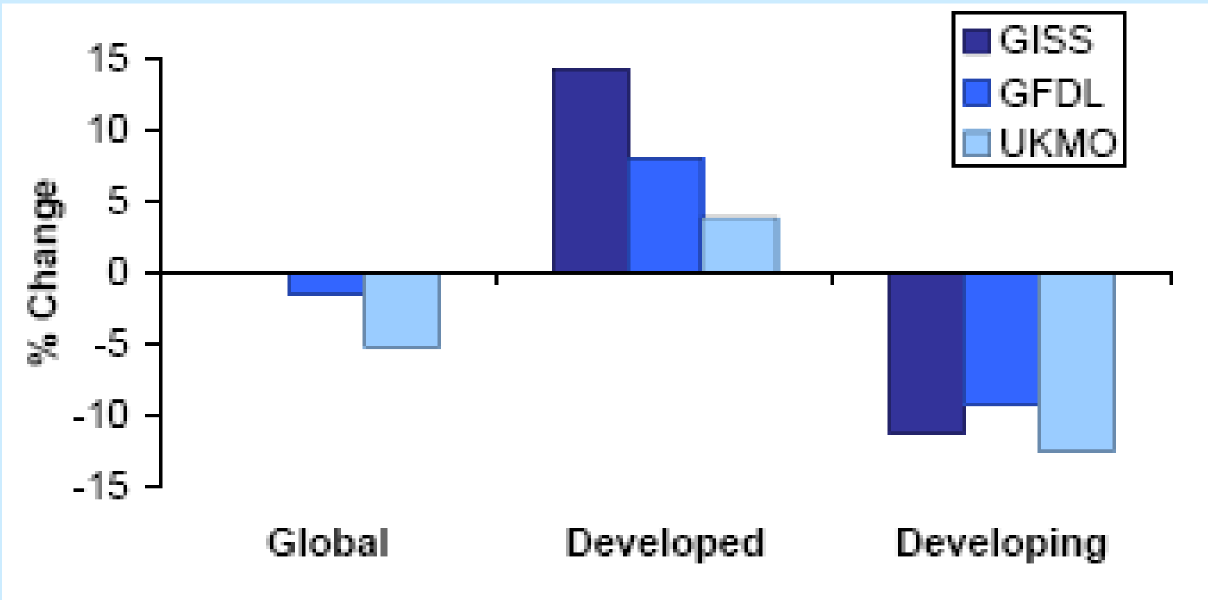
Annual deaths worldwide from various causes



Source: IEA World Energy Outlook 2006

One example of the asymmetry of the likely effects of climate change

Figure 3.5 Change in cereal production in developed and developing countries for a doubling of carbon dioxide levels (equivalent to around 3°C of warming in models used) simulated with three climate models (GISS, GFDL and UKMO Hadley Centre)



Source: Parry et al. (2005) analysing data from Rosenzweig and Parry (1994)

Note: Percent changes in production are relative to what they would be in a future with no climate change. Overall changes are relatively robust to different model outputs, but regional patterns differ depending on the model's rainfall patterns – more details in Fischer et al. (2005). The work assumed mostly farm-level adaptation in developing countries but some economy-wide adaptation in developed countries. The work also assumed a strong carbon fertilisation effect - 15 – 25% increase in yield for a doubling of carbon dioxide levels for responsive crops (wheat, rice, soybean) and a 5 – 10% increase for non-responsive crops (maize). These are about twice as high as the latest field-based studies suggest – see Box 3.4 for more detail.

Source: Stern Review

Sources of Energy

- **World's primary energy supply (approximate)**:

  80 % - burning fossil fuels (44% oil, 31% coal, 26% natural gas)

  10% - burning combustible renewables and waste

  5% - nuclear

  5% - hydro

  0.5% - geothermal, solar, wind, . . .

NB Primary energy defined here for hydro, solar and wind as equivalent primary thermal energy

electrical energy output for hydro etc is also often used, e.g. hydro ~ 2.2%

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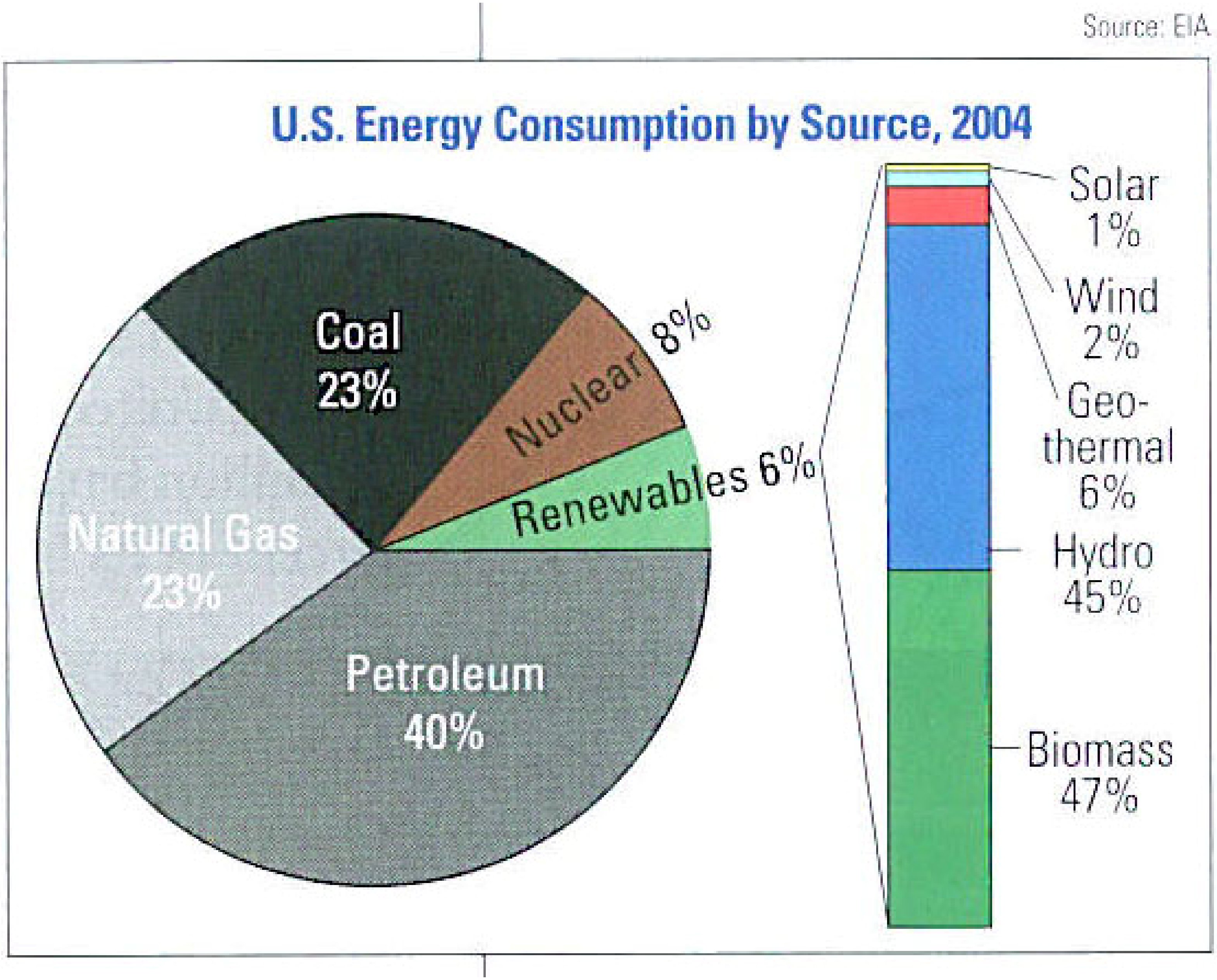

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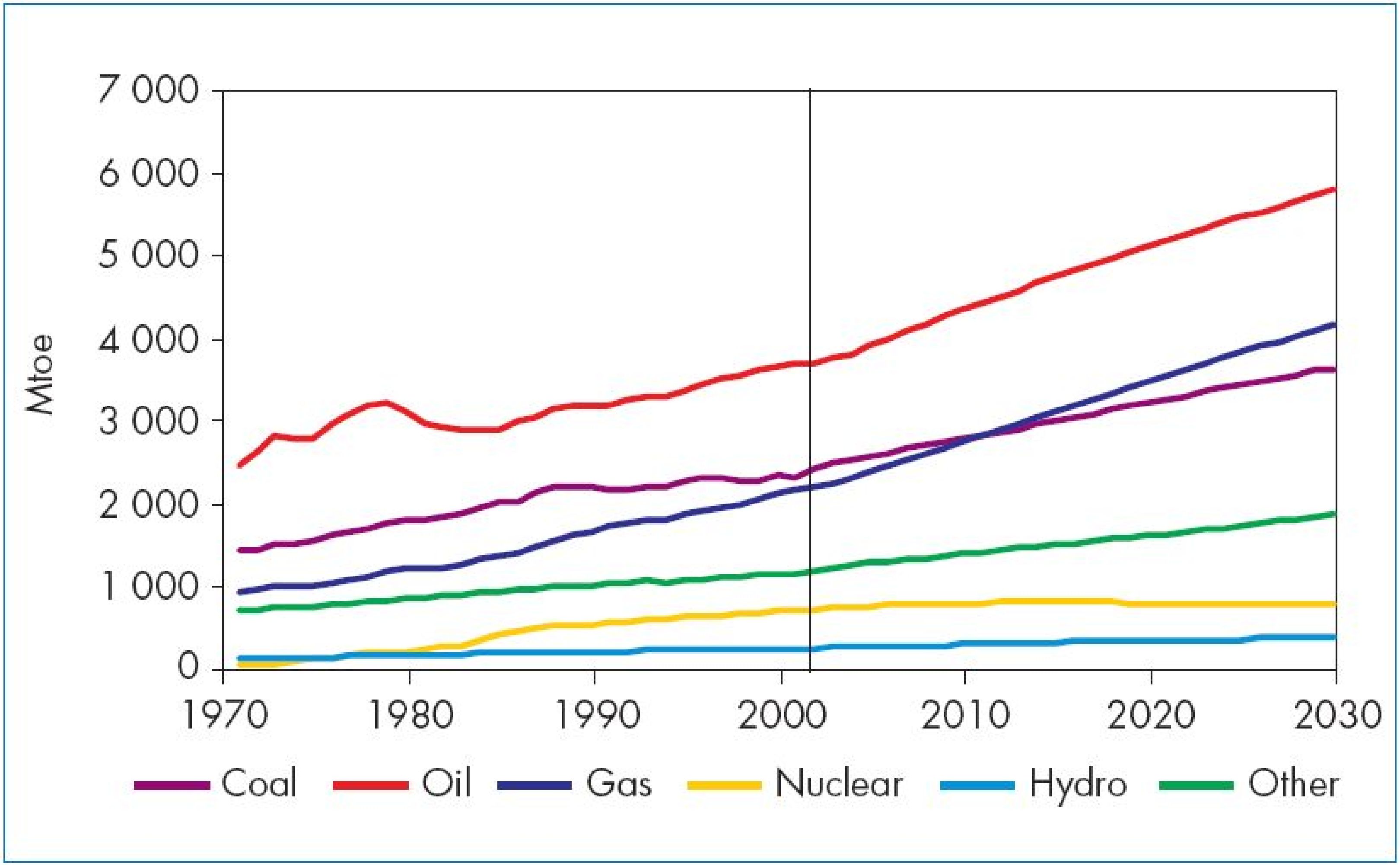
Figure 2.2: **World Primary Energy Demand by Fuel**



Source: IEA 2004 (2006 projections – slightly faster growth for coal, renewables, and nuclear; slower for oil and gas – **coal now expected to provide 15% more than gas in 2030**)

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Fossil Fuels

are

– **generating debilitating pollution**

(300,000 coal pollution deaths pa in China, where the World Bank estimated that in 1995 air and water pollution cost $54 billion and 7.4 million working person years are lost every year due to pollution related illness)

– **and driving potentially catastrophic climate change**

and will run out sooner or later

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? Perhaps

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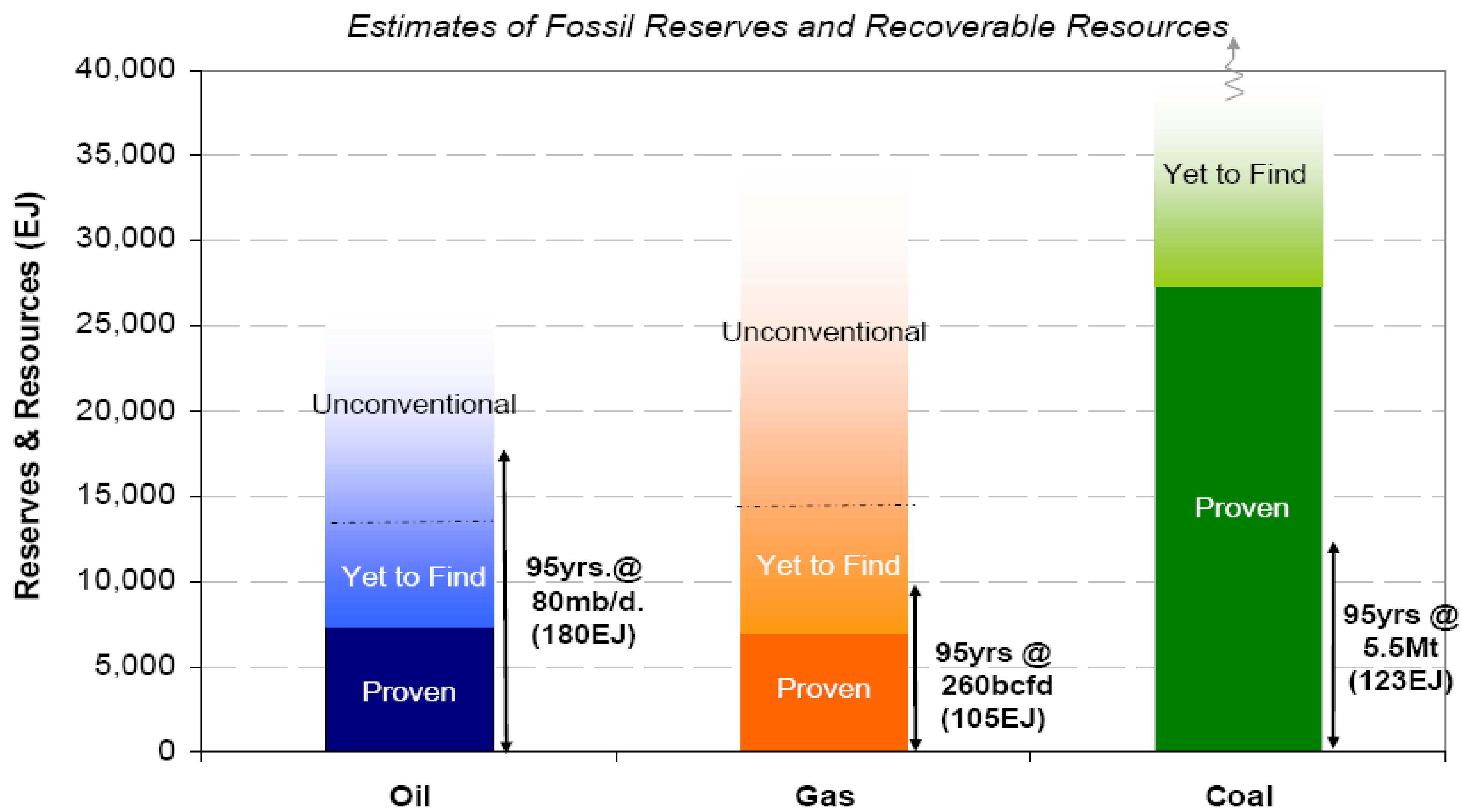
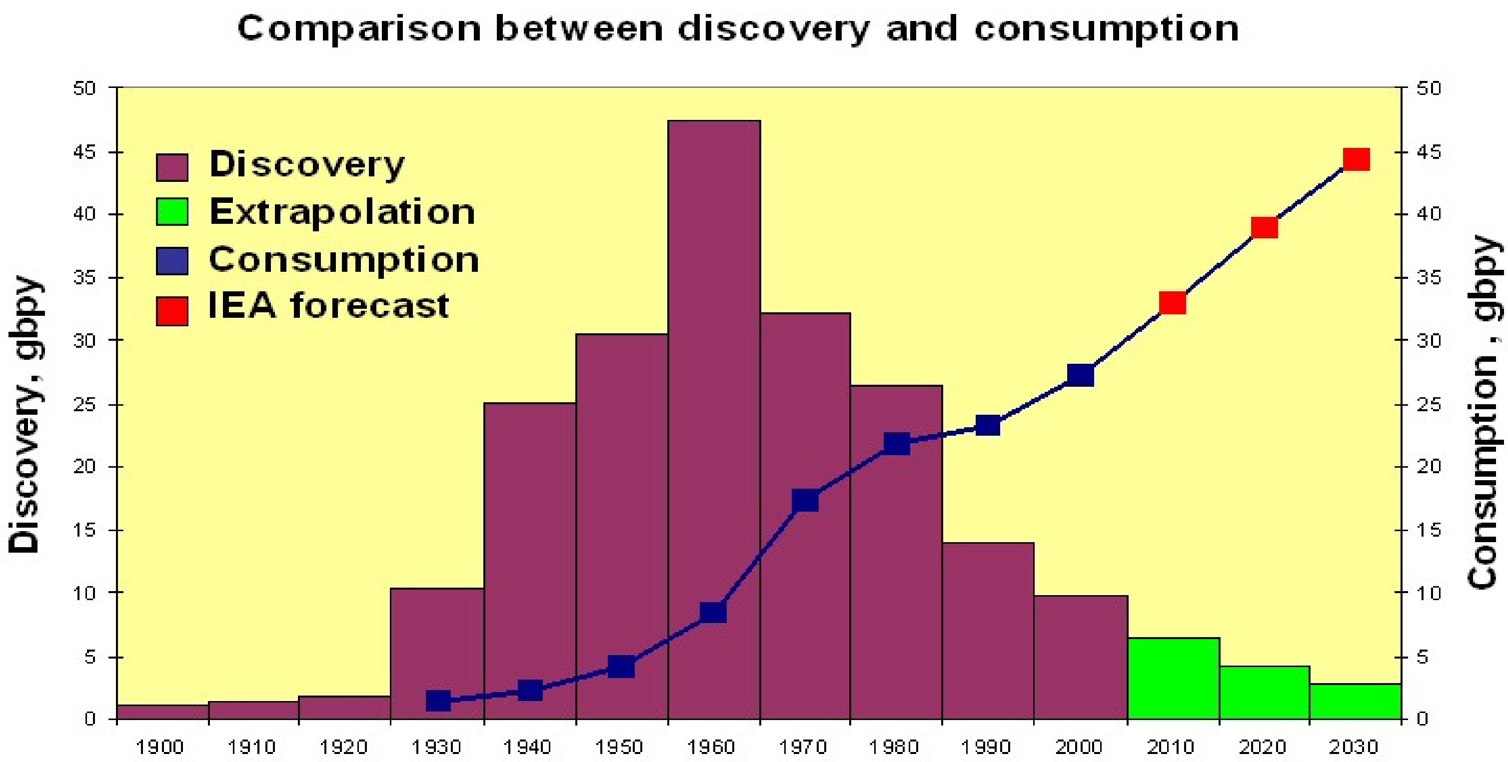


Source: World Energy Assessment 2001, IHS, WoodMackenzie, BP Stat Review 2005, BP estimates

With current growth, the 95 year (2100) line will be reached in:

- **2067 for oil** (growth 1.3% pa but growth will ⇨ decline beyond 'Hubbert peak')
- **2058 for gas** (growth 2.0% pa)
- **2060 for coal** (growth 1.8% pa)

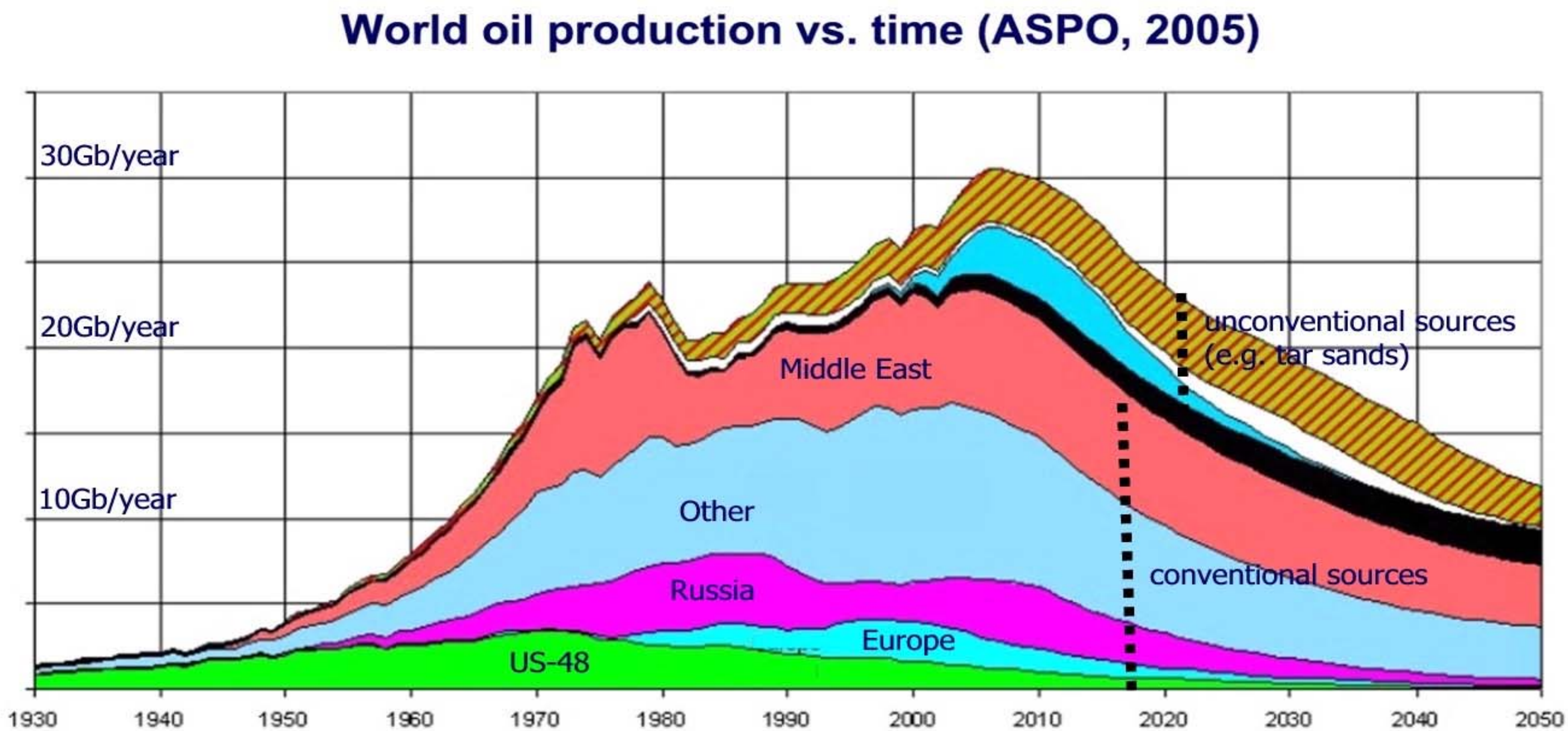
Context – Oil and Gas Supply Security



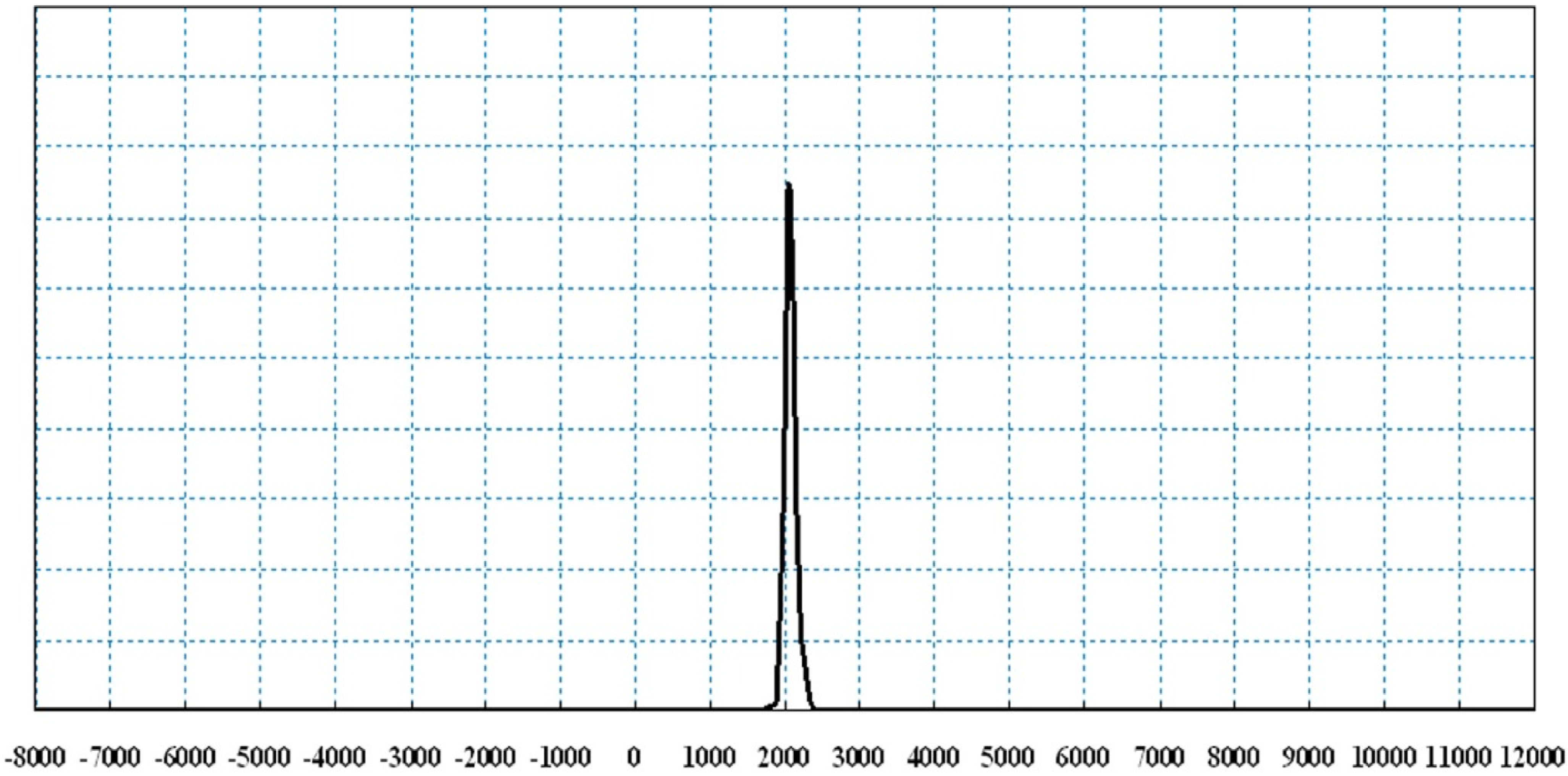
Source: Uppsala Hydrocarbon Depletion Study Group

Note: discoveries back-dated

Context – Oil and Gas Supply Security



Source: ASPO



Fossil Fuel Use

- a brief episode in the world's history

UNCONVENTIONAL OIL

Unconventional oil resources* are thought to amount to 'at least' 1,000 billion barrels (compared to 2,300 billion barrels of conventional oil remaining according to the USGS)

*oil sands in Canada, extra heavy oil in Venezuela, shale oil in the USA,…

- **generates 2% of global oil supply today → 8% by 2030**

Expected increase mainly in Canada. Cost of producing synthetic crude (which is very sensitive to price of gas or other fuel used → steam injected to make bitumen flow) is currently $33/barrel (vs. a few $s/barrel in Saudi Arabia)

Production of 1 barrel of crude requires 0.4 barrels of oil equivalent to produce steam

Use of Energy

- **Electricity production uses ~ 1/3 of primary energy***
  (more in developed world; less in developing world)

  - this fraction could (and is likely in the future to) be higher

  * at ~ 35% efficiency

- **End Use** (globally/USA)

  ≈ 25% industry (33%)

  ≈ 25% transport (28%)

  ≈ 50% built environment (39%)
  (private, industrial, commercial)

  } ≈ USA:35-40% domestic (UK: 31%)

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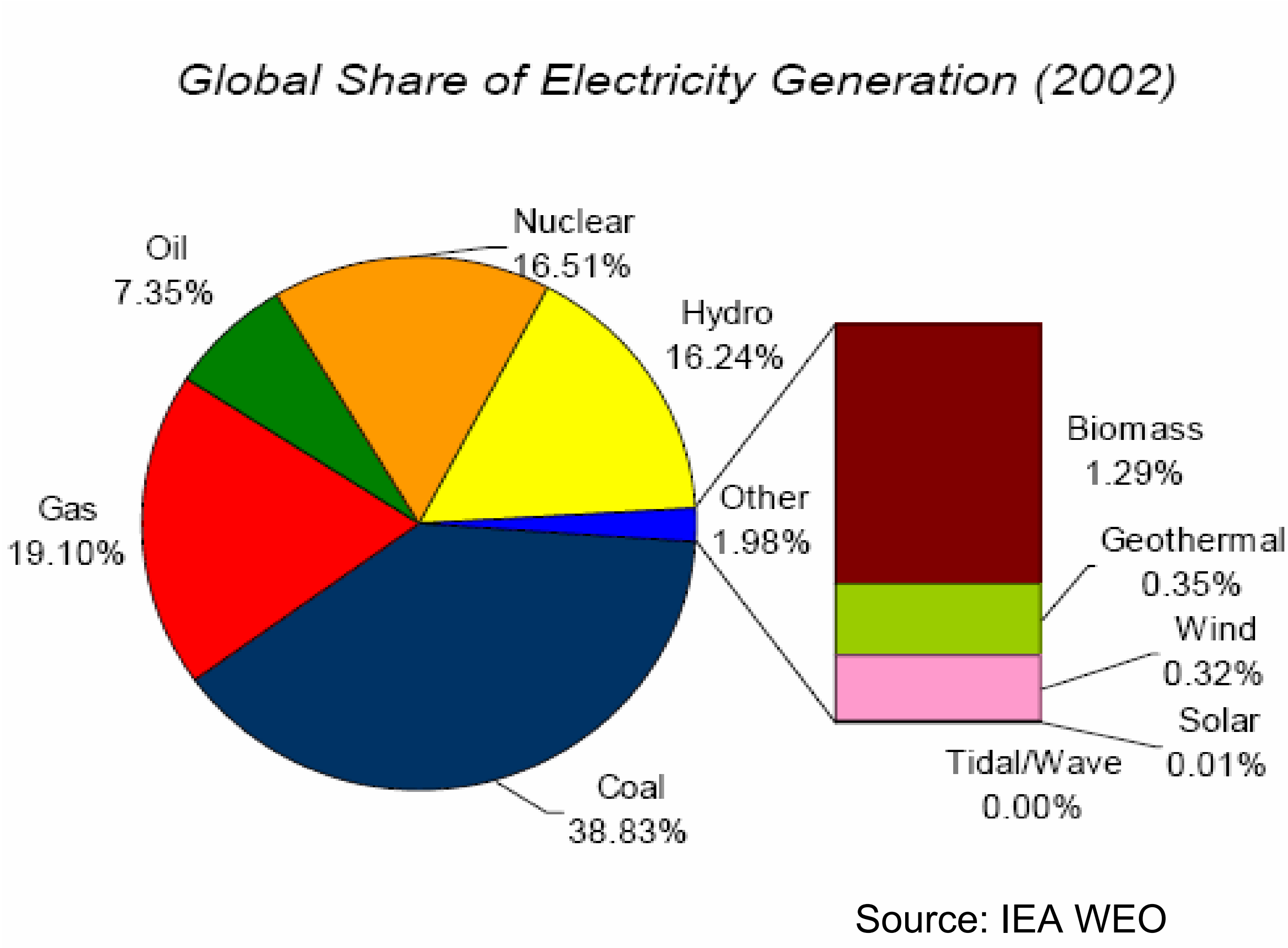
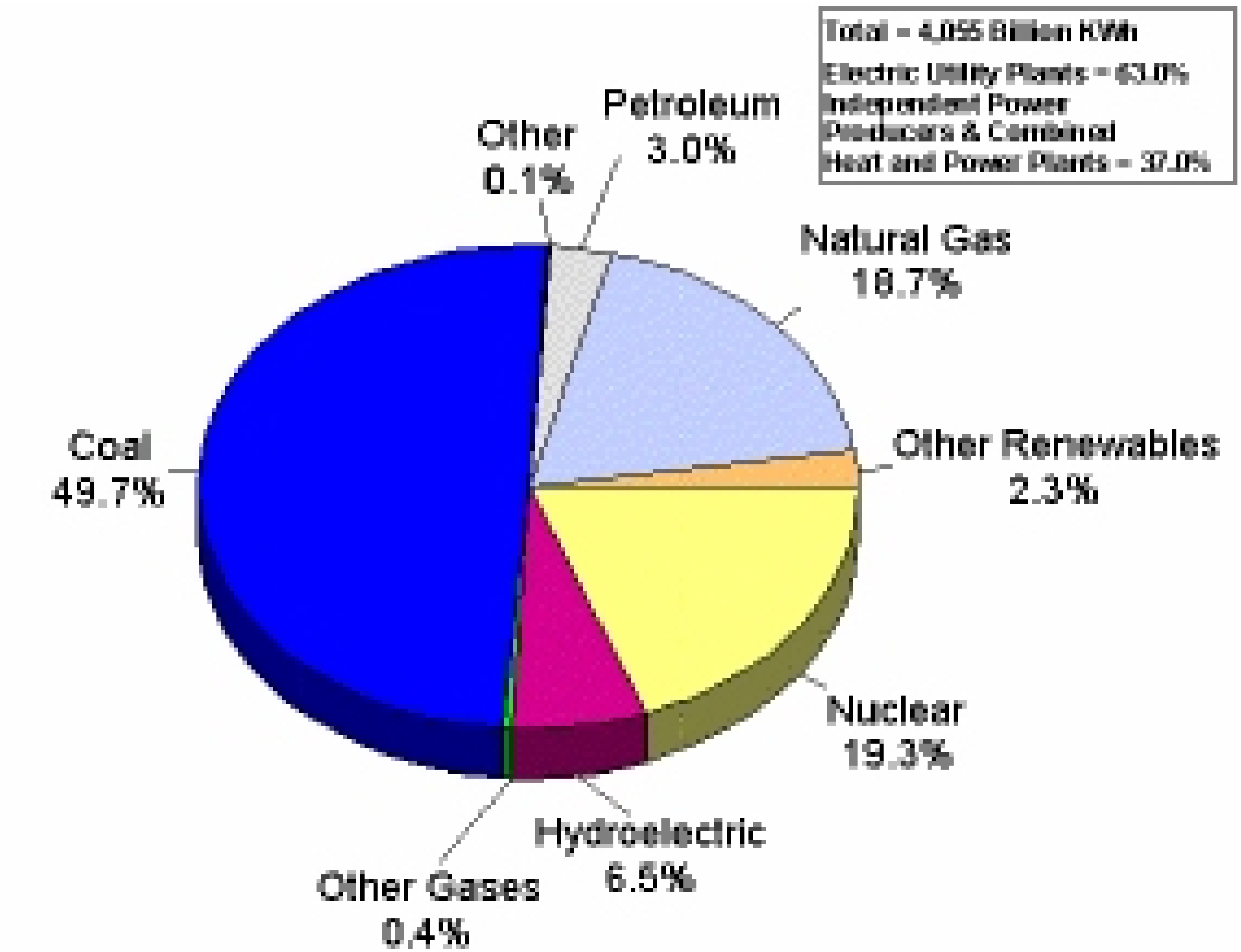


Note that mixture of fuels used → electricity is very different in different countries

e.g. coal ~ 35% in UK, ~76% in China (where hydro ~ 18%)

Sources of Electricity in USA



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Conclusions on Energy Challenge

- Large increase in energy use expected, and needed to lift billions of people out of poverty
- Seems (IEA World Energy Outlook) that it will require increased use of fossil fuels
  - which is causing devastating pollution and driving potentially catastrophic climate change*
  - will run out sooner or later

There is therefore an urgent need to reduce energy use (or at least curb growth), and seek cleaner ways of producing energy on a large scale

IEA: "Achieving a truly sustainable energy system will call for radical breakthroughs that alter how we produce and use energy"

***Ambitious goal for 2050 - limit CO2 to twice pre-industrial level. To do this while meeting expected growth in power consumption would need 50% more CO_2-free power than today's *total* power**

US DoE "The technology to generate this amount of emission-free power does not exist"

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Meeting the Energy Challenge

No silver bullet: solution will be a cocktail

- Introduce **fiscal measures** and **regulation** to change behaviour of consumers, provide incentives to encourage the market to expand use of low carbon technologies, stimulate R&D by industry…

- **New/improved technologies (candidates below)** will be essential, based on increased investment in energy research*

*****_public funding down 50% globally since 1980 in real terms; world's energy R&D budget ~ 0.25% of energy market of ~ $4.5 trillion a year_ _(so 10% cost increase → over $450,000 million a year!)_

Note – when considering balance of R&D funding, should bring market incentives/subsidies (designed to encourage deployment of renewables) into the picture

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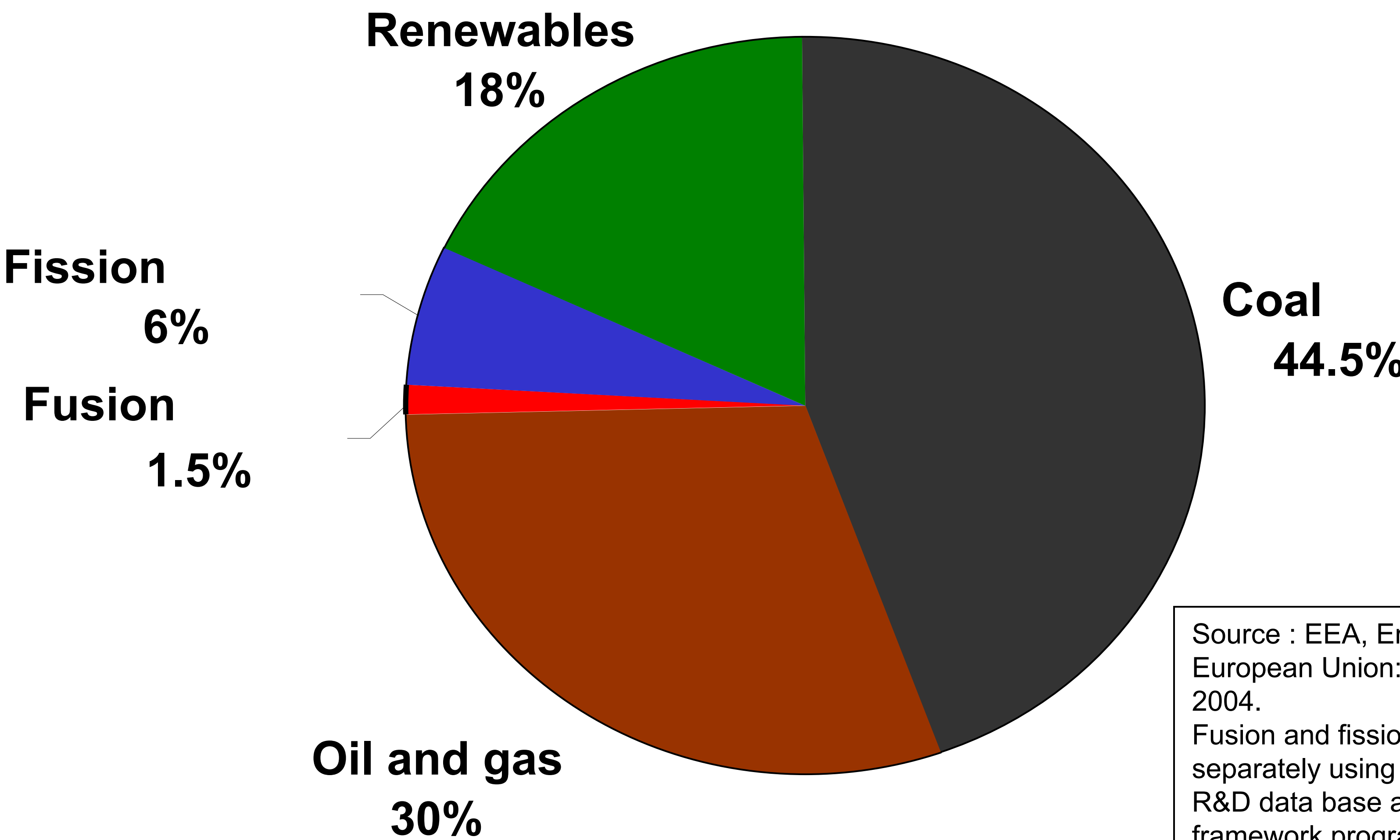
Energy subsidies (€28 bn pa) **+ R&D** (€2 bn pa) **in the EU ~ 30 Billion Euro (per year)**



Source : EEA, Energy subsidies in the European Union: A brief overview, 2004.
Fusion and fission are displayed separately using the IEA government-R&D data base and EURATOM 6th framework programme data

Potential of Some Technical Means to Meet the Challenge

- Improved efficiency and lower demand
- Renewables
- Cleaner coal (with carbon capture and sequestration)
- Nuclear fission
- Fusion

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Energy Efficiency

- **Production e.g.** world average power plant efficiency ~ 30% → 45% (state of the art) would save 4% of anthropic carbon dioxide
  – use of flared gas in Africa could produce 20 GW (= half Africa's current electricity)
- **Distribution** – typically 10% of electricity lost (→ 50% due to 'non-technical losses' in some countries: need better metering)
- **Use:** better insulated homes, CHP (40% → 85-90% use of energy)
  smart/interactive grid
  more efficient transport

Huge scope but demand is rising faster

Note: Energy intensity (= energy/gpd) fell 1.6% pa 1990-04; 2005-30 – 1.7% pa Ref. Scenario [1.3% OECD], - 2.2% pa Alt. scenario [1.6% OECD])

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

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The Built Environment

Consumes ~ 50% of energy
(transport 25% and industry 25%)

→ nearly 50% of UK CO_2 emissions due to constructing, maintaining, occupying buildings

Improvements in design could have a big impact

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

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…)

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TRANSPORT ~ 25% of primary energy

Road transport

- **Growing rapidly** e.g. IEA thinks 700 million light vehicles today → 1,400 million in 2030 (China: 9m → 100m; India: 6.5 m → 56m)

(For the world's per capita petrol consumption to equal that in the USA, total petrol consumption would have to increase almost ten fold)

- **Huge scope for more efficient** (lighter, less powerful) **cars*** → safer + less congestion in S England

There have been huge improvements in efficiency – but they have been used to provide more powerful, heavier cars

* **Litres/100 km:**	2004	2030 ref. scenario	2030 alt. scenario
N America	11.6	11.3	7.8
Europe	7.7	6.1	5.2
China	11.3	9.0	7.5

- **After the end of oil?** Biofuels (see later), coal & gas → oil, hydrogen, electric…

Hydrogen

- **Excites public and politicians**

    - no CO_2 at point of use

- **Only helpful if no CO_2 at point of production**

e.g. - capture and store carbon at point of production

- produce from renewables (reduced problem of intermittency)
- produce from fission or fusion

(production by electrolysis, or 'thermo [high temperature] - chemical cracking' of water)

- **Usually considered for powering cars**:

Excellent energy/mass ratio but energy/volume terrible

Need to compress or liquefy (uses ~ 30% of energy, and adds to weight), or absorb in light metals (big chemical challenge)

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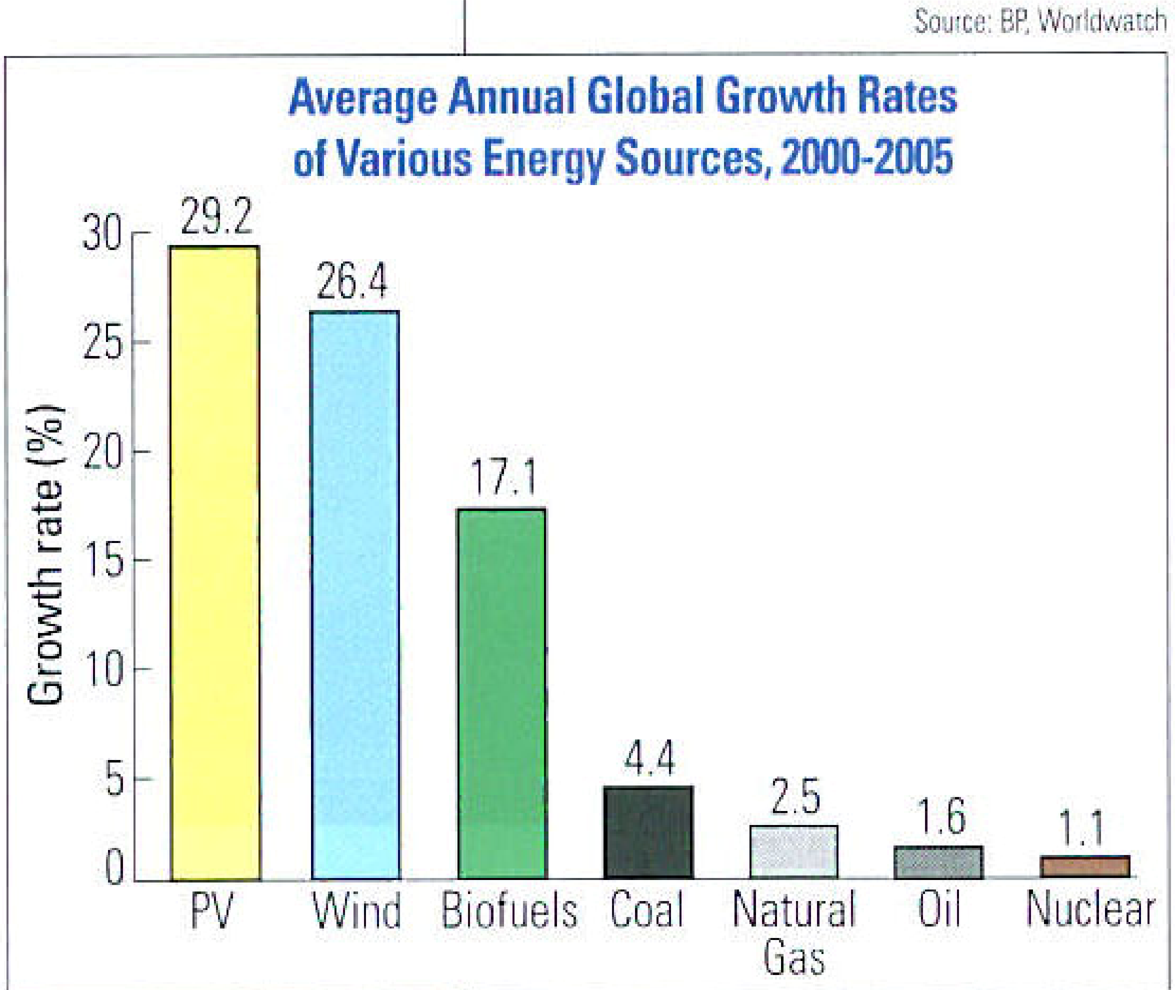
Renewables - small today (apart from hydro), but growing rapidly (although investment of ~ $40bn pa is only ~ 20% of total): **What is their potential?**



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Renewables – Introduction and Summary

- **Estimating the potential of renewables ~ many assumptions**

Some are easy to express/understand (e.g. how much of the solar power falling on the earth's surface can be captured), but others (e.g. how much of wind energy can be captured) are not - treat statements on the following slides with care!

- **The conclusions** (to be judged relative to world use ~14 TW) **are**

• **Solar** could *in principle* power the world – given breakthroughs in energy storage and costs (which should be sought)

• **Hydro** is already significant and could probably be expanded to ~ 1 TW

• **Wind** and **burning biomass** are capable in principle of contributing on the TW scale (*perhaps* a lot more in the case of biomass)

• **Geothermal**, **tidal** and **wave energy** will not contribute on this scale, but should be fully exploited where sensible

***Conclusions are very location dependent**, e.g. 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;…*

Potential of Renewables I

(Seek significant fraction of world's 14 TW consumption)

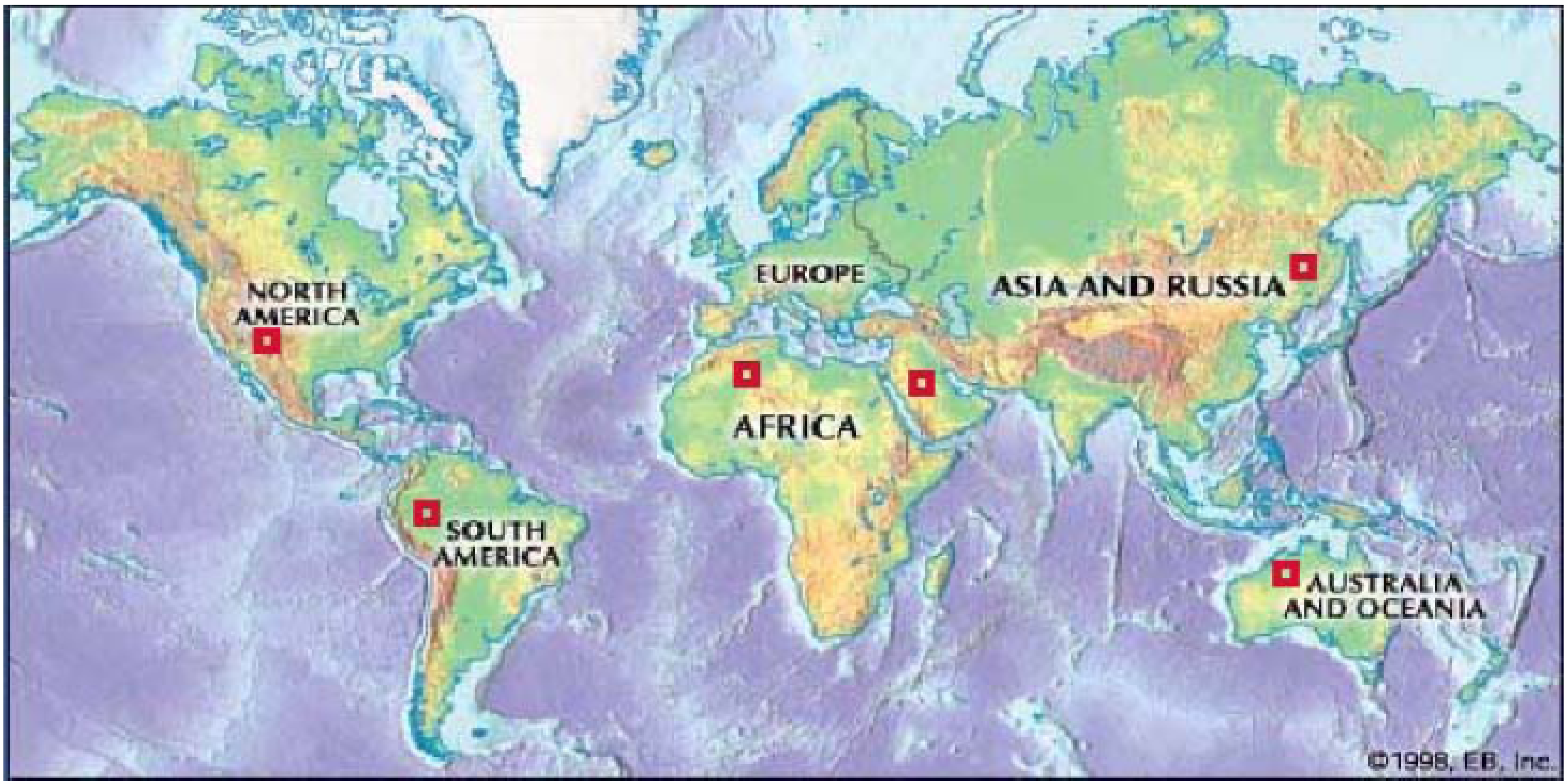
- **Solar** - 85,000 TW reaches earth's surface → 25,000 TW on land, if capture [PV] 0.5% at 15% efficiency ⇒ **19 TW** ~ 1.35x current total use

but: cost, location, timing → storage? [note – lose (conversion efficiency)^2]

- **Tidal** - input 3 TW; at reasonable sites - 0.2 TW peak/0.06 TW average (for barrages: underwater tidal streams could do better)

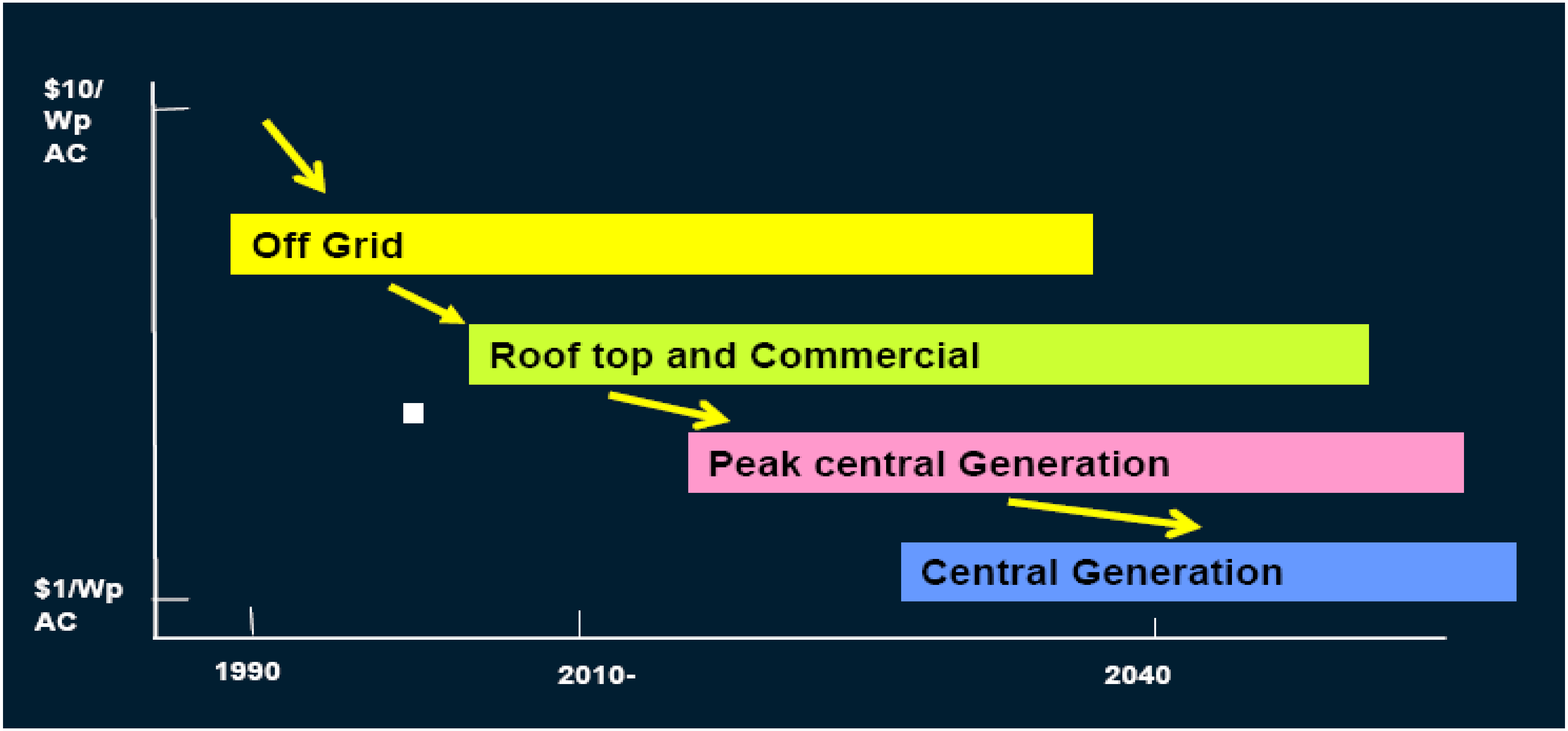
- **Waves** - 1 TW available in principle on continental shelves, 0.1 TW in shallow water

Solar concentration (parabolic troughs → steam/turbines; towers → high T/hydrogen) and heating



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

Source: Lewis et al 2003c



Projected cost of photovoltaic solar power?

$1/W$_p$AC → 2.6 €-cents/kWhr in California
(4.7 in Germany)

- requires cost ~ cost of glass!

Potential of Renewables II

- **Wind** - 200 TW input ⇒ no more than a few TW available (bottom of atmosphere)

- **<u>Biomass</u>** - 40 TW from *all* current growth (farms + forests etc) ⇒ absorbing CO_2 [average solar → biomass efficiency ~ 0.2%; sugar cane ~ 1.5%], conversion to useable form inefficient

- **Hydro –** 1.5 TW_e max, 1 TW_e useful, 0.3 TW_e already in use

- **Geothermal** - total flux out of earth* ~ 10 TW → maximum useful 0.1 TW (well exploited where sensible: 10 GW installed) ; more available by 'mining' up to 100 GW?

* not renewable, but essentially infinite

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BIOFUELS I

Today → 1% of road transport fuel using 1% of available arable land

85% ethanol, from cereals in US (44% of total), sugar in Brazil (48%)

15% bio-diesel, from rapeseed, sunflowers, palm oil (EU → 87% of total)

2030:

Reference scenario: 3% of road transport fuel* using 2.5% of arable land

** use of transport fuel up 55% from today in reference scenario*

Alternative scenario: 5% of road transport fuel* using 3.8% of arable land

** use of transport fuel up 38% from today in alternative scenario*

Obvious benefits for security of supply + *potentially* less CO_2,

but very dependent on crop and yield, energy embedded in fertiliser and irrigation, emissions in fertiliser production, energy intensity of conversion process etc (note other environmental effects from change of land use)

Cost currently relatively high – need incentives/subsidies

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BIOFUELS II

Fields/wells → wheels analysis:

US study: corn based ethanols → 13% less CO_2/km than petrol (net energy saving only 20%)

Brazil: sugar based ethanols → 90% less CO_2/km (net energy saving 88%)

EU study: sugar beet could save 40-60% of CO_2

But: New York Times recently reported that palm oil from Malaysia and Indonesia may → up to 20% *more* CO_2/km than petrol!

R&D: use of husks& stalks as well as starch → second generation biofuels using much less land thereby allowing big expansion, with perhaps ultimately

→ 90% less CO_2/km than petrol

→ cost as low as $40-50/barrel

(Very) extreme estimate: 16,700 Mtoe pa (50% more than today's total) by 2050 without jeopardising food supplies, forests or biodiversity – but this assumes big increases in agricultural productivity as well as successful commercialisation of second generation biofuels
+ availability of water

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Large Scale Base-load Electricity*

Today ~ 2 TW_e from

- Fossil fuels (1.3 TW_e) – so cleaner coal and gas + capture and sequestration of carbon (if practical) very important
- Nuclear (0.3 TW_e)
- Hydro (see above: 0.3 TW_e could →1 TW_e)

Future

- Fusion (in principle unlimited)
- Possibly solar (see above: in principle many TWs)

* which (*pace* advocates of micro-generation*) is needed

* who see it as a panacea. The advantages come with CHP (→ increased efficiency in using primary energy, especially during heating season), but small scale generation is inevitably less efficient (and more expensive) than large-scale central generation, and the grid would have to be adapted to allow many small scale generators to sell their surplus

Cleaner Coal

- **Increase efficiency**

UK fleet today: (34-39)%   State of art is ~ 46%

EU goal: 55% (needs new materials above 50%)

- **Carbon/CO_2 capture and storage** ('sequestration') **– CCS**

Possible in principle from coal or gas power stations (35% of total of CO_2 from fossil fuels) and from some industrial plants (not from cars, domestic) – needs to last well beyond end of fossil fuel era (and not leak too much)

Downsides

– not proven on large scale (from coal: 3Mt captured in 2003 vs. 9,593 Mt produced), *but can build 'capture ready' plants now*

– would increase cost by (1-2)p/kWhr; needs CO_2 cost above $25/tonne to be viable

–decrease efficiency by ~10% (i.e. 45% → 35%)

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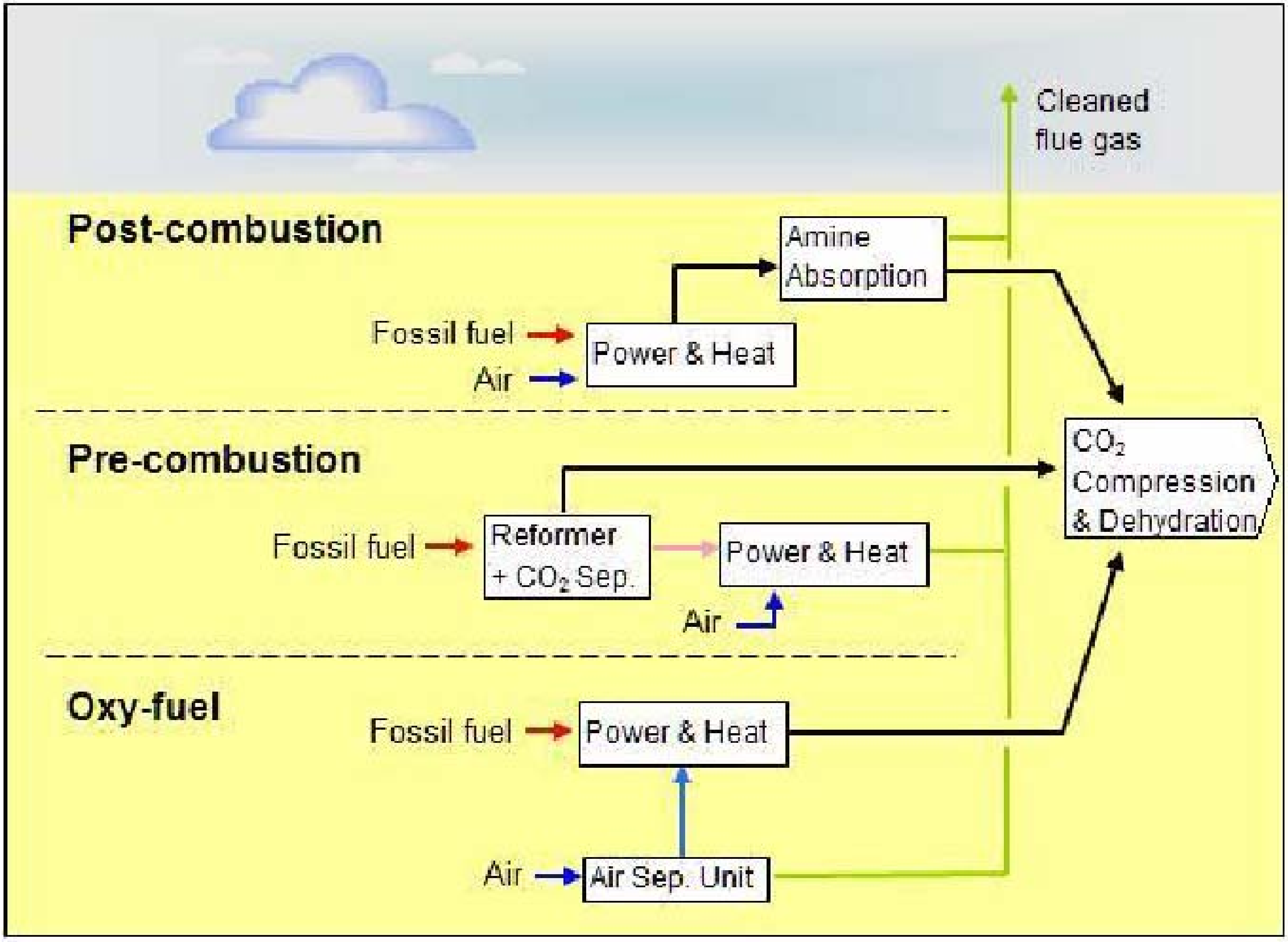
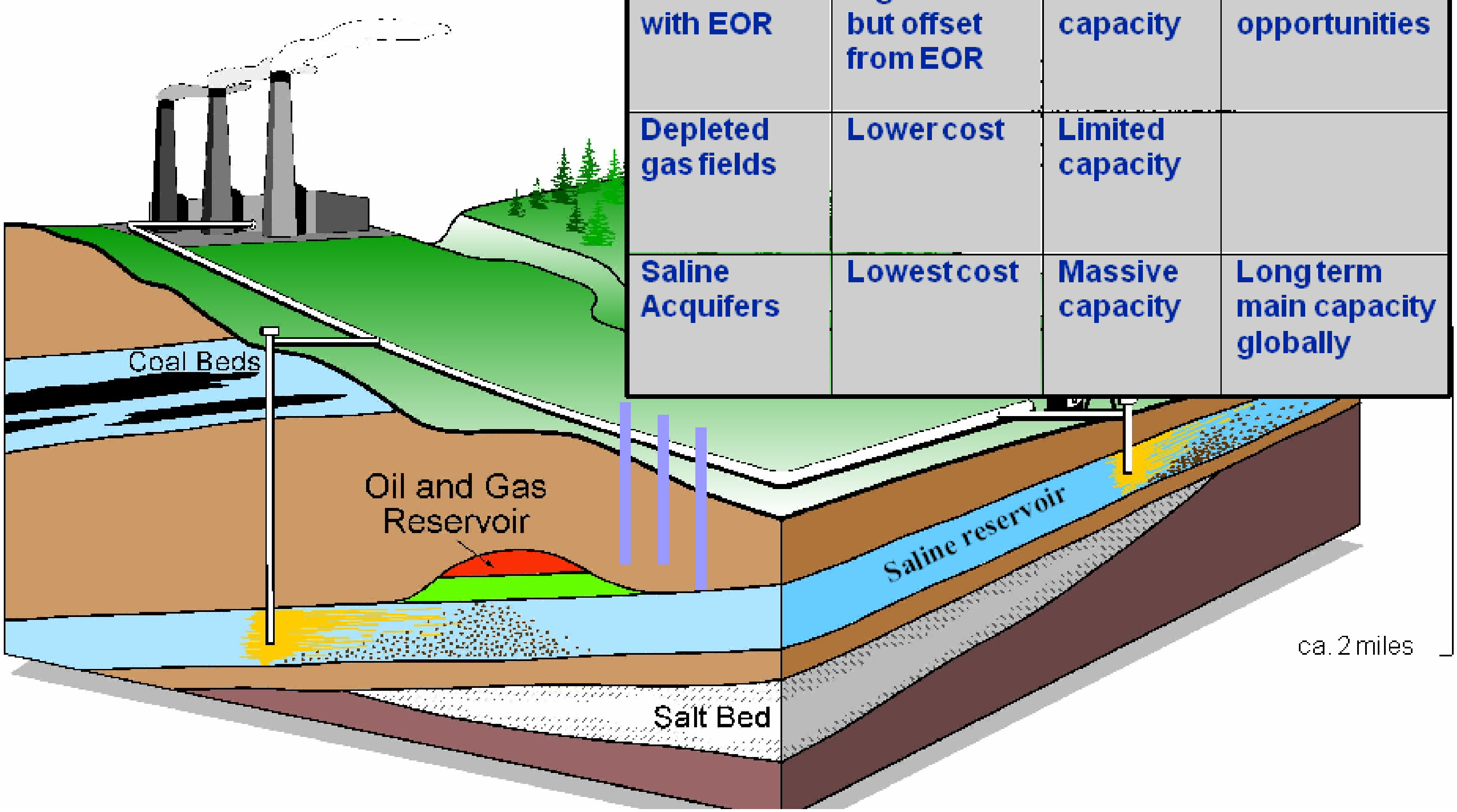
Carbon Dioxide Capture Technologies



After capture, compress (>70 atmos. → liquid) transmit and store (>700m):

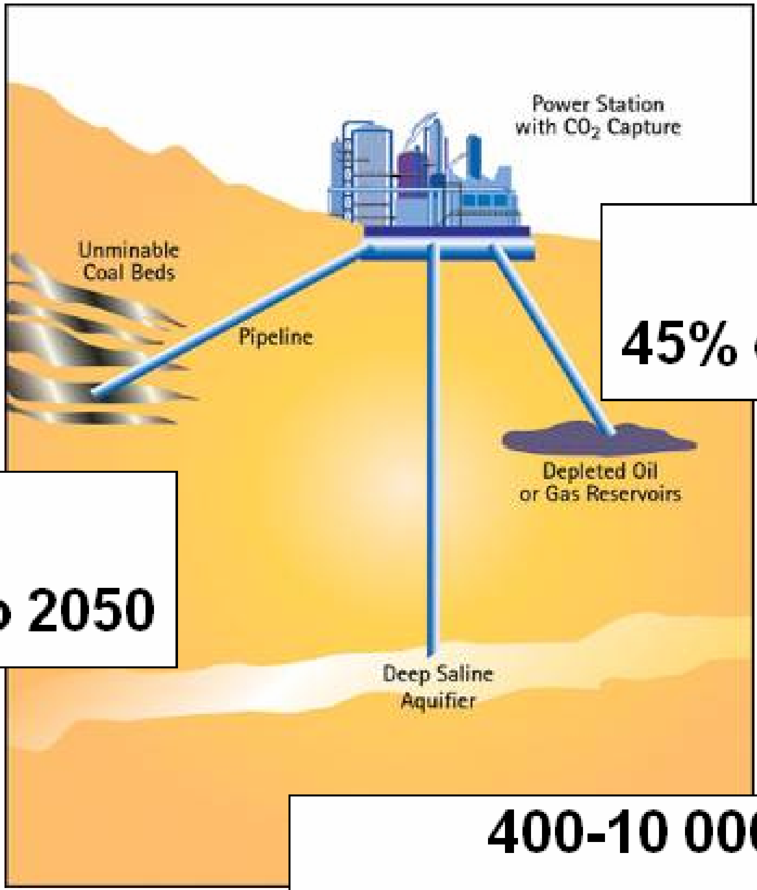
CO_2 storage options

	Cost	Capacity	When
Oil – fields with EOR	Higher cost but offset from EOR	Limited capacity	Earliest opportunities
Depleted gas fields	Lower cost	Limited capacity	
Saline Acquifers	Lowest cost	Massive capacity	Long term main capacity globally



Geological Storage Potential

Courtesy of IEA GHG R&D Programme



920 Gt CO_2

45% of Emissionsto 2050

40 Gt CO_2

<2% of Emissionsto 2050

400-10 000 Gt CO_2

20-500 % of Emissionsto 2050

substantial storage potential

Conclusions on Carbon Capture and Storage

- **Very promising/potentially important, especially if saline aquifers OK (said to be plenty in China and India)**
- **Large Scale demonstration very important**

 - lots of talk, e.g. about BP plants in Scotland and California

 - EU Zero Emissions Power strategy proposes 12 demonstration plants (want many, in different conditions) by 2015

- **It will require a floor for the price of carbon**

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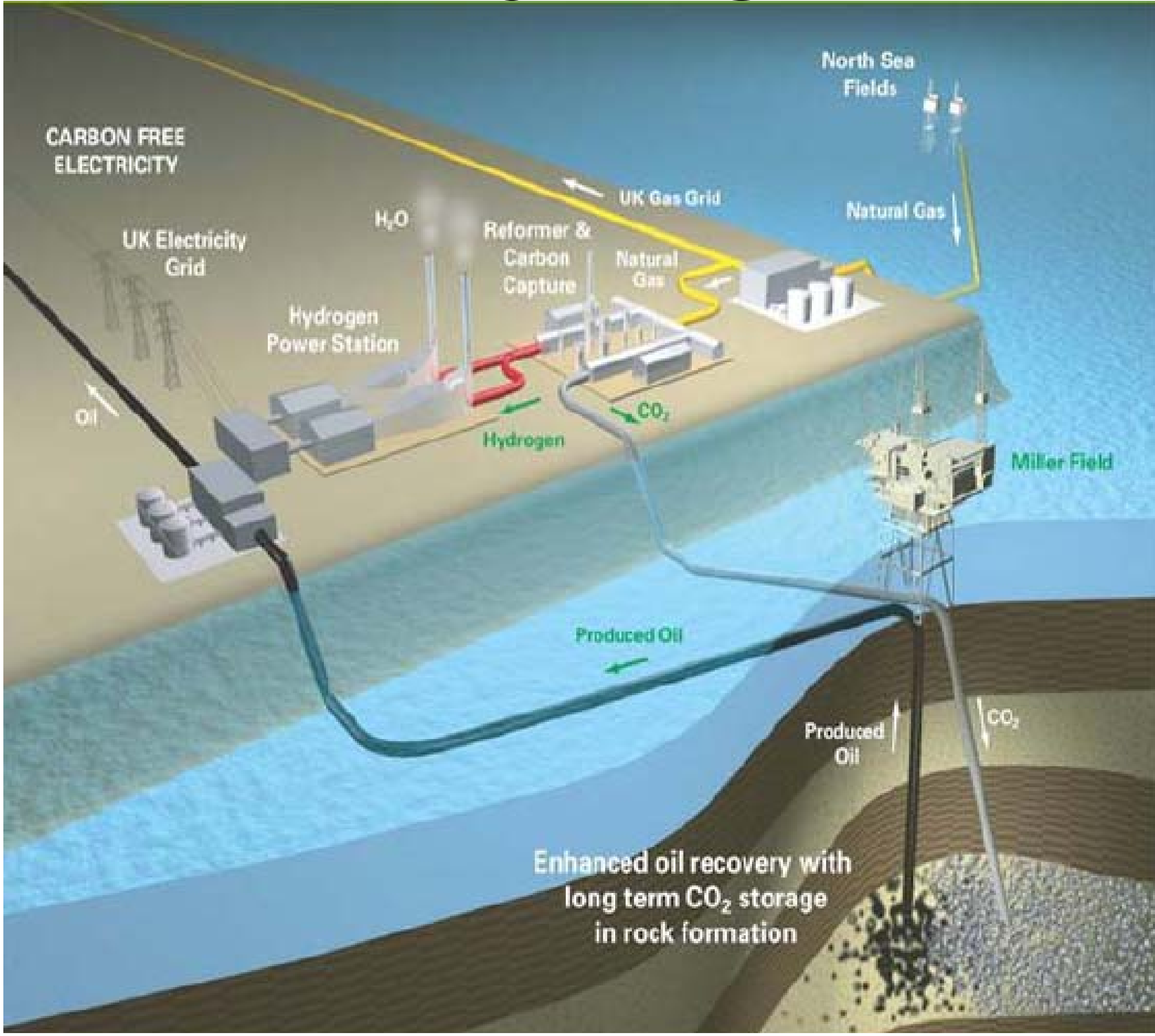
BP Hydrogen Power Plant



- CCS is a material CO_2 mitigation option for power
- Technologies largely proven
- 1MtCO_2 p.a. pilot plant operating in Algeria
- First large scale hydrogen power plant announced in Scotland
- Single 350MW plant in UK generates more carbon free electricity than entire UK wind park
- But need right policy framework to be viable

Nuclear Power I

- **Recent performance impressive** – construction on time and budget, excellent safety record, cost looks OK
- **New generation of reactors (AP1000, EPR)** – fewer components, passive safety, less waste, lower down time and lower costs
- **Constraints on expansion**

- snail's pace of planning permission (in UK +…)
- concerns about safety
- concerns about waste
- proliferation risk
- plus the technical constraints on next slide

Nuclear Power II

- **Technical constraints on expansion**

- waste storage space ⎤ breeders*, reprocessing,
- exhaustion of Uranium* ⎦ incineration?

* Resources reported on next slide

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

U/Pu cycle: large plutonium inventory – slow ramp up (unless kick-started using Pu stockpile)

Th/U cycle: large fissile ^{233}U inventory – fast ramp up, but it needs a highly enriched ^{235}U or Pu core (or accelerator driven spallation neutrons)

Using breeders would put up cost

[Note: 4 of 6 ‘Generation IV’ models are breeders]

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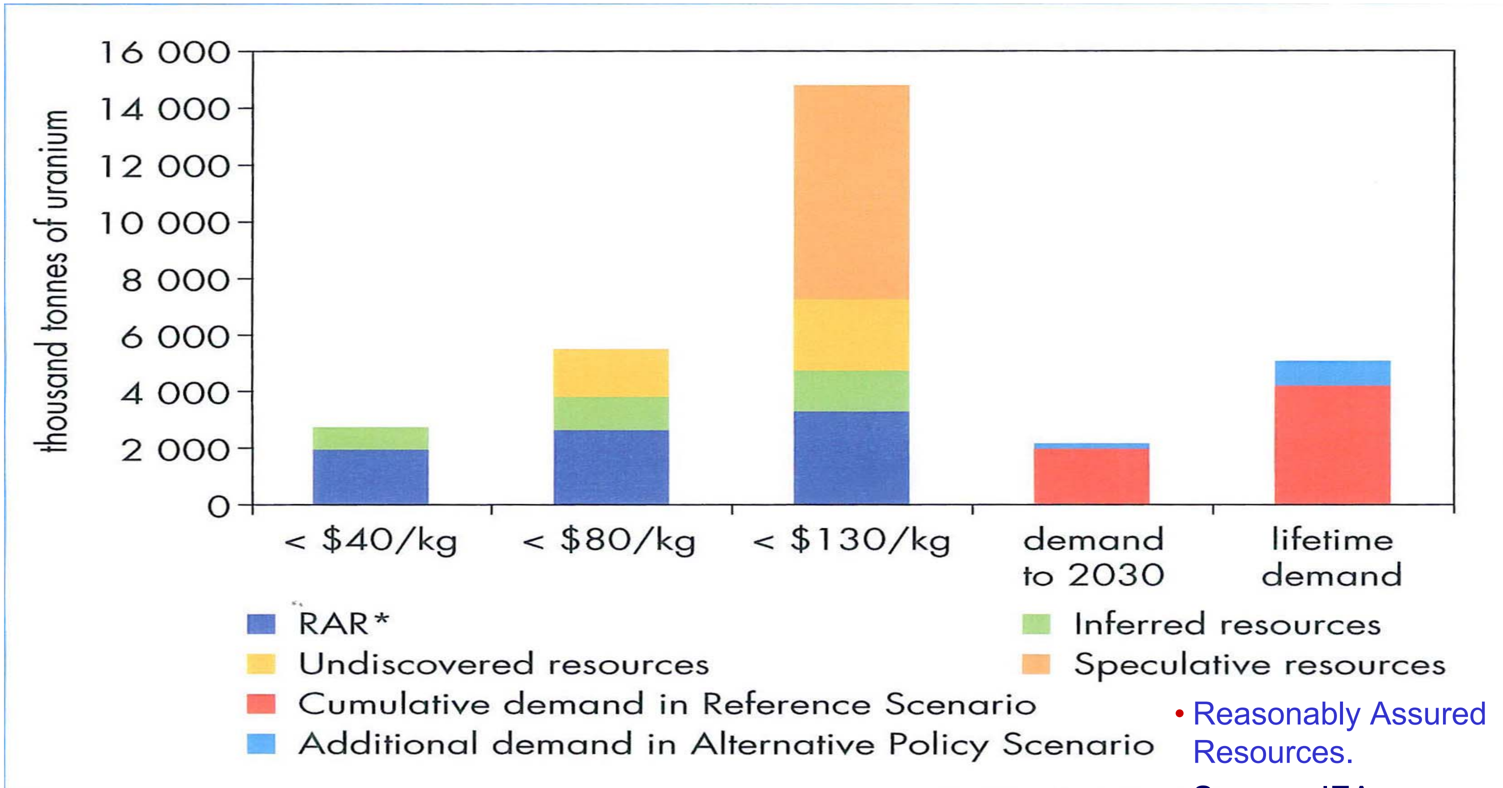
Uranium Resources vs. Cumulative Demand

If all speculative resources shown here exist → 120 years at IEA's expected 2030 use (14%);

If nuclear → 45% (removing half fossil fuels) → 40 years



• Reasonably Assured Resources.

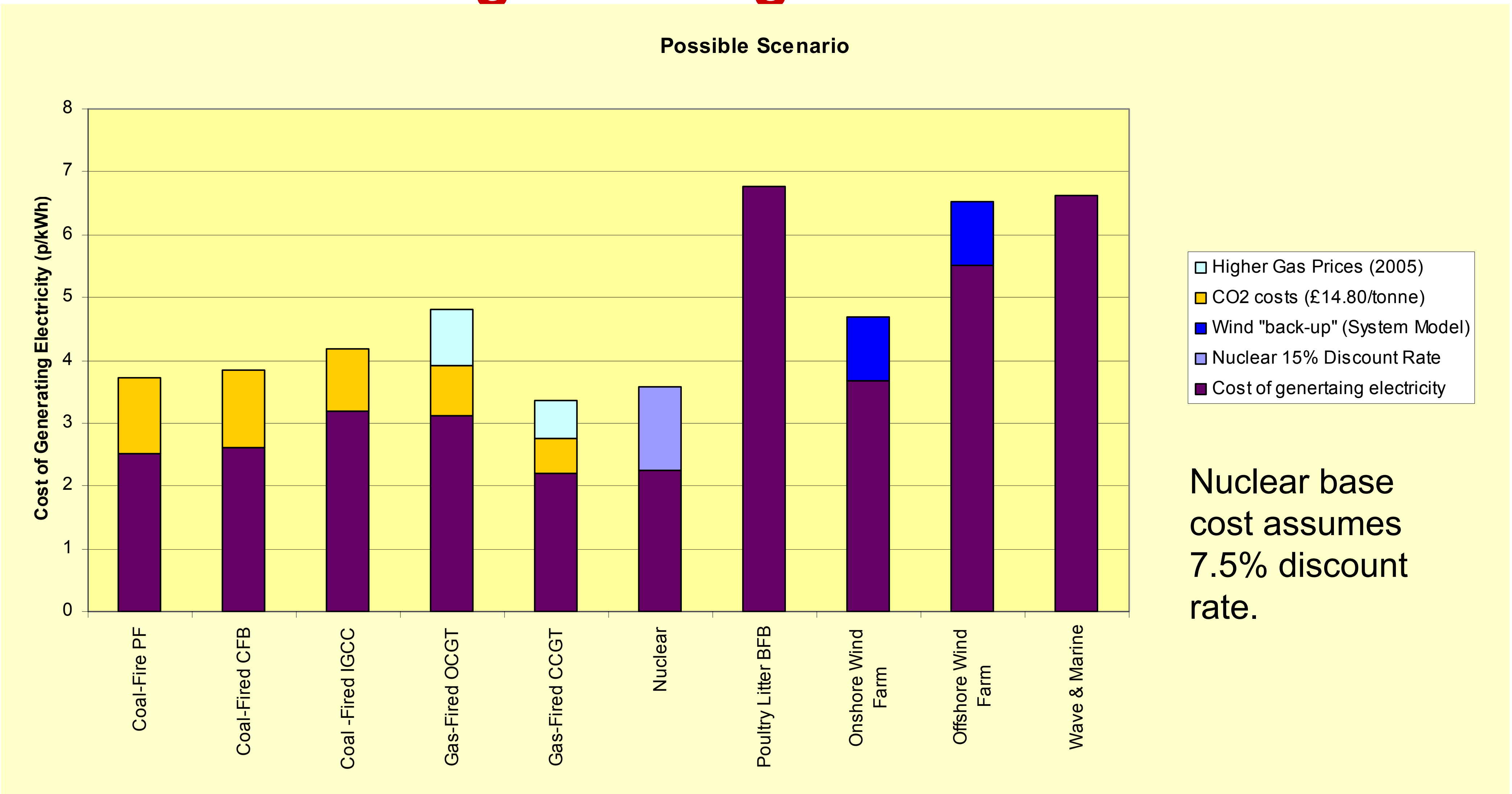
Source: IEA

But: cost of nuclear power insensitive to cost of U (+ $100/kg → + $0.25c/kWhr) *which is already over $200/kg*

Estimates of resources vs. cost vary dramatically, but unless U can be extracted economically from sea water, we will need breeders (or something else) sometime in the future when the fossil era is over

Recent anti-nuclear arguments have emphasised cost

Royal Academy of Engineering study of generating costs:



Nuclear base cost assumes 7.5% discount rate.

FUSION: D + T → He + N + 17.6 MeV

The raw fuels are lithium (→ T) and water (→ D)

The lithium in one laptop battery + half a bath of water would produce 200,000 kW-hours of electricity

= (total UK [US] electricity production)/population for 30 [15] years

Challenges:

1) **Heat D-T plasma to over 100 M ^{0}C** = 10xtemperature of core of sun, **while keeping it from touching the walls**

This Is done using a ‘magnetic bottle’ (tokamak)

The Joint European Torus (JET) at Culham in the UK has produced 16 MW of fusion power

2) **Make a robust container** (able to withstand huge neutron bombardment ~ 2MW/m^2)

3) **Make it work reliably**

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FUSION (Cont)

Attractions: unlimited fuel, no CO_2 or air pollution, intrinsic safety, no radioactive ash or long-lived nuclear waste, cost will be reasonable *if* we can get it to work reliably

Disadvantages: not yet available, walls gets activated (but half lives ~ 10 years; could recycle after 100 years)

Next Steps:

- **Construct a power station sized device** (→ at least 10 times more energy than input) – it is called **ITER** and is being built by EU, Japan, Russia, USA, China, S Korea, India in S France
- **Build a Fusion Materials Irradiation Facility (IFMIF)**

IF these steps are taken in parallel, then - given adequate funding, and no major adverse surprises **- a prototype fusion power station (‘DEMO’) could be putting power into the grid within 30 years** ***- could be 20 years if we move to a low-performance DEMO in parallel with ITER and IFMIF***

Can it all add up to a solution?

- The IEA Alternative Policy Scenario
- Wedges
- Economic instruments and the political challenge

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IEA Scenarios

- **Reference Scenario**

Government policies already enacted or adopted, although many not fully implemented: + 55% CO_2 emissions in 2030

- **Alternative Policy Scenario**

Policies and measures currently being considered by governments: + 30% CO_2 emissions in 2030 (reduction relative to Ref Scenario: 78% efficiency; 10% nuclear; 12% renewables)

IEA: 'formidable hurdles' to adoption & implementation which 'will take considerable political will – many bound to encounter resistance from industry and consumer interests'

- **Beyond the Alternative Policy Scenario**

Identifies measures (also increase security of supply) which lead to CO_2 emissions in 2030 the same as today – but they are quite drastic and run out of steam in 2030

– *will discuss bolder 'Wedges', which claim to go to 2050*

Cost Effectiveness of the Alternative Scenario

World wide to 2030:

- Supply side investment saved: $3.0 trillion*

  *out of over $29 trillion in reference scenario, which won't necessarily be available

- Additional demand side investment*: $2.4 trillion

  * by consumers, who cumulatively save $8.1 trillion in power bills – so investment very cost effective (even with an enormous discount rate as pay back times ~ 3 years in OECD/1.5 years developing countries)

Gains biggest in developing world

'low hanging fruit'; demand side work cheaper

but harder to implement than in developed world

Barriers to the Alternative Scenario

- **Many more individual investment decisions*, by people**

  - such as landlords, developers who won't be paying the power bills

  - in the developing world, without access to capital

  - in developed world, without a great interest in individually small savings/efficiency *(or any: otherwise why buy a BMW?)*

  * supply side investment in 250MW power station = demand side saving from 14 million Europeans (80% of those who buy refrigerators each year) buying 40% more efficient ($A \rightarrow A^{++}$) refrigerators *(without increasing the capacity, or keeping their old fridges running in the garage)*

- **Lack of awareness of potential savings and lack of information on energy performances**

Longer term: 'Wedges' (Pacala & Socolow)

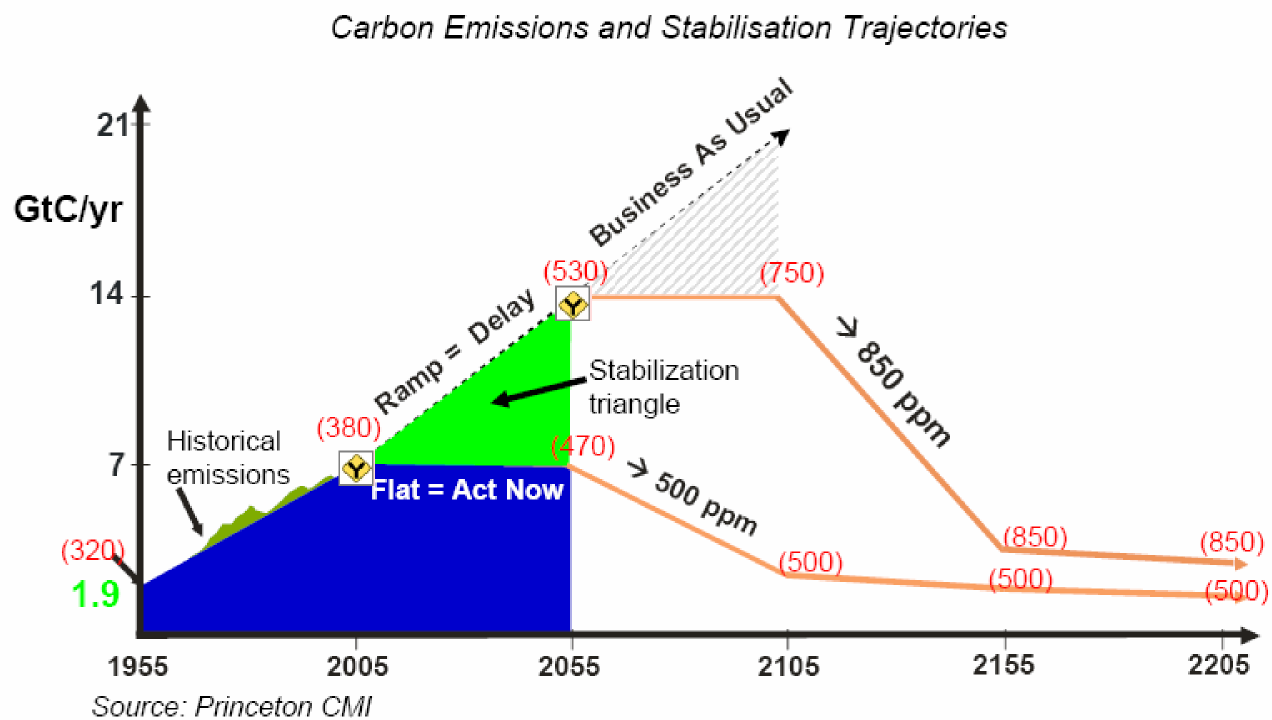
– reduce a heroic challenge to a limited set of monumental tasks

- **Simple extrapolation → +7Gt/year of CO_2 in 50 years** (~ life time of power station)

- **Look for 'wedges'**

  - technologies which exist

(efficiency, renewables, nuclear,…)



Note: values in parentheses are ppm. Note the identity (a fact about the size of the Earth's atmosphere): 1 ppm = 2.1 GtC.

although many need scaling up, **that might each save1/7th of increase** (1Gt/year in 2056; integrated saving of 25 Gt)

Possible Wedges

- **Efficiency** – 2 billion cars 30 → 60 mpg (or half use)
  – 25% less in all buildings
  – all new coal power plants → 60% efficient (high T)
- **Nuclear** – +700 GW (2xpresent; phase out of nuclear → need half an extra wedge)
- **Renewables** – 2 million 1 MW_e windmills replacing coal (50xpresent) *or* 4 million → hydrogen for cars
  – 2000 GW_e solar (700xpresent) replacing coal
- **CCS** – on 800 GW_e from coal (or 1600 GW gas)

……**note after 50 years need 5 more wedges** (more unless existing wedges can continue to grow) **+** oil and gas running out → problem exacerbated by increasing use of coal?

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Conclusions on Wedges

- **Good news** that can find wedges that would do the job until 2050 (but this has given false comfort to some people)
- **Bad news** that filling *any* of the wedges is very challenging, obviously won't happen over night, overall won't reduce costs, and each wedge will run out of steam
- **Should think of wedges as showing that the challenge, while enormous, is not completely impossible**

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Economic Challenges and Possible Instruments

(won't discuss adapting to climate change)

Climate change is an 'externality' generated locally (mostly in developing countries up to now) but felt globally (worst effects in developing countries) in the future – enormous challenge

- global, long lead times, involves major risks and uncertainties

■ According to UK 'Stern Report': **climate change is 'probably the greatest and most wide-ranging failure of markets ever seen'**

Report attempts to analyses effects and cost of climate change and economic tools to attack problem

Central conclusion: "benefits of strong early action outweigh costs"

Report also recommends "at least doubling R&D …priorities include PV, biofuels, fusion and materials science"

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Tools

- **Regulation**: important in many cases (e.g. building regulations) and when demand is very price-inelastic, e.g. road transport – price helps [US vs. European cars] but we keep driving, and proposed 120g/km EU limit is good

- **Energy price** drives innovation (which regulation does not do so well) + reduces consumption. M**odalities:**

- **Carbon tax** – only implicitly controls CO_2

Simple (if on fuel, would need reclaim [e.g.] for plant with CCS?)

- **Emissions trading** – explicitly controls CO_2 *(for items covered)*

Liked by economists – gains where most easily found, but problem of allocations: grandfathering (c/f EU scheme), or - better in principle - auction

Cannot impose on individual emitters

Does not give the certainty needed to enable investment, e.g. in CCS

Need tax (giving floor) + emissions trading with auctions??

Problems/challenges

- **Monitoring** (e.g. judging degree and permanence of CCS), **sanctions**
- **Global equity**

- need bias to developing world
- allocate some permits to developing world, auction the rest?

Clean Development Mechanism

- **Worldwide political will to reach a global agreement – the biggest challenge of all**

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 ('wedges')
- Need to use all sensible measures (increased efficiency, renewables where appropriate, more hydro, nuclear, CCS, biofuels, solar, fusion [we hope] in longer term,…)
- Need fiscal incentives, regulation, carbon price, more R&D, political will (globally)

The time for action is now

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