Cheap clean energy for all in the 21st Century?

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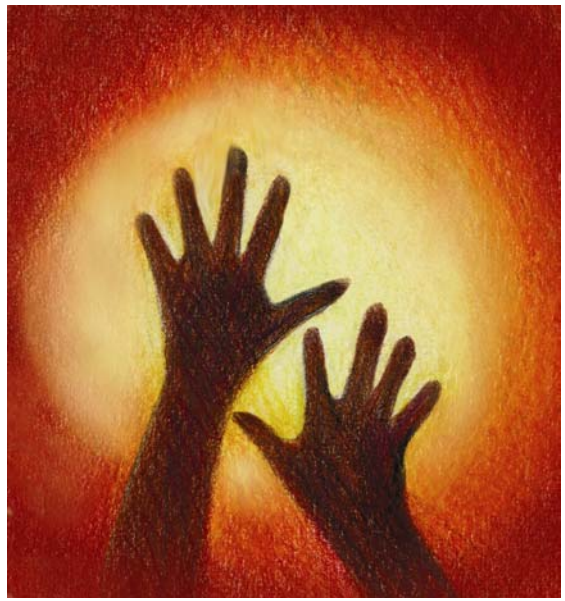


A macro view of global population

2 billion in 21st century

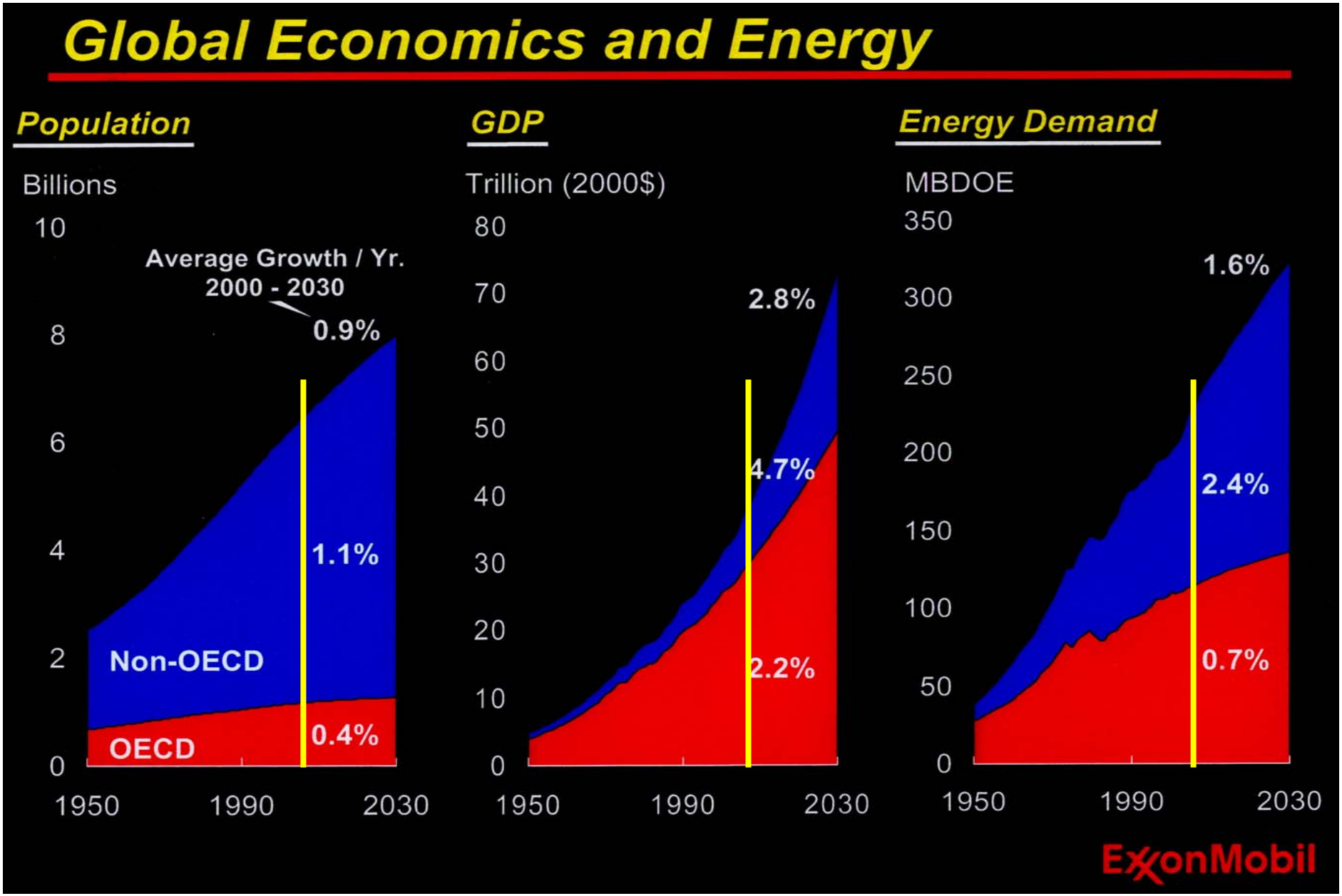
Health
Education
Energy
Water
Job Skills

1.5B people in Transition

3 billion in 18th century with less than $2 ppp/day

(Additional 2.5B will start here)

Energy ⇔ development



3B poor (~1B homes) need access to energy

- **Cooking and potable water:**
  - 1 liter (1/4 gal) of kerosene per day

~2 MBoe per day

- **Light:**
  - 100 watts (7 ⊗ 13W florescent bulbs)
- **Entertainment/Communications:**
  - TV/computer at 200-500 watts

~200 Gigawatts

These additional resources would revolutionize the development of the poor

Quality of Life

Each day each American uses

Source: Greg Swift

4+1 global grand challenges

- Carbon neutral fossil (coal)
- Solar PV/CSP at capital cost $1/watt
- H_2 produced from non-fossil sources
  - Photochemical, thermal splitting of H_2O
- Closed nuclear fuel cycle to enable safe, secure, sustainable nuclear energy
- Efficient energy **use**, storage and transmission
- Fusion – the ultimate "source"

A tale with nine parts

Outline

1) The energy infrastructure is huge (~$15 trillion)
2) Climate Change – an uncontrolled experiment
3) Cheap clean energy – an economic opportunity
   - Alternatives have a market niche but are small today
4) USA lacks energy (conventional oil, gas) security
5) Middle East & Russia control oil and gas
6) Increasing competition (China, India)
7) Can we continue to bank on a military solution
8) Unconventional fuels: 2-3X pollution and CO_2
9) **Energy efficiency ↔ behavior change**

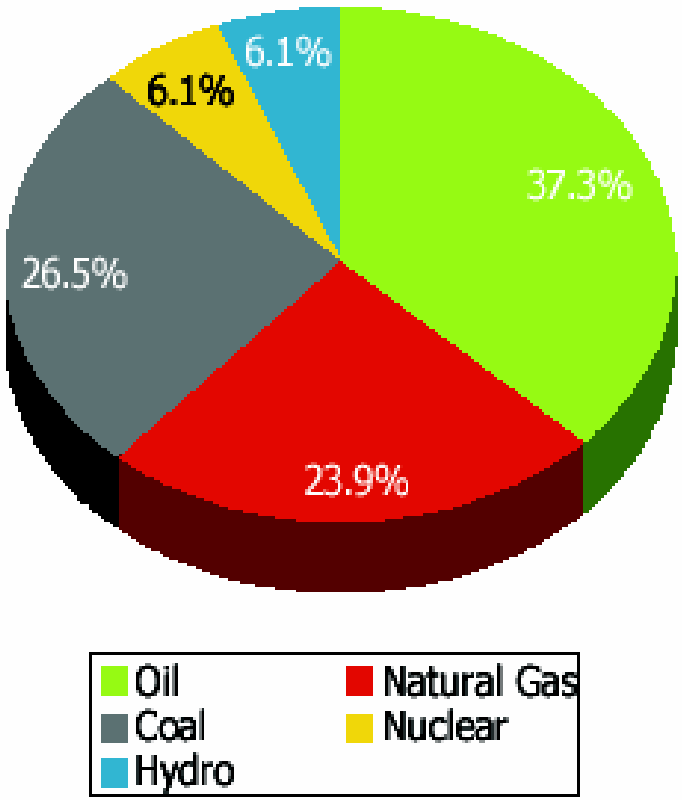
A mind-boggling global infrastructure (~$15 trillion) provides modern energy/mobility to ~3.5 billion people

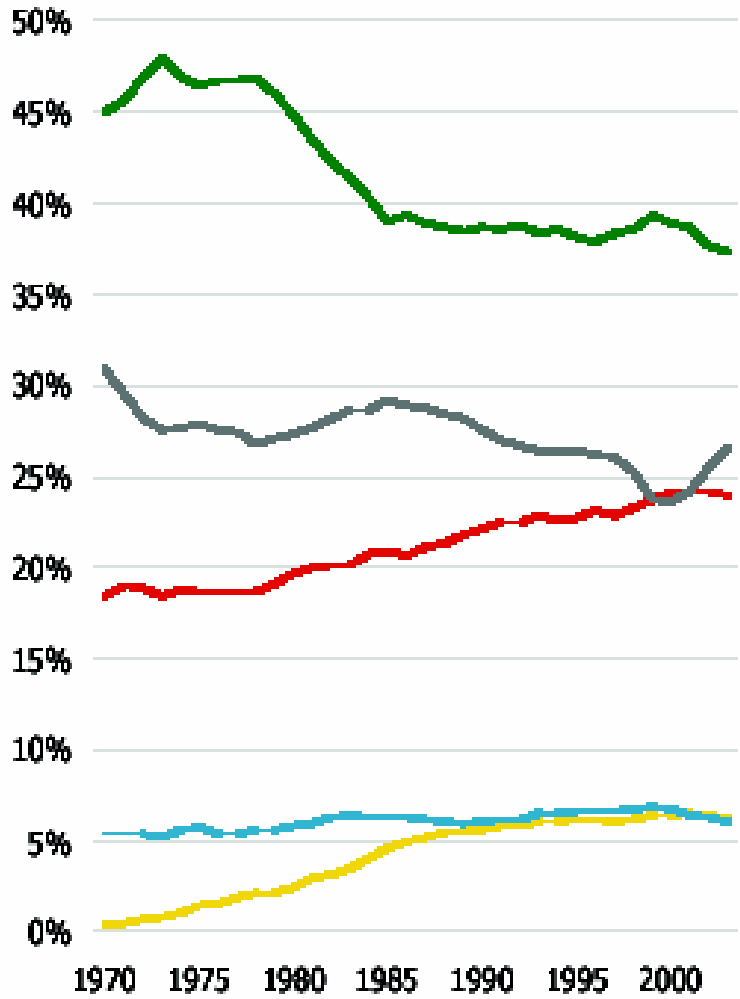
- Oil and gas contracts, rigs, exploration technology
- Tankers and pipelines
- Refineries, LNG facilities
- Auto industry
- 600 (+220) million cars (+trucks) running on gasoline
- Service stations and gasoline stations
- Existing coal/gas electricity generation plants

1. This cannot be changed overnight!

current and historical global energy mix

Current global energy supply is dominated by fossil fuels – oil has been the largest component of the energy mix for many decades; gas has grown strongly since the 1970's; coal has been growing in the last four years; hydro is constant and nuclear has plateaued





Source: BP Statistical Review

Global consumption is ~13 trillion watts of primary power in 2006

To sustain an adequate standard of living (4kw) for 8 billion people (population by 2025), and without improvements in efficiency, we need ~2.5 times today's energy use.

GOAL: 32 Twatts ~ 10Twatts electric

The simplest solution is

Unconstrained supplies of

- **Gasoline**
- **Natural gas**

Conventional + unconventional

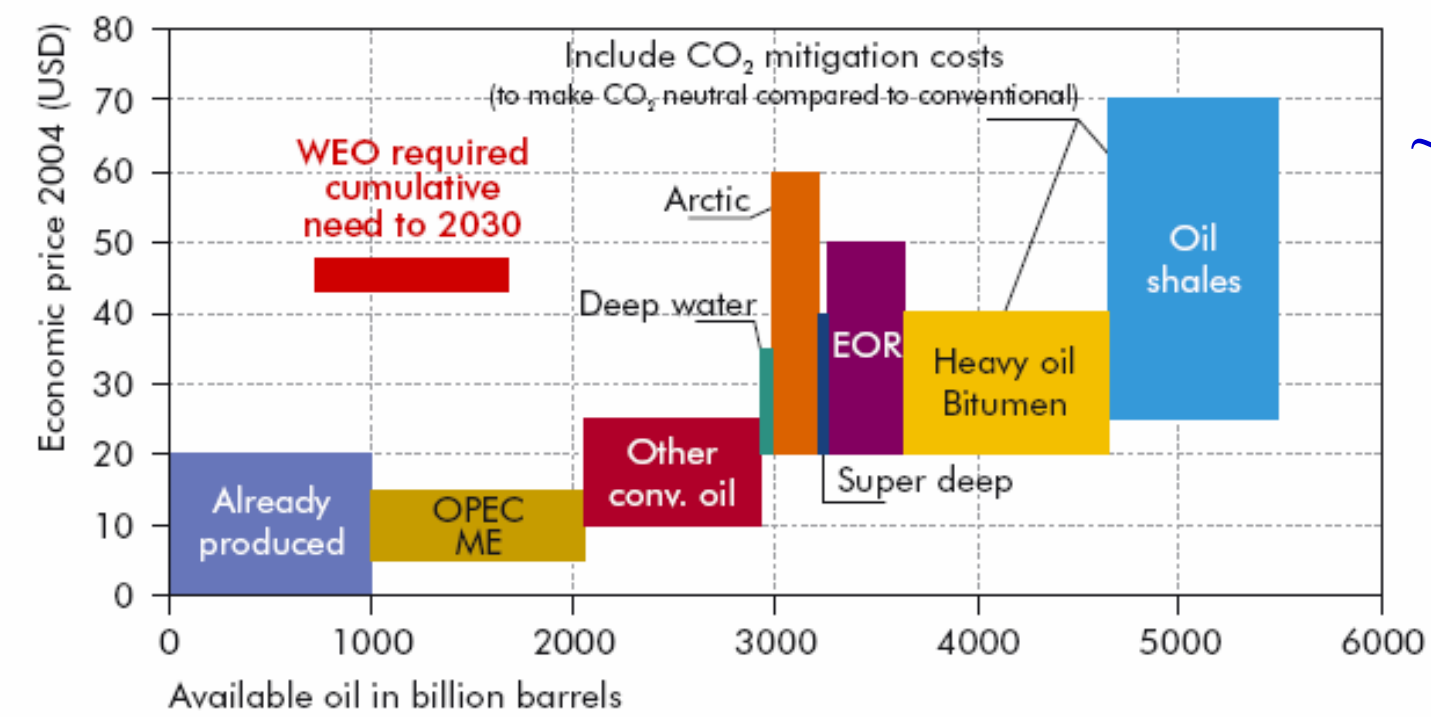
Can provide all our needs for electricity, heat, transportation.

Environmental stewardship requires Carbon capture and sequestration

Burning fossil fuels for next 100 years

Av. (current)	Tera Tons C	CO_2
• OIL: 100 (85) Mbo/day	→ **0.5**	½ accumulates in the atmosphere & **2.1 GtC = 1 ppm**
• Gas: 1.0 (0.3) Tcf/day	→ **0.5**	
• Coal: 21 (14) M tons/day	→ **1.4**	

~1000ppm

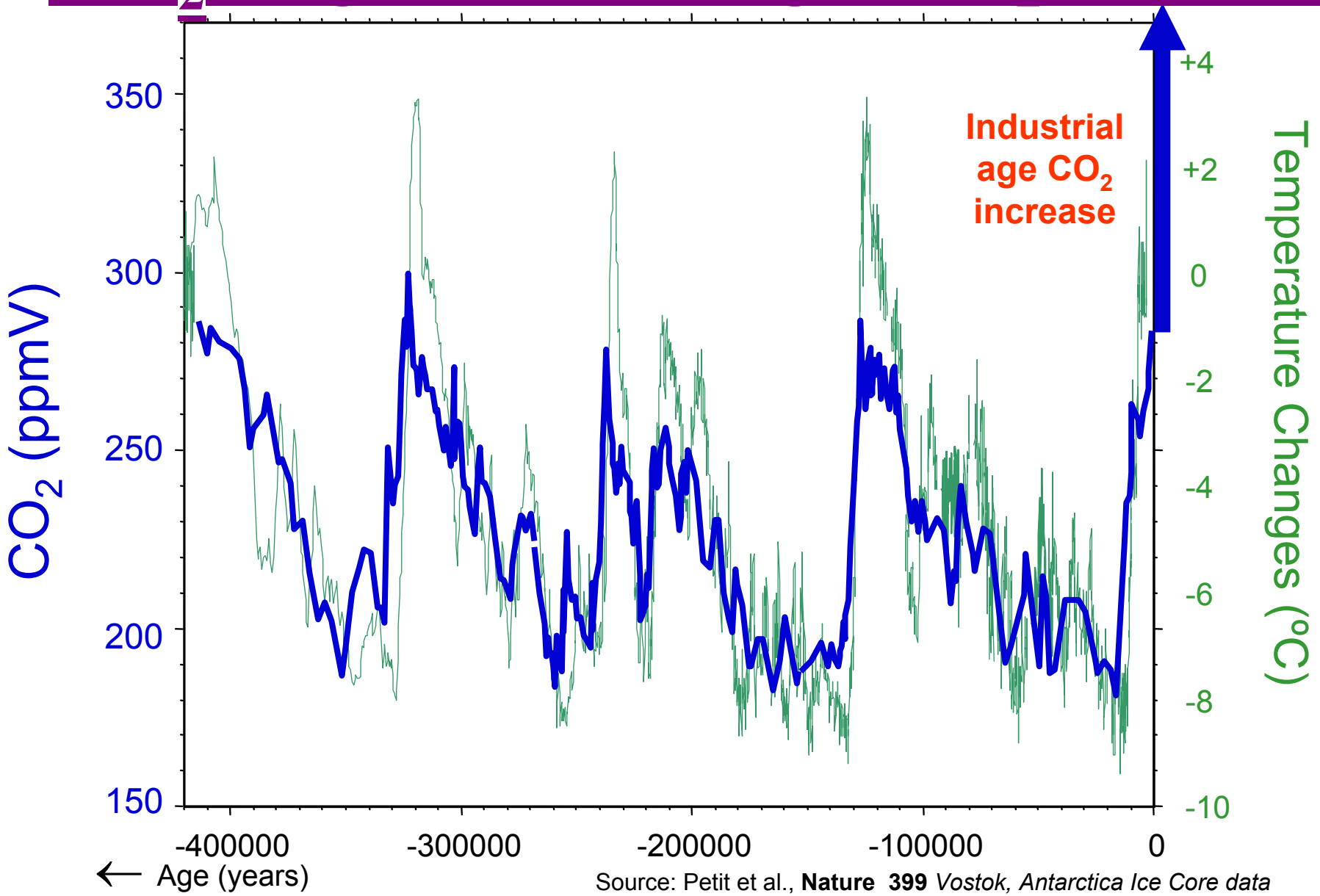


3.7 T barrels

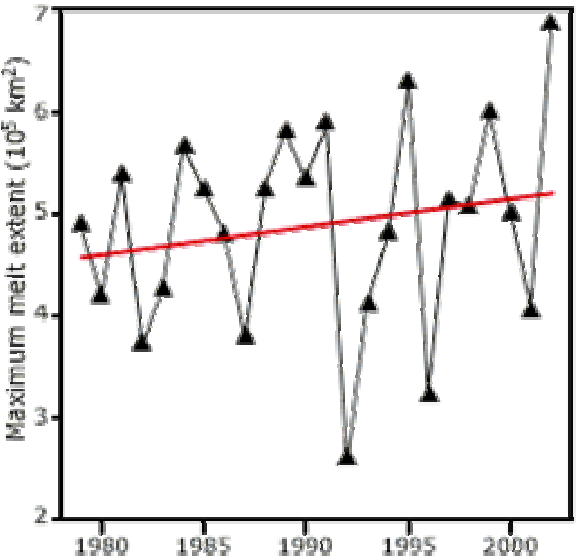
Fossil Fuels and Environment

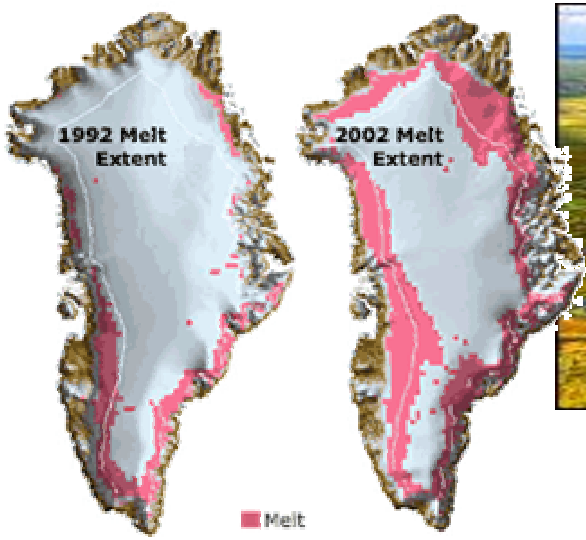
In the 20th century we started to act on pollution (mercury, NOx, SOx, acid rain, soot, ...) but <u>not</u> CO_2 and the associated global climate change

CO_2 & global average temperature



CO_2 is a greenhouse gas. *It forms a blanket around the earth that causes warming*





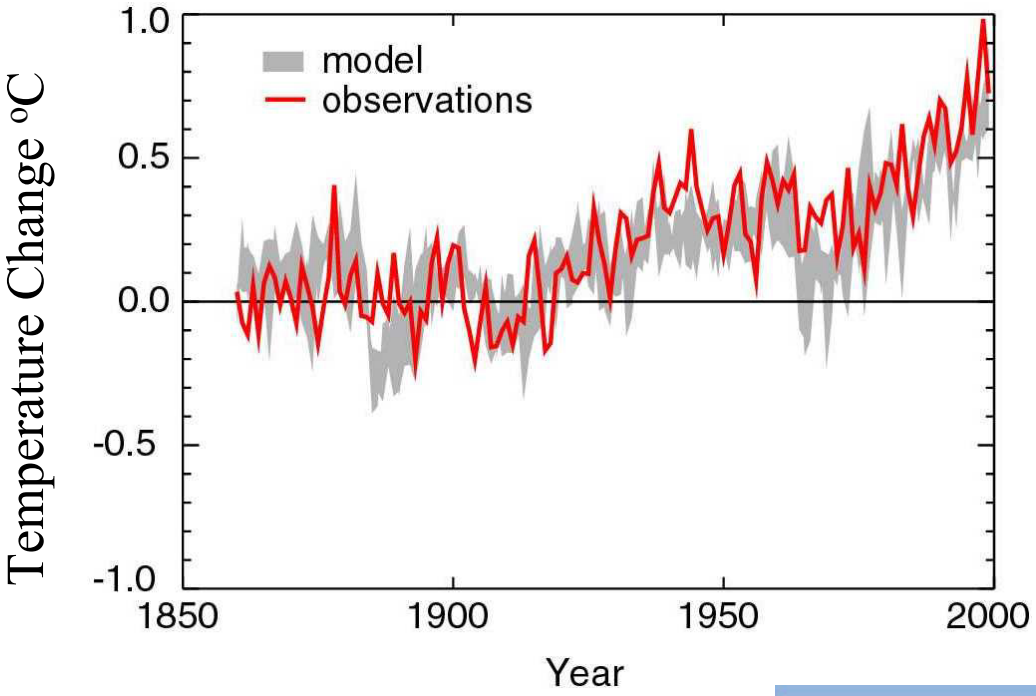
http://earthobservatory.nasa.gov/Study/vanishing/

Melting of glaciers in Greenland and around the world. Is it global warming?

Melting of permafrost

CO_2 cycle and warming is a non-linear phenomena

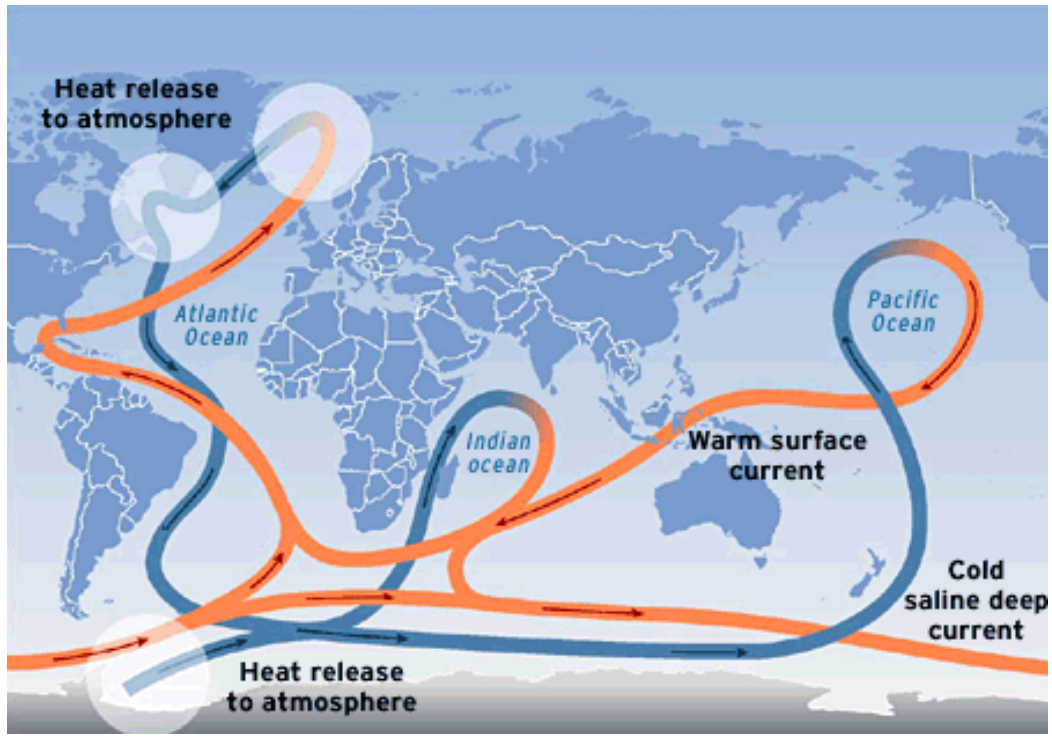
Intense storms



Increasing evidence for temperature rise due to fossil-fuel burning

Possibility of catastrophic change:

Shutdown of the thermohaline in 10s of years



Are we in the non-linear regime of CO_2 cycle/warming?

- CO_2 is the most oxidized form of carbon
  - 10-50 year cycle with terrestrial and shallow ocean (saturated)
  - 400-2000 year cycle – deep ocean
- Thermal capacity of earth ➔ we are observing response to CO_2 loading of 30-40 years back

Sequestration of CO_2 ⇒ First capture and then store 25 gigatons CO_2 / year!

2. Climate change is the largest, costliest, most dangerous, uncontrolled experiment ever done by mankind

Clean Energy: an Economic Opportunity

- **Clean electric power**
- **Robust electric power grids**
- **Fuel for Transportation**
- **Efficient autos/machines/appliances**

are increasingly value-added products.

10 Terawatts of electric power translates to a $12billion/day market at $0.05 kWhr

Getting all three – cheap, clean and copious supply – is the challenge

- **Plenty of fossil Carbon**
  - **Oil, natural gas, coal**
  - **heavy oil, shale, clathrates, …**
- **Fungible at $50+/barrel (Coal-to-Liquids)**

Issues with fossil fuels

- **Environmental impact**
- **Green house gasses**

Alternates: How much and how soon?

All alternatives to fossil fuels have a market niche

• Nuclear	~400 GW	?
• Hydro	~400 GW	~600 GW
• Wind	60 GW_p	+30%/year
• Solar PV	4 GW_p	+30%/year
• Geothermal	25 GW (e+th)	
• Biofuels	1 Mboe/day	?

3. But none is large enough!

Paradigm change is needed in order to provide affordable & clean energy to all!

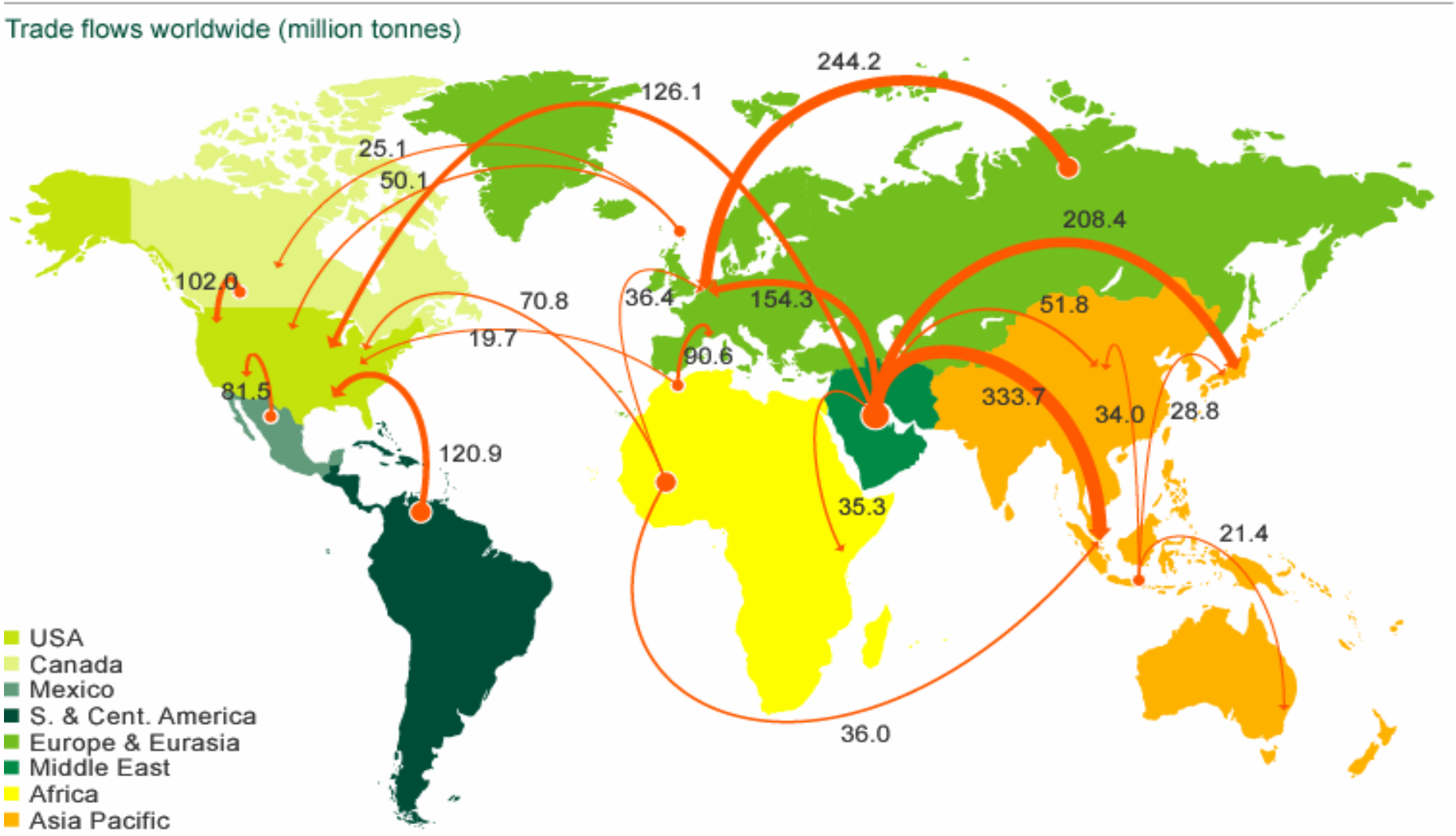
4. Energy Security

Where do we get our oil and natural gas from?

And

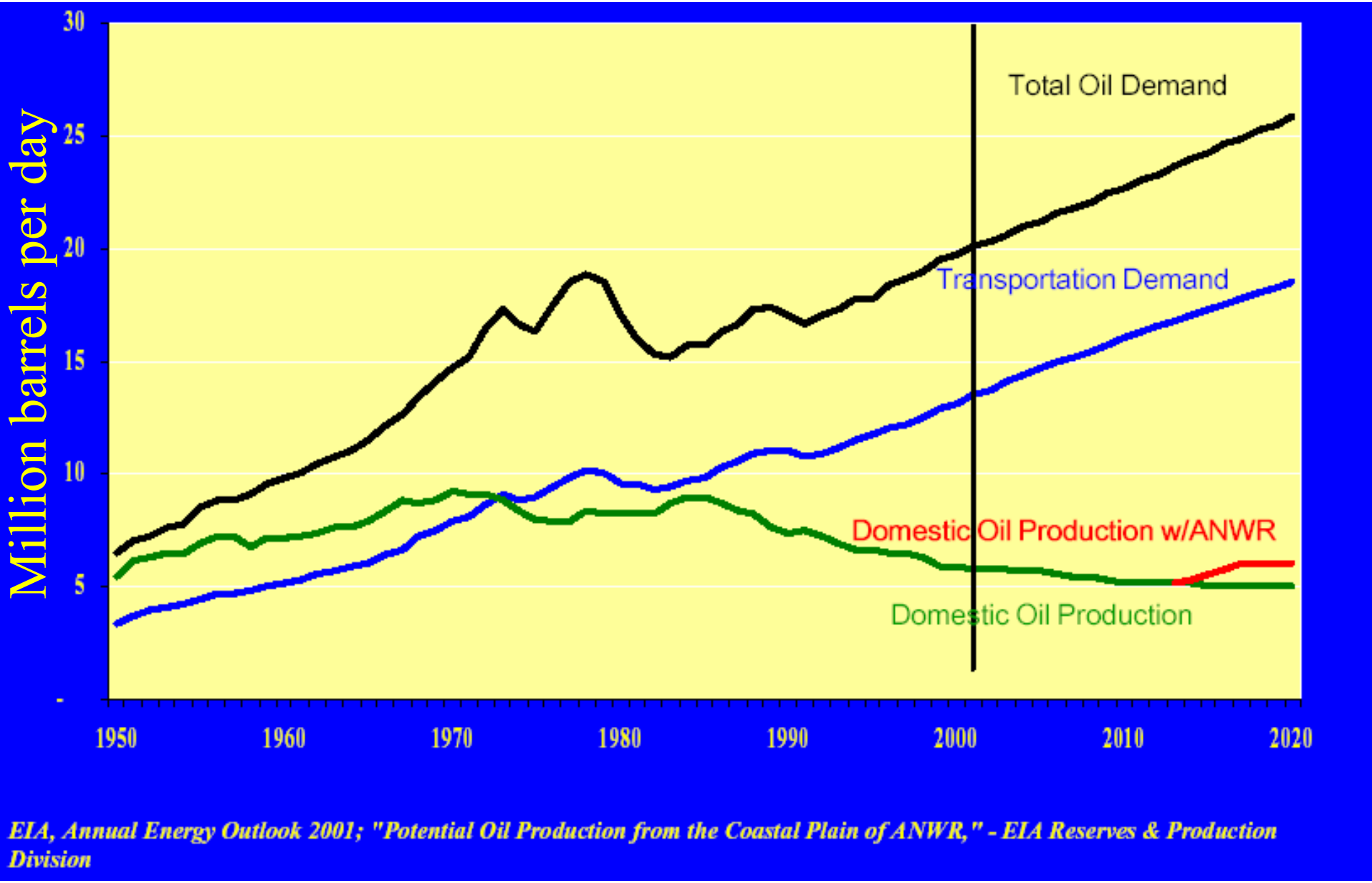
Emerging challenges to this supply?

Oil is easy to move and trade



BP 2004

US oil consumption: Large (~25% of global) & Growing

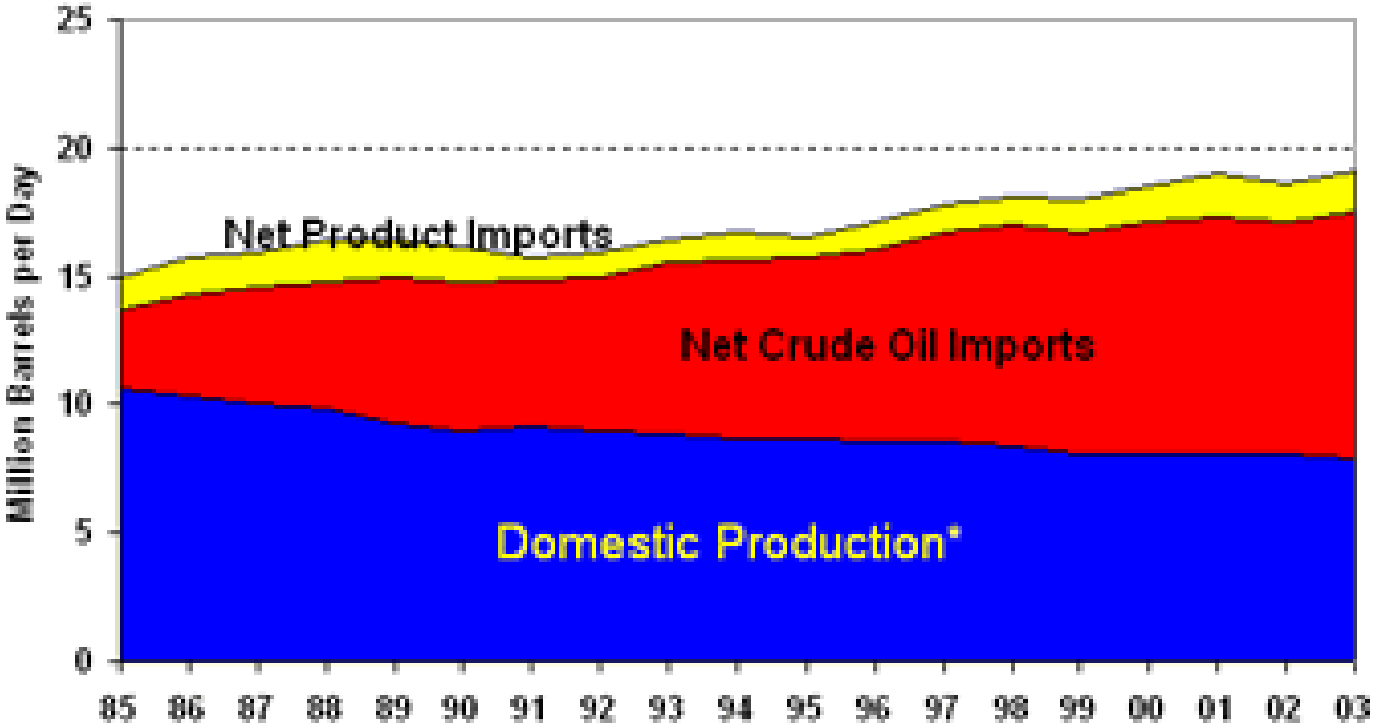


EIA, Annual Energy Outlook 2001; "Potential Oil Production from the Coastal Plain of ANWR," - EIA Reserves & Production Division

Problems with business as usual

- **USA imports 2/3 of oil it uses**
- **Share of imported natural gas is set to increase rapidly**
- **Market saturated, volatile, unstable**
- **Producing nations are unstable**
- **CO_2 emissions → global warming**

US imports ~2/3 of its oil

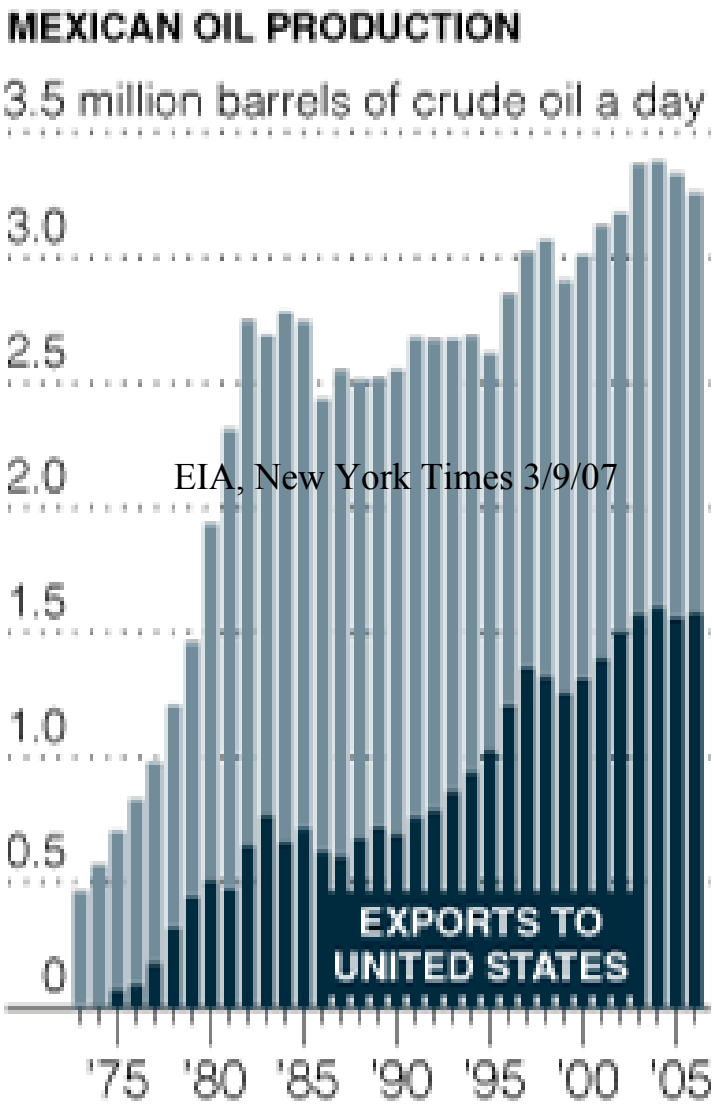


Friendly nations cannot fulfill our oil needs

Middle East:	2.5 M barrels	Canada	2.2 M barrels
Africa:	2.4 M barrels	Mexico:	1.4 M barrels
Russia:	0.4 M barrels	Venezuela:	1.3 M barrels
		North Sea:	0.7 M barrels

(EIA 6-12/06)

Decline in production in friendly nations

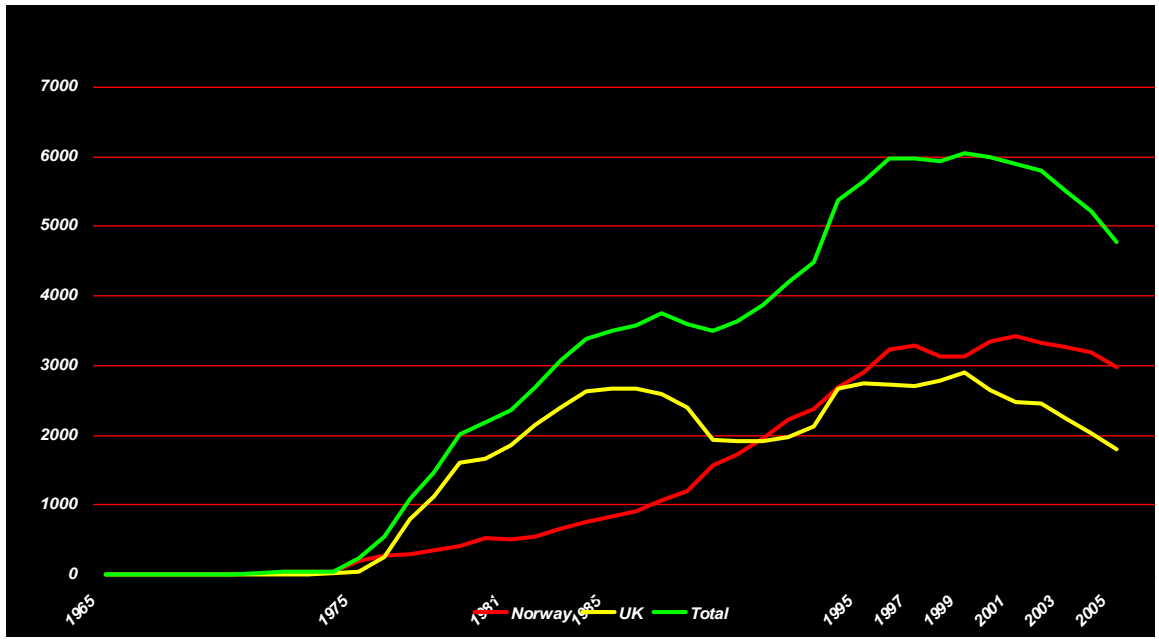


EIA, New York Times 3/9/07

North Sea (UK, Norway)

Peaked in 1999 at 6.05 million bbl/day.

1999-2005: average decline at 3.4% to 4.8 million bbl/day in 2005

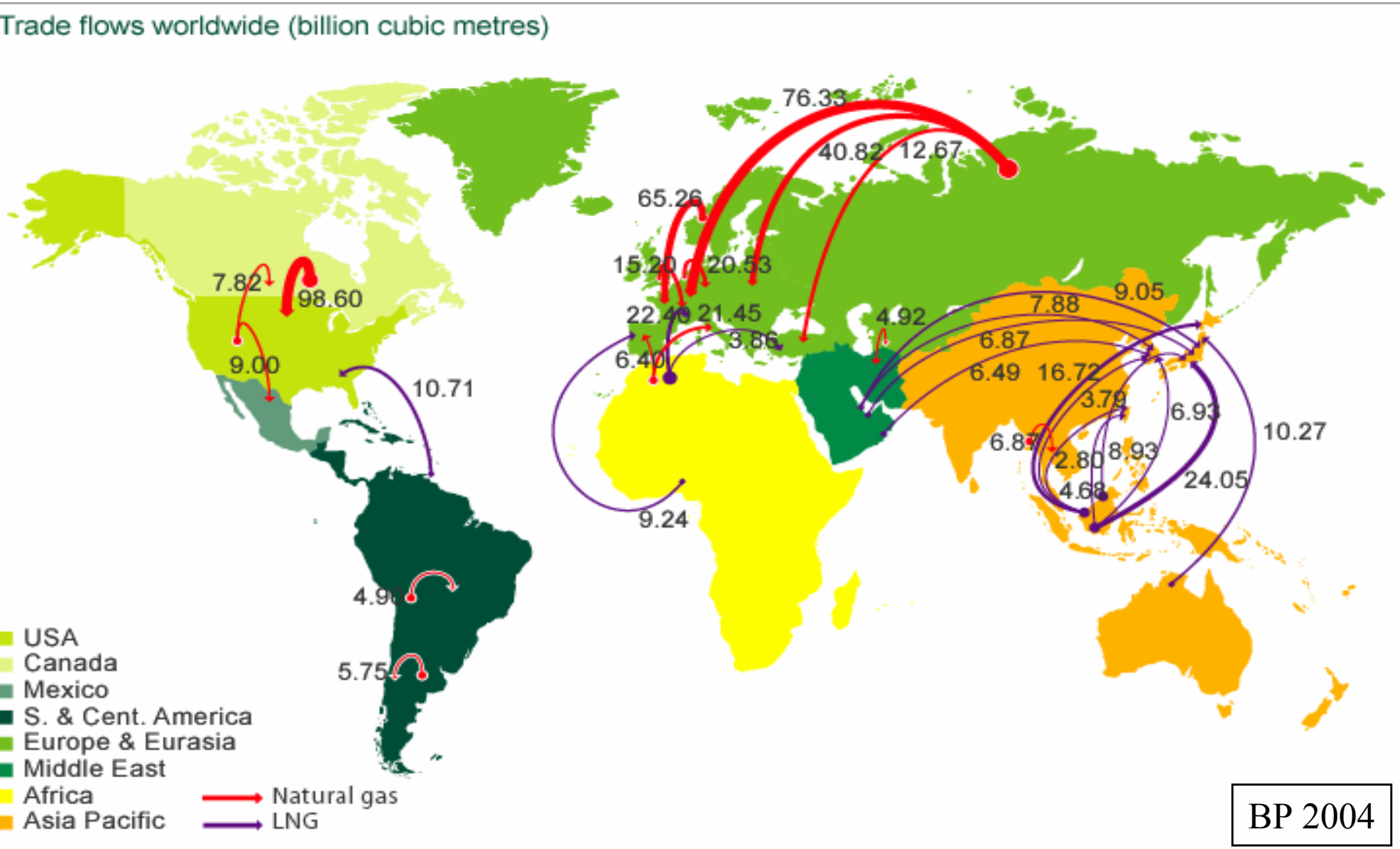


BP Statistical review

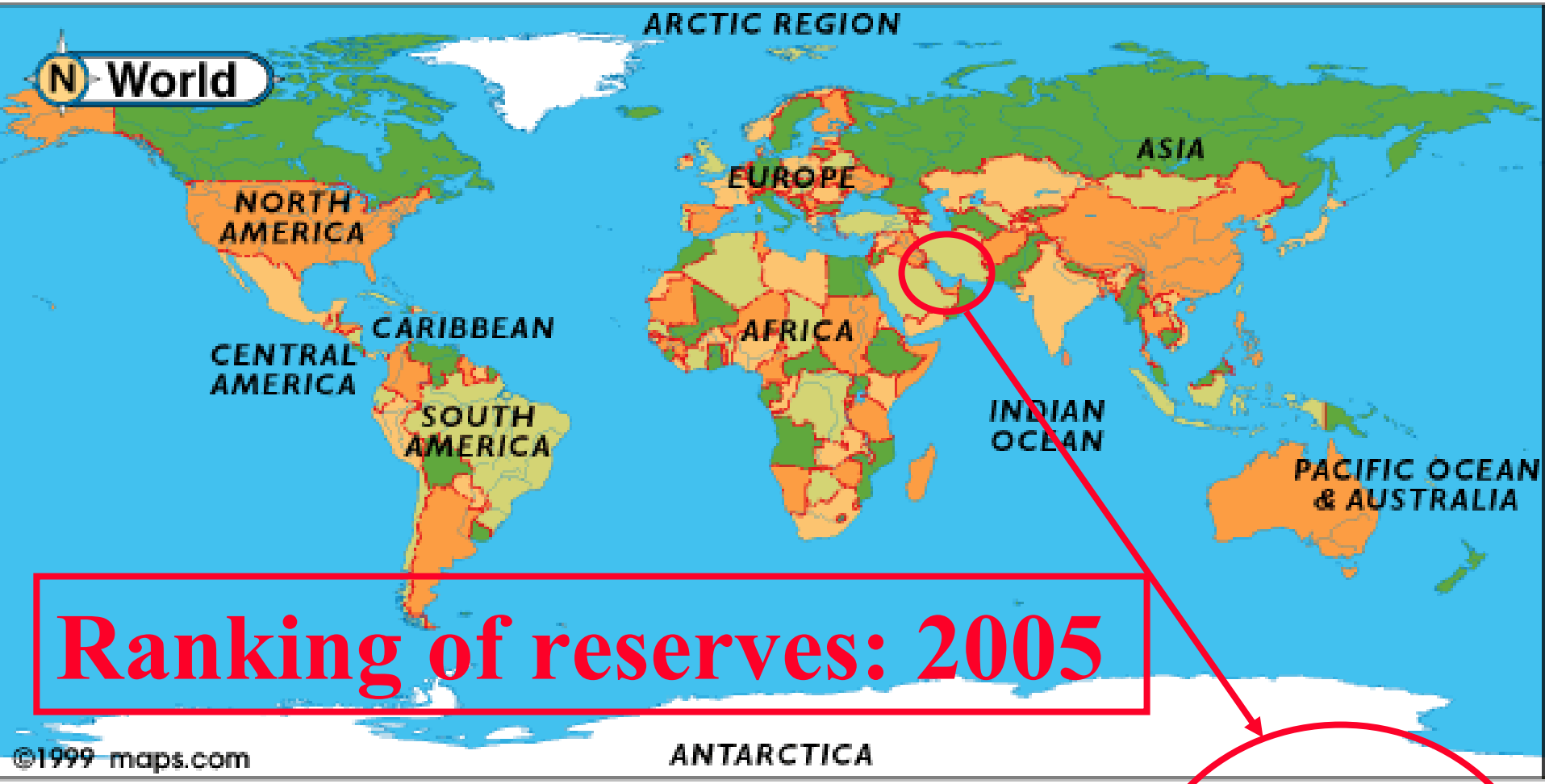
INVESTMENT

Peak Oil

Major natural gas trade movements



BP 2004



Ranking of reserves: 2005

USA 12,6,1

China 11,-,3

EU -, -, 4

Russia 8,1,2

India -, -, 5

AT -, -, -

Persian Gulf

OIL 1,2,3 4,5

GAS 2,3,4, 5,10

No Coal

Fast forward to 2020

USA ?,-,1

China -,-,3

EU -, -, 4

Russia ?,1,2

India -, -, 5

AT -, -, -

? → EOR

Persian Gulf

OIL 1,2,3 4,5

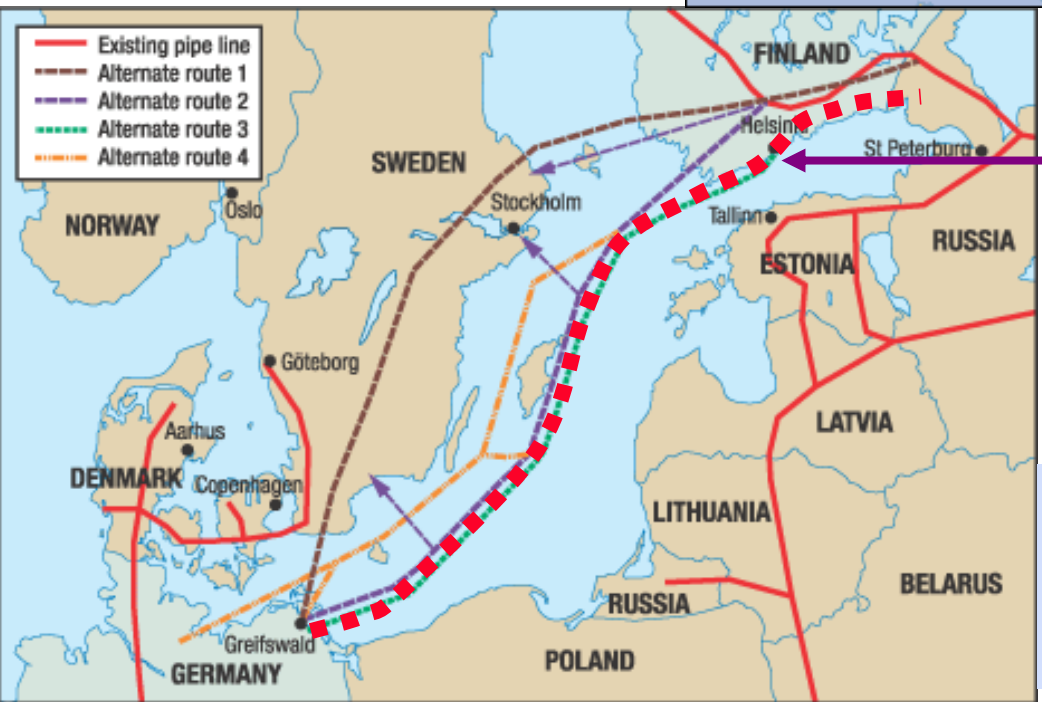
GAS 2,3,4, 5,9

No Coal

5. Middle East and Russia control conventional natural gas and oil


Who gets CA, Russian oil and gas?
She who owns the pipe lines?
To North America
Murmansk
Bering Sea
Severomorsk
St Petersburg
Arkhangelsk
To Western Europe
Moscow
West Siberian plain
Central Siberian plateau
Yakutsk
Kamchatka
URALS
Ufa
Perm
Surgout
RUSSIA
KOVYKTA GAS FIELDS
SAKHALIN-I
SAKHALIN-II
De Kastri
South Kuril Islands
Sokorodino
Prigorodnoye
Khabarovsk
HOKKAIDO
Omsk
Tomsk
Novosibirsk
Krasnoyarsk
Taishet
Angarsk
Lake Baikal
Irkutsk
To Western Europe
Atyrau
Kenkiyak
Caspian Sea
Aral Sea
Atasu
KAZAKHSTAN
UZBEKISTAN
TURKMENISTAN
Alashankou
Karamay
Dushanzi
Urumqi
XINJIANG-UIGHUR
MONGOLIA
Ulan-Bator
Daqing
Harbin
Shenyang
Nakhodka
Vladivostok
Perevoznaya
JAPAN
NORTH KOREA
SOUTH KOREA
HONSHU
Beijing
Tianjin
Jinan
KYRGHIZSTAN
TAJIKISTAN
AFGHANISTAN
IRAN
Towards Pakistan and India
Strait of Hormuz
PAKISTAN
TIBET
CHINA
ZHEJIANG
Shanghai
Pacific Ocean
INDIA
NEPAL
BHUTAN
TAIWAN
Senkaku archipelago: gas exploration in the east China sea
0 500 1000 1500 2000km
Energy-producing countries
Countries that want energy resources from Russia and central Asia (and need energy because of fast, strong economic growth)
Disputed frontiers
Major gas and oil exporting projects under construction
To the east
In use
To the west
In use
Existing oil and gas routes (renovated Soviet network) in the Urals and west Siberia, towards points that link with projected oil and gas pipelines
Break in transit: oil carried in tankers
Refineries
Permafrost
Proven oil and gas reserves
Oil
Gas
PHILIPPE REKACEWICZ

Which countries will get Russian natural gas in 10 years time?



New pipeline from Russia to Germany bypasses Ukraine and Eastern Europe

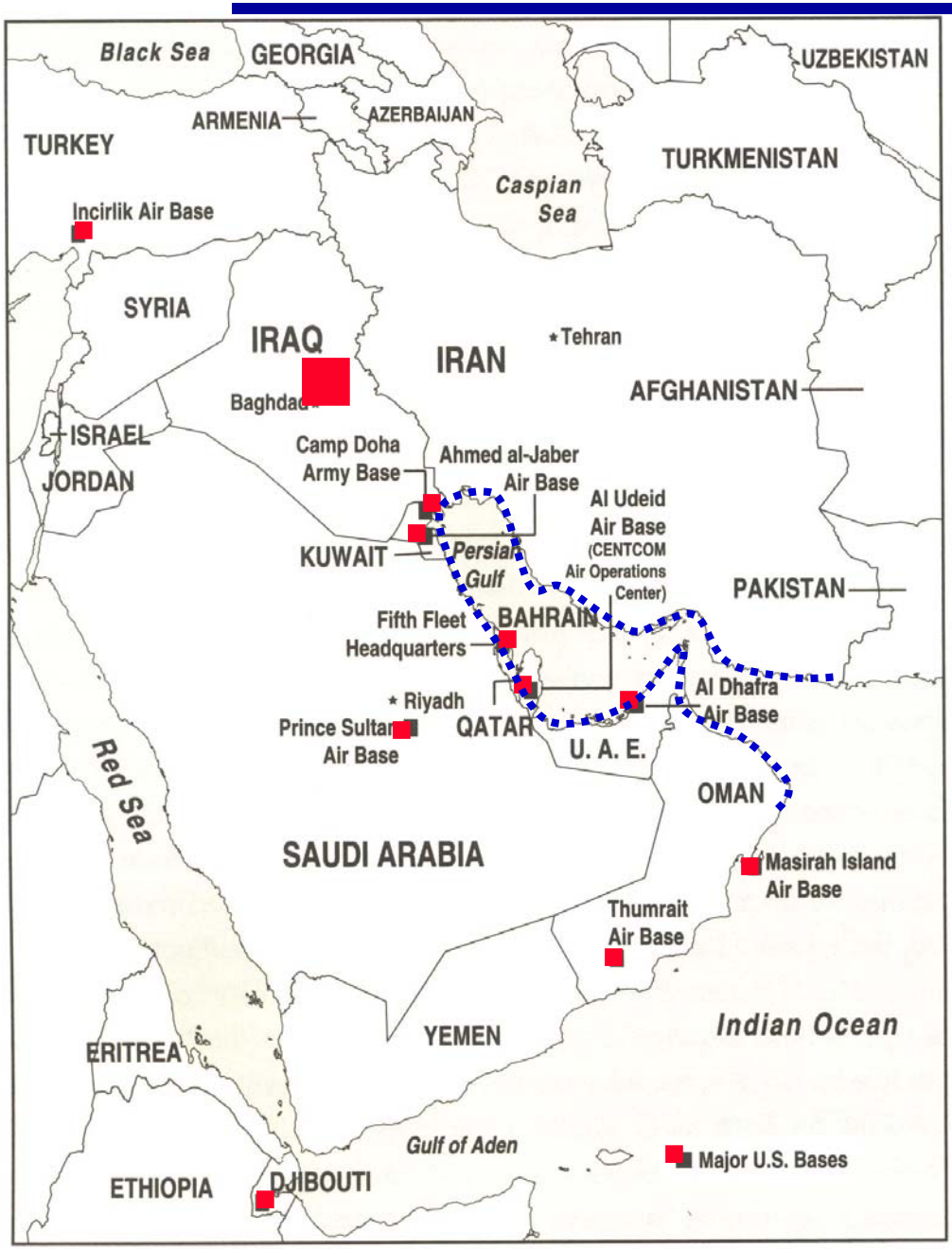
Natural destination is Europe & Asia

6) The global oil (gas?) situation has been anticipated by the US and has guided its policies since WWII

Oil: key driver of foreign policy

- 1945
  - F. Roosevelt and King Abdel Aziz “oil for security”
- 1947: Truman Doctrine
  - Stop the spread of communism (Greece, Turkey, Iran)
- 1957: Eisenhower Doctrine
  - Protect friendly interests
- 1969: Nixon
  - Protect interests through surrogate friendly rulers
- 1980: Carter Doctrine
  - To protect Saudi Arabia and the free flow of oil from the Persian Gulf
- 1983: Establishment of Central Command
  - Protecting the free flow of oil from the Middle East and Central Asia

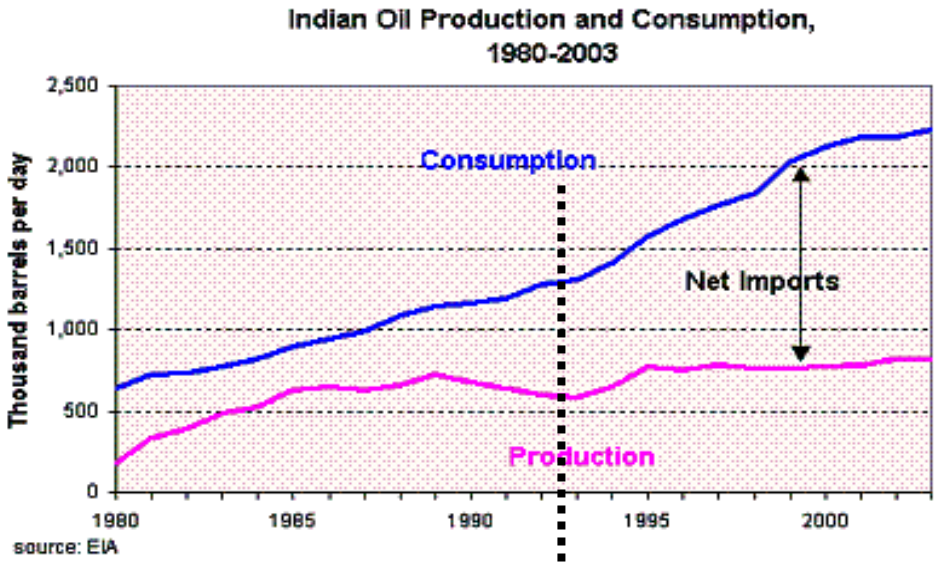
US bases in the Middle East

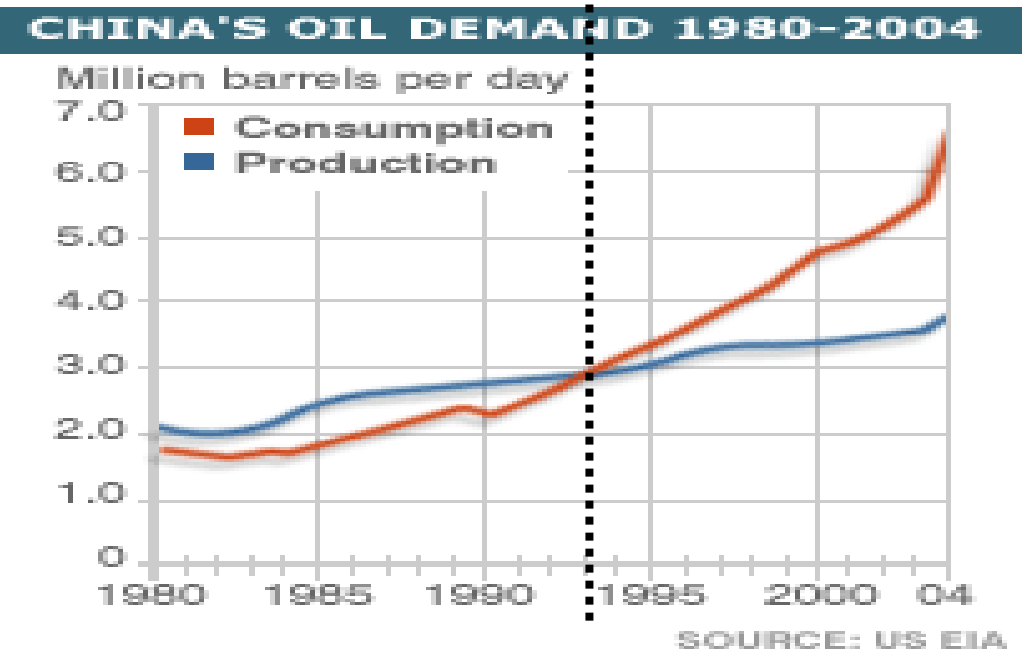


A very successful but costly military investment to protect the flow of oil (=prosperity)

6. Can we continue to bank on this solution?

7. Increasing competition for oil and gas



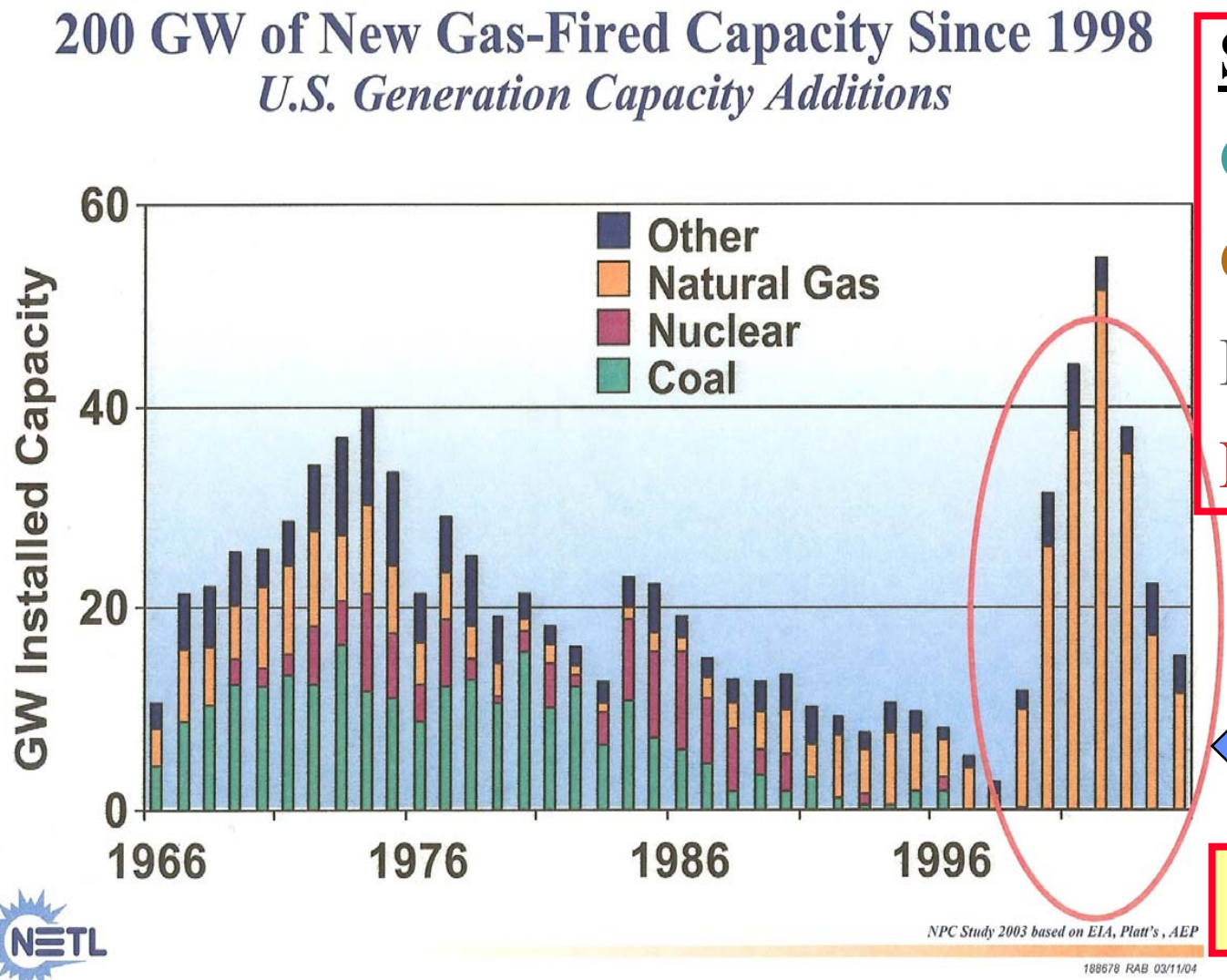


China & India are making deals with Iran, Sudan, …

Oil Imports 1994-2004	
USA	+4% / year
Japan	-1% / year
India	+8% / year
China	+31% / year

8) Will coal or natural gas or nuclear or solar dominate power generation?

See 2007 MIT study on the Future of Coal



Starting in 1980s

Coal was dirty

Gas was cheap

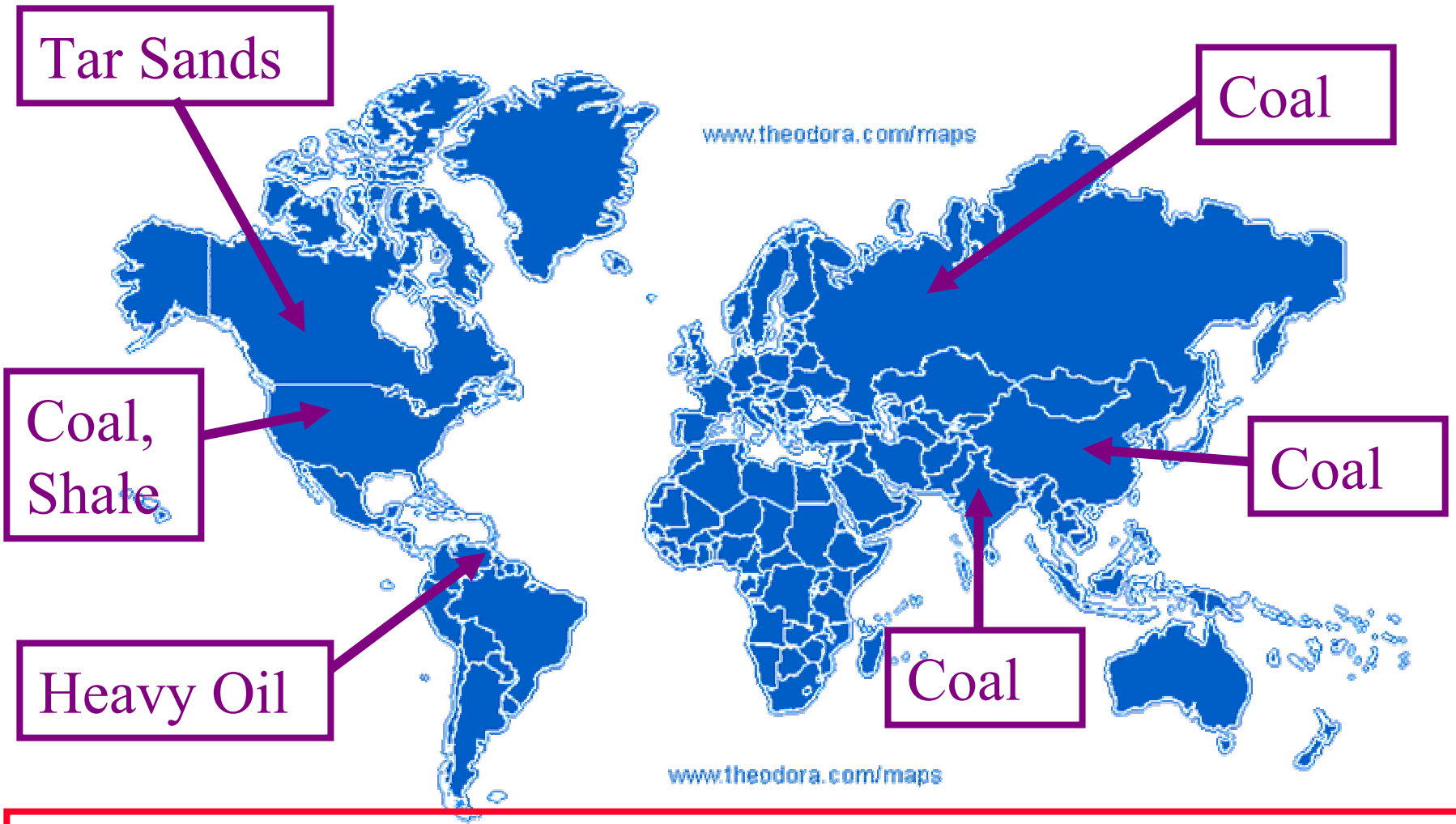
Hydro was flat

Nuclear was bad

Gas

Need cheap gas

Unconventionals: Large reserves



Problem: pollution, environment, CO_2

To use "coal" the US must lead the world by innovating clean coal technology for generating electricity and producing oil

Navajo Power Plant (4 corners NM)

– pollution

Need R&D to – CO_2

Worldwide > 1 TW of new coal PP in next 20 years

FutureGen (No emissions)
10+ years away

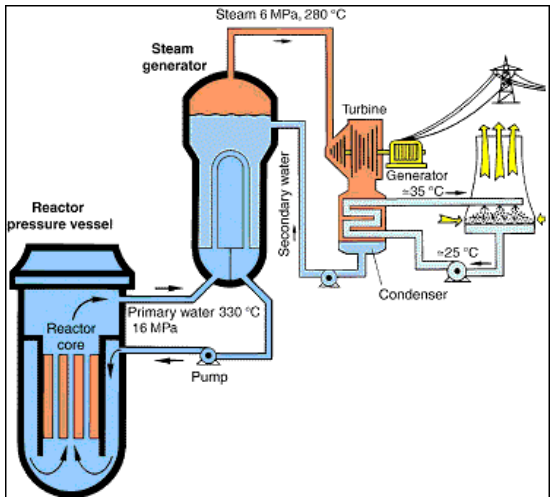
Nuclear power: "CO_2 clean"

- Principles of nuclear fission are known
- Natural ^{235}U is limited
- Rapid scale up requires R&D

- Closed fuel cycle
- Gen IV reactors
- Breeder reactors
  - $^{232}Th \rightarrow {}^{233}U$
  - $^{238}U \rightarrow {}^{239}Pu$

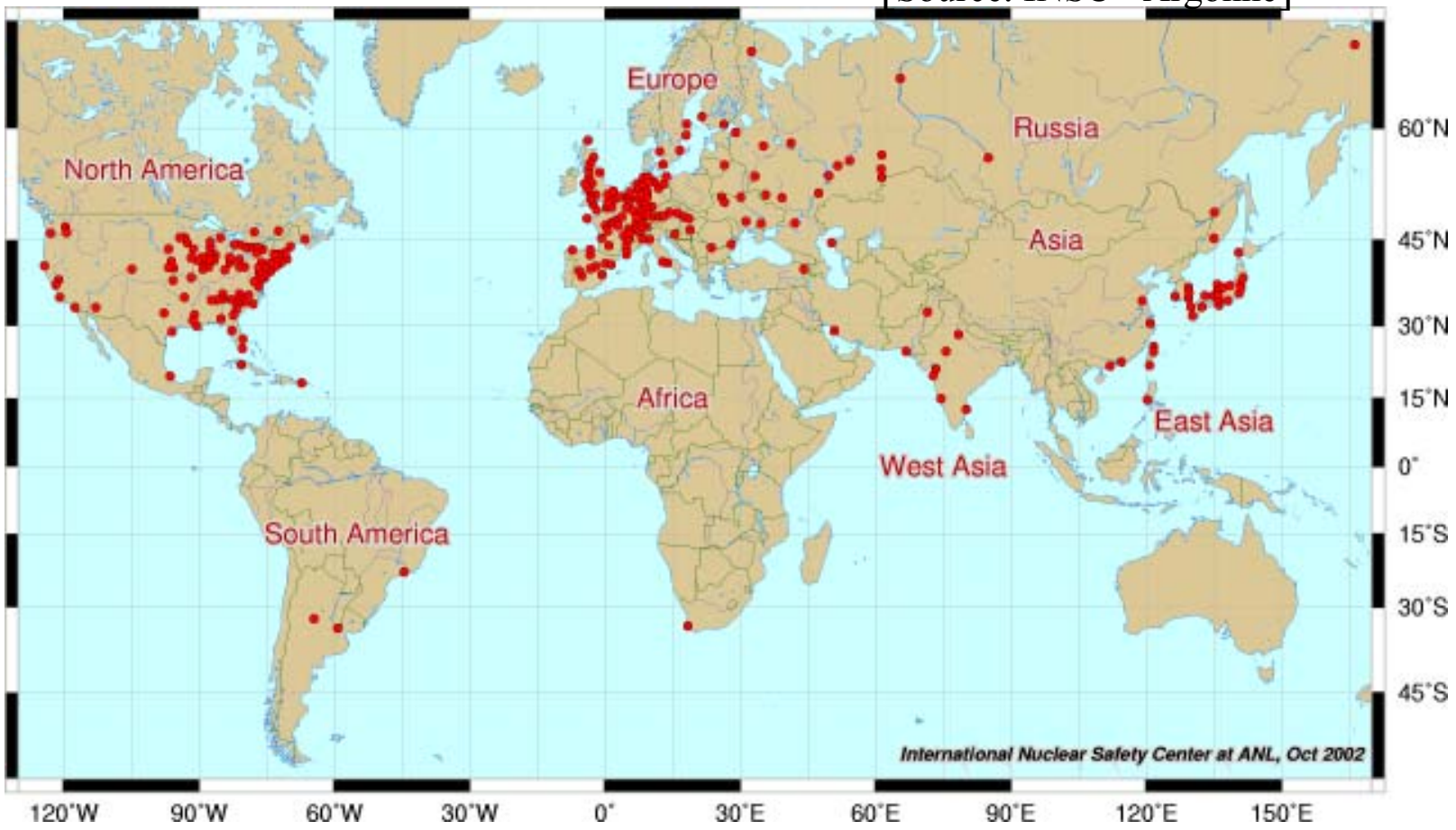
- Fear of accidents
- Proliferation
  - HEU, ^{239}Pu
- Waste management

Not in my backyard



400 Nuclear Power Reactors

[Source: INSC - Argonne]



To replace 10 Terawatts by nuclear power would require 10,000 one GW plants – 1 new plant a day for 30 years.

Don't have enough nuclear scientists or engineers

8) Power generation

Urgent need for timely action:

Need 10-15 years to plan, build and understand costs of commercial plants

What we build today will have a lifetime of 40-70 years (through much of 21st century)

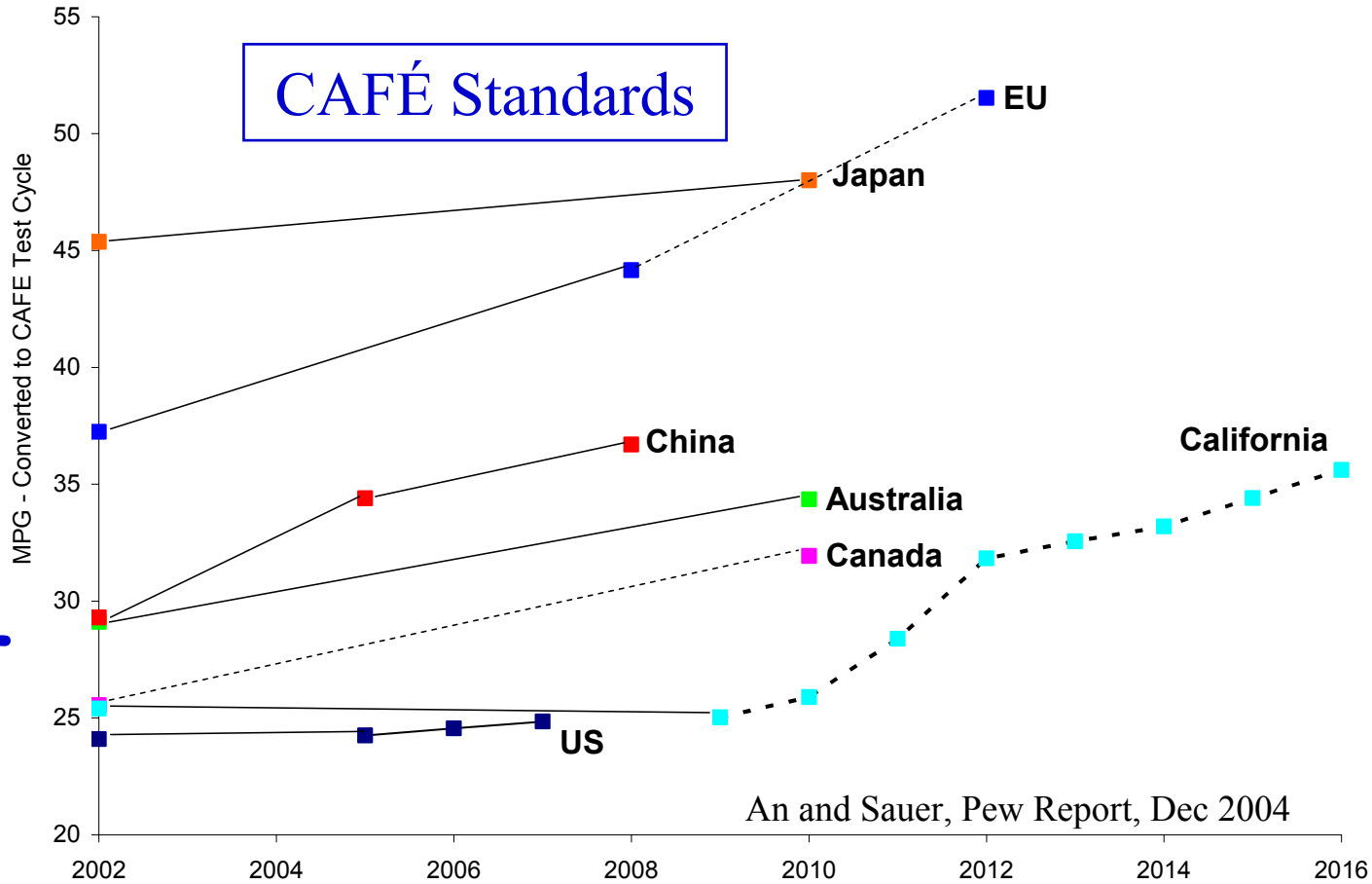
China (and soon India) will build ~1 GW coal power plants a week for next 10 years

9) While people argue about their favorite "solution" (each has drawbacks & potential), there is consensus on *energy efficiency*

A factor of ~50% improvement possible with today's technology

Short term Option: Behavior Change

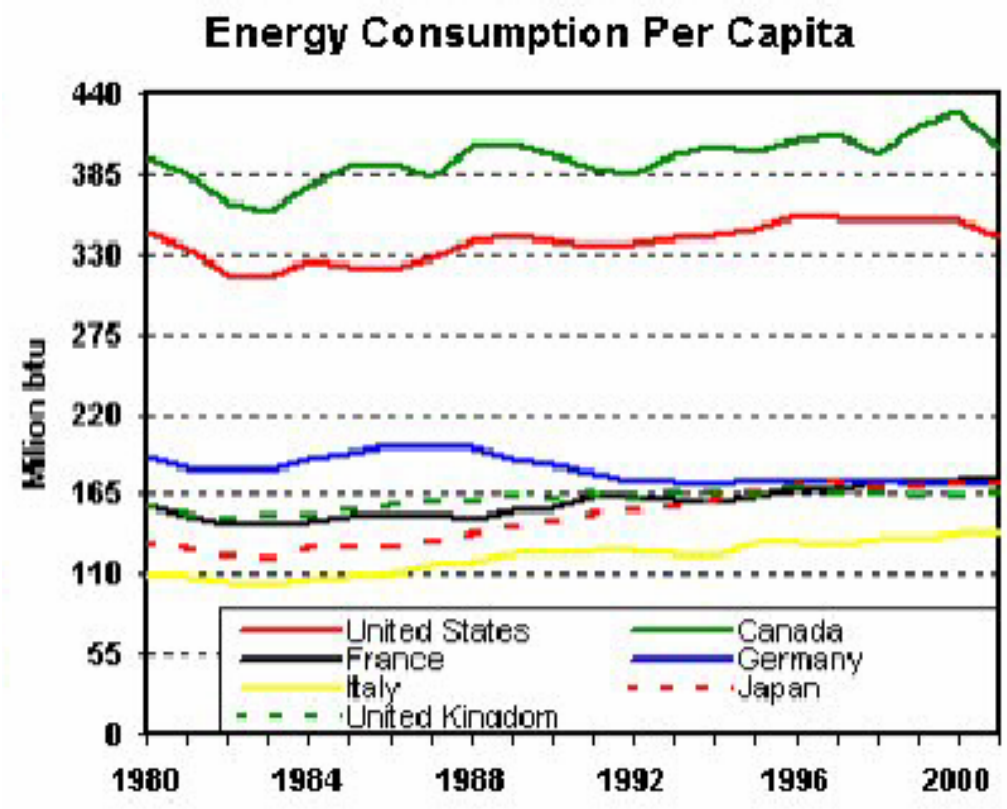
- Lighting
- Appliances
- Heating
- Cooling
- Transport



Drive less and Drive fuel efficient cars

Tanzania: fruit seller - flame [above]; 1-watt white LED [below]
Source: Art Rosenfeld

The US should lead the world in energy efficiency



Cannot have cheap clean energy for all (at tera scale) without key S&T R&D

- Separation/capture of CO_2 from mixed gas streams
- Secure and effective long-term storage of CO_2.
  - Geologic, mineralization, …

} **CCS**

- Hydrogen from water without using fossil energy:
  - Electrolysis of water (inexpensive and efficient electrodes)
  - Photochemical and/or thermo-chemical splitting of water
- PV, CSP ($1/watt & 100+ GW/year production)
  - nano and/or bio PV materials & systems integration
- Closed nuclear fuel cycle and advanced reactors
  - separation of SNF, transmutation, fuel reassembly, waste
- Fusion?

No large scale (1 TW) deployment in next 20 years

No source is intrinsically good or bad or clean or dirty. It is a lifecycle systems issue

	Gasoline	*Nuclear*	*Solar today*
1) Cost	✓	✓	✗
2) Density	✓	✓	✗
3) Storage	✓	✓	✗
4) Portability and mobility	✓	✓	✗
5) Scale	✓	✓	✗
6) Unintended consequences	✓	✓	?

The need is so large that we will exploit *all* sources. Must close the cycle, determine realistic lifecycle costs and think equity if we want cheap clean energy for all

Summary

- **Need for modern energy is global**
- **Access should be a global right**
- **Environmental impact is global**

To have affordable access by all <u>and</u> to mitigate environmental impacts we must address the energy challenge as a global responsibility

Energy Security

= National Security

= Economic security

= Environmental Security

= Future of our children

Senator Lugar: "energy is the albatross of U.S. national security"

Brookings: 13 March 2006

Industrialized nations must lead the R&D for clean and affordable energy NOW (= hope for all mankind)

The poor are most vulnerable to climate change and will not have the resources to mitigate the impacts

Hope versus Hunger

As a civilization we understand the threats and we have tools to deal with them

Will we grow the will and act in time?