What will the global energy landscape look like over the next 50 years?

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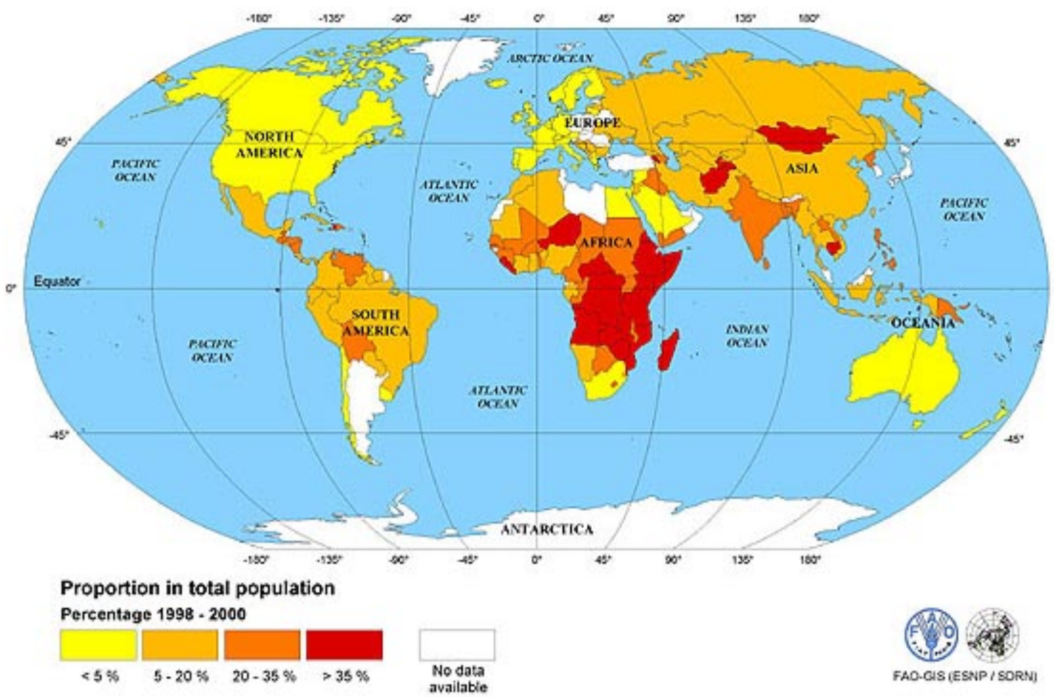

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Summary

This talk summarizes the transformations in energy systems that have taken place in the last 10 years and examines the evolving energy needs and supplies. Based on development needs, resource, infrastructure and technology constraints I outline a scenario of what the energy landscape will look like over the next 50 years.

History in Making:

The youth are demanding meaningful jobs, a better quality of life & better governance

How will countries create jobs and develop areas of comparative advantage for trade?

How will countries fuel their development and mitigate climate change?

History in Making:

The youth are demanding meaningful jobs, a better quality of life & better governance

How will countries create jobs for 7+ billion people and develop areas of comparative advantage to sustain trade and development?

How will countries fuel their development and mitigate climate change?

Context of these lectures

- Development
- Energy Security
- Pollution and Climate Change

The Energy-Development-Environment-Climate Challenge

Energy is a primary driver of development: All energy resources will be utilized as they become economical or are subsidized

- The goal is to optimize portfolio over
  - Indigenous fuel, water, mineral resources
  - Regional resources (Regional trade)
  - Minimize environmental impact
  - Mitigate climate change (reduce GHG emissions)

The cost of large-scale fuel or energy systems imports will remain high → countries vulnerable to geo-politics

Developing a credible roadmap to GHG-neutral systems

- Focusing on "peak-oil", declining oil/gas/coal/U resources in one field, one country, etc., is not a compelling strategy. There is plenty of economically accessible fossil fuel for the next 50 years for global need.
- There are compelling forces driving choices countries make
  - Energy security
  - Cost
  - Economic development
  - Easily available fossil fuels
  - Technology
  - Uncertainty of and unfamiliarity with emerging options
  - Social and political pressures
- There is no free lunch. Society must develop a coherent/realistic framework
  - What risk society is willing to accept with respect to impacts of a given energy system
  - What time-evolving adjustments society is willing to make if environmental degradation and climate change is an unacceptable risk

Developing a credible roadmap to GHG-neutral systems

- All forms of energy will be exploited. $$$ talk & underlie sustainability
- There is plenty of easily accessible fossil fuels for the next 50 years globally.
- Define acceptable risk and environmental impact for each energy system
- Coal is the most polluting and highest GHG emitter → fuel substitution
- Natural Gas can replace coal and oil. It can be more than just a bridge fuel for the next 30 years. It can foster regional cooperation.
- Natural Gas is globally distributed and can fuel development in large parts of the world and significantly reduce CO_2 emissions from BAU scenarios.
- Developing grid scale storage is the biggest science opportunity and essential for integrating solar and wind beyond ~20%
- Nuclear power has to be part of the large-scale solution – making it safe
- Conservation and energy efficiency must be a high & immediate priority
- Incentivize/monitor energy companies to be environmentally responsible
- Long-term, stable investment in R&D
- Long-term realistic Policy

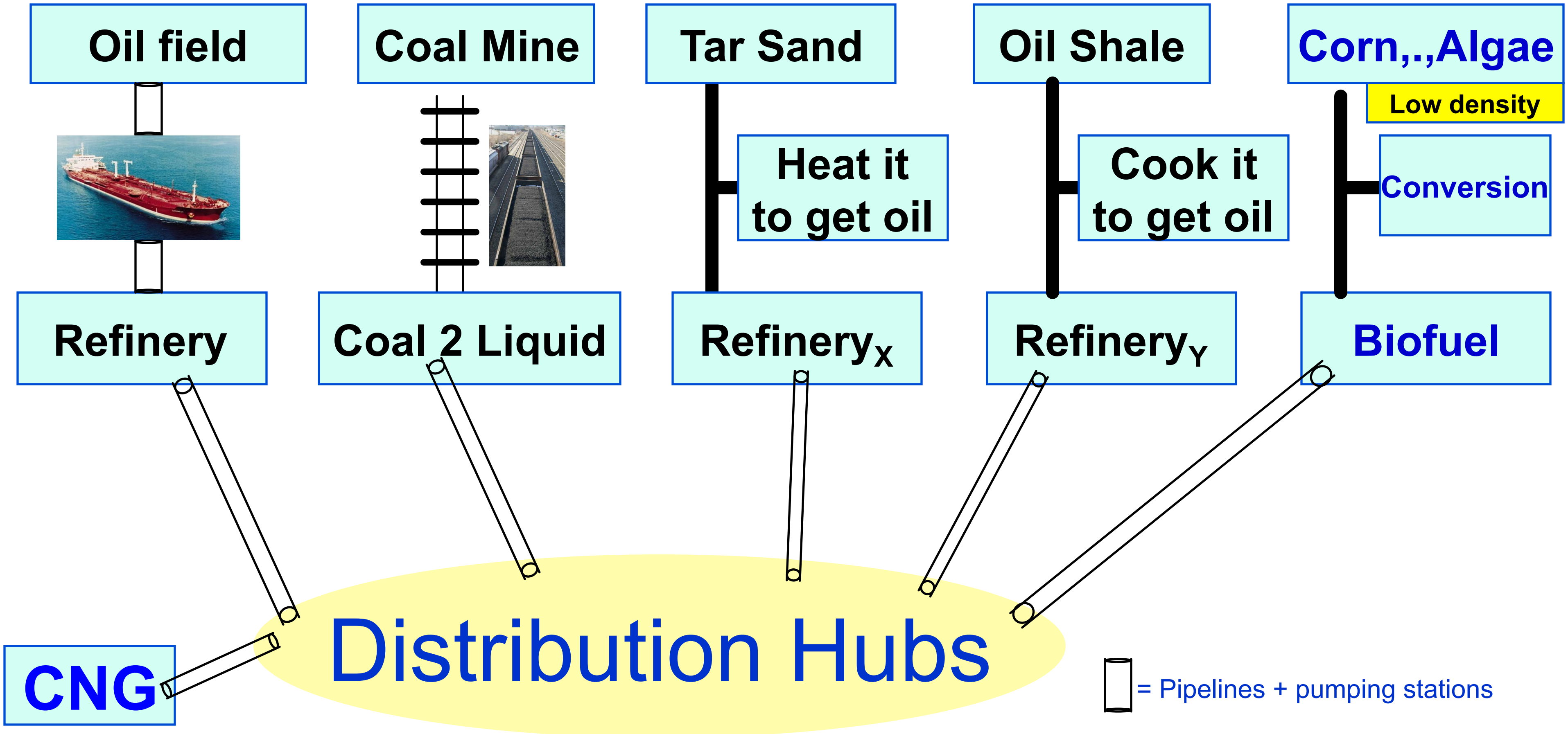
Modern Energy Needs

Transportation Fuels

Electric Power Generation

Heat (buildings, kilns, …)

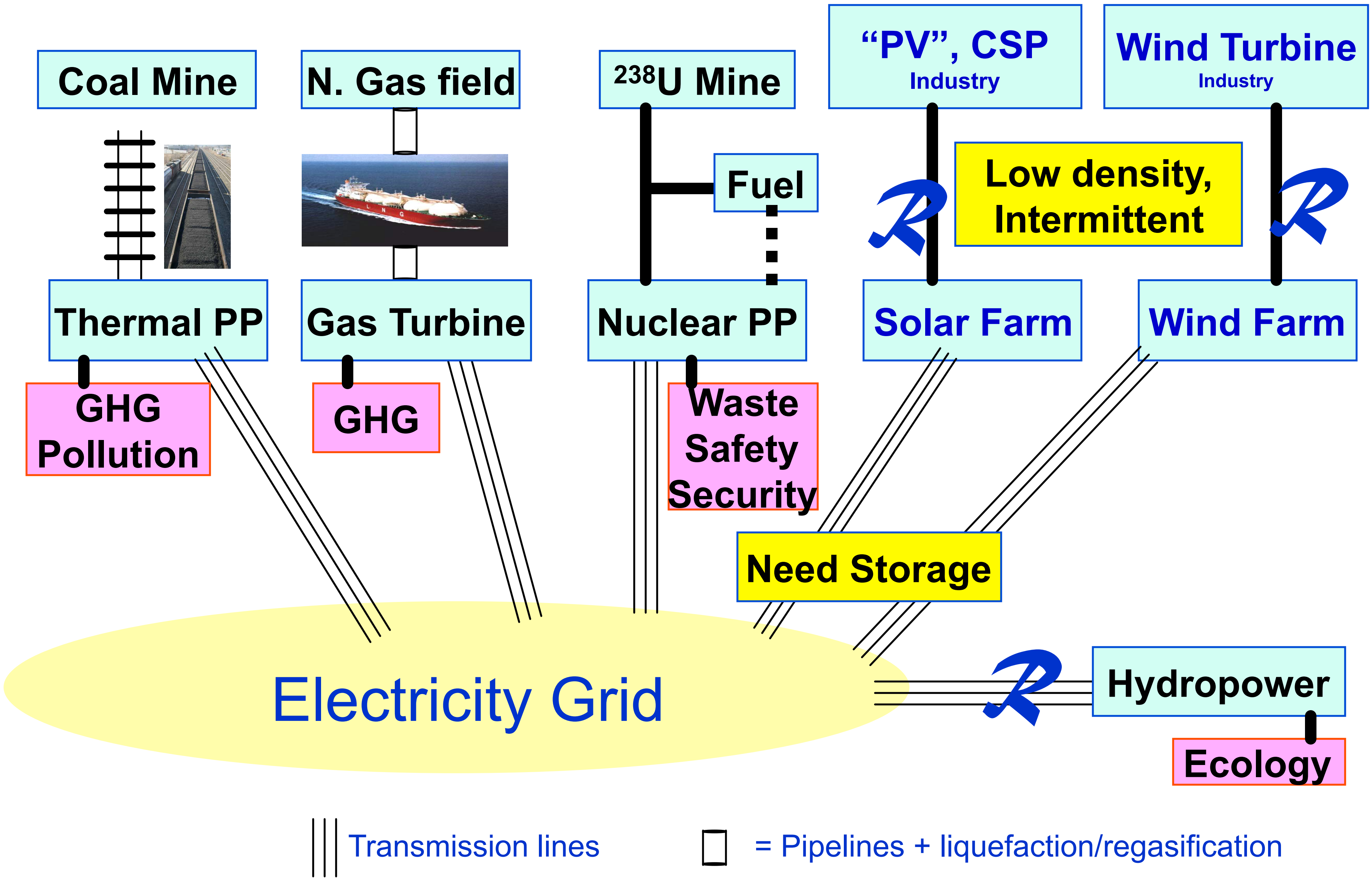
Transportation fuels: Lifecycle Cost Comparison



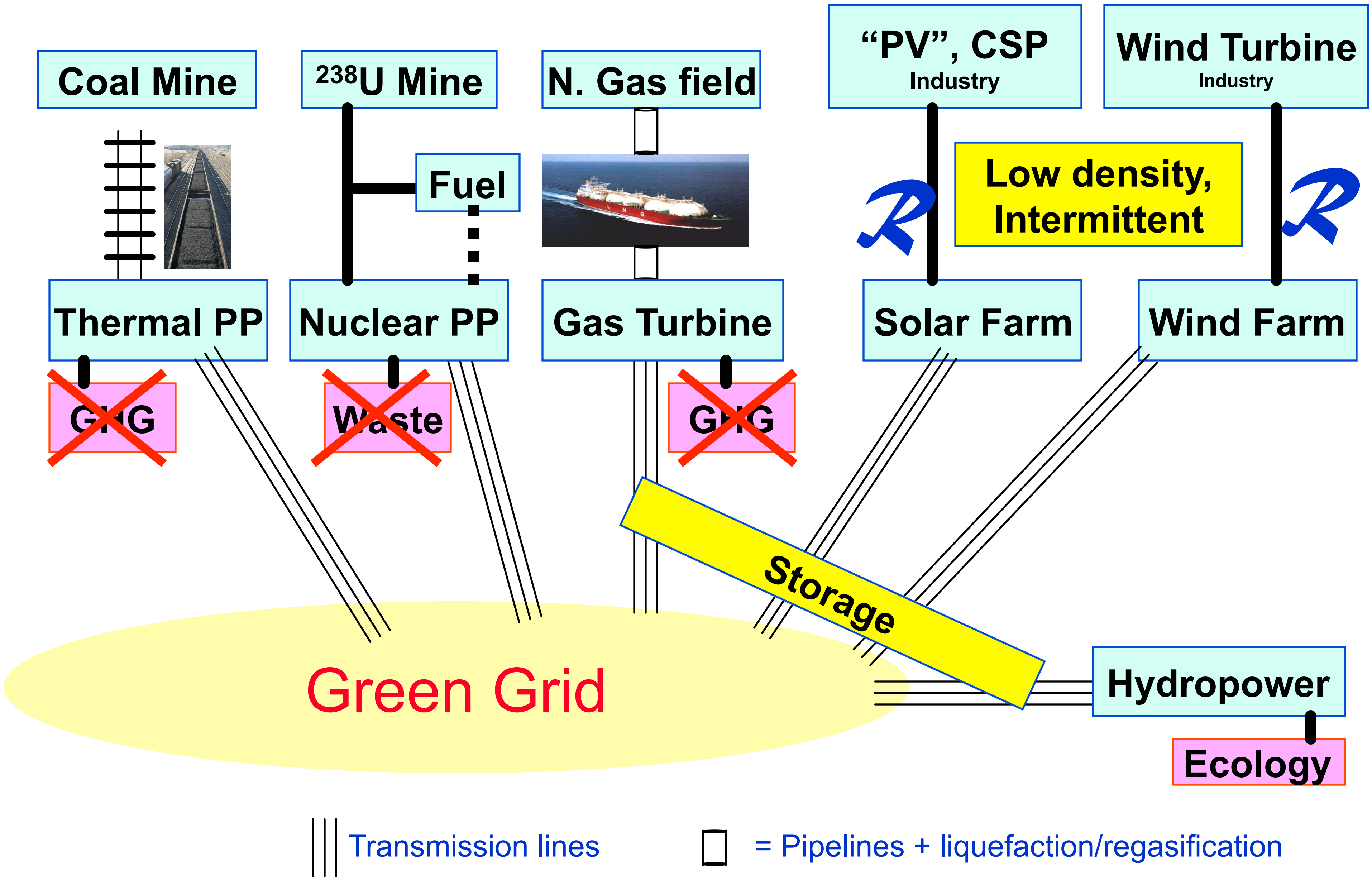
Today ⇒ All Fuels Produce GHG

Future ⇒ [Hybrid] Electric Vehicles

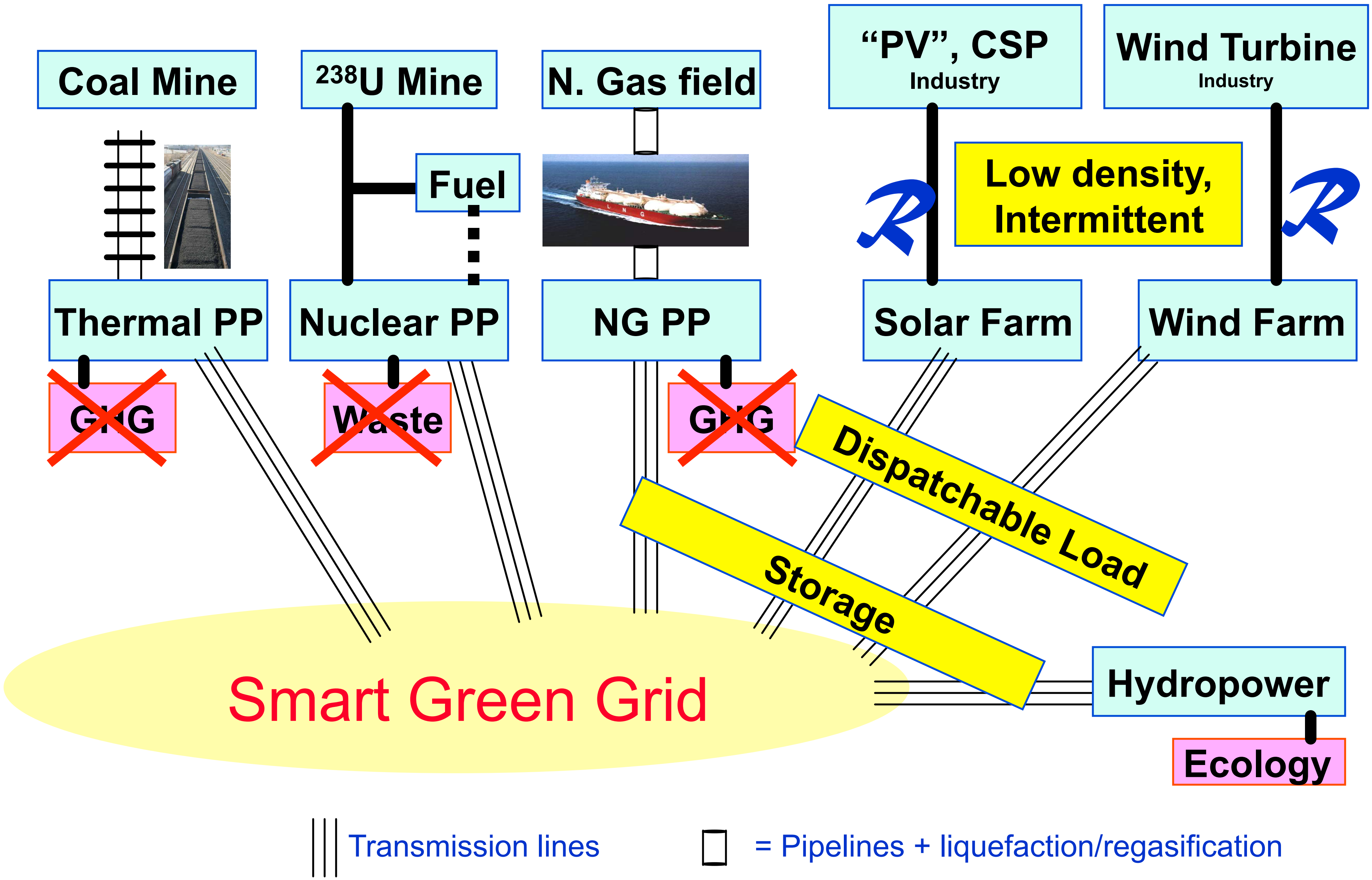
Electric Power System: Lifecycle cost comparison



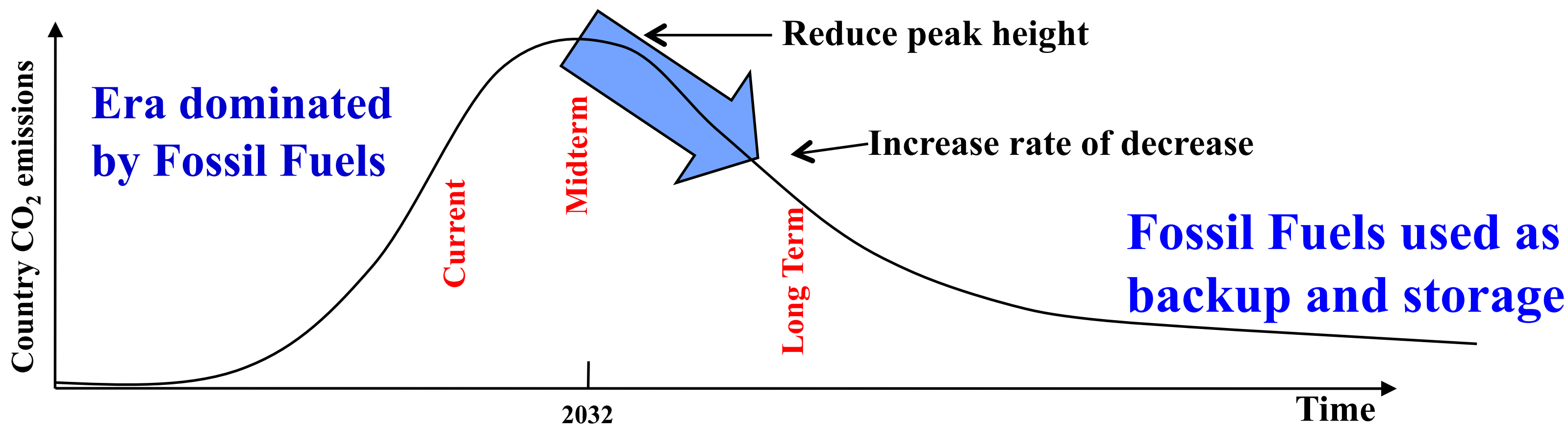
Electric Power System: Lifecycle cost comparison



Electric Power System: Lifecycle cost comparison



Transition to Carbon-Neutral Systems



- Progressively reducing carbon intensity
- Reducing the peak height
- Reaching the peak early in development
- Developing cost-effective carbon-neutral systems to accelerate the transition

Efficiency

Technology

Fuel Substitution

All alternatives to fossil fuels have a market niche

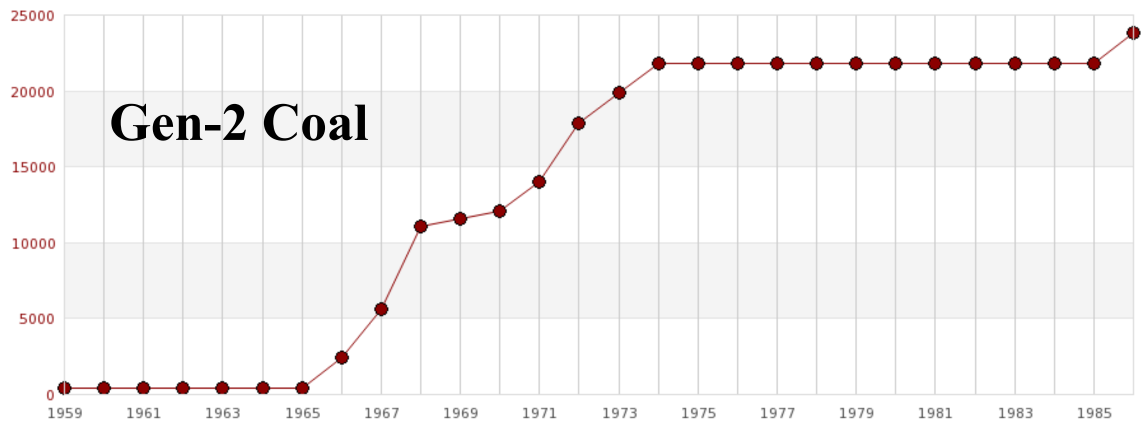
		2010 GW	TWh	Potential
Electric Power	• Nuclear	375 GW	2600TWh	?
	• Hydro	1010 GW	3800TWh	~1500 GW
	• Wind	198 GW_p	400TWh	+~30%/year
	• Solar PV+Th	40 GW_p	60TWh	+~50%/year
	• Geothermal	11 GW	67.2TWh	
	• Fossil	~4000 GW	20000TWh	~5000 GW
Fuel	• Biofuels	<2.0 MM boe/day		?
	• Oil	83 MM bbl/day		?

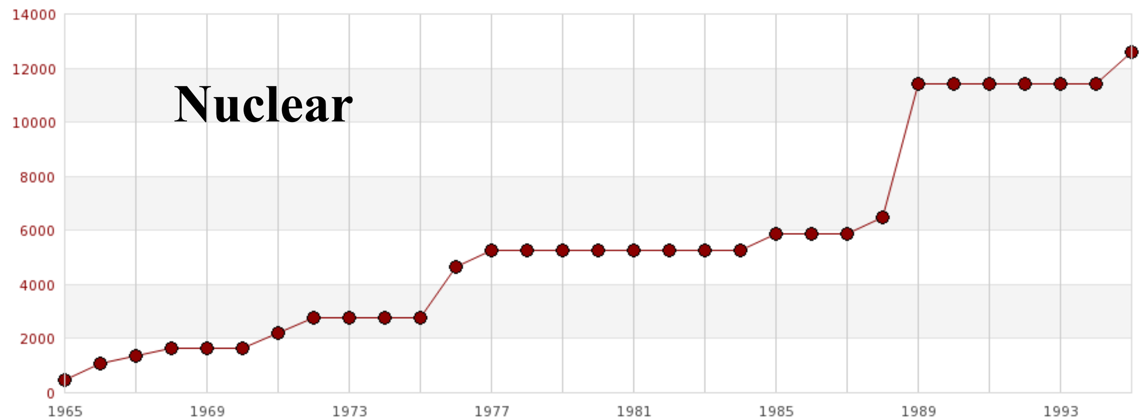
But none is large enough today to meet

World Requirements of 10 [20] TW_e

Need technological breakthroughs

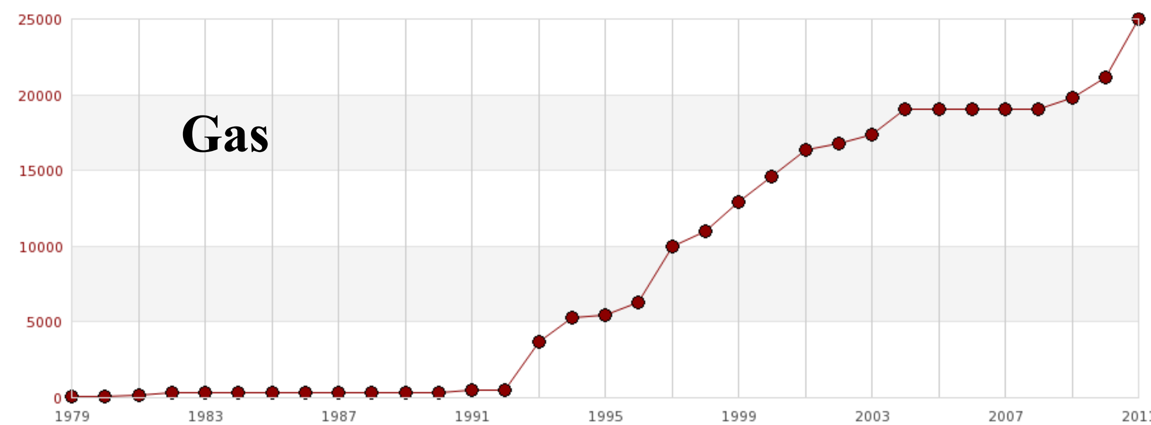
Example: Evolution of UK's Installed Capacity (MW)





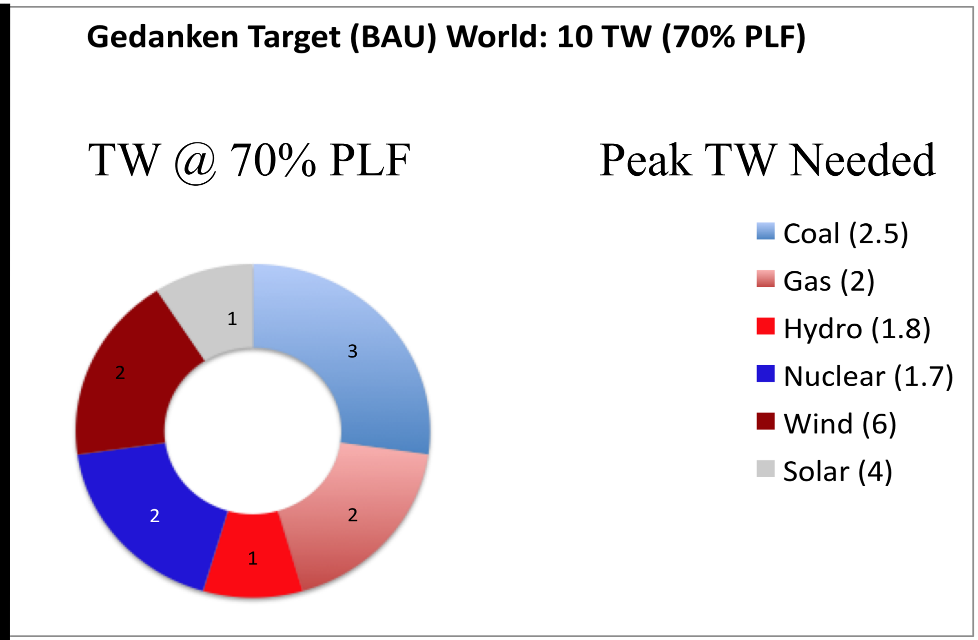
Well-defined Periods of growth aligned with technology and resource growth

→ 30-60 yr lifetime



Compromise Solution: Wedges by 2050 for 10TW electric power & 125Mbo/day

- Need **10 TW** Electric Power:
  - **10 Wedges of 1 TW ←→ 6000 TWh**



- Need **125 mbo/day** Liquid Fuel:
  - **12.5 Wedges of 10** million barrels oil/day

Biofuels: Their contribution may increase to 5 Mbo/day

Estimates based on what historic trends suggest can be done

Technology and Innovation
7 Grand Challenges

- Carbon neutral use of fossil fuels (especially coal)
- Economic Solar & Wind ($1/watt$_p$) + Grid Integration
- Storage and Transmission of electric energy
- Closed nuclear fuel cycle to enable safe, secure, sustainable nuclear energy
- Biofuels ⇐ Pest-resistant, self-fertilizing, low water using, easily degradable biomass
- H_2 / liquid fuel produced from non-fossil sources
  - From Photochemical and/or thermal splitting of H_2O
- Fusion – the ultimate power "source"

"Solution Wedge" Likely / Unlikely by 2030

$$ & Risk
- **Carbon neutral use of fossil fuels (especially coal)**
- **Economic Solar & Wind ($1/watt$_p$) + Grid Integration**

Need
- **Renewable storage of electric energy**
- **Closed nuclear fuel cycle to enable safe, secure, sustainable nuclear energy**

Scale, Impact, R&D
- ***Biofuels ⇐ Pest-resistant, self-fertilizing, low water using, easily degradable biomass***

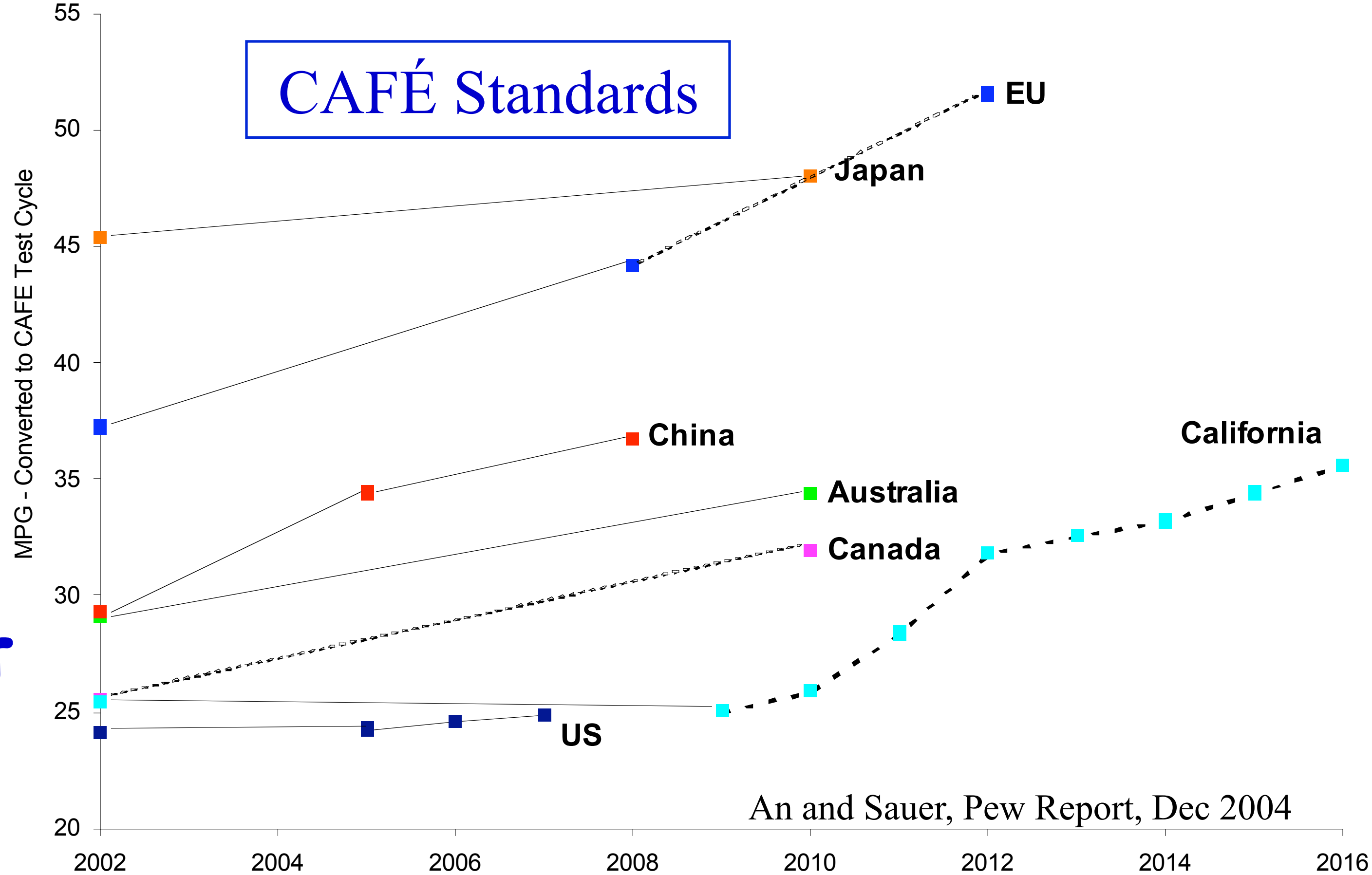
R&D
- ***H_2 / liquid fuel produced from non-fossil sources***
  - *From Photochemical and/or thermal splitting of H_2O*
- ***Fusion – the ultimate power "source"***

Conservation is a very significant low hanging fruit: First Priority

- Can reduce per capita footprint by 25-50%
- Technology exists
- Demonstration examples at scale exist
- Need
  - Education
  - Local expertise for installing and maintaining systems
  - Incentives, regulations (CAFÉ, building codes) and Policy
  - Behavior change

Behavior Change: At Best Incremental

- Lighting
- Appliances
- Heating
- Cooling
- Transport



Drive less and Drive fuel efficient cars

Electric Power and air-conditioning (HVAC--heating and cooling) needs of suburbia can already be met through

- Solar (both PV and thermal)
- Ground source (heat-pump/geo-solar) systems
- Better insulation of buildings

Needs Building Regulations and Codes

Short-term: the US is in a "comfortable" position

- Existing coal and nuclear power plants are paid for.
  No incentive for utility companies to shut them down.
  - Life extension preserves their profits
  - US has the largest coal reserves
  - No hunger to create an enlightened national energy policy
- Large underutilized capacity in gas turbine power plants built during 1985-2004 – no immediate threat/shortage
  - Relies on continued availability of cheap gas (shale gas)
- US has the lowest CAFÉ standards for private cars/trucks
  - Stupid
- Challenge: Manufacturing capacity moved/moving off-shore
  - How long will US lead in innovation without manufacturing capability?
  - Public confidence in safety, security, safeguards of nuclear plants as manufacturing moves to Asia

Anthropogenic Climate Change:

Emissions of Green House Gases

- 2011 Emissions of CO_2 = 32-34 Gigatonnes/year
- 2011 concentrations = 391 ppm

? Natural recycling = 16-18 Gigatonnes/year

- Increase in CO_2 levels ~ 2 ppm/year
- $1^{o}C$ rise in temp ~ 100 ppm (parts per million)

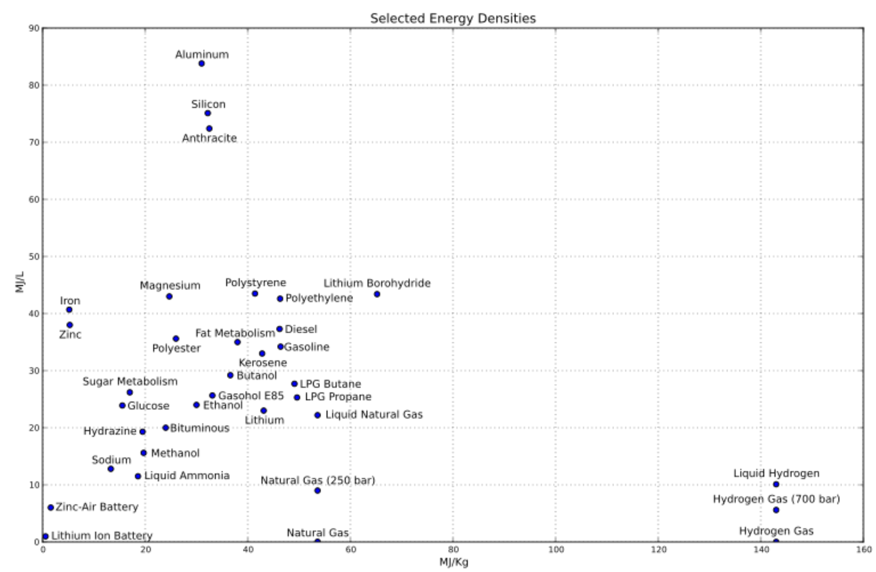
To stabilize CO_2 levels ~ 3 Gigatonnes/year

Requires >90% Decarbonization

BAU: CO_2 Intensity of generation

Fuel (Efficiency)	**Chemical Composition**	**Specific Energy MJ/kg**		**Intensity of Gen. (GT CO_2/TWh)**
Coal (35%)	CH	20-35		~1
Oil	CH_2	46		~0.7
Gas CCGT (57%)	CH_4	54		~0.5
Wood	CH_2	18		

1kWh = 3.6 MJ



http://en.wikipedia.org/wiki/File:Energy_density.svg

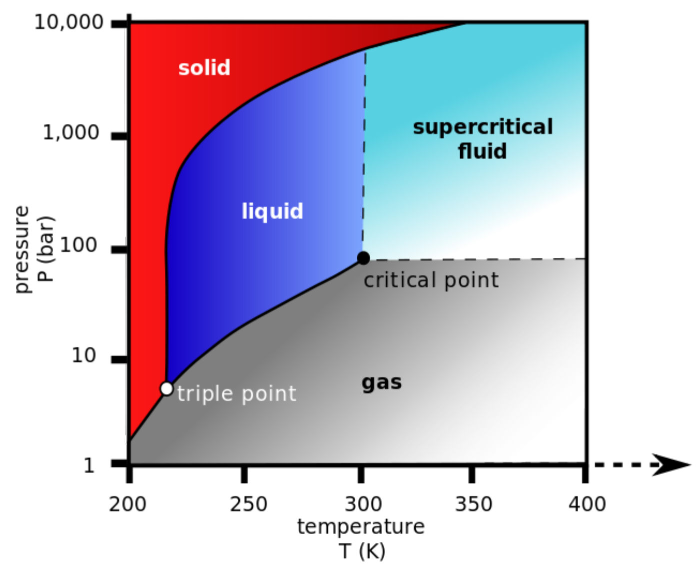
Properties of CO_2

Properties

- Critical point is at
  7.38 MPa at 31.1 °C
- Density 0.77 kg/Liter (liquid at 56 atm and 20 °C)
  1 GT = 1.3 cubic kilometers
- Highest oxidized form of C
- Lifetime in atmosphere is 1000s-10000 years

CCS

- Separation of CO_2
- Compression
- Transport
- Injection
- Monitoring



Determining Acceptable Risk and Environmental Impact

- All economical forms of energy will be exploited
- All energy systems have associated risk and environmental impacts
- Unlikely to have enforceable international laws in the short- to medium-term.
- Societies must define socially acceptable
  - Risk (economic, health, security, safety)
  - Impact on the environment (land, water, air, biosphere)
- Societies must hold companies/governments accountable to negotiated norms & regulations

Coal & Oil are the largest sources of CO_2

- 2011 coal consumption ~ 7.5 Gigatonnes
- CO_2 emissions due to coal ~ 16 Gigatonnes

- 2011 oil Consumption ~ 4 Gigatonnes
- CO_2 emissions due to oil ~ 12 Gigatonnes

85% of coal mined is used to generate electric power.

Can it be replaced by another resource?

Cheap Coal fueled development in the 20th century

It's use will persist through at least the first half of the 21st century

The Future of Coal: 20 Countries

- USA (1000/230000)
- Germany (183/41000)
- Poland (135/5700)
- Czech, Ukraine, Bulgaria, Romania, Greece, Turkey (350/42000)
- Russia (325/157000)
- Kazakhstan (110/33000)
- China (3250/114000)
- Japan, Korea, Taiwan (35%)
- Vietnam (45/150)
- Australia (424/76000)
- Indonesia (306/5500)
- India (570/60000)
- South Africa (255/30000)

(#) =Annual (produced/Reserves) MT (%) % power generated by coal: **BP2011**

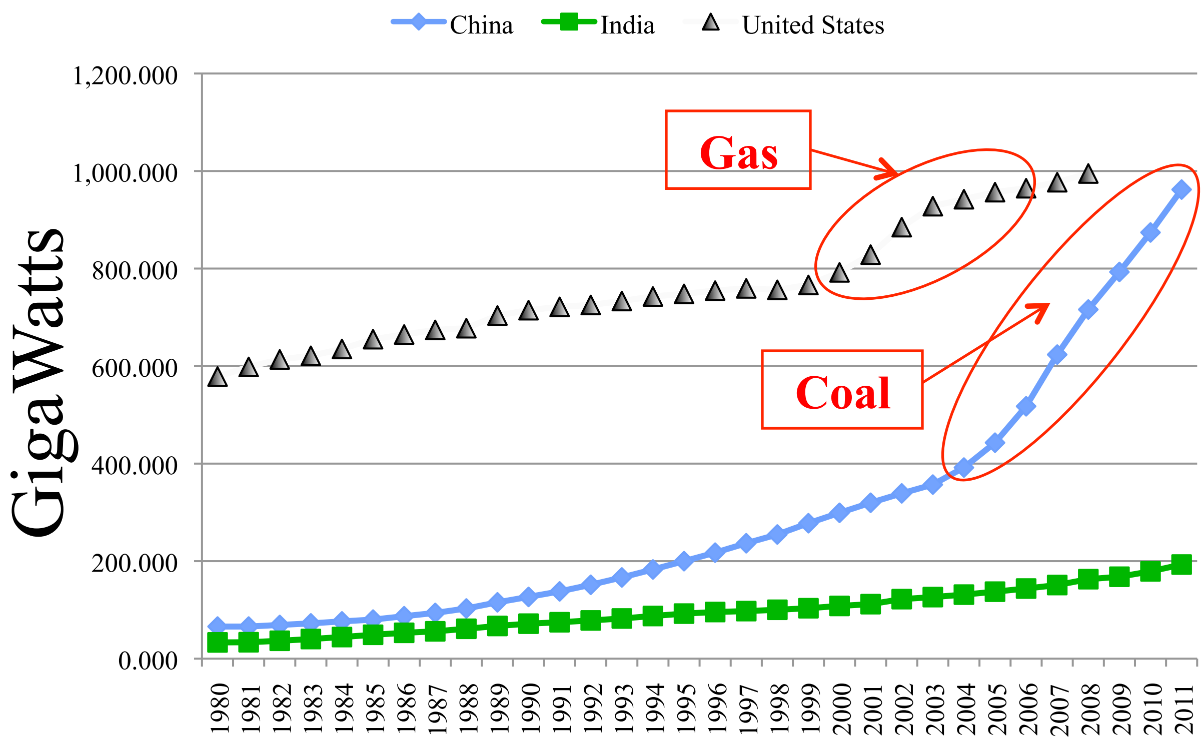
Major Exporters (2009)

	Million short tons/year
• Australia	390
• Indonesia	265
• Russia	130
• Columbia	76
• South Africa	74
• USA	60
• Canada	32

Exported coal is: ~50% coking and 50% thermal

BP2011

Installed Capacity: China, India, USA



Electric Power Generation:
USA: **50% Coal**
China: 80% Coal
India: 70% Coal

Coal capacity will saturate → China & India each plan 500+ GW of nuclear capacity in addition to coal and gas PP to meet their power needs

Source: EIA, http://www.world-nuclear.org/info/inf63.html

Manufacturers of Thermal Power Systems

Major Technology Innovators & Manufacturers

- Siemens (Germany)
- Mitsubishi (MHI), Hitachi, Toshiba (Japan)
- Alstom (France)

Major Manufacturers

- China: Dongfang, Harbin, Shanghai
- Europe: Ansaldo, Asea Brown Boveri (ABB)
- Russia: LMZ, Kharkov, … (now Power Machines)

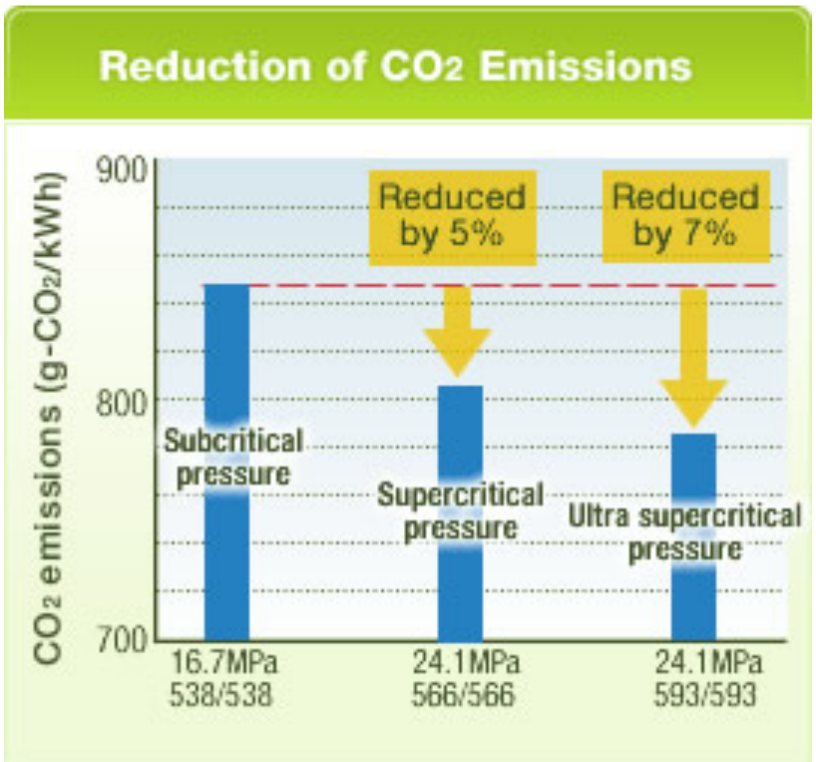
Regional Manufacturers

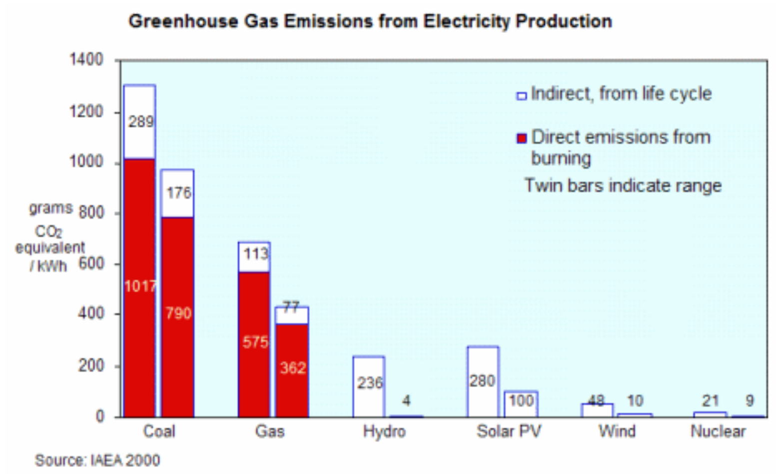
- India: BHEL (Skoda, …), Larson & Toubro (MHI)
- S. Korea: Doosan (going global)

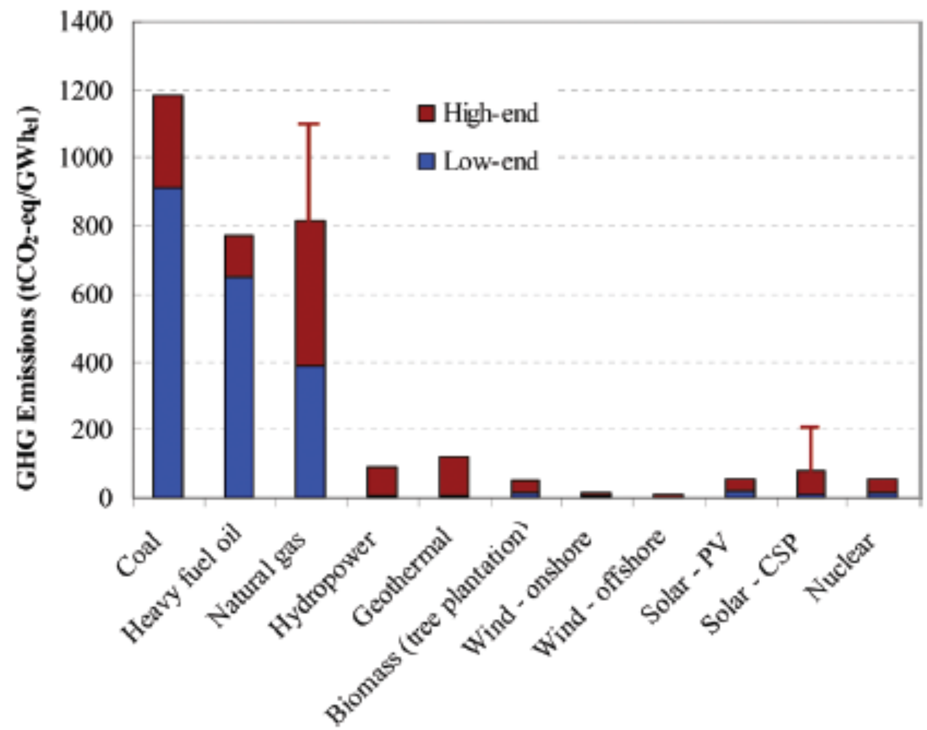
"Clean" Coal:
Reducing polluting emissions from Power Plants

- Coal beneficiation and covered storage
- Mine head plants to reduce coal transportation
- Flue gas desulphurization units for SOx
- Electrostatic precipitators / filters for particulates
- Low NOx burners
- Supercritical & Ultra-supercritical steam systems
  - Higher efficiency → lower CO_2 emissions
- Integrated gasification combined cycle

CO_2 Intensity of power generation







http://www.hitachi.com/environment/showcase/solution/energy/thermal_power.html

www.architecture2030.org/files/CoalPhaseoutUS2030_full_EST.pdf

"Clean" Coal: Implementation

- USA

?

- China
- Japan, Korea, Taiwan

Latest technology Power Plants

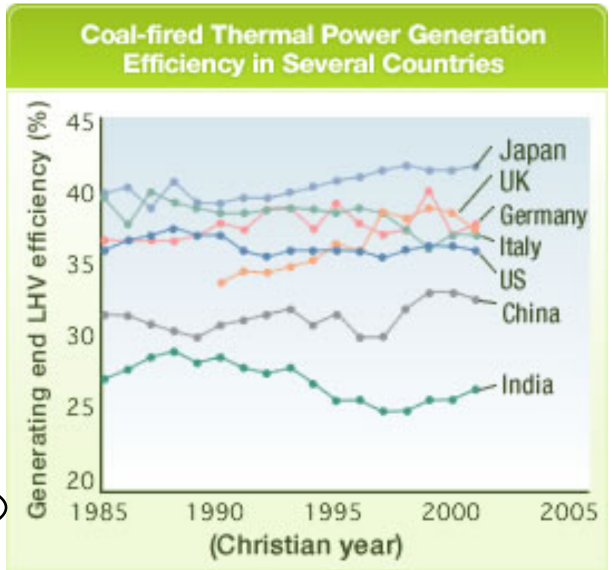
- Vietnam
- Australia
- Indonesia
- India

- UK, Germany
- Poland
- Czech, Ukraine, Bulgaria, Romania, Greece, Turkey

EU mandates

- Russia
- Kazakhstan

- South Africa



Costs countries are willing to incur

- Electrostatic precipitators
- Flue gas desulphurization (FGD) units
- Low NOx burners

For coal-fired plants these add

- 15-20% in capital cost and O&M costs
- Significant operating cost for FGD units
- Use about 5-7% of electric energy generated

Countries that can switch to gas relatively easily

- USA

- UK, Germany
- Poland
- Czech, Ukraine, Bulgaria, Romania, Greece, Turkey

- Russia
- Kazakhstan

- China (Growth using shale gas)
- Japan, Korea, Taiwan
- Vietnam
- Australia
- Indonesia
- India

- South Africa

Almost all of these countries will have nuclear power plants. ??GW??

Countries to Watch

- Japan
- Taiwan
- South Korea
- India

- They are "Islands"
- Fossil Energy Poor
- Major importers of oil, gas, coal
- Will need to maintain/ develop trade niches in manufacturing/services to pay for fuel

These countries and Europe need to evolve to carbon-neutral systems out of necessity

BAU: In the short term coal use will continue to grow at 2-2.5%/yr

My guess, based on the 20 major consumer countries and resource distribution, is that coal use will peak at about 9 Gigatonnes/yr

9 Gigatonnes of coal → ~18 Gigatonnes of CO_2

First Large-scale Change from BAU → **Lecture 2**

Natural gas will be the multi-use bridge fuel.

Trade of NG provides a motivation for regional cooperation and development

Replacing power generation from coal by gas → ~10 Gigatonnes of CO_2 instead of 18