The development-energy-environment-climate challenge: Transforming the global energy system

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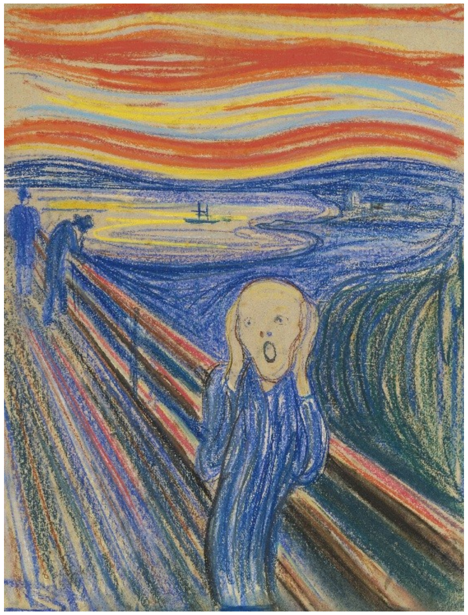
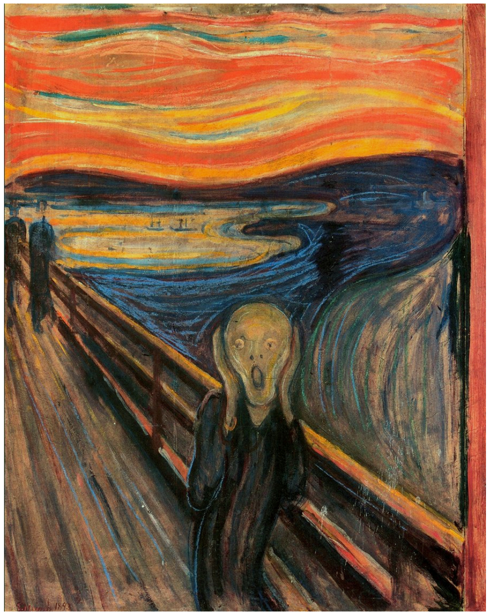
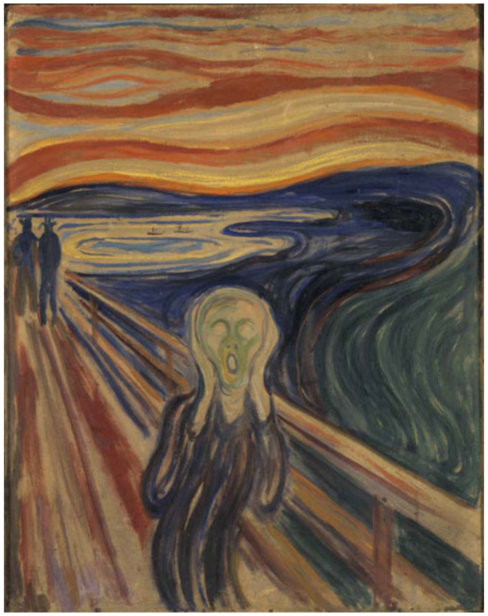

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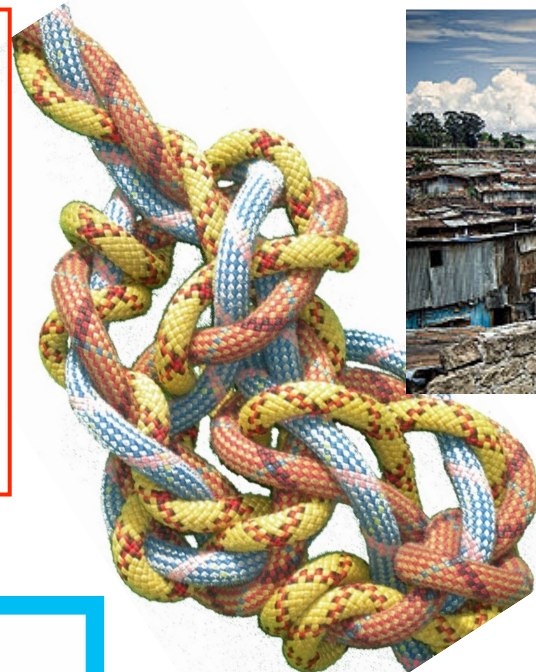
Sustainable Development:
The development-energy-environment-climate challenge

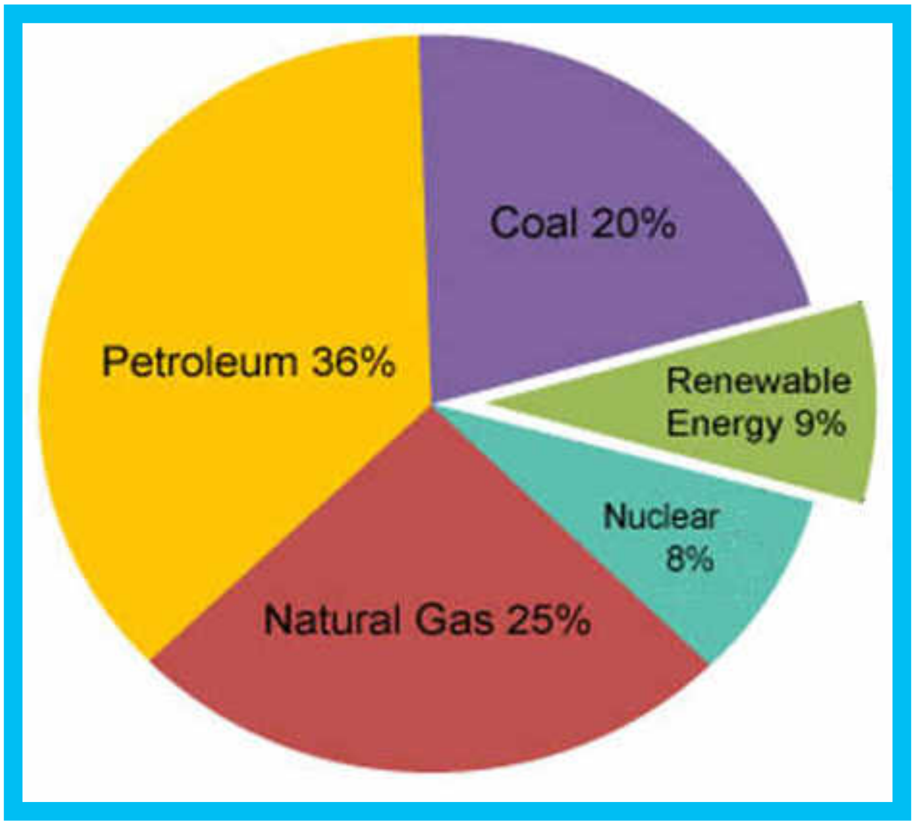
- Development: moral imperative, creates resilient societies, facilitates transformations, *drives politics*
- Energy: basis of modern technological societies
- Water: basis of life, non-fungible
- Environment: health and sustainability
- *Climate: the driver of the need to transform to carbon-neutral energy and transportation systems*

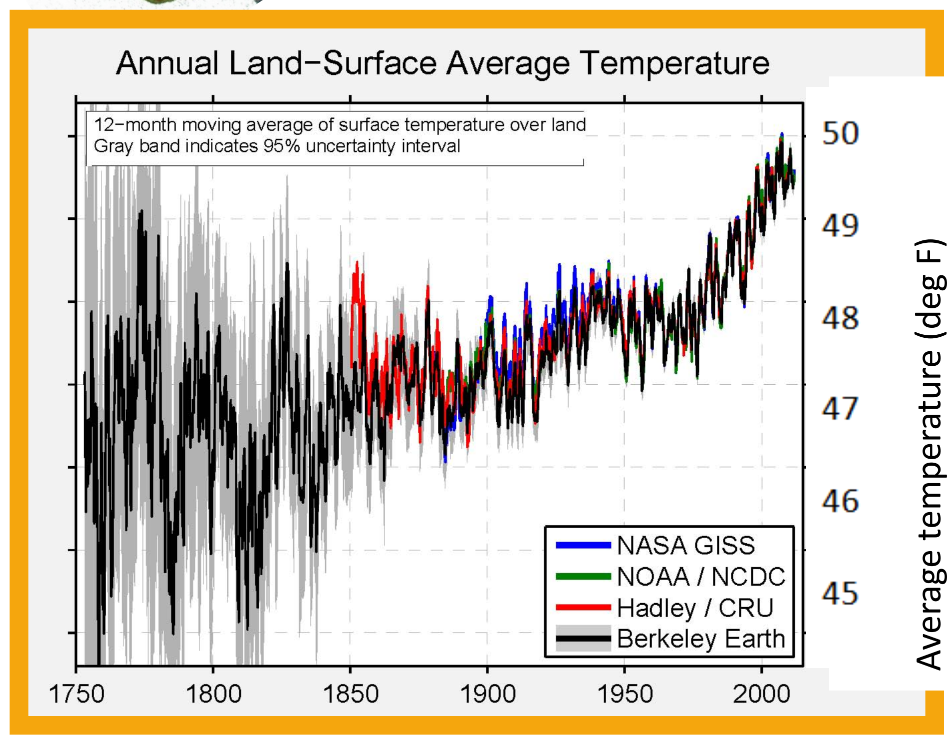
Climate Change: Impacts are global, long-term and likely catastrophic

A daunting knotty challenge:
Economic Development,
Energy, Climate.

No easy/ideal solution!
What should/will we do?

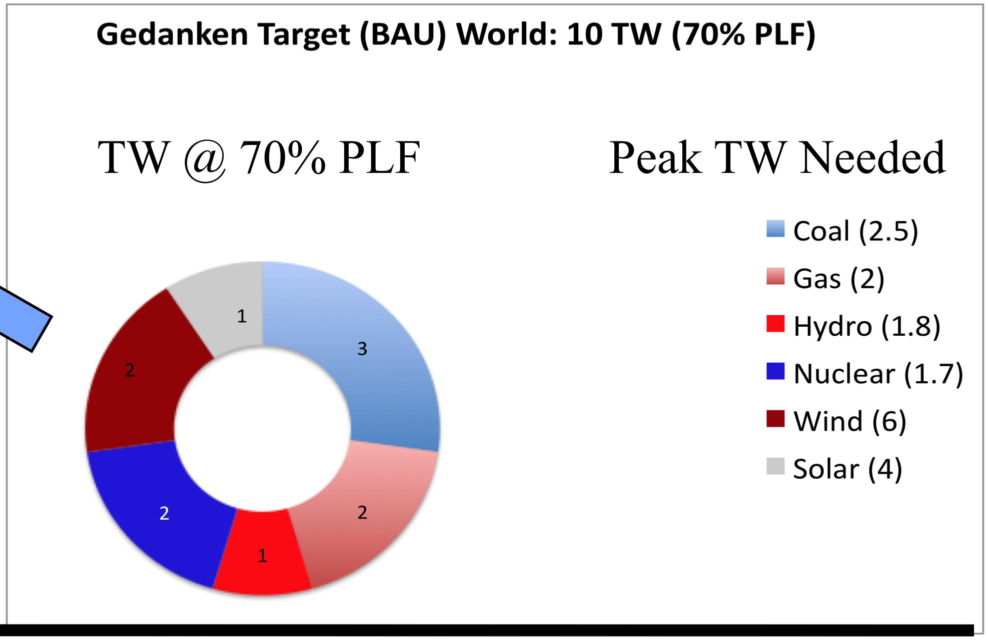






Meeting the global energy need in 2050: 10TW electric power & 125Mbo/day

- 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 grow to 5 Mbo/day

Estimates based on historic trends & efficiency gains

The goal is clear

Need cheap clean carbon-neutral energy for electric power and transportation needs.

The challenge is

meeting these needs without using fossil fuels (and nuclear power in some countries)

Fossil fuels: Nature's amazing energy storage

- High Energy density: energy per kilogram
- High Power density: Power per unit volume
- Safe: Do not self combust and are easy to use
- Transport: Easy to transport around the world
- Easy and cheap to extract from the ground:

Challenges: Environment, Climate Change

Is there enough fossil fuel globally?

Recoverable resources depend on

1) Total geological amount in the Earth's crust
2) Technology
3) Price we are willing to pay
4) Environmental damage we are willing to accept

Deep horizontal drilling and hydraulic fracturing have opened up new fields and resources

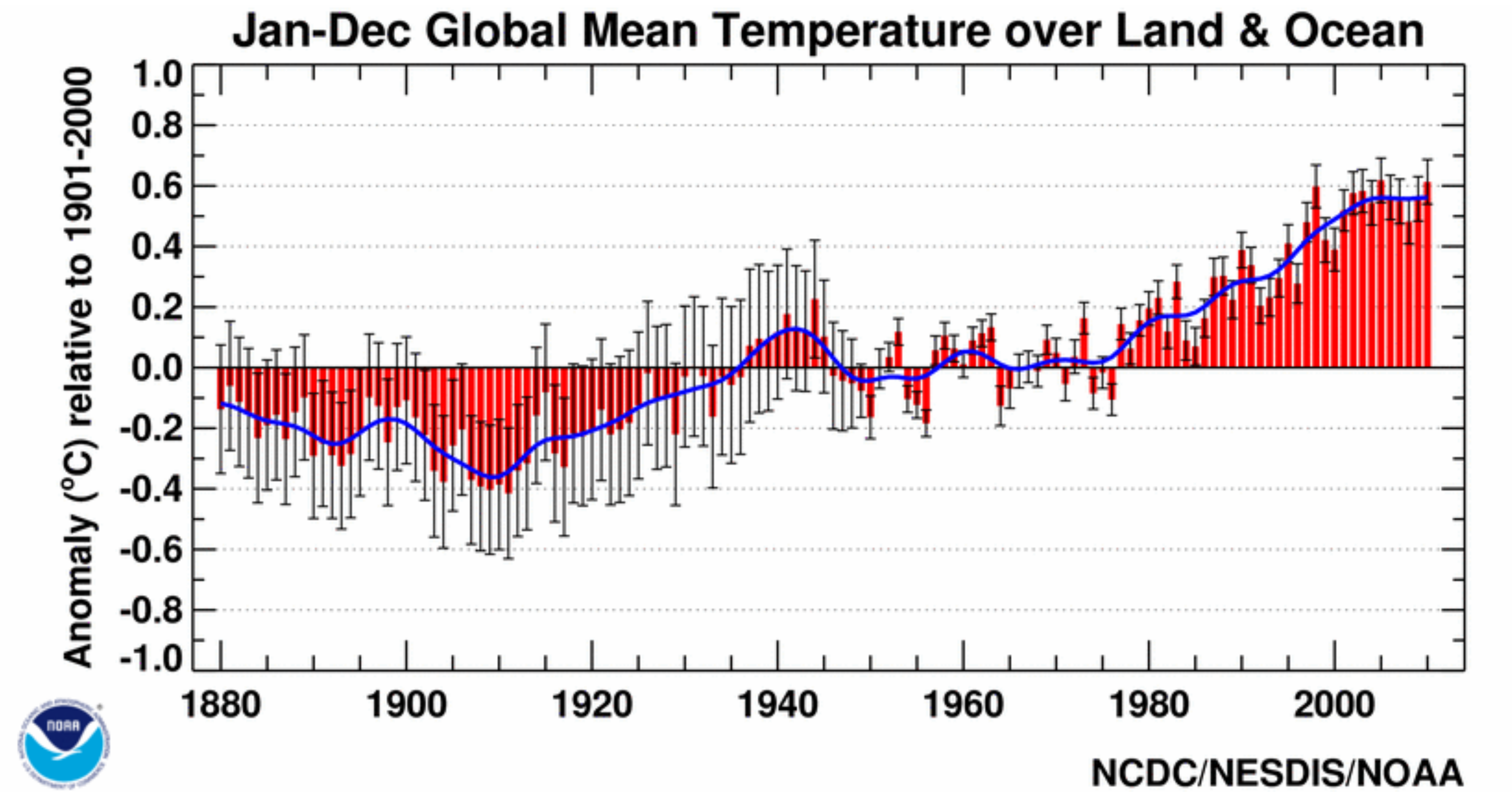
1) Tight oil and gas
2) Deep Sea reservoirs
3) The Arctic

YES: For at least a 100 years, since C is fungible

Why change the global energy system?

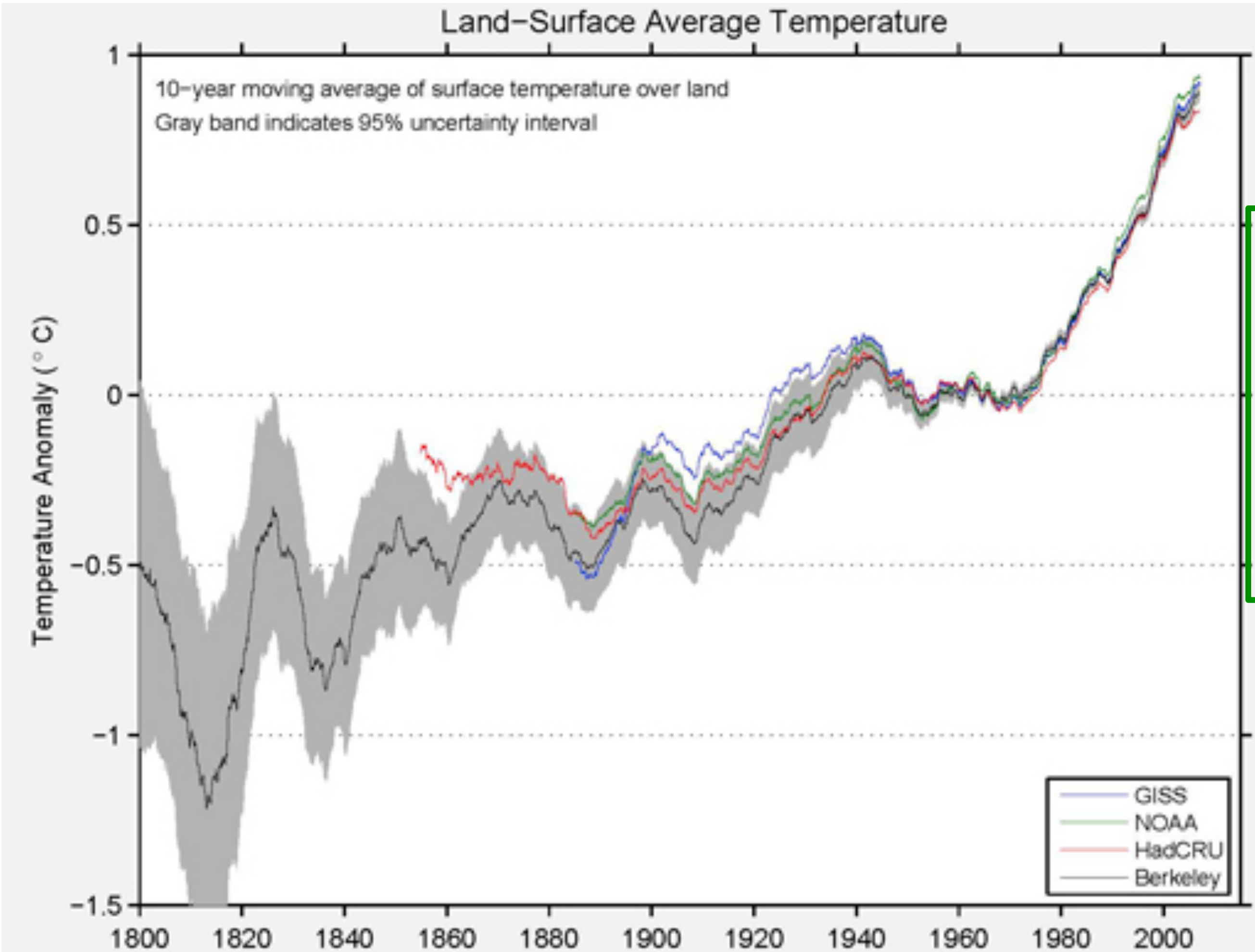
Why act now?

The mean temperature is changing



Mean temperature rise since 1900 ~ 0.74^{o}C

Land Temperature Anomaly

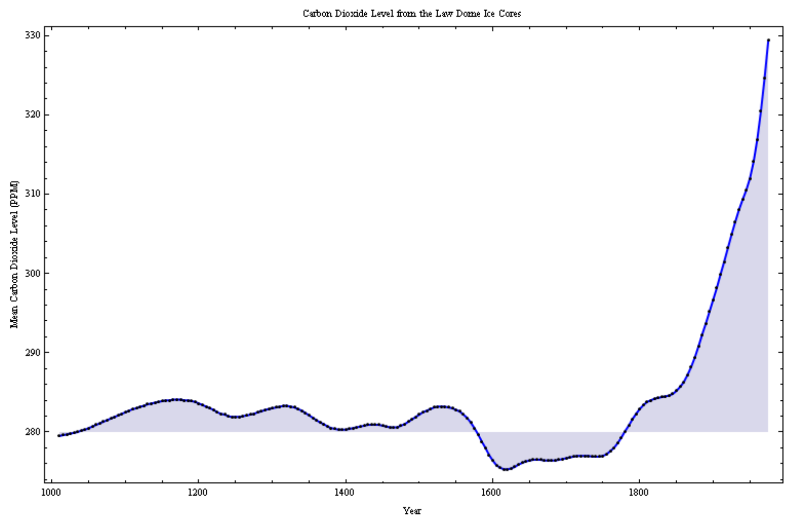


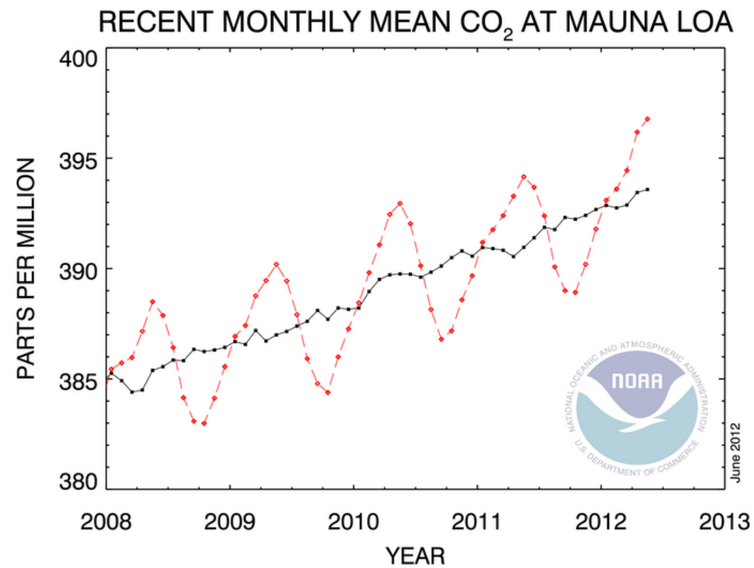
We do not know the full consequences of current 395 ppm of CO_2!!!

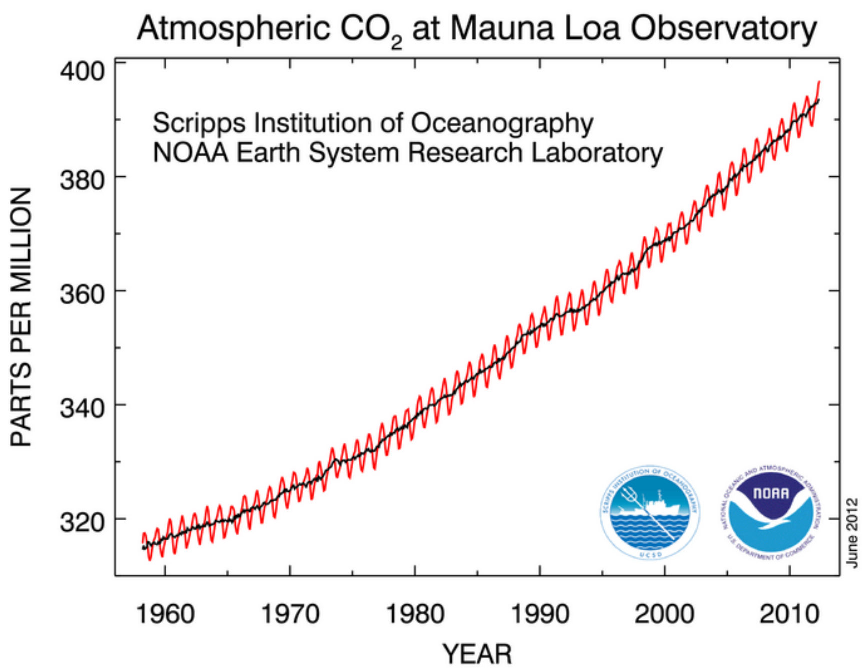
A change in T_{av} (land) from 20 year patterns between 1800-1960 to a uniform growth after 1970. Rise in mean temperature since 1970 ~ 0.9°C

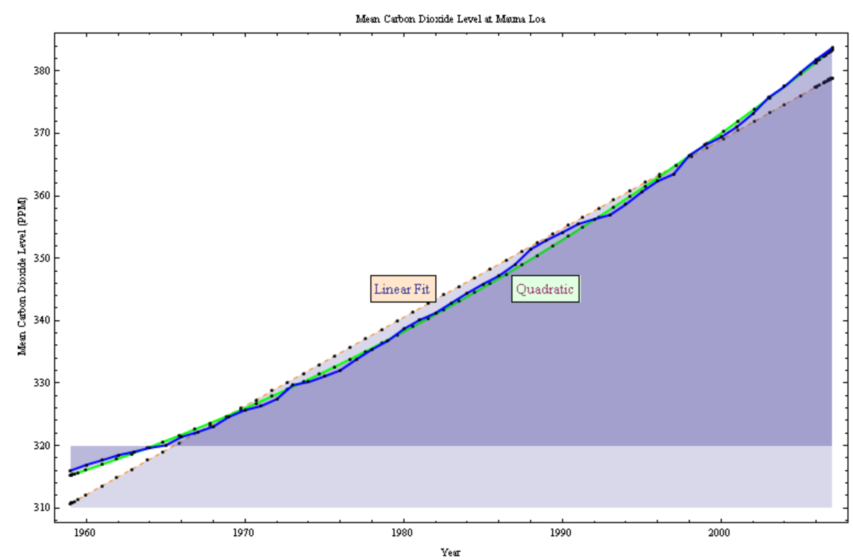
Source: http://berkeleyearth.org/analysis/

Rising CO_2 levels

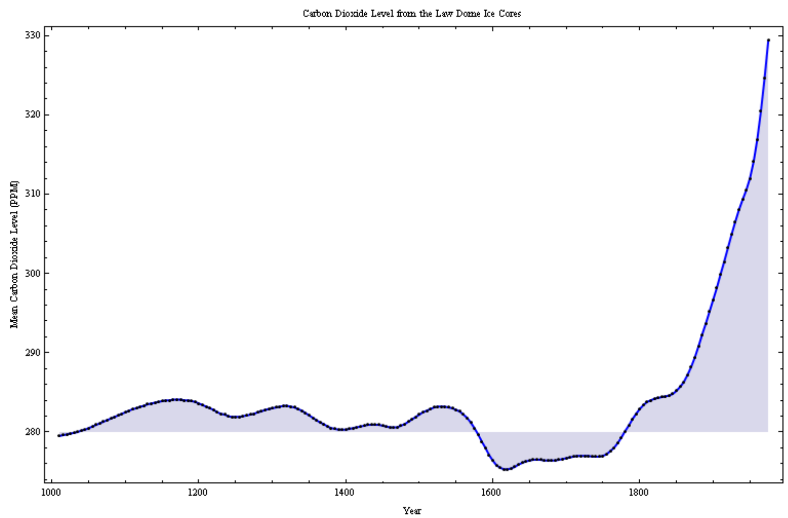


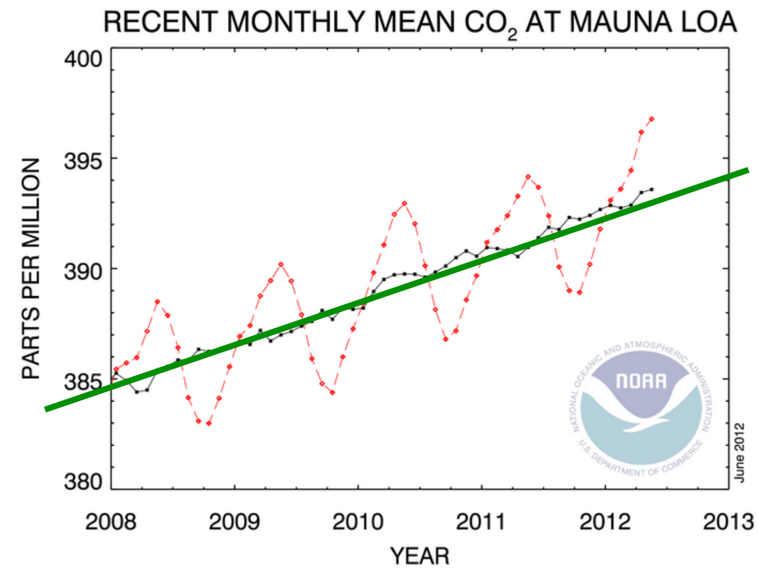


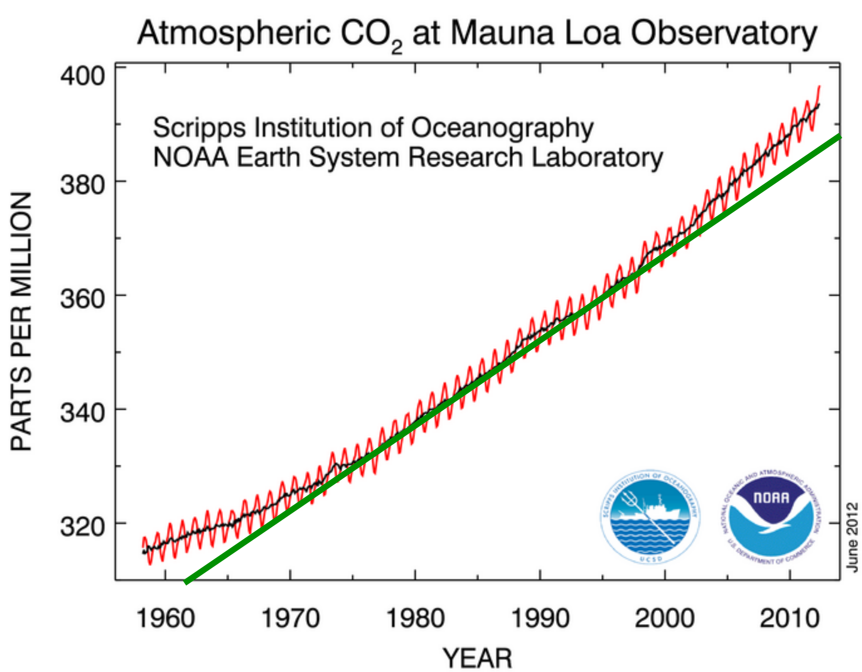


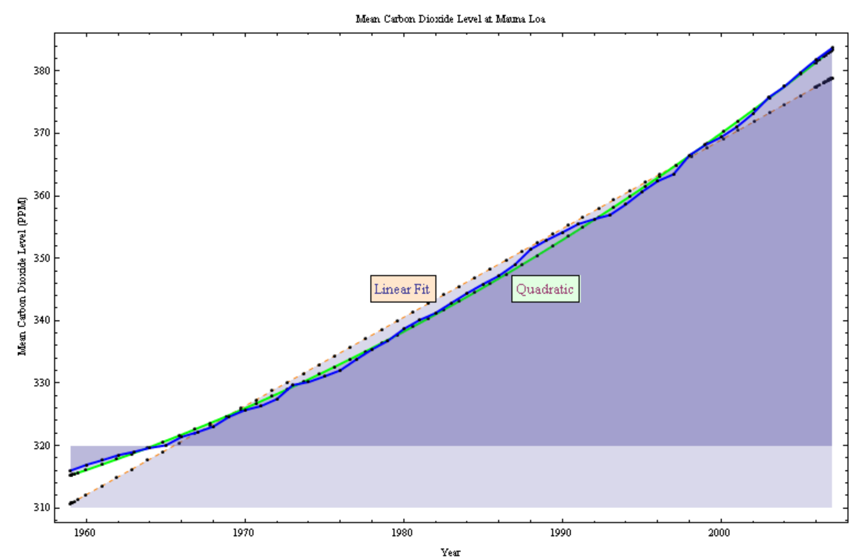


Rising CO_2 levels



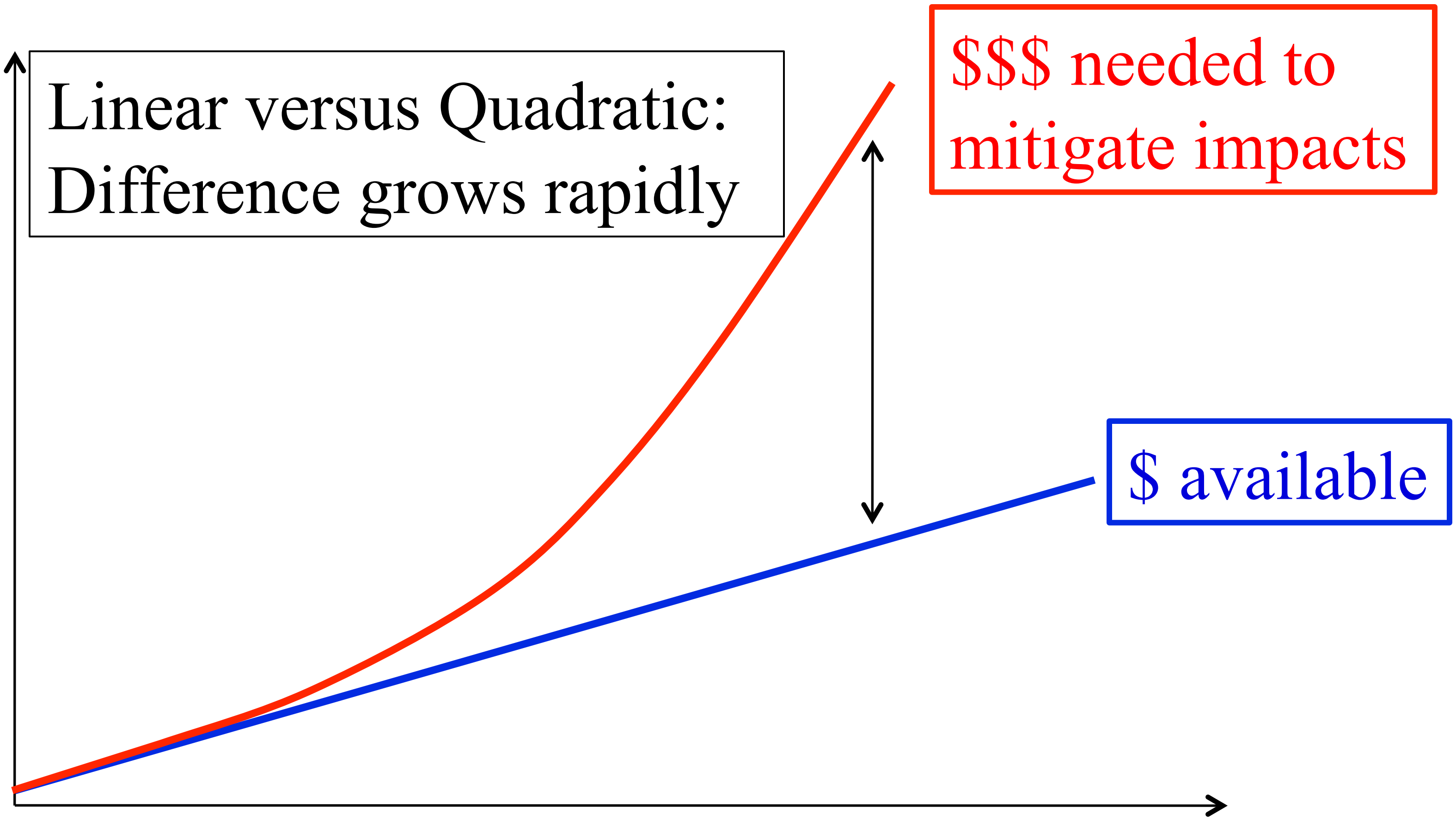






Why we must act with Urgency?

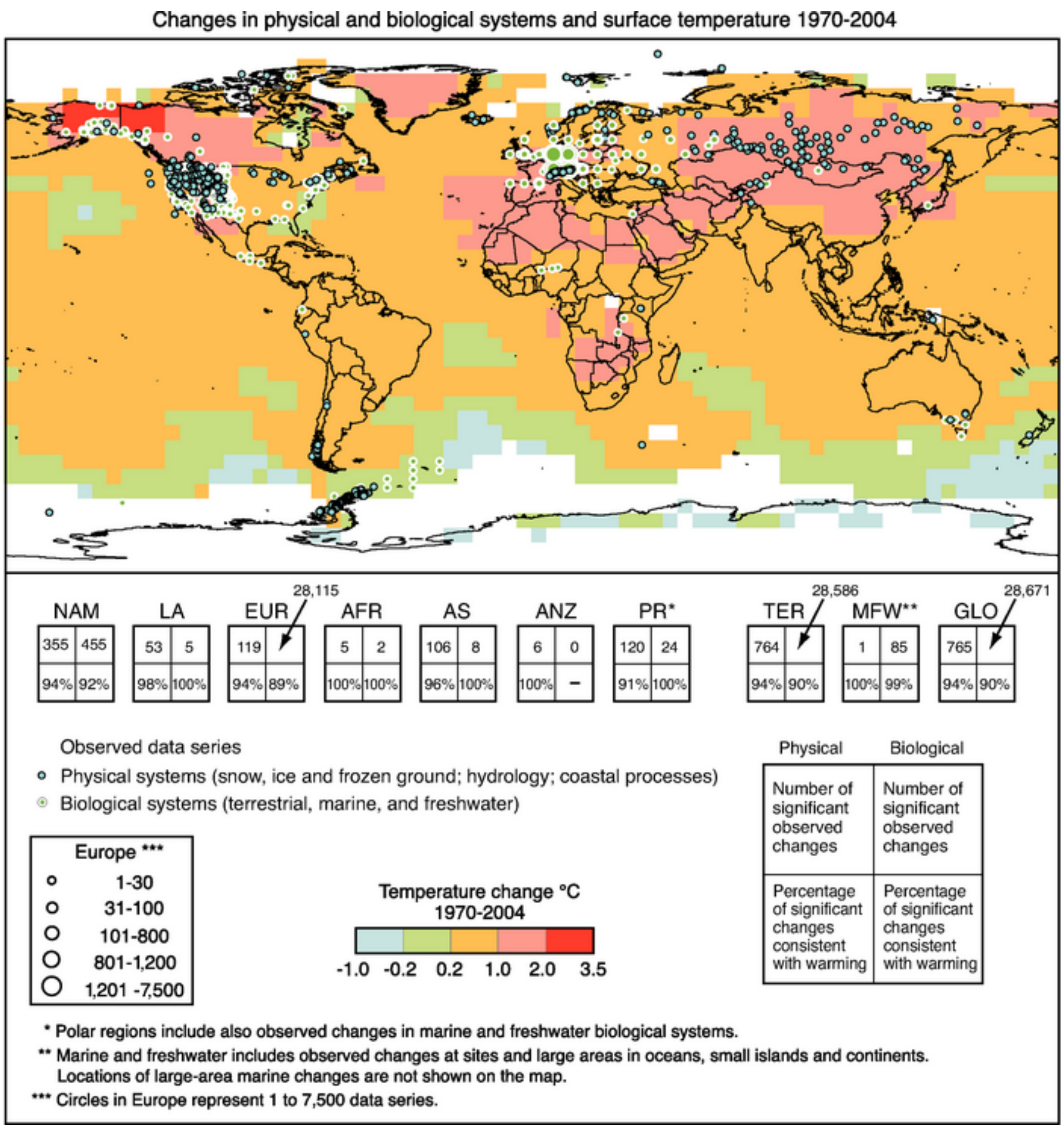
We don't know if/when/how the highly coupled natural systems can run out of control



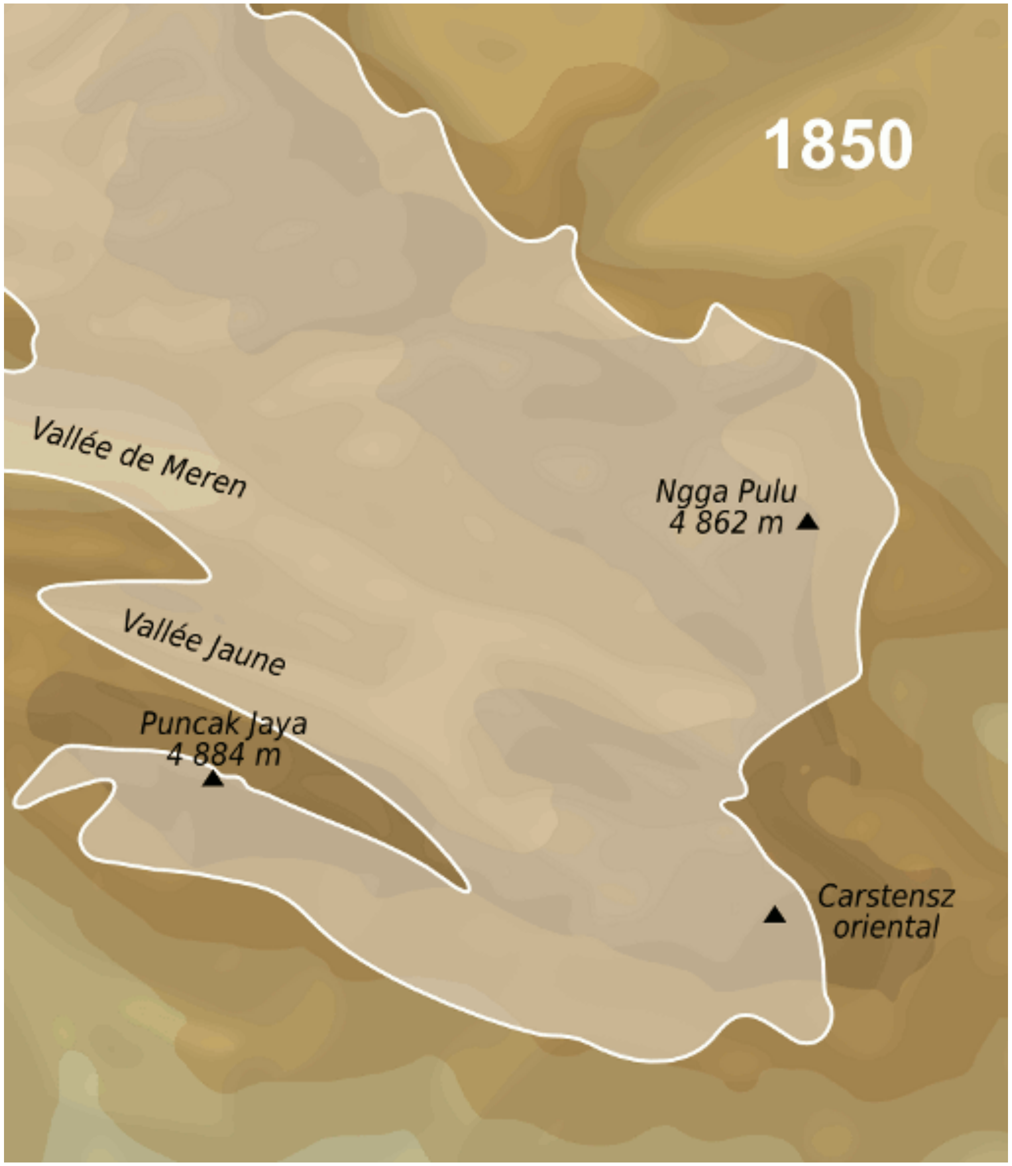
Impacts:

Uncover changes & trends by study of time series of biological & physical systems.

Once change is established, the much harder job is to assign cause-and-effect



Source: IPCC 2007 (WGII)



Receding glaciers

Puncak Jaya glacier on New Guinea's highest mountain, Mount Carstensz (4,884m /16,024 ft) is estimated to have covered an area of 20 km^2 (7.7 sq mi) in 1850

Source (very easy reading): http://en.wikipedia.org/wiki/Retreat_of_glaciers_since_1850

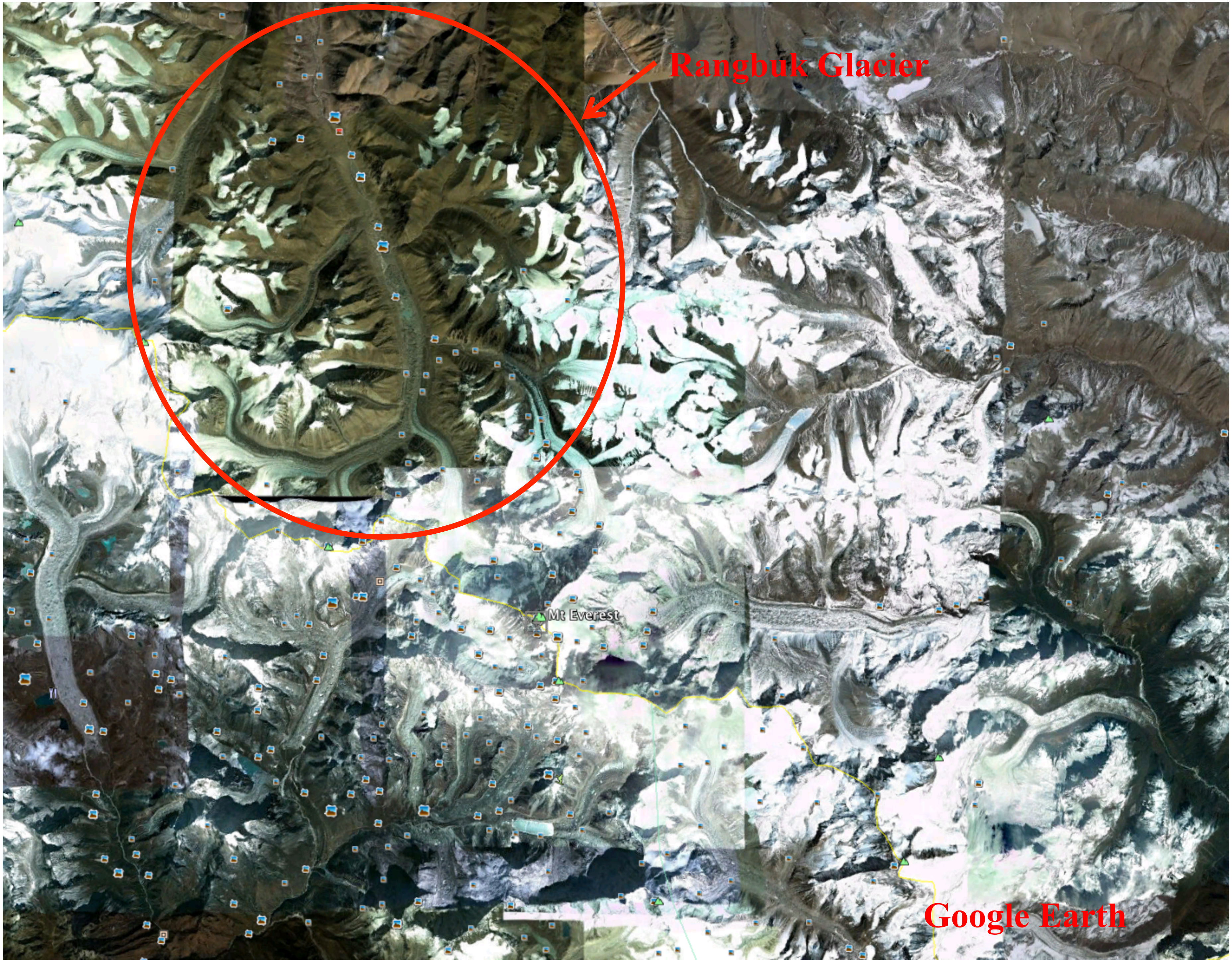
Rangbuk Glacier Mt. Everest

1921
E.O.Wheeler

Drop by 100m

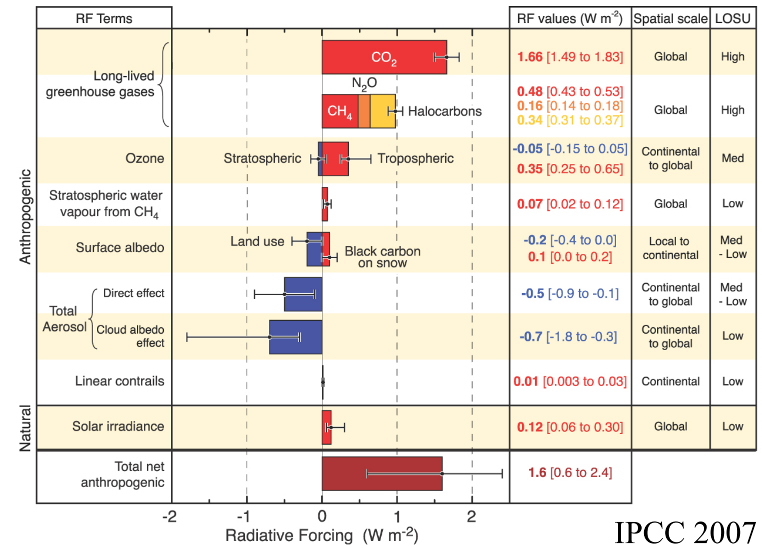
2011
D. Breashears

Source: Science 337: 793-795 (2012)


Rangbuk Glacier
Mt Everest
Google Earth

The global climate system is very complex: We are just beginning to understand cause-effect

- Impacts of El Nino, La Nina, Pacific decadal oscillation (PDO), Atlantic multi-decadal oscillation (AMO), North Atlantic oscillation (NAO), ...
- Impacts of solar activity, Milankovitch cycles
- Increase in T_{av} due to radiative forcing of
  - Green house gases
  - Black soot, aerosols
  - Water vapor (clouds)
  - Land, cloud, permafrost changes



IPCC 2007

Understanding each, prioritizing, and developing strategy and policy to address "them" is important

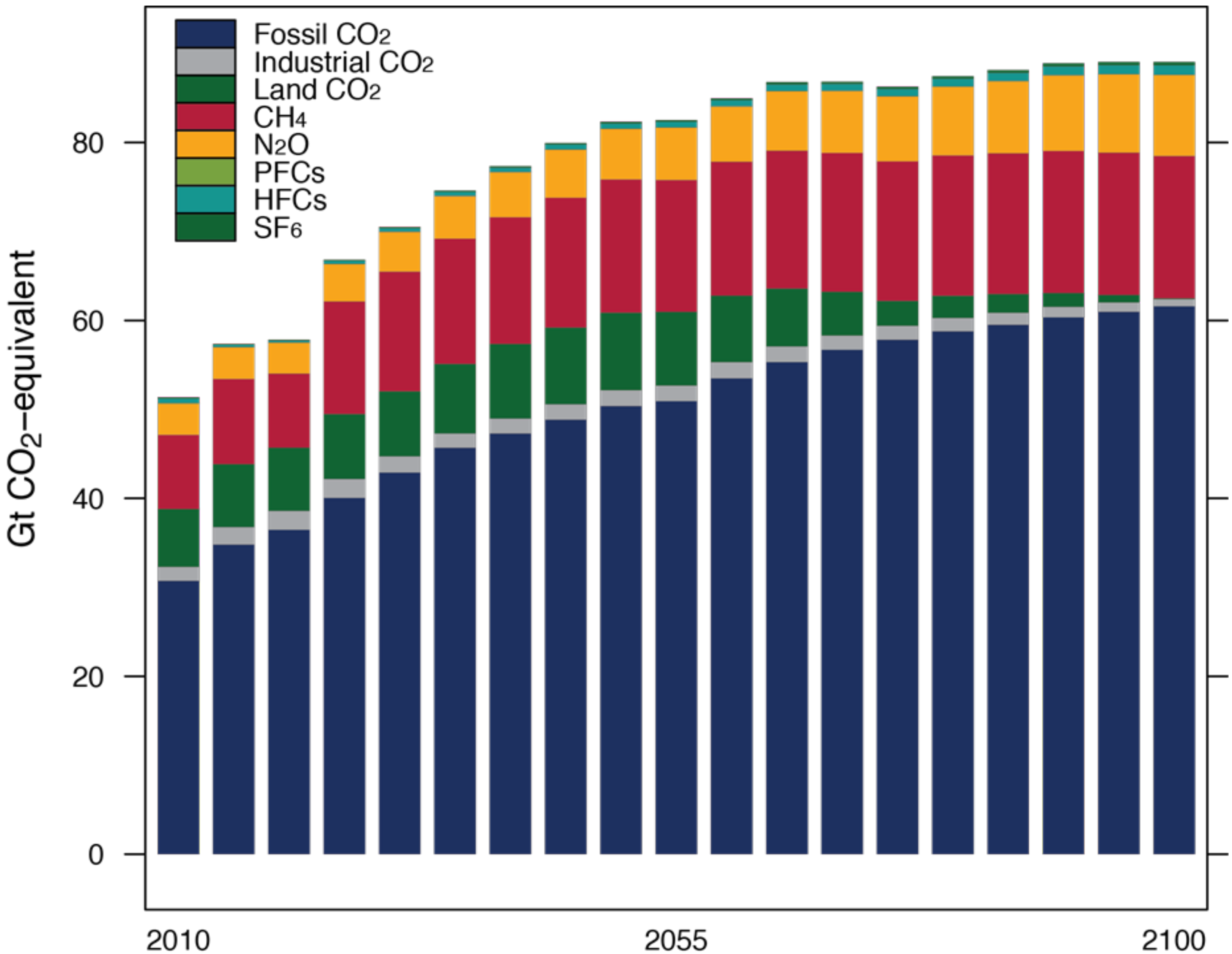
Anthropogenic Emissions of Green House Gases

- 2011 Emissions of CO_2 = 32-34 Gigatonnes/year
- ? Natural recycling = 16-18 Gigatonnes/year
- 2012 concentrations = 393 parts per million (ppm)
- Increase in CO_2 levels ~ 2.6 ppm/year
- 1°C rise in temp ~ 100 ppm (parts per million)

To stabilize CO_2 levels	~ 3 Gigatonnes/year

Requires	>90% Decarbonization

Greenhouse Gas Emissions: All Sources



Source: MIT Joint Program Outlook, 2011 - Jacoby

Climate Change: I will use the general definition – due to all sources

- Natural variations
  - Solar activity
  - El Nino, La Nina, decadal oscillations, NAO, ...
- Anthropogenic
  - GHG, black carbon, sulphates, …
  - Land use
- Natural causes
  - volcanoes, fires, ...

Impacts and losses depend on the full variation

To mitigate climate change, how can we de-carbonize the global energy system?

2050 global needs:

- 10 terrawatts of electric power
- 125 million barrels of oil/day

Review of the high points of the carbon world

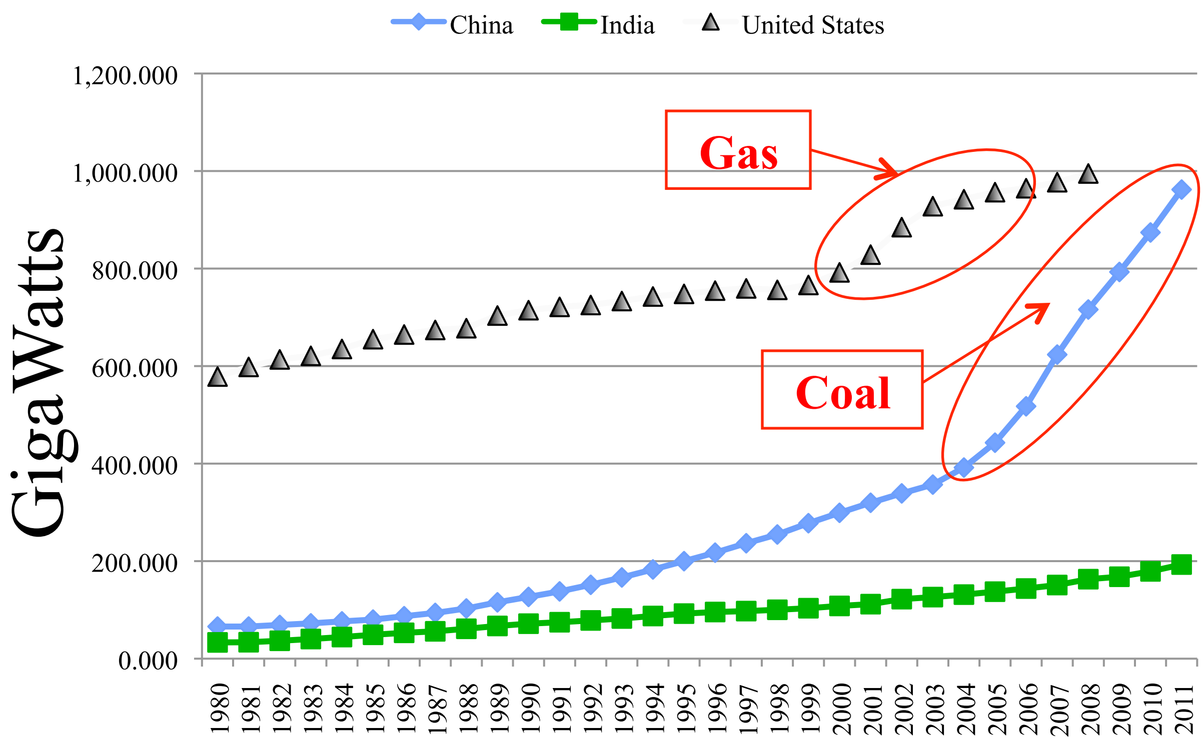
Energy security is the highest priority of all countries

Coal and Gas for power generation

- ~21 countries dominate coal use
  - Future big players: China, India, USA
- Natural gas is/will be the dominant fuel in many regions of the world
- Urbanization is proceeding at a very rapid rate
  - Numbers of Mega-cities and large cities are growing and will remain centers of economic activity. (2/3 of all Australians live in the 5 largest cities.)
  - Large centralized power plants have the benefit of economy of scale.

2020-2050: Coal and gas will retain >4TW capacity

Total Installed Capacity: China, India, USA



Electric Power Generation:

USA: 50% Coal

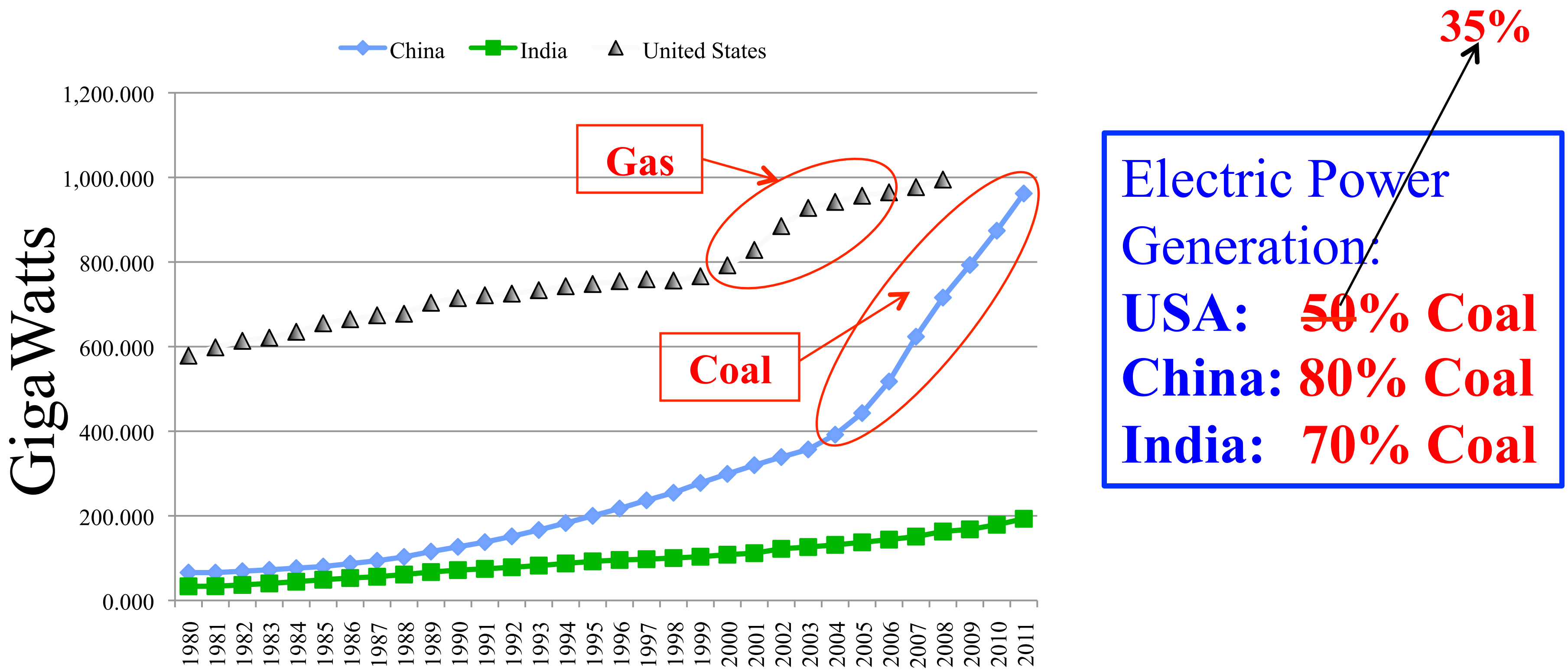
China: 80% Coal

India: 70% Coal

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

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

Cheap gas in the U.S. is replacing coal



Current coal reserves give a R/P ~ 30 years for

China → 600GW

India → 300GW

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

Coal-fired power: 21 Countries

- USA (1000/230000)
- UK (18/228)
- Germany (183/41000)
- Poland (135/5700)
- Czech, Ukraine, Bulgaria, Romania, Greece, Turkey (350/42000)
- China (3250/114000)
- Japan, Korea, Taiwan (35%)
- Vietnam (45/150)
- Australia (424/76000)
- Indonesia (306/5500)
- India (570/60000)
- Russia (325/157000)
- Kazakhstan (110/33000)
- South Africa (255/30000)

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

(BP2011)

By 2050 only 7/21 coal rich countries

- USA (1000/230000)
- ~~UK~~ (18/228)
- Germany (183/41000)
- ~~Poland~~ (135/5700)
- ~~Czech~~, Ukraine, ~~Bulgaria~~, ~~Romania~~, ~~Greece~~, ~~Turkey~~ (350/42000)
- ~~China~~ (3250/114000)
- ~~Japan~~, ~~Korea~~, ~~Taiwan~~ (35%)
- ~~Vietnam~~ (45/150)
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- Kazakhstan (110/33000)
- South Africa (255/30000)

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

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

Growth using shale gas

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

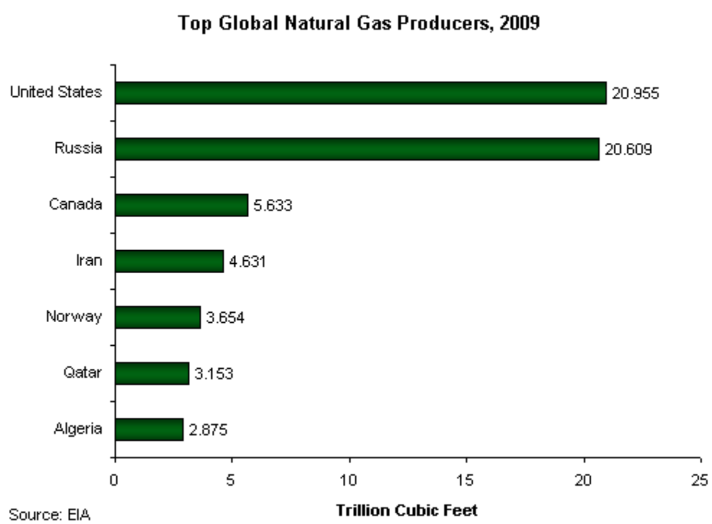
Natural Gas: the new multi-purpose fuel

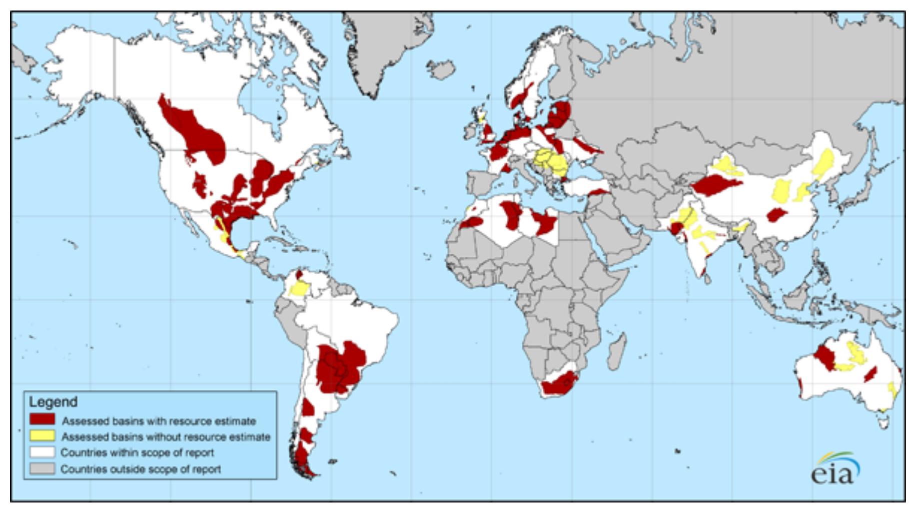
Dominant in

- South America (after Hydro)
- North Africa
- Middle East
- Central Asia, Iran
- Russia

Major fuel in

- North America
- Europe
- South-east Asia
- Australia
- China (Shale Gas)





Shale Gas: USGS

Liquid fuels

Limited alternatives to oil & gas!

- BAU: world will need 125 Mboe/day (→18 Gigatonnes CO_2) by 2050 assuming 1%/year growth rate.
- Volatility of oil price → fuel efficiency (12→24 km/L cars)
- Arable land and water will be major limiting factors in growth of transportation fuels from biomass (fuel versus food).
- Not clear if the cost of algae based bio-fuels will come down sufficiently. Water intensity of production favors rain rich or costal areas. Cost and water needs will limit growth
- **We should have a much clearer estimate of the growth potential of electric vehicles by 2030**
- **Transition to effective public transport systems requires significant policy input, regulations, and infrastructure**

Industry operational paradigm: Can it be Changed?

- Coal, Gas, Oil, Nuclear: Industry pursues fuel guarantees in lock-step with PP capacity addition
- Solar and Wind: Pursue spinning reserve (backup/ storage) in lock-step with PP capacity addition
  - This paradigm allows 20-30% penetration of solar+wind

For larger % of solar and wind, need the integration of different generation resources and load management through a smart grid

PP = Power Plants

Options for reducing GHG emissions

Decarbonizing the global economy

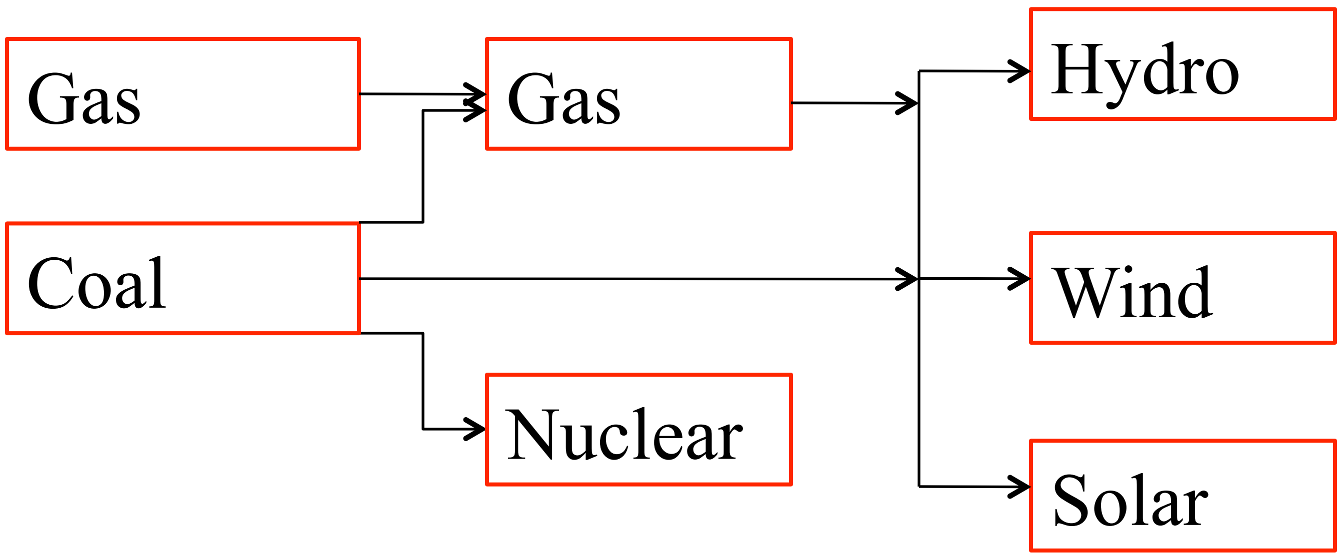
$$CO_2 = \text{Population} \times \frac{\text{GDP}}{\text{Population}} \times \frac{CO_2}{\text{Energy}} \times \frac{\text{Energy}}{\text{GDP}}$$

~+1%	~+4%	~-0.1%	~-1.5%
Population stabilization: a political hard sell	Prosperity: historically it has driven people, policy and politicians	Carbon Intensity: De-carbonize technology	Energy Intensity: Efficiency

Reading: "The Science and Politics of Global Climate Change", Dessler and Parson, Cambridge University Press;
"The climate fix", Roger Pielke Jr., Basic Books, 2010

Decarbonizing: Technology

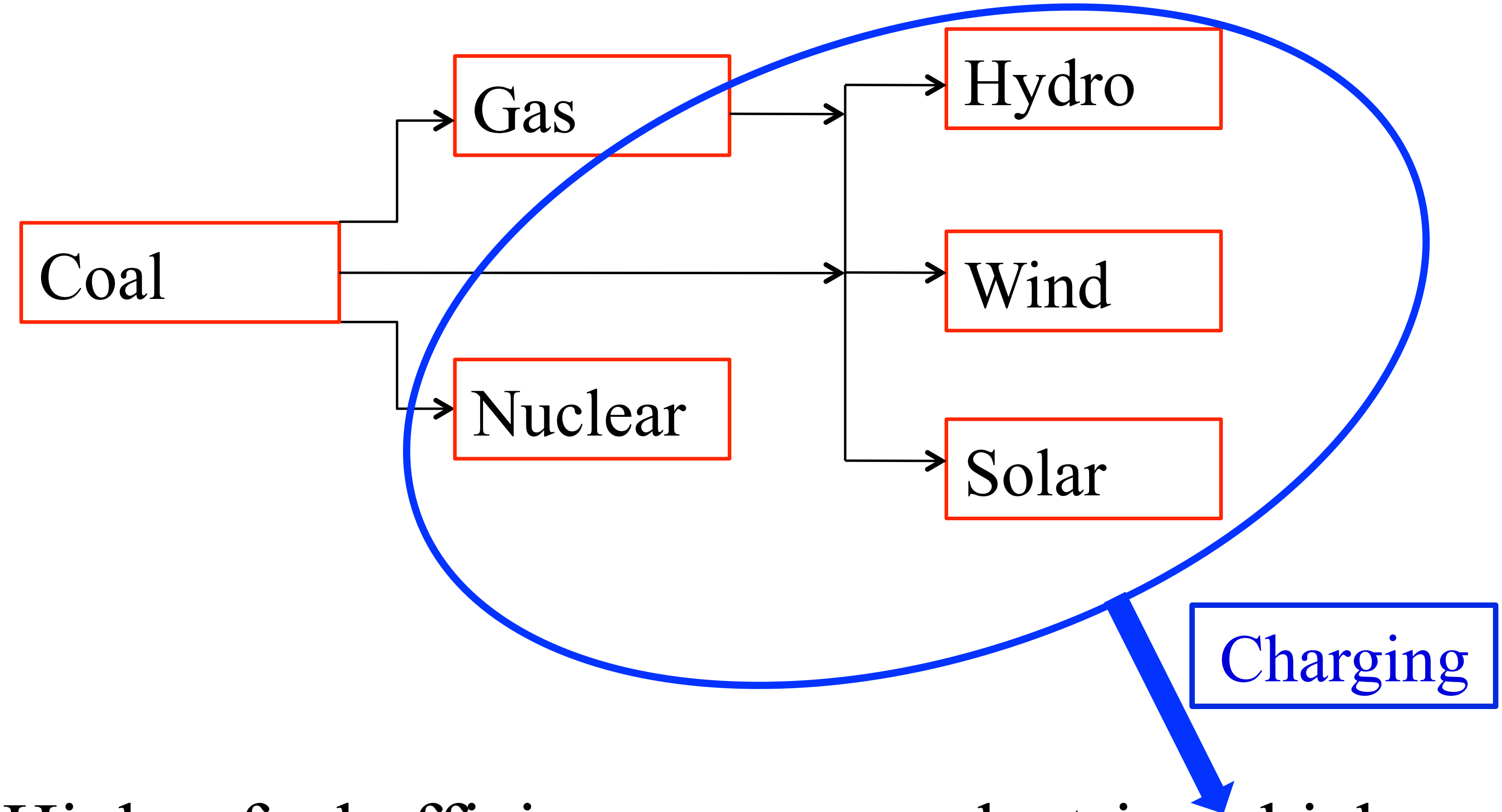
- Fuel Substitution



- Transportation Sector
  - Higher fuel efficiency cars → electric vehicles
  - Biofuels

Decarbonizing: Technology

- Fuel Substitution



- Higher fuel efficiency cars → electric vehicles

Decarbonizing: Scaling up Alternatives

- Non-fossil alternatives for power
  - Nuclear
  - Hydro
  - Wind
  - Solar
  - Novel / Other technologies (they have to scale)
- Large Growth in solar and wind will require
  - Advanced materials
  - Grid-scale storage
  - Smart Green Grid

Can we get to 10TW without nuclear for baseload?

Nuclear Power

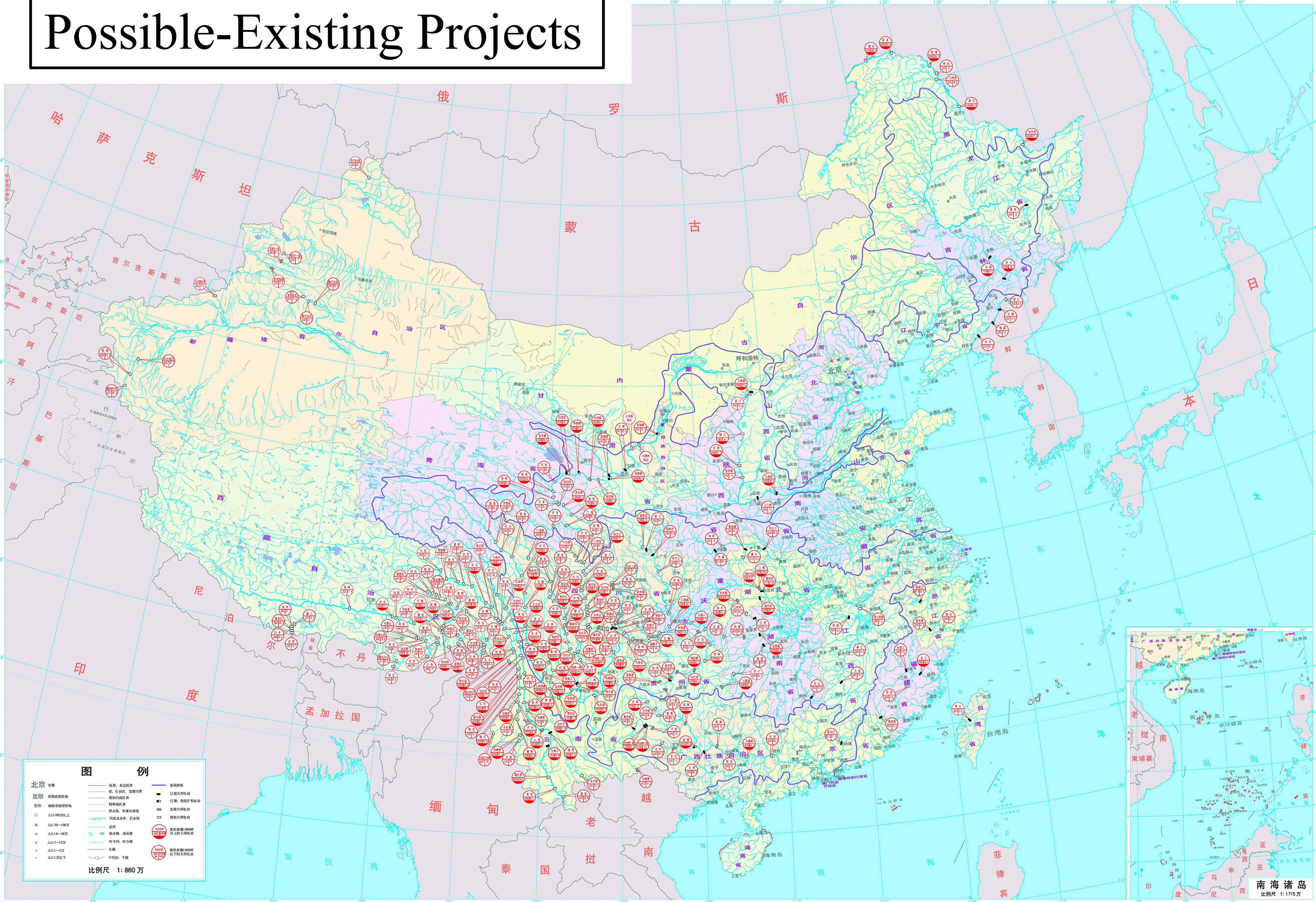
- Only 3 countries (USA, China, India) want over 100 GW of nuclear capacity → New starts in USA crucial to development
- Major capacity addition planned in China and India
- Gen III+ LWR will dominate installations for 20-40 years
- Standardization will reduce risk & help speedup deployment
- The ~21 countries with large operating coal-fired capacity are low risk vis-à-vis nuclear proliferation and safeguards
- Future and growth potential of fast breeder reactors and thorium based reactors is uncertain. Need R&D
- Need R&D in fuel processing and waste management

Realistic Growth: 370 GW → 850 GW by 2050

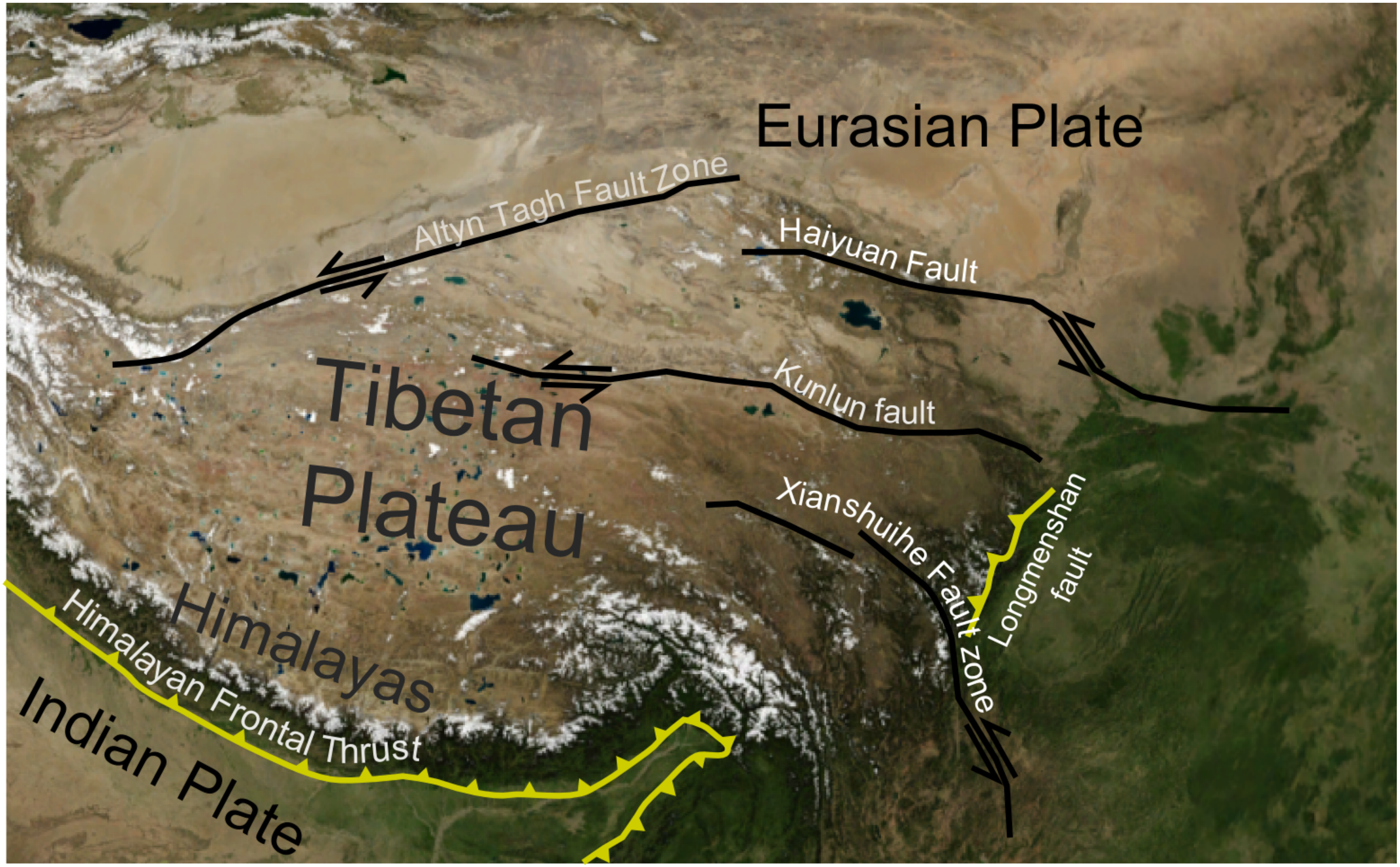
Hydropower

- The potential of most rivers has already been exploited
- Contention for water amongst riparian states will increase. Scarcity will increase the probability for wars over water.
- Major development planned by China and India
- A large fraction of Chinese development is planned in high Himalayas (Tibet)
  - Steep hillsides with narrow valleys
  - Prone to large landslides
  - Active earthquake zone with major faults

Possible-Existing Projects



This is an Active Seismic Zone



Map Source: Terry Wallace

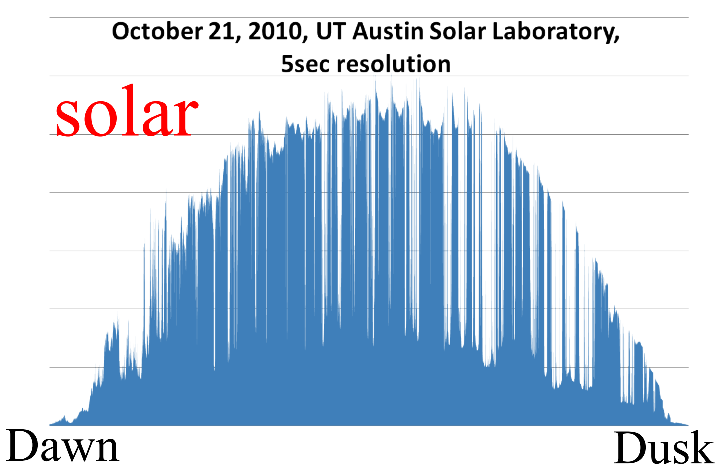
Solar and Wind

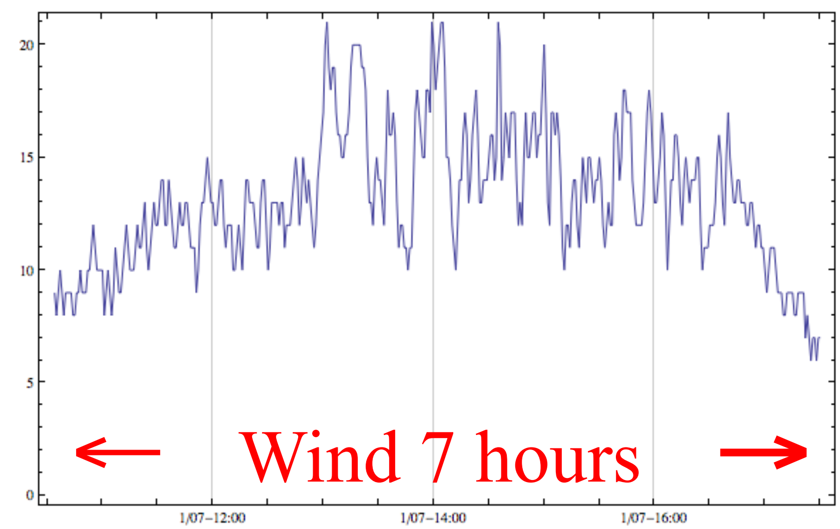
- On a purely kWh cost basis (2012)
  - Wind is competitive with gas-fired power plants
  - Solar is 2-3X more expensive:
    For sustainability, need costs to come down to $2/Watt$_p$ installed
- Intermittency & daily/seasonal variations are key challenges

Can solar and wind supply a large fraction of the electric power?

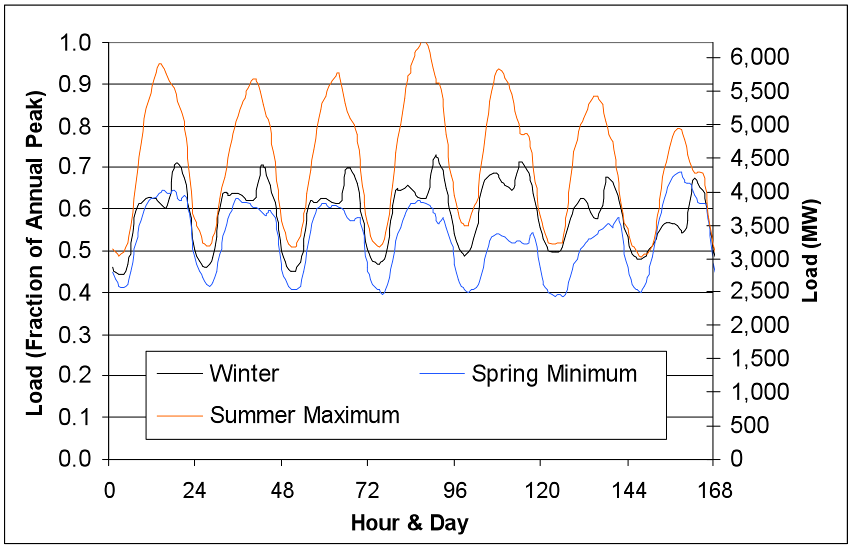
What will provide power when the sun is not shining and/or the wind is not blowing?

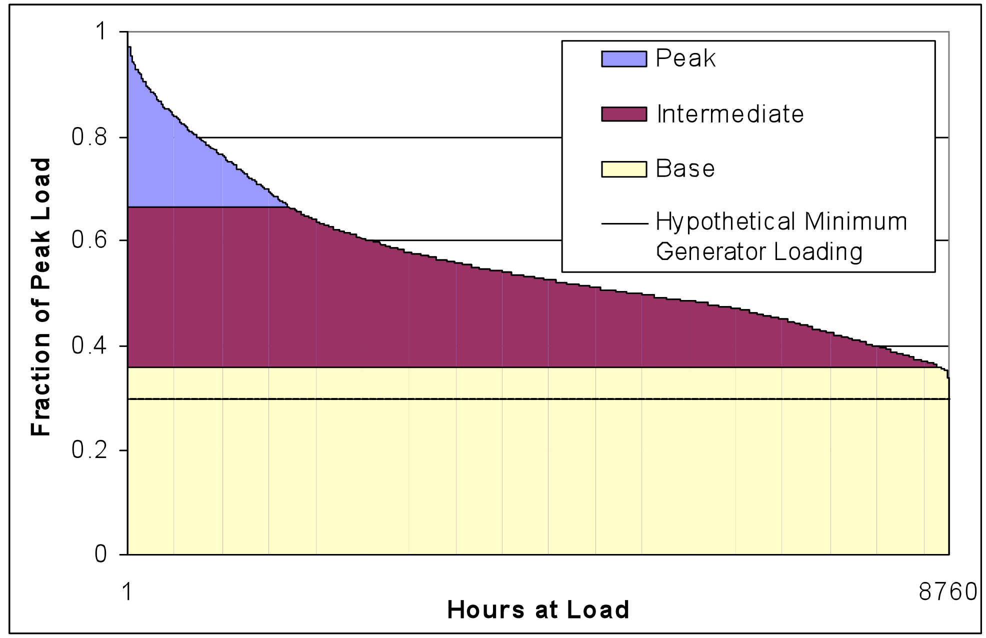
Dealing with large variations in both generation of electric power and load without blackouts!





Variability in demand & generation





- Day, week and seasonal variations in demand and generation
- Need to plan for highest peak load if brownouts unacceptable

Source: Paul Denholm, NREL

Storage is key:

- There are only two large-scale storage systems that provide backup to solar and wind:

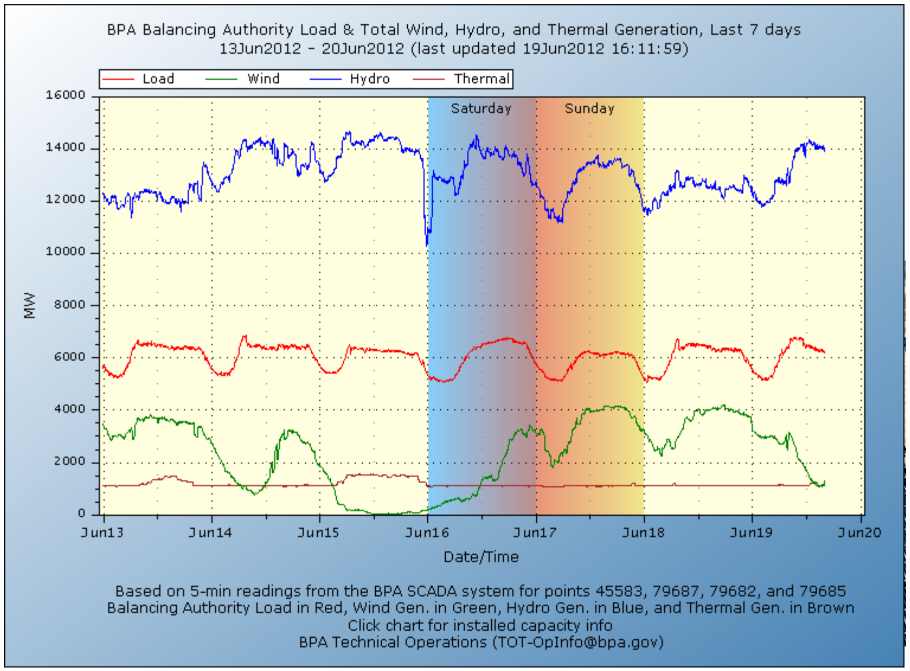
- Hydro: (reservoir based)
  - seasonal regulation: only about 40% of rated capacity
- Hydro: (pumped storage)
  - daily regulation: only 40% of day in generation mode

Limited potential

- Gas Turbines
  - These are oil or gas based with natural gas being the more efficient
  - Unlimited potential but large GHG emissions if required to cover 50-70% of the load on a typical day

Smart Grid is the second key:

- Integrated power generation, transmission, distribution and information systems
- Management of generation to minimize fossil-fuel use
  - integrating the full potential of solar and wind
- Demand management to
  - compensate for fluctuations in wind and solar generation by controlling load
  - Reduce/balance peak loads



Decarbonizing: Efficiency

- Energy efficient buildings
  - HVAC → solar and heat pump geothermal
- Effective Public Transport
  - Efficient, reliable, accessible, affordable, safe
- Energy efficient industrial processes
- Redesigning cities
  - Less individual driving needed
  - More suitable for public transport

Geo-engineering: Carbon capture and storage (CCS)

- Volume Needed: 1T C = 3.67T CO_2 = 4.75 cubic meters
  - Storing 1GT C will require ($1.7 \times 1.7 \times 1.7 = 4.75$) km^3
- Reservoirs are not usually near large point sources but 100s—1000s km away
- Large pipeline, handling & monitoring infrastructure required
- Uncertainty in environmental impacts/leakages
- Carbon separation technology (even at coal PP) not yet demonstrated at commercial scale (Tianjin IGCC in China)

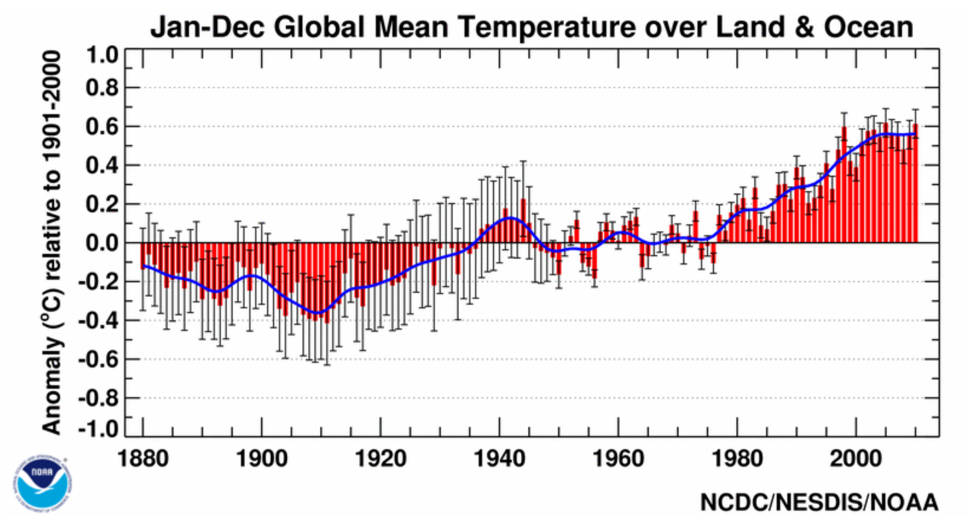
Geo-engineering: Desperation + Hubris!

1. Pinatubo Option: Dispersing ~5.5 million tonnes of sulphur (SO_2) into the stratosphere to seed aerosols

2. Cloud brightening: fine water droplets to increase reflectivity

3. Ocean fertilization: spray iron dust to stimulate algae growth

4. Carbon Capture and Sequestration



Good Reading: Eli Kintisch, "Hack The Planet", John Wiley, 2010

Sobering Lessons

- Magnitude of the challenge: the lack of alternatives at terrawatt (10^{12}) scale
- Major transformations take decades
  - coal → nuclear → gas (new additions) in the US has been a 25 year cycle
- Major transformations are often not repeatable
  - France gets ~80% of electric power from nuclear.
    The challenge now is – how to decarbonize the rest (60%) of its economy
- As developed nations become more service oriented, manufacturing shifts overseas (China). It reduces their GHG footprint but not global emissions
- In spite of economic downturn (2008-09) and increasing efficiency (miles/liter), the world still consumed 85 million boe/day (more people more cars)
- While the goal/need to stabilize CO_2 levels is clear, we do not today have a realistic roadmap (alternatives) to get us there. "Prosperity" wins elections!
- We can make major reductions by proceeding with realistic targets and creating political [social] buy in based on ***win-win (✓)*** options

There is a lot of low lying fruit to pick!

Strategy and Policy

Strategies for reducing anthropogenic GHG, climate change & impacts

- Prevention
  - ✓ Decarbonizing the economy
  - ✓ Not building in vulnerable areas / following codes
- Mitigation
  - – Geological sequestration (after point source and air capture)
  - ✓ Biological sequestration (forests and soil)
  - – Mineralization
  - – Geo-engineering (sulphates in air, seeding oceans,, ...)
- Adaptation
  - ✓ Forecasting and warning
  - ✓ Resilience: developed societies with safety nets

We will need a combination of all three

There are large uncertainties in all three

- Prevention (reducing emissions)
  - road map to decarbonizing the economy?
- Mitigation
  - Is the scale of carbon sequestration required feasible?
  - Are novel geo-engineering schemes practical?
  - Are risks of unintended consequences acceptable?
- Adaptation
  - Adequate forecast and timely warning of extreme events?
  - Will earth/bio/human systems have sufficient resilience?

Instruments of energy-climate policy

- Market based
  - Cap and Trade: Permits to bound total emissions
  - Taxes: Cut down marginal cost of last ton of CO_2 emitted
- ✓ Performance standards
  - CAFE Standards (automobile fleet km per Liter)
  - Building codes
- Government investment/spending
  - ✓ Investment in R&D to create alternatives
  - Subsidies
  - Rebates
- ✓ Education & awareness leading to smaller CO_2 footprint

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  - Subsidies
  - Rebates
- ✓ Education & awareness leading to voluntary reductions

There also are large uncertainties in

- Resource estimates – quantity, quality, cost
- Variations in regional and global climate
- Attribution: cause and effects
- Impacts and losses

- All of these uncertainties will remain significant even with increasing R&D and understanding
- The traditional role of science – precise and definite answers– will remain limited by these uncertainties
- **Policy will have to be made under these uncertainties and *politicians will have to defend any such policy over decades***

Science, motivation, cost-effectiveness and cause-and-effect better be sound

In a climate of uncertainty in

- Economy
- Energy Technologies
- Climate science and impacts

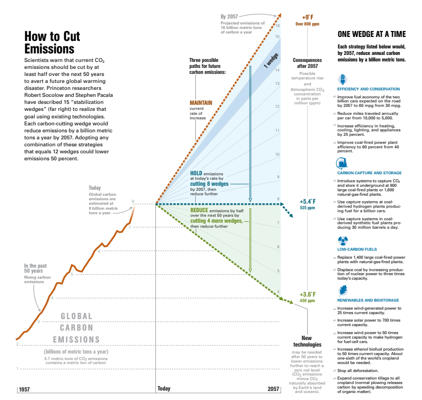
Even as solar and wind grow,
The familiar fossil fuels will also grow

Scenarios

Pacala & Sokoloff Wedges (2007)

• We have the technology: 15 strategies to create 8 wedges, each reducing emissions by over 1 billion tons of carbon/year by 2057

- ✓ Double mileage 30→60mpg of 2B cars
- ✓ Decrease miles travelled by half
- ✓ Efficiency in HVAC, lighting, appliances by 25%
- ✓ Efficiency: coal power plants 40→60%
- • CCS from 800 1GW coal power plants
- • H_2 from coal for 1B cars & CCS
- • Coal→Synfuel 30Mboe/day + CCS
- • Replace 1400 coal plants by gas
- ✓ 3X nuclear capacity to replace coal
- ✓ 25X Wind (2.5 TW)
- ✓ 700X Solar
- • 25X windmills to produce H_2 for fuel cell cars
- • 50X ethanol using 1/6 world cropland
- • Stop all deforestation
- ✓ Expand conservation tillage in all agricultural soils worldwide



Overly dependent on CCS!

Source: Princeton Environmental Institute at Princeton U. http://cmi.princeton.edu/wedges/

Pielke Framework

- Do not have adequate energy technology to decarbonize the global economy. Innovation in both efficiency & production
- Addressing climate change is a bigger issue than just GHG. CC policy has been hampered by focus on GHG

1. Set realistic goals (many may address climate only obliquely) that embrace development
2. Need broad based innovation in energy technologies. Even geo-engineering should be on the table
3. Fund innovation by an upstream carbon tax (tax to fund innovation & not climate change)
4. Progress should be continuously monitored and policy adjusted based on performance

Source: Roger Pielke Jr., "The climate fix", Basic Books, 2010

Gedanken 2050 scenario revisited

See Slide 3

	Target: Peak TW expected by 2050	Equivalent TW at 70% PLF 2050	Achievable TW at 70% PLF	Proposed/ Achievable
Coal	2.5	3	2.5	83%
Gas	2	2	2.5	125%
Hydro	1.8	1	0.8	80%
Nuclear	1.7	2	1	50%
Wind	6	2	1.33	67%
Solar	4	1	0.5	50%

Coal & Gas will still contribute ~60% of power globally, down from ~75% today

Priorities:

Broad based R&D in energy-climate science and technology

Innovation Fund:
If I was allowed to pick only 5 Priorities

- Storage: 3X Battery for cars (Higher power and energy density and longer life). ***Fuel cells? Grid scale storage?***
- Solar PV at $2/Watt$_p$ installed & 200 GW/yr manufacturing (16 X 2012 capacity) *Address the issue of rare Energy Critical Elements*
- Forecasting and control systems
  - *Smart Grid* to integrate solar and wind & load balance:
- Carbon Capture and Storage (CCS)
- Nuclear Fuel Cycle: reprocessing & waste management

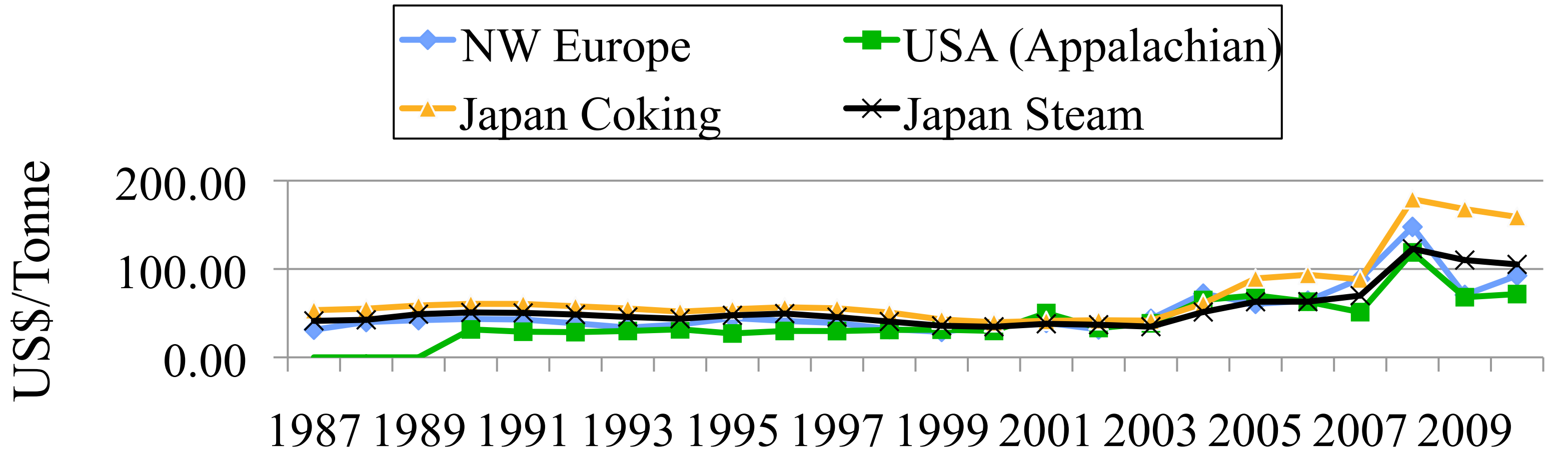
4 Infrastructure Priorities

- Cities and communities planned around energy efficiency
- Public transport & electric long-haul railway
- Energy efficient buildings
- Solar/geothermal hot water and HVAC systems

What lies ahead

- Environmental Impacts & loss of species
- Accumulating evidence of Climate Change
- Uncertainty in maturity/scale of alternatives
  - Uncertainty in date at which GHG emissions will peak
- Volatility in price of fossil fuels for many countries
  - Many countries will be unable to afford clean energy (or even fossil-fuel) systems → this will severely impact Energy Security and Development?

Coal and Gas Prices: Expect Volatility



Source: BP Statistical Review 2011

Impacts and Consequences

- Environmental Impacts & loss of species
- Accumulating evidence of Climate Change
- Uncertainty in maturity/scale of alternatives
- Volatility in price of fossil fuels for many countries

→ Will continue to push countries and the world to reassess their energy needs. Without credible alternatives, the transformation will be slow, uneven, and painful.

→ Impacts of climate change (with/without economic shocks) likely to be catastrophic in the 21st century

Conclusions

- Uncertainty in science, technology, policy, impacts will persist
- Under market driven scenarios, stabilizing CO_2 emissions to 30 GT/yr (2010 levels) by 2050 is unlikely
- Resource constraints/distribution of oil, gas, and coal (conventional and unconventional) will lead to large price volatility. There will be steady & growing pressure towards carbon-neutral systems
- Significant progress in decarbonization can be made if
  - Low hanging fruit (energy efficiency) is picked
  - Nuclear power grows in the 21 coal using countries
  - Smart grid that integrates wind and solar becomes the norm
  - Growth in electric vehicles and public transport systems
- Wind and solar technology will continue to mature → reach 20% capacity
- We will not be able to provide adequate power to 9+ billion people globally
- The global poor without access to energy will have a growing barrier to development and will be significantly impacted by climate change

In the 21st century the world will not stop using fossil fuels because there is not enough, but because there are cleaner cost-effective alternatives

By 2050, most of the easily accessible conventional sources of coal, gas and oil will have been exploited and depleted except in few countries with the largest reserves.

Unconventional oil & gas is more costly
→ large volatility in price and access

Finally: What is the DEEC Challenge?

- The global system is being pushed to [over] the edge of sustainability and natural recovery on all fronts making it vulnerable to catastrophic failures
- Formulating consistent policy over decades in the face of uncertainty & costs requires exceptional leadership
- **Enlightened Governance**
  - **Outstanding Leadership**
  - **Trust**
  - **Transparency/No Corruption**
  - **Bi-partisan Politics**

Playing dice with nature:

All faces are the same and nature gets to call

Extras

Dire need for developing enabling long-term energy-climate policy

- Creating incentives and an environment in which efficiency and demand reduction pays
- Investing in R&D—investment fund
- Setting attainable and phased goals for transformation to carbon-neutral systems
- Performance monitoring and evaluation
- Long-term integrated approach to understanding and evaluating climate change and impacts due to all causes – changes in land use, natural variations, GHG, black carbon, aerosols, clouds, ...

Population without access to energy

- Population growth rate of 75 million/year is mostly in the poorest 25% — Africa and South Asia
- Poor are highly vulnerable to climate change
- Moral imperative to provide global population with modern opportunities for development
  - affordable access to energy (lowest cost)
- Development, education, access to modern birth control methods leads to population stabilization
- Population growth often leads to long-term destabilizing factors: civil wars, deforestation, poor governance, migration, ...
- Population stabilization—an important goal

Good News: Unprecedented changes are taking place

- Any 1.5-12V battery doable function can be powered by batteries that can be recharged by a PV panel*
  - LED: revolutionize room/space lighting
  - Cell phones → Computers: access to global communications
- Electric power for individual homes (off-grid and grid-connected) is fast becoming cost effective
  - Photovoltaic (PV) at \$3-4/W_p installed will be a game changer
- Developing vaccines & eradicating diseases
- Improvements in agriculture
- Wind turbines are cost-effective and technology is mature

***need to reduce capital costs for access by the poor**

Unprecedented changes are taking place

- There is growing awareness of climate change
- Many countries (and states within them) are developing regulations and providing incentives to increase efficiency and to decarbonize
- Developing countries have significantly reduced their environmental footprint
- Many international companies have incorporated "green" development into their business practices.
- The automobile and appliances industries are transforming
  - Future of private transport: Robot driven dispatch vehicles

But GHG emissions are still growing

Extra: Coal and Gas

Coal and Gas: strategy for growth

- Lock-step development of resource and usage
  - Assume using most efficient technology of today
  - Coal power plant bundled with ~30 year coal resource
  - 1 TW coal PP @70% PLF requires ~3BT coal/year
  - CCGT to Gas pipeline or LNG terminal
  - 1 TW gas CCGT @70% PLF requires ~1.2B cum/year
- Capacity saturation based on domestic coal resources
  - China: ~600 GW of coal PP capacity
  - India : ~300 GW of coal PP capacity

Significant coal export capacity 2050+: USA, Russia, Australia

The price of coal will rise significantly post 2030 when a large part of ongoing PP capacity addition will be in place

BAU: Coal-fired generation

- Installed Capacity: ~ 2 TW
- Average efficiency of generating units: ~32%
- Coal Consumption: ~ 7 Gigatonnes
- CO_2 emissions: ~ 14 Gigatonnes

2050

- – Generating units → [ultra]supercritical (42+%)
- – Installed Capacity ~2TW
  (we assume it will reach ~ 3TW by 2030 & then decrease)
- – Will consume ~ 7 Gigatonnes of coal
- – Will produce ~ 14 Gigatonnes of CO_2

BAU: Gas-fired Generation

- Installed Capacity: ~ 1.5 TW
- Gas Consumption: ~ 1.5 Trillion cubic meters/yr
- Need to reduce gas leakage and gas flaring

2050

- Capacity will reach ~ 2.5TW
- Generating units → Combined Cycle Gas Turbines (~58%)
- Will consume ~ 3 Trillion cubic meters/yr
- Will produce ~ 5.5 Gigatonnes of CO_2

Gas has mostly replaced oil and is slowly replacing coal

BAU scenario for coal & gas will persist

- Alternatives (wind and solar) unlikely to scale up to even my Gedanken numbers ($6TW_p$ and $4\ TW_p$) by 2050
- To scale wind from 200 GW to 6 TW, need average annual growth rate of 10% (includes replacement of 1 TW retired)
- To scale solar from 40 GW to 4 TW, we need average annual growth rate of 13.5% (includes replacement of 0.5 TW retired)
  - Will require breakthroughs in materials/nano science and substitutes for "rare" energy critical elements to scale up production
  - fully functional smart grid to integrate wind & solar
  - Grid-scale storage
- *Key question: Will countries replace inefficient coal units by latest technology or nuclear or social pressure will force phase out of both?*

Today: grid-scale backup for wind & solar are hydro and gas