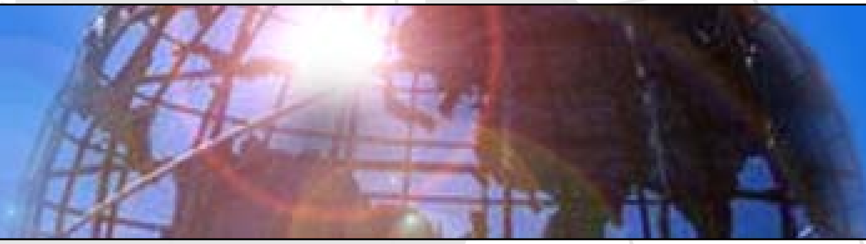
Stanford University

Precourt Institute for Energy

MBARI
Moss Landing
February 13, 2013



Transforming Energy in the 21st Century

Lynn Orr

The Challenge

Meeting Needs

- World population of 7 billion growing to ~9 billion. 2 billion people currently have no access to modern energy systems
- Improving standard of living in growing economies of developing world
- Increasing demand for energy, food, land, and materials.

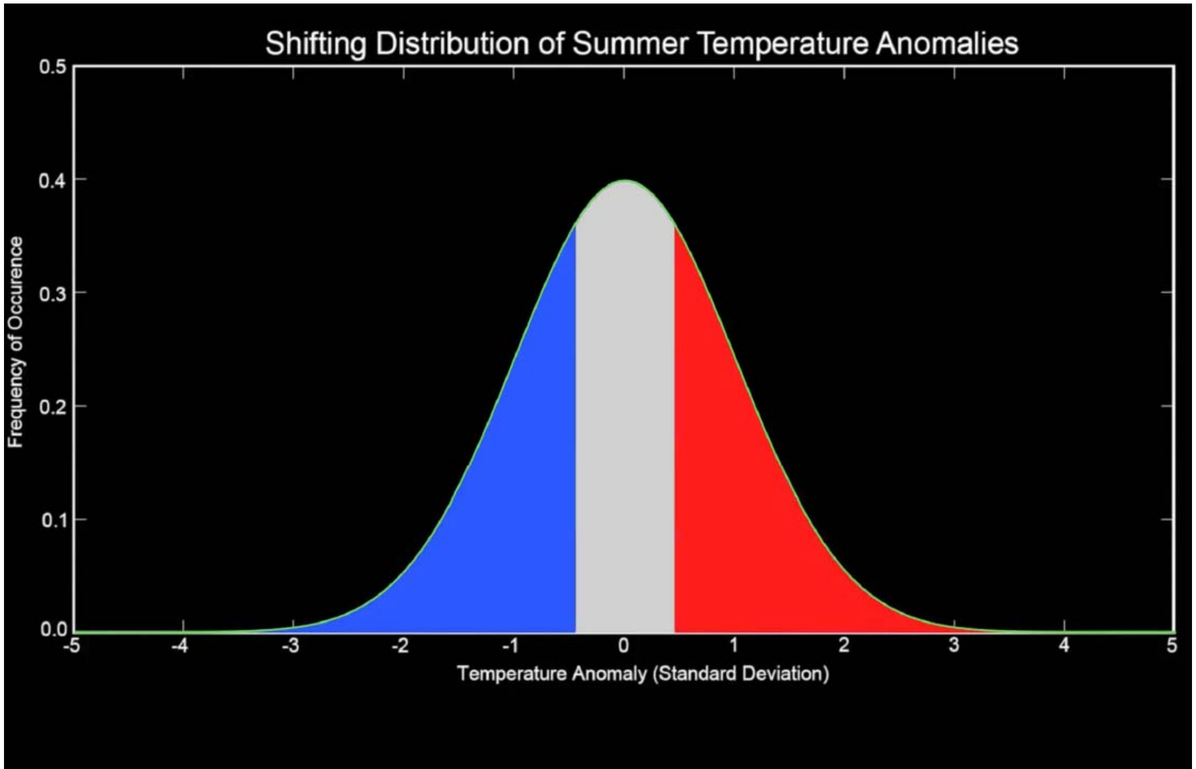
Protecting, Restoring, and Sustaining Global Biogeochemical Systems

Component Challenges

- Water supply
- Food supply (strongly linked to water supply)
- **Energy – with constraints on CO_2 and other GHG emissions**

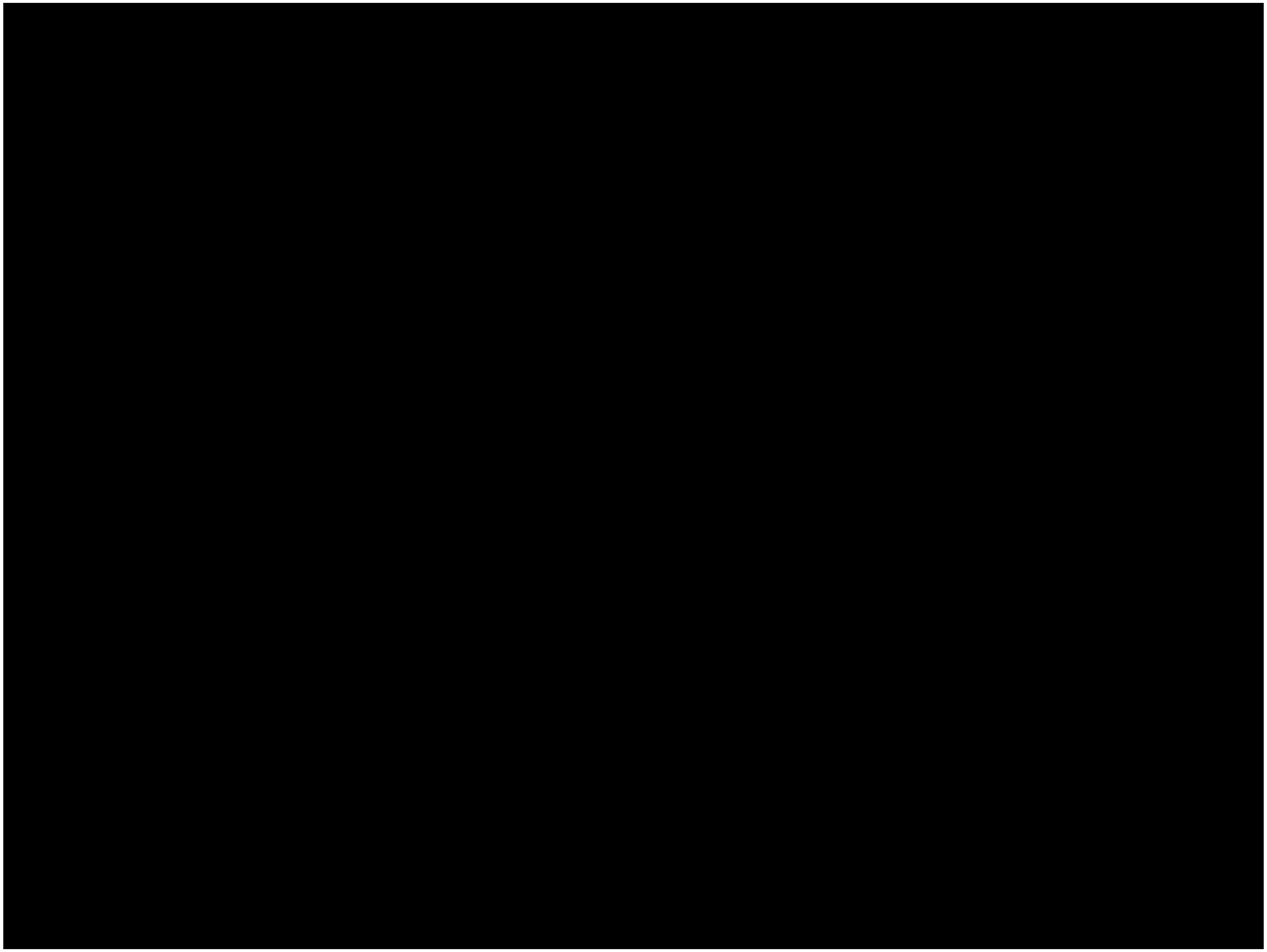
Is climate really changing?

- Observed summer temp anomalies, from direct measurements of air temps at met stations (land data)
- 1951-1980 baseline
- No modeling required, strictly observations
- How does the distribution of temp anomalies change?

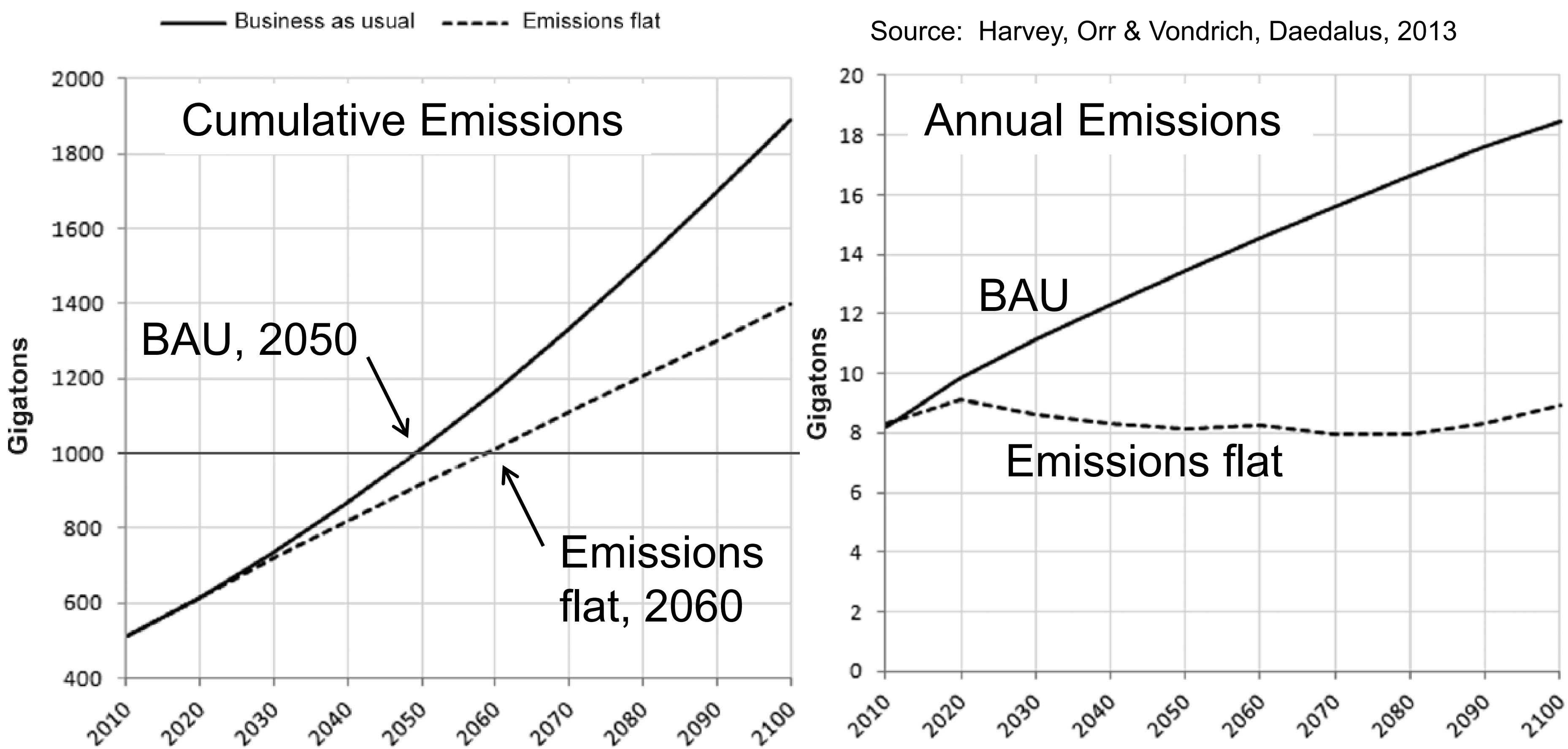


Hansen, Sato, Ruedy, "Perception of climate change," *PNAS*, Aug. 6 (2012)

Summer temperature anomalies

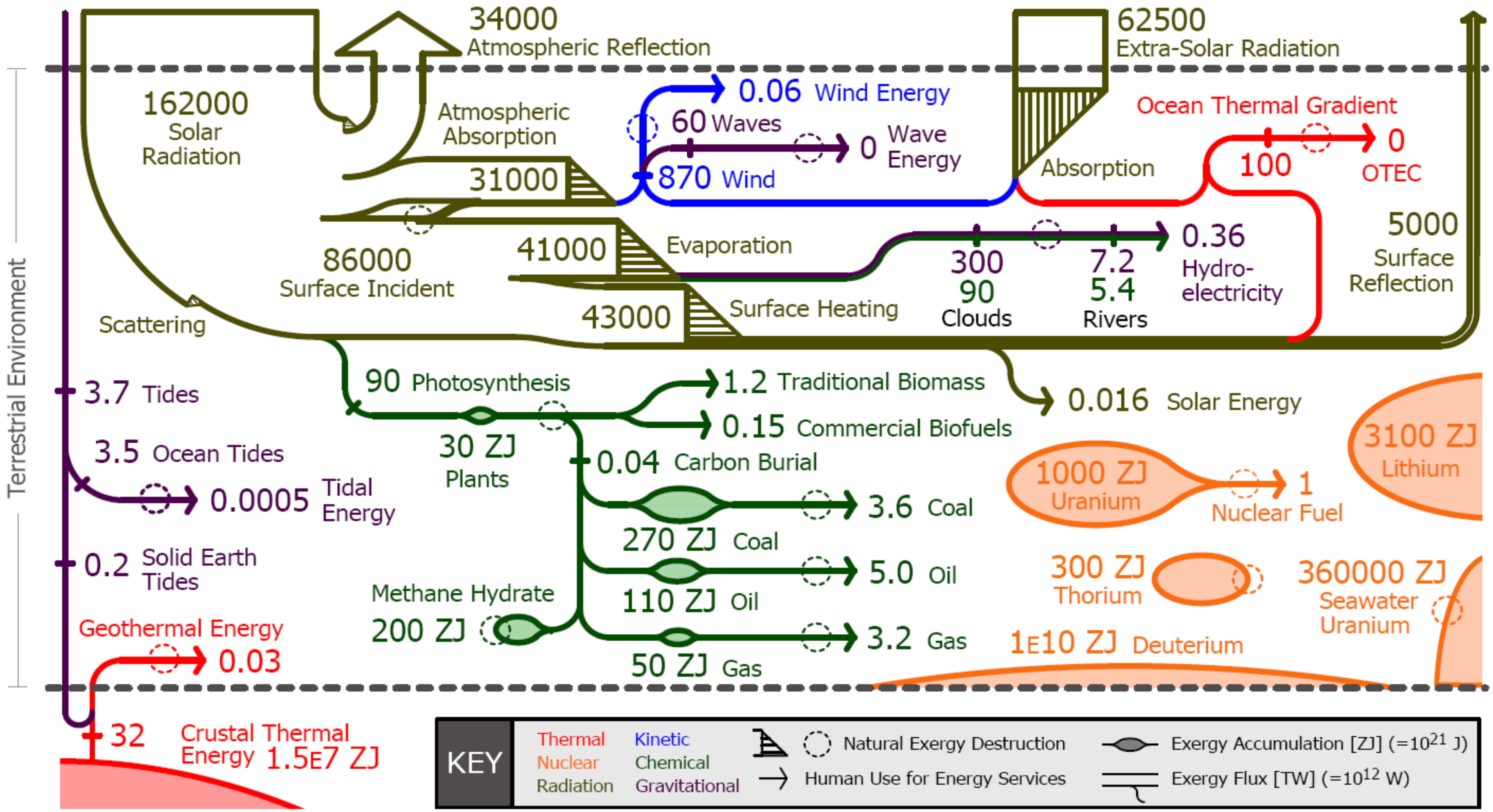


A trillion tons – deep reductions in carbon emissions are required



Climate models suggest that we can emit no more than about 10^{12} tons of carbon if we wish to hold average temperature increase to about 2˚C – and we have already done about half that. Even if all new energy supplies have zero carbon emissions, we reach a trillion tons in about 2060.

What resources can we use?
Exergy flow of planet Earth (TW)

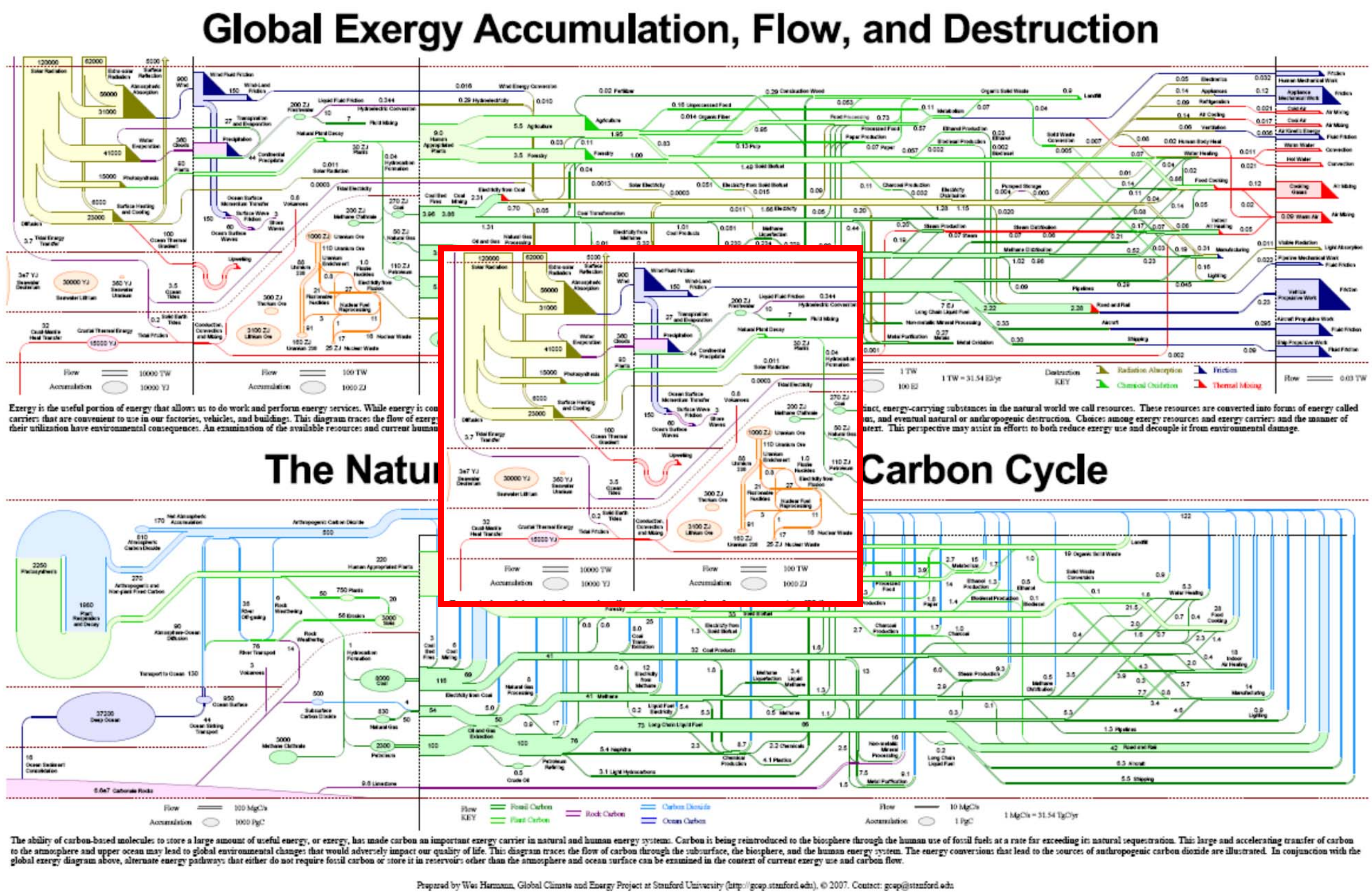


Exergy is energy that can be converted to another useful form: electricity, mechanical work, or heat.

Current Global Exergy Usage Rate ~ 15 TW (0.5 ZJ per year)

Assessment of Global Exergy Sources and Flows

Wes Hermann, A.J. Simon, Ljuba Miljkovic

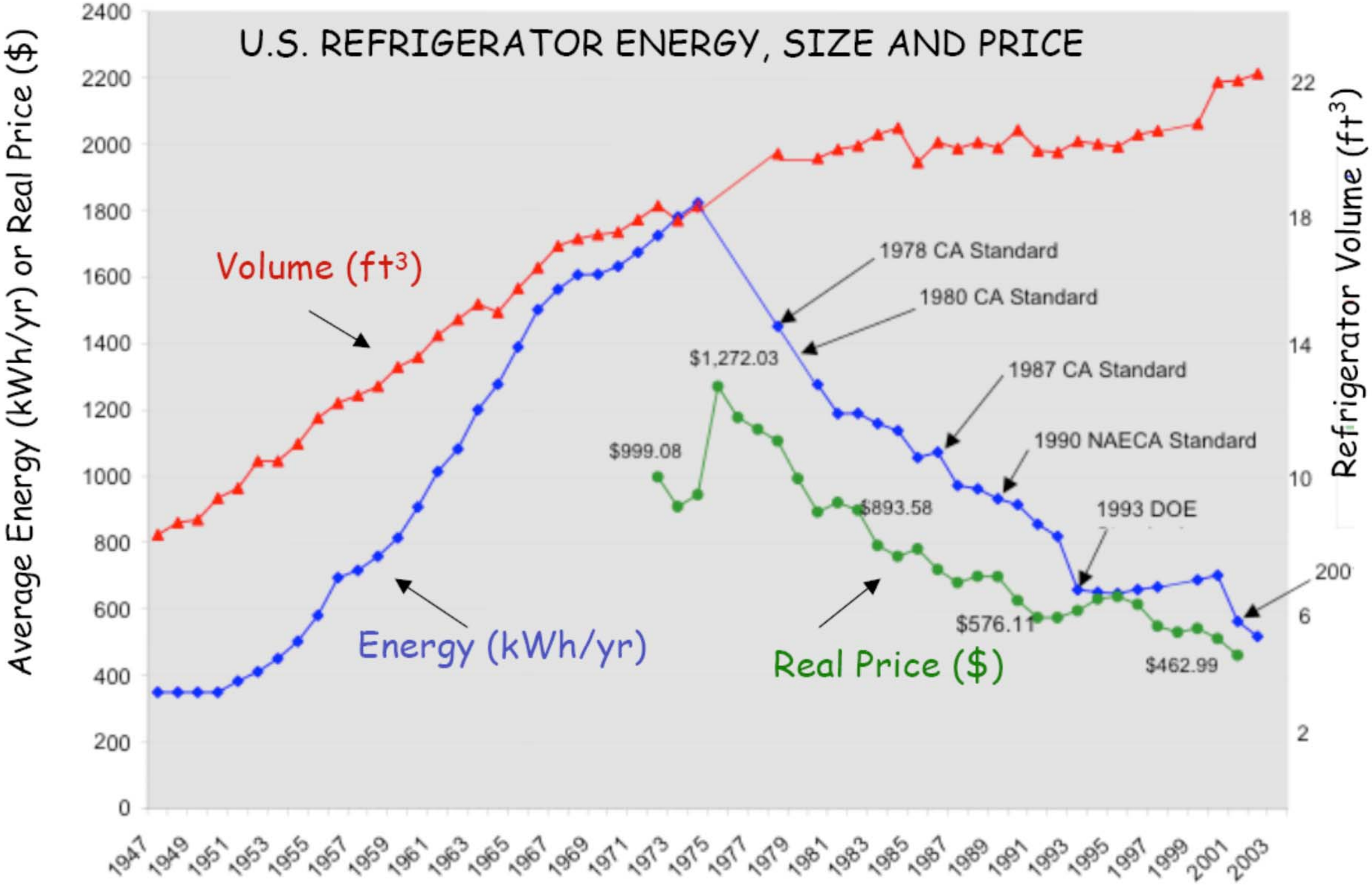


Source: W. Hermann, GCEP Systems Analysis Group 2004.

Options for Reducing GHG Emissions

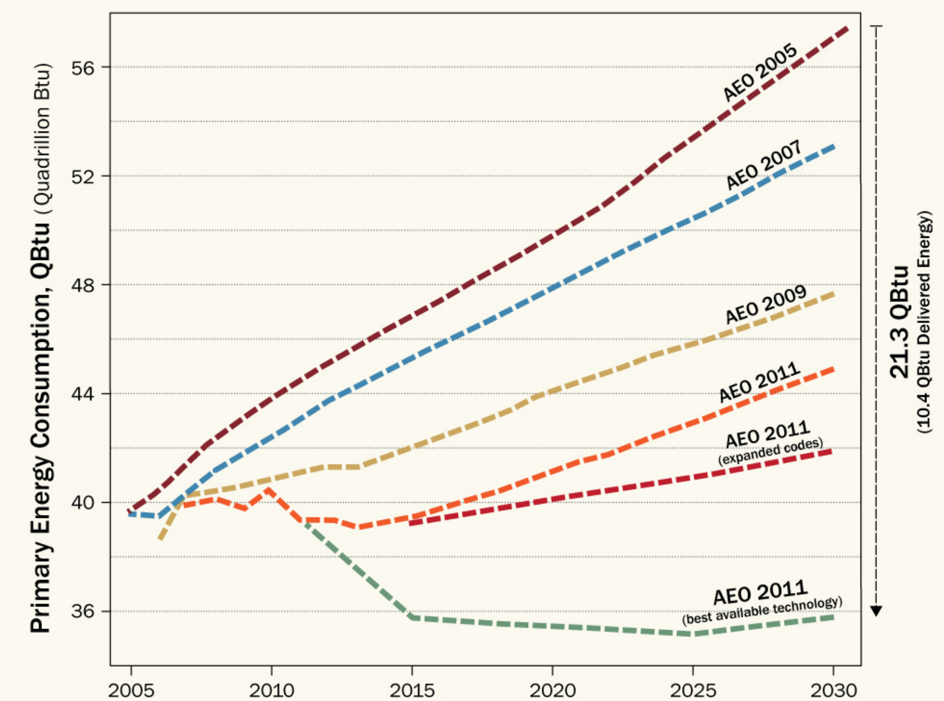
- Increase the efficiency of energy conversions
- Switch to primary energy resources that have no or lower carbon emissions:
  - Wind, solar, nuclear, geothermal
  - Biomass (with minimal fertilizer, water pumping, …)
  - CH_4 instead of coal (~1/2 the CO_2 per unit energy in the fuel, and higher efficiency in the power plant)
- Reduce the number of energy conversions (fuel to heat to electricity to heat; sunlight to sugars, to ethanol, to mechanical work in a vehicle) – each conversion has an efficiency, typically much less than 100%
- Capture some of the CO_2 and store it somewhere other than the atmosphere

An Efficiency Success Story



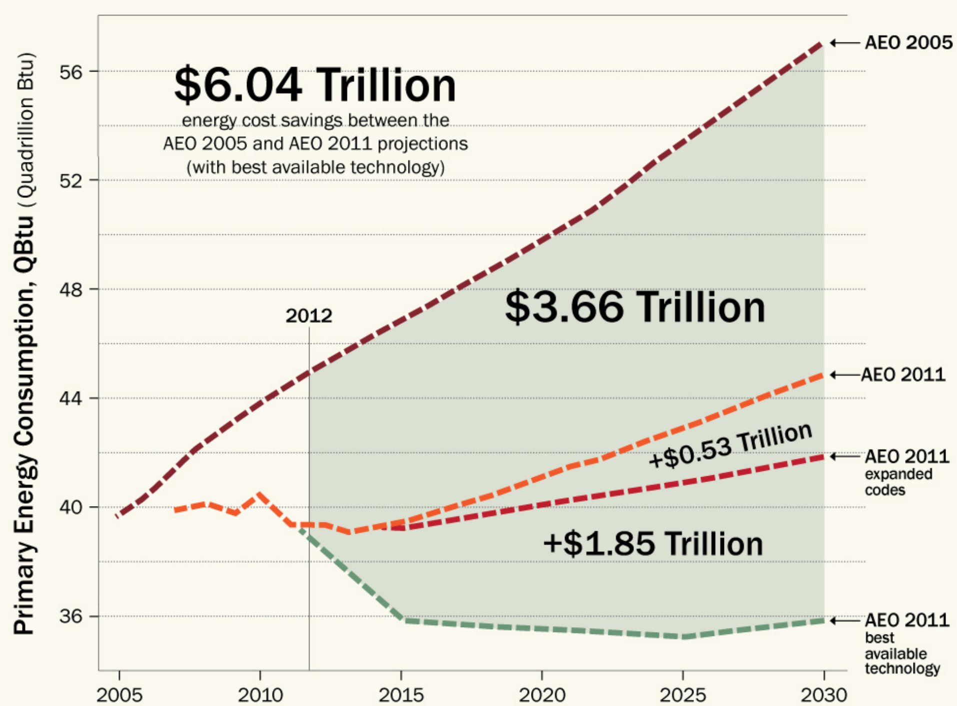
70% energy savings, 60% cost savings, 20% bigger since 1975

More efficient buildings



U.S. Residential and Commercial Energy Consumption
Projections from 2005 to 2030

Source: ©2012 2030, Inc. / Architecture 2030. Data Source: EIA AEO 2005, 2007, 2009 and 2011.
Notes: 21.3 Qbtu of primary energy is the equivalent of approximately 10.4 Qbtu delivered energy, or the energy delivered from 994 large 500MW coal plants.
AEO 2005 only provides projections to 2025. Architecture 2030 extended the forecast to 2030.

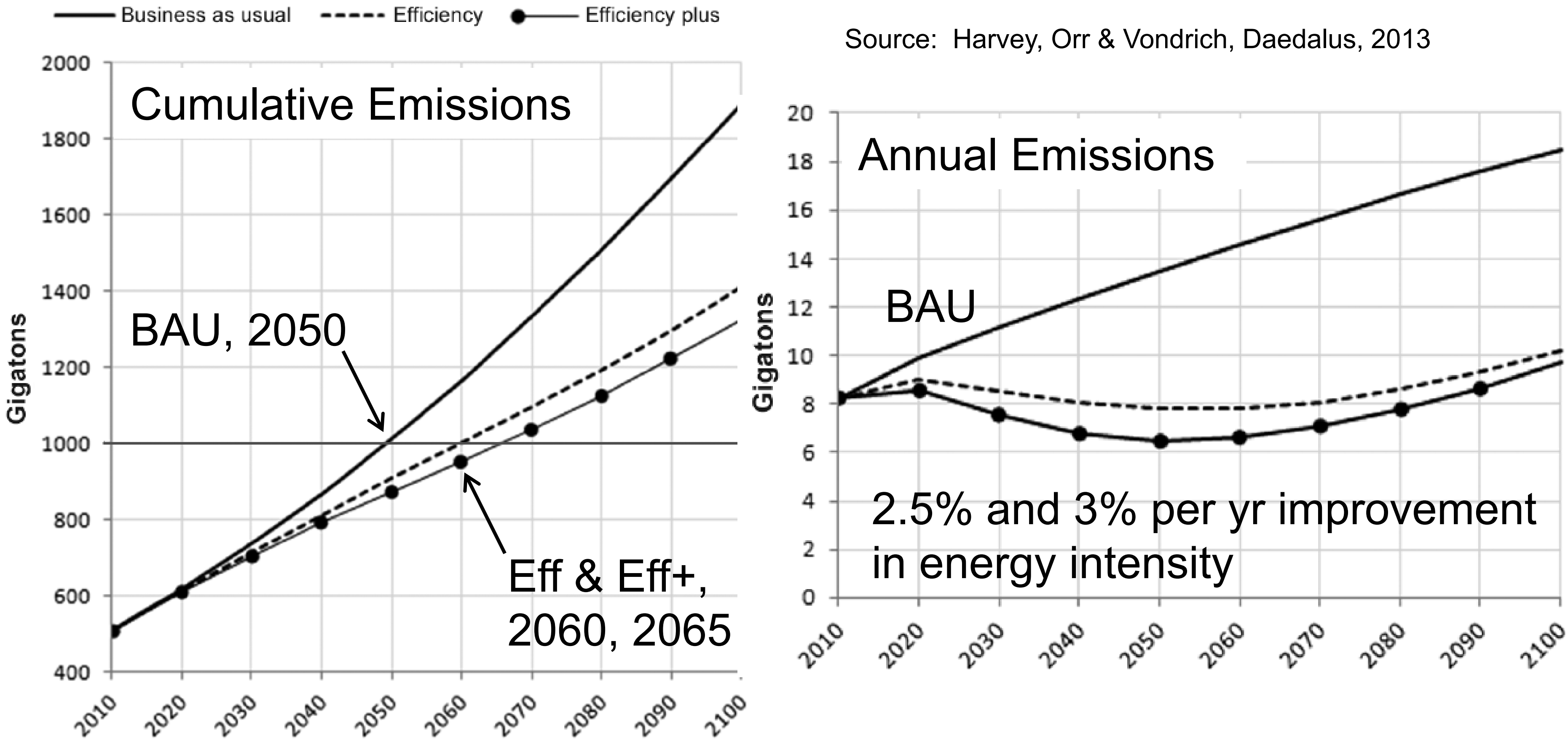


U.S. Residential and Commercial Energy Consumption
Projections and Cost Savings

Source: ©2012 2030, Inc. / Architecture 2030.
Data Source: EIA AEO 2005 and 2011 (figures in 2009 dollars). DOE EERE 2010 Building Energy Data Book.
Notes: AEO 2005 only provides projections to 2025. Architecture 2030 extended the forecast to 2030.

These savings are possible because US energy efficiency is poor. Europe and Japan do much better. The challenge for the developing world is to build in efficiency as their economies grow – China is a positive example

Energy efficiency buys valuable time



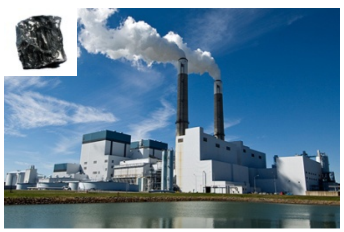
Assumed BAU energy intensity improvement is 1.1% for 2010-2050. Efficiency reduces emissions for a while, but eventually growth in energy use wins. Investment now in efficiency buys time to implement other changes, and much of it has negative amortized cost.

Energy Conversions

- All energy systems start with some primary energy resource and convert it to some more useful energy service
- All energy conversions are less than 100% efficient: well engineered systems exceed 50% of theoretical max
- Example – IC automobiles: primary resource is petroleum → gasoline (~85%) → internal combustion engine → mechanical work (16-32%) → waste heat – well to wheel efficiency14-27%
- Systems with fewer conversions can be more efficient

Average Conversion Efficiencies

Nuclear – 30%



Coal – 30-40%

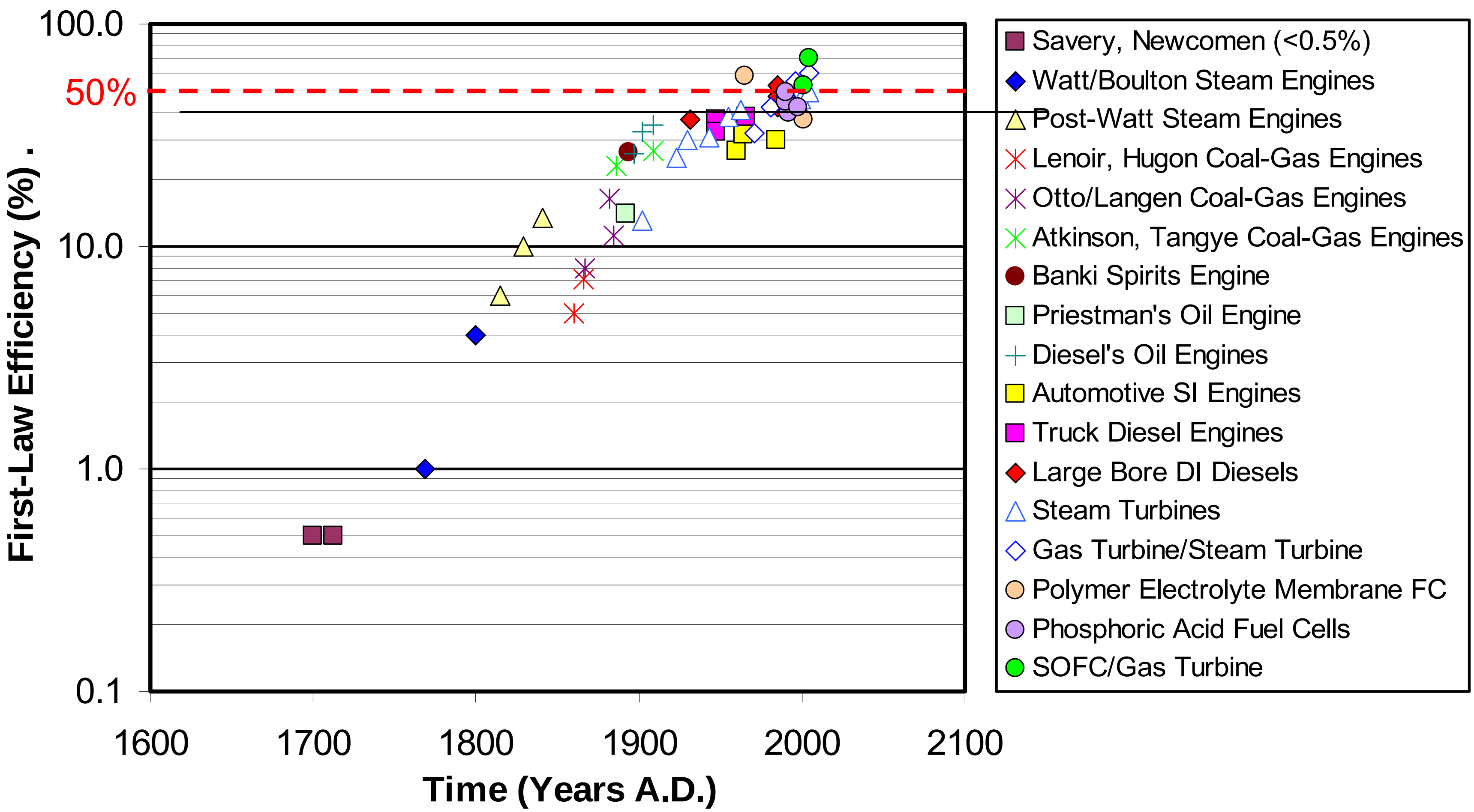
Natural Gas – 40-60%

Wind – 50%

Solar – 15%

Source: US EIA, http://www.eia.doe.gov/cneaf/electricity/epa/epata6.html

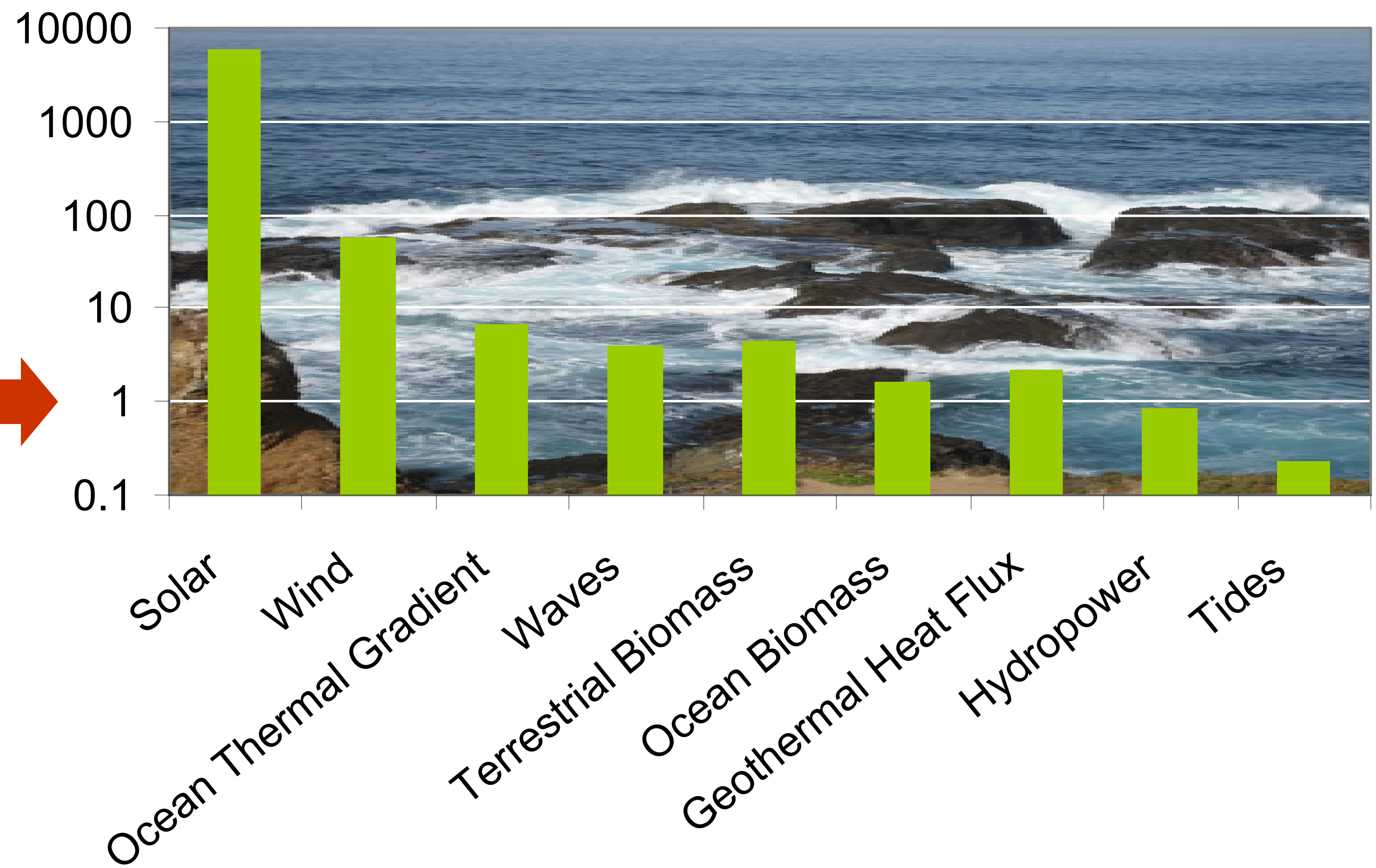
Conversion Efficiency of “Engines”



Source: C. Edwards, GCEP

Renewable Global Exergy Flows

Human Use of Energy (15 TW)



Exergy sources scaled to average consumption in 2004 (15 TW)

From Hermann, 2006: Quantifying Global Exergy Resources, Energy 31 (2006) 1349–1366

Wind

- Close to competitive now with no subsidy for onshore locations with good wind resource
- Better offshore resource, but higher costs
- A 1MW wind turbine can offset ~2500 t CO_2/yr, 400,000 turbines for 1 Gt CO_2/yr
- Intermittency will require a much more capable grid!
- Wind resources may or may not be close to electricity demand

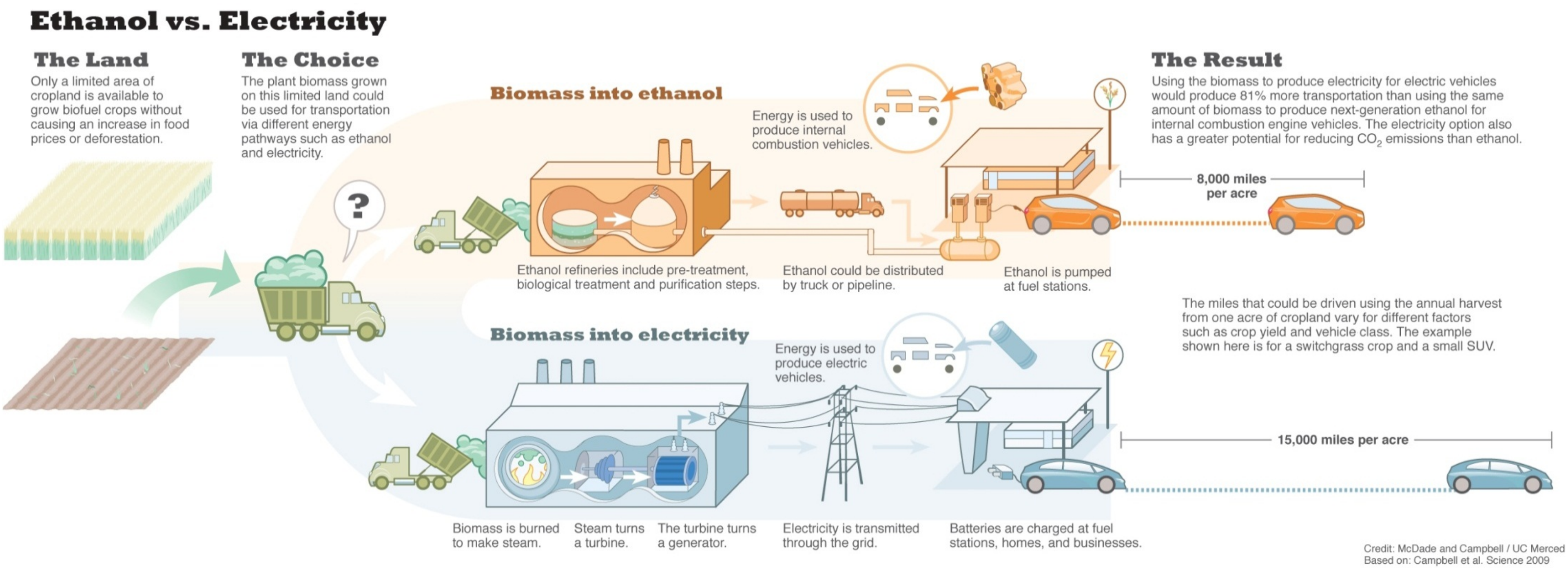
Biomass

- Biofuels – possible significant contribution but not enough to do all fuel use
- Plants are low efficiency solar fuels collectors: corn, 0.4%, sugar cane 0.8%. Need to use a bigger fraction of the stored energy (cellulose, lignins)
- Algae is a more efficient solar collector (8%)
- Ethanol from corn ~30% better than gasoline on CO_2 emissions (if credit given for byproducts and if great care used in separation of EtOH from water).
- Biodiesel will remain small if produced from seed oils
- Land area, water use, fertilizer, competition with food are issues

Courtesy of Steve Long et al

Ethanol?

- Issues: overall conversion efficiency and life cycle energy production, hydrophylic fuel
- Cellulosic EtOH uses a bigger fraction of the biomass
- Lignins are still a problem



Source: Campbell, Lobell, and Field (2009), Science, 324; 1055-1057

Energy's Impacts

Switching from corn to perennial plants and cellulosic biofuel has multiple benefits

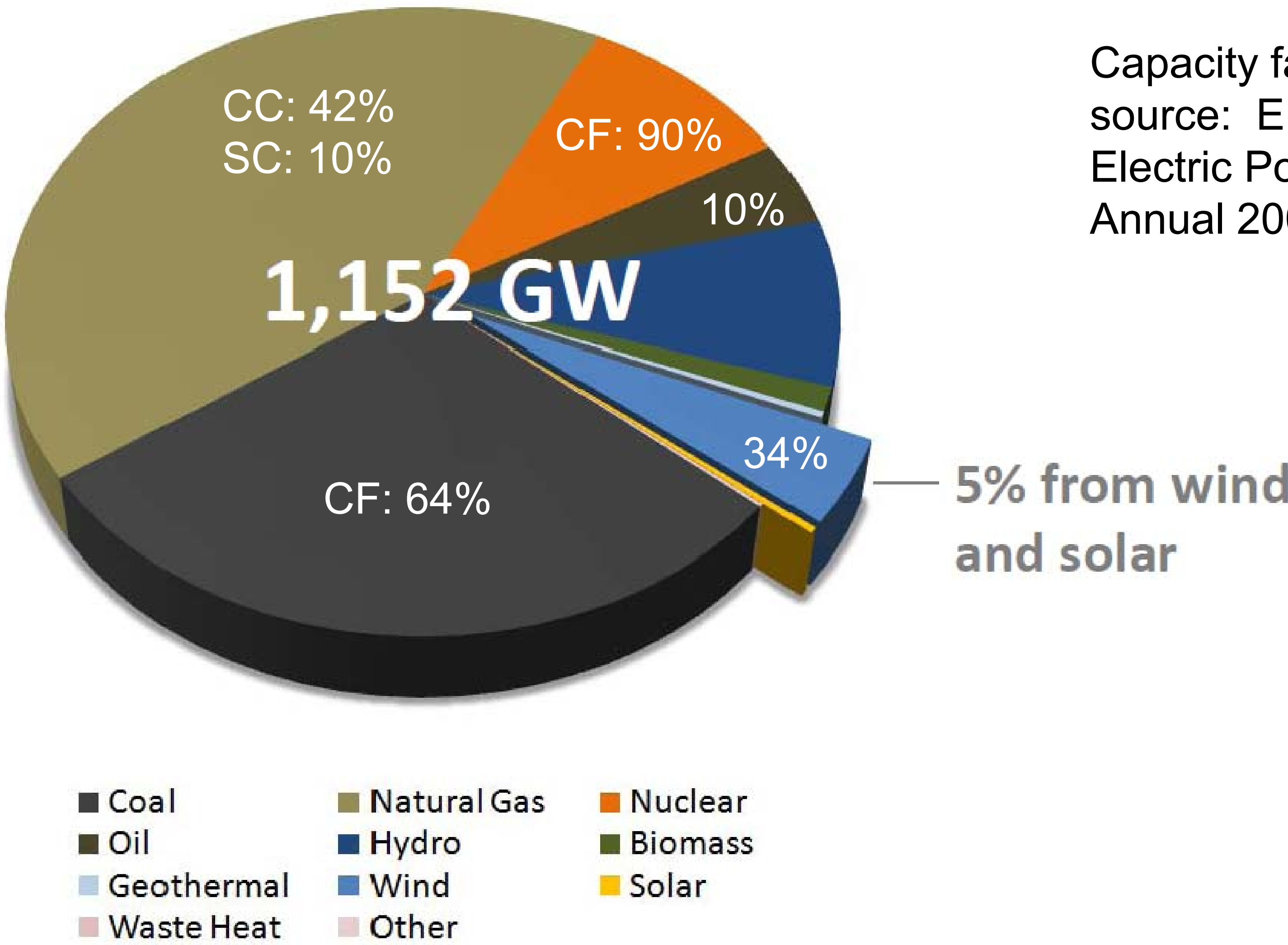
- Better energetic efficiency
- Miscanthus extends growing season by two months
- Added reflectivity creates 6X benefit of corn's GHG offset
- Local cooling from evapo-transpiration
- Biofuel analysis must include land use issues

David Lobell, Chris Field (Environmental Earth System Science)

Solar Electric Power Generation

- Solar – huge resource, cost is the primary issue
- 4000 km^2 of 15% efficient PV cells replaces coal-fired power to save 1 Gt CO_2/yr
- Intermittencies: day/night, cloud cover (~days), winter/summer
- Solar thermal (with concentration) can have higher efficiency and can include storage, lower coe than PV

US Installed Generating Capacity
(but remember differences in capacity factors)



Capacity factors source: EIA Electric Power Annual 2009

Source: FERC, Office of Energy Projects, Energy Infrastructure Update, Sep 2012

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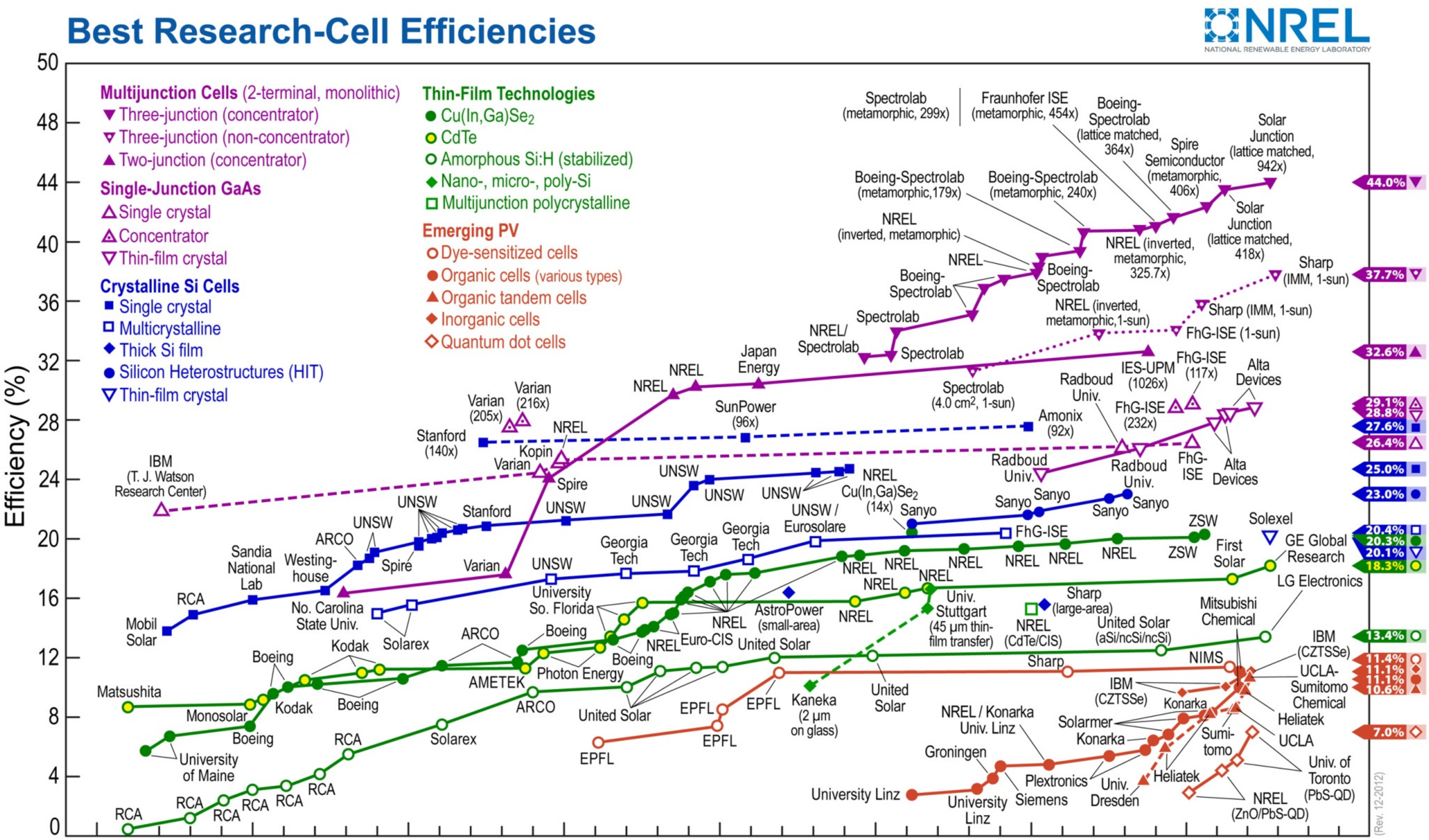
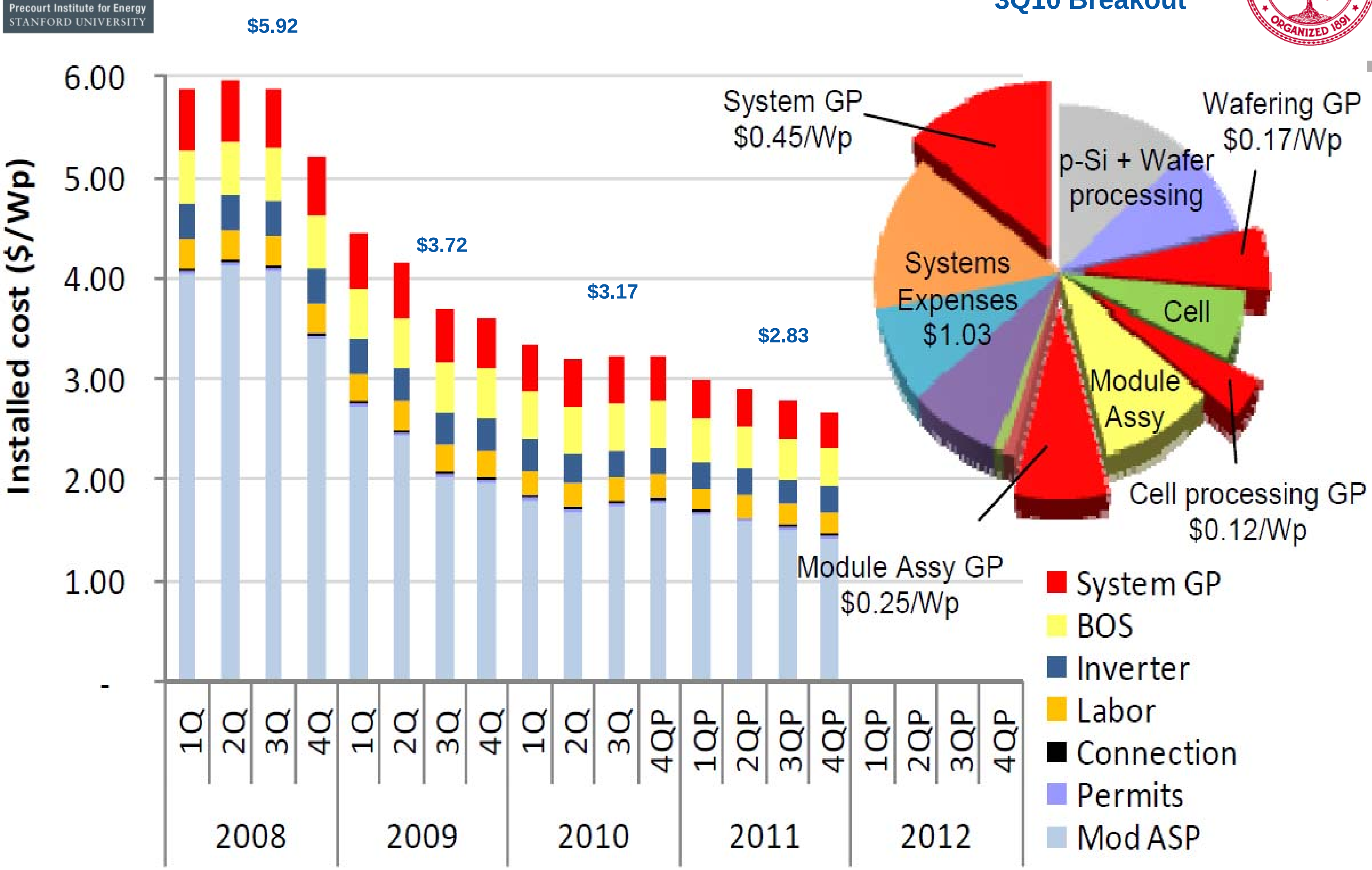
Efficiency of Solar Cells



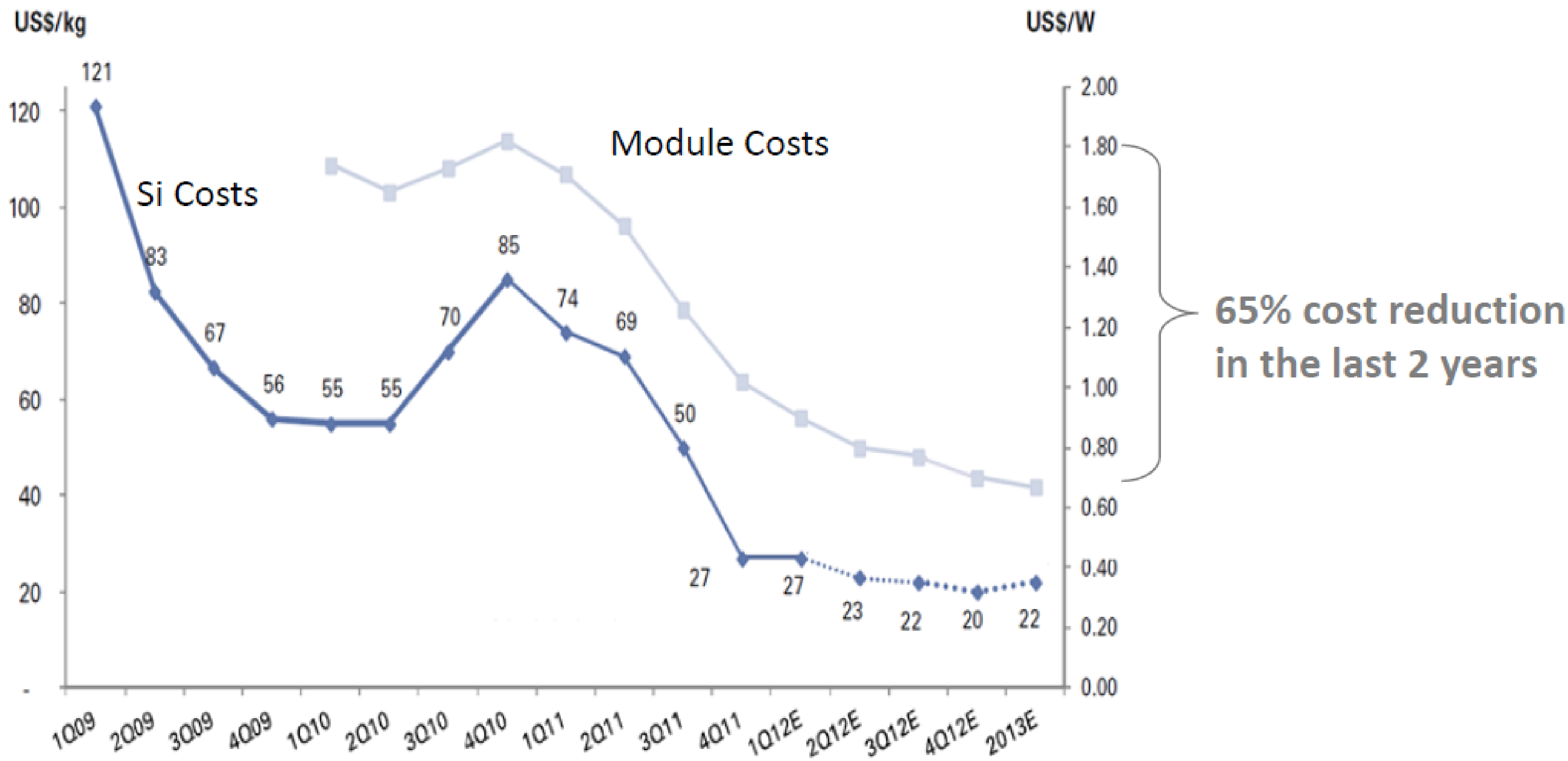
Source: http://www.nrel.gov/ncpv/images/efficiency_chart.jpg

Installed System Price per Watt, 2008-2011



Original Source: Deutsche Bank, January 2011; Systems are global (i.e., blended across geographies)
My source: R. Swanson, IEEE PV Specialists Conf., June 2011, as quoted by McGehee

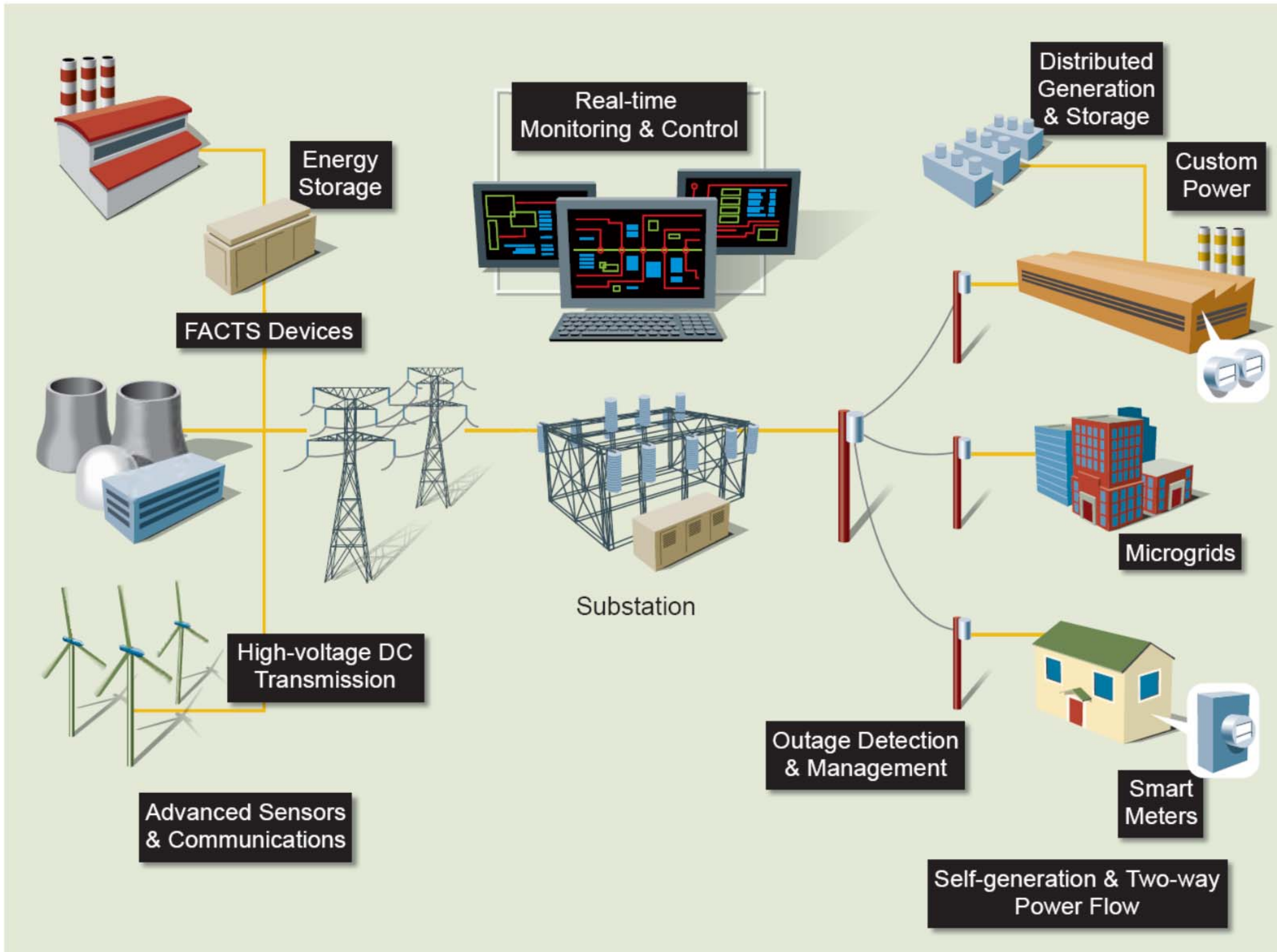
Manufacturing efficiency and oversupply in PV market has led to deep cost reductions



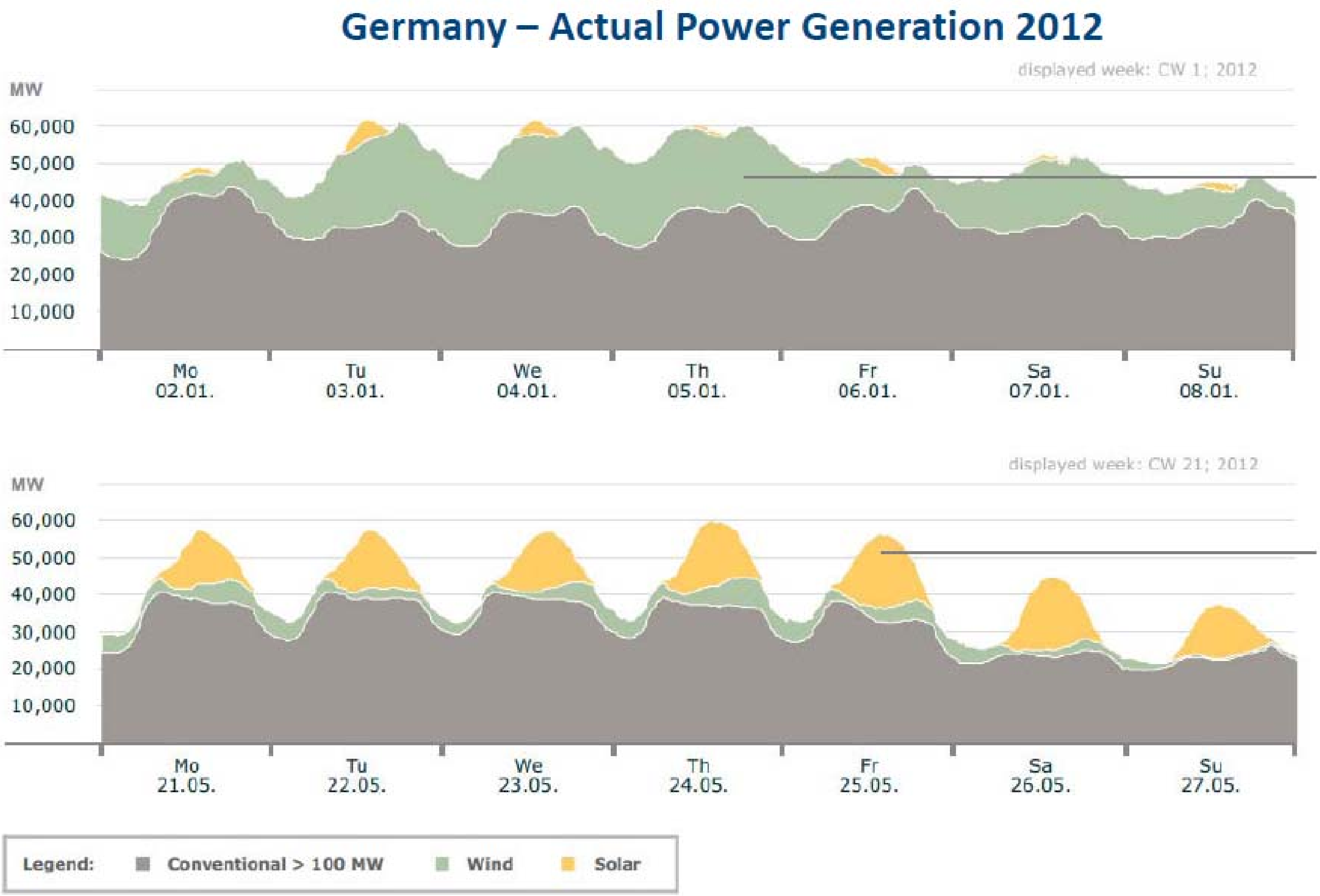
Source: Goldman Sachs, PV Insights

The grid of the future

- Able to move power from resource areas to loads, tolerate intermittency
- Sensor laden
- Active controls on power flows
- Secure and robust to local failures
- Storage
- Demand follows supply (load balancing and shifting



Wind plus solar mitigates intermittency

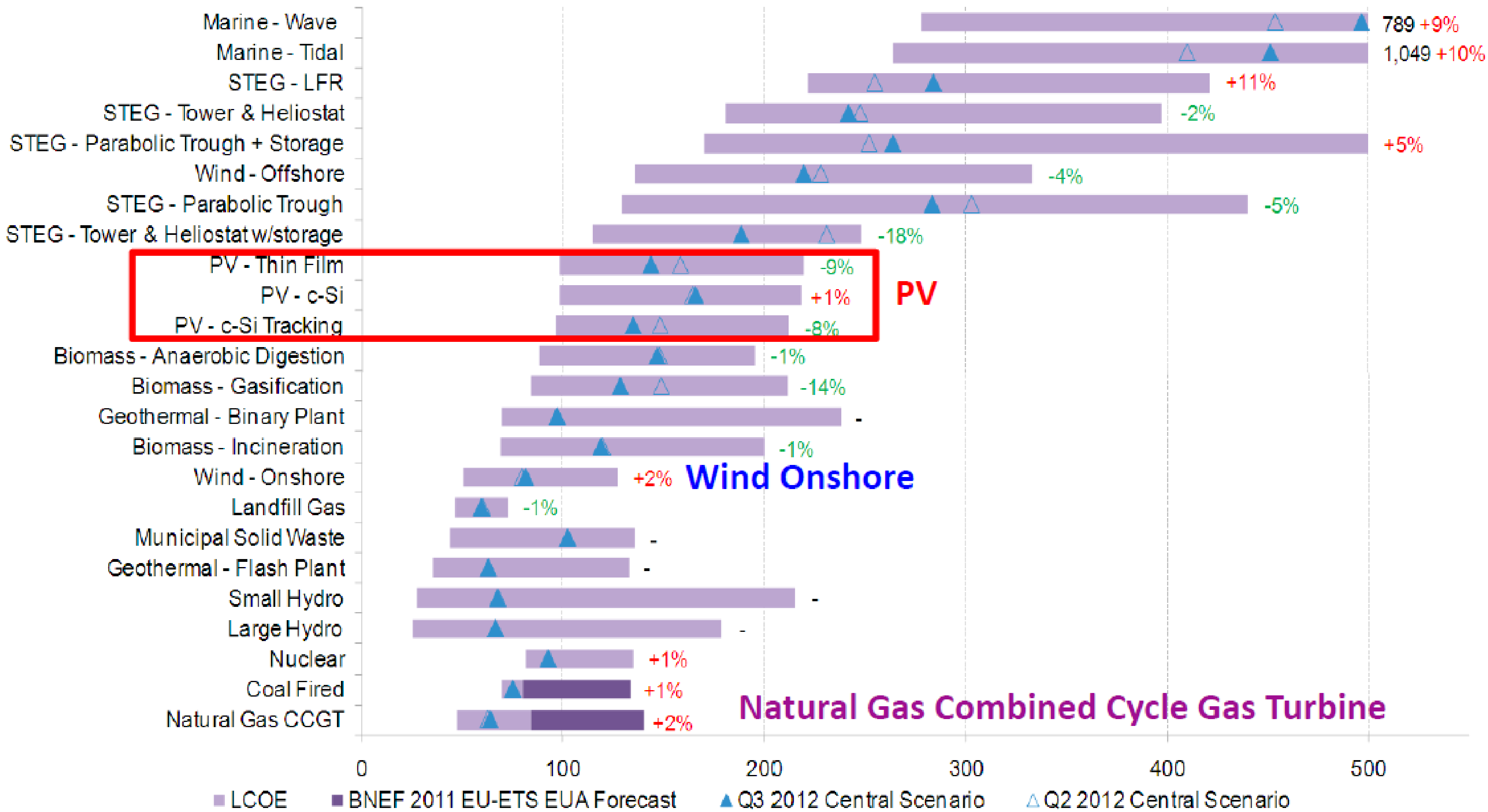


Jan 2012: Wind
24.1GW power
2.6TWh energy

May 2012: Solar
22.4GW power
1.1TWh energy

Source: Fraunhofer ISE, Data: EEX

Levelized cost of electricity, Q3 2012 ($/MWh)



Source:Bloomberg New Energy Finance. Note: Carbon forecasts from the Bloomberg New Energy Finance European Carbon Model with an average price to 2020 of $30/mt. Coal and natural gas prices from the US EIA and BNEF. Percentage change represents change from Q2 2012

Source: Bloomberg New Energy Finance

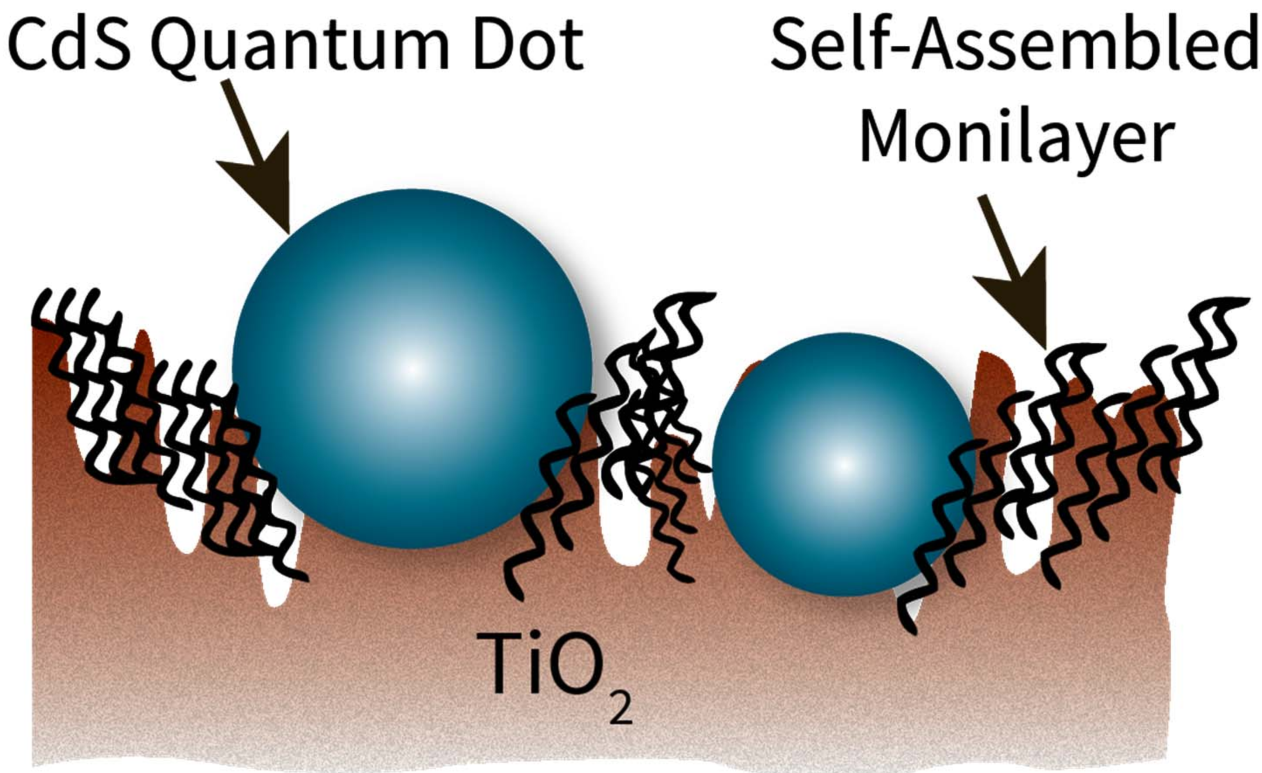
Advanced Energy Materials

Quantum dot sensitized solar cells increase cell efficiency

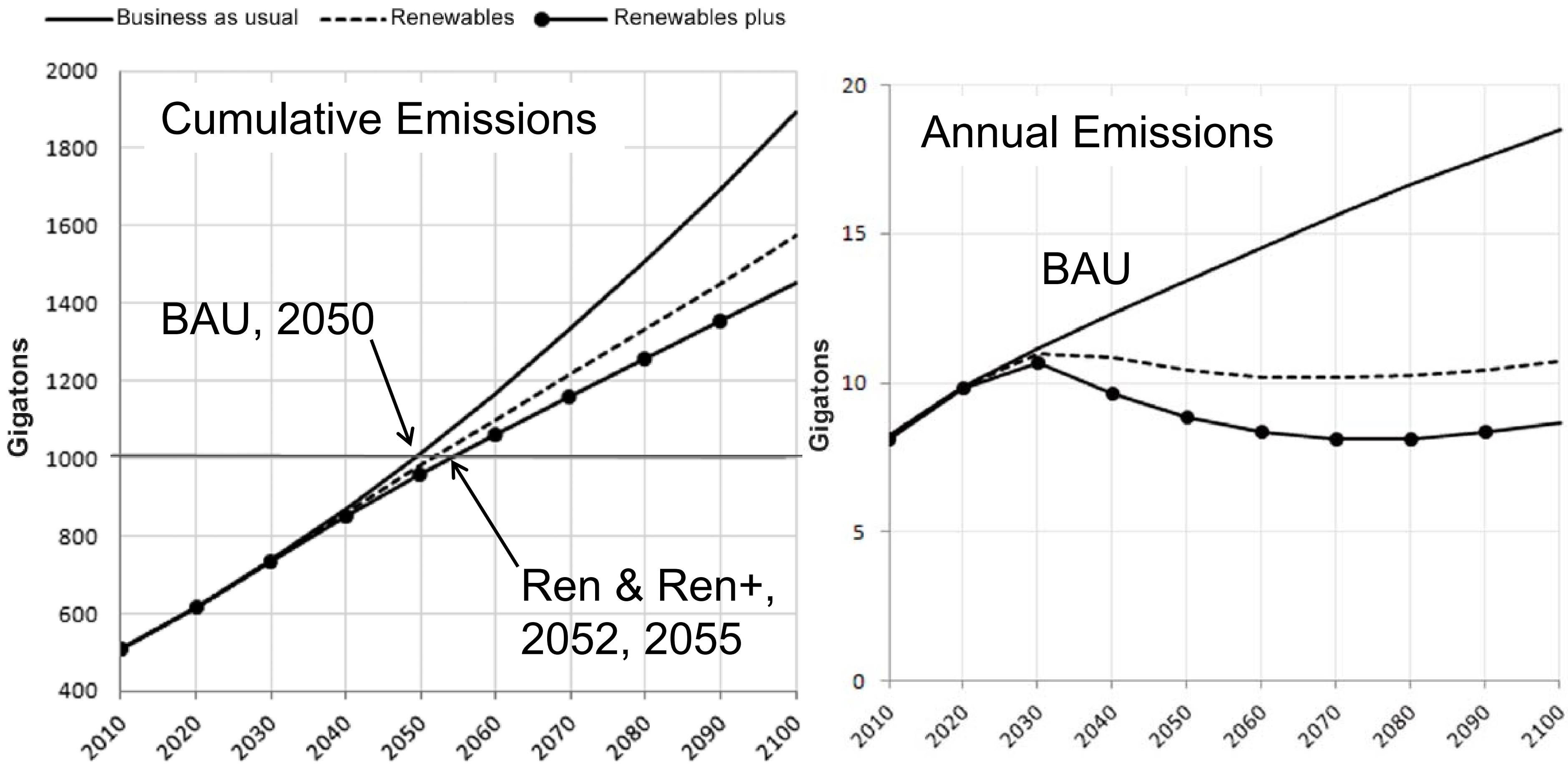
- Atomic layer deposition to grow quantum dots
- Control size to expand usable light spectrum
- One photon may cause multiple exciton generation
- Self-assembled carbon monolayer tripled efficiency

Stacey Bent (Chemical Engineering)

Mike McGehee (Materials Science and Engineering)

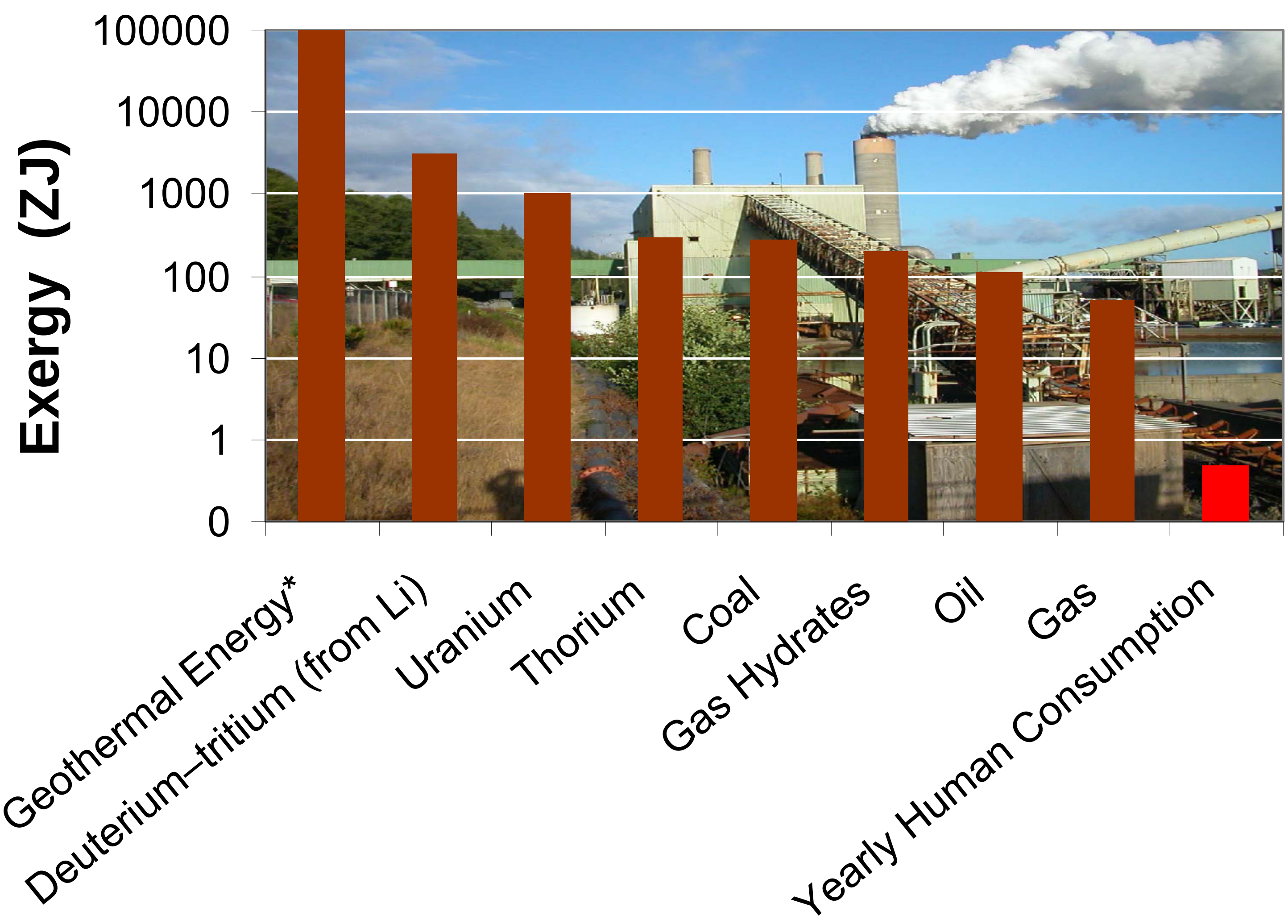


Impact of aggressive deployment of renewables



Ren: 60% reduction in renewable costs starting in 2013, Ren+: 70% reduction in 2013. It takes time to turn over power plant capital stock and penetrate big markets!

Global Exergy Stores



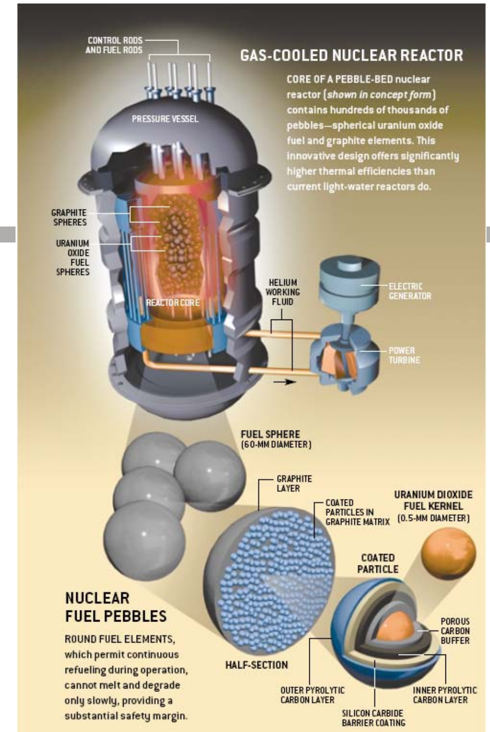
From Hermann, 2006: Quantifying Global Exergy Resources, Energy 31 (2006) 1349–1366

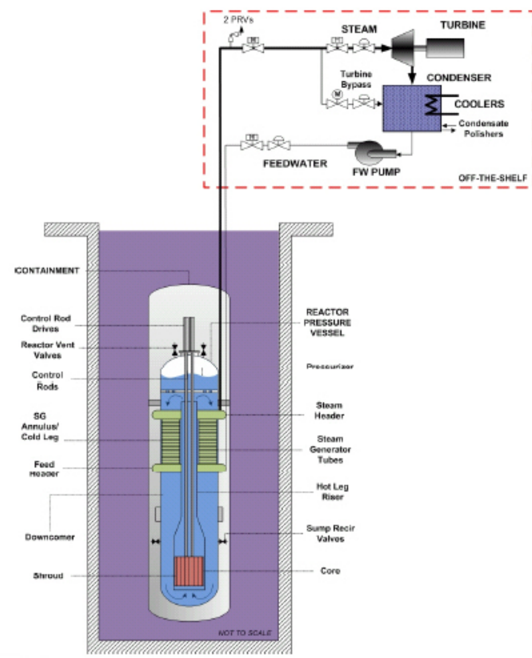
Exergy Stores

- Annual human consumption: 0.5 ZJ
- Large stores of exergy available >>100 x annual consumption
  - e.g. geothermal stored heat, uranium, thorium, lithium, fossil fuels
- Cost and environmental impact of producing (mining), processing, and waste disposal are primary limiting factors
- Large fossil fuel resources available
  - But, low-cost, high-quality oil is becoming more difficult to come by
  - Natural gas is relatively abundant – half the CO_2 of coal per unit of energy
  - Large quantities of lower quality oil resources (e.g. oil shale and tar sands) but they have significantly higher lifecycle CO_2 emissions
  - Abundant coal, heavy oil have high CO_2 emissions per unit of energy converted for use

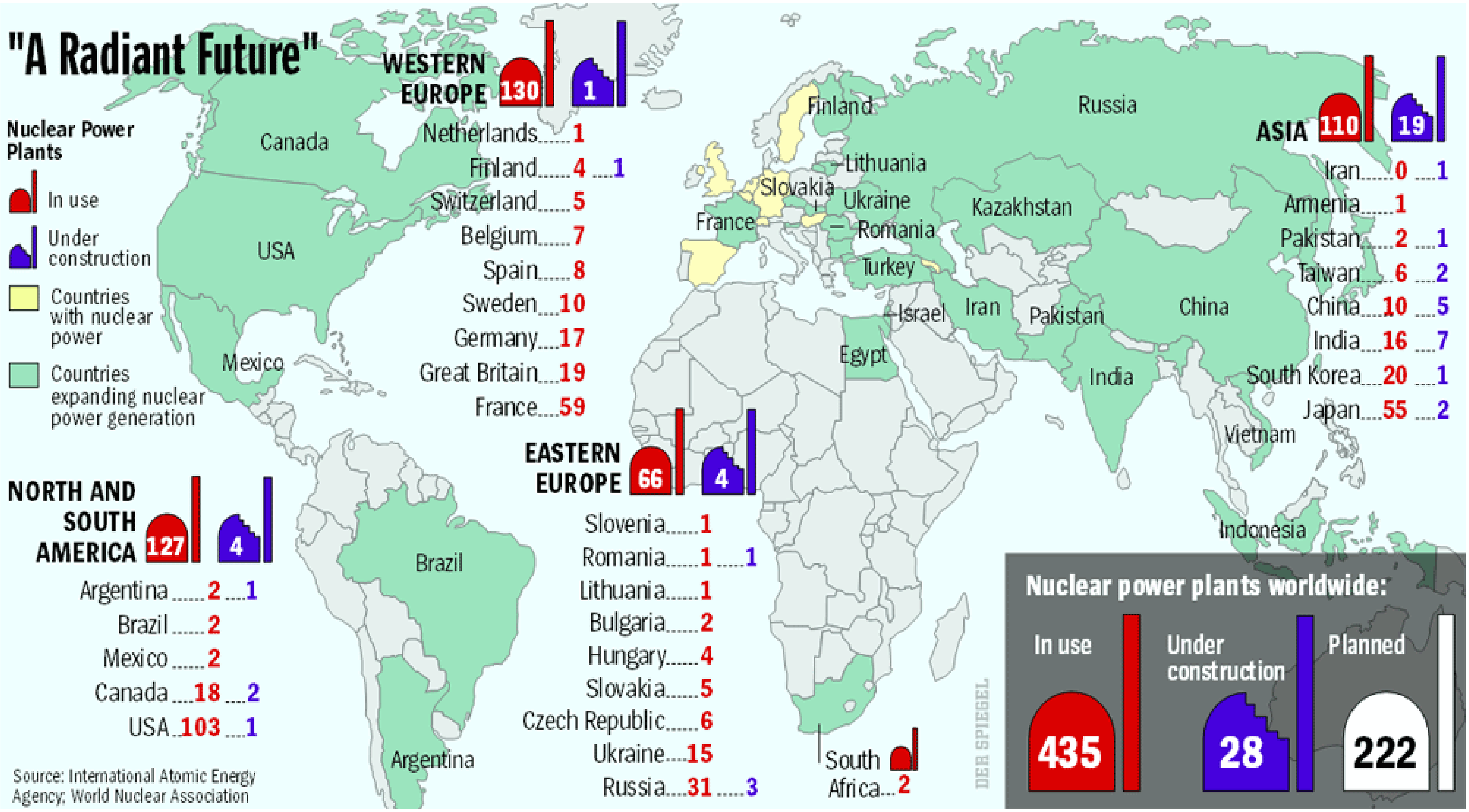
Nuclear Power

- Nuclear power – no CO_2 emissions (except for the concrete and steel in the plant)
- Safety: strong regulation, modern design, careful operation required
- Waste storage – new fuel cycles can reduce but not eliminate waste – total volume is small, but it is dangerous stuff.
- Potential for nuclear weapons proliferation
- 80% of electric power in France, China building (or planning 20 new nukes, US building two plants, considering applications for others
- New designs: passive cooling systems, small modular reactors, new fuel cycles, …, cost is still a big issue





Pre-Fukushima: Increasing use of nuclear power expected



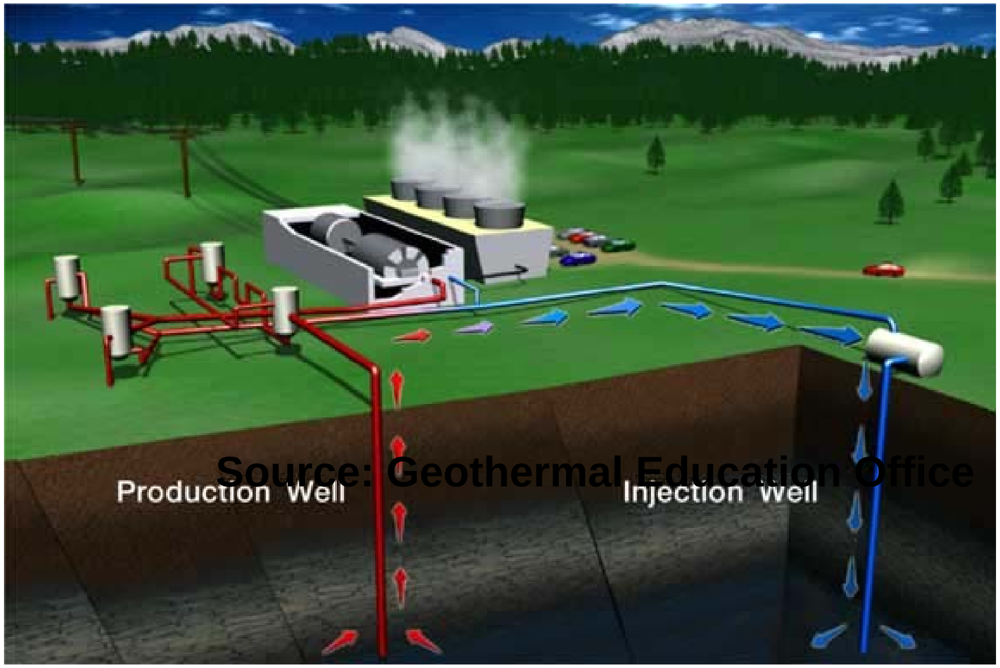
Numbers are from Jan 2009. In October 2010 441 are operating and 58 are under construction

Nuclear Power

- Low GHG baseload has high value – should be part of the mix
- Fukushima: significant review of spent fuel storage systems – a positive outcome from a terrible disaster
- Fuel reprocessing: reduce but not eliminate waste, will be very expensive
- US nuclear power will likelyremain paralyzed by a worries about safety and waste storage
- China and other nations will continue to build new plants
- Fusion? Several decades away (at least)

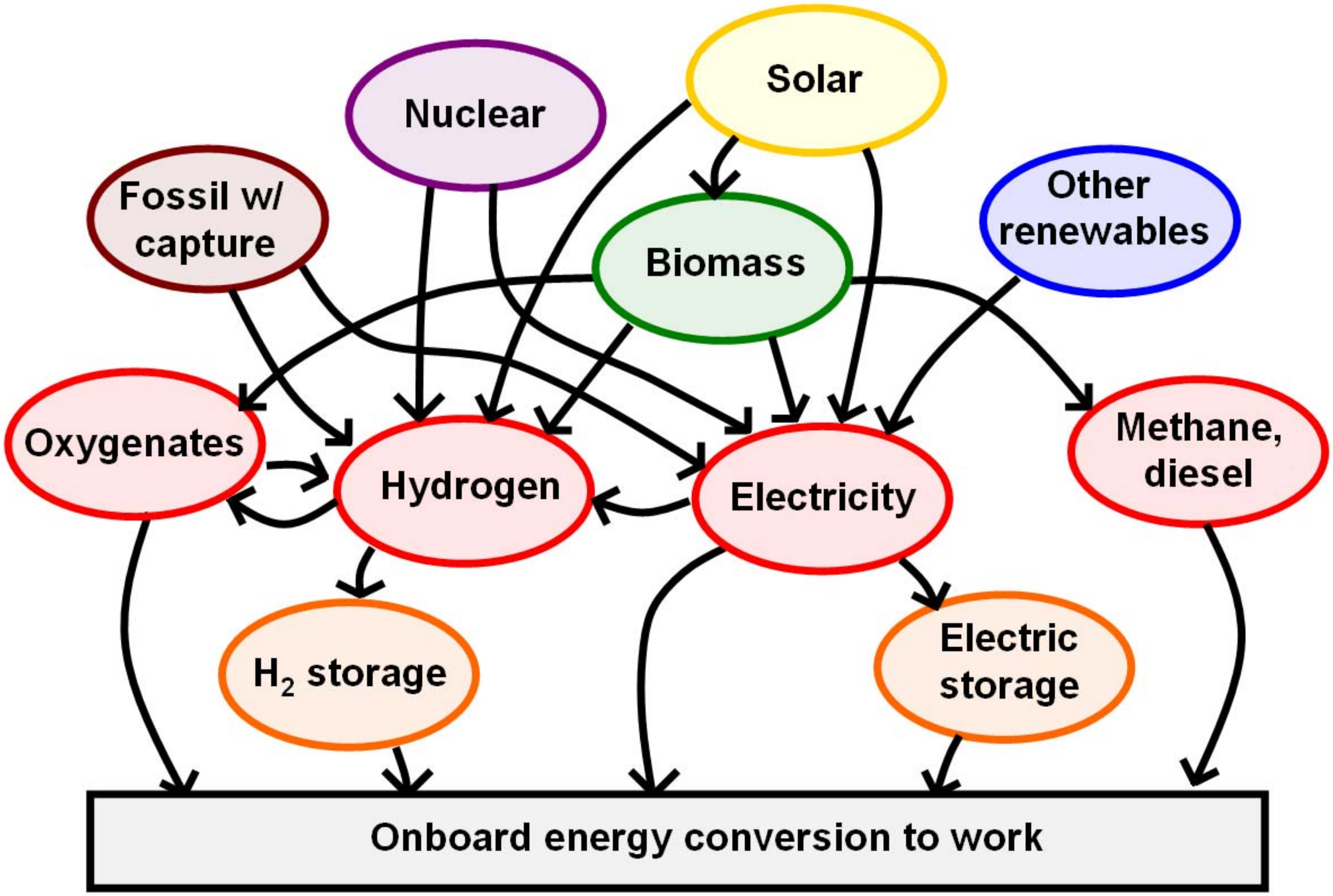
Geothermal Power

- Very large resource of heat stored in the crust
- Best in areas of high geothermal gradient, naturally fractured, with water present
- Dry rocks: drill one well, fracture, drill to intersect fractures
- Fracturing makes small earthquakes
- COE dominated by drilling costs



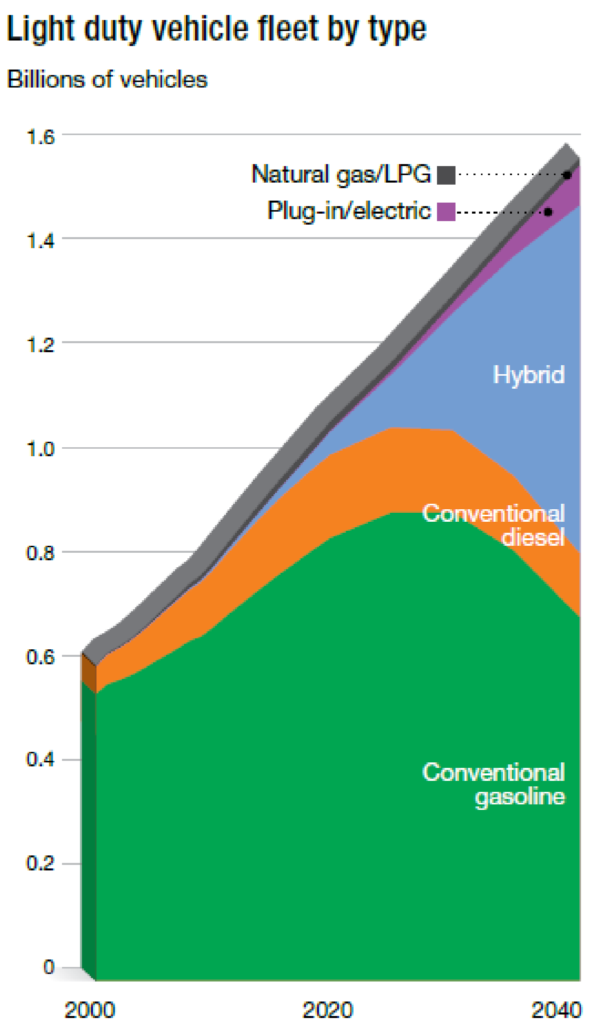
Source: Geothermal Education Office

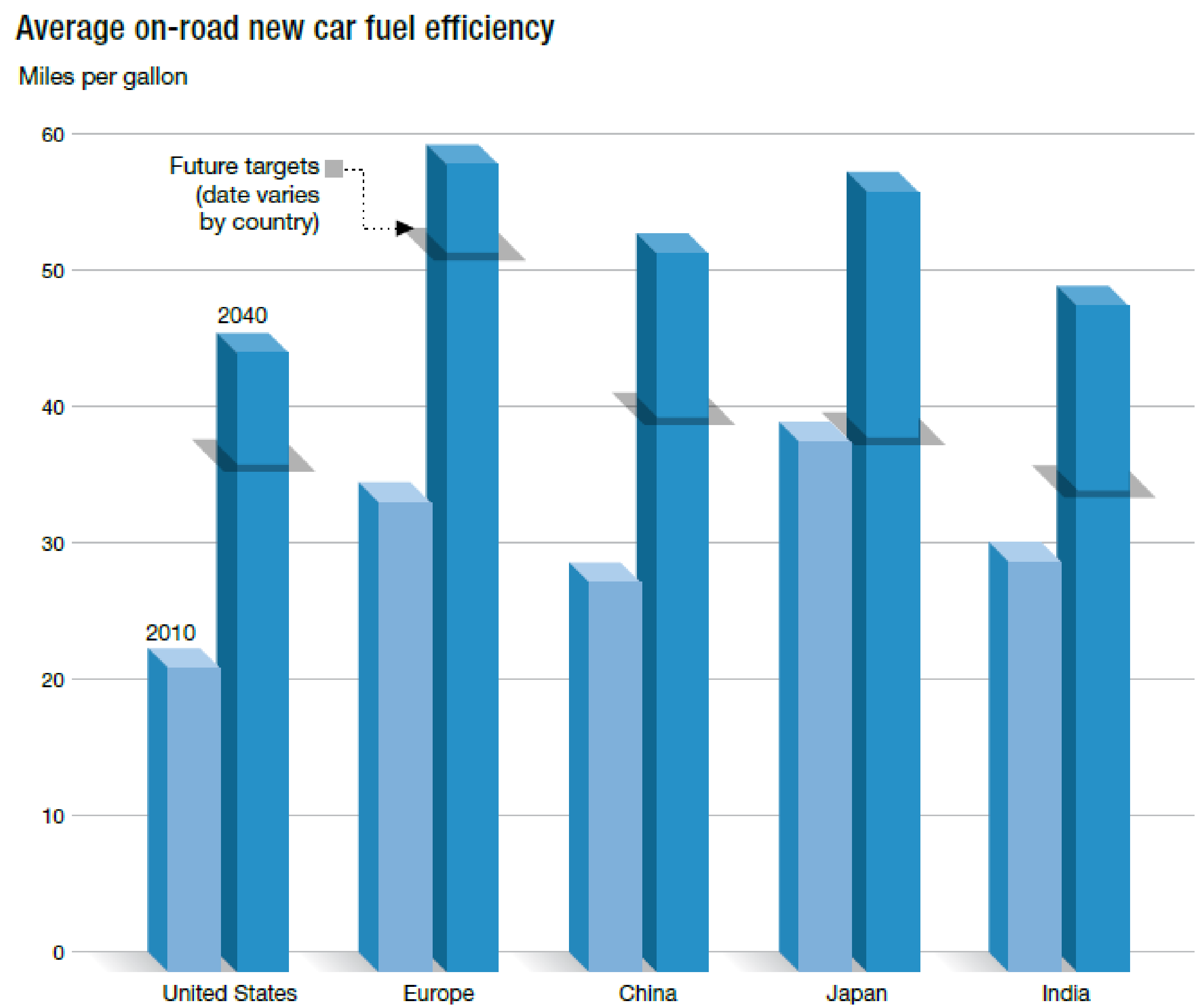
Energy Conversions for Transportation



Energy resource → carrier (storage) → mech. work → waste heat

Projected light duty vehicle efficiency



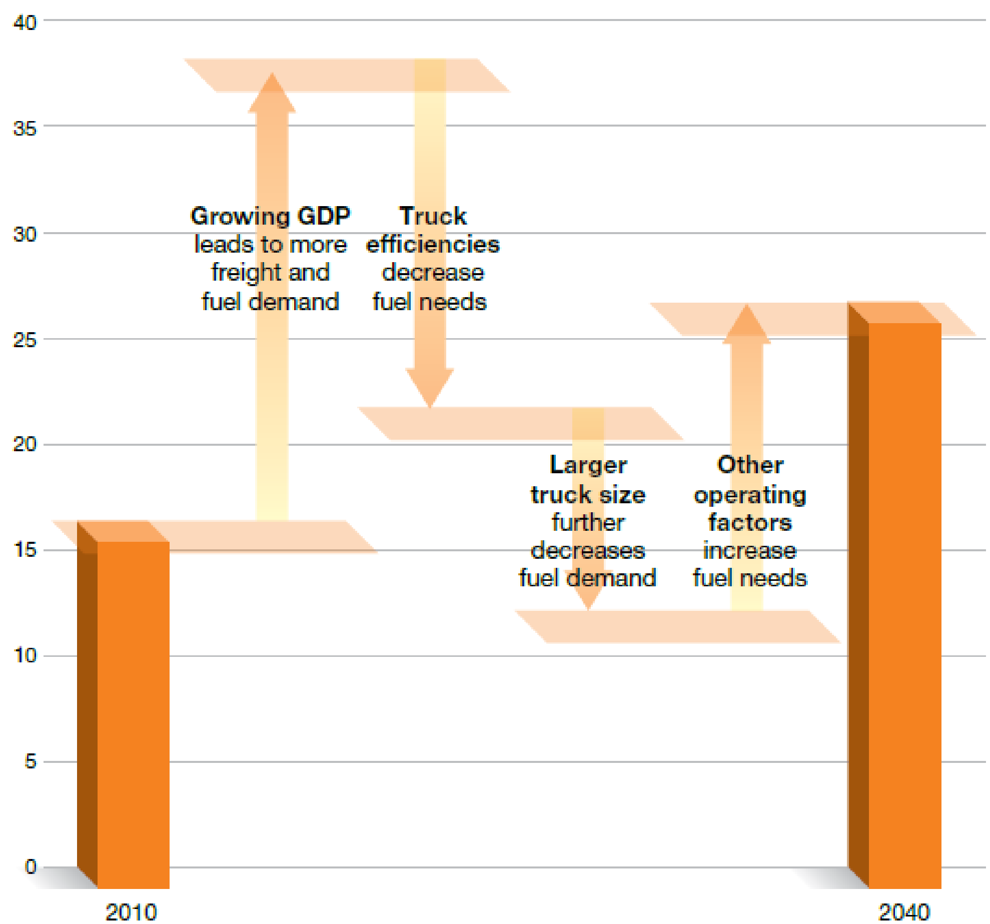


Source: ExxonMobil Energy Outlook 2012

More efficient vehicles help, but demand for transportation fuels still grows

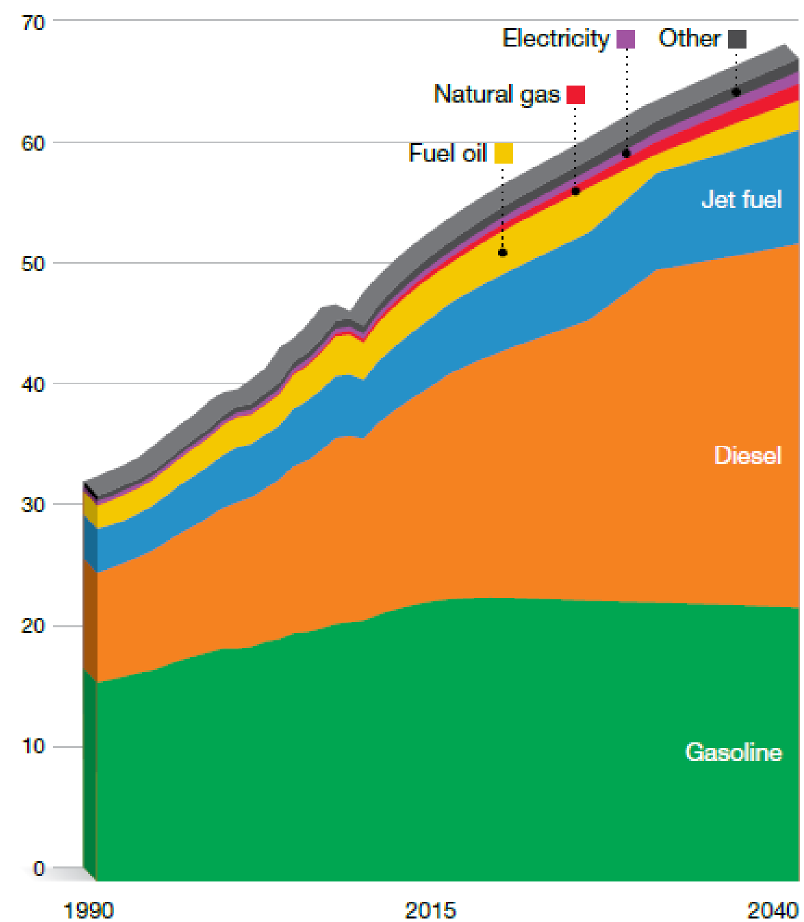
Heavy duty demand changes

Millions of oil-equivalent barrels per day



Transportation fuel demand

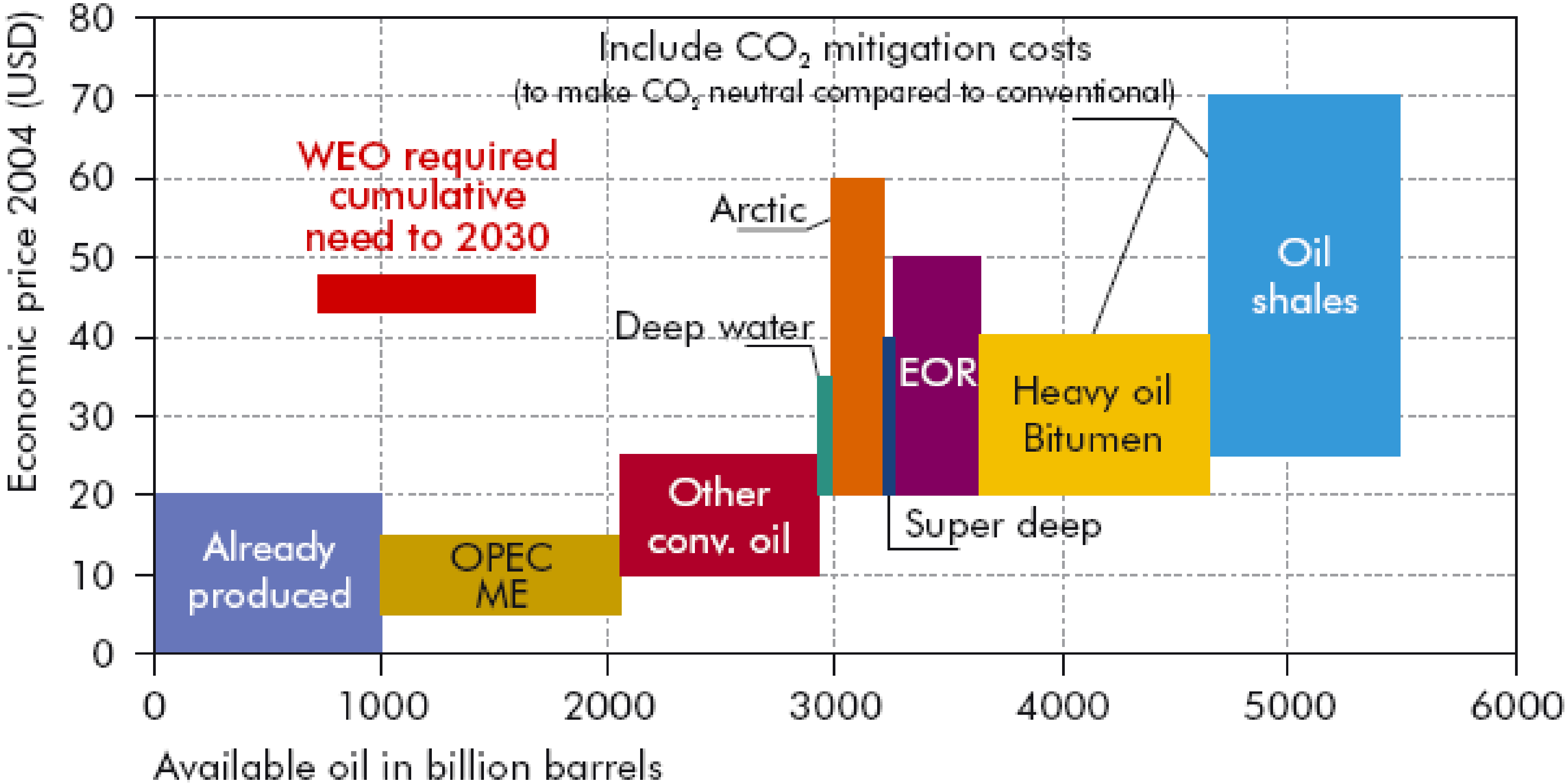
Millions of oil-equivalent barrels per day



Source: ExxonMobil Energy Outlook 2012

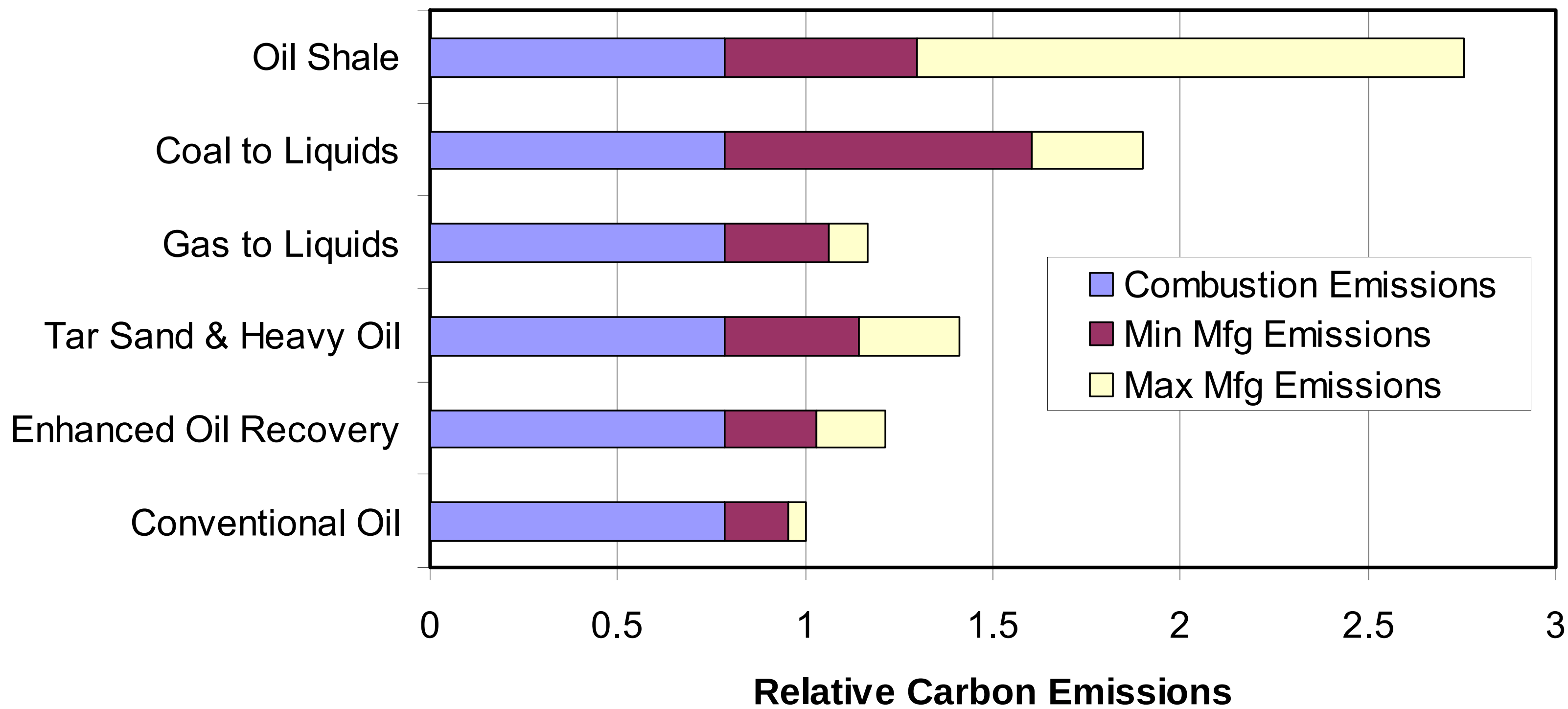
Oil Supply and Cost

Availability of oil resources as a function of economic price



Source: IEA (2005)

Relative Carbon Emissions of Alternative Hydrocarbon Fuels



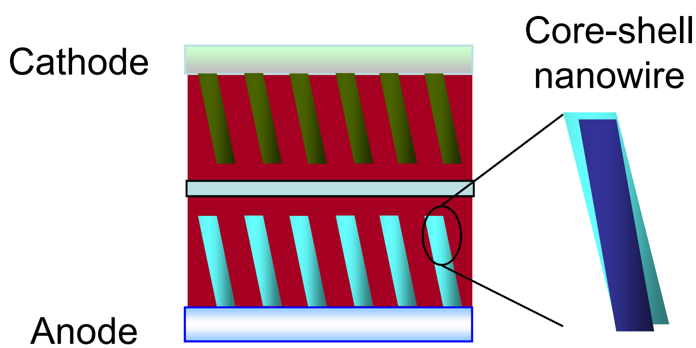
- Production of alternative liquid fuels from coal, tar sands, or oil shales increases GHG emissions significantly
- Volumes of CO_2 storage required to mitigate the upstream emissions will be very large if coal, tar sands and heavy oils are used to offset a significant fraction of conventional hydrocarbon use.

Source: Farrell & Brandt, Env. Res. Let. 1, 2006

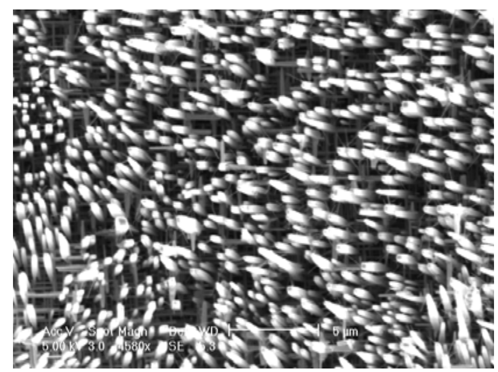
Nanowire Lithium-Ion Batteries as Electro-chemical Energy Storage for Electric Vehicles

Yi Cui, Fritz Prinz (Stanford)

- Develop Li-ion batteries with close-packed, core-shell nanowire electrodes for high-energy, high-power and long-life applications in electric vehicles.
- Approach:
  - Exploit the anisotropy, shape, and large surface area of nanowires to obtain efficient electron conduction and ionic transport.
  - Engineer the interface between the nanowire electrodes and the electrolyte for better chemical stability
  - Explore the facile strain relaxation at nanoscale to improve the mechanical stability.
  - Design an efficient nanowire battery device architecture.



Nanowire Battery



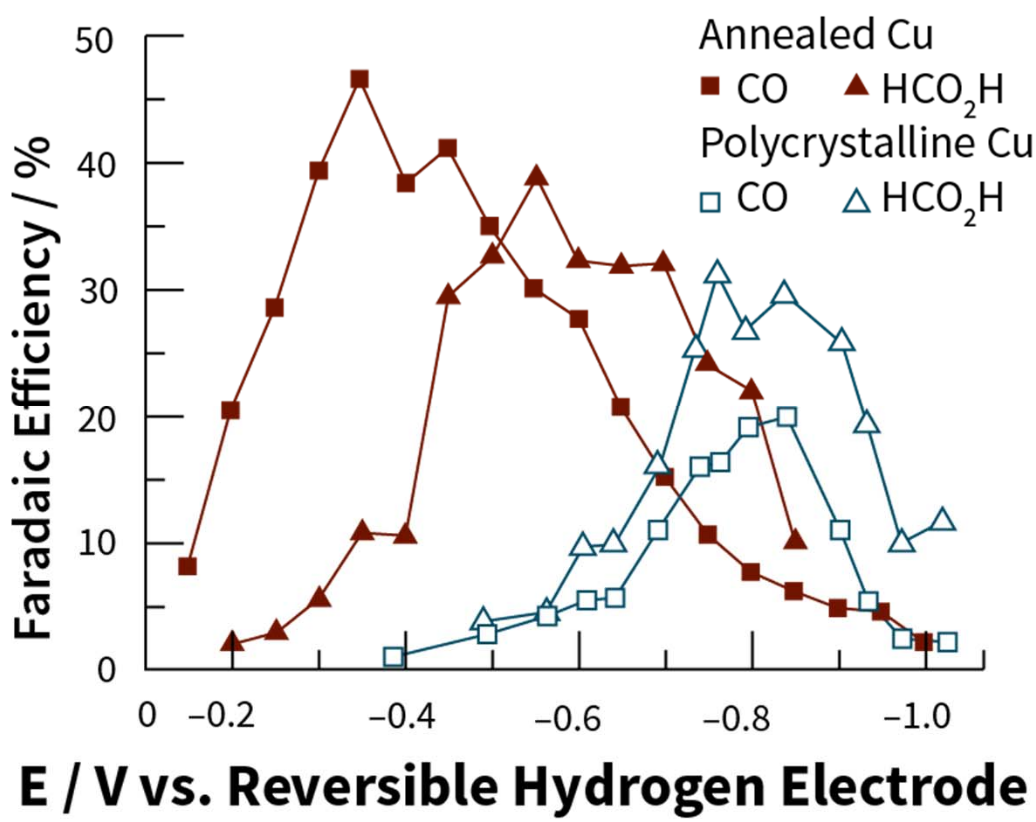
Nanowire Forest

Advanced Hydrocarbon Resources

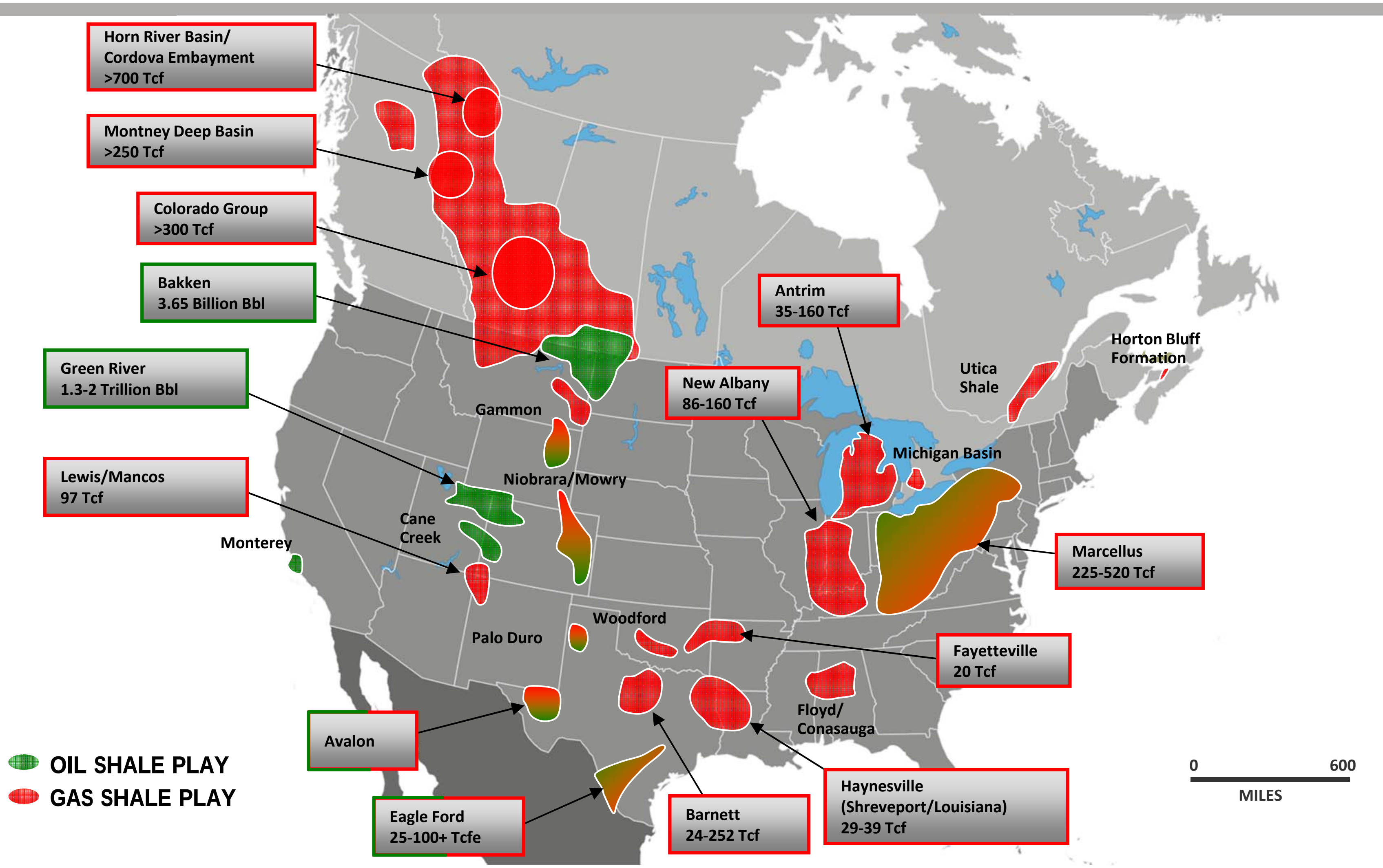
Converting carbon dioxide, water and electricity into synthetic fuels

- Transportation fuels
- Energy storage
- Use existing fuel infrastructure
- Copper electrode catalysis
- Novel electrode synthesis:
  - More efficient CO_2 reduction
  - More stable material

Matthew Kanan (Chemistry)



North American Shale Plays



~2300 TCF (85% Shale Gas)
U.S. Consumption 23 TCF/yr

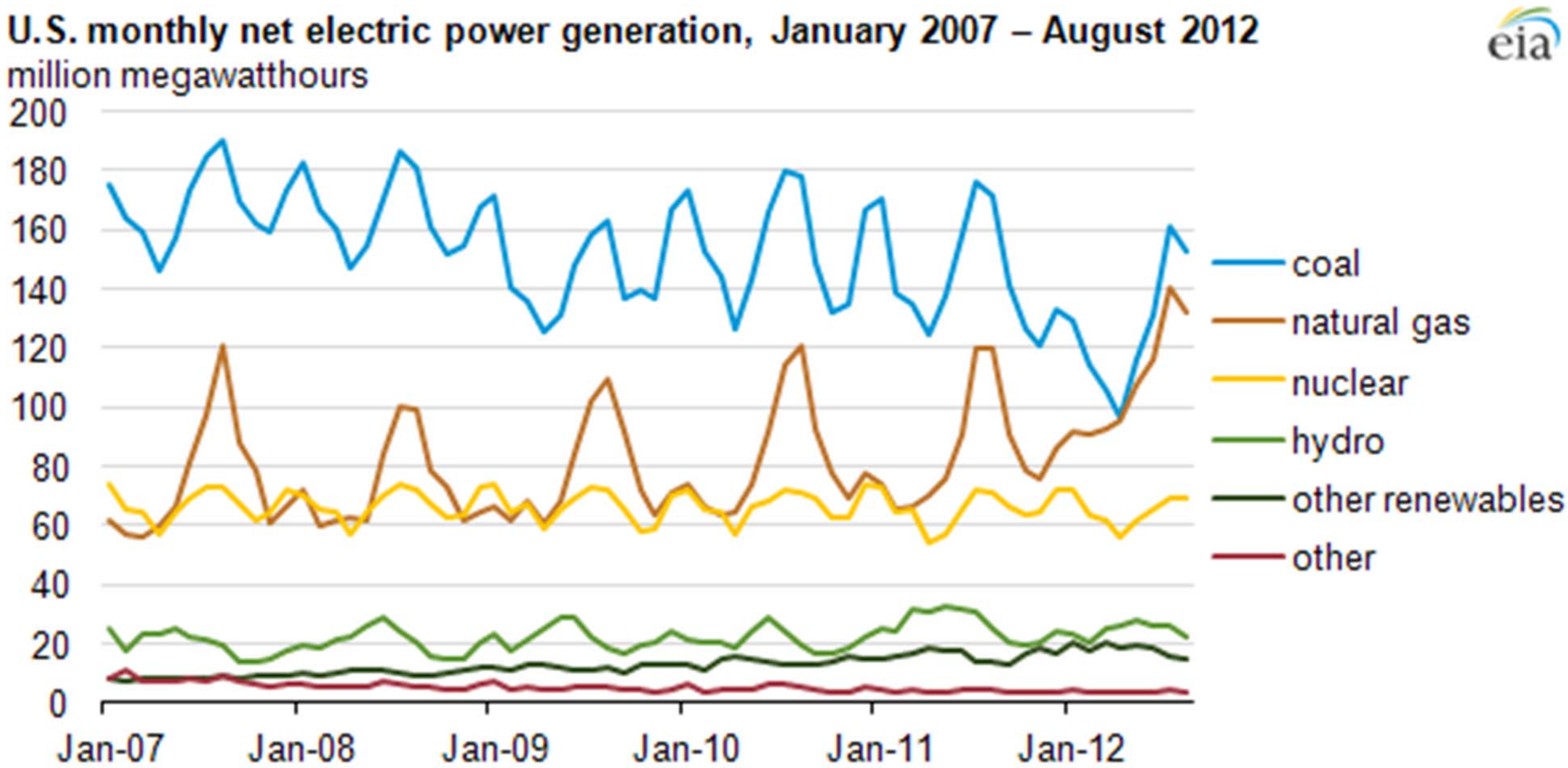
Substituting Natural Gas for Coal in Electric Power Generation

- Reduced SOx, NOx, particulate, Hg emissions
- Reduced mining impacts, ash disposal
- Reduced CO_2 emissions per kWh generated:
  - 57% less CO_2 per unit energy in fuel for natural gas
  - Better power plant efficiency
    - 32% old coal
    - 35% NG single cycle
    - 60% NG combined cycle
- CO_2/kWh reductions: NG 48%, NGCC 70% (if no leakage of CH_4)

Source: http://www.flickr.com/photos/davipt/164341428/sizes/l/in/photostream/

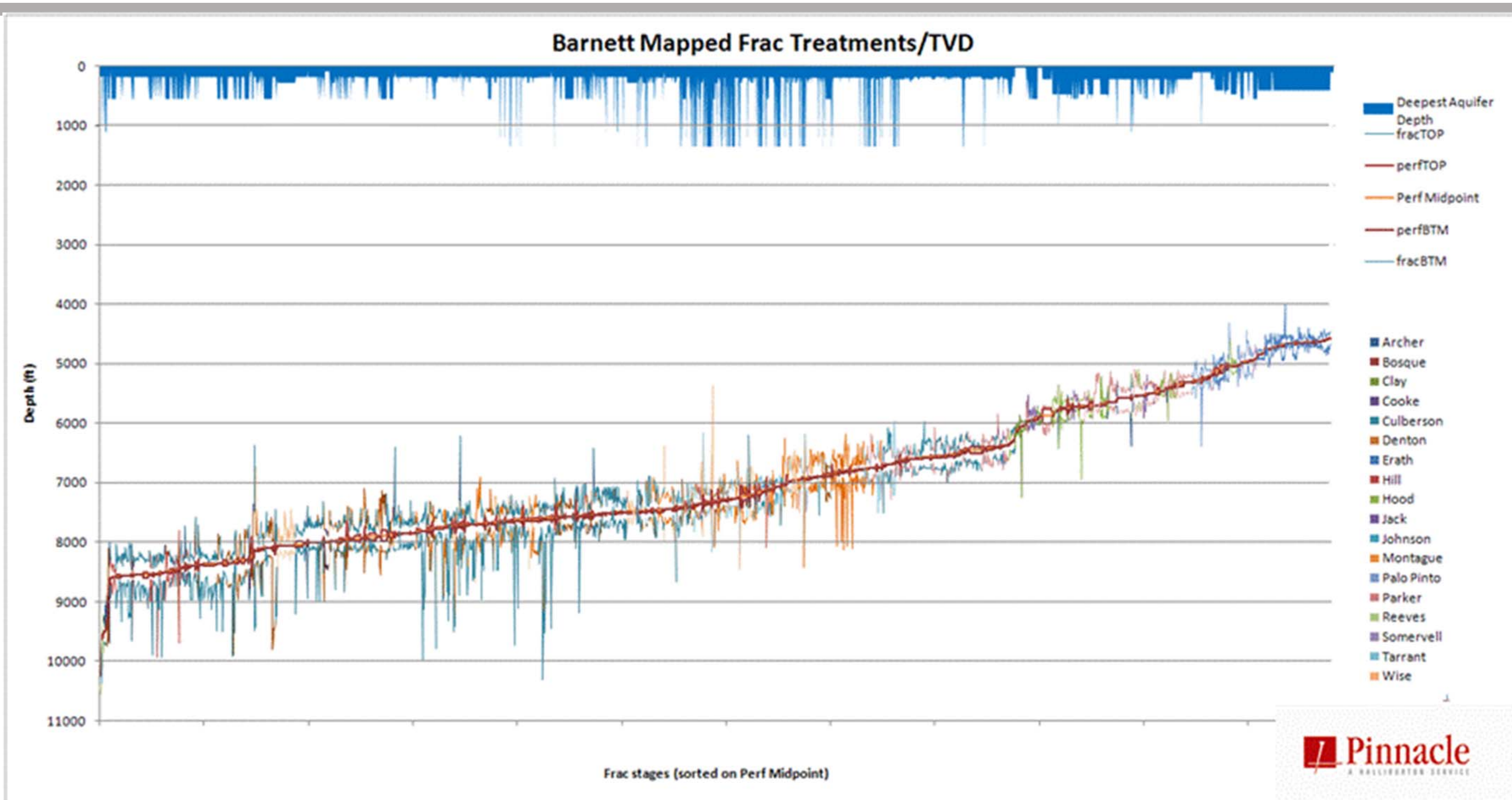
Source: http://www.sitheglobal.com/projects/goreway.cfm

Power Generation: Gas and Coal



Utilities have used inexpensive gas in spare single cycle gas turbines, some repowering of coal facilities. Future EPA rules on Hg emissions, efficiency will put pressure on old coal plants.

Depth of Affected Region Affected by Hydraulic Fracturing



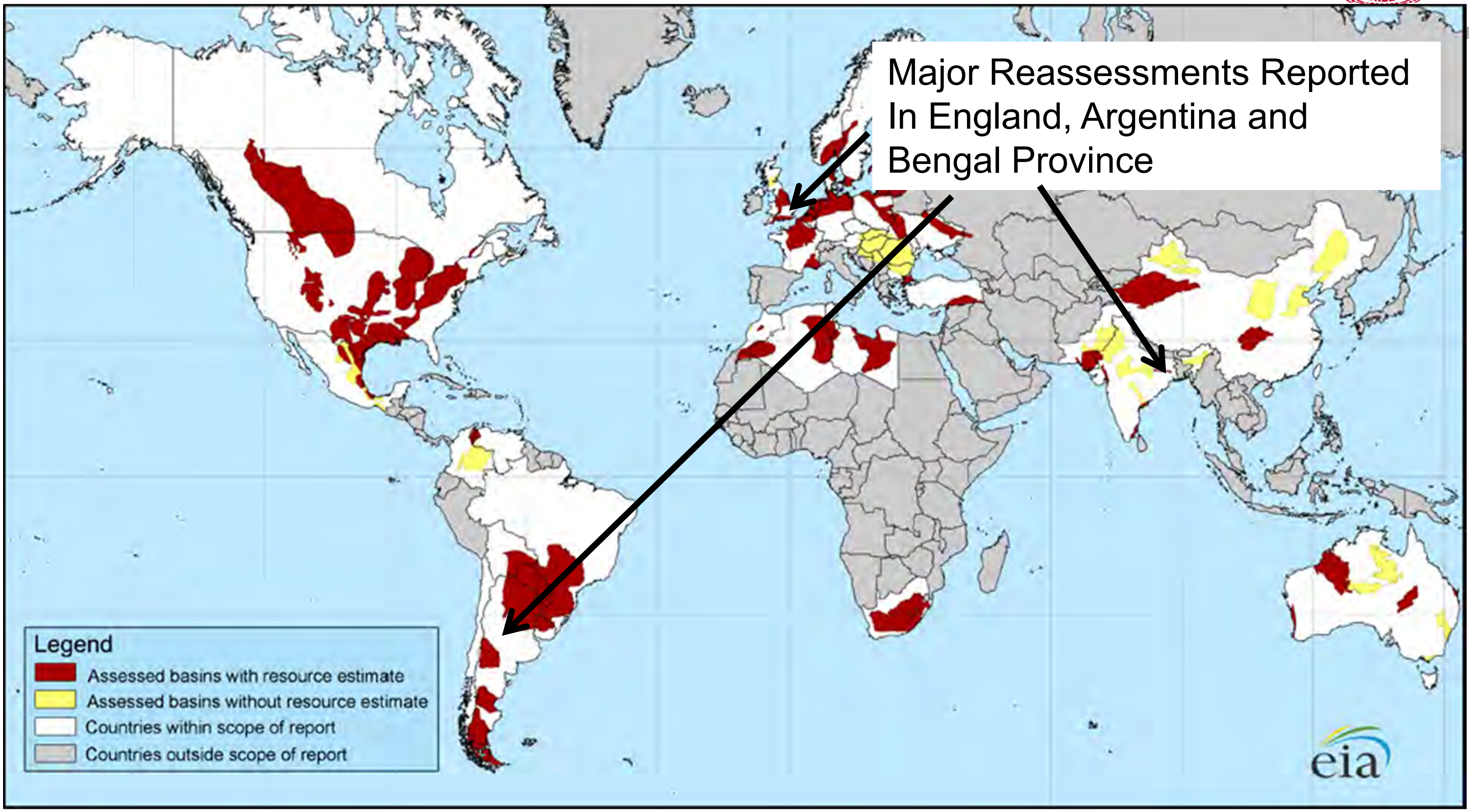
Fisher (2010)

http://nwis.waterdata.usgs.gov/nwis/inventory

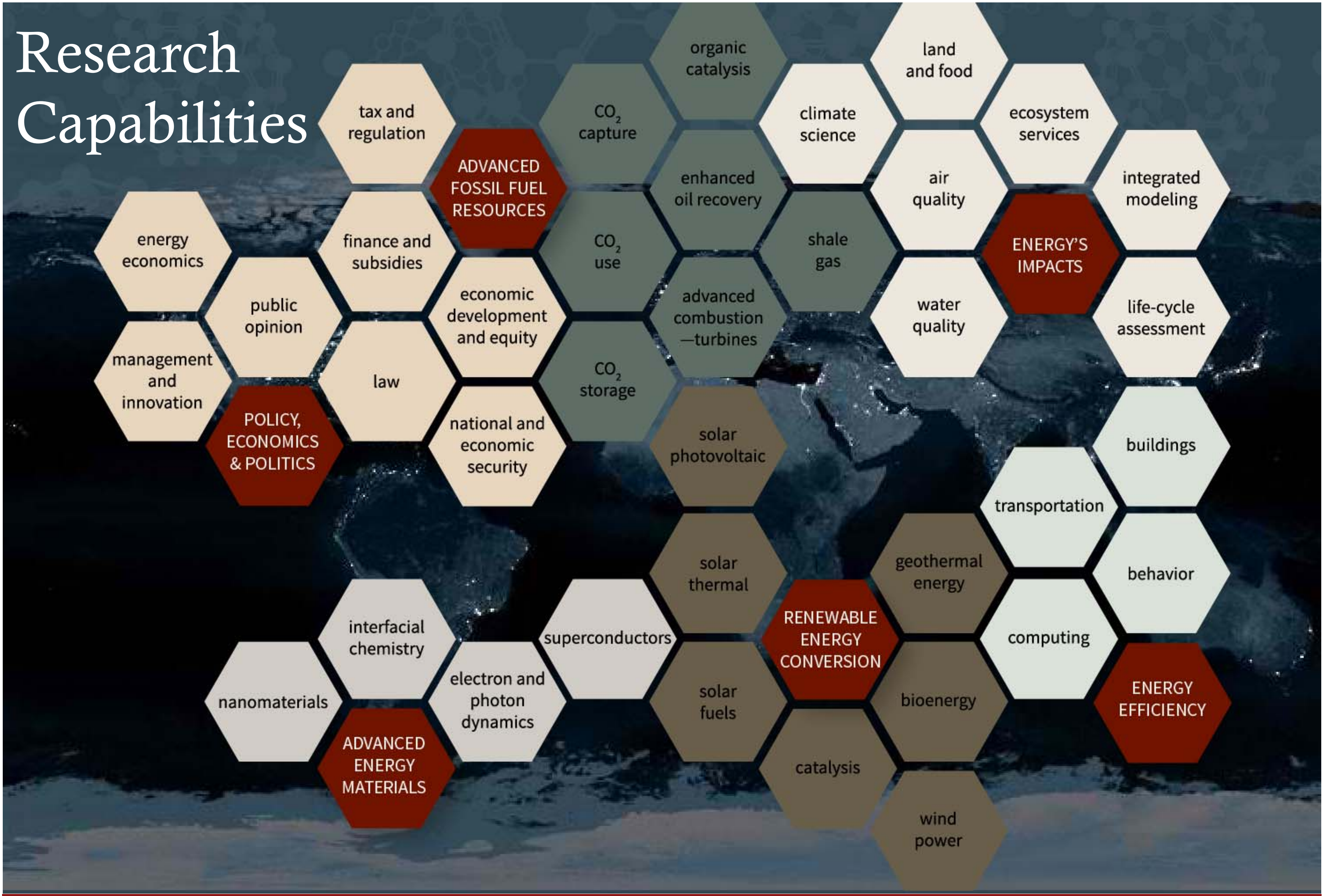
Environmental Issues for Shale Gas Production

- Drilling – lots of drilling required, reduce surface impacts by multiple wells per pad
- Lots of water required for fracturing – use formation and flowback water to reduce fresh water requirements
- Composition of frac fluids – some states require disclosure
- Flowback water can contain contaminants – capture for treatment or reuse, dispose of or treat properly
- Contamination of surface aquifers – a well construction issue: set casing to top of producing formation, test cement job integrity
- Induced seismicity: monitor and have plan if event detected
- Fugitive methane emissions – eliminate venting during well completions, careful attention to leak prevention – this is essential to prevent escape of a potent GHG

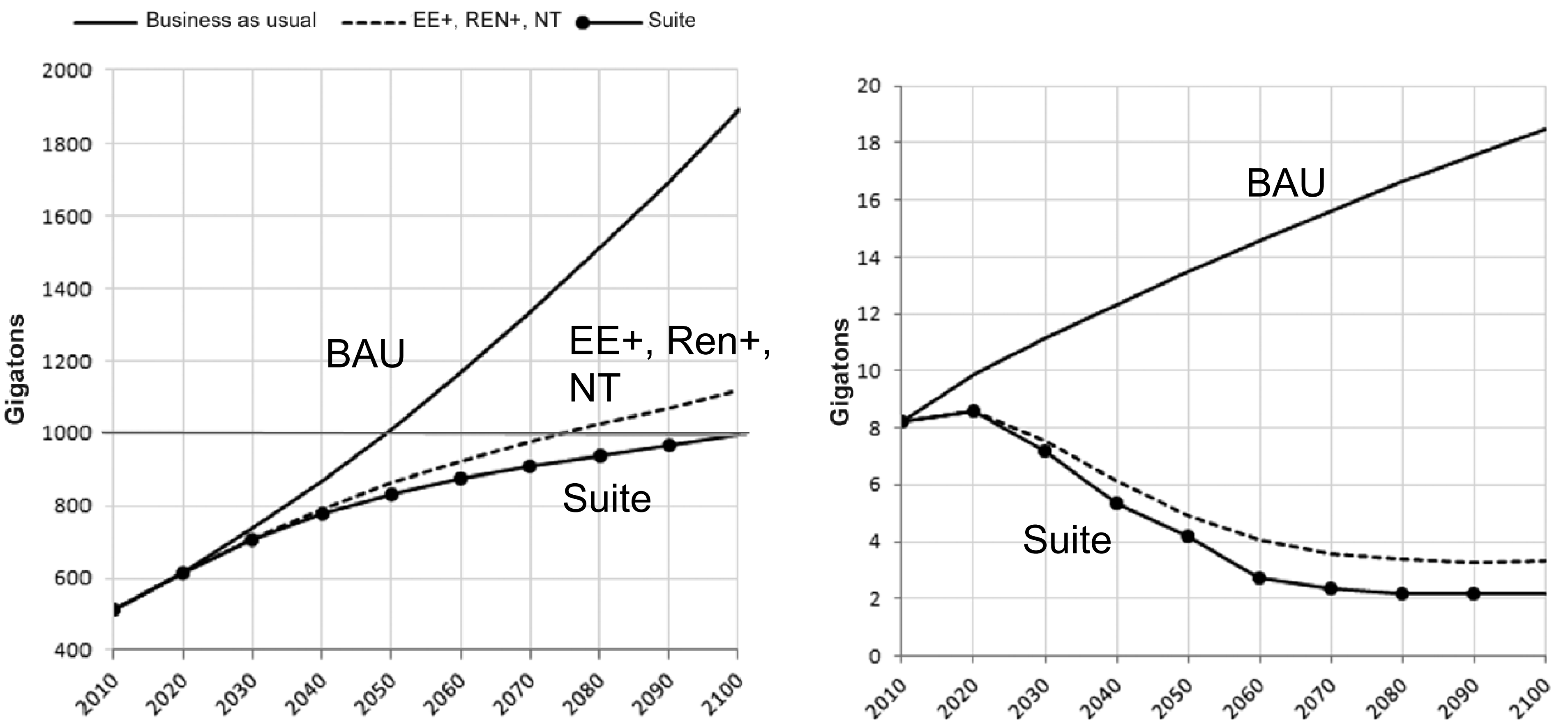
Global Shale Plays



~22,600 TCF of Recoverable Reserves
6600 TCF from Shale (40%)
Current use ~160 TCF/year

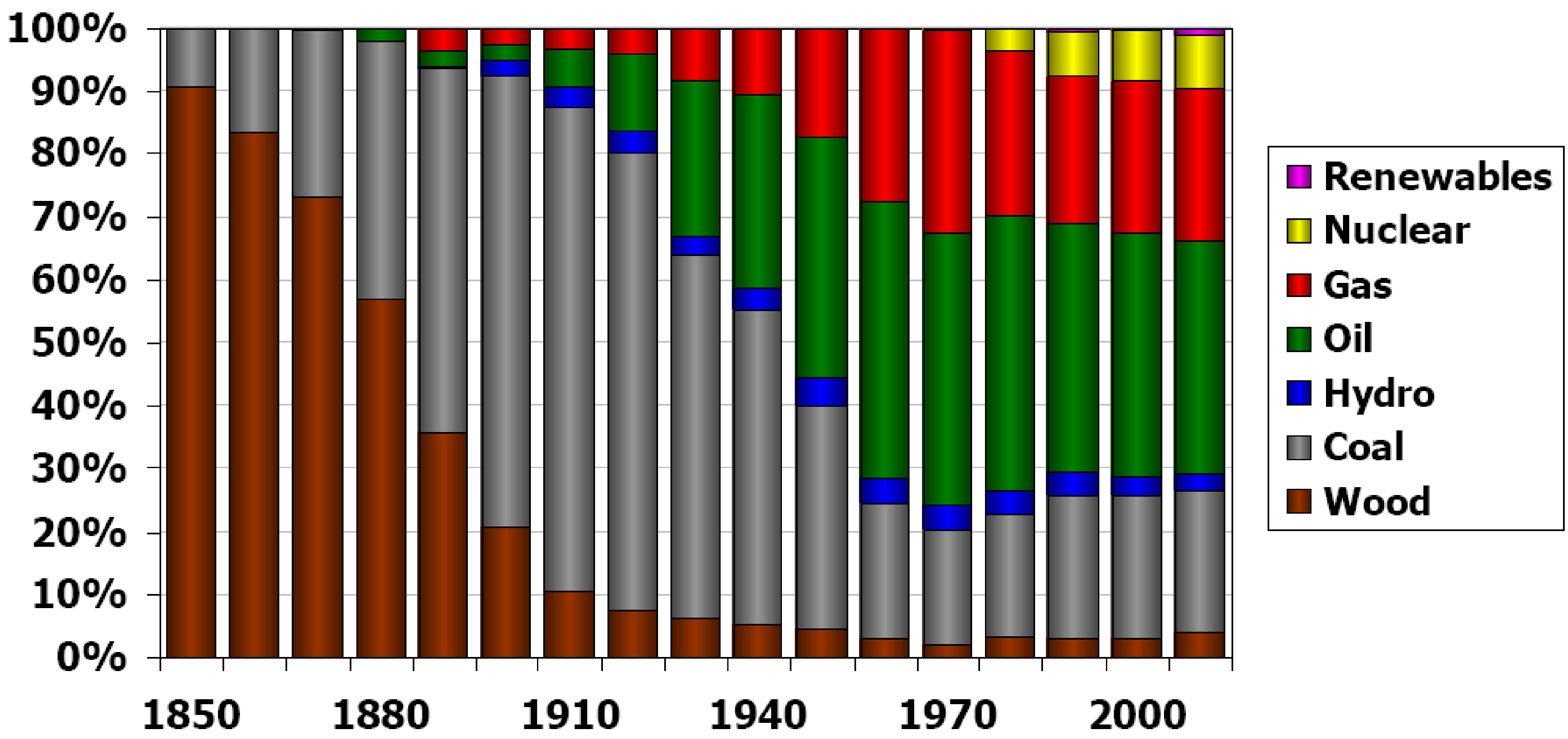

Research Capabilities
tax and regulation
ADVANCED FOSSIL FUEL RESOURCES
CO_2 capture
organic catalysis
climate science
land and food
ecosystem services
energy economics
public opinion
finance and subsidies
economic development and equity
CO_2 use
enhanced oil recovery
shale gas
air quality
ENERGY'S IMPACTS
integrated modeling
management and innovation
POLICY, ECONOMICS & POLITICS
law
national and economic security
CO_2 storage
advanced combustion —turbines
water quality
life-cycle assessment
solar photovoltaic
buildings
transportation
behavior
solar thermal
geothermal energy
RENEWABLE ENERGY CONVERSION
computing
interfacial chemistry
superconductors
nanomaterials
electron and photon dynamics
solar fuels
bioenergy
ENERGY EFFICIENCY
ADVANCED ENERGY MATERIALS
catalysis
wind power

A suite of GHG reductions



Suite: aggressive efficiency (EE+), renewables (Ren+), new technology development (NT), plus land use changes and $25/ton carbon tax starting in 2025 – delays the trillionth ton to 2100 – We need the full portfolio.

Energy Transitions: US Energy Supply Since 1850



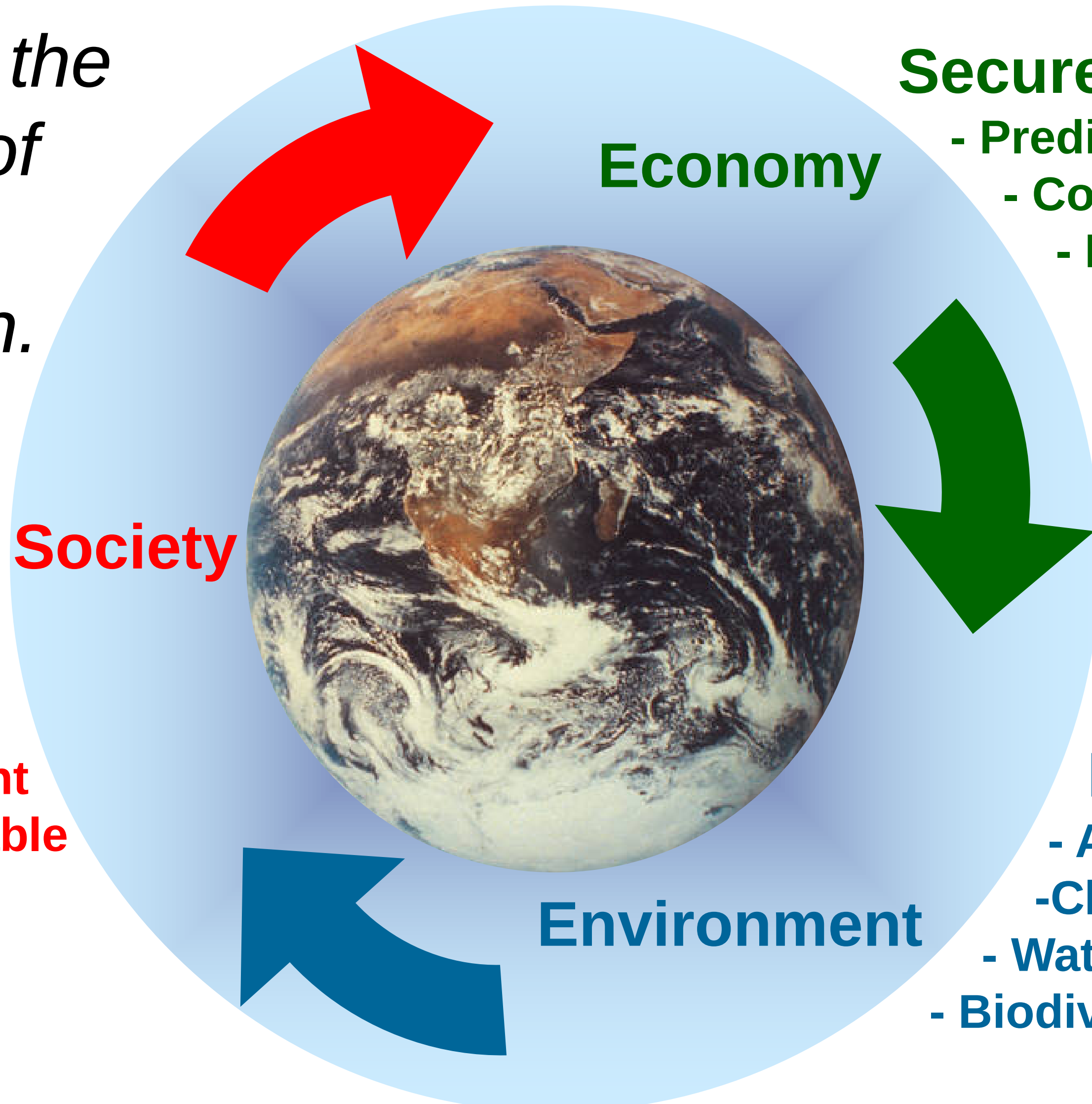
Another energy transition is underway now. Your job is to lead that transition!

Summary

- The transition to energy systems with much lower GHG emissions is one of the grand challenges we humans must face in this century. We need to demonstrate in this century that we can live on this planet in a way that protects the global systems that sustain us.
- There is no single solution to this challenge. We need to work on a broad portfolio of approaches, with a spectrum of time scales and sources of support. We need all the tools we have plus some we need to invent.
- A multi-decade transition is underway – we need to start now on a sustained effort to reduce carbon emissions
- So, let's get to work (we can do this!):
  - Now: Energy efficiency, cost effective solar and wind, conservation
  - Beginning: Low carbon electricity generation, reducing the fraction of coal in the energy mix
  - Ongoing: Research to provide plenty of new options

A Sustainable Energy System

Energy is the lifeblood of modern civilization.

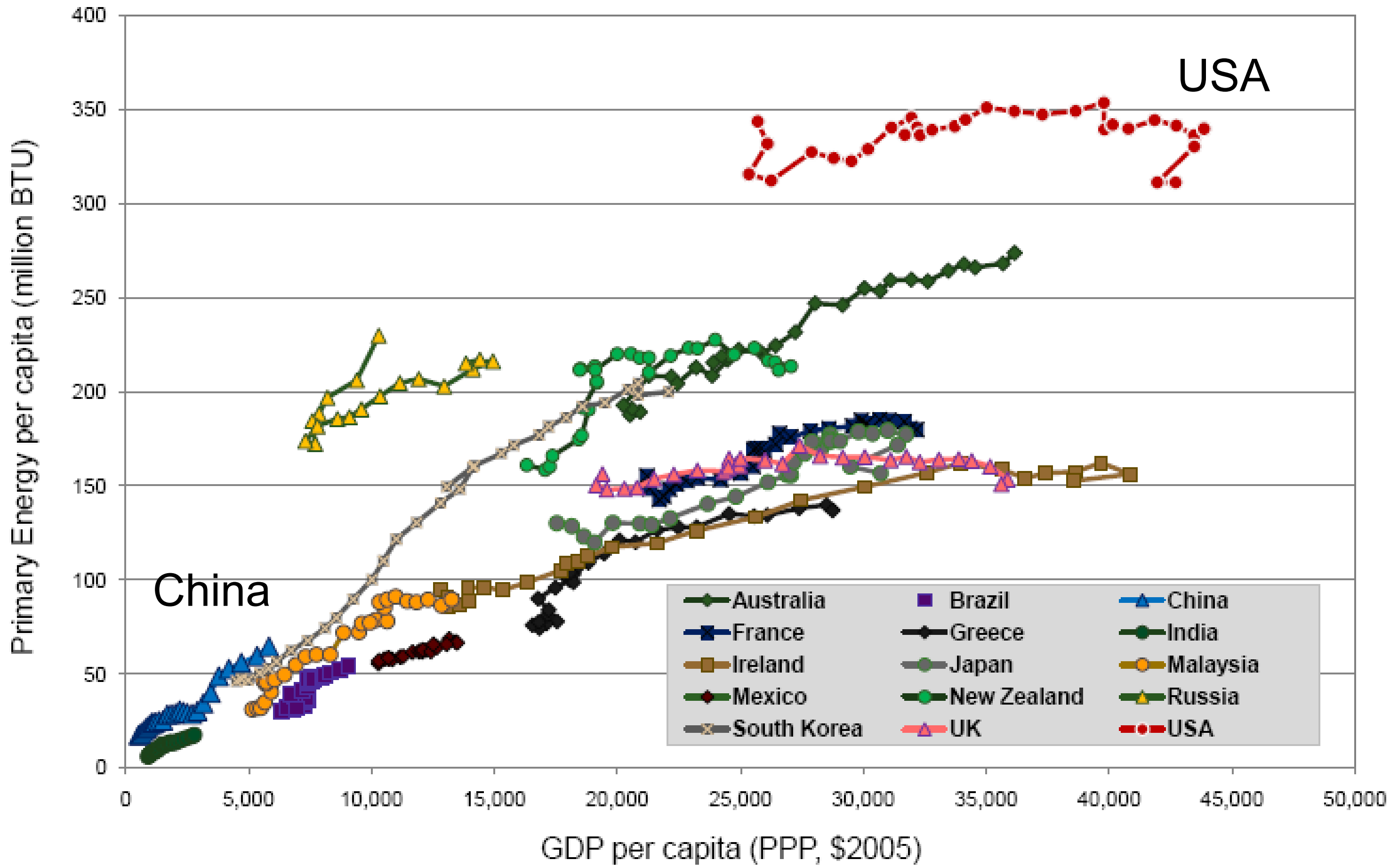


Secure
- Predictable
- Competitive
- Resilient
- Profitable
- Compatible with National interests

Accessible
- Affordable
- Abundant
- Reliable
- Useful
- Efficient
- Equitable

Protective
- Air Quality
- Climate
- Water Resources
- Biodiversity

Per Capita Energy Use vs Per Capita GDP (1980-2010)



GDP and energy use per capita will likely continue to grow in the developing world – remain stable or decline elsewhere

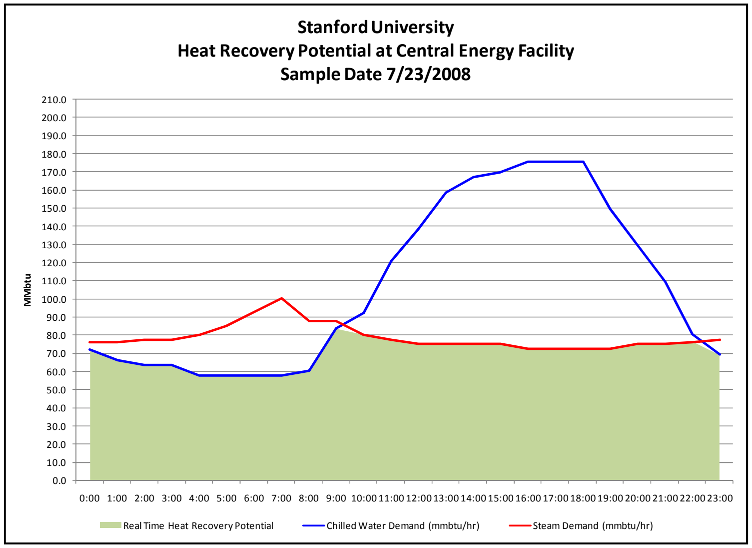
Sustainable Stanford

New central energy plant to replace Cardinal CoGen in 2014

New central energy facility to be built in 2014

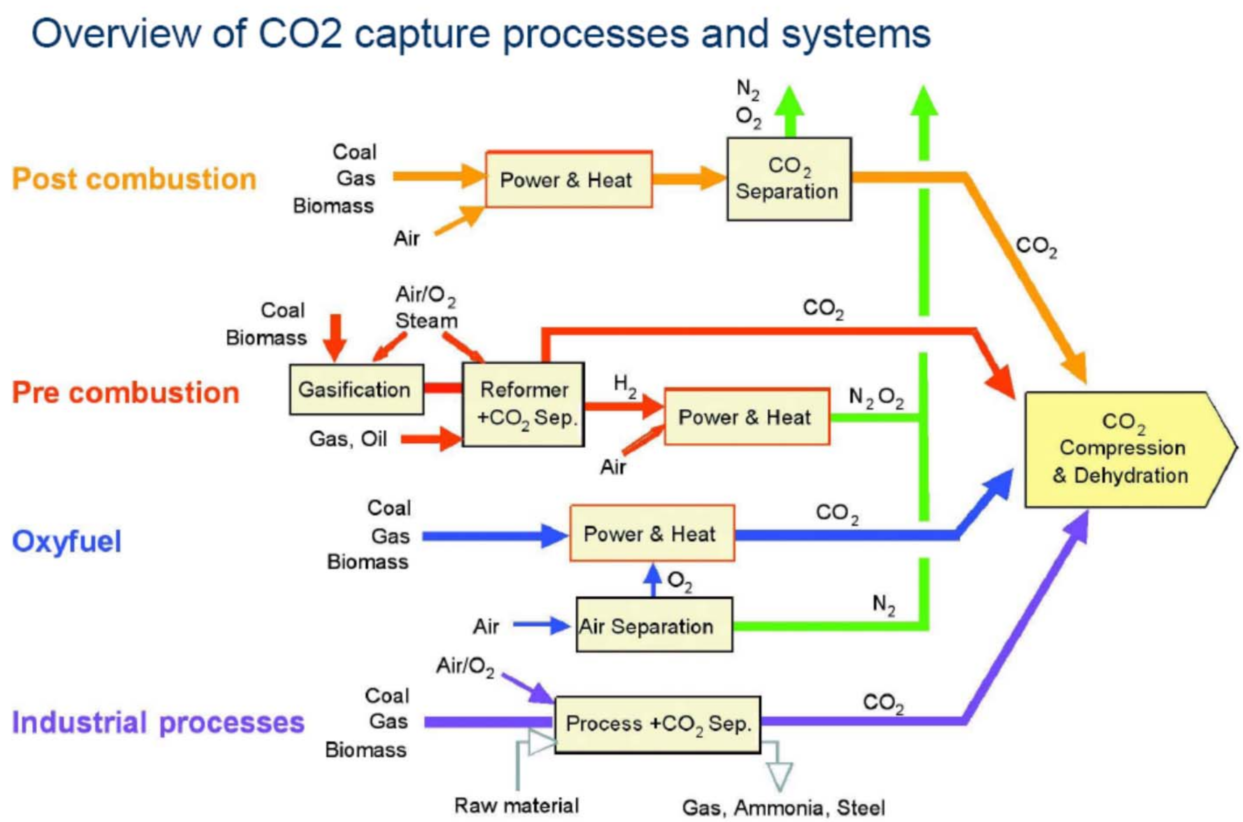
Cardinal cogeneration plant

- **Reduce fuel use by 30%**
- **Reduce CO_2 emissions by 50%**
- **Reduce water use by 18%**
- **Save $300M over 35 years**



Multiple routes for capturing CO_2

- Gas separation processes are available at commercial scale
- CO_2 is routinely separated from natural gas
- Early storage field tests have used CO_2 that must be separated anyway (Sleipner, In Salah, Weyburn)



SRCCS Figure TS-3

Source: IPCC Special Report Carbon Capture & Storage, 2006

What to do with the separated CO_2? Can geologic storage contribute?

- Geologic formations are known to store buoyant fluids (oil and gas) for geologic time.
- Technologies for CO_2 injection are well established, based on experience in enhanced oil recovery.
- Porous formations that are potential storage locations are widely distributed geographically.

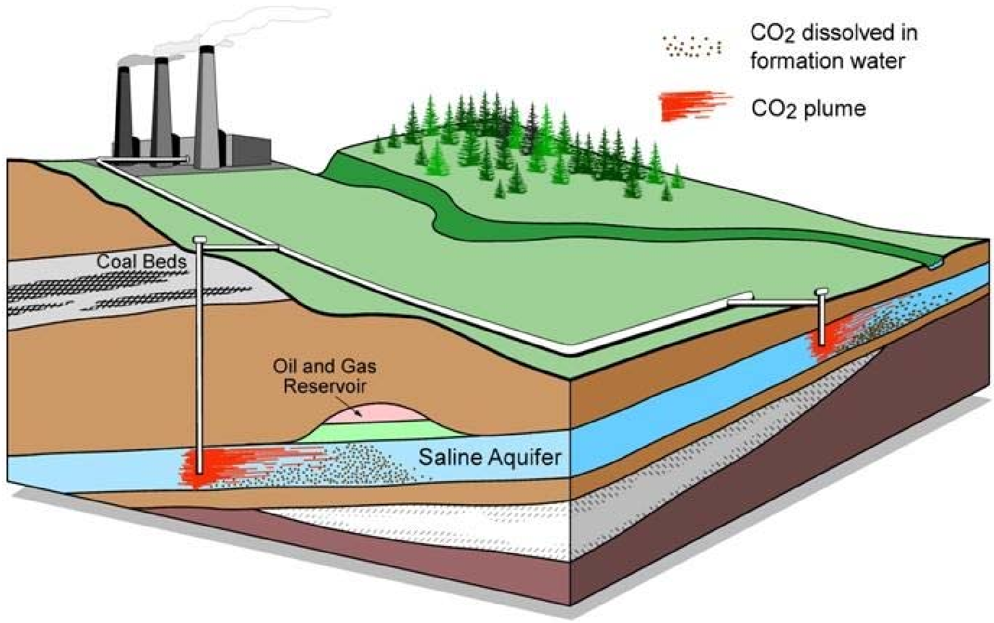
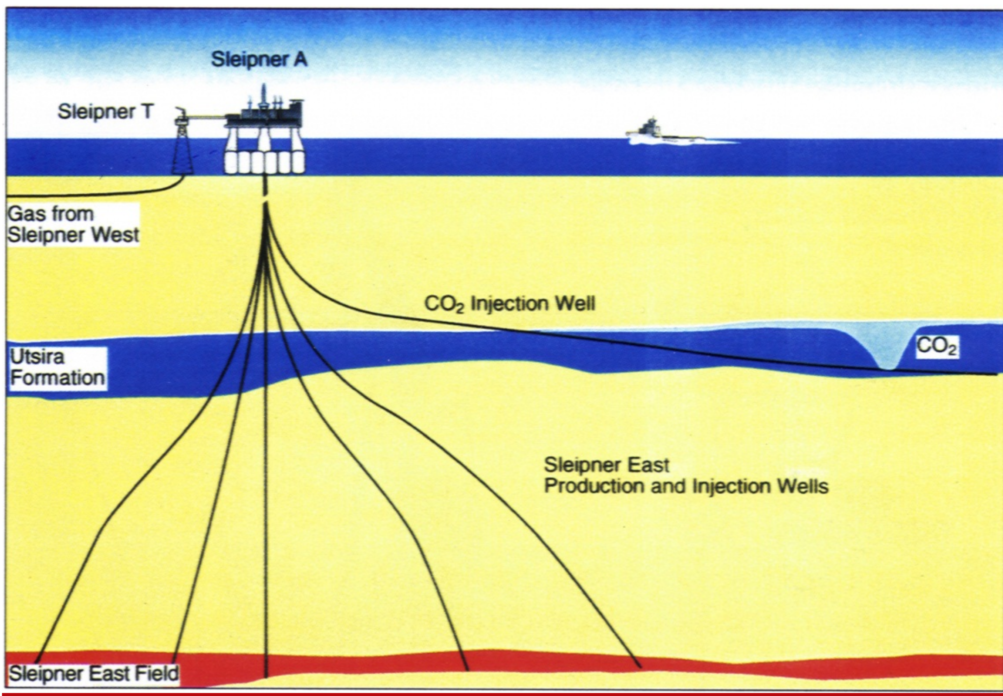


Figure 1.

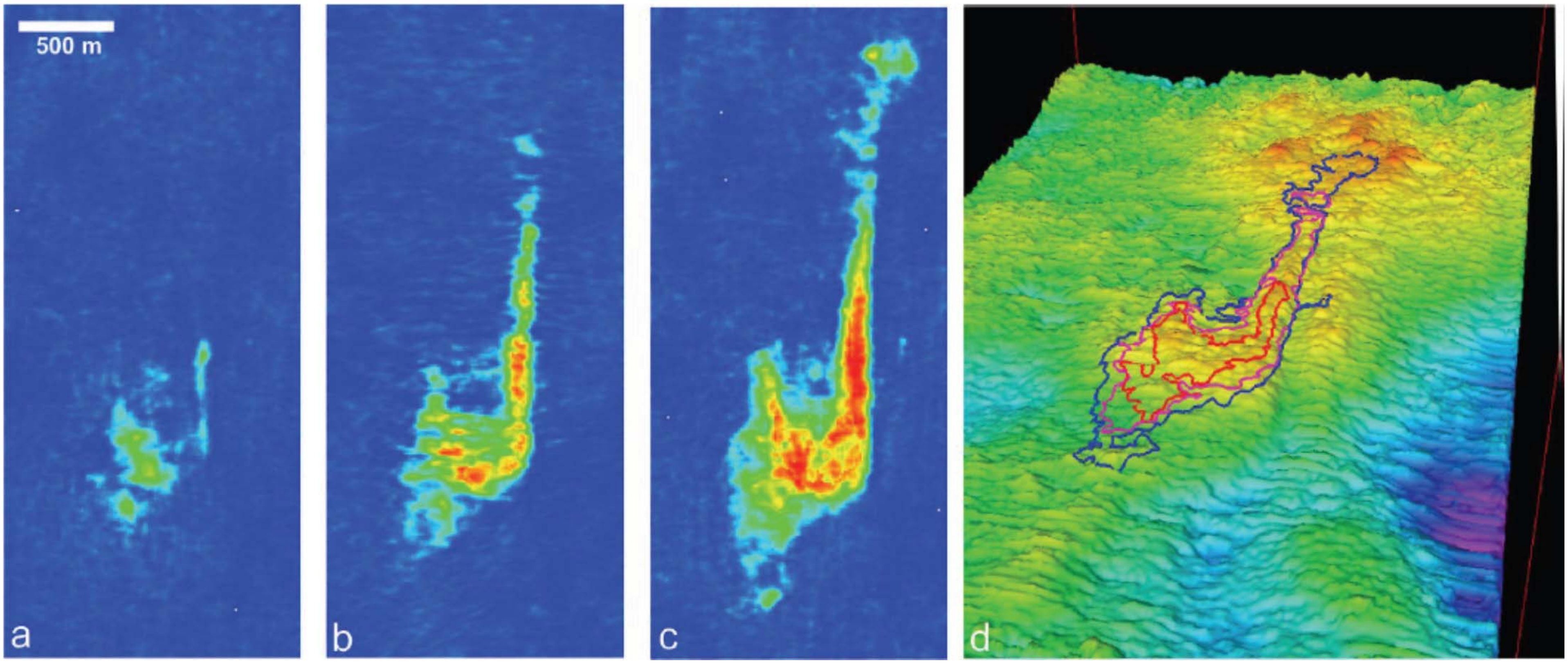
Image source: Dan McGee, Alberta Geological Survey

Aquifer Injection in the North Sea

- Sleipner West: 1 million tonnes/yr injection.
- CO_2 separated from produced gas.
- Carbon tax avoided.



Seismic Images: Sleipner Plume Evolution



2001 **2004** **2006** **CO_2-water contacts**

Source: Chadwick et al., Greenhouse Gas Technology Conference, 2009

Reality check: the volumes are very large!

- At a CO_2 density of 500 kg/m^3 (1000 m depth at 50˚C), injection of 1 billion tonnes/yr of CO_2 is equivalent to ~ 35 million barrels/day.
- At a CO_2 density of 700 kg/m^3, 1 Gt CO_2 is equivalent to ~ 25 million barrels/day.
- Worldwide emissions of CO_2, ~ 25 Gt/yr:
  ~ 625 – 825 million barrels/day!
- World oil production is currently ~85 million barrels/day.
- These volumes are large enough that it is clear that CO_2 storage in geologic formations will be but one of a variety of ways to reduce CO_2 emissions to the atmosphere.