Observations

• Energy is an essential component of modern societies, strongly linked to agriculture and food production, communications, transportation, …

• Energy is a primary way humans interact with global systems.

• We humans mostly take both the natural systems and their services as well as the availability of energy supplies completely for granted.

• It’s time to do better!
A brief history of energy use by humans

- 800,000 BCE? Fire domesticated.
- 2500 BCE? Wind-driven sailing vessels
- Middle ages: wind mills used for grinding grain, pumping water.
- 1700s – steam engine, various versions
- 1838 – fuel cell invented (Grove)
- 1864 – internal combustion engine (Marcus, gasoline, spark ignition)
- 1879 – invention of light bulb (Swan, Edison)
- 1892 – diesel engine (Diesel, compression ignition)
- 1880s (DC), 1896 (AC) – central electricity generation and early electric grids (Edison, Westinghouse)
- 1820s – town gas grids in England
- 1930 – jet engine
- 1950 – photovoltaic cells (Bell Labs)
Figure 5: Oil production rate, from US Energy Information Administration, International Petroleum Monthly, July 2008, and oil price in US $ (equalized to year 2007), from BP (2008). Oil production includes oil and natural gas liquids (NGL).

Source: Roland Horne, Stanford University
Recent History of Oil Prices

• 1970s – easily available supply of oil exceeds demand by only a million barrels per day or so

• In that situation, any disruption of a portion of supply causes significant price volatility

• Supply and demand respond to higher prices, but with long time constants for response
  – More attention to energy efficiency (but automobile population turnover is slow)
  – Exploration, and if successful, new production – also slow
  – Alternative energy resources developed

• Eventually, increased supplies, reduced demand lead to oil price collapse in 1986

• Any of this sound familiar? Is the situation different now?
CO₂, CH₄ and N₂O Concentrations
- far exceed pre-industrial values
- increased markedly since 1750
due to human activities

Relatively little variation before
the industrial era
Predicted Global Average Temperature

Source: IPCC, 2007
The oceans have taken up ~400 Gt of fossil fuel CO₂. Global surface oceans now remove 20-25 Mt CO₂/day. Decline in pH (0.1 since industrial revolution) affects bicarbonate, carbonate ion concentrations, rates of fixation of CaCO₃ by assorted critters in the trophic chain, potential for feedbacks with temperature change.

Source: Oceanography Vol.17, No.3, Sept. 2004
### Projected Decreases and Timing of CO$_2$ Emission Reductions

#### Global mean

<table>
<thead>
<tr>
<th>Stabilization level (ppm CO$_2$-eq)</th>
<th>temperature increase at equilibrium (ºC)</th>
<th>Year global CO$_2$ needs to peak</th>
<th>Year global CO$_2$ emissions back at 2000 level</th>
<th>Reduction in 2050 global CO$_2$ emissions compared to 2000</th>
</tr>
</thead>
<tbody>
<tr>
<td>490 – 535</td>
<td>2.4 – 2.8</td>
<td>2000 - 2020</td>
<td>2000- 2040</td>
<td>-60 to -30</td>
</tr>
<tr>
<td>535 – 590</td>
<td>2.8 – 3.2</td>
<td>2010 - 2030</td>
<td>2020- 2060</td>
<td>-30 to +5</td>
</tr>
<tr>
<td>590 – 710</td>
<td>3.2 – 4.0</td>
<td>2020 - 2060</td>
<td>2050- 2100</td>
<td>+10 to +60</td>
</tr>
<tr>
<td>710 – 855</td>
<td>4.0 – 4.9</td>
<td>2050 - 2080</td>
<td></td>
<td>+25 to +85</td>
</tr>
<tr>
<td>855 – 1130</td>
<td>4.9 – 6.1</td>
<td>2060 - 2090</td>
<td></td>
<td>+90 to +140</td>
</tr>
</tbody>
</table>

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*IPCC, WGIII, 4$^{th}$ Assessment Report*

*The scale of the challenge is enormous: even with deep reductions in emissions, significant temperature rise is likely.*
So what do we do about this?

• Look for energy efficiency at every turn – there is plenty of room for efficiency improvement with technologies we have today, especially in the US (lots of near-term opportunities in buildings, lighting, vehicles, etc).
• But growth in demand, particularly in the developing world, will require that new technologies be brought on line if greenhouse gases emissions are to be reduced at the same time.
• The challenges go well beyond the technical issues! We need behavioral changes, better policies for energy, and plenty of international effort.
• Above all, we need plenty of ideas and talented people to put them to work.
• Universities like Stanford have an important role to play.
Conversion Efficiency of “Engines”

Source: C. Edwards, GCEP
What resources can we use?
Exergy flow of planet Earth (TW)

Human activities = ~15 TW, ~30 by 2050
Renewable Global Exergy Flows

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

- **Solar and wind are the largest resources**
  - Solar: 6,000 times current human energy use
  - Wind: 60 times current human energy use
  - But, cost, intermittency and variable global distribution must be addressed
  - Energy storage and a more capable grid will be critical to dealing with intermittency
  - High cost of solar impedes widespread deployment (for now)

- **Terrestrial and marine biomass resource** is about 6 times greater than current human consumption
  - Biomass is likely to continue to contribute as an energy resource but with limits due to competition for land use, water, food production …

- **Other renewable energy resources may provide local resources but will have limited impact on global energy supply**
  - Waves and tides have small gravity head
  - OTEC – small gradients mean low efficiency conversions
Cost of Electricity

Levelized Cost Comparison for Electric Power Generation
With $100 per Ton Tax on Carbon (2007 Fuel Prices)

Source: J. Weyant, Energy Modeling Forum, Stanford University
Grid Issues

- Current grid grew from connections among regional grids
- Addition of large fractions of wind and solar electric power generation will require changes:
  - Many widely distributed, modest size intermittent sources – new architectures?
  - Need capacity over longer distances, distributed sensing, active controls, storage …
- Policy and regulatory issues abound
Global Exergy Stores

Alternatives: Nuclear

- Nuclear power – no CO$_2$ emissions (except for the concrete and steel in the plant).
- Waste storage – new fuel cycles can reduce but not eliminate waste.
- Nuclear proliferation is an international issue.

• 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
Energy Research at Stanford

Program on Energy & Sustainable Dev
- Electricity Markets
- Global Natural Gas Markets
- Energy Services in Low-Income Communities
- National Oil Comps & World Markets
- Climate Change Policy after Kyoto
- Emerging Global Coal Market

Precourt Institute for Energy Efficiency
- Buildings
- Transportation/Vehicles
- Behavior and Decision Making
- Systems Analysis
- Modeling
- Policy

Global Climate and Energy Project
- Fundamentals of energy conversions w low GHG emissions
- Advanced Solar PV
- Bioenergy Conv
- Carbon Capture & Storage
- Electrochemistry (fuel cells & batteries)
- Hydrogen
• The Global Climate and Energy Project (GCEP) was established to conduct pre-commercial research necessary to underpin technology options needed to reduce GHG emissions from energy use.

• It is a 10-year, $225M commitment to lay the basis for technologies that could have a significant impact on a global scale.

Mission

To Conduct Fundamental Research to Develop Technology Options for Growth in Energy Use With Significantly Reduced Greenhouse Gas Emissions.

ExxonMobil  TOYOTA  Schlumberger  GCEP  External Institutions in US and Worldwide
Energy Conversions for Transportation

- Fossil w/ capture
- Nuclear
- Solar
- Other renewables
- Biomass
- Oxygenates
- Hydrogen
- Electricity
- Methane, diesel
- H₂ storage
- Electric storage

Onboard energy conversion to work
Increasing Efficiency and Lowering Costs of Solar PV

"Third Generation" Concepts

GCEP research efforts include a broad array of new approaches to reducing the cost and enhancing efficiency of solar energy conversion.

GCEP High Efficiency PV Program

- hot carrier
- TPVs, thermionics
- intermediate band, up-converters, tandem (n=3)
- multiple exciton generation
- tandem (n=2), down-converters

GCEP research efforts include a broad array of new approaches to reducing the cost and enhancing efficiency of solar energy conversion.
Directed Evolution of Novel Yeast Species to allow fermentation of xylose, a major component of hemicellulose

New xylose utilizing strain

Non xylose utilizing strain

Cellulose fibrils

Increased cellulose accumulation for enhanced biomass

CESA4

CESA7

CESA8

Cellulose

Hemicellulose

Lignin

Novel precursors for simplified degradation of lignin

Novel screen for plants with enhanced saccharification

Increased cellulose accumulation for enhanced biomass

Cellulose fibrils

Directed Evolution of Novel Yeast Species to allow fermentation of xylose, a major component of hemicellulose

New xylose utilizing strain

Non xylose utilizing strain

Engineering pathways in *E.coli* for Biodiesel production

GCEP Research Projects in Biofuels
Development of Innovative Gas Separation Membranes Through Sub-Nanoscale Control

Shingo Kazama, Katsunori Yogo, Teruhiko Kai, Kousuke Uoe, Shuhong Duan, Naoki Yamamoto, RITE

Composition: CO₂ 40 vol% / H₂ balance
Temperature: <150 °C for carbon membrane, 200 °C> for zeolite membrane
Pressure: 4 MPa
What could be done with CO$_2$ from oxidation reactions?

Options for Geologic Storage of CO$_2$

- Oil and gas reservoirs: enhanced oil and gas recovery.
- Deep formations that contain salt water.
- Coal beds (adsorbed CO$_2$ replaces adsorbed CH$_4$).

Image source: Dan McGee, Alberta Geological Survey
An example: a transition pathway for electric power generation (EPRI)

*Achieving all targets is very aggressive, but potentially feasible.*

Conclusions

• Changing the world’s energy systems to reduce GHG emissions is a big challenge, but it can be met by a sustained effort on many fronts (including universities).
• There is way too much coal and heavy oil in the world – avoiding relying on it, or capturing and storing the CO₂ from it, is essential if we are to control atmospheric concentrations of CO₂.
• There is no single, simple solution to this challenge.
• There is much to do, but there is much that can be done, on a variety of time scales:
  – Much better energy efficiency now
  – Adding more renewable and low GHG technologies available now to the energy mix
  – Research on a wide-ranging portfolio of energy resources and conversion methods for applications in the long term
  – Work on the policy and regulatory structures at all levels that will make these transformations possible