Chemical & Biomolecular Engineering at Georgia Tech

**ATLANTA, GEORGIA**
- Economy is 6th in United States, 15th in world
- Airport is world’s busiest

**GEORGIA TECH**
- Largest college of engineering in the United States
- Only U.S. institution with all graduate engineering programs in top 10 (USNWR 2014)
- Only U.S. institution in top 5 for R&D spending in both chemistry and chemical engineering (NSF data, 2013)

**ChBE at GEORGIA TECH**
- 1000+ undergraduate students
- 200+ Ph.D. students
- No. 1 in United States in NTU 2013 Performance Ranking

www.chbe.gatech.edu/aiche2014
GRAND CHALLENGES FOR ENERGY PRODUCTION IN THE 21ST CENTURY

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The Grand Challenges of Energy Production in the 21st Century

• Global energy production faces three grand challenges.

• First is the need to decarbonize the energy production. Current energy related carbon emission accounts for more than half of the global carbon emission of 10 GtC per year.

• Second, there is the imperative need to manage the demand side. Even if we can radically decarbonize our energy, with the escalating demand we are likely to surpass the Earth’s sustaining capacity.

• Last but definitely not the least; global energy production should consider its impacts on other resources such as water, food and arable land, dependencies that has often been overlooked.
Resource Consumption for Material Production
(Energy Required for Top 7 Materials: 1.5 TW – 10% of Global Energy)

- Ratio based on mix design for 30 MPa compressive strength at 28 days (http://www.ctre.iastate.edu/pubs/sustainable/strublesustainable.pdf)
Optimistic Projection of Future Efficiency for 2050 Material Demand

Even with most optimistic projections of future efficiencies in supply chain, energy efficiency, yield losses, maximum recycling rates, and de-carbonization of energy supplies, reaching 2050 target of 50% less CO$_2$ emissions is impossible due to increasing demand.

Source: Allwood, et al. (2011)
ETP 2012 – Choice of 3 Futures

2DS
a vision of a **sustainable** energy system of reduced Greenhouse Gas (GHG) and CO₂ emissions
The 2°C Scenario

4DS
reflecting pledges by countries to cut emissions and boost energy efficiency
The 4°C Scenario

6DS
where the world is now heading with potentially **devastating** results
The 6°C Scenario
Choosing the Future Energy System

CO₂ Target – 70% Reduction

Current Trajectory

Observed Emission

- 6 Degree Scenario
- 4 Degree Scenario
- 2 Degree Scenario

1990 2000 2010 2020 2030 2040 2050

Gt C per year

5.0 Gt C (-31%)

11.5 Gt C (-72%)

6.6 Gt C (-60%)

4.4
How to Fund the Global Energy Revolution?

### Required Investments in Energy Sector to Limit Temperature Rise to 4°C

<table>
<thead>
<tr>
<th>Category</th>
<th>Changes in Annual Investment Flows 2010-2029 [Billion USD2010 per year]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Electricity Generation</td>
<td>100</td>
</tr>
<tr>
<td>Renewable</td>
<td>90</td>
</tr>
<tr>
<td>Nuclear</td>
<td>40</td>
</tr>
<tr>
<td>Power Plant with CCS</td>
<td>30</td>
</tr>
<tr>
<td>Fossil Fuel Power Plant without CCS</td>
<td>-60</td>
</tr>
<tr>
<td>Extraction of Fossil Fuel</td>
<td>-110</td>
</tr>
<tr>
<td>Energy Efficiency</td>
<td>320</td>
</tr>
</tbody>
</table>

**Total Investment per Year = .580 Trillion 2010 USD**

**Source:** Climate Change 2014: Mitigation of Climate Change, IPCC Working Group III
HOW TO TRANSFORM ENERGY PRODUCTION: Technological Options
WWIII - The Plan

• To power the world with 11.5 TW Wind Water and Solar energy
  • 51% by wind (5.8 TW)
    • 3.8 million large wind turbines (5 MW each), 0.8% in place
  • 40% by solar (4.6 TW)
    • 1.7 billion rooftop PV systems (0.003 MW each), <1% in place
    • 89,000 PV and concentrated solar power plants (300 MW each)
  • 9% by water (1.1 TW)
    • 900 hydroelectric plants (1,300 MW each), 70% in place

Jacobson and Delucchi, 2009
U.S. Renewable Resources

<table>
<thead>
<tr>
<th>Resource</th>
<th>Solar PV/CSP</th>
<th>Wind</th>
<th>Geothermal</th>
<th>Water Power</th>
<th>Biopower</th>
</tr>
</thead>
<tbody>
<tr>
<td>Theoretical Potential</td>
<td>206,000 GW (PV)</td>
<td>8,000 GW (onshore)</td>
<td>39 GW (conventional)</td>
<td>140 GW</td>
<td>78 GW</td>
</tr>
<tr>
<td></td>
<td>11,100GW (CSP)</td>
<td>2,200 GW (offshore to 50 nm)</td>
<td>520 GW (EGS)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>4 GW (co-produced)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Credit: Paul Denholm 2010
Fusion Energy: Is it still Science Fiction?

• ITER (International Thermonuclear Experimental Reactor) is an international nuclear fusion research and engineering megaproject, which is currently building the world's largest experimental tokamak nuclear fusion reactor adjacent to the Cadarache facility in the south of France.

• The ITER fusion reactor itself has been designed to produce 500 megawatts of output power.

• Construction of the ITER facility began in 2007, and the capital costs are now estimated to be US$50 billion, roughly 10 times the original figure.

• The facility is now expected to finish its construction phase in 2019.

• It will start commissioning the reactor that same year and initiate plasma experiments in 2020, but there is no plan to begin full deuterium-tritium fusion until 2027—if the ITER team can solve the technical challenges involved.

• The first commercial demonstration fusion power plant, named DEMO, is proposed to follow on from the ITER project.
Fusion Energy: Is it still Science Fiction?

ITER'S TOKAMAK — TOO HOT TO HANDLE
Fusion scientists often describe the job of containing a hot plasma in magnetic fields as akin to holding jelly using rubber bands.

Coils for magnetic field
These superconducting magnets run both laterally and longitudinally around the machine. They are the 'rubber bands' that suspend the plasma in ITER's core.

External heating
In addition to the solenoid, ITER will use external radio waves and microwaves to heat the plasma to more than 100 million degrees centigrade.

Solenoid
A superconducting coil at the centre of the machine, the solenoid helps to stabilize the plasma and heats it through induction.

Blanket
The blanket surrounding the plasma absorbs neutrons and heat from the fusion reaction. It must be made of materials that can withstand high levels of radiation.

Plasma
Most likely consisting of deuterium and tritium, the plasma suspended within the reactor will release up to ten times the amount of energy it absorbs.

Diverter
The diverter absorbs hot helium atoms from the fusion reaction. It must be able to withstand extreme temperatures and high levels of radiation.
The Future of Fusion Energy?

• Engineers at the University of Washington have designed a concept for a fusion reactor.
• When scaled up to the size of a large electrical power plant, it would rival costs for a new coal-fired plant with similar electrical output, they claim.
• They explained that building a fusion power plant producing 1 GW (1 billion watts) of power would cost $2.7 billion (£1.7 billion), while a coal plant of the same output would cost $2.8 billion (£1.8 billion), according to their analysis.
• Design builds on existing technology and creates a magnetic field within a closed space to hold plasma in place long enough for fusion to occur.
• Engineers at the University of Washington claim the design is cheaper than building a coal power station - but warn a full-sized version is years away.
• When compared with the fusion reactor concept in France, the new design is much less expensive at roughly one tenth of the cost of ITER and would produce five times as much energy.
The Potential of Thorium as Nuclear Fuel

• **Advantages:**
  
  - The Th-U fuel cycle does not irradiate Uranium-238 and therefore does not produce transuranic (bigger than uranium) atoms like Plutonium. (Th-U waste will degrade to its background ore radiation levels in 300 years)
  
  - Thorium is more abundant in Earth’s crust than Uranium, at a concentration of 0.0006% vs. 0.00018% for Uranium (factor of 3.3x). US has a Thorium reserve of 440 Mt, about 25% of Global Reserve.
  
  - Thorium is a hitchhiker element for rare-earth metals.
  
  - Thorium is generally accepted as proliferation resistant compared to U-Pu cycles. By avoiding plutonium altogether, thorium cycles are superior in this regard.

• **Disadvantages:**
  
  - Thorium fuel is a bit harder to prepare.
  
  - We don’t have as much experience with Th.
Natural Gas as a Bridge to Cleaner Energy

"Electricity produced from natural gas can emit just half the CO₂ as the same amount of electricity from coal."

• Concerns:
  • Fugitive methane from energy production is a major source of GHG emissions.
  • Recent estimates put the total released from energy activities in 2010 at around 125–129 million tonnes of methane per year (4.2–4.4 billion tonnes of CO₂ equivalents), with 80–90 Mt from oil and gas supply and distribution (2.7–3.1 Gt CO₂e).
  • For comparison, this is the equivalent of 16–18% of the 17 Gt CO₂ emitted from oil and gas combustion in 2010.

Decentralized Combined Heat and Power (Natural Gas): Perkins + Will, Atlanta Office

- Air cooled Microturbines are used to for heating and cooling using Absorption Chillers and supply 40% of the total electricity.

Adding Distributed Generation as part of the Grid:

<table>
<thead>
<tr>
<th>Water Reduction:</th>
<th>&gt;50%</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂ Reduction:</td>
<td>15 - 40%</td>
</tr>
<tr>
<td>NOₓ Reduction:</td>
<td>~90%</td>
</tr>
</tbody>
</table>
Solar and Nuclear Costs: The Historic Crossover

Increasing safety regulations are escalating the cost of nuclear power globally.
Global GHG Abatement Cost Curve beyond Business-as-Usual – 2030

Note: The curve presents an estimate of the maximum potential of all technical GHG abatement measures below €60 per tCO$_2$e if each lever was pursued aggressively. It is not a forecast of what role different abatement measures and technologies will play.

Source: Global GHG Abatement Cost Curve v2.0
THE ROLE OF ENERGY STORAGE (IMPORTANT FOR RENEWABLE ENERGY SUPPLY)
The Growing Demand for Energy Storage

• California Public Utilities Commission created a new program in 2013 requiring utilities to procure 1.325 GW of new storage by 2024.
  • This is enough to produce power at peak output for over 1 million California homes.
• Under this new program, the utilities must issue requests for offers (RFO) with defined megawatt targets for each RFO.
• The targets are divided into three “buckets”:
  1. transmission-interconnected;
  2. distribution-interconnected and
  3. behind-the-meter projects such as electric vehicles or home battery systems for solar.
• According to Pike Research, the total U.S. energy storage market could surpass 14 GW by 2022. However, to get there, the price of such systems installed must fall to about $700-$750 per kWh.
• New York increases the incentive for energy storage. Energy systems that can provide on-peak reduction will pay $2,600 per kW for thermal storage and $2,100 per kW for battery storage systems.
Energy Storage Technologies

- The diverse energy storage approaches currently deployed around the world can be divided into six main categories:
  
  1. **Solid State Batteries**: a range of electrochemical storage solutions, including advanced chemistry batteries and capacitors
  
  2. **Flow Batteries**: batteries where the energy is stored directly in the electrolyte solution for longer cycle life and quick response time
  
  3. **Flywheels**: mechanical devices that harness rotational energy to deliver instantaneous electricity
  
  4. **Compressed Air Energy Storage**: utilizes compressed air to create a potent energy reserve
  
  5. **Thermal**: capturing heat and cold to create energy on demand
  
  6. **Pumped Hydro-Power**: creates large-scale reservoirs of energy with water (80% efficient)
  
  7. **Hydrogen**: Electrolyze Water and recover energy using a fuel cell (30 to 40% efficient)
Flow Batteries

• A Flow Battery is a type of rechargeable battery where rechargeability is provided by two chemical components dissolved in liquids contained within the system and separated by a membrane.

• Ion exchange (providing flow of electrical current) occurs through the membrane while both liquids circulate in their own respective space.

• Cell voltage ranges, in practical applications, from 1.0 - 2.2 V.

• While it has technical advantages such as potentially separable liquid tanks and near unlimited longevity over most conventional rechargeables, current implementations are comparatively less powerful and require more sophisticated electronics.

• Different classes of flow cells have been developed, including redox, hybrid and membraneless.
Vanadium: The Metal for Powering

- Vanadium Redox Batteries
  - “Cellcube” (for the smallest model)
    - Cost: $100,000
    - Footprint: a parking bay
    - Storage capacity: 100 kWh

- Storage principle
  - One tank for electron releasing: blue → yellow
  - The other tank for electron receiving: green → violet
  - A matching number of protons (H+) passing across membrane between the two solutions

Source: Laurence Knight, “Vanadium: The metal that may soon be powering your neighbourhood”. BBC News 13 June 2014
Flywheel Energy Storage System

- The flywheel energy storage system is a kinetic-energy-based storage device that contains a flywheel rotor assembly and a motor / generator.
- This assembly is designed to operate at high speeds (>20,000 RPM) to achieve highest energy storage density (Wh/kg).
- When power is being removed from the grid the motor/generator converts electric power into mechanical energy to spin the flywheel.
- When power is required to be delivered to the grid the motor/generator converts this mechanical energy back to electric power.
- This conversion takes place using commercial high power conversion electronics.
Compressed Air Energy Storage

- Compressed Air Energy Storage (CAES) plants are largely equivalent to pumped-hydro power plants in terms of their applications, output and storage capacity.
- But, instead of pumping water from a lower to an upper pond during periods of excess power, in a CAES plant, ambient air is compressed and stored under pressure in an underground cavern.
- When electricity is required, the pressurized air is heated and expanded in an expansion turbine driving a generator for power production.
Pumped Heat Electrical Storage

- In Pumped Heat Electrical Storage (PHES), electricity is used to drive a storage engine connected to two large thermal stores.
- To store electricity, the electrical energy drives a heat pump, which pumps heat from the “cold store” to the “hot store” (similar to the operation of a refrigerator).
- To recover the energy, the heat pump is reversed to become a heat engine.
- The engine takes heat from the hot store, delivers waste heat to the cold store, and produces mechanical work.
- When recovering electricity the heat engine drives a generator.

Recoverable Electrical Energy 30 MWh
Hydrogen Energy Storage

- Electricity can be converted into hydrogen by electrolysis. The hydrogen can be then stored and eventually re-electrified.
- The round trip efficiency today is as low as 30 to 40% but could increase up to 50% if more efficient technologies are developed.
- Despite this low efficiency the interest in hydrogen energy storage is growing due to the much higher storage capacity compared to batteries (small scale) or pumped hydro and CAES (large scale).
Pumped Hydro-Power Projects in US

Licensed Pumped Storage Projects

<table>
<thead>
<tr>
<th>State</th>
<th>Capacity (MW)</th>
<th>State</th>
<th>Capacity (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CA</td>
<td>2,943</td>
<td>NJ</td>
<td>365</td>
</tr>
<tr>
<td>CO</td>
<td>300</td>
<td>NY</td>
<td>1,400</td>
</tr>
<tr>
<td>CT</td>
<td>31</td>
<td>OK</td>
<td>260</td>
</tr>
<tr>
<td>GA</td>
<td>1,120</td>
<td>PA</td>
<td>1,322</td>
</tr>
<tr>
<td>MA</td>
<td>1,746</td>
<td>SC</td>
<td>1,576</td>
</tr>
<tr>
<td>MI</td>
<td>1,658</td>
<td>SC/NC</td>
<td>710</td>
</tr>
<tr>
<td>MO</td>
<td>408</td>
<td>VA</td>
<td>2,722</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>TOTAL CAPACITY 16,571 MW</td>
</tr>
</tbody>
</table>

Source: FERC Staff, April 1, 2014
HOW TO TRANSFORM THE ENERGY SCENARIO:
Policy Options
China-US Carbon Deal: The Significance

- The **US pledged to cut carbon by 26-28% by 2025, compared to 2005 levels.**
  - The current goal was to reduce emission by 17% by 2020.
  - It would double the pace at which it is reducing its emissions.
- However, it’s a smaller cut than that agreed by the EU. Its 40% cut by 2030 is compared to a higher baseline of 1990.
- **China pledged to cap its rapidly growing carbon emissions by 2030, or earlier if possible.**
- **China has pledged to get 20% of its power from zero-carbon sources by 2030.**
  - It is already on track for 15% by 2020.
- The US-China deal is highly significant in the clear signal it sends to the energy industry, who will invest trillions of dollars in the coming decades.
- China’s pledge of 20% clean energy by 2030 means 800-1,000GW of new wind, solar, nuclear and other zero-emission technology. That addition alone is about the same size as the entire US electricity sector today.
# The Effect of Montreal Protocol

## Emission Reduction by policies/actions, Billion Tonnes CO₂ Equivalent

<table>
<thead>
<tr>
<th>Policy/Action</th>
<th>Cumulative emissions</th>
<th>Period</th>
<th>Annual emissions*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Montreal protocol</td>
<td>135.0bn</td>
<td>1989–2013</td>
<td>5.6bn</td>
</tr>
<tr>
<td>Hydropower worldwide</td>
<td>2.8bn</td>
<td>2010</td>
<td>2.8bn</td>
</tr>
<tr>
<td>Nuclear power worldwide</td>
<td>2.2bn</td>
<td>2010</td>
<td>2.2bn</td>
</tr>
<tr>
<td>China one-child policy</td>
<td>1.3bn</td>
<td>2005</td>
<td>1.3bn</td>
</tr>
<tr>
<td>Other renewables worldwide</td>
<td>600m</td>
<td>2010</td>
<td>600m</td>
</tr>
<tr>
<td>US vehicle emissions &amp; fuel economy standards†‡</td>
<td>6.0bn</td>
<td>2012–25</td>
<td>460m</td>
</tr>
<tr>
<td>Brazil forest preservation</td>
<td>3.2bn</td>
<td>2005–13</td>
<td>400m</td>
</tr>
<tr>
<td>India land-use change</td>
<td>177m</td>
<td>2007</td>
<td>177m</td>
</tr>
<tr>
<td>Clean Development Mechanism</td>
<td>1.5bn</td>
<td>2004–14</td>
<td>150m</td>
</tr>
<tr>
<td>US building &amp; appliances codes</td>
<td>3.0bn</td>
<td>2008–30</td>
<td>136m</td>
</tr>
<tr>
<td>China SOE efficiency targets</td>
<td>1.9bn</td>
<td>2005–20</td>
<td>126m</td>
</tr>
<tr>
<td>Collapse of USSR</td>
<td>709m</td>
<td>1992–98</td>
<td>118m</td>
</tr>
<tr>
<td>Global Environment Facility</td>
<td>2.3bn</td>
<td>1991–2014</td>
<td>100m</td>
</tr>
<tr>
<td>EU energy efficiency</td>
<td>230m</td>
<td>2008–12</td>
<td>58m</td>
</tr>
<tr>
<td>US vehicle emissions &amp; fuel economy standards‡‡</td>
<td>270m</td>
<td>2014–18</td>
<td>54m</td>
</tr>
<tr>
<td>EU renewables</td>
<td>117m</td>
<td>2008–12</td>
<td>29m</td>
</tr>
<tr>
<td>US building codes (2013)</td>
<td>230m</td>
<td>2014–30</td>
<td>10m</td>
</tr>
<tr>
<td>US appliances (2013)</td>
<td>158m</td>
<td>2014–30</td>
<td>10m</td>
</tr>
<tr>
<td>Clean technology fund</td>
<td>1.7bn project lifetime</td>
<td>na</td>
<td></td>
</tr>
<tr>
<td>EU vehicle emission standards</td>
<td>140m</td>
<td>2020</td>
<td>na</td>
</tr>
</tbody>
</table>

*Annual emissions are cumulative emissions divided by the relevant period. The estimate for the current emissions avoided under the Montreal protocol is eight billion tonnes of CO₂e. The annual figure for the collapse of the USSR refers to the years 1992–98. †Cars and light trucks ‡Heavy trucks

---

See following panel for sources and explanations
The Window for Action is Rapidly Closing for a 2°C Scenario

65% of our carbon budget compatible with a 2°C goal already used

Total Carbon Budget: 790 GtC

Amount Used 1870-2011: 515 GtC

Amount Remaining: 275 GtC
What Needs to be Done to Limit Temperature Rise to 2°C

Zero GHG Emission by 2100
Where are the Federal Subsidies Directed?

- **Carbon Capture and Storage**: 0.30
  - $2.3 billion

- **Renewable Energy**: 6.00
  - $12.2 billion

- **Corn Ethanol**: 5.00
  - $16.0 billion

- **Fossil Fuels**: 16.30
  - $70.2 billion

**Note:**
- All the values are in billions of USD
- Values represent total of Government directed subsidy dollars from 2002 to 2008 (in 2008 dollar)
The Burden of Fossil Fuel

**Big burden**
Cost of mortality from PM 2.5* exposure, as % of GDP, 2010, 15 largest CO₂ emitters

Source: New Climate Economy

*Small airborne particles responsible for most of the health effects of outdoor air pollution
Final Thoughts

• Admittedly, the challenges are daunting and the magnitude of what we have to do is frightening.

• Unless we act upon now, the future would be much scarier.

• **Even at Less than 2°C**
  - Arctic sea icecap disappears; Droughts spread through the sub-tropics, accompanied by heat waves and intense wildfires.

• **At 5°C-6°C**
  - Global average temperatures would be hotter than for 50 million years.
  - The entire Arctic would be ice-free all year round.
  - Most of the tropics, sub-tropics and lower mid-latitudes would be too hot to be habitable.
  - Sea level rise would be sufficiently rapid that coastal cities across the world are largely abandoned.

  “Even if we can’t know what future citizens will actually value and believe in, we can still consider their interests, on the reasonable assumption that they will somewhat resemble our own (everybody needs breathable air, for example),” and since our ethical and political values do always align, we “should consider introducing agents who can vote in a far-seeing and impartial way.” – Thomas Wells

• **We as Engineers, Academics and Decision-makers have a much greater role to play to steer us and the world in the right direction.**
THANK YOU!

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