Institute for Energy Efficiency

John Bowers
Director

www.engineering.ucsb.edu/energyefficiency
The growing consumption of energy in its current source mix, needed to sustain or facilitate access to a high standard of living, will have major negative impacts on our environment, economy, and geopolitical relationships. In addition to developing alternative sources of energy, we need to slow the rate of growth in consumption and, ideally, stop or reverse it. While both the supply and the demand sides of the energy consumption equation must be addressed, the demand side can be addressed more effectively and far more rapidly than the supply side.
Global Carbon Emissions Are Rising Rapidly

In the past 50 years, rising carbon emissions have contributed to the increase in global carbon emissions. Today, global carbon emissions are estimated at 8 billion metric tons a year.

3.7 metric tons of CO₂ emissions contain a metric ton of carbon.

Year

Global Carbon Emission (billion metric tons/year)
HUMAN DEVELOPMENT INDEX, a measure of basic human well-being used by the United Nations, reaches a plateau at about 4000 kilowatt hours of annual electricity use per capita. Sixty nations were analyzed, representing 90% of Earth’s population. (Adapted from ref. 3.)
Reversing the Carbon Emission Curve.

By breaking the carbon ‘culprits’ into definable wedges UCSB strives to reduce the overall impact on the future of the total emissions by focusing on the areas in which we have unique strengths and expertise:

- Lighting and Displays
- Computing and Networks
- Energy Conversion, Transmission and Storage
- Dynamics of Energy Efficiency
- Transportation Materials
UCSB Energy Efficiency Institute

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Some of the UCSB Wedges:
- Replace light bulbs with LEDs: 10x more efficient
- Improve building lighting/heating/cooling efficiency
- Energy scavenging: Turn waste heat into electricity, developing novel, high efficiency thermoelectrics
- Energy Efficient Electronics: Reduce energy consumption in data centers, computers, routers
- Energy Efficient Networking
- Organic Photovoltaic Materials
- Materials for Efficient Transportation
- Control and Optimization of Systems
- Micro-Scale Processing: Energy Efficient Chemical Processing

Temperature Rise
+9.0 Deg. F

14 Billion

Global Carbon Emission (tons/year)

1958 2008 2057

+3.6 Deg. F
E²I Mission

The mission of UCSB’s Energy Efficiency Institute is to develop technologies of broad application that consume significantly less energy than their predecessors. E²I’s interdisciplinary research efforts will be rapidly deployed through both entrepreneurial and collaborative commercialization.
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E²I will focus its efforts on five technology areas:

Strategic Technologies

- Lighting and Displays
- Energy-Efficient Electronics and Networks
- Energy conversion, transmission and storage
- Transportation Materials
- Dynamics of Energy Efficiency
E²I Research Areas

- **Lighting (DenBaars)**
  - Illumination (DenBaars, Hu, Lange, Mishra, Nakamura, Petroff, Seshadri, Speck, Van del Walle, Weishbuch)

- **Computing and Networks (Chong)**
  - Energy-efficient electronics (Brewer, Cheng, Mishra, Rodwell, Wolski, Yue)
  - All optical circuits (Blumenthal, Bowers, Coldren)
  - Silicon photonics (Bowers)
  - Energy-efficient networking (Agrawal, Almeroth, Belding, Almeroth, Suri, Madhow, Petzhold, Sherwood, Suri, Wolski)
  - Spintronics and quantum computation (Awschalom)

- **Energy conversion, transmission and storage (Heeger)**
  - Photovoltaics (Heeger, Hu, Bazan, Kramer, Lee, Wudl, Hawker)
  - Thermoelectrics (Bowers, Gossard)
  - Catalysis (MacFarland, Chemlka, Scott)
  - Hydrogen generation and storage (Mishra)
  - Fuel Cells and Batteries (Chmelka, Kramer, McFarland, Metiu, Buratto, Doherty, Morse, Stuky)

- **Transportation Materials (Zok)** (Evans, Clarke, McMeeking, Zok, Levi, Israelachvili)
  - Weight
  - Functional temperature range
  - Friction

- **Dynamics of Energy Efficiency**
  - Building (Mezic)
  - Process (Soh, Homsy, Squires, Doherty, Leal, Pennathur, Meinhart, Mezic)
  - Manufacturing
  - Systems Control (Khammash, Hespanha, Teel, Doyle, Seborg, Smith, Rose, Kokotovic, Mezic, Paden)
Solid State Lighting and Energy Center

Shuji Nakamura, Steve DenBaars, Jim Speck, …

- If a 150 lumen/watt LED source were used worldwide, then in the United States alone we would realize **$115 billion cumulative savings by 2025**.
- We would also eliminate the need for 133 new power stations, save 258 million metric tons of carbon and save 273 trillion watt-hours per year in energy.
- See DenBaars talk later in this session.

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**Luminous Efficiency (lm/W)**

- Fluorescent
- Compact Fluorescent
- Incandescent bulb
- GaAsP:N (red, yellow)
- AlGaAs/GaAs (red)
- AlInGaP/GaP (red, orange, yellow)
- InGaP (red, orange)
- InGaN (green)
- InGaN (blue)
- SiC (blue)

**Time (years)**

- Thomas Edison’s first bulb
- GaAsP
- Thomas Edison’s first bulb: GaP, ZnO

**160 lm/W**
Computing and Networks

- US business spends $3.3 Billion to power data centers
- The Internet consumes 5% of the world's electricity.
- Companies spend more money powering data centers than on the servers themselves.
- We can do better.

- Google at Columbia River Gorge => hydroelectric power
  - ~$700M facility
  - Contract for 42MW reported
- Second $700M site being evaluated in San Antonio
  - Googleplex => network of such centers world wide
- Microsoft claims $2B in expenditures for next year
- **Bill Weihl**, “Energy Czar” at Google in response to our ideas:
  - “Energy efficiency is a critical issue for data centers today, for Google and for the entire IT industry. I think it's a great thing that academic institutions are taking an interest in this area, particularly in taking an interdisciplinary systems approach to the problem.”
Need for Invention

Power Wall: Module Heat Flux Trend

Integrated Circuit 1957

* R. Schmidt, T-C. Chen, IBM
Energy-Efficient Electronics - Opportunities for Integrated Research from Devices to Applications
(See Tim Cheng’s subsequent talk)

- Workloads/services
- Servers
- Packaging/cooling
- (micro-) architecture
- Circuit optimization
- Device engineering
**Power:**
SoA: 100 GB/sec ~ 1 Tb/sec = 1,000 Gb/sec × 25mw/Gb/sec = 25 Watts
Could be reduced significantly, but requires major changes to physical layer.

**Pins:**
Bus-width = 1,000/5 = 200, about 400 pins (differential)

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*Too much power, too many signal pins*
- I/O power should be < 10% of total CPU socket power
Today's High Speed Interconnects

Optical | Copper

- Metro & Long Haul: 0.1 – 80 km
- Chip to Chip: 1 – 50 cm
- Board to Board: 50 – 100 cm
- Rack to Rack: 1 to 100 m

Decreasing Distances

Goal: Drive optical to high volumes and low costs

From: M. Paniccia, Intel
Problem: Silicon has Indirect Gap—doesn’t emit light

Energy

Conduction band

Low internal quantum efficiency in bulk silicon ($10^{-6}$)

Absorption

Indirect radiation recombination

Valence band

Wavevector
Why Silicon Photonics?

Today’s photonics based on InP and GaAs foundries. If you can make it on Si in a CMOS fab, why do anything else?
Hybrid Silicon Lasers

Deposit III-V crystalline layers on Si. Presently, 4” wafer scale, moving to 6” Q2 ‘08.
**IBM Cell processor**

**Communication**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technology process</td>
<td>90nm SOI with low-κ dielectrics and 8 metal layers of copper interconnect</td>
</tr>
<tr>
<td>Chip area</td>
<td>235mm²</td>
</tr>
<tr>
<td>Number of transistors</td>
<td>~234M</td>
</tr>
<tr>
<td>Operating clock frequency</td>
<td>4Ghz</td>
</tr>
<tr>
<td><strong>Power dissipation</strong></td>
<td>~100W</td>
</tr>
<tr>
<td><strong>Percentage of power dissipation due to global interconnect</strong></td>
<td>30-50%</td>
</tr>
<tr>
<td>Intra-chip, inter-core communication bandwidth</td>
<td>1.024 Tbps, 2Gb/sec/lane (four shared buses, 128 bits data + 64 bits address each)</td>
</tr>
<tr>
<td>I/O communication bandwidth</td>
<td>0.819 Tbps (includes external memory)</td>
</tr>
</tbody>
</table>
IBM Integration Concept

• 3D layer stacking will be prevalent in the 22nm timeframe

• Intra-chip optics can take advantage of this technology

• Photonics layer (with supporting electrical circuits) more easily integrated with high performance logic and memory layers

• Layers can be separately optimized for performance and yield

Source: J. Kash, IBM OIDA Forum on Silicon Photonics
IBM Possible On-Chip Optical Network Architecture

Deflection-switch based

Cell Core
(on processor plane)

Gateway
(on processor and photonic plane)

Electrical Control Network

Photonic Network

Deflection Switch

OIDA Forum on Silicon Photonics
1 Terabit/s Transmitter

Optical Fiber

Multiplexer

25 modulators at 40Gb/s

25 hybrid lasers

A future integrated terabit per second optical link on single chip
Commercial driver: Telecom
Traffic Crossing the AT&T Network

5% of electrical power today. How much in 10 years?

Source: K. Cambron, AT&T Labs
Optical Switching

- The Internet uses about 4% of the world’s electricity today, and that is growing rapidly to 10%.
- About half of that usage is in electrical core switches.
- Eliminating the OEO conversion, and switching optically eliminates about 1W per Gbit/s of information transmission. For a 1 Tbit/s switch, that is a savings of 10 kW per node.
The Challenge of Energy Demand in Buildings

U.S. buildings consume
- 39% of total U.S. energy
- 71% of U.S. electricity
- 54% of U.S. natural gas

U. S. buildings produce 48% of carbon emissions

Commercial building energy intensities are increasing
- Current energy bill $120 billion.
- Electrical Energy consumption doubled in last 18 years
- 25% growth projection through 2030

Enormous potential energy savings
- 4 Quads by 2030 for a savings of $80 billion

Sources: High Performance Commercial Buildings: A Technology Roadmap, U.S. DOE., US GBC, DOE EIA CBECS Database, Table C2A and 5B.
Integrated Building Systems

- Large savings are projected to arise from an integrated approach to building design, where low-impact materials, heating and cooling, lighting and windows, and onsite power systems are integrated into a “smart building” system. UCSB, with its strength in dynamical systems, controls, fluid dynamics and materials, and its connections to National Laboratories and commercial sector is well-positioned to lead in this area.

Energy Storage and Retrieval

For efficient use of produced energy, efficient ways of storing it are being developed. Shown in the figure is carbon-fiber composite flywheel system being developed by UCSB ME spin-off Power Ring Inc.

Energy Harvesting and Off-Grid Generation

On-site energy generation for use in buildings and broader is an important research area at UCSB. Energy can be harvested from nanoscale processes via harvesting of currents induced by pressure in nanometer-sized pores.

Energy Efficient Data Centers

Increased use of data-center buildings by companies such as Google, requires efficient ways of redistributing cooling energy for efficient computation. Combined efforts of faculty at UCSB’s ME and CS departments leads to new technology solutions in this area.
Interdisciplinary Research: Systems of Systems

- Buildings Design & Energy Analysis Team
- Windows & Lighting Team
- Domestic/International Policies, Regulation, Standards, Markets
- Demonstration Team
- HVAC Team
- Natural Ventilation Team
- Sensors, Networks, Communications Controls Team
- Power Delivery & Demand Response Team
- Integration & Building Operating Platform (BOP) Team

IEE: The Institute for Energy Efficiency
GreenScale

- Idea: use economies of scale and the ability to control activities deterministically to build large-scale, energy efficient data centers
  - Machines are not people
    - Heat properties are well understood
    - Behavior is relatively deterministic
    - Can be scheduled, descheduled, crashed, shut off, etc. at will
  - Buildings are far more “homogeneous” than human occupied buildings
    - Few people, homogenous equipment population, robotic operator support
- Important subcategory of Smart Building
  - Good driving application for dynamical systems
  - Very interesting to major tech. Players
    - Google, Microsoft, Amazon, Intel
Computer Science and GreenScale

• Research in *power optimization*
  – GreenScale data center needs to incorporate power optimization into the building control path
  – It is possible to drive HVAC and power control from computational load and sensing data
    • CS has a number of researchers who are studying the relationships between computational load, sensing, and power usage
• Research in *scalable systems*, dynamism, and virtualization
  – GreenScale requires that the large-scale computing infrastructure adapt to control requirements
  – Dynamic resource allocation and provisioning
  – Fault management
    • CS embodies expertise in high-performance distributed systems and scalable virtualization
• Goal: study and develop the computer science necessary to realize “Smart Data Centers” by exploiting economies of scale
  – Synergistic, collaborative, and interdisciplinary approach
Energy Efficient Technologies Vehicles

(Evans, Clarke, McMeeking, Zok, Levi, Israelachvili)

- We can help design all-electric vehicles that provide family transportation, with a cost, range and reliability that would allow penetration of this very competitive market sector.

- Lightweight materials, more efficient energy storage, reduced friction.

- Clearly, achieving this target requires development, at fundamental and product/system levels, well beyond the current state of the art.
Improvements in Engine and Airframe Efficiency Mitigate Fuel Consumption Growth

- Demand for air travel has grown more than twice as fast as economic growth (measured by total GDP).

- Because of continued improvements in engine and airframe efficiency, jet fuel consumption has grown at a rate only 1/3 that of air traffic since 1970.
Advances in thermostructural materials have led to sustained improvements in fuel efficiency. Future gains will rely on use of ceramic composites, intermetallics and new generations of coatings.
Further Advances in Turbine Technology Will Require New High-Temperature Materials

- Thermal barrier coatings and ceramic composites will play central roles in enabling future increase in turbine temperatures and engine efficiency.
Energy Conversion, Transportation and Storage

- Photovoltaics (Heeger, Hu, Bazan, Kramer, Lee, Wudl, Hawker)
- Thermoelectrics (Bowers, Gossard)
  (see next talk from Gossard)
- Catalysis (MacFarland, Chemlka, Scott)
- Hydrogen generation and storage (Mishra)
- Fuel Cells and Batteries (Chmelka, Kramer, McFarland, Metiu, Buratto, Doherty, Morse, Stukey)
Organic Photovoltaic Materials
(Center for Polymers and Organic Solids)

More energy from sunlight strikes the earth in one hour than all of the energy consumed by humans in an entire year. Improved efficiency is essential to the effective, widespread use of solar energy.

Offers the capability to develop:

- New developments in nanotechnology, biotechnology, materials and physical sciences which can enable leaps in progress toward globally scalable systems for solar energy.

Fig. 1. Solar electricity costs as function of module efficiency and cost.
Bio-Templated Nanostructured Photovoltaics

Evelyn Hu

Approach:

- Use semiconductor and metallic nanoparticle building blocks
- Use selective biological templates to form heterogeneous nanowires and films
- Engineer and optimize charge separation and collection at the local scale

Pattern of peptides defines nanoscale structure
Peptides like ‘selective velcro’, chosen to attach to only a specific material

Structuring Photovoltaic Materials at the Nanoscale:

- Broad-spectrum absorption without epitaxial constraints
- Efficient carrier collection and high photon absorption
- Pathways to low-cost fabrication

Semiconductor nanoparticle

Genetically modified virus

Heterogeneous Au-CdSe films Show photo-response and Enhanced conductivity
Chancellor’s green building policy:
• UCOP announced a green building policy.
• All buildings programmed at July 1, 2004 would be LEED Silver.
• Pursue certification for existing buildings as the program develops.

Energy conservation: biggest impact for our $2000-2006 Conservation Projects:
• Saved $6.7M in electrical usage through energy conservation programs.
• Obtained $1.7M in grants and utility rebates
• Reduces CO\textsubscript{2} emissions by 7000 metric tons per year
• Offsets equivalent of \( \frac{1}{2} \) million sq. ft. of new building space!

Proposed Conservation Projects, 2007-2009:
• Projects in place to save more than $1.4M per year
• Reduces CO\textsubscript{2} by another 6500 metric tons per year
• Better quality, more efficient operating systems

For more information on the Sustainability Program, please visit [www.sustainability.ucsb.edu](http://www.sustainability.ucsb.edu)
Summary

• There are many ways we can reduce our energy consumption without reducing our quality of life.
• At UCSB, we are working on a number of promising technologies.
• Collaboration with colleagues and technology transfer to companies is important to success.
• Please join us.