Digital Infrastructure in a Carbon-Constrained World

SciPM 2009
Workshop on the Science of Power Management
Arlington, VA
April 9, 2009

Dr. Larry Smarr
Director, California Institute for Telecommunications and Information Technology
Harry E. Gruber Professor,
Dept. of Computer Science and Engineering
Jacobs School of Engineering, UCSD
The Planet is Already Committed to a Dangerous Level of Warming

90% of the Additional 1.6 Degree Warming Will Occur in the 21st Century

Additional Warming over 1750 Level

Temperature Threshold Range that Initiates the Climate-Tipping

V. Ramanathan and Y. Feng, Scripps Institution of Oceanography, UCSD
September 23, 2008

www.pnas.orgcgidoi10.1073pnas.0803838105
Atmospheric Aerosols Cool Climate—Cleaning Air Pollution will Accelerate Warming!

Outside Beijing 11/9/2008
“It Will Be the Biggest Single Peacetime Project Humankind Will Have Ever Undertaken”
The IPCC Recommends a 25-40% Reduction Below 1990 Levels by 2020

- On September 27, 2006, Governor Schwarzenegger signed California the Global Warming Solutions Act of 2006
  - Assembly Bill 32 (AB32)
  - Requires Reduction of GHG by 2020 to 1990 Levels
    - 10% Reduction from 2008 Levels; 30% from BAU 2020 Levels
    - 4 Tons of CO$_2$-equiv. Reduction for Every Person in California!
- The European Union Requires Reduction of GHG by 2020 to 20% Below 1990 Levels (12/12/2008)
- Australia has Pledged to Cut by 2020 its GHG Emissions 5% from 2000 Levels via the World's Broadest Cap & Trade Scheme (12/15/08) [~5% Below 1990 Levels]
- Neither the U.S. or Canada has an Official Target Yet
  - President Obama Has Endorsed the AB32 2020 Goal
ICT is a Critical Element in Achieving Countries Greenhouse Gas Emission Reduction Targets

GeSI member companies:
- Bell Canada,
- British Telecomm. Plc,
- Cisco Systems,
- Deutsche Telekom AG,
- Ericsson,
- France Telecom,
- Hewlett-Packard,
- Intel,
- Microsoft,
- Nokia,
- Nokia Siemens Networks,
- Sun Microsystems,
- T-Mobile,
- Telefónica S.A.,
- Telenor,
- Verizon,
- Vodafone Plc.

Additional support:
- Dell,
- LG.

SMART 2020: Enabling the low carbon economy in the information age

www.smart2020.org
The Global ICT Carbon Footprint is Roughly the Same as the Aviation Industry Today

But ICT Emissions are Growing at 6% Annually!

- The assumptions behind the growth in emissions expected in 2020:
  - takes into account likely efficient technology developments that affect the power consumption of products and services
  - and their expected penetration in the market in 2020

Most of Growth is in Developing Countries

- ICT includes PCs, telecoms networks and devices, printers and data centres.
- Compounded annual growth rate.
Reduction of ICT Emissions is a Global Challenge – U.S. and Canada are Small Sources

U.S. and Canada Fall From 25% to 14% of Global ICT Emissions by 2020

www.smart2020.org
A System Approach is Required to Reduce Internet’s Greenhouse Gas Emissions

- Estimates Needed for CO2 Emissions from Each Subcomponent
- Beware of Tradeoffs:
  - “I will clean up my campus by getting rid of clusters and computing in the cloud”
  - Is This a Net Reduction?

Source: Rod Tucker, U Melbourne
The Global ICT Carbon Footprint by Subsector

The Number of PCs (Desktops and Laptops) Globally is Expected to Increase from 592 Million in 2002 to More Than Four Billion in 2020

<table>
<thead>
<tr>
<th>Year</th>
<th>Telecoms infrastructure and devices</th>
<th>Data centres</th>
<th>PCs, peripherals and printers</th>
<th>% of GtCO₂e</th>
</tr>
</thead>
<tbody>
<tr>
<td>2002</td>
<td>28</td>
<td>14</td>
<td>57</td>
<td>% of 0.53</td>
</tr>
<tr>
<td>2007</td>
<td>37</td>
<td>14</td>
<td>49</td>
<td>% of 0.83</td>
</tr>
<tr>
<td>2020</td>
<td>25</td>
<td>18</td>
<td>57</td>
<td>% of 1.43</td>
</tr>
</tbody>
</table>

CAGR %

5 7 5

* Printers were 11% of the total ICT footprint in 2002, 8% in 2007 and will be 12% in 2020.

www.smart2020.org
The Composition of the PC Carbon Footprint

Laptop Emissions Grow 50-Fold!

2002
100% = 247 MtCO₂e
- Laptops (6 MtCO₂e)
- Desktops with LCD monitors (16 MtCO₂e)
- Desktops with CRT monitors (226 MtCO₂e)

2020
100% = 643 MtCO₂e
- Desktops with CRT monitors (0 MtCO₂e)
- Laptops (333 MtCO₂e)
- Desktops with LCD monitors (309 MtCO₂e)

Desktops with CRT monitors represented 44% of the total ICT footprint (91% of 49%).

Desktops with LCD monitors and laptops represented 4% of the total ICT footprint (8% of 49%).

Laptops will represent 22% of the total ICT footprint (52% of 42%).

Desktops with LCD monitors will represent 20% of the total ICT footprint (48% of 42%).

GreenLight Project

www.smart2020.org
Composition of the Data Center Carbon Footprint

2020 Estimate Includes Savings from Virtualization, Smart Cooling, and Broad Operating Temperature Envelope)

2002
100% = 76 MtCO$_2$e

- Volume servers (27 MtCO$_2$e)
- Cooling systems (24 MtCO$_2$e)
- Power systems (13 MtCO$_2$e)
- Mid-range servers (5 MtCO$_2$e)
- Storage systems (4 MtCO$_2$e)
- High-end servers (2 MtCO$_2$e)

Volume servers represented 5% of the total ICT footprint (36% of 14%).

Data centre cooling systems represented 4% of the total ICT footprint (32% of 14%).

2020
100% = 259 MtCO$_2$e

- Volume servers (136 MtCO$_2$e)
- Cooling systems (70 MtCO$_2$e)
- Power systems (62 MtCO$_2$e)
- Storage systems (18 MtCO$_2$e)
- High-end servers (5 MtCO$_2$e)
- Mid-range servers (2 MtCO$_2$e)

Volume servers will represent 9% of the total ICT footprint (52% of 18%).

Data centre cooling systems will represent 4% of the total ICT footprint (21% of 18%).

Volume Servers Dominate

www.smart2020.org
Composition of the Global Telecoms Footprint

Broadband Connection Emissions Up 12-Fold!

**2002**
100% = 151 MtCO$_2$e
- Mobile (66 MtCO$_2$e)
- Fixed narrowband (64 MtCO$_2$e)
- Telecom devices (18 MtCO$_2$e)
- Fixed broadband (4 MtCO$_2$e)

**2020**
100% = 349 MtCO$_2$e
- Mobile (179 MtCO$_2$e)
- Fixed narrowband (70 MtCO$_2$e)
- Telecom devices (51 MtCO$_2$e)
- Fixed broadband (49 MtCO$_2$e)

Mobile phones represented 3% of the total ICT footprint (11% of 30%).
Fixed broadband represented 1% of the total ICT footprint (3% of 30%).

Mobile phones will represent 1% of the total ICT footprint (6% of 25%).
Mobile phones will represent 13% of the total ICT footprint (51% of 25%).
Fixed broadband will represent 4% of the total ICT footprint (14% of 25%).
ICT Industry is Already Acting to Reduce Carbon Footprint

Sun's 'portable' Blackbox data center
Company unveils new one-box data center
Sun Microsystems' CEO Jonathan Schwartz showed off the company's new "Project Blackbox" in a Menlo Park, Calif., parking lot Tuesday. Sun says the gear is not only preassembled, but it's tough and arrives ready to run.

Buying Green
Updated 10:47 a.m. EST, Wed November 28, 2007
Google pushes 'green' power initiative

How Microsoft is going green
Biodiesel trucks, solar-powered data centers are just a couple environmentally friendly track
By John Fontana, Network World, 01/09/2008

Intel Becomes Largest Purchaser of Green Power in the U.S.
Company Tops EPA Green Power Partner List, Vows to Drive for Greater Efficiency While Spurring Growth in Renewable Market

IBM Project Big Green
Big Green Banner
Project Big Green is a $1 billion investment to dramatically increase the efficiency of IBM products. New IBM products and services,
Data Centers Will Require Advanced Cooling Environments

Projected Heat-Flux
W/cm²

T芯片 = 85 °C
T inlet = 25 °C

IBM
Krell Study

Source: PNNL Smart Data Center-Andrés Márquez, Steve Elbert, Tom Seim, Dan Sisk, Darrel Hatley, Landon Sego, Kevin Fox, Joe Khaleel (http://esdc.pnl.gov/)
Electricity Usage by U.S. Data Centers: Emission Reductions are Underway

Source: Silicon Valley Leadership Group Report July 29, 2008
CITRIS and HP:
Energy Aware Design and Control

- Wireless Sensor Networks @ CITRIS
  - “Micro-Climate” and Use at Each Blade in the Server Farm
- CITRIS/HP Redesign and Sensing Saves Up to 45% of Cooling Power Use
- Saving ~$400K/yr in Typical Center

Source: Paul Wright CITRIS, Profs Van Carey and David Auslander
<table>
<thead>
<tr>
<th>Strategy</th>
<th>Objectives</th>
</tr>
</thead>
</table>
| Develop a Testbed Datacenter Facility to Promote Energy Efficiency in Collaboration with other National Labs, industry leaders, and Energy-Focused Organizations | ▶ Demonstrate and Compare Innovative Cooling Technologies  
▶ Research Potential Savings in Power Conversion  
▶ Partner with Vendors and Chip Manufacturers to Mature New Technologies in a Operational Datacenter Environment  
▶ Promote Power Aware Computing |

Source: PNNL Smart Data Center-Andrés Márquez, Steve Elbert, Tom Seim, Dan Sisk, Darrel Hatley, Landon Sego, Kevin Fox, Moe Khaleel (http://esdc.pnl.gov/)
The NSF-Funded GreenLight Project
Giving Users Greener Compute and Storage Options

| UCSD Structural Engineering Dept. Conducted Sun MD Tests May 2007 |
|---|---|---|
| Sun Microsystems | 7 Racks plus Network | Takes up 2 Parking Spaces |
| UCSD Jacobs School of Engineering | | Data Power Cooling |

- Measure and Control Energy Usage:
  - Sun Has Shown up to 40% Reduction in Energy
  - Active Management of Disks, CPUs, etc.
  - Measures Temperature at 5 Levels in 8 Racks
  - Power Utilization in Each of the 8 Racks
  - Chilled Water Cooling Systems

Source: Tom DeFanti, Calit2; GreenLight PI

UCSD (Calit2 & SOM) Bought Two Sun MDs May 2008
The GreenLight Project: Instrumenting the Energy Cost of Computational Science

- Focus on 5 Communities with At-Scale Computing Needs:
  - Metagenomics
  - Ocean Observing
  - Microscopy
  - Bioinformatics
  - Digital Media

- Measure, Monitor, & Web Publish Real-Time Sensor Outputs
  - Via Service-oriented Architectures
  - Allow Researchers Anywhere To Study Computing Energy Cost
  - Enable Scientists To Explore Tactics For Maximizing Work/Watt

- Develop Middleware that Automates Optimal Choice of Compute/RAM Power Strategies for Desired Greenness

- Partnering With Minority-Serving Institutions Cyberinfrastructure Empowerment Coalition

Source: Tom DeFanti, Calit2; GreenLight PI
Research Needed on How to Deploy a Green CI

- **Computer Architecture**
  - Rajesh Gupta/CSE

- **Software Architecture**
  - Amin Vahdat, Ingolf Kruger/CSE

- **CineGrid Exchange**
  - Tom DeFanti/Calit2

- **Visualization**
  - Falko Kuster/Structural Engineering

- **Power and Thermal Management**
  - Tajana Rosing/CSE

- **Analyzing Power Consumption Data**
  - Jim Hollan/Cog Sci

- **Direct DC Datacenters**
  - Tom Defanti, Greg Hidley

http://greenlight.calit2.net
New Techniques for Dynamic Power and Thermal Management to Reduce Energy Requirements

**Dynamic Power Management (DPM)**
- Policies Capable of Optimal DPM for a Given Class of Workloads
- Machine Learning to Adapt
  - Select Among Specialized Policies
  - Use Sensors and Performance Counters to Monitor
  - Multitasking/Within Task Adaptation of Voltage and Frequency

**Dynamic Thermal Management (DTM)**
- Workload Scheduling:
  - Power vs. Thermal Management
  - Runtime Adaptation to Obtain Best Temporal and Spatial Profiles Using Closed-Loop Sensing
  - Negligible Performance Overhead
- Machine Learning for Dynamic Adaptation
- Proactive Thermal Management

**NSF Project Greenlight**
- Green Cyberinfrastructure in Energy-Efficient Modular Facilities
- Closed-Loop Power & Thermal Management

System Energy Efficiency Lab (seelab.ucsd.edu)  
Prof. Tajana Šimunić Rosing, CSE, UCSD
GreenLight Project: Putting Machines To Sleep Transparently

Somniloquy Enables Servers to Enter and Exit Sleep While Maintaining Their Network and Application Level Presence

Rajesh Gupta, UCSD CSE; Calit2

IBM X60 Power Consumption

- Sleep (S3): 0.74W (88 Hrs)
- Somniloquy: 1.04W (63 Hrs)
- Baseline (Low Power): 11.05W (5.9 Hrs)
- Normal: 16W (4.1 Hrs)
Improve Mass Spectrometry’s Green Efficiency
By Matching Algorithms to Specialized Processors

- Inspect implements the Very Computationally Intense MS-Alignment Algorithm for discovery of unanticipated rare or uncharacterized post-translational modifications.

- Solution: Hardware Acceleration with a FPGA-Based Co-Processor
  - Identification and Characterization of key kernel for MS-Alignment Algorithm
  - Hardware Implementation of Kernel on Novel FPGA-based Co-Processor (Convey Architecture)

- Results:
  - 300x Speedup & Increased Computational Efficiency
  - Large Savings in Energy Per Application Task
Virtualization at Cluster Level for Consolidation and Energy Efficiency

- Fault Isolation and Software Heterogeneity, Need to Provision for Peak Leads to:
  - Severe Under-Utilization
  - Inflexible Configuration
  - High Energy Utilization
- Usher / DieCast enable:
  - Consolidation onto Smaller Footprint of Physical Machines
  - Factor of 10+ Reduction in Machine Resources and Energy Consumption

Source: Amin Vadhat, CSE, UCSD
GreenLight Provides a Environment for Innovative “Greener” Products to be Tested

Quadrics Was Designed to Use 20% and 80% Less Power per Port Than Other Products in the 10 GigE Market
UCSD is installing zero carbon emission solar and fuel cell DC electricity generators.

San Diego’s Point Loma Wastewater Treatment Plant produces waste methane.

UCSD 2.8 Megawatt Fuel Cell Power Plant uses methane.

2 Megawatts of solar power cells being installed.

Available late 2009.
Zero Carbon GreenLight Experiment: DC-Powered Modular Data Center

• Concept—Avoid DC to AC to DC Conversion Losses
  – Computers Use DC Power Internally
  – Solar and Fuel Cells Produce DC
  – Both Plug into the AC Power Grid
  – Can We Use DC Directly (With or Without the AC Grid)?

• DC Generation Can Be Intermittent
  – Depends on Source
    – Solar, Wind, Fuel Cell, Hydro
  – Can Use Sensors to Shut Down or Sleep Computers
  – Can Use Virtualization to Halt/Shift Jobs

• Experiment Planning Just Starting
  – Collaboration with Sun and LBNL
  – NSF GreenLight Year 2 and Year 3 Funds

Source: Tom DeFanti, Calit2; GreenLight PI

Sun Box <200kWatt
Power Management in the Cellular Infrastructure: Calit2 Achieves 58% Power Amplifier Efficiency

Standard Commercial Base Station Power Amp is 10% Efficient

Power Transistor Tradeoffs:
- Si-LDMOS, GaN, & GaAs
- Price & Performance

Power Amplifier Tradeoffs:
- WiMAX & 3.9GPP LTE
- Efficiency & Linearity

Digital Signal Processing Tradeoffs:
- Pre-Distortion, Memory Effects & Power Control
- MIPS & Memory

Source: Don Kimball, Calit2

www.universityofcalifornia.edu/news/article/19058
CalRadio:
Enabling Energy Reduction Research in Smart Radios
CalRadio Opens Up Each Layer to Your Software

<table>
<thead>
<tr>
<th>#</th>
<th>ISO- Layer</th>
<th>CalRadio 1b Processing Element</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>Application</td>
<td>ARM Processor – User App</td>
</tr>
<tr>
<td>6</td>
<td>Presentation</td>
<td>ARM Processor - ucLinux</td>
</tr>
<tr>
<td>5</td>
<td>Session</td>
<td>ARM Processor - ucLinux</td>
</tr>
<tr>
<td>4</td>
<td>Transport</td>
<td>ARM Processor - ucLinux</td>
</tr>
<tr>
<td>3</td>
<td>Network</td>
<td>ARM Processor - ucLinux</td>
</tr>
<tr>
<td>2</td>
<td>Data Link</td>
<td>DSP - MAC</td>
</tr>
<tr>
<td>1</td>
<td>Physical – hardware connection</td>
<td>RF Module – Baseband Processor</td>
</tr>
</tbody>
</table>

Interlayer communications are very simple!
CalRadio as a Testbed for Power Management

- A 802.11 MAC
  - Fully 'C' Programmable
  - Implemented in a Low-Power DSP
- Fast and Easily Tested Control of the Power Dynamics
- Not Constrained to Standard 802.11 PHY/MAC Protocols
- Increased QoS Within a Channel Yielding Better Power Management

CalRadio Research Areas:
- Alex Snoeren - RTS/CTS Multi-Hop Management
- Curt Schurgers - Packet by Packet Energy Management
- Per Johanson - Battery Life Management in Mesh Networks
- Danko Antolovic – 16 Antenna Diversity Transceiver

Source: Doug Palmer, Calit2
Application of ICT Can Lead to a 5-Fold Greater Decrease in GHGs Than its Own Carbon Footprint

While the sector plans to significantly step up the energy efficiency of its products and services, *ICT’s largest influence* will be by enabling energy efficiencies in other sectors, an opportunity that could deliver *carbon savings five times larger* than the total emissions from the entire ICT sector in 2020.

--Smart 2020 Report

Major Opportunities for the United States*

- Smart Electrical Grids
- Smart Transportation Systems
- Smart Buildings
- Virtual Meetings

* Smart 2020 United States Report Addendum

www.smart2020.org
Use University Campuses as Green IT Testbeds

• Campuses are Small Cities
  – Consolidated Clusters over Dedicated Optical Channels
  – Low Energy Mobile Infrastructure
  – Sensors and Actuators in Intelligent Buildings
  – Low Carbon Transportation System
  – Smart Electricity Grid
  – Ubiquitous Teleconferencing
  – Research on How to Change End User Behavior

• Calit2 is Partnering with UCSD and UCI
  – “Green Living Laboratories of the Future”