Sustainable Data Center

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HP LABS AROUND THE WORLD
Global talent, local innovation
HP LABS RESEARCH AREAS
Innovation at every touch point of information
Sustainable Ecosystem Research Group

- Sustainable Data Center
  - Integrated management of IT, power and cooling towards a Net-Zero energy data center

- Resource Management as a Service
  - Improve sustainability of urban infrastructure
  - All the resources needed to run a building or a campus or a city – resources like light, water, power, waste management -- are all orchestrated and optimized
Sustainability: A Holistic Perspective

Reducing overall available energy consumption

Available Energy

Available Energy consumed by IT

Available Energy saved by application of IT
Data Centers at the Core

Emerging data centers

IT industry: 2%
Total carbon emissions: 98%
The rest of the global economy: 2%

Number of Data Centers

<table>
<thead>
<tr>
<th>Data Center Size</th>
<th>Number of Installations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single Rack</td>
<td>1,000,000</td>
</tr>
<tr>
<td>Computer Room</td>
<td>100,000</td>
</tr>
<tr>
<td>Midsize DC</td>
<td>10,000</td>
</tr>
<tr>
<td>Enterprise DC</td>
<td>1,000</td>
</tr>
<tr>
<td>Large DC</td>
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Source: Gartner Group, March 2011

Data Centers at the Core
Technical Approach

Integrated Supply-Demand Management based on Service Level Agreements

**Supply Side:**
- Lifecycle perspective
  - available energy (exergy) required in extraction, manufacturing, operation and reclamation
- Utilize local sources of available energy
- Examine available energy in waste streams

**Demand Side:**
- Provision resources based on the needs
- Integrated management of IT, Power and Cooling

**Supply and Demand Integration**
Sustainable Data Center
Key Components and Key Elements

<table>
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<tr>
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<th>Power</th>
<th>Cooling</th>
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<td>Integrated Control</td>
<td>Advanced Analytics &amp; Visualization</td>
<td>Pervasive Cross-layer Sensing</td>
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<tr>
<td>Flexible, Configurable and Efficient Micro-grids</td>
<td>Data Center Scale Lifecycle Design</td>
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extraction | manufacturing | operation | End of Life
Sustainable Data Center Research Elements

Lifecycle Design

- IT
  - Integrated Control
  - Advanced Analytics and Visualization
  - Pervasive Cross-layer Sensing
  - Flexible and Efficient Resource Microgrids
  - Data Center Scale Lifecycle Design

- Power

- Cooling

- extraction
- manufacturing
- operation
- End of Life
Lifecycle Perspective

Minimizing product lifecycle exergy consumption at design time

“sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs”

the Brundtland Commission of the United Nations, 1987
Lifecycle Perspective

Energy or Exergy as a measure

Energy refers to quantity of energy, available energy quantifies the useful portion (or quality) of energy.

- The quantity of energy was conserved
- The usefulness of energy was destroyed
# Sustainable Data Center Research Elements

## Flexible Actuators

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**Life Cycle Phases:**
- Extraction
- Manufacturing
- Operation
- End of Life
Data Center Infrastructure
Examples of Flexible Infrastructure Components

Power
- Power microgrids
- Dynamic power control

Cooling
- Cooling microgrids
- Variable speed blowers
- Adaptive vent titles

IT
- Virtualization
- Dynamic resource allocation

Power Supply
- PV Power
- CRACs

Data Center Demand

Cooling Supply
- Water Economizer
- Outside Air Economizer

Power Infrastructure
Sustainable Data Center Research Elements

Cross-Layer Sensing

- Integrated Control
- Advanced Analytics and Visualization
- Pervasive Cross-layer Sensing
- Flexible and Efficient Resource Microgrids
- Data Center Scale Lifecycle Design

extraction manufacturing operation End of Life
Pervasive Cross-Layer Sensing

IT Hardware (Servers, etc.)

Sea of Sensors
Dozens of sensors monitor power and temperature within IT equipment

Facilities Power and Cooling

iPDU and Remote Sensing
Hundreds of sensors monitor power and cooling resources at facility-level

IT Software (Applications and Services)

Service Health Reporter and Insight Control
Software sensors monitor the health of applications and services
Sustainable Data Center Research Elements

Advanced Analytics

- Integrated Control
- Advanced Analytics and Visualization
- Pervasive Cross-layer Sensing
- Flexible and Efficient Resource Microgrids
- Data Center Scale Lifecycle Design

- extraction
- manufacturing
- operation
- End of Life
Advanced Visualization
Data Mining
Pattern mining of chiller ensemble

**Motif Mining** applied to water and air cooled chiller ensemble

Annual Savings: 359 MWh (~10%); 179,580 G direct water; 287, 328 Kg CO₂

Ref: Deb Patnaik, Manish Marwah, Ratnesh Sharma, and Naren Ramakrishnan, Temporal Data Mining Approaches for Sustainable Chiller Management in Data Centers, ACM Transactions on Intelligent Systems and Technology, 2011,
Sustainable Data Center Research Elements

Integrated Control Systems

- Integrated Control
- Advanced Analytics and Visualization
- Pervasive Cross-layer Sensing
- Flexible and Efficient Resource Microgrids
- Data Center Scale Lifecycle Design

- extraction
- manufacturing
- operation
- End of Life
Autonomous Control
Dynamic Provisioning of IT and Cooling Resources based on the needs

Three key goals
– Avoid doing nothing
– Do nothing well
– Meet SLAs
Data Center Cooling Delivery and Distribution

Cold and Hot

Warm air returned from racks to CRAC units via room or ceiling return

Cold air supplied from CRAC to rack units via plenum under raised floor

Data Center Cooling Delivery and Distribution

Conventional Room Control

- A carry over from room level comfort cooling,
- Regulates the return air temperature to a given setpoint
- Fans are typically fixed speed running continuously at 100%
- Individual Air Handlers are self controlled and not coordinated
- Results in very cold air being supplied to the room ~ 12°C / 55°F on average due to mixing in the room
Data Center Cooling Delivery and Distribution

Conventional Room Control
Data Center Cooling Delivery and Distribution

Dynamic Zonal Cooling Control

- Regulate cooling on the supply side of the air handlers.
- Supply air cooling is regulated by sensing temperature at the intake of equipment racks.
- Fans use variable speed control.
- A much higher supply air temperature ~ 68-72°F, a much higher return air temperature ~ 85-95°F.
Cooling Control in Data Center Level

Zonal Effects of the CRAC units

Regions of Influence

TCI: Thermal Correlation Index:

\[ TCI(CRAC_i, Temp_j) = \frac{\Delta Temp_j}{\Delta CRAC_i} \]

Cooling Control in Data Center Level

Thermal Correlation Index (TCI)
Cooling Control in Data Center Level

Coordinated CRAC Control

Cooling Control in Data Center Level

Coordinated CRAC Control Results

Conventional Mode

Dynamic Zonal Cooling Mode

35% Energy savings
Improved reliability

HP Labs Data Centre
Palo Alto, CA

Local Cooling Control

Adaptive Vent Tile

- Damper
- Actuator

Diagram:
- AVT Base station
- Actuator
- Vent Tiles
- AC Power
- Microcontroller
- Network
- DATA ACCESS LEVEL
- 1-Wire
- AVT Manager
- 12-24 VDC Power
Local Cooling Control

Vent Tile

- Nonlinearity
- Inter-correlation

Local Cooling Control
Adaptive MPC AVT control driven by Inlet temperatures

\[
\min J(V) = \sum_{i=1}^{hp} \left( \|T(k + i) - T_{ref}\|_Q^2 \right) + \sum_{i=0}^{hu-1} \left( \|V(k + i + 1) - V(k + i)\|_{R_1}^2 \right) + \sum_{i=0}^{hu-1} \left( \|V(k + i + 1)\|_{R_2}^2 \right)
\]

\[
T(k + i) = AT(k + i - 1) + BV(k + i)
\]

\[
T(k + i) \leq T_{ref}, \ i = 1,2,..., hp
\]

\[
V(k + i) \leq \bar{V}, \ i = 0,1,..., hu - 1
\]

\[
V(k + i) \geq \bar{V}, \ i = 0,1,..., hu - 1
\]

Ref: Zhikui Wang etc., KRATOS: automated management of cooling capacity in data centers with adaptive vent tiles, IMECE2009, November 13-19, Lake Buena Vista, Florida, USA
Local Cooling Control

Local cooling on-demand delivery through Adaptive Vent Tile

Before Control

After Control

Tile Openings (%)

0
50
100

Temperatures(C)

20
25
30

44% Less Cooling Air Flow Needed

Ref: Zhikui Wang etc., KRATOS: automated management of cooling capacity in data centers with adaptive vent tiles, IMECE2009, November 13-19, Lake Buena Vista, Florida, USA
Dynamic Resource Allocation in Virtualized Server Environments

- Determine IT resources needed to maintain application performance
- Dynamically adjust IT resources based on needs

Dynamic Resource Allocation in Virtualized Server Environments

Application controller

Dynamic Resource Allocation in Virtualized Server Environments

![Graph showing RUBiS Response Time and Dynamic CPU shares]

Dynamic CPU shares allocated to each component of the application

[Legend: Web Server, Application Server, Database Server]
Dynamic Capacity Provisioning of Server Farm

Combine predictive and reactive control to allocate resources at multi-time scales

- Identify long-term sustained patterns
- Proactively provision for base workload (every a few hours)
- Reactively handle any excess workload (every a few minutes)

Dynamic Capacity Provisioning of Server Farm

- Predictive
- Reactive
- Hybrid

- Normalized response time
- Normalized power consumption
- Normalized provisioning changes

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Integrated Management of IT and Cooling

- A data center is a dynamic thermal environment
  - There are significant non-uniformities
  - Some locations in a data center are much more efficiently cooled than others
- A significant opportunity for energy savings lies in the integrated control and placement of IT workloads placement according to cooling efficiency
Integrated Management of IT and Cooling

LWPI: Local Workload Placement Index

\[ LWPI_{node} = (T_{ref} - T_{inlet}) + \sum_{CRAC} TCI_{node=crac} (SAT_{CRAC} - SAT_{CRAC,MIN}) - (T_{inlet} - T_{vent}) \]

Thermal Management Margin

Air Conditioning Margin

Hot Air Recirculation

Integrated Management of IT and Cooling

High-level architecture

- Dynamically adjust IT resources based on needs
- Dynamically re-arrange workloads
- Opportunistically turn on and turn off idle servers
- Use LWPI to guide workload placement
- Adjust cooling resources in response to IT needs

Integrated Management of IT and Cooling
experimental Testbed

HPL Palo Alto data center
- 20 physical servers
  - 9 in Rack 10
  - 11 in Rack 34
- 35 Virtual Machines
- 2 interactive 3-tier apps
- 29 computational workloads
- 10 hour experiment
Integrated Management of IT and Cooling

results

![Workload demand](image1)

![Number of running servers](image2)

![Server power](image3)

![CRAC blower power](image4)
Integrated Management of IT and Cooling

CDF of response times

- 35% IT power reduction
- 16% cooling power reduction
- No performance degradation

Anticipated Savings Per Year
(2MW data center)

<table>
<thead>
<tr>
<th></th>
<th>Energy</th>
<th>Costs</th>
<th>CO2</th>
<th>Water</th>
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<tbody>
<tr>
<td></td>
<td>4.9GWh</td>
<td>$492,000</td>
<td>2915 tons</td>
<td>4,700,000 Gallons</td>
</tr>
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</table>

Integrated Management of Supply and Demand
HPL Palo Alto Data Center

PV micro grid

Outside air

Data center

Chiller COP

Outside Air Temperature (°C)

Load (kW)

Goals:
• Avoid doing nothing
• “Do nothing” well
• Keep the energy budget balanced

Data center supply side

Cooling infrastructure power demand

Data center energy demand side
Integrated Management of Supply and Demand

**1. Prediction**

- **Supply-side Prediction**
  - Renewable power prediction
  - Cooling capacity prediction

- **IT Demand Prediction**

**2. Planning**

- **DC Operation Constraints:**
  - Net-zero energy operation
  - Net-zero costs operation
  - Maximize use of renewable energy
  - Minimize dependability on Grid

- **IT Workload Planning**
  - Integrate Supply and Demand Side
  - IT Demand Shaping
  - Power capping

**3. Execution**

- **Dynamic IT Provisioning**
- **Dynamic Cooling Provisioning**

**4. Verification and Reporting**

- **Measurement Verification**
**Integrated Management of Supply and Demand**

**Supply-aware**

![Supply-aware Diagram]

**Supply-oblivious**

![Supply-oblivious Diagram]


**Sustainable IT Ecosystems**

**Server Farm at the Dairy Farm**

How could a hypothetical farm of 10,000 dairy cows fulfill the power requirements of a 1MW data center?

Data Centers at the Core
for management of resources at community scale

Sustainable Data Center

Power

Healthcare

Education

Water

Transport

Ecosystem of Clients
City 2.0
Enabled by a Sustainable IT Ecosystem

- Power: Policy-Based Control & Operation
- Transport: Knowledge Discovery, Data Mining, Visualization
- Water: Pervasive Sensing Infrastructure, Aggregation, Dashboard
- Waste: Scalable & Configurable Resource Microgrids

- Life-Cycle Design: Traditional Ecological Engineering

Mgmt
Design
Research Opportunities and Challenges

- End-to-end Optimization
- Analytics for Sustainability
- Multi-scale Adaptive Control
- Integrated Control of Power, Cooling and IT
- Integrated Supply and Demand Management
- Beyond IT
Acknowledgement

The work presented in this talk has been contributed by the team of Sustainable Ecosystems Research Group at HP Labs, students and professors at CMU and Caltech: