Energy Efficiency and Sustainability of Data Centers

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Data Centers – a focus of information processing energy efficiency

Key Challenges

Growing consumption of power
~ 4 MW each, 10x for future Centers
Energy cost of supercomputing becoming prohibitive
Cooling consumes half

Energy efficient operation
Reduce cost and carbon footprint

Sustainability:
minimize lifecycle energy resources (exergy) consumed
Data center energy use

EPA study: doubling time for DC energy use: about 5 years

2006: 1.5% of US total electricity use (61 billion kWh)

2011: 3% of US total electricity use
      (122 billion kWh, ~ $10 billion)

2010, DC servers estimated to consume about 2 percent of the world's electricity, (~34 1,000-megawatt power plants)

Strategies for Data Center Efficiency/Sustainability

Efficient Electrical Power
- AC to DC conversion

Efficient Thermal Management
Design for Efficiency
- Energy/exergy design analysis
- Liquid cooling strategies

Efficient Cooling Control
- model based (exergy aware) controls

Load Distribution Control

Use Sustainable Components and Systems
- Assess using lifecycle exergy consumption

Use Renewable, Low Carbon Energy Sources
- Solar powered data center electronics and cooling
**EXERGY**

**Exergy** => (available energy) energy fully convertible to work

=> quantifies the amount of useful energy flowing (quantity and quality)

Energy flowing through the data center is not consumed, it is degraded

Electricity (organized) → heat (disorganized)

Modeling exergy destruction throughout the data center predicts where energy inefficiencies are greatest

Exergy destruction quantifies value of useful energy resources lost

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**Life-Cycle Exergy Analysis**

Important to consider life-cycle in analysis

[Diagram showing the life-cycle phases of material extraction, manufacturing, operation, recycling/disposal, and transportation]
Sustainability indicators are historically classified in one of three groups:
- environmental
- social
- economical

Life-cycle exergy consumption is an environmental metric. Its strength lies in the fact that it is a thermodynamically based, scientifically rigorous quantity that in a single value allows for the comparison of mass inputs and energy inputs of different quality.

Other environmental sustainability indicators that track different quantities throughout the life-cycle:
- Tracking mass – Material Input per Service Unit (MIPS)
  - tracks the mass of all the material inputs required
  - normalizes by a service unit of the product or process
- Tracking embodied energy – emergy
  - tracks all of the available energy that went into a product or process over its life-cycle
  - emergy of an object is the sum of all the exergy that went into making it
  - similar to life-cycle exergy consumption, but not exactly the same
  - (life-cycle exergy consumption accounts for external exergy destruction)
Sustainability metrics (cont.)

- Tracking all material and energy inputs and outputs – 
  Life-Cycle Assessment (LCA)
  - this metric tracks all of the mass and all of the energy flows
  - then evaluates the environmental impacts of flows
  - not a single, scientifically based metric
  - many environmental impacts that come out of a LCA
  - provides a complete picture of environmental effects, but can often be contradictory and don't easily lend themselves to ranking design choices

Advantages of Life-Cycle Exergy Analysis

- Tracks sum of all consumption of energy resources in product life cycle
- Accounts for thermodynamic differences of energy resources in a consistent way
- Inefficient life cycle components (high exergy destruction rates) are easily identified and assessed
Operational Performance:
Vision:
Fast, easy to use analysis software to predict data center energy performance

Fast compact models of data center energy performance

Uses:
• Fast parametric optimization of new DC designs
• Integrate compact models into smart digital controllers
• Fast, easy assessment of evolutionary design changes
Fast Compact Performance Model

- Numerically solve equations for
  - air flow
  - energy transport
  - exergy transport and destruction

Use Matlab GUI Platform for Design

- Use for
  - rapid design analysis
  - digital control

Assessment: Full CFD Comparison

Flexible Input Process

Visualization Tools Development

Operational exergy destruction analysis - standard control volume formulation

\[
\dot{X}_j = \sum_j (1 - \frac{T_o}{T_j})\dot{Q}_j - \dot{W}_{cv} + \sum_i \dot{m}_i \dot{\phi}_i - \sum_e \dot{m}_e \phi_e
\]

\[
\dot{\phi} = (h - h_o) - T_o (s - s_o)
\]

- Using above equations, can calculate exergy consumed from operation
- Studies have been performed examining how different operational parameters effect exergy consumption
Thermal performance and energy efficiency of data center designs

Data Center Basics

- Cool air from CRAC (Computer Room Air Conditioning) units enters via floor tiles, passes through server racks to cool them.
- Warm air exits via ceiling outlets, generally back to the CRAC unit.
- High power consumption: Can reach 100+ kW for a 500 sq ft. room.

Compact Model of Potential flow and Convective Transport

- Finite difference formulation, programmed in MATLAB
- Potential flow
  - Velocity is the gradient of the potential \( \phi \).
  - \( \mathbf{v} = \nabla \phi \).
  - Assumes incompressibility, no vorticity:
  - \( \nabla \cdot \mathbf{v} = 0 \).
  - Boundary conditions are defined at cell boundaries using potentials set in “virtual cells.”
- Convective energy transport
  - Steady state, energy transport is convection dominated.
  - Full mixing within each subdivided cell in the system.
  - Server heat generation applied immediately downstream of racks.
  - Simplified governing energy equation:

\[
\int_{\partial A} \rho C_p v T \, dA = Q_{\text{gen}}
\]
COMPACT vs. CFD: Flow

- Same model inputs used with ANSYS FLUENT to generate velocity and temperature fields
  - Intended for comparison to COMPACT, to provide a benchmark as a compact CFD model
**COMPACT vs. CFD: Temperature**

- Velocity and temperature fields generated by COMPACT GUI, including vortex superposition:
  - ~4400 cells, under 30 seconds
- ANSYS FLUENT solution:
  - ~5.5 million cells, 70 minutes

**Experimental Validation**

- Recorded measurements at a HP Laboratories data center
  - Temperature measurements on racks and in aisles
  - Power consumption of server racks
  - Room inlet/outlet flow measurements
- Initial results:
  - Significant over-prediction of temperatures in areas of high recirculation, likely due to lack of accounting for buoyancy effects
As expected, full CFD slightly outperforms the compact model.
- Performance can be comparable to FLUENT for said cases.
- Given heavy computational and other associated costs with full CFD, COMPACT is a feasible first-order design tool.

Full life cycle exergy consumption

Vision:
Analysis tools to predict life cycle exergy consumption data for IT systems.
Analysis tools to predict life cycle exergy consumption data for IT systems

Uses:
• strategies to minimize lifecycle exergy consumption
• Highest exergy consumption elements are greatest sources of inefficiency – prime targets for improvement

Established library of exergy consumption data and submodels for:
- Material extraction and processing (steel, aluminum, copper, plastics, etc.)
- Manufacturing processes
- Transportation
- Disposal/recycling
- Ancillary equipment (example: CRAC units)
Features of life cycle exergy analysis (LCEA) software

- contains library of exergy data and submodels for materials, manufacturing processes, transportation, end of life exergy consumption
- includes COMPACT determination of operational exergy consumption
- can analyze life cycle exergy consumption for
  - Devices
  - Clusters of devices (DC subsystems)
  - Entire virtual data centers
- GUI menu-driven assembly of components, systems
- GUI selection of output analysis tools
- Submodel for exergy consumption in CRAC units

Example device life cycle exergy analyses
(typical data center operating conditions)

2U-rack-mounted server with two Intel Pentium III 1.0 GHz processors, one 36 GB SCSI hard disk drive, one CD-ROM drive, and one floppy disk drive

  - one hard drive bay used, transport by ship
  - all of the hard drive bays full, transport by ship
  - all of the hard drive bays full, transport by air

30 ton CRAC unit manufactured by Stulz Air Technology Systems, Inc.
Tools to analyze energy efficiency and sustainability

COMPACT

- Fast parametric optimization of new DC designs
- Integrate compact models into smart digital controllers (model dynamic response)
- Fast, easy assessment of evolutionary DC design changes

LCA software

- compare different stages within a system or component’s lifecycle on a common basis
- highest exergy consumption elements are greatest sources of inefficiency – prime targets for improvement
- compare multiple systems in stages or overall
- design components and systems to minimize lifecycle exergy consumption

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Acknowledgements
Support from Hewlett Packard Research Laboratory, Palo Alto, UC Discovery Grant, CITRIS
Collaborators: Chandrakant Patel, Cullen Bash, Amip Shah (HP Laboratories)
UCB Graduate Students: Guislain Doljac, Christopher Hanneman, Michael Toulouse, David Lettieri