Basic Research Needs in Mathematics & Computation for Complex Energy Systems


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We need to do more transformational research at DOE … including

computer design tools for commercial and residential buildings that enable reductions in energy consumption of up to 80 percent with investments that will pay for themselves in less than 10 years

Secretary Steven Chu, March 5, 2009
Key Messages

Buildings are critical to reducing energy consumption
>50% energy use reduction possible

System integration is hard
correct installation of many interacting components, tuning the system, changing use patterns and external environment, and degradation over time

Combining passive and active components is hard
complicated multi-scale dynamics that change significantly with weather, occupancy and use patterns

There are productive targets for research in mathematics and computation
  1. Characterization of dynamics and uncertainty
     ability to deal with integration issues in complex system configurations
  2. Control
     ability to develop reduced order models and to design, analyze and implement optimal control sequences
  3. Simulation enabled design and operations
     ability to use models for design, installation and commissioning, and prognostics and diagnostics throughout the building lifecycle
When It Comes to Energy, Buildings Matter

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

Building produce
- 48% of U.S. carbon emissions

Low Energy Buildings: Examples and Challenges

**LEED Design**

20-50% Reduction

Tulane Lavin Bernie
New Orleans LA
150K ft², 150 kW hr/m²
1513 HDD, 6910 CDD
Porous radiant ceiling, humidity control, zoning, efficient lighting, shading

**Very Low Energy**

>50% Reduction

Deutsche Post
Bonn Germany
1M ft², 75 kW hr/m²
6331 HDD, 1820 CDD
No fans or ducts, slab cooling, façade preheat, night cool

**Misses on Design**

Designs over-predict gains by ~20-30%

Cambria Office Building
Design Intent: 66% (ASHRAE 90.1);
Measured 44%

**KfW Building, Frankfurt, GERMANY**

Design Intent: 100kWH/m2/yr

Misses on Operation

Three years of seasonal tuning on passive stack ventilation
Buildings Don’t Achieve Their Efficiency Potential

Barrier: Scalability
- Climate specific
- Multiple subsystems
- Dynamic energy flows
- Implication on Cost
  - Hardware/process for calibration
- Implication on Risk
  - No Design ProCert/quality process

Barrier: Robustness
- Unknown sensitivities
- No supervisory control
- Implication on Cost
  - No ProCert process/quality process
  - Commissioning costs/process
- Implication on Risk
  - Control of design in handoffs

Barrier: Productivity
- No diagnostics/guaranteed performance without consulting
- Implication on Cost
  - Measurement costs
  - Recommissioning costs
- Implication on Risk
  - Facility operations skillsets
  - Unbounded costs to ensure performance

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What’s Needed: Accelerated, Predictive Computation

**Scalability**
Current methodology and tools provide design guidance for very low energy buildings in weeks to months.

Need: hours to days on desk top hardware, **a 50X improvement**.

**Installation and Commissioning**
Current methodology and tools routinely take > three months for initial commissioning of building subsystems.

Need: one week, **a 10X improvement**.

**Quality**
Current design tools can achieve 30% accuracy in estimating energy flows to drive design tradeoffs and decision.

Need: 5% accuracy with quantification of uncertainty and connection to commissioning and controls, **a 5X improvement**.
## DOE and DoD Investments in Building Efficiency

### Technology Readiness Level

<table>
<thead>
<tr>
<th>Level</th>
<th>In service</th>
<th>9</th>
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<tbody>
<tr>
<td>Development</td>
<td>Qualification/Certification</td>
<td>8</td>
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<tr>
<td>First Engine to Test (FETT)</td>
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<td></td>
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<tr>
<td>Demonstration</td>
<td>Engine Demo / Prototype</td>
<td>6</td>
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<tr>
<td>Rig/core (expanded design space)</td>
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<td>Rig test (minimal design space)</td>
<td>4</td>
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<tr>
<td>Concept</td>
<td>Proof of concept</td>
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<tr>
<td></td>
<td>Technology concept</td>
<td>2</td>
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<tr>
<td></td>
<td>Basic principles (Idea) or Technology gap (Need)</td>
<td>1</td>
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**Lacking Proof Points for Scalable Deployment of System Solutions**

**Lacking Fundamental Research Investments**

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Current DOE and DoD Investments: Technology Maturation and Deployment Focused

Transform commercial building retrofit practices to improve energy efficiency by 50% that can be adopted and implemented in the marketplace over the next 10 years

EO 13514 - Starting in 2020, all new federal buildings must be designed to achieve zero-net-energy by 2030

“With respect to facilities energy, the military’s most valuable role will be as a testbed for next generation technologies coming out of laboratories in industry, universities and DOE”

Dr. D. Robyn, DUSD-I&E, Feb. 24, 2010

House Armed Services Subcommittee on Readiness

https://gpichub.org/
2010 Industry-Academia-National Lab Meeting

“…to frame areas for computational science that will lead to improvements in the delivery and operation of low energy buildings.”

Participants: National Labs, industry, academia – community meeting and report

Integration-Enabled High Performance Buildings
Robust engineering and operation of complex interfaces

Problem: Hybrid HVAC systems take advantage of building material for thermal storage, natural ventilation and passive heating/cooling systems to match occupancy demand

Challenge: Fundamental understanding of energy/thermal/air flows and their coupling to dynamics of disturbances such as weather, occupancy, co-design of building HVAC and envelope systems, robust control architectures, uncertainty

Benefit: 30-50% reduction in ventilation energy demand, gains in occupant health/productivity
Complexity in Building Systems

Components do not have mathematically similar structures and involve different scales in time or space;
The number of components are large/enormous;
Components are connected in several ways, most often nonlinearly and/or via a network. Local and system-wide phenomena depend on each other in complicated ways;
Overall system behavior can be difficult to predict from behavior of individual components. Overall system behavior may evolve qualitatively differently, displaying great sensitivity to small perturbations at any stage.


Going from 30% efficiency to 70-80% efficiency

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Reduced-Order Modeling of Large-scale Uncertain Dynamic Systems

Need models including fully coupled dynamics (envelope, air flow, equipment, controls); extract ROM (via balanced truncation)

Complexity of Lyapunov equations & sampling

- $O(n^3) \times m$
- $n$ model order (~1000)
- $m$ order of uncertain parameter (~10000)

Uncertainty propagation and quantification for fully coupled building models with dynamic parameter uncertainties are computationally intractable

Complexity of quasi-Monte Carlo with dynamic uncertainty

- $O(1/\sqrt{n}) \times m$
- $n$ sampling points (~10000)
Building energy models only capture the building envelope and steady state conditions: need dynamics, controls and tools to effectively track uncertainty.

The range of different physics and the span of time and length scales involved in full building simulation cripple current solvers and the ability to efficiently carry out uncertainty quantification for dynamic situations.

Control and on-line optimization of multi-scale, multi-physics, uncertain systems with available models and algorithms is computationally intractable.
Computational Science Research Needs

**Multi-Scale Dynamics and Uncertainty**

- Multi-scale analysis techniques for large scale heterogeneous dynamic building systems
- Dynamical system theory tools for system level analysis of invariant building dynamics
- Fast propagation of uncertainty and sensitivity analysis in large scale heterogeneous fully coupled fluid-thermal, dynamic systems
- Dynamic analysis tools for standard low energy consumption systems
- Uncertainty descriptions of system level models for building design
- Design methodology and tools for Federal (GSA/DoD) and commercial buildings and systems

**Controls**

- Techniques for large-scale PDE control and optimization with non-local boundary conditions and uncertainty
- Parallel optimization techniques for closed-loop large-scale uncertain dynamic building systems
- Extraction of low order models suitable for optimization and control design of uncertain, multi-scale building systems
- Model-based failure mode effects and analysis for fully-coupled whole building models
- Use of low order models for design, optimization and supervisory control
- Validation of supervisory control performance, stability boundaries & robustness margins
- Tools to automate failure mode detection & isolation for buildings
- Controls and Diagnostics implementations for Federal (GSA/DoD) and commercial buildings

**Modeling**

- Model reduction techniques for large-scale fully coupled dynamic building phenomena and models
  - Models for validation and verification of large scale building control designs with uncertainty
- Open source equation based model platform
  - Object oriented standard component libraries (proprietary parameters at lowest level)

Goal: new knowledge / understanding; Mandate: open-ended
Focus: phenomena; Metric: knowledge generation

Goal: practical targets; Mandate: restricted to target
Focus: performance; Metric: milestone achievement

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<table>
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<th>Year 1</th>
<th>Year 2</th>
<th>Year 3</th>
<th>Year 4</th>
<th>Year 5</th>
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<tr>
<td>Industry Products/Services</td>
<td>Concept Demonstration (Pilots) (Industry Led)</td>
<td>TRL 6-9</td>
<td>TRL 3-6</td>
<td>TRL 1-3</td>
<td>Integrated System Design Software Optimization &amp; Control Toolbox System Diagnostics Tools</td>
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- **Year 1**
  - High Fidelity Multi-scale Computations
  - Model Reduction Techniques
  - Dynamical Systems Theory For Multi-scale Phenomena
  - Optimal Control Theory
  - Uncertainty Propagation Techniques
  - Large-scale Data Assimilation Techniques
  - Design Flows for Integrated Systems & V&V Techniques

- **Year 2**
  - Preliminary Design Decision Support Tools
  - Integrated System Simulation & Design Tools Optimization & Control Design Tools System Commissioning Tools

- **Year 3**
  - Robust Control Design & System Diagnostics Tools
  - Embedded System Design Tools

- **Year 4**
  - Advanced Simulation, Analysis & Modeling Toolkit
  - Scalable Software Methods for Design
  - Reduced-order Models for Control Design
  - Robust Distributed Control Design Tools
  - Automated FDD Tools, Model-based FMEA
  - Auto-code Generation Tools for Embedded System V&V Toolchain
  - Fast Uncertainty Quantification & Propagation Tools

- **Year 5**
  - Multi-scale Simulations & Solvers
  - >50% energy savings with modular solutions
  - 5X↓ in energy/comfort performance uncertainty

- **Year 6**
  - >10X↓ reduction in installation/commissioning cost
  - >10X↑ in solution space exploration

- **Estimate**
  - $10M/year

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Recommended Next Steps

Hold ASCR Workshop in Fall 2011

Workshop objectives
  determine thematic areas;
  projects and metrics;
  identification of participants
Thank You
Computation: Can’t Brute Force This

 Whole Building Simulations (complex geometry, multiple sub-systems, and realistic indoor and external uncertainties)

 Multi-zone Building Simulation (simplified geometry and boundary conditions)

 Isolated Thermal Environment in an Individual Zone/Room

10 TFlops → 10 Pflops Computation Capability*

Complexity (scale, dynamics, nonlinearity, uncertainty…)

* Assuming less than 1hour turnaround for practical design calculations