Basic Research Needs in Mathematics & Computation for Complex Energy Systems

Report of an Industry-Academia-National Lab Meeting on Opportunities for Dynamics & Control in Energy Efficient Buildings

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Advanced Scientific Computing Advisory Committee (ASCAC)

Rockville, MD

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Making Buildings Better

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

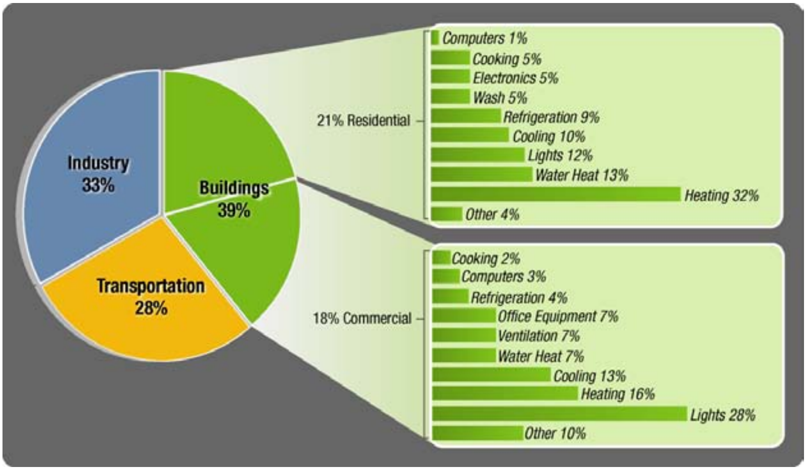
Combining passive and active components is hard

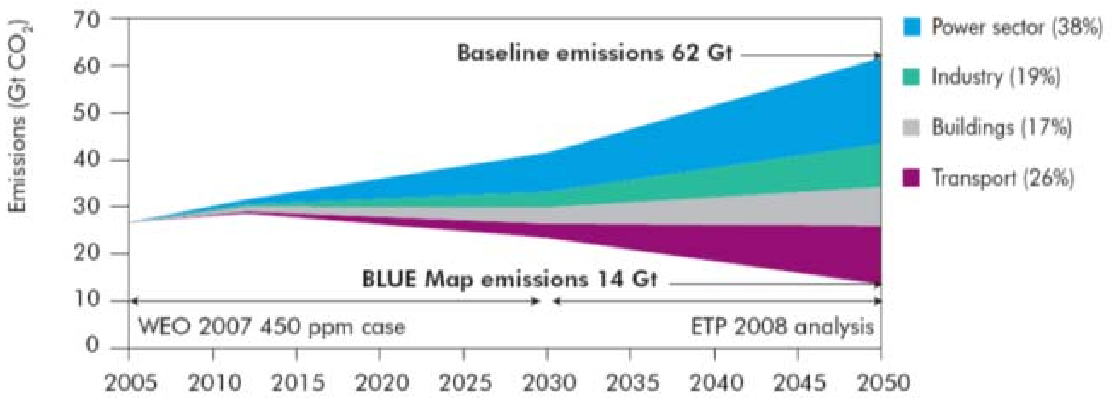
complicated multi-scale dynamics that change significantly with weather, occupancy and use patterns

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



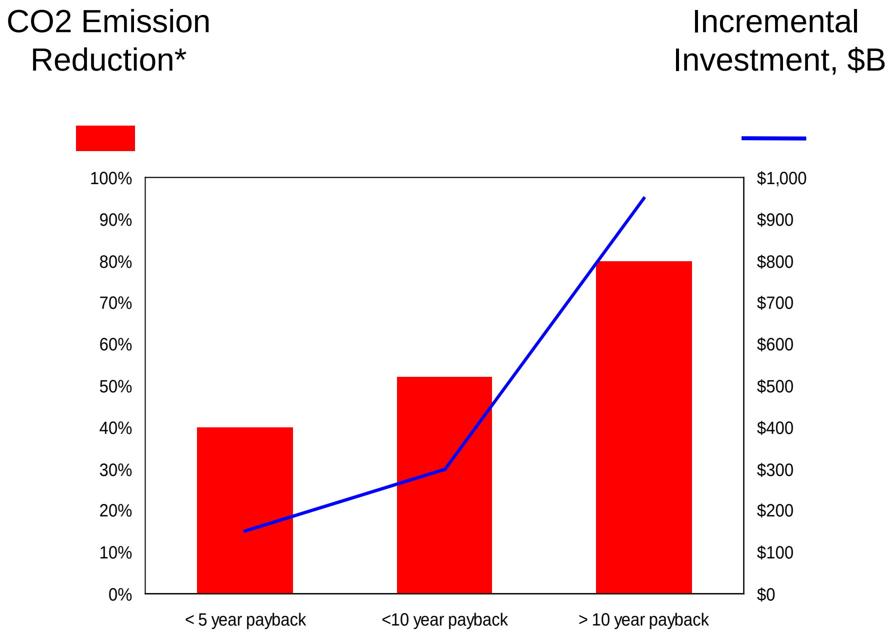


Buildings consume

- 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



Sources: Ryan and Nicholls 2004, USGBC, USDOE 2004, IEA Energy Technology Perspective 2008, www.wbcsd.org

Low Energy Buildings: Examples and Challenges

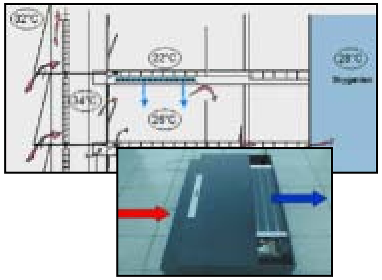
Tulane Lavin Bernie
New Orleans LA
150K ft^2, 150 kW hr/m^2
1513 HDD, 6910 CDD

LEED Design
20-50% Reduction

Porous radiant ceiling, humidity control, zoning, efficient lighting, shading

Very Low Energy
>50% Reduction

Deutsche Post
Bonn Germany
1M ft^2, 75 kW hr/m^2
6331 HDD, 1820 CDD
No fans or ducts, slab cooling, façade preheat, night cool

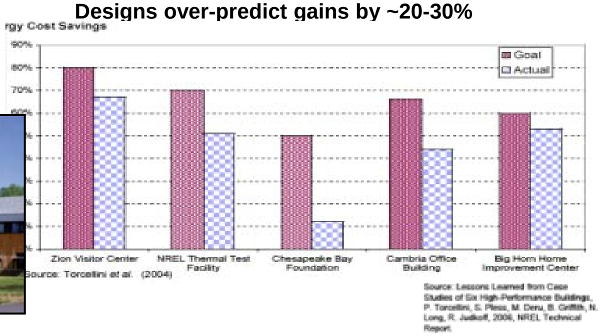


Misses on Design

Cambria Office Building

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

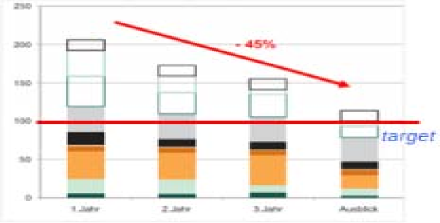
Designs over-predict gains by ~20-30%



KfW Building, Frankfurt, GERMANY

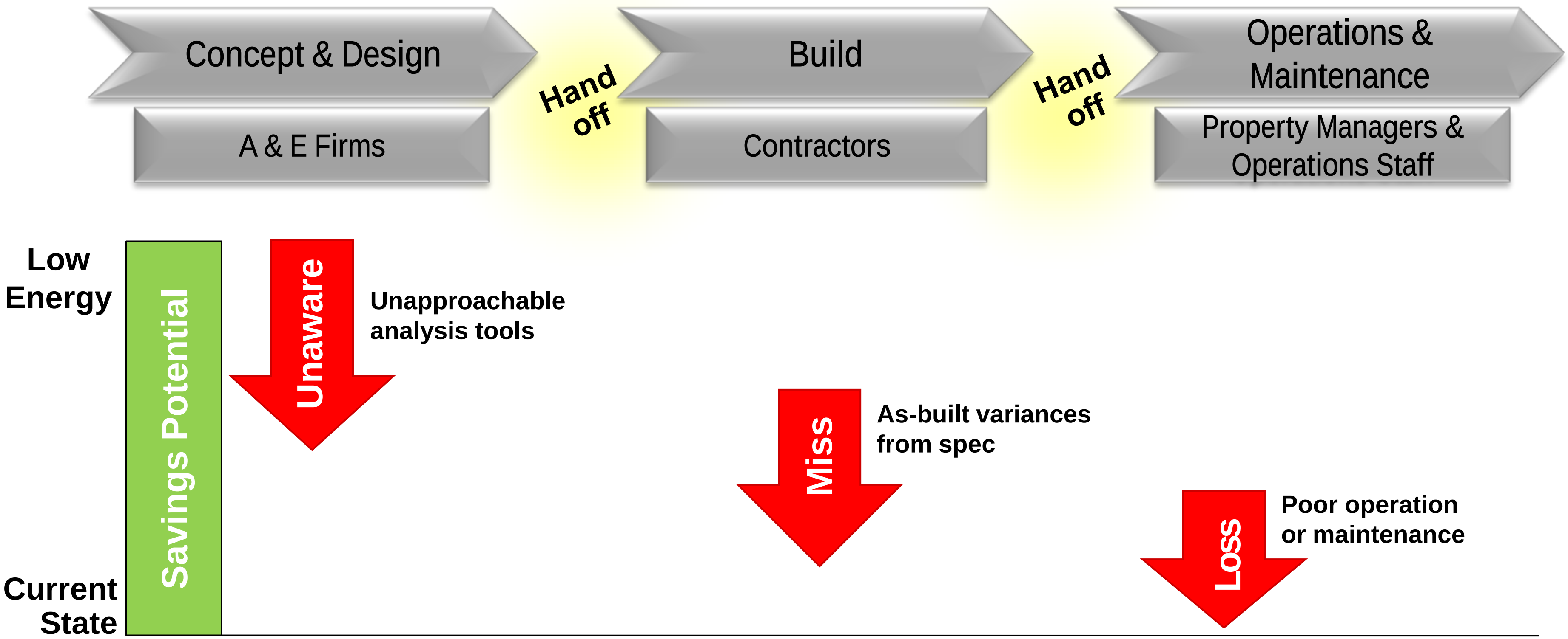
Design Intent: 100kWH/m2/yr

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

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.

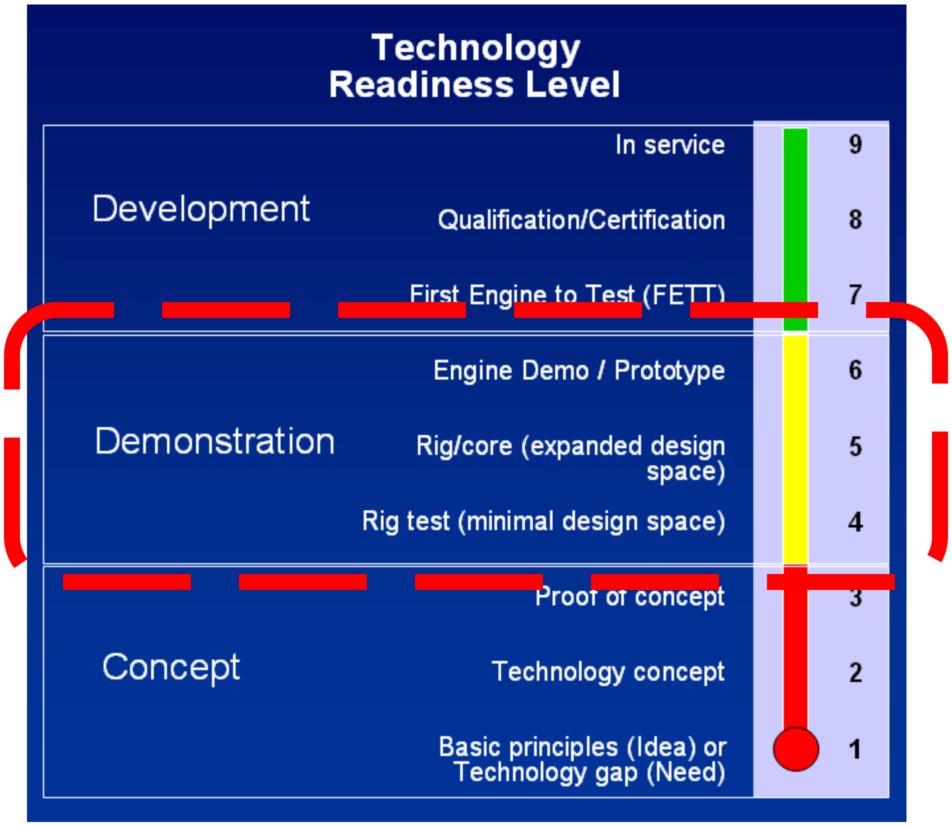
Need: one week, **a 10X improvement.**

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



Lacking Proof Points for Scalable Deployment of System Solutions

U.S. Department of Energy
Energy Efficiency and Renewable Energy

GPICHUB

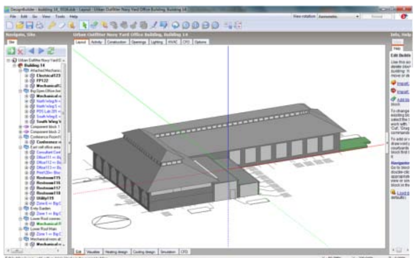
ESTCP

Lacking Fundamental Research Investments

Current DOE and DoD Investments: Technology Maturation and Deployment Focused

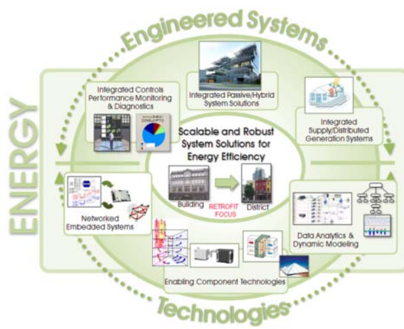
U.S. Department of Energy
Energy Efficiency and Renewable Energy

GPICHUB



Retrofit Design Tools

System Technologies

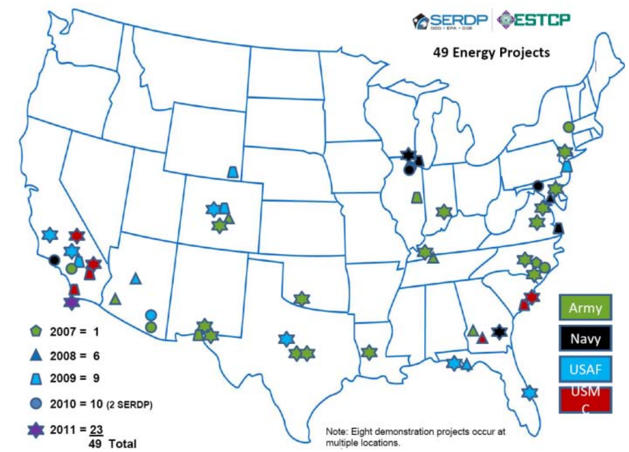


Demonstration Testbeds

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

https://gpichub.org/


Federal Register
Thursday,
October 8, 2009
Part VII
The President
Executive Order 13514—Federal leadership in Environmental, Energy, and Economic Performance



"Military Installations as Test Beds for Innovative Energy Efficiency Technologies", J. Galvin (SERDP/ESTCP Partners Symposium, Dec. 2010)

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

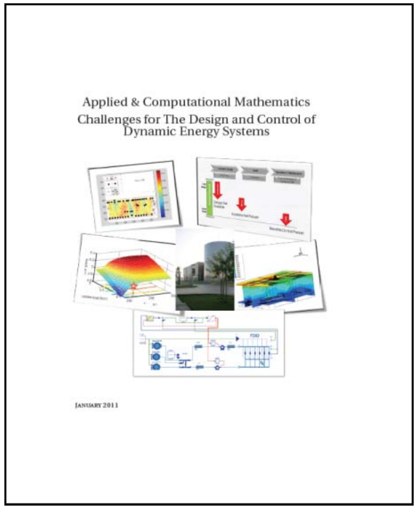
House Armed Services Subcommittee on Readiness

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

Material archived on wiki at www.engineering.ucsb.edu/~mgroup/wiki/index.php/Computational_Science_for_Building_Energy_Efficiency_Meeting_July_8-9_2010

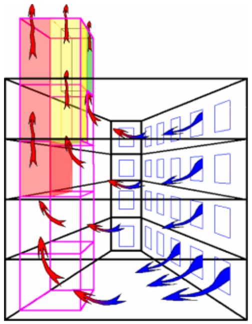

Applied & Computational Mathematics
Challenges for The Design and Control of Dynamic Energy Systems

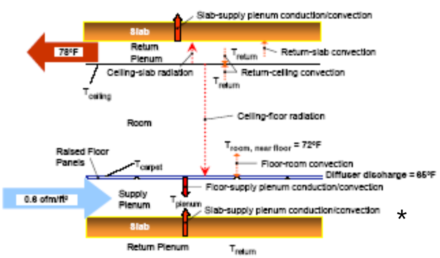
JANUARY 2011

Integration-Enabled High Performance Buildings

Robust engineering and operation of complex interfaces

Integrated Envelope and HVAC Systems
Natural, Passive and Hybrid Ventilation





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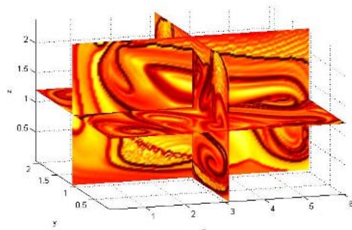
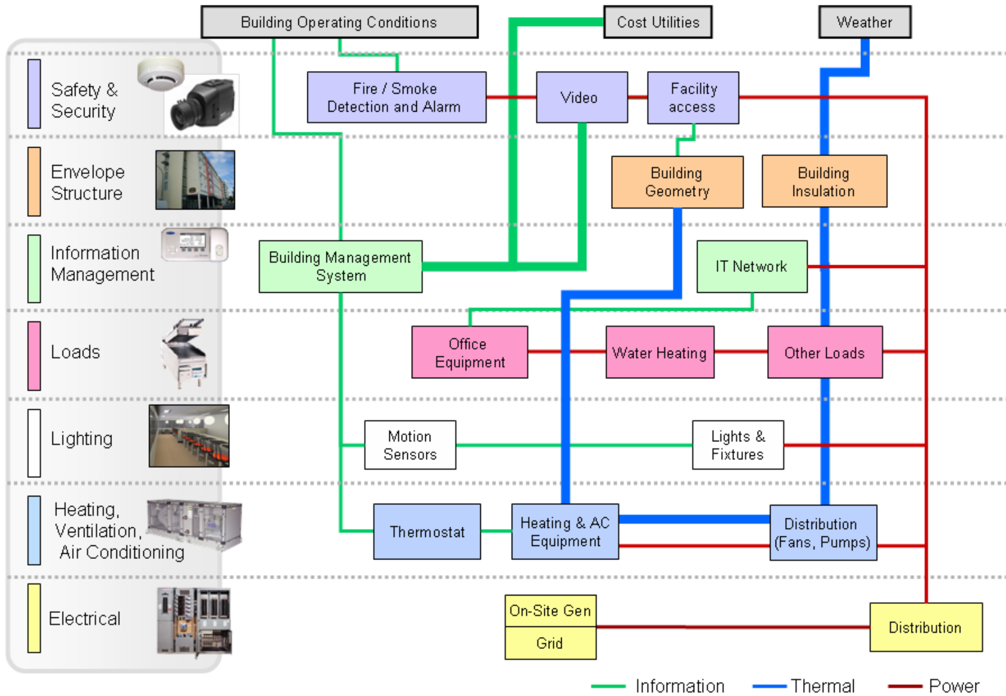




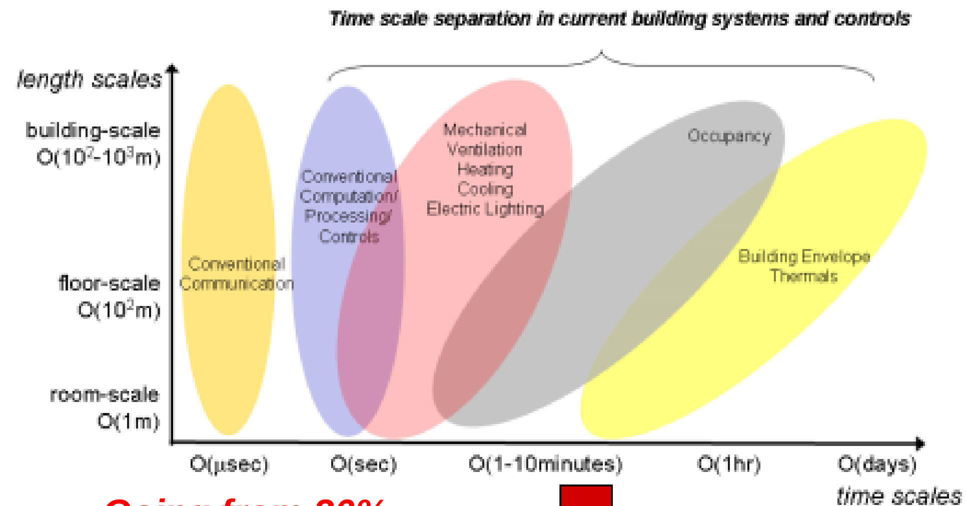
Problem: Hybrid HVAC systems take advantage of building material for thermal storage, natural ventilation and passive heating/cooling systems to match occupancy demand

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

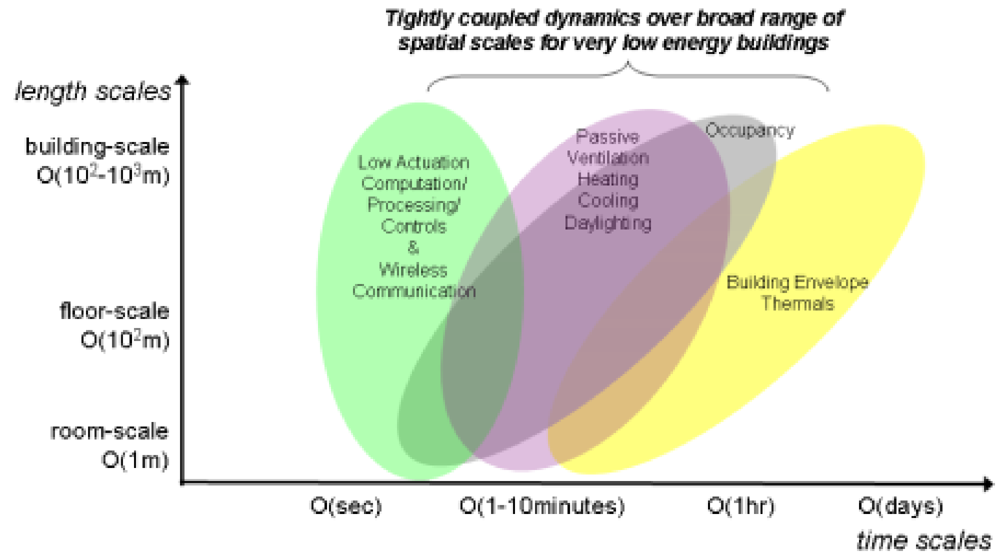
Benefit: 30-50% reduction in ventilation energy demand, gains in occupant health/productivity

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.



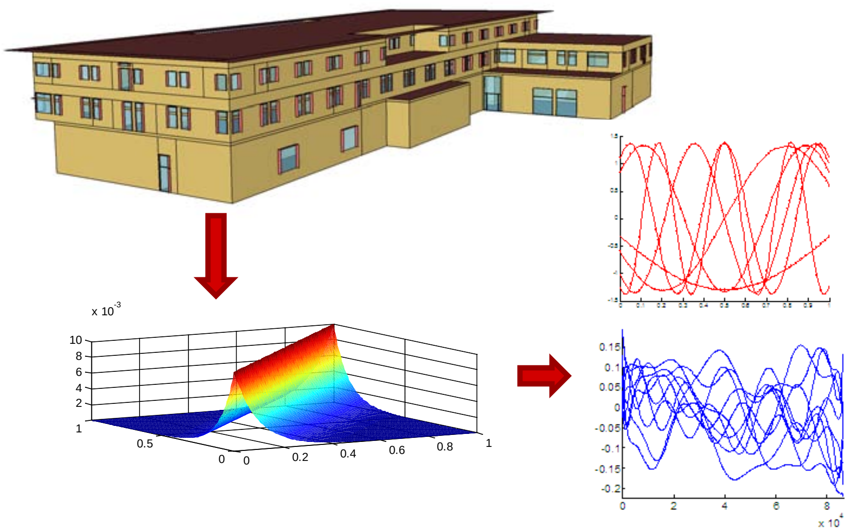
Going from 30% efficiency to 70-80% efficiency



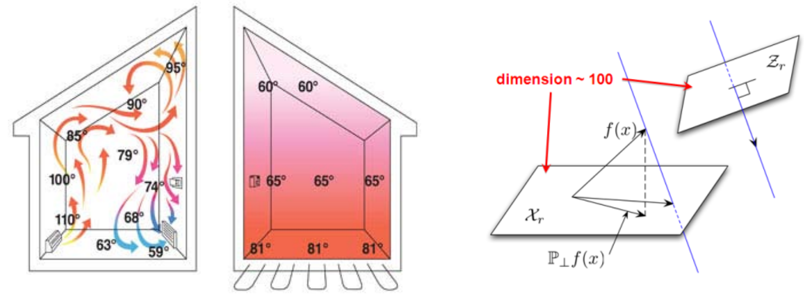
From APPLIED MATHEMATICS AT THE U.S. DEPARTMENT OF ENERGY: Past, Present and a View to the Future, David L. Brown, John Bell, Donald Estep, William Gropp, Bruce Hendrickson, Sallie Keller-McNulty, David Keyes, J. Tinsley Oden and Linda Petzold, DOE Report, LLNL-TR-401536, May 2008.

Computational Barriers & Industry Metrics

Large-scale Uncertainty Propagation Highly Coupled Dynamic Systems



Reduced-Order Modeling of Large-scale Uncertain Dynamic Systems



$$
\left.\begin{aligned} x_{k+1} &= Ax_k + Bu_k \\ y_{k+1} &= Cx_{k+1} \end{aligned}\right\} \quad y_k = CA^kB
$$

Ahuja, Surana, Cliff, SIAM Conference on Applications of Dynamical Systems, 2011

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

Complexity of quasi-Monte Carlo with dynamic uncertainty

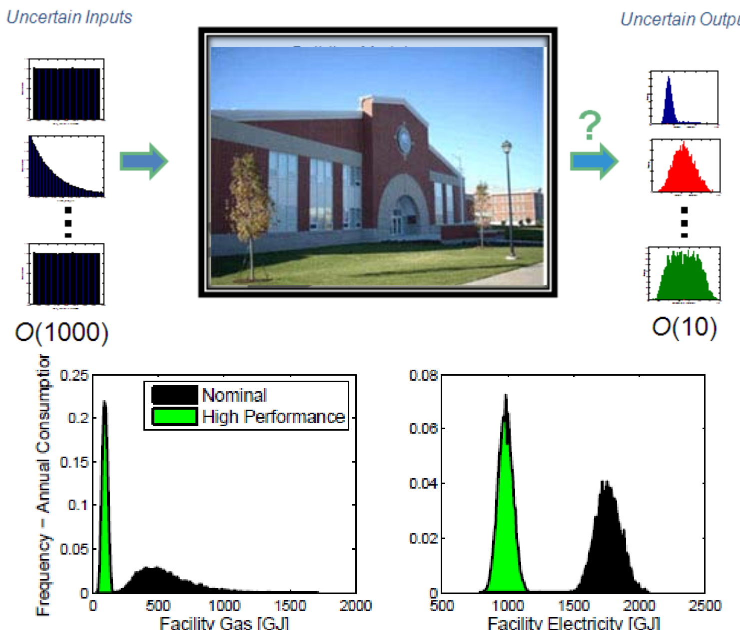
- O(1/sqrt(n))xm
- n sampling points (~10000)
- m order of param. of dynamic uncertainty (~10000)

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

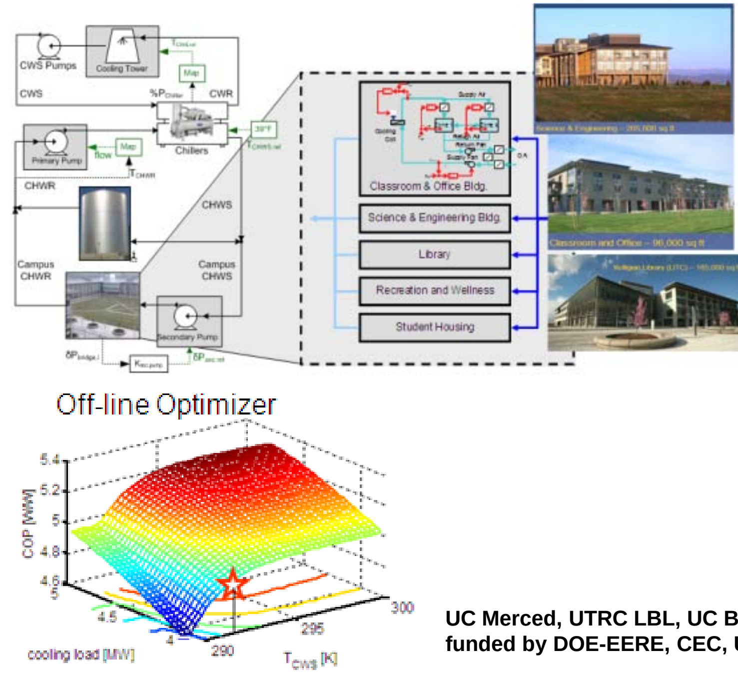
Complexity of Lyapunov equations & sampling

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

Uncertainty and Optimization: Progress & Gaps



AimDyn Inc, UTRC
funded by DoD/ESTCP



UC Merced, UTRC LBL, UC Berkeley
funded by DOE-EERE, CEC, UTRC

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

Discovery Research	Use-inspired Basic Research	Applied Research	Technology Maturation & Deployment

Multi-Scale Dynamics and Uncertainty

Discovery Research	Use-inspired Basic Research	Applied Research	Technology Maturation & Deployment
• 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

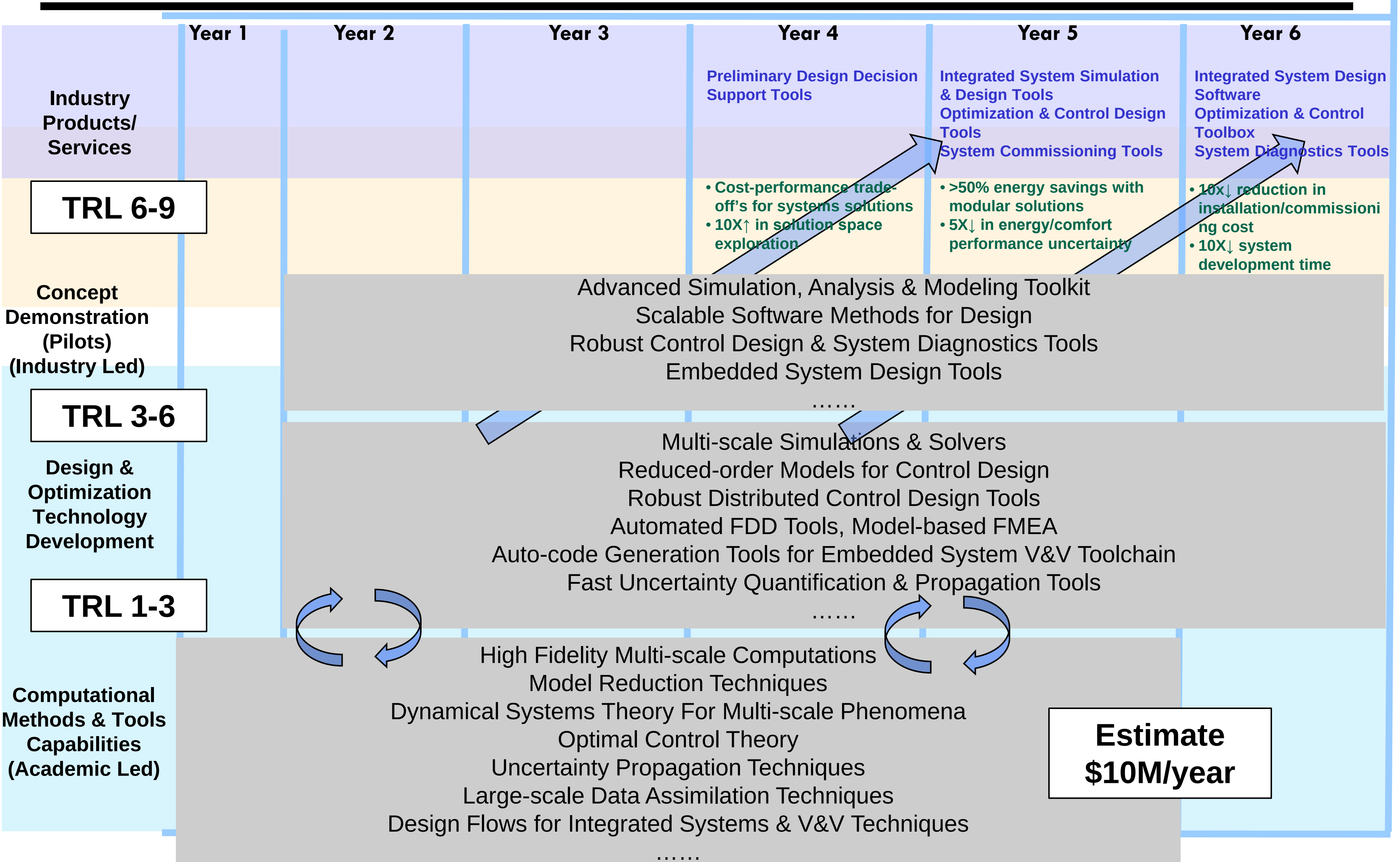
Discovery Research	Use-inspired Basic Research	Applied Research	Technology Maturation & Deployment
• Techniques for large-scale PDE control and optimization with non-local boundary conditions and uncertainty • Parallel optimization techniques for closed-loop large-scale uncertain dynamic building systems	• 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

Discovery & Use-inspired Basic Research	Applied Research & Technology Maturation
• 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

Roadmap For Development Of Computer Tools for Design, Optimization and Control of Energy Efficient Buildings



Recommended Next Steps

Hold ASCR Workshop in Fall 2011

Workshop objectives
- determine thematic areas;
- projects and metrics;
- identification of participants

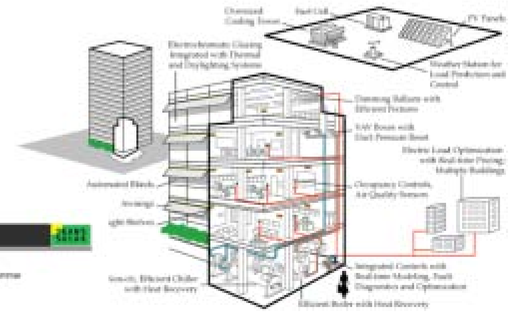
Thank You

Computation: Can't Brute Force This

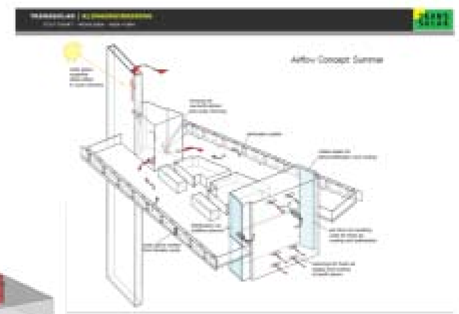
Whole Building Simulations (complex geometry, multiple sub-systems, and realistic indoor and external uncertainties)

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

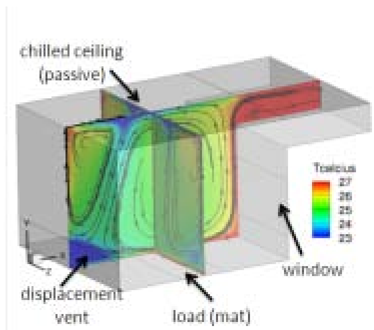
Isolated Thermal Environment in an Individual Zone/Room



from LBNL



from Transolar Engineering



from UTRC/VT

10 TFlops → 10 Pflops Computation Capability*

Complexity (scale, dynamics, nonlinearity, uncertainty…)

* Assuming less than 1hour turnaround for practical design calculations