Buildings-related research: simulation, validation, and beyond urban-scale energy modeling

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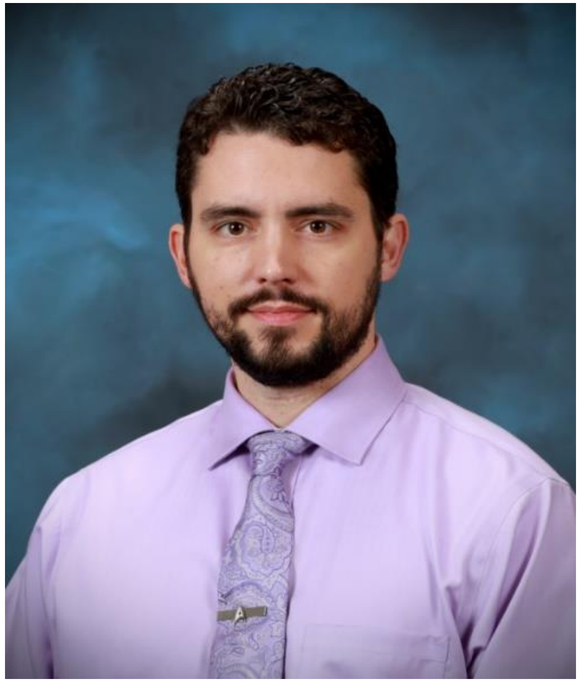
Oak Ridge National Laboratory

Syracuse University
Syracuse, New York
October 11, 2019

Joshua New, Ph.D., C.E.M., PMP, CMVP, CSM

- **Career**
  - 2009+ Oak Ridge National Laboratory, R&D staff
    - ETSD, Building Technology Research & Integration Center (BTRIC), Building Integration & Control Research Group
    - Climate Change Science Institute, Urban Dynamics Institute
  - 2012+ The University of Tennessee, Joint Faculty
- **Education**
  - The University of TN, (2004-2009), Knoxville; Ph.D. Comp. Sci.
  - Jacksonville State University, AL (1997-2001, 2001-2004)
    M.S. Systems&Software Design, double-B.S. Computer Science and Mathematics, Physics minor
- **Professional Involvement**
  - IEEE, Senior Member (top 8%)
  - ASHRAE, defines international building codes
    - TC1.5, Computer Applications, Voting member and officer
    - TC4.2, Climatic Information, Voting member and officer
    - SSPC169, Weather Data for Building Design Standards (24% of page count of building code), Voting member
    - TC4.7, Energy Calculations, Voting member and officer
    - SSPC140 and ASHRAE Guideline 14 involvement



Certifications

- AEE, Lifetime Member
  - Certified Energy Manager
  - Certified Measurement & Verification Professional
- PMI, Member
  - Project Management Professional
- Certified Scrum Master

Artificial Intelligence

- President's National S&T Council's Machine Learning and Artificial Intelligence Subcommittee's Artificial Intelligence Consortium

OAK RIDGE National Laboratory

What are National Laboratories?

- System of facilities and labs overseen by DOE for advancing S&T to fulfill the mission
  - "Crown jewels" of the nation's research institutions
- 17 national labs
- Most began in WW2 to develop radar, computer, and atomic bomb

Office of Science Laboratories

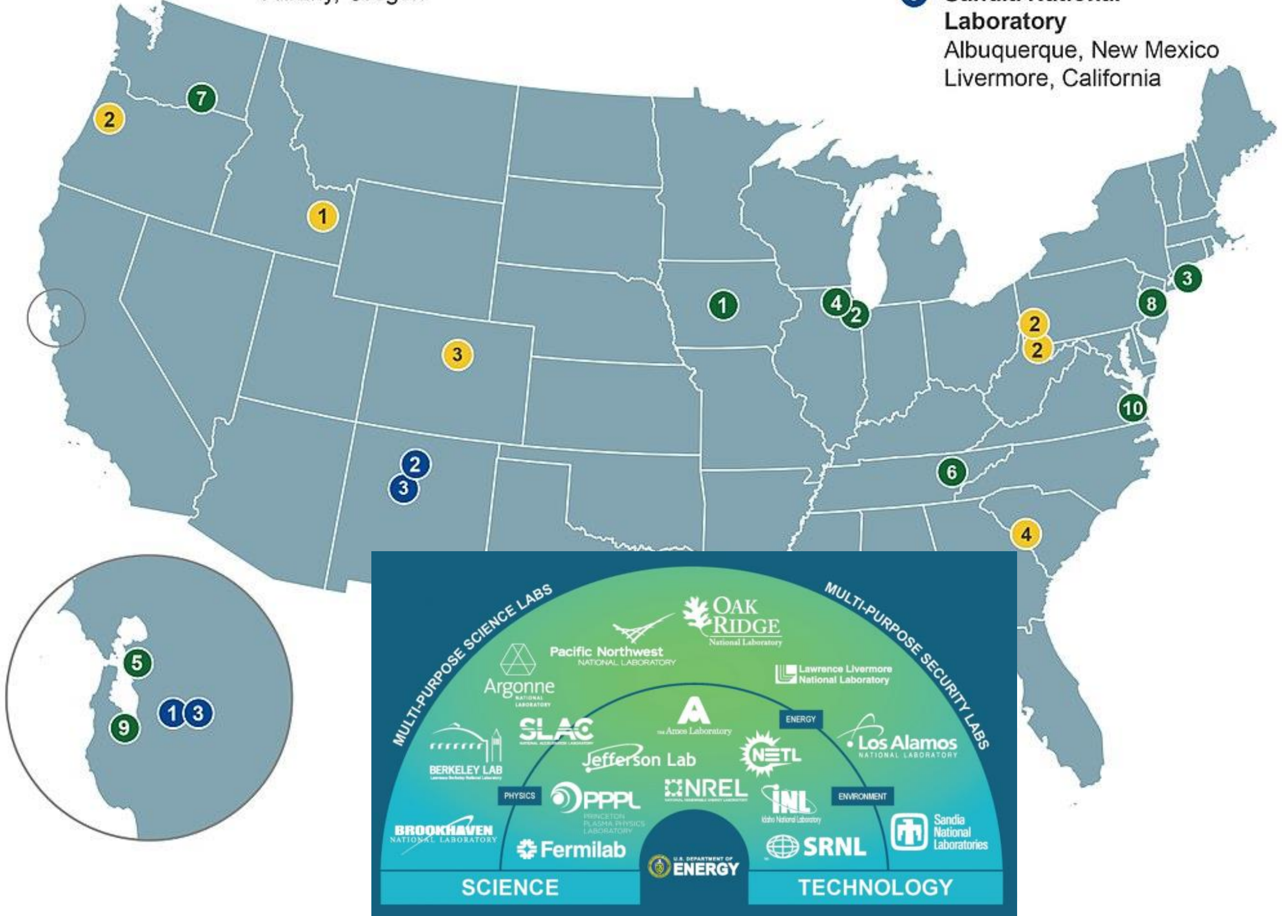
1. **Ames Laboratory**
   Ames, Iowa
2. **Argonne National Laboratory**
   Argonne, Illinois
3. **Brookhaven National Laboratory**
   Upton, New York
4. **Fermi National Accelerator Laboratory**
   Batavia, Illinois
5. **Lawrence Berkeley National Laboratory**
   Berkeley, California
6. **Oak Ridge National Laboratory**
   Oak Ridge, Tennessee
7. **Pacific Northwest National Laboratory**
   Richland, Washington
8. **Princeton Plasma Physics Laboratory**
   Princeton, New Jersey
9. **SLAC National Accelerator Laboratory**
   Menlo Park, California
10. **Thomas Jefferson National Accelerator Facility**
    Newport News, Virginia

Other DOE Laboratories

1. **Idaho National Laboratory**
   Idaho Falls, Idaho
2. **National Energy Technology Laboratory**
   Morgantown, West Virginia
   Pittsburgh, Pennsylvania
   Albany, Oregon
3. **National Renewable Energy Laboratory**
   Golden, Colorado
4. **Savannah River National Laboratory**
   Aiken, South Carolina

NNSA Laboratories

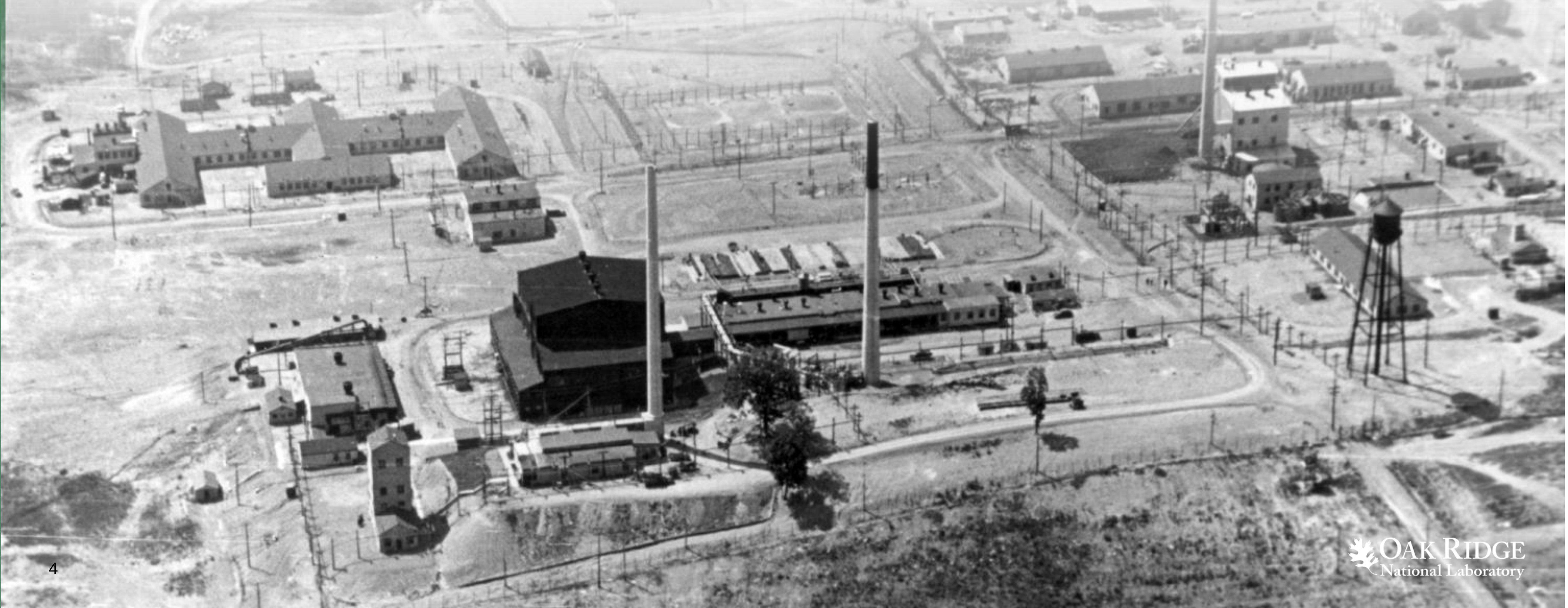
1. **Lawrence Livermore National Laboratory**
   Livermore, California
2. **Los Alamos National Laboratory**
   Los Alamos, New Mexico
3. **Sandia National Laboratory**
   Albuquerque, New Mexico
   Livermore, California



Oak Ridge National Laboratory evolved from the Manhattan Project

ORNL in 1943

The Clinton Pile was the world's first continuously operated nuclear reactor



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UT-Battelle, LLC began managing ORNL in April 2000

The University of Tennessee

- An ORNL partner since 1946
- State-funded Science Alliance started in 1982, to build programs with ORNL
- 14 UT-ORNL Governor's chairs
- Shared research and joint appointments
- Joint institutes in advanced materials, biological sciences, computational sciences,
  neutron sciences, and nuclear physics

Battelle Memorial Institute

- A long standing relationship with DOE
- Develops and deploys technology worldwide
- Manages or co-manages 7 DOE national laboratories: ORNL (with UT), Brookhaven, Idaho, Lawrence Livermore, Los Alamos, NREL, and Pacific Northwest

ORNL Internships (K-Faculty)

Undergraduate Students

- DOE Community College Internships (CCI)
- DOE Science Undergraduate Laboratory Internships (SULI)
- Higher Education Research Experience – Entering Freshmen (HERE-EF)
- Higher Education Research Experiences (HERE)
- Institute for Advanced Composite Manufacturing Innovation Internship Program
- Laboratory Technology (Lab Tech)
- Nuclear Engineering Science Laboratory Synthesis (NESLS)
- Great Lakes Colleges Association/Associated Colleges of the Midwest, Oak Rid Science Semester (ORSS)

Recent Associate's and/or Bachelor's Graduates

- DOE Science Undergraduate Laboratory Internships (SULI)
- Higher Education Research Experiences - Recent AAS/BS Graduates (HERE)
- Laboratory Technology Program (Lab Tech)
- Post-Bachelor's Research Associate Program

Graduate Students

- Advanced Short- Term Research Opportunity (ASTRO)
- Computational Science & Technology Advanced Research Studies (C-STARS)
- Higher Education Research Experiences (HERE)
- Higher Education Research Experience (HERE) - Thesis or Dissertation Research
- Institute for Advanced Composite Manufacturing Innovation Internship Program (IACMI)
- National GEM Consortium Fellowship Program (GEM)
- Nuclear Engineering Science Laboratory Synthesis (NESLS)
- The Bredesen Center

Recent Master's and/or Ph.D. Graduates

- Advanced Short-Term Research Opportunity (ASTRO)
- Post-Master's Research Associate Program
- Computational Science & Technology Advanced Research Studies (C-STARS)
- Post-Doctoral Associate
- ORNL Distinguished Fellowships

Faculty

- DOE Visiting Faculty Program (VFP)
- Higher Education Research Experiences - Faculty (HERE)
- ORNL Historically Black Colleges and Universities / Minority Education Institution Faculty Summer Research Program (HBCU/MEI)
- Joint Faculty Appointments (JFA)

Search "ORNL Internships" – most summer internship applications due January 10.

The UT-ORNL partnership creates value for both institutions

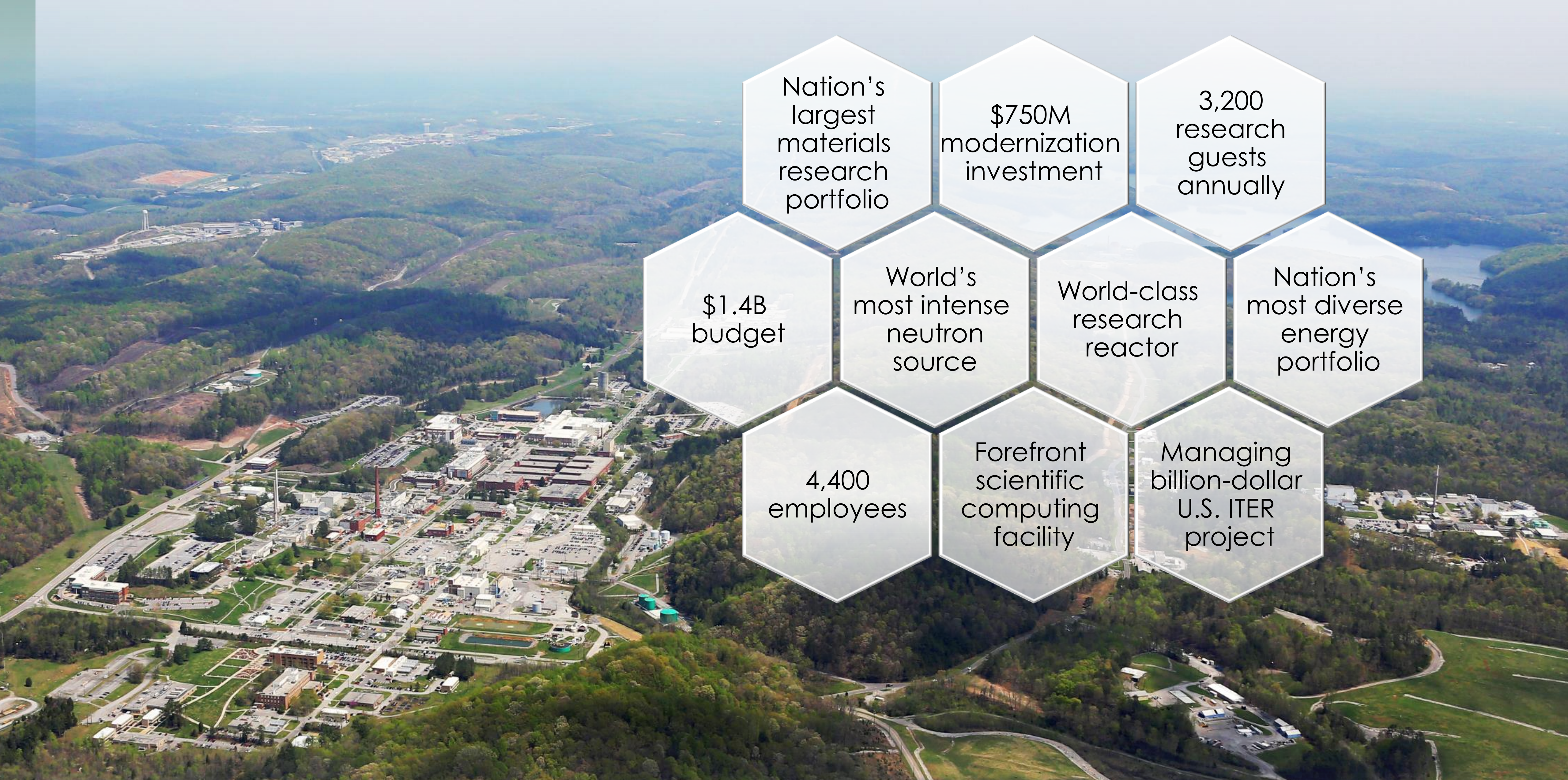
Financial resources

- State of Tennessee investments
  - Governor's Chairs
  - Facility construction
  - Bredesen Center startup
  - RevV! voucher program
- R&D funding
  - Joint proposals
  - Subcontracts
- UT-Battelle award fee

Joint activities

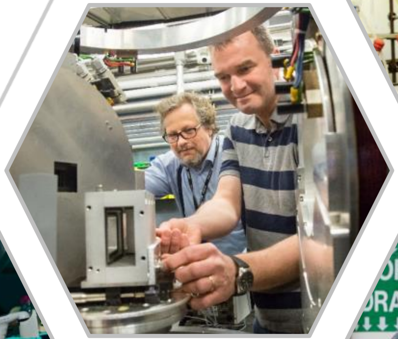
- Bredesen Center
- Science Alliance
- Graduate School of Genome Science and Technology
- Joint institute operations
- Institute for Advanced Composite Manufacturing Innovation
- Joint faculty appointments

ORNL is DOE's Largest Science and Energy Laboratory



Our vision for ORNL: World's premier research institution

Focus on the most difficult problems



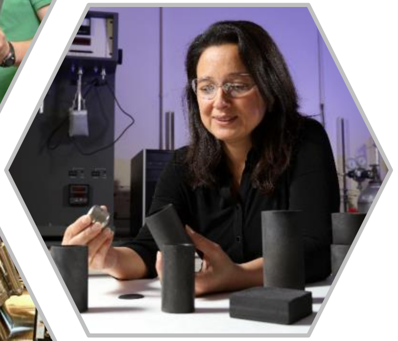
Conduct world-leading research

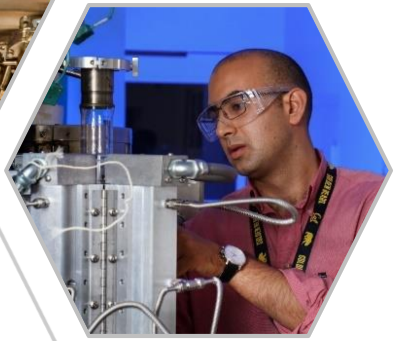
Ensure the nation's energy future

Relentlessly pursue institutional effectiveness

Deliver innovative break-throughs

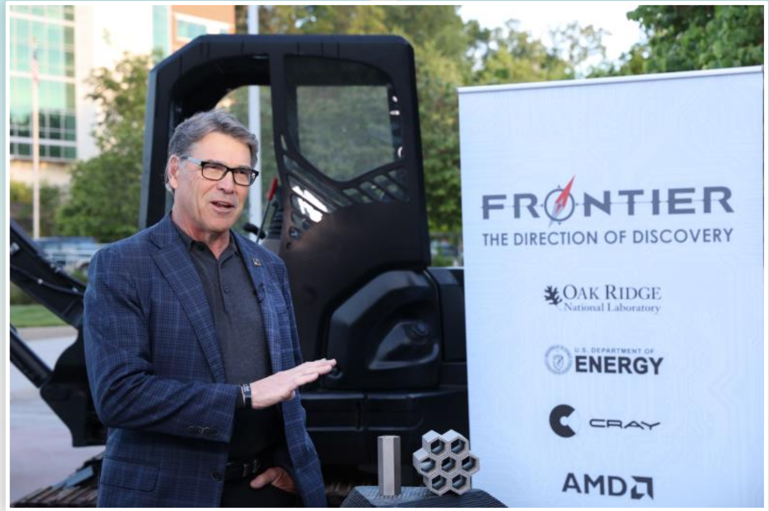
Strengthen national security



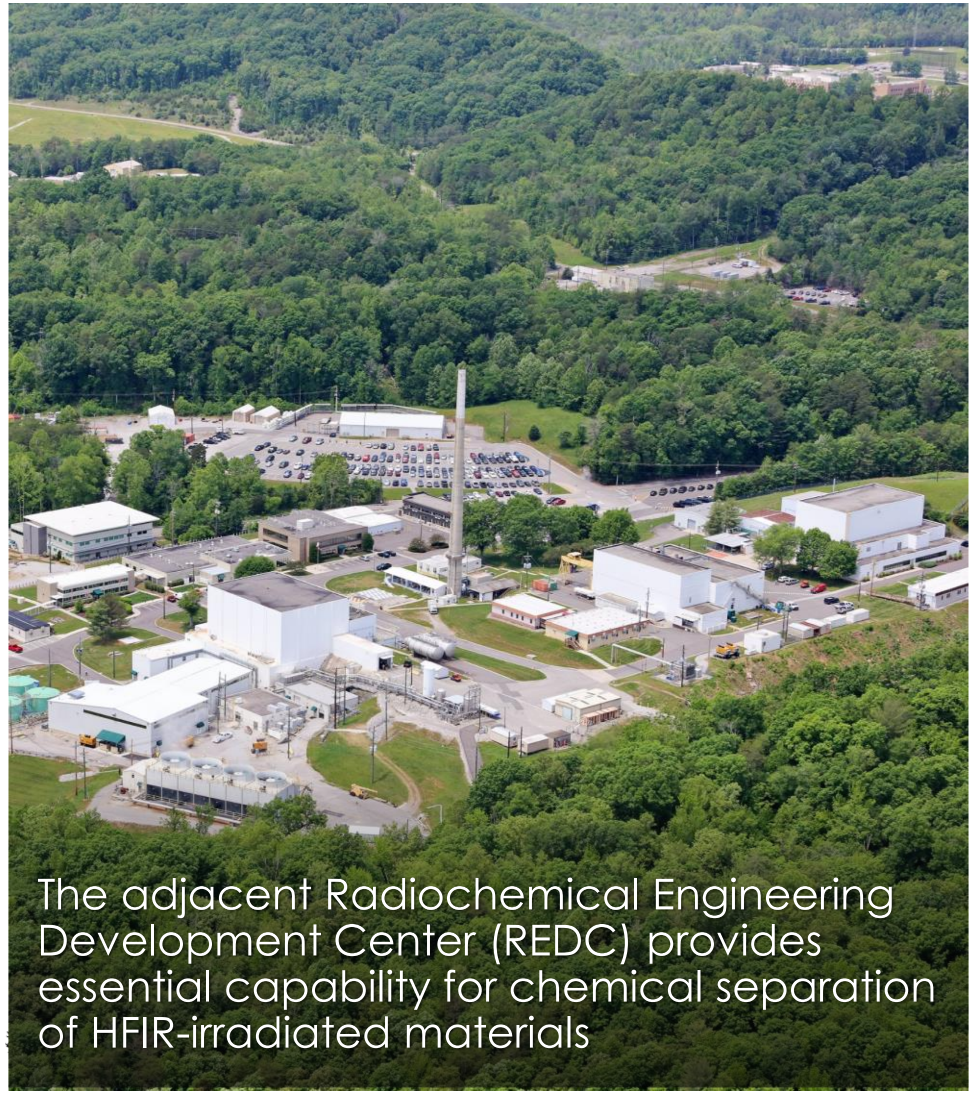


We are being challenged to deliver on a wide variety of projects

Neutrons	Computing	Nuclear	Isotopes	Multiple programs
Proton Power Upgrade Second Target Station	OLCF-5: Frontier Exascale Computing Project	US ITER Project Office Material-Plasma Exposure Experiment Transformational Challenge Reactor	Domestic Uranium Enrichment Centrifuge Experiment Stable Isotope Production Facility Stable Isotope Production and Research Center	Translational Research Capability Low-Vibration, Low-EMF Imaging Capability Research Operations Support Center Craft Resource Support Facility



Keeping ORNL at the forefront in Nuclear: High Flux Isotope Reactor (HFIR)



The adjacent Radiochemical Engineering Development Center (REDC) provides essential capability for chemical separation of HFIR-irradiated materials

We are exploring options for sustaining and enhancing HFIR's unique capabilities

- Steady-state neutron scattering experiments that require the highest brightness beams
- Production of heavy actinides and other rare isotopes that require the highest neutron intensities
- Radiation damage research at the highest damage rates
- Neutron activation analysis at the highest sensitivity
- Fundamental neutron and neutrino physics at the highest steady-state fluxes

Keeping ORNL at the forefront in Neutrons: 2 upgrades at the Spallation Neutron Source (SNS)

Proton Power Upgrade (PPU): Double power of existing accelerator structure

- Increases peak brightness of beams of pulsed thermal neutrons from First Target Station (STS)
- Provides new capabilities for atomic resolution and fast dynamics
- Provides a platform for STS

Second Target Station (STS): Build a second target station with initial suite of instruments

- Optimized for pulses of cold neutrons of unprecedented peak brightness
- Provides new capabilities for measurements across broader time, length, and energy scales, in real time and on smaller samples

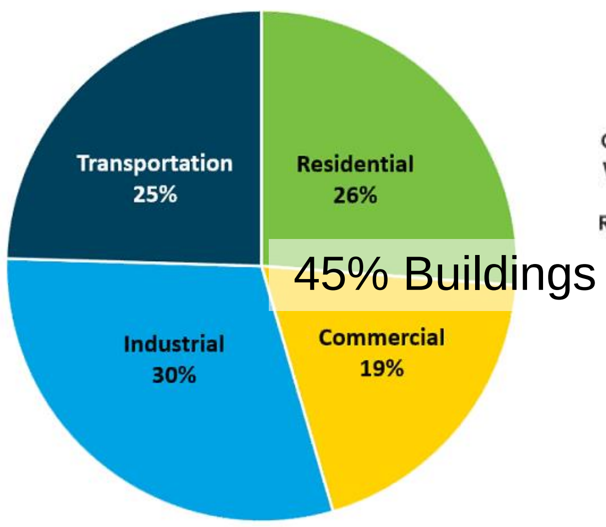
OAK RIDGE National Laboratory

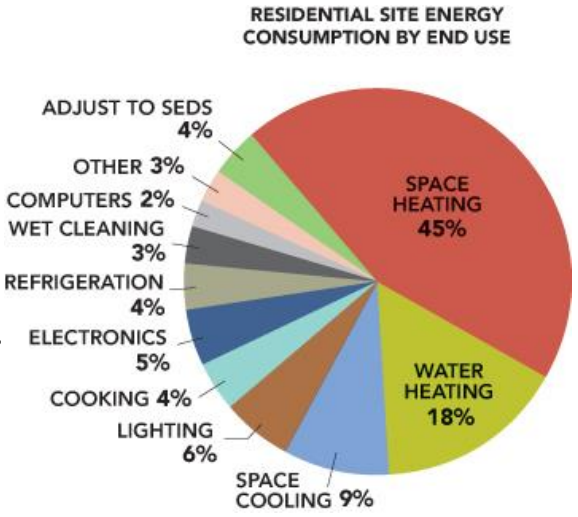
Keeping ORNL at the forefront in Computing: #1 Jaguar, Titan, Summit, Frontier?

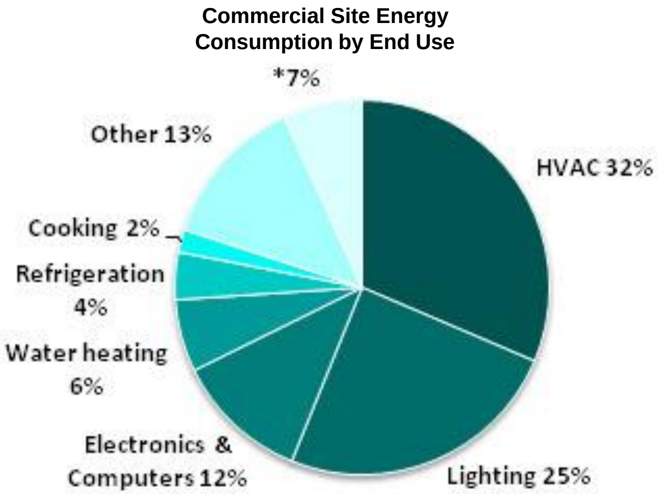
We are actively engaged in leading High Performance Computing Resources

- Several of the world's #1 fastest supercomputers in the world
- Competitively-awarded compute time
- Oak Ridge Leadership Computing Facility (OLCF) support system
- Infrastructure investments for larger machines requiring more power
- Key industrial partnerships for new chip architectures and HPC design
- Strategic focus on Artificial Intelligence

Energy and Buildings Overview







Buildings consume 73% of the nation’s electricity

Source: U.S. Energy Information Administration, January 2016 to January 2017, *Monthly Energy Review – Table 2.1*.

124 million U.S. buildings
$395 billion/yr energy bills

Goal of the DOE
Building Technologies Office:
30% energy reduction per sq. ft.
by 2030 compared to 2010 baseline

Building Energy Modeling – building descriptions + weather = estimated building energy consumption

$9B/yr – ESCO; $7B/yr – utility EE
$14B/yr – DR management systems
0.3% modified, BEM < 10% of those

Building Technologies Office

- $220M per year
- Multi-Year Program Plan
  - Emerging Technologies
  - Residential Buildings Integration
  - Commercial Buildings Integration
  - Appliance & Equipment Standards
  - Building Energy Codes
- Logic Models
- Scout
  - High Impact Technologies (HITs)
- Initiatives, Technology Areas, etc.

OAK RIDGE National Laboratory

ORNL and Building Energy Efficiency

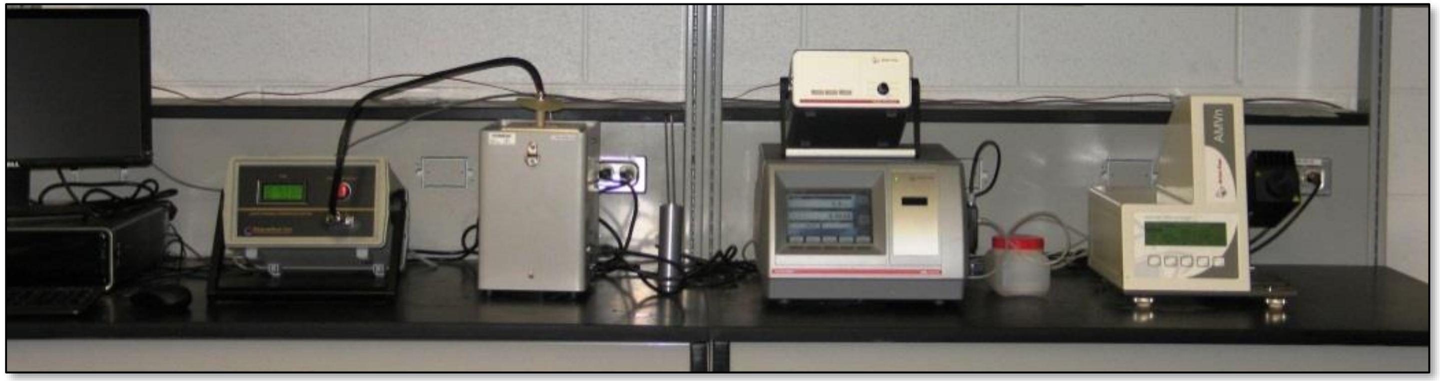
- 40+ years of applied R&D leadership in buildings
- DOE's only national user facility for buildings R&D
  - Building Technologies Research & Integration Center (BTRIC)
- Trust/respect of government agencies, industry, and universities here and abroad
  - 22 ASHRAE Awards and multitude of others
- Proven ability to bridge gap between basic science and early stage applied R&D, and couple to industry for later stage R&D and implementation
- Economic impacts and jobs from many industry partner products in the market, saving energy in real buildings

Equipment research: Lab facilities

Environmental chambers

Compressor calorimeters

Heat exchanger R&D loops



Working fluid physical properties measurement

Envelope research: Lab facilities

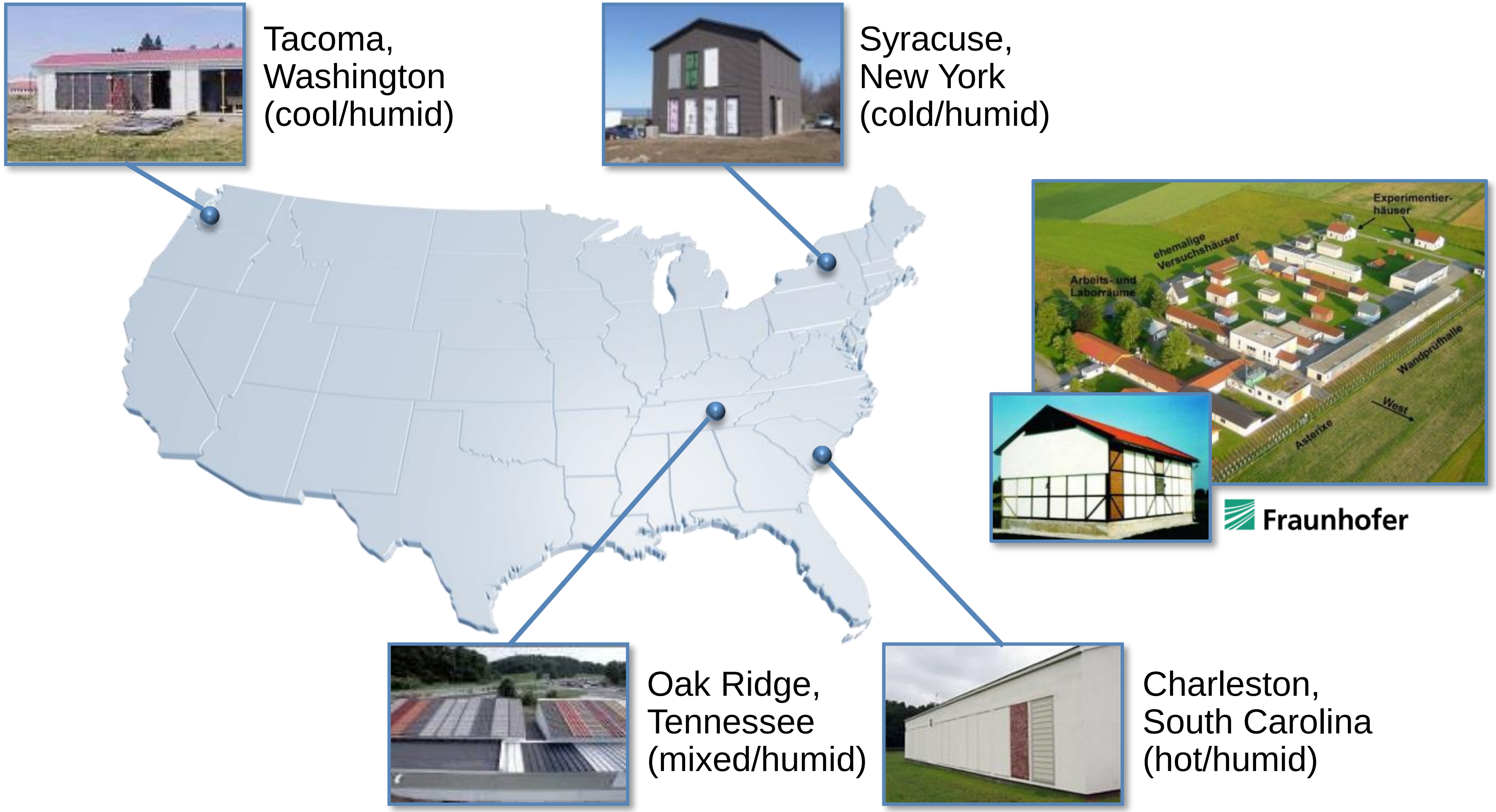
Heat flow through roof/attic assemblies

Heat flow through wall assemblies

Air/moisture flow through wall assemblies

Hygrothermal properties of materials

Envelope research:
Natural exposure facilities



OAK RIDGE
National Laboratory

System/building integration: Research facilities (commercial)

- Realistic experimental platforms for evaluating emerging energy efficiency technologies before market introduction
- Enabling holistic research on whole-building models, controls, fault detection and diagnostics, etc., during development

Light commercial buildings:
Flexible Research Platforms (FRP) at ORNL

System/building integration: Research facilities (residential)

- Residential (~15 min. data)
  - Yarnell (37 sensors)
  - Wolf Creek (4x 356 sensors/building)
  - Campbell Creek (3x 144 sensors/bldg.)
    - Temperatures
    - Plugs
    - Lights
    - Range
    - Washer
    - Radiated heat
    - Dryer
    - Refrigerator
    - Dishwasher
    - Heat pump air flow
    - Shower water flow
    - Etc.

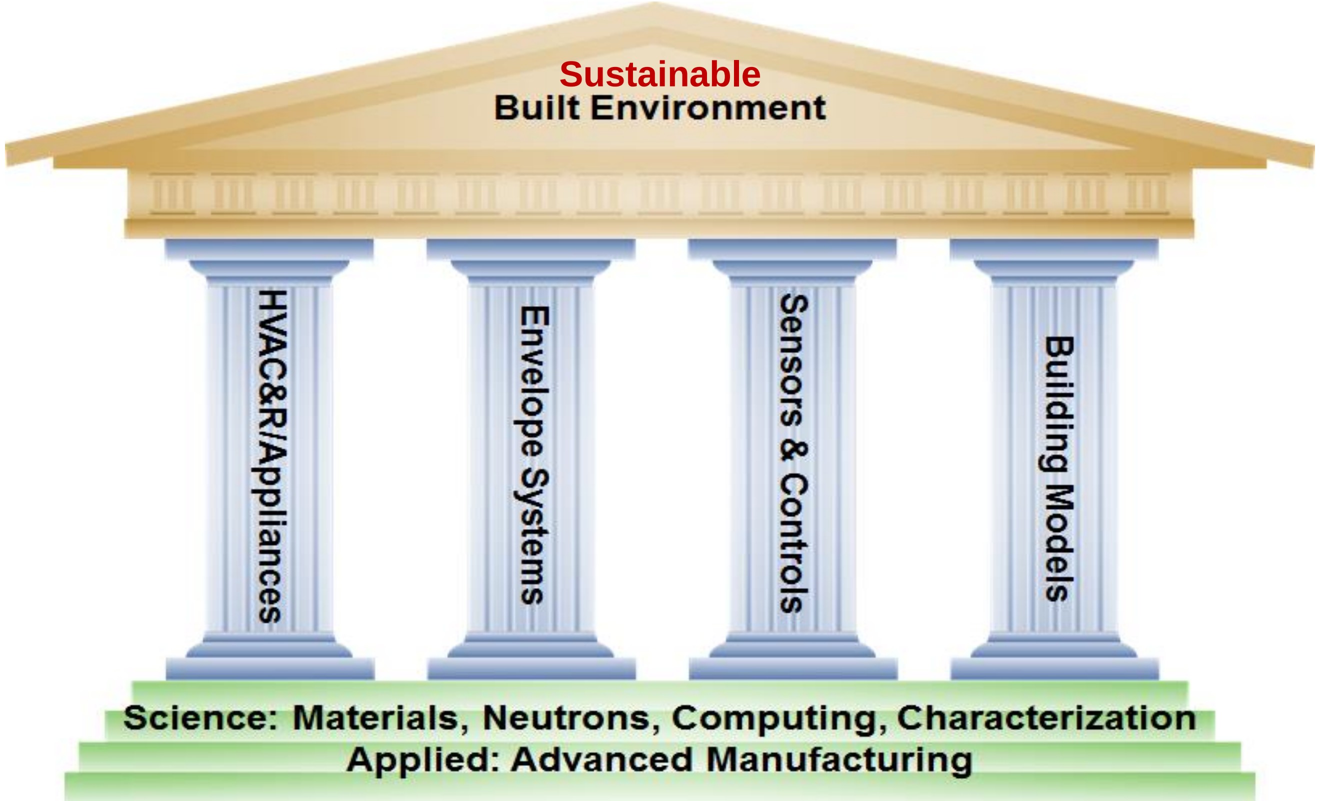
OAK RIDGE
National Laboratory

Vision of the Buildings Program at ORNL

Vision: Efficiency-Doubled, Same-Cost Buildings that are Resilient and Foster Renewable Energy and Grid Reliability

10 years: New building technologies and practices introduced have achieved market thresholds enabling them to be required through minimum efficiency standards and codes, thereby locking in efficiency-doubled, same-cost buildings by 2050.

3 years: New building technologies and practices having the potential to enable efficiency-doubled, same-cost buildings are beginning to reach the market.



Equipment R&D

ClimateMaster's Revolutionary Heat Pump

- R&D effort between ORNL and ClimateMaster
- Ultrahigh-efficiency geothermal heat pump providing space heating, cooling, and water heating
- Based on modeling, laboratory evaluation, and field tests, the Trilogy 45 Q-mode can save 60% of annual energy use and cost in residential applications versus new minimum efficiency air-source heat pumps and electric resistance storage water heaters
- First geothermal heat pump ever certified by AHRI to exceed 40 EER (ratio of cooling capacity to power input)
- ClimateMaster received the 2013 *R&D 100 Award* from R&D Magazine, which highlights commitment to deploying cutting-edge technology and helping people save money and energy

CLIMATEMASTER®

Two novel clothes dryer technologies save energy, cost, and time

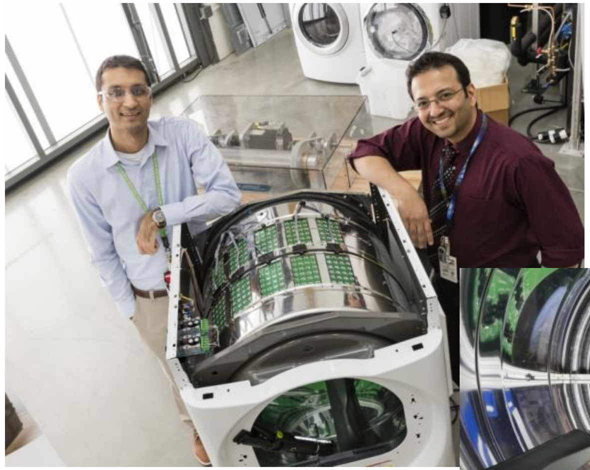
Ultrasonic Dryer

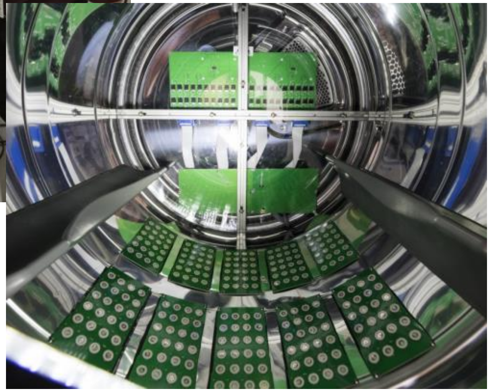
World's first ultrasonic dryer

Uses vibrations instead of heat to extract moisture as cold mist blown away with room-temperature air

Potential to make full-sized clothes dryer 3x to 5x more energy efficient than conventional dryers

Typical drying time reduced to 15-20 minutes





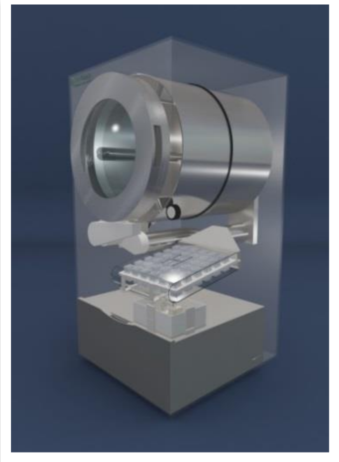
Thermoelectric Dryer

Novel, thermoelectric clothes dryer with potential to achieve heat pump dryer efficiency levels at much lower cost

Simpler installations with ventless designs

Target energy factor >6 lb/kWh, a major improvement over electric resistance dryers (3.7 lb/kWh)

Current efforts focus on air-based designs to accelerate market introduction and ensure favorable drying time and cost effectiveness



Envelopes R&D

Additive Manufacturing and Integrated Energy (AMIE)

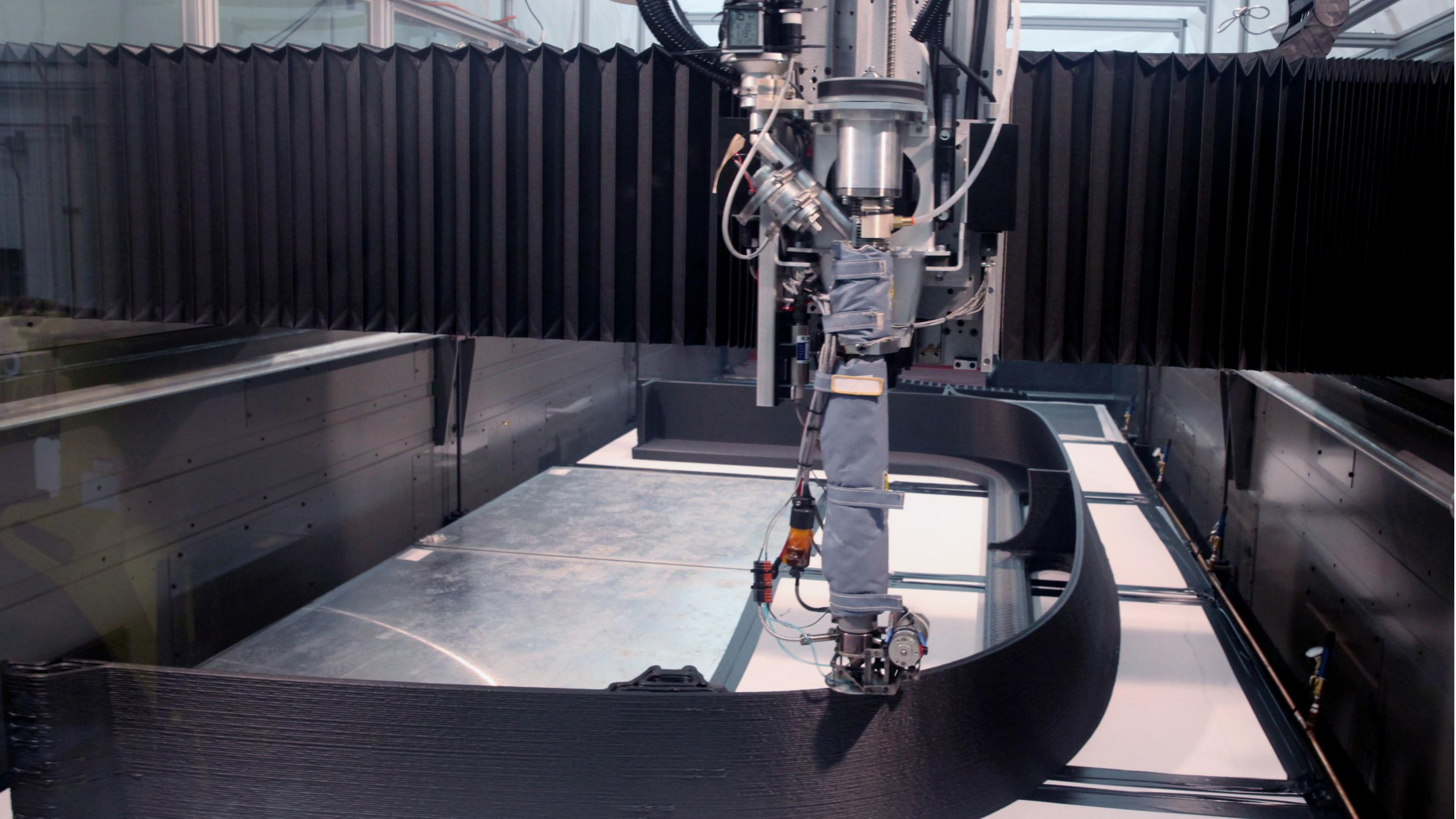
2016

GOVERNOR'S CHAIR ENERGY + URBANISM
THE UNIVERSITY OF TENNESSEE
OAK RIDGE NATIONAL LABORATORY
SKIDMORE, OWINGS & MERRILL LLP

THE UNIVERSITY of TENNESSEE UT KNOXVILLE

SOM

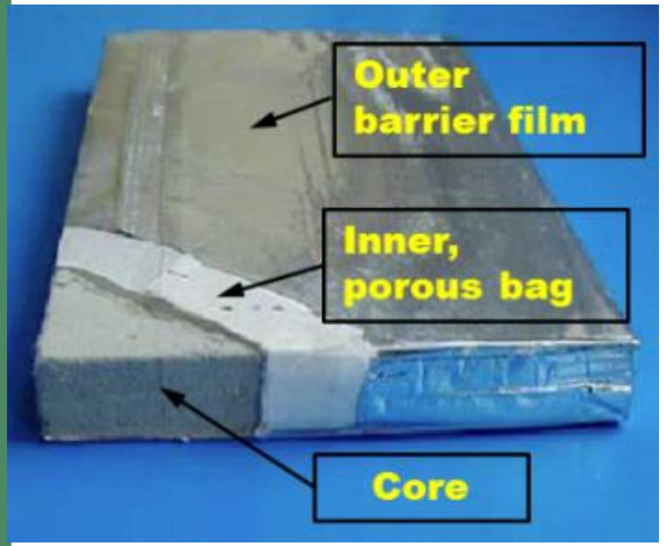
OAK RIDGE National Laboratory

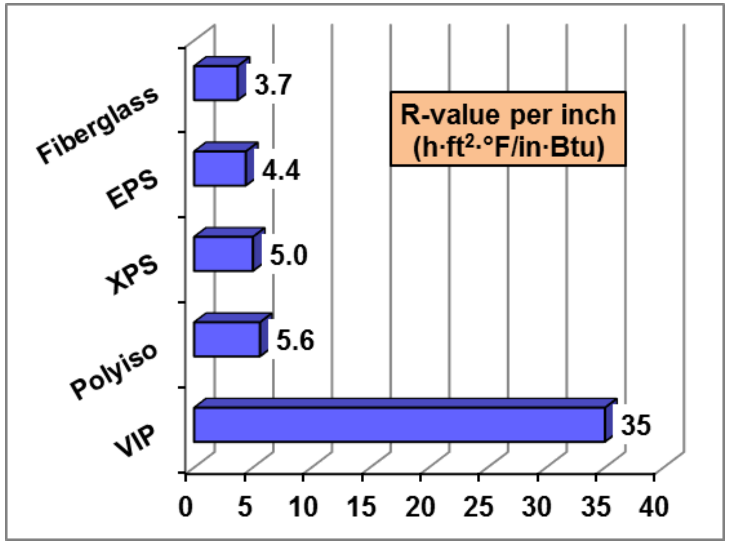


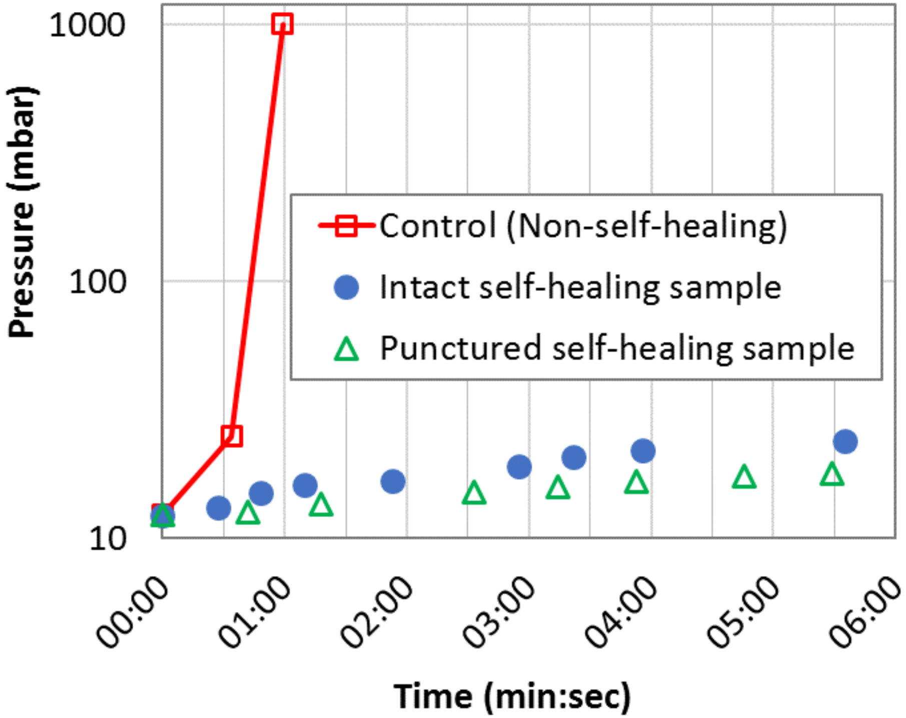
ASSEMBLY SEQUENCE

Self-Healing Films for Vacuum Insulation Panels (VIPs)

- Typical VIP: evacuated core encapsulated within barrier films
- Damage to barrier film reduces R/inch to regular insulation levels
- Proof-of-principle of self-healing films: maintain film impermeability after puncture







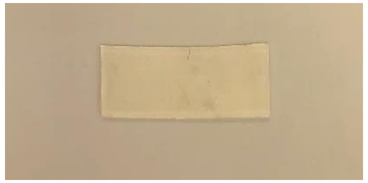
Primer-Less Self-Healing Sealant

Joints are among the weakest areas in the air and water barrier systems of building envelopes

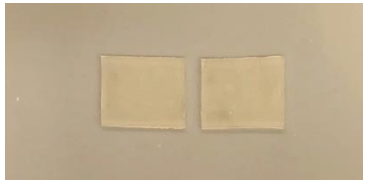
Adhesion Failure

Cohesion Failure

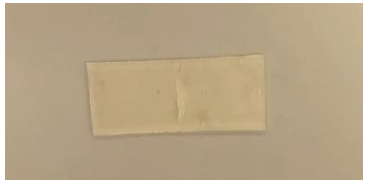
Original sample



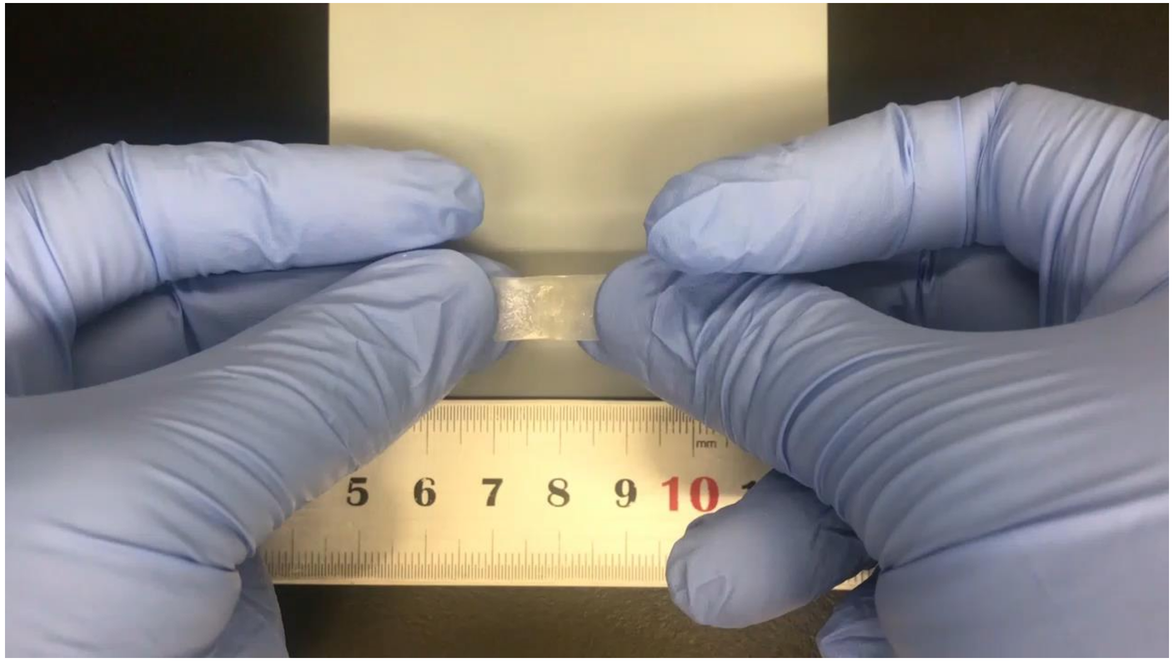
Sample cut into 2 pieces



Sample pieces touching



After 15 minutes of “healing”



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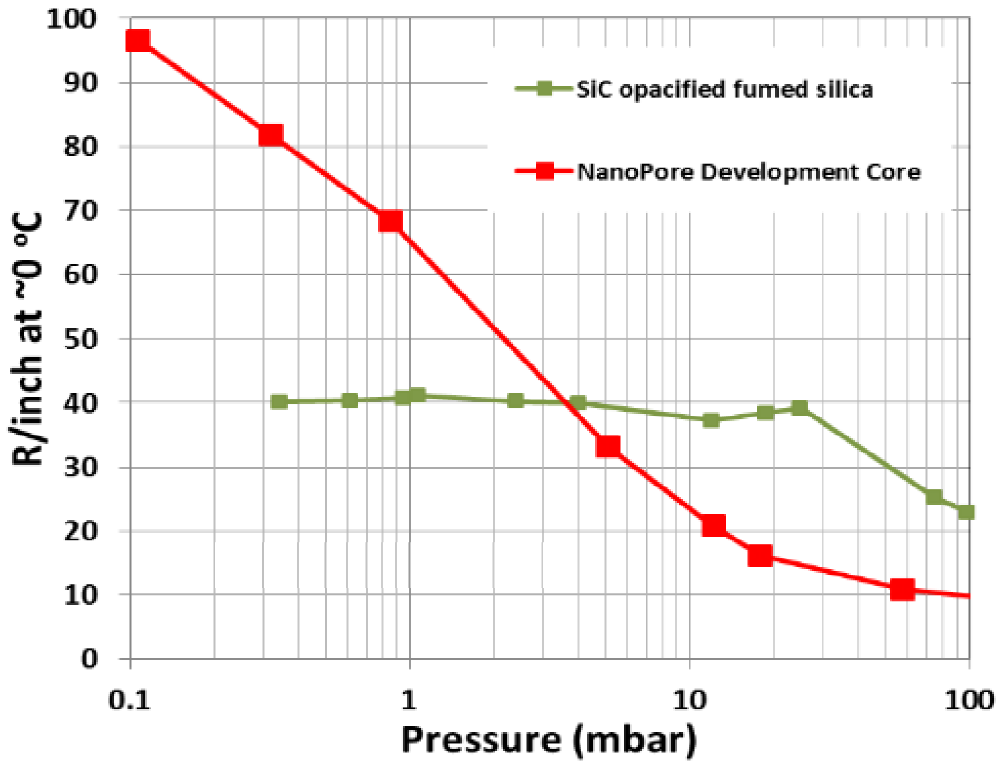
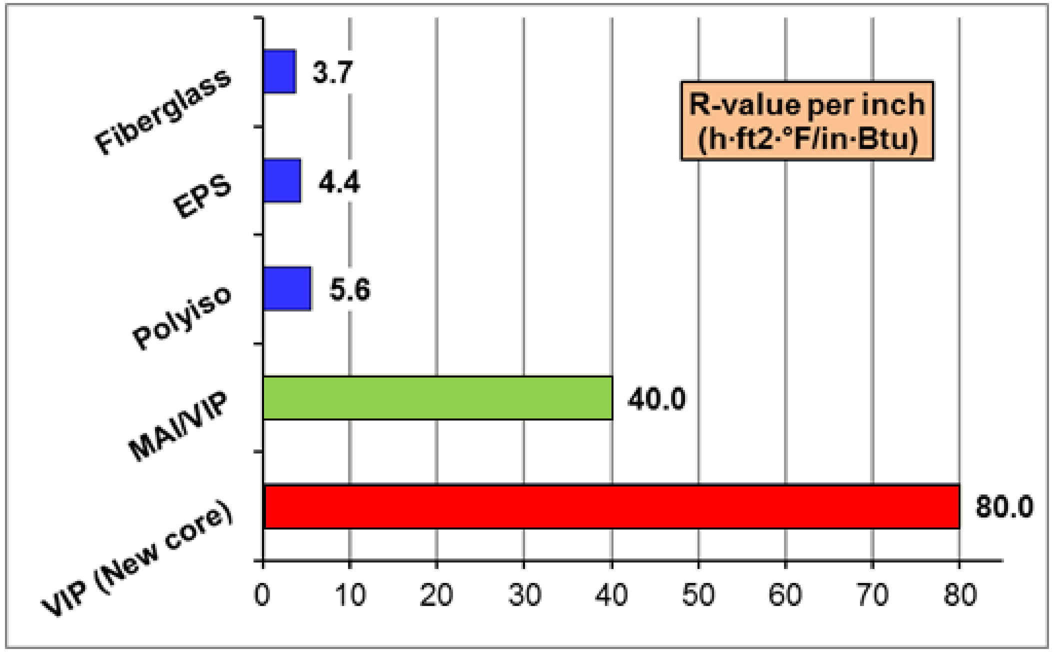
Ultra-High R/inch VIP with New Core Material

New core-based VIPs

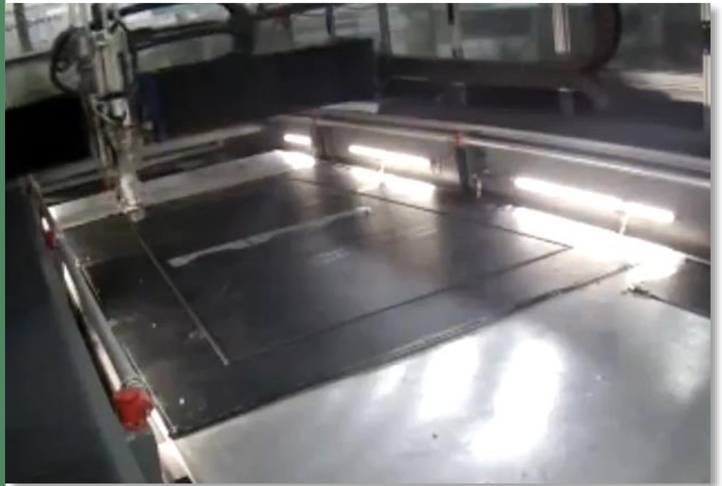
- R80/inch
- Cost projection of \$0.02/ft^2/R-value
- Thinner panels: lower material and shipping costs, and reduce installation thickness

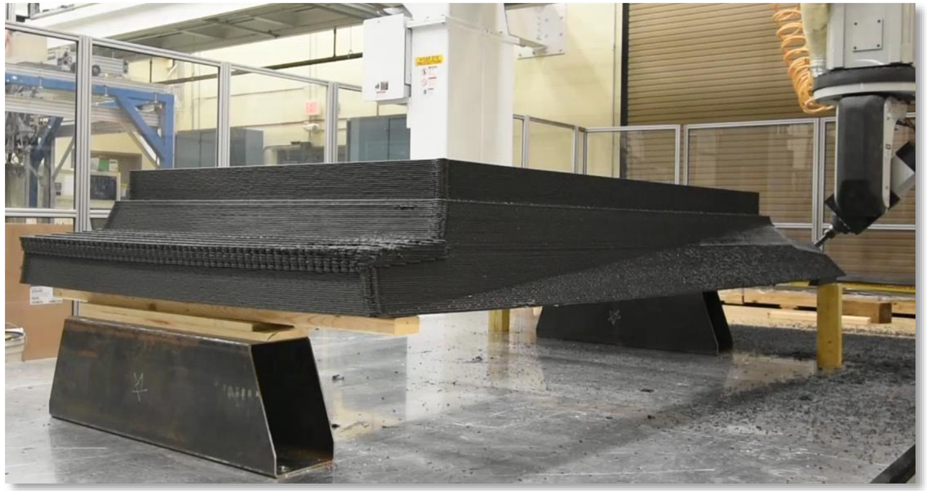




3D Printed Complex Molds for Precast Concrete

3D Printing → **Machining** → **Mold**





Casting setup → **Concrete casting** → **Precast parts**

National Laboratory

Domino Site A Building

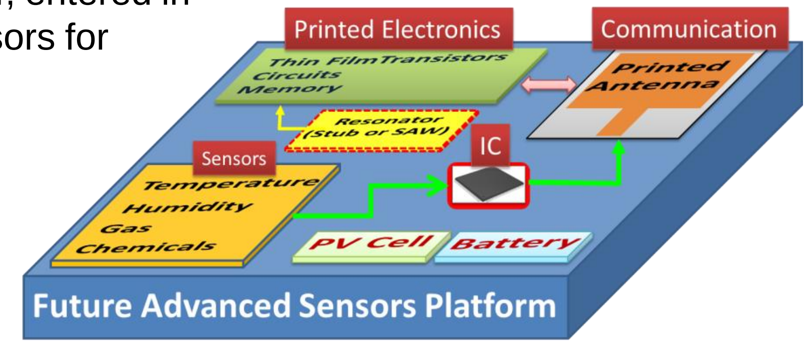
First building with precast façade made with 3D printed molds

Sensors & Controls R&D

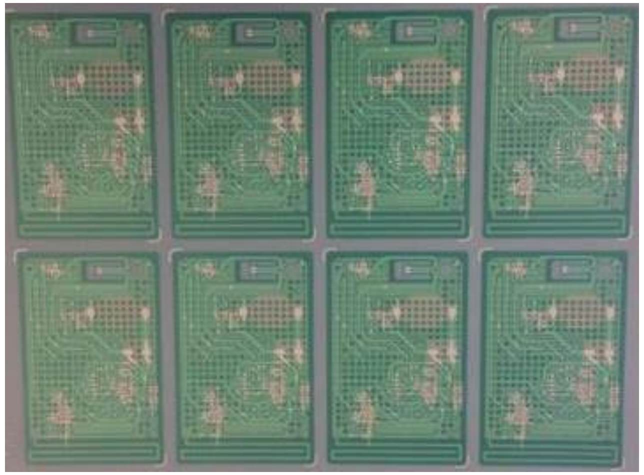
ORNL and Molex Develop Low-Cost Wireless Sensors for Buildings

Increasing accessibility to affordable information

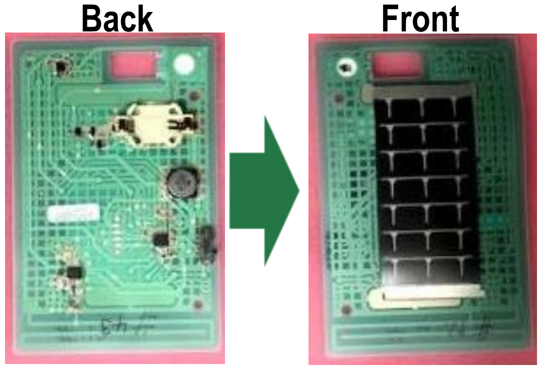
Oak Ridge National Laboratory and Molex, a premier international electronics manufacturer, entered in to a Cooperative Research and Development Agreement to develop low-cost wireless sensors for buildings applications and commercial availability.



- Peel-and-stick wireless sensor, measuring “4.75’ x 3’ x 0.23.’
- Uses additive techniques on thin-film, flexible, and light-weight substrates.
- Contains photovoltaic cells that harvest energy from artificial indoor light and powers a rechargeable battery. The platform includes integrated circuitry for sensor signal processing, onboard computation, wireless communication and an antenna.



Print components on flexible substrates



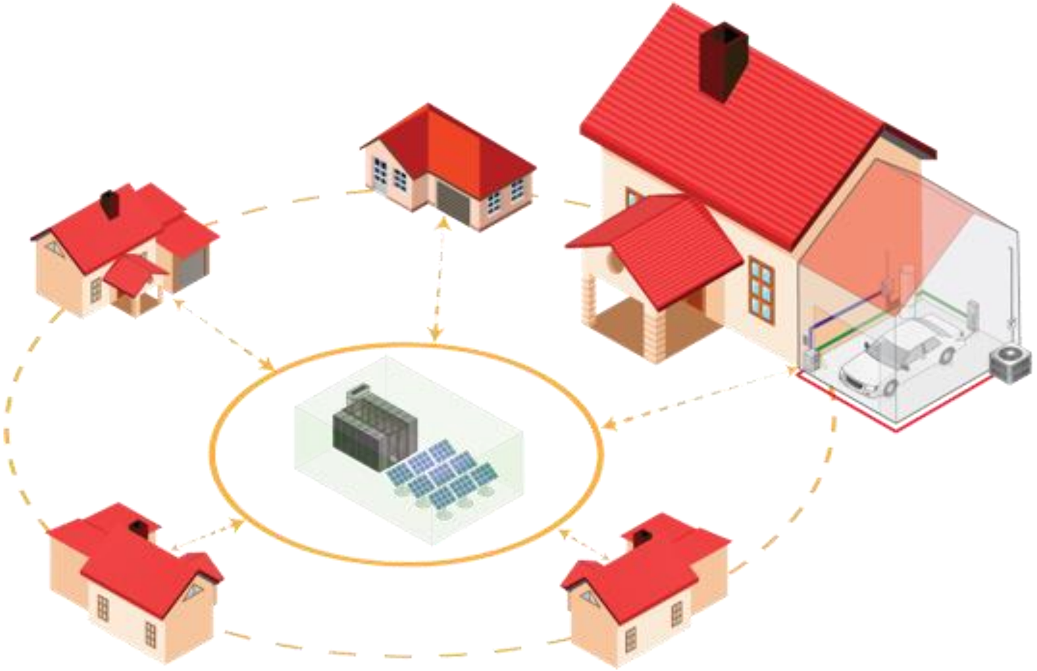
Add discrete components using pick-and-place

Samples for OEMs

The ultra-low power smart sensors collect and send data to a receiver, which can capture data from many different peel-and-stick nodes and provide information to the controls for the energy-consuming systems. The more information received, the better the building’s energy management. Both new construction and retrofitted buildings can benefit from ORNL’s smart sensors.

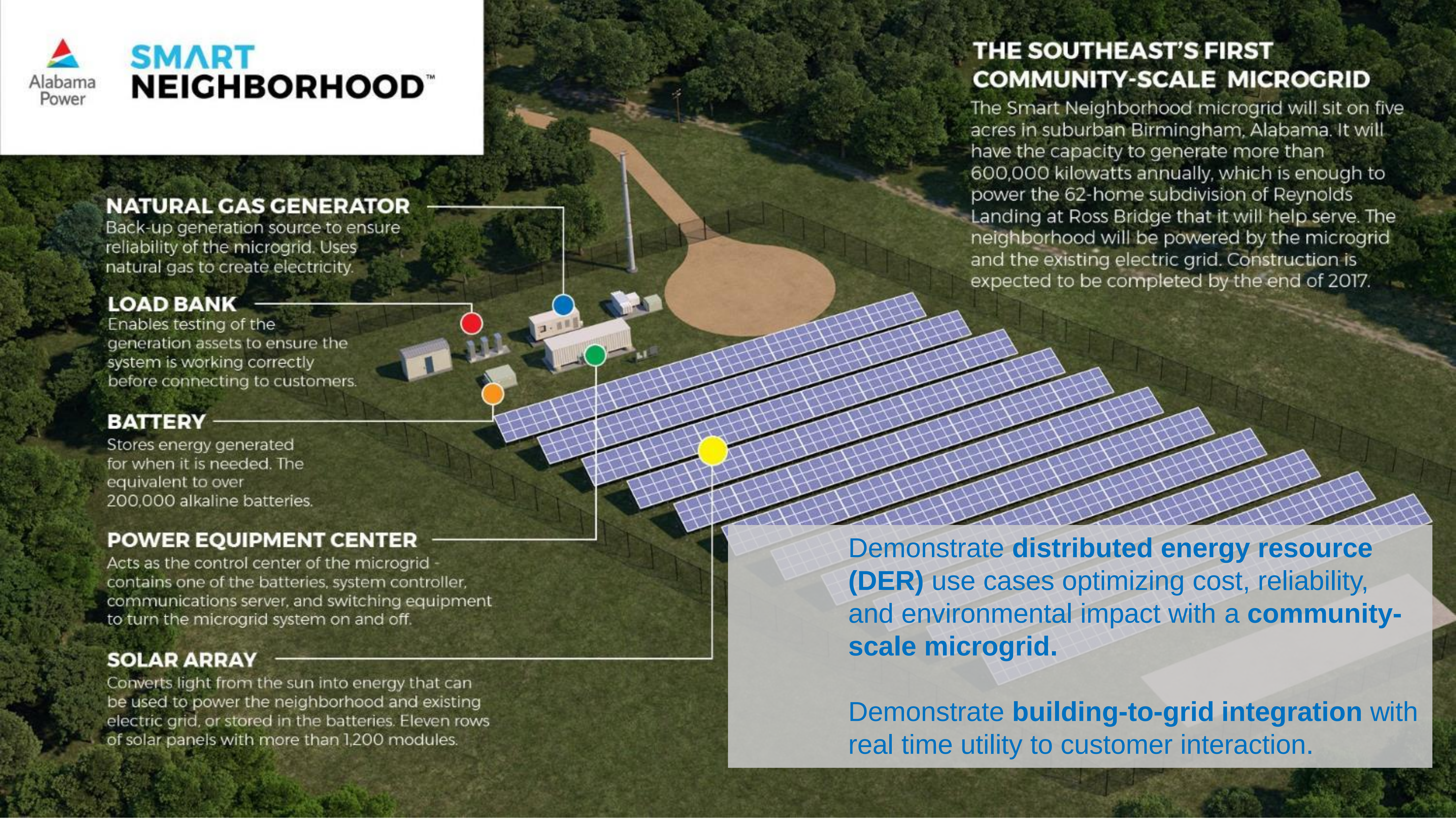
Connected and Transactive Neighborhoods
Smart Neighborhood

- An exploration with Southern Company on a possible future encompassing microgrids and customer side controls.
- Develop and demonstrate a neighborhood-level transactive energy and controls research platform to investigate grid integration, scalable distributed control and end-use energy management.
- Co-optimization of cost, comfort, environment, and reliability by controlling grid generation assets and home owner end devices through transactive control.



First-of-its-kind, **transactive** residential microgrid in the Southeast

A planned neighborhood of 62 homes with **energy efficient construction** and **connected home devices** providing an improved customer experience.



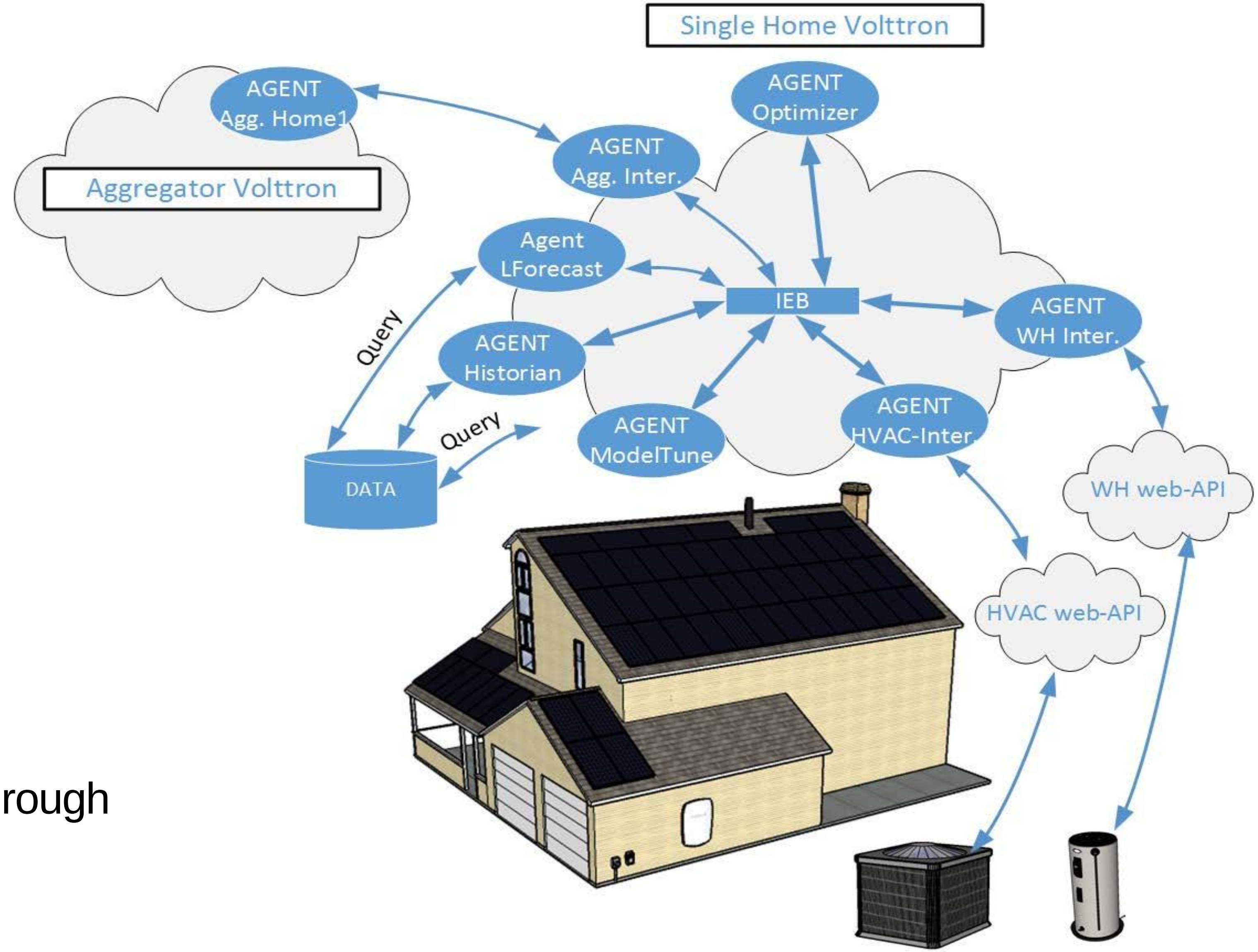
Demonstrate **distributed energy resource (DER)** use cases optimizing cost, reliability, and environmental impact with a **community-scale microgrid.**

Demonstrate **building-to-grid integration** with real time utility to customer interaction.

Agent based approach using VOLTTRON

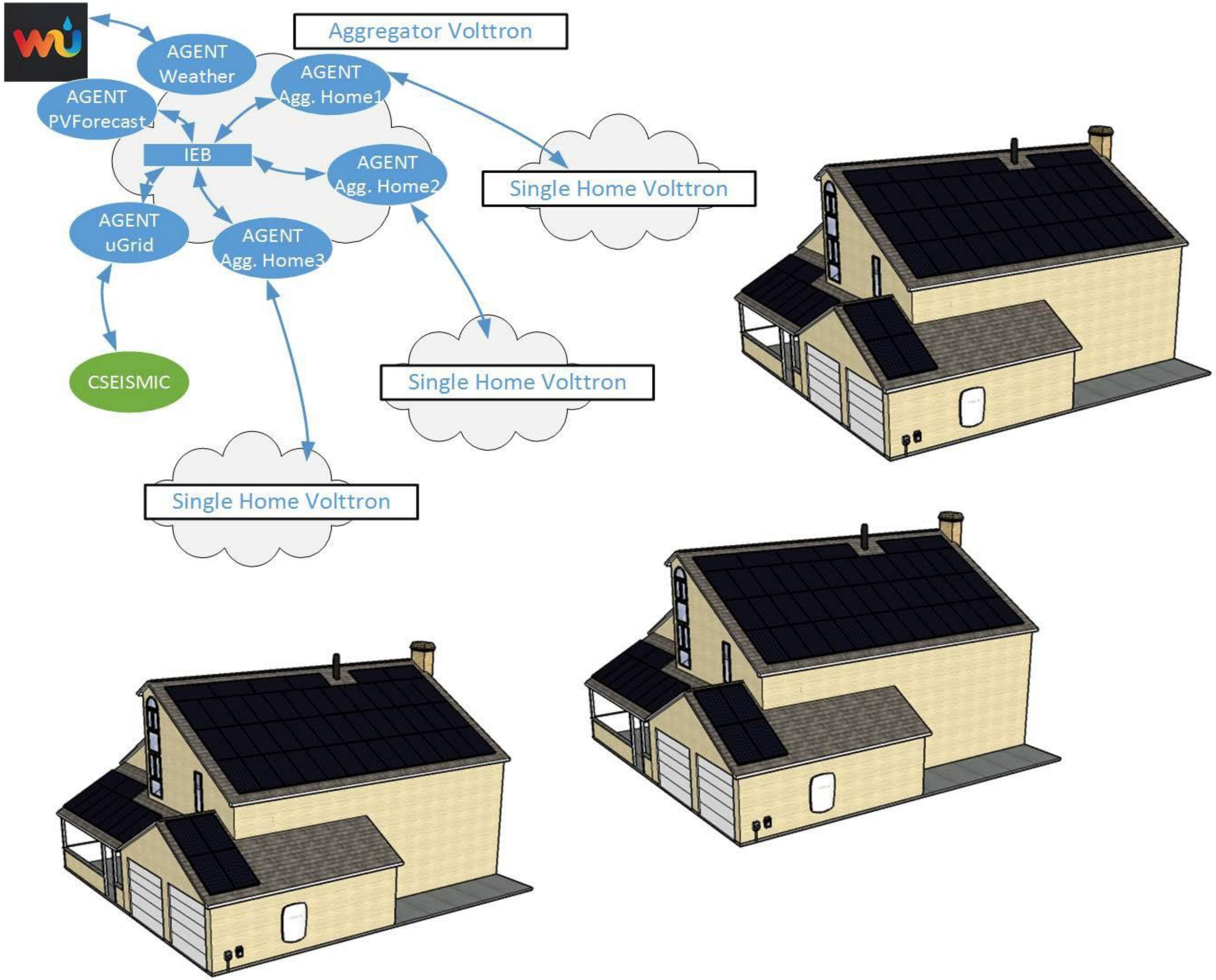
- Each home VOLTTRON™ instance will support a number of different agents:
  - Optimizer
  - HVAC Interface
  - WH Interface
  - Learning Algorithms
  - Historians
  - Forecasting Algorithms

- Interfaces to HVAC and WH are through vendor provided API.



Agent based approach using VOLTTRON

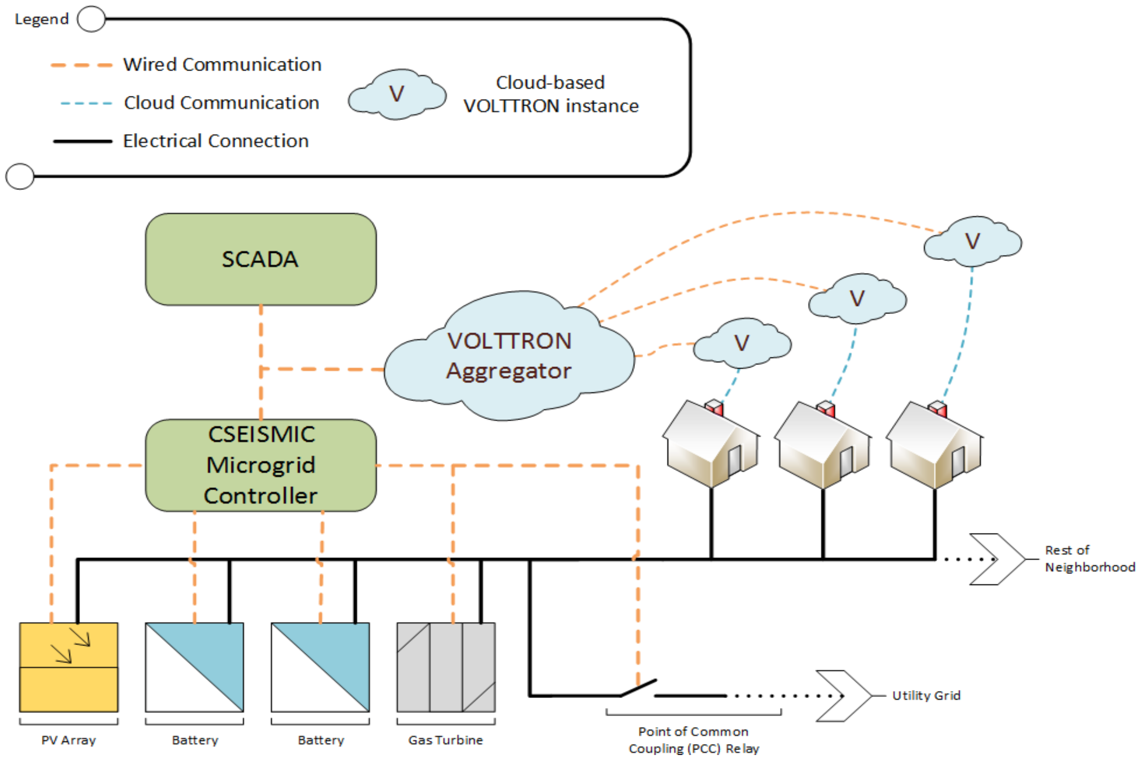
- Each home within the community will have a single VOLTTRON™ instance.
- The communication to Microgrid Controller will go through an aggregation VOLTTRON™ instance that compiles data and transacts with Microgrid.



Transactive Methodology

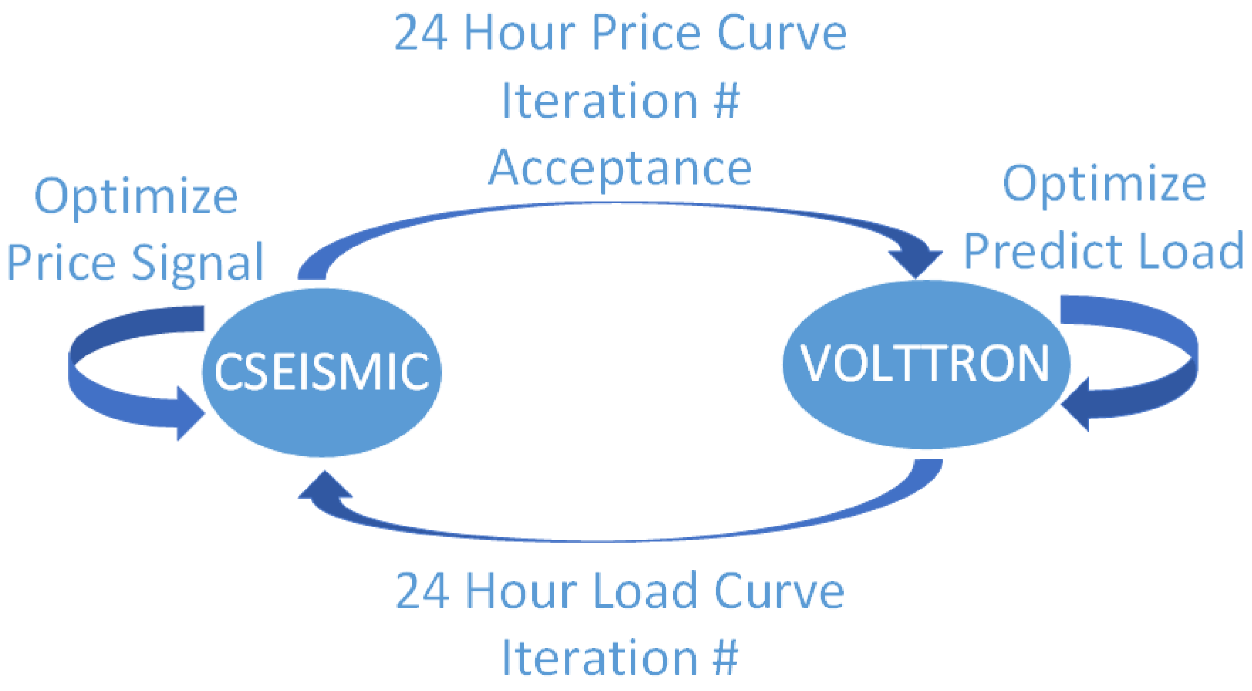
- **Prioritize cost:** The goal of generation management will be to reduce cost to "pool" participants. The goal of demand management is to reduce cost to the individual customers and utility.
  - Based on weather, solar irradiance, and load forecasts coupled with time of use pricing, the neighborhood master controller will optimize battery storage, generation, and "virtual storage" to minimize overall system cost.

- **Prioritize reliability:** The goal is to demonstrate improved reliability for all customers served in the microgrid.
  - Loads would be cycled to provide a level/flat and continuous aggregate load (to help the generator and reduce the battery's PV smoothing requirements).



Transactive Methodology

- Microgrid controller and VOLTTRON ‘negotiate/transact’ a load/price
- Microgrid controller optimizes resources and creates 24 hour pricing offer.
- VOLTTRON allocates price signals to loads which optimize and provide total load projection
- This process iterates until Microgrid controller meets minimum convergence criteria.



Building Energy Models and Tools

ASHRAE Climate Zones

- Based on weather stations, most w/ 18+ yrs of quality data (1961-1990)

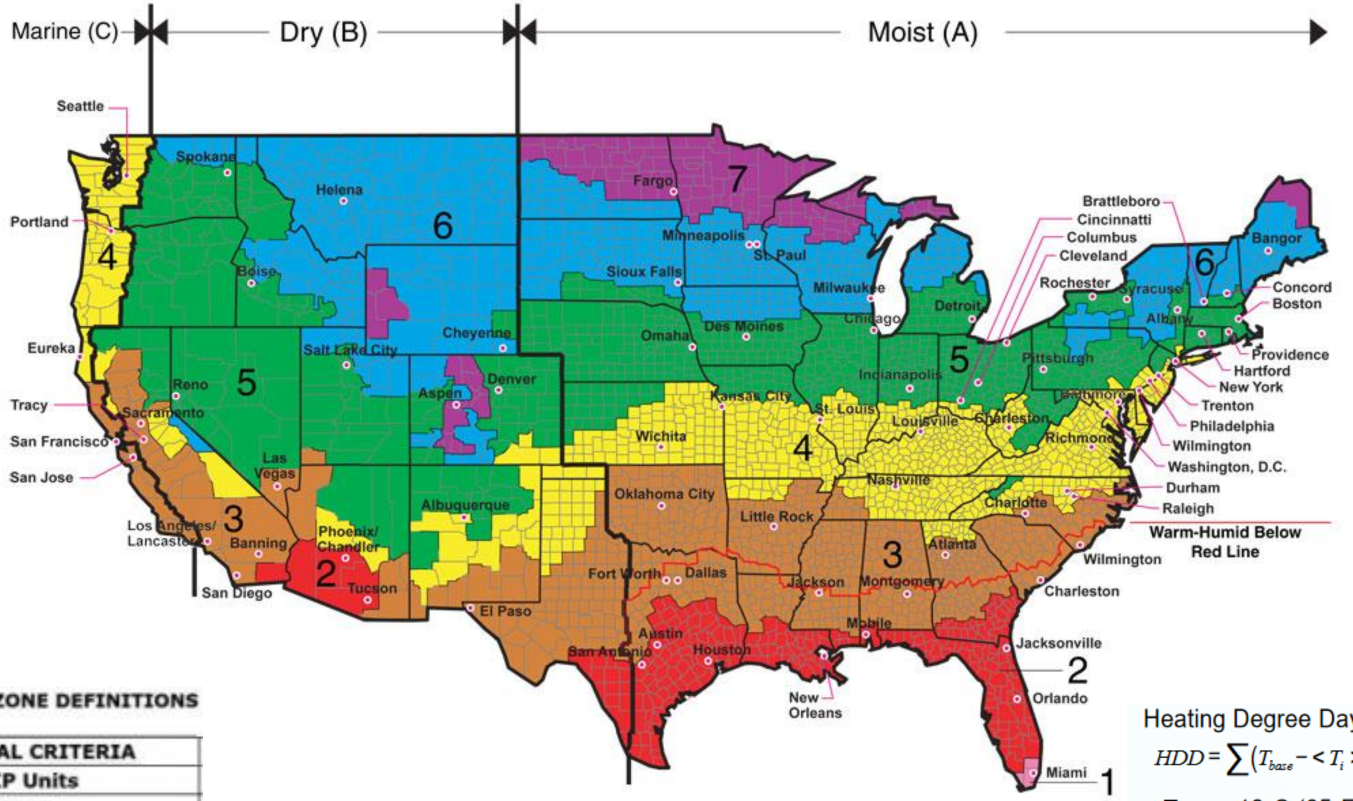


TABLE 301.3(2) INTERNATIONAL CLIMATE ZONE DEFINITIONS

ZONE NUMBER	THERMAL CRITERIA IP Units
1	9000 < CDD50°F
2	6300 < CDD50°F ≤ 9000
3A and 3B	4500 < CDD50°F ≤ 6300 AND HDD65°F ≤ 5400
4A and 4B	CDD50°F ≤ 4500 AND HDD65°F ≤ 5400
3C	HDD65°F ≤ 3600
4C	3600 < HDD65°F ≤ 5400
5	5400 < HDD65°F ≤ 7200
6	7200 < HDD65°F ≤ 9000
7	9000 < HDD65°F ≤ 12600
8	12600 < HDD65°F

Updated every 4 years (2021)

Climate Zone 0 (extremely hot):
10,800 < CDD 50°F
Int'l Energy Conservation Code (IECC) adopts for 2018 code

Heating Degree Days:

$$HDD = \sum (T_{base} - \langle T_i \rangle)^+$$

T_{base} = 18°C (65°F)

Cooling Degree Days:

$$CDD = \sum (\langle T_i \rangle - T_{base})^+$$

T_{base} = 10°C (50°F)

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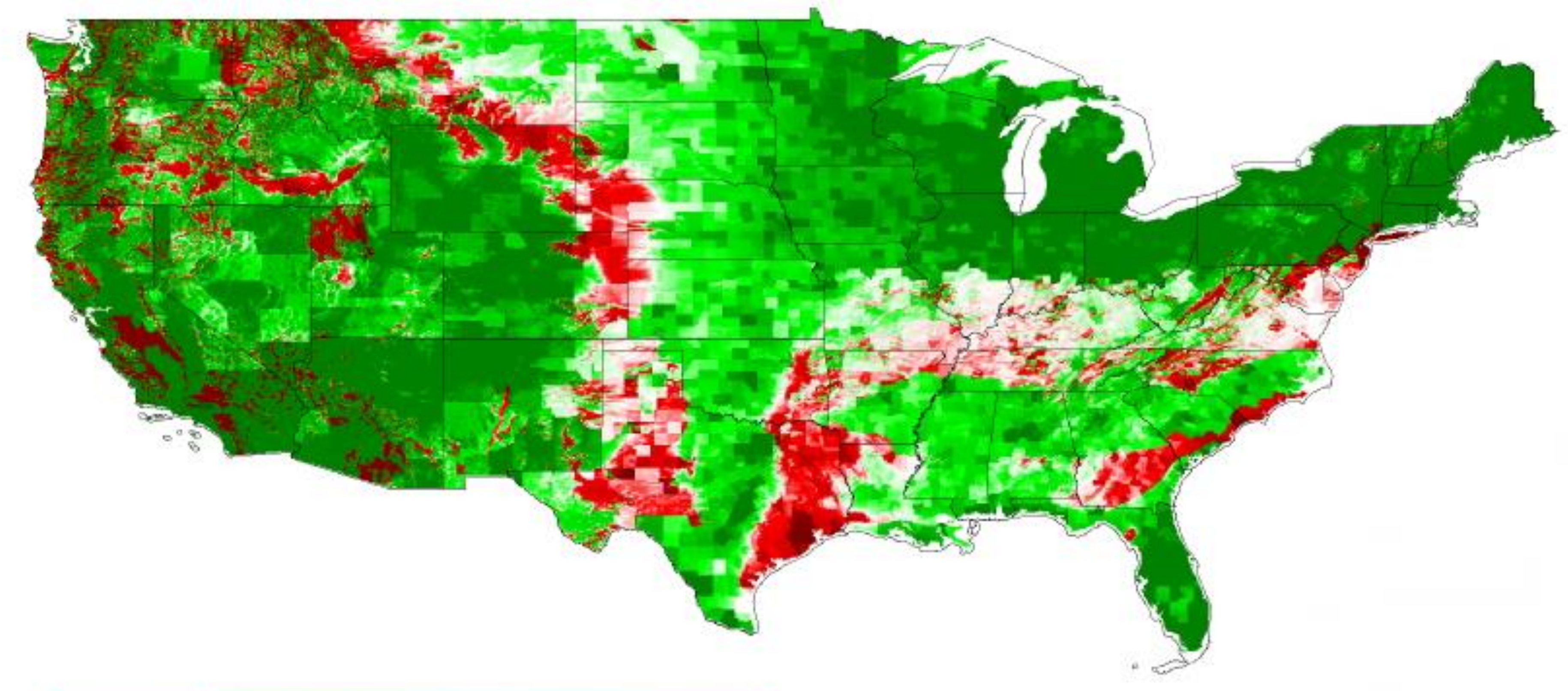
Building-adjusted CZ improvement

- What other (e.g. political) variables should be included?
- How could the nation's energy security and critical infrastructure resiliency be improved by incorporating future scenarios into the built environment?
- **How much energy and $ could be saved by having a forward-looking climate-aware building code?**



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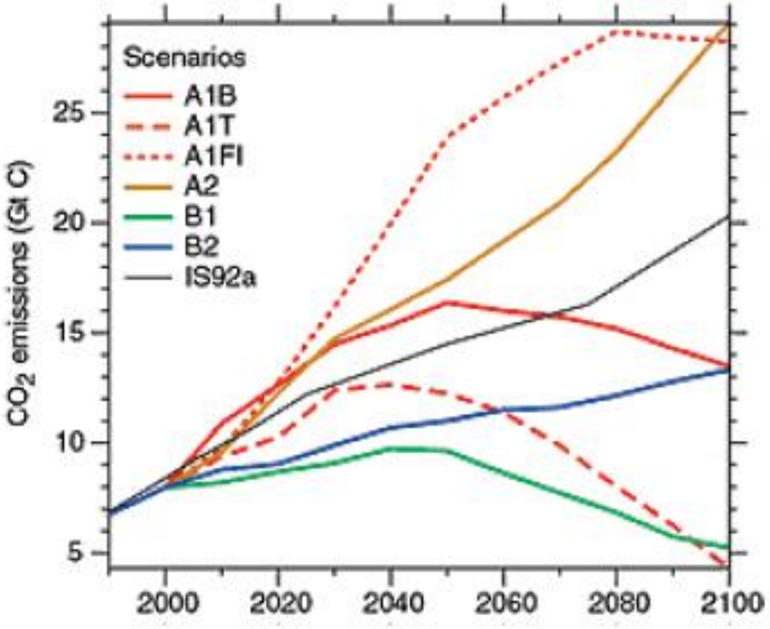
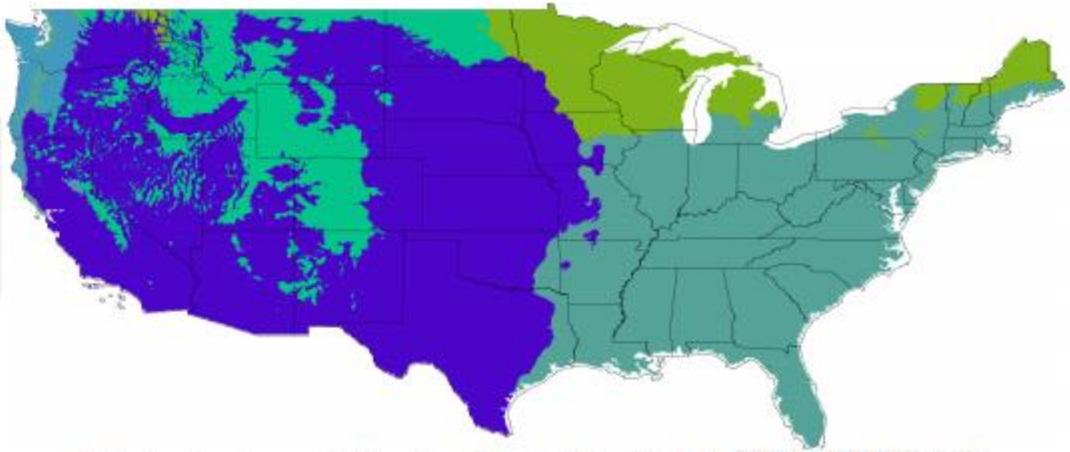
Climate Change Impacts

Contemporary Period

Clustering-based Climate Zones (K=5): HadGCM A1FI 2050





Clustering-based Climate Zones (K=5): HadGCM A1FI 2100

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BTO Modeling Tools

Products: state-of-the-art & industrial strength

- $98 million since 1995
- EnergyPlus engine: established
  - Bentley, Trane TRACE, Autodesk, ASHRAE, CEC
- Spawn-of-EnergyPlus: cyberphysical control
- OpenStudio middleware: market-facing

Ecosystems: for developers & end-users

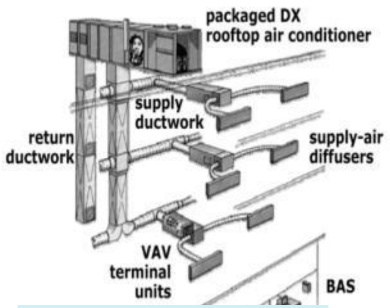
- Partner with companies & professional organizations
- http://unmethours.com

Saves Energy

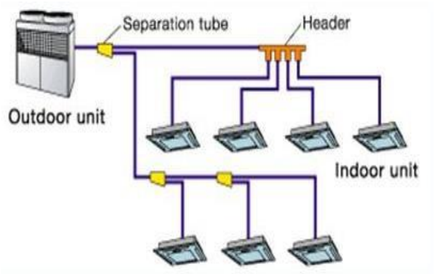
- Individual ECMs (5-20% savings) vs.
  Holistic optimization (30-50% savings)
- 600 TBTU / year by 2030 [BTO p-tool conservative]
- Will track integrative design & simulation use
  via AIA+2030 Commitment
- Prototype development,
  AEDGS, prescriptive guides,
  standards

Measured performance of multiple HVACs

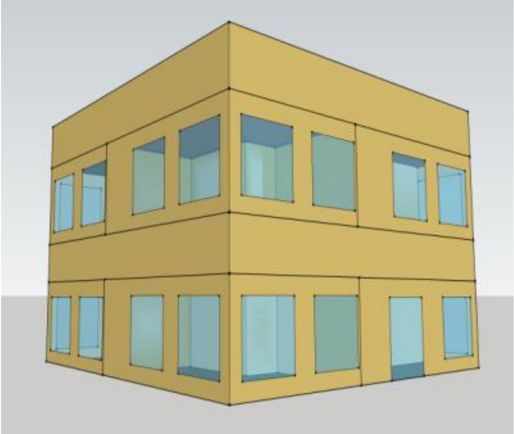
(same building, occupancy, weather)

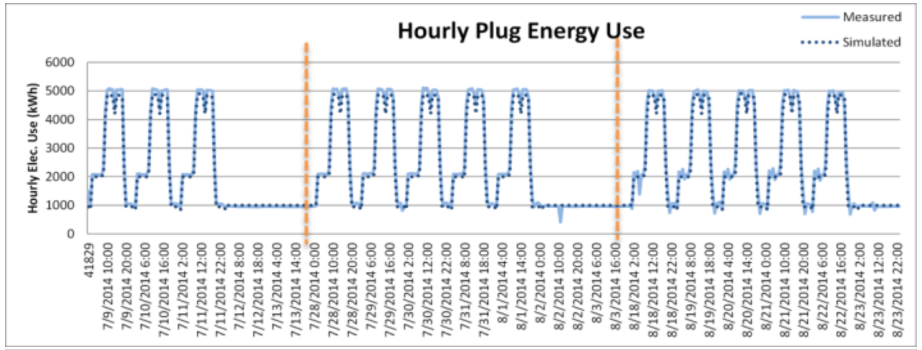


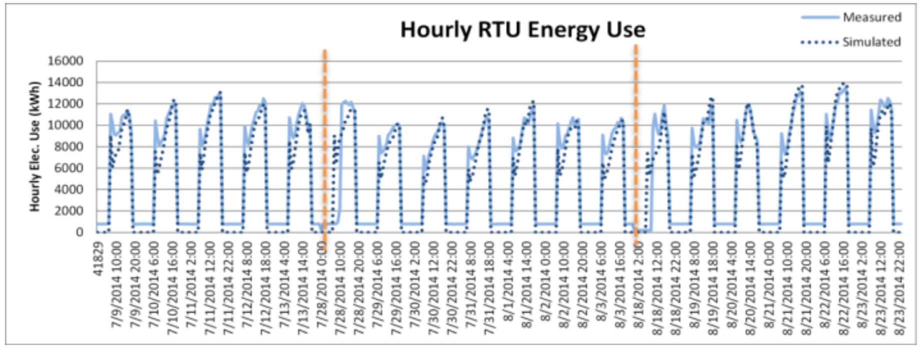
RTU/VAV

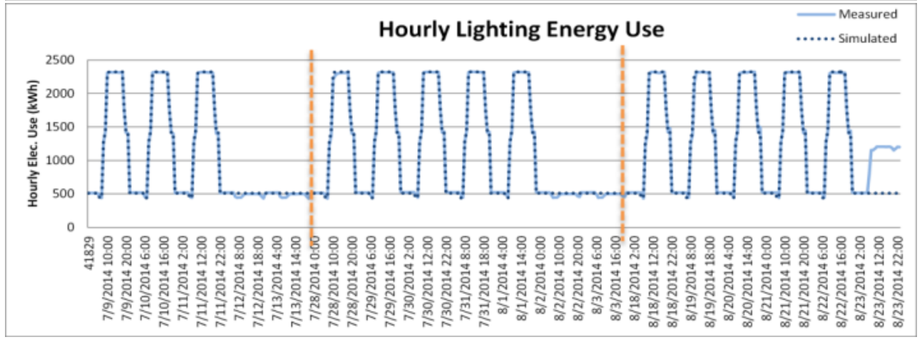


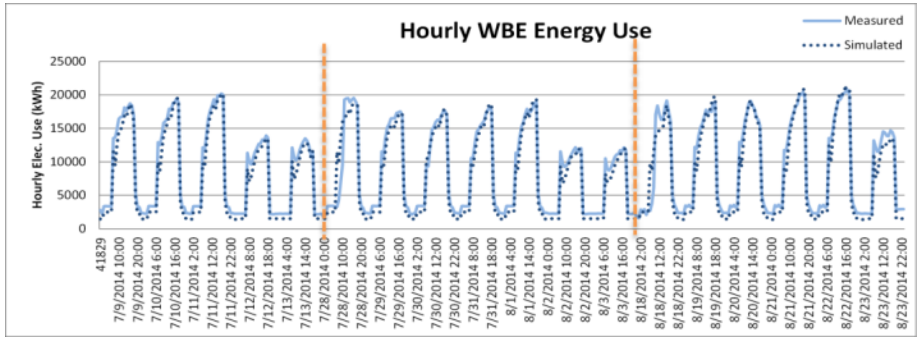
VRF











(~1,000 sensors @ 30-second resolution)

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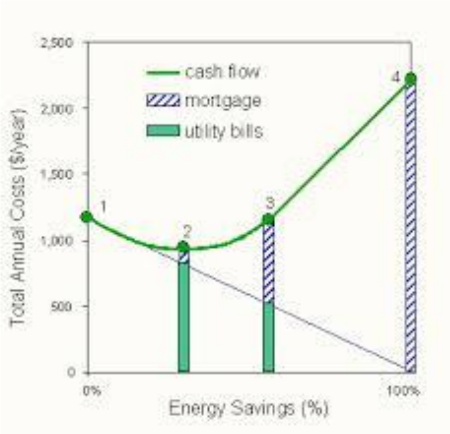
Investment-grade BEM

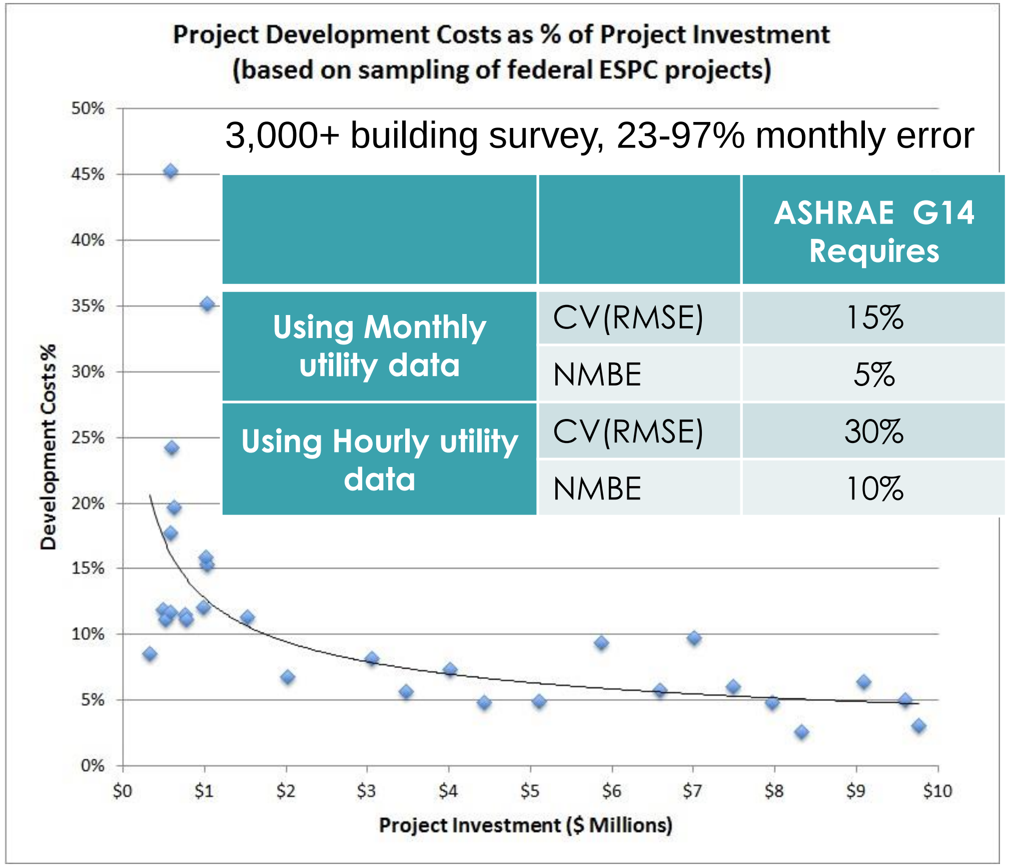
Simulation Engine and Analysis Platform
U.S. Dept. of Energy
$98M, 1995–?

EnergyPlus **OpenStudio**

Free, open-source (GitHub),
free support community (unmethours.com)



Optimal Return on Investment
(for building energy savings)



3,000+ building survey, 23-97% monthly error

		ASHRAE G14 Requires
Using Monthly utility data	CV(RMSE)	15%
	NMBE	5%
Using Hourly utility data	CV(RMSE)	30%
	NMBE	10%

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Autotune Calibration

51

HPC scalability for desktop software

Titan is the world's fastest buildings energy model (BEM) simulator

>500k building simulations in <1 hour

130M US buildings could be simulated in 2 weeks

8M simulations of DOE prototypes (270 TB)

CPU Cores	Wall-clock Time (mm:ss)	Data Size	EnergyPlus Simulations
16	18:14	5 GB	64
32	18:19	11 GB	128
64	18:34	22 GB	256
128	18:22	44 GB	512
256	20:30	88 GB	1,024
512	20:43	176 GB	2,048
1,024	21:03	351 GB	4,096
2,048	21:11	703 GB	8,192
4,096	20:00	1.4 TB	16,384
8,192	26:14	2.8 TB	32,768
16,384	26:11	5.6 TB	65,536
32,768	31:29	11.5 TB	131,072
65,536	44:52	23 TB	262,144
131,072	68:08	45 TB	524,288

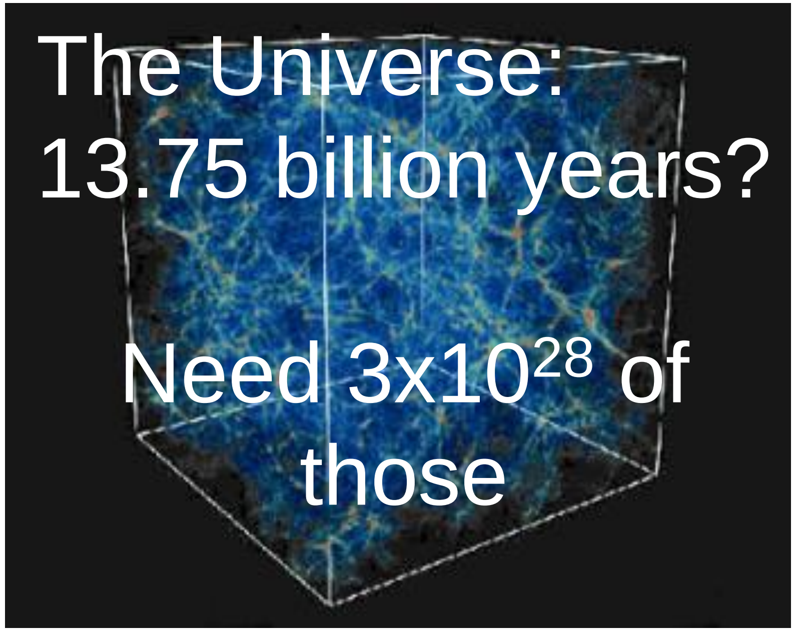
More data than the Hubble Space Telescope amassed in 20 years

Problems/Opportunities:

Thousands of parameters per bldg

We chose to vary 156

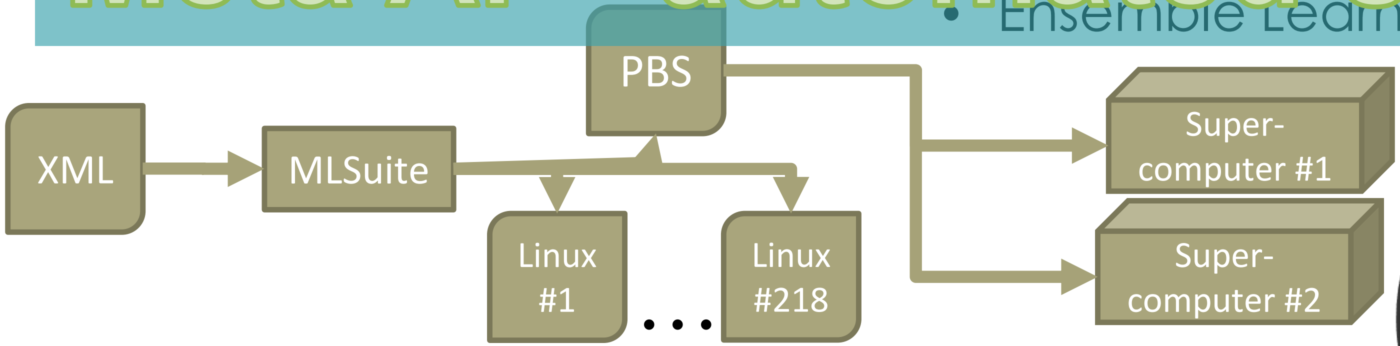
Brute-force = 5×10^{52} simulations



MLSuite: HPC-enabled suite of Artificial Intel.

- Linear Regression
- Feedforward Neural Network
- Support Vector Machine Regression
- Non-Linear Regression
- K-Means with Local Models
- Gaussian Mixture Model with Local Models
- Self-Organizing Map with Local Models
- Regression Tree (using Information Gain)
- Time Modeling with Local Models
- Recurrent Neural Networks
- Genetic Algorithms
- Ensemble Learning

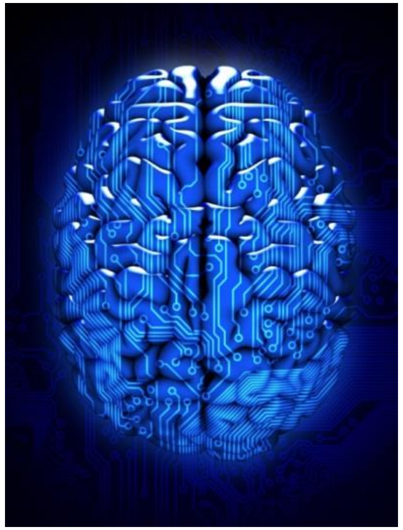
Meta AI – automated science



***Acknowledgment:* Dr. Lynne Parker (Deputy Director of White House's AI Initiative); Dr. Richard Edwards (doctoral student, now Amazon's ad analytics)**

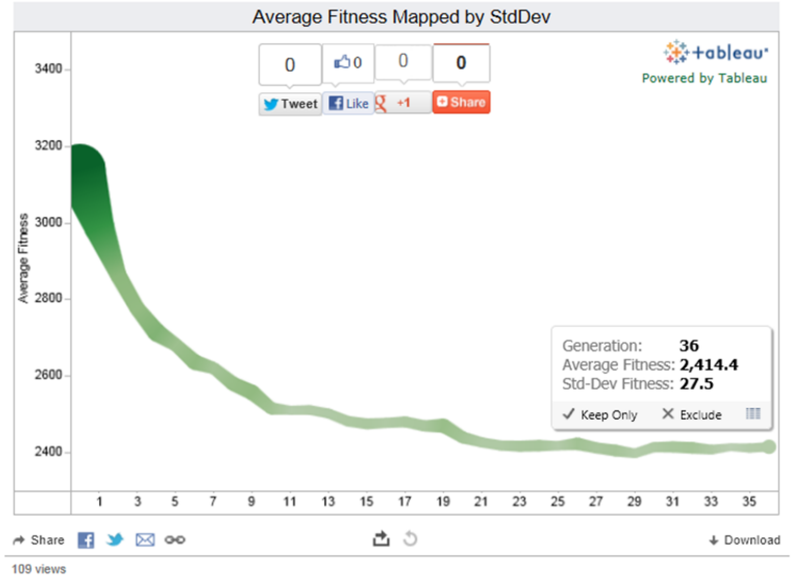
Evolutionary combination

Island Hopping



2 of 19 experiments

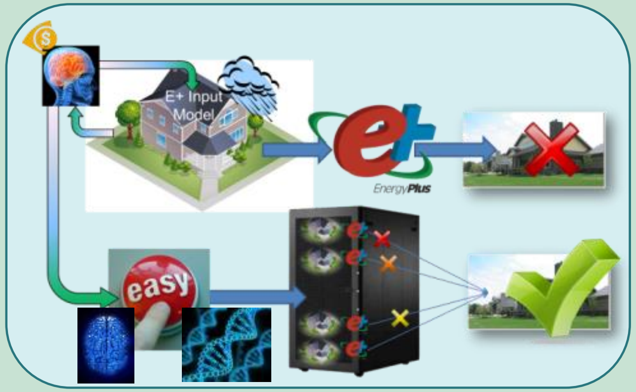
1. Abbreviated Schedule
2. Island-model evolution



Autotune Calibration Results

National HPC Resources → Applied Research → Industry and building owners

High Performance Computing
- Different calibration algorithms
- Machine learning – big data mining
- Large-scale calibration tests



Features
- Calibrate any model to data
- Calibrates to the data you have (monthly utility bills to submetering)
- Runs on a laptop and in the cloud

- 35 Publications: `http://bit.ly/autotune_science`
- Open source (GitHub): `http://bit.ly/autotune_code`

Results

		ASHRAE G14 Requires
Monthly utility data	CVR	15%
	NMBE	5%
Hourly utility data	CVR	30%
	NMBE	10%

Results of 20,000+ Autotune calibrations (15 types, 47-282 tuned inputs each)

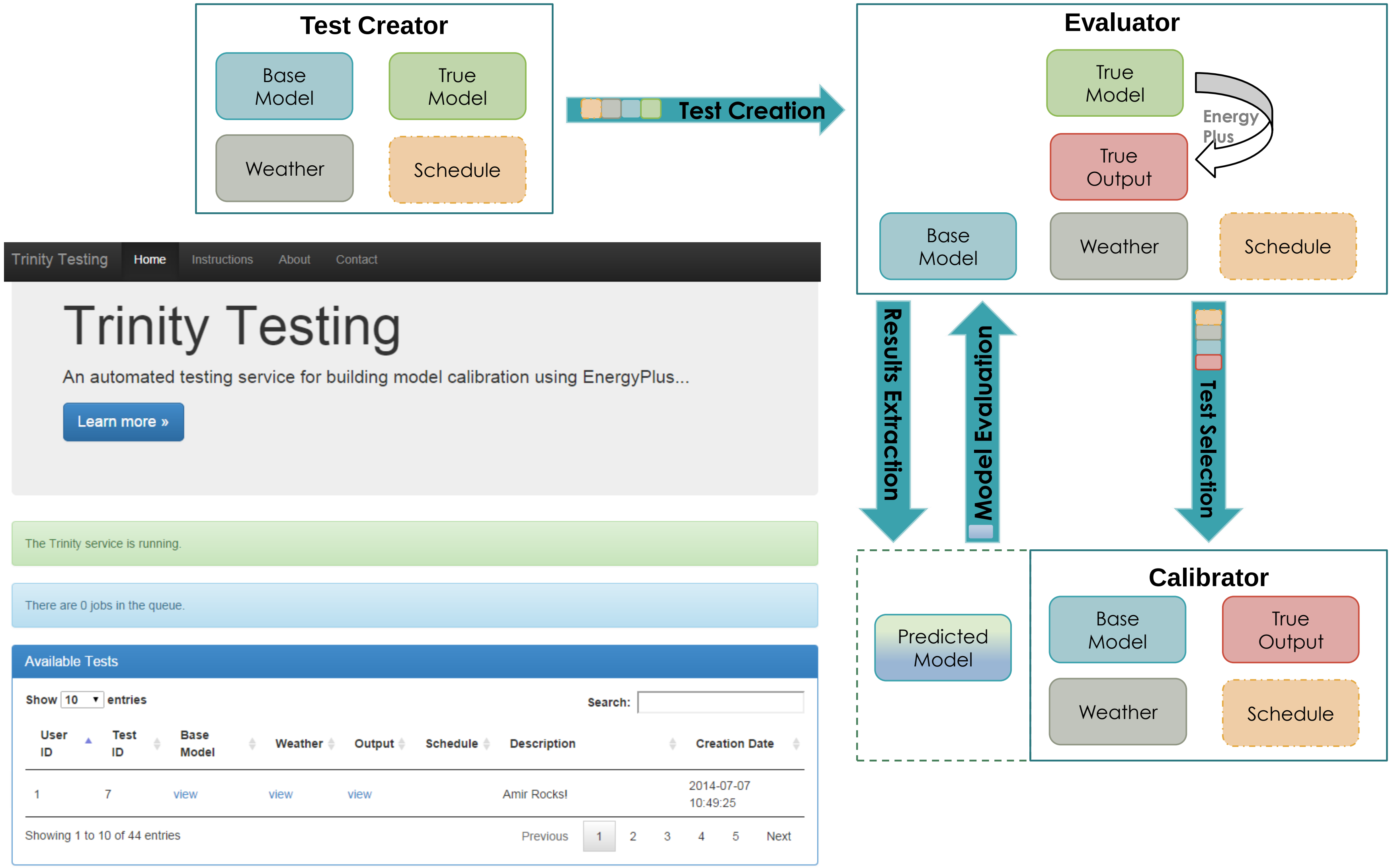
Other error metrics

Residential home	Tuned input avg. error
Within 30¢/day (actual use $4.97/day)	Hourly – 8% Monthly – 15% 3 bldgs, 8-79 inputs

Leveraging HPC resources to calibrate models for optimized building efficiency decisions

Calibration – input-side error

ANSI/RESNET Standard 1201-2016 “Standard Method of Test for the Evaluation of Building Energy Analysis Model Calibration Methods”



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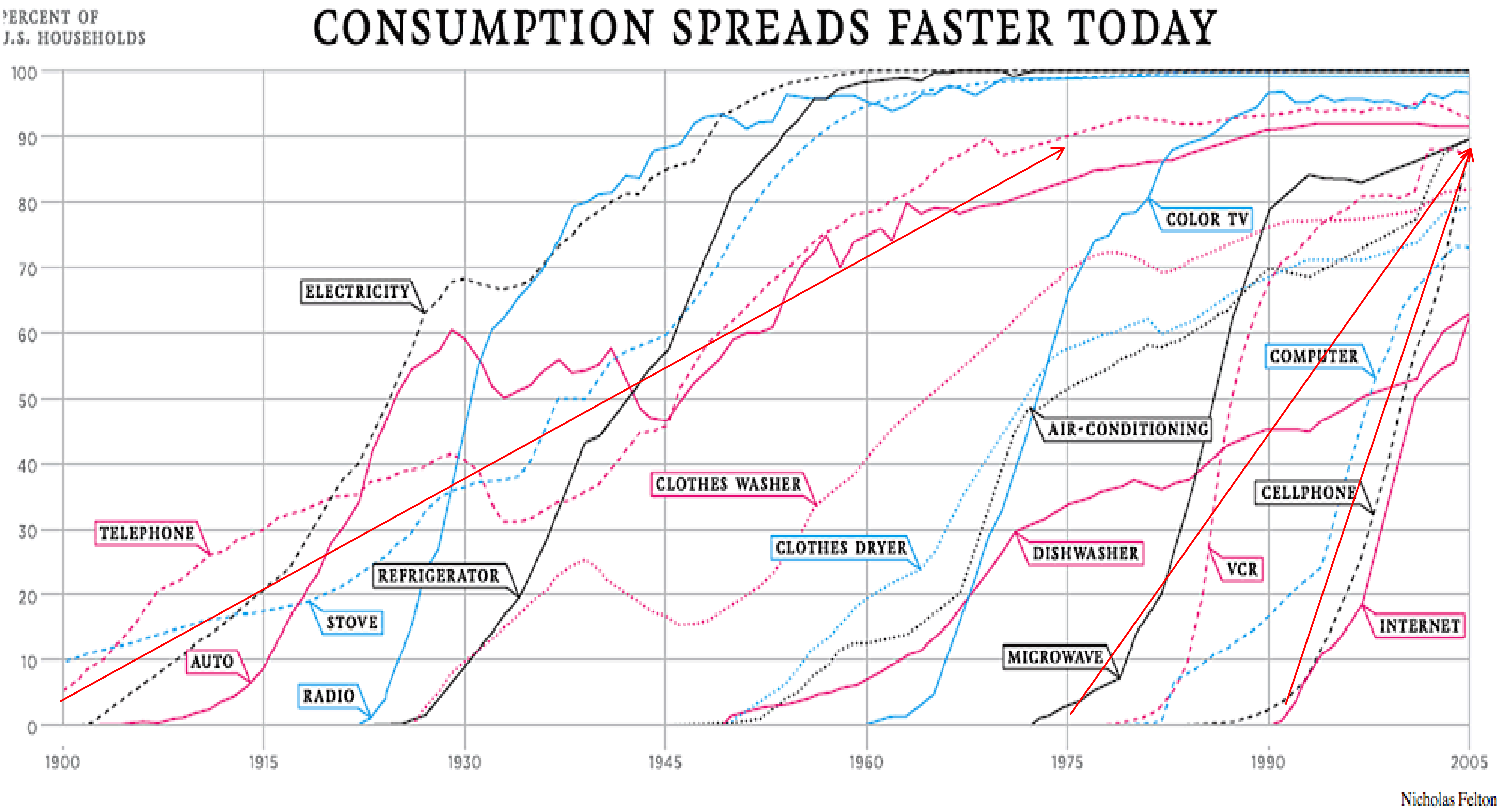
Technology Adoption Rates Accelerate

Strategic Research



Strategic Research

Wireless Broadband IoT Age Is Upon Us

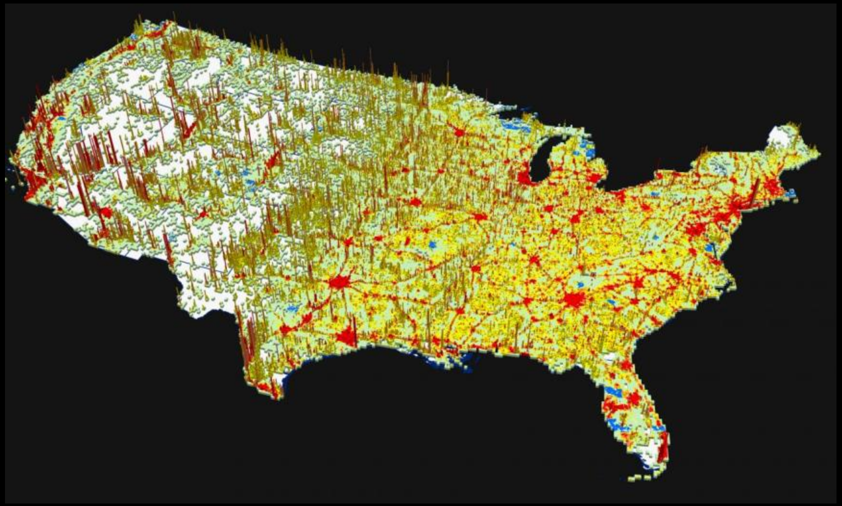
Papal Conclave 2005

Strategic Research

Wireless Broadband IoT Age Is Upon Us

Papal Conclave 2013

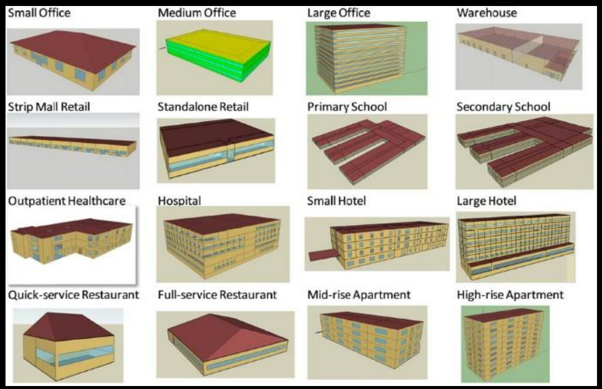
Model America 2020 – BEM for every U.S. Building



Goal: Stimulate private sector activity and academic research for a sustainable built environment

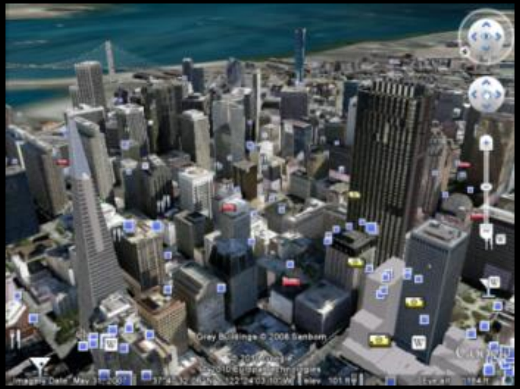
1. Extract important inputs from available data

2. Create initial building energy model(s)



DOE Prototype Buildings

3. Make models available online

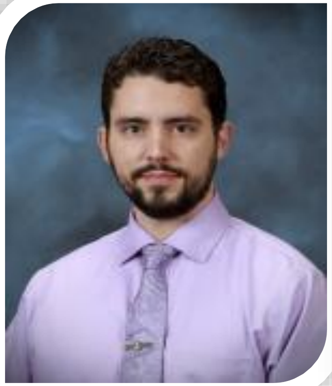


Download BEM via street address

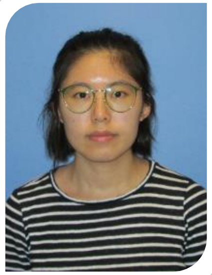
IGA
- Walkthrough Audit
- Calibration to measured data

Acknowledgements

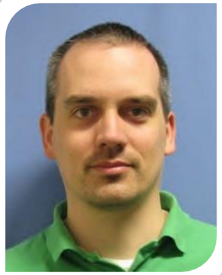
- U.S. Department of Energy
- National Nuclear Security Administration
- Oak Ridge National Laboratory
- Building Technologies Office
- Office of Electricity



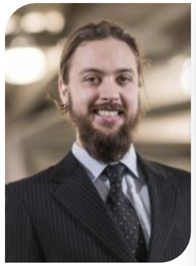
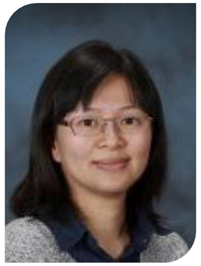
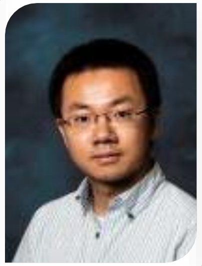






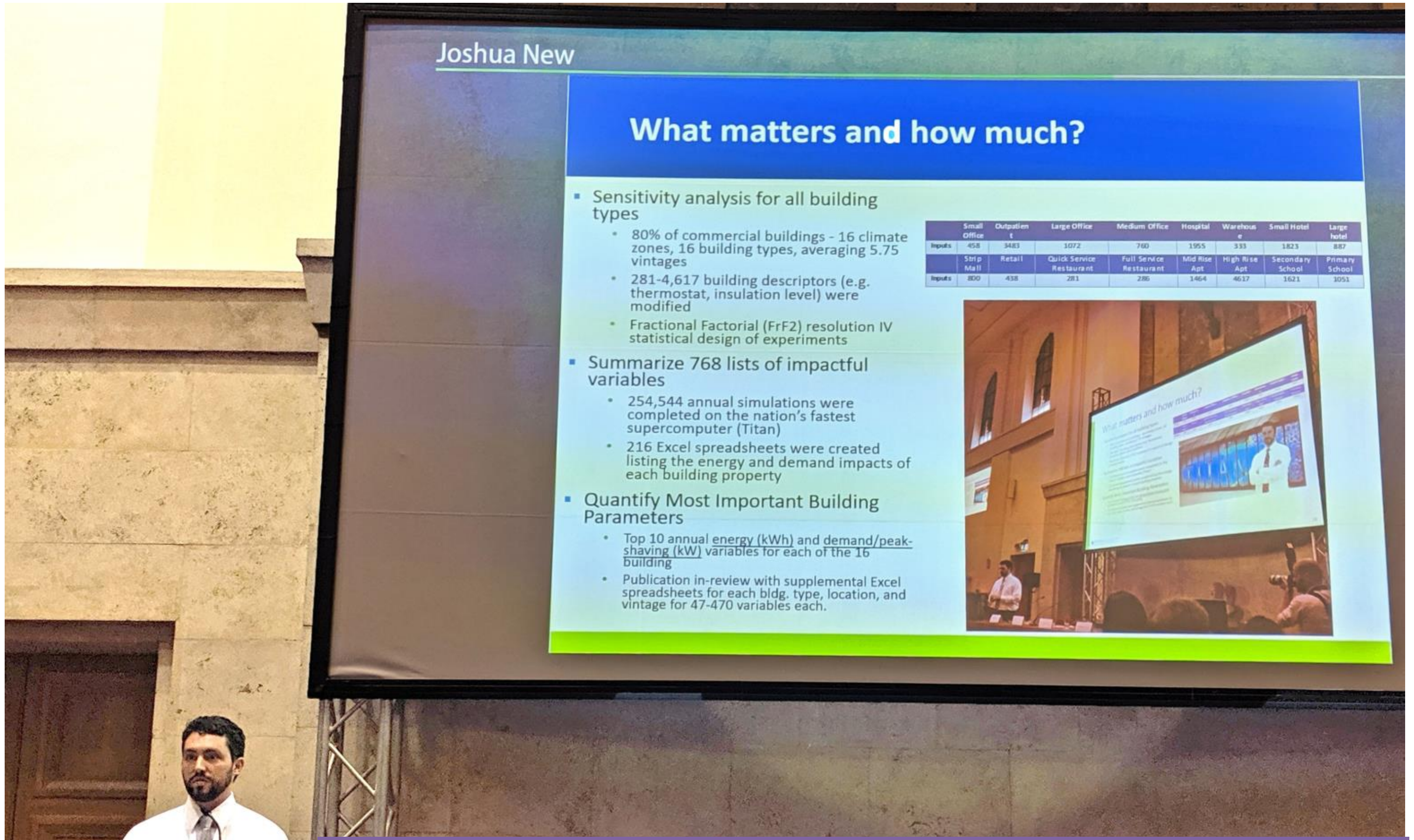




What matters and how much?

- Sensitivity analysis for all building types
  - 80% of commercial buildings - 16 climate zones, 16 building types, averaging 5.75 vintages
  - 281-4,617 building descriptors (e.g. thermostat, insulation level) were modified
  - Fractional Factorial (FrF2) resolution IV statistical design of experiments
- Summarize 768 lists of impactful variables
  - 254,544 annual simulations were completed on the nation's fastest supercomputer (Titan)
  - 216 Excel spreadsheets were created listing the energy and demand impacts of each building property
- Quantify Most Important Building Parameters
  - Top 10 annual energy (kWh) and demand/peak-shaving (kW) variables for each of the 16 building
  - Publication in-review with supplemental Excel spreadsheets for each bldg. type, location, and vintage for 47-470 variables each.



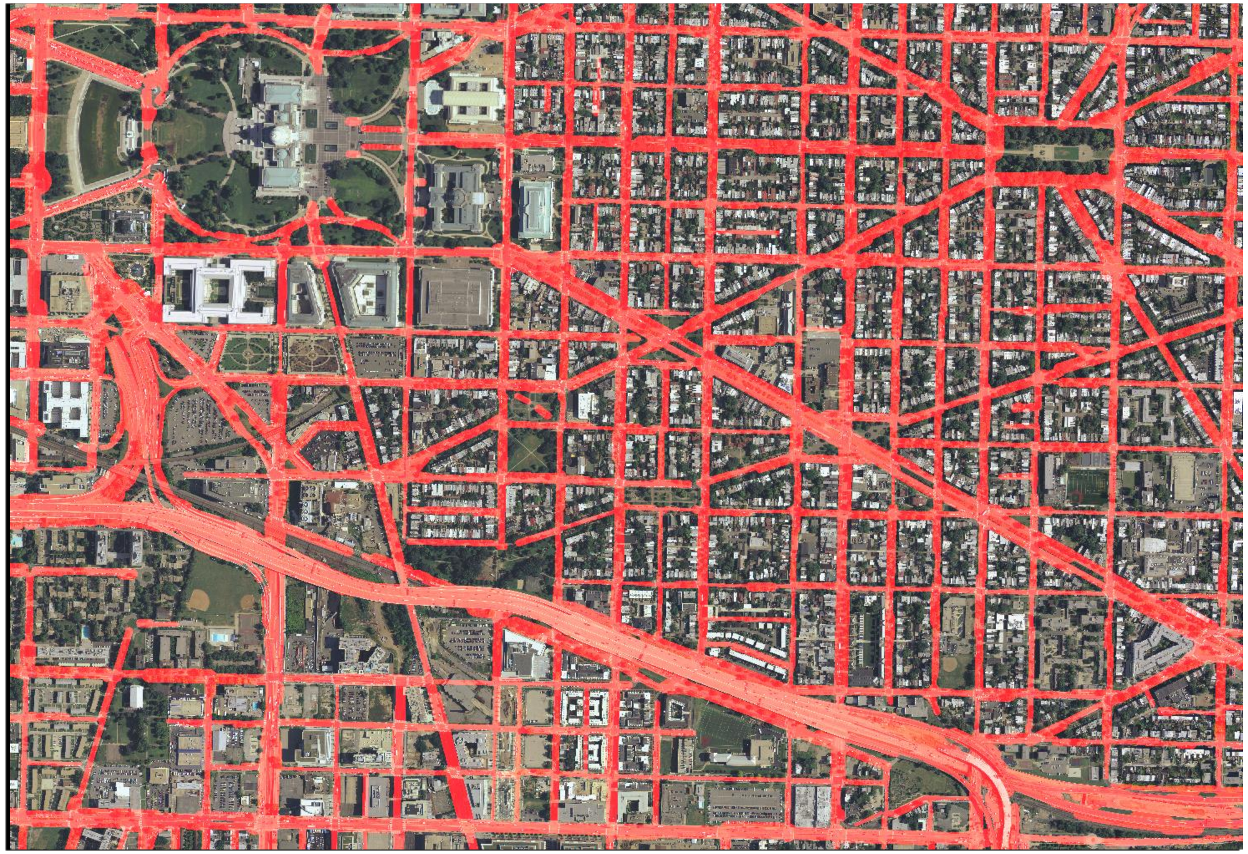
	Small Office	Outpatient	Large Office	Medium Office	Hospital	Warehouse	Small Hotel	Large hotel
Inputs	458	3483	1072	760	1955	333	1823	887
	Strip Mall	Retail	Quick Service Restaurant	Full Service Restaurant	Mid Rise Apt	High Rise Apt	Secondary School	Primary School
Inputs	800	438	281	286	1464	4617	1621	1051

Data Sources

- Database and image sources for urban model generation
  - Satellite and airborne imagery
  - Cartographic data
  - Ground level images
  - Elevation data
  - Building information databases
  - 3D building model databases

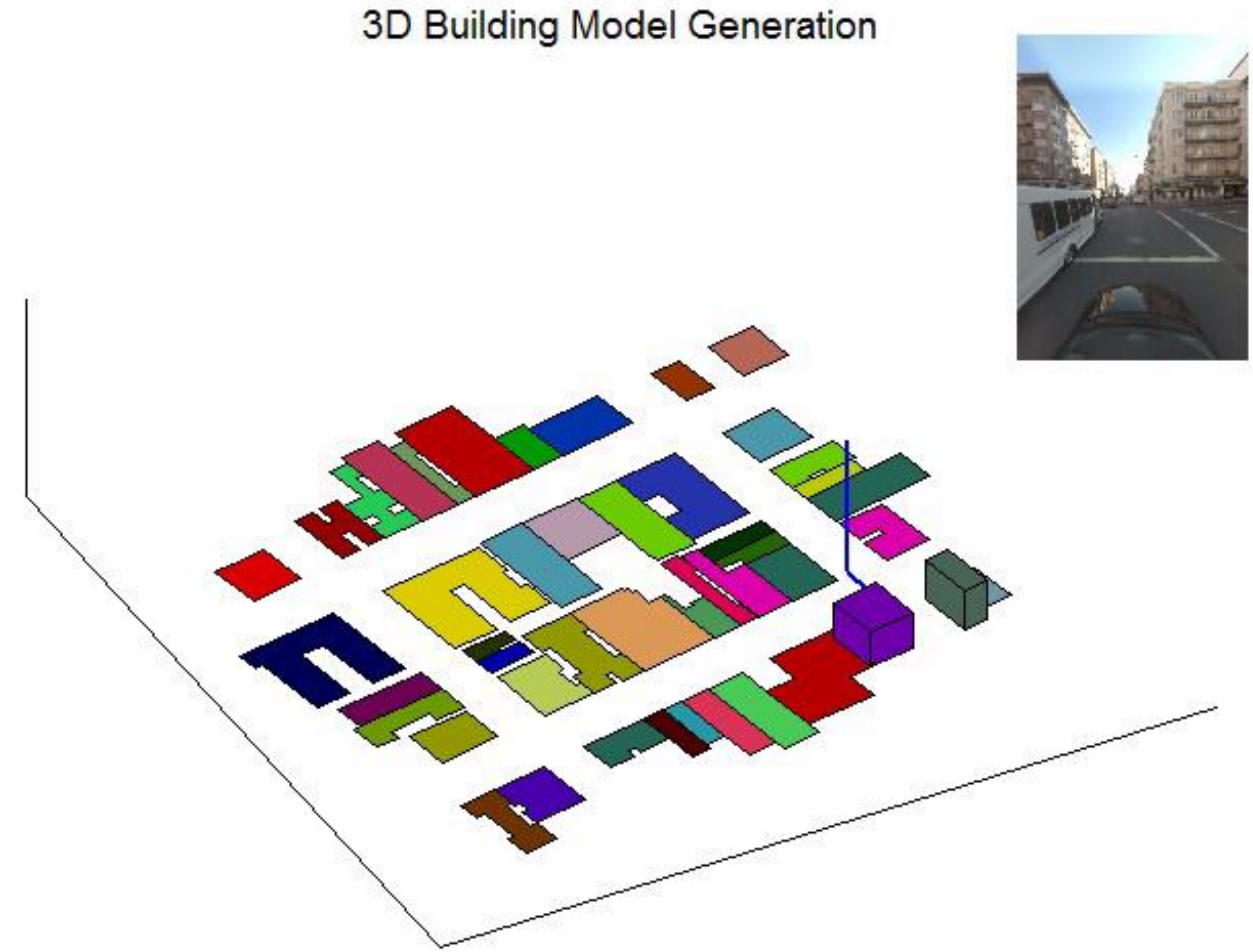
	Short Title
Summary	Satellite imagery, including panchromatic and multispectral images
Data type	Image
Company	
Website	
Temporal resolution	Cities - 3-11 times per week
Spatial resolution	0.3 m
Measure accuracy	
Cost	\$11 per sq. km
Format	GeoTiff
Mapping to building input variables	Building footprints
Mapping to area properties	Vegetated areas, road surface, buildings, parking lots
Mapping to material properties	Road pavement materials (e.g., concrete, asphalt), parking lots (e.g., gravel, soil)
Coverage of US	Over 10 million km^2 of coverage of the contiguous US
Orientation	Aerial
Existing internal software	N/A
Existing expertise	Remote sensing data analysis tool
Restrictions	N/A
Comments	

Building Footprints from Satellite Imagery

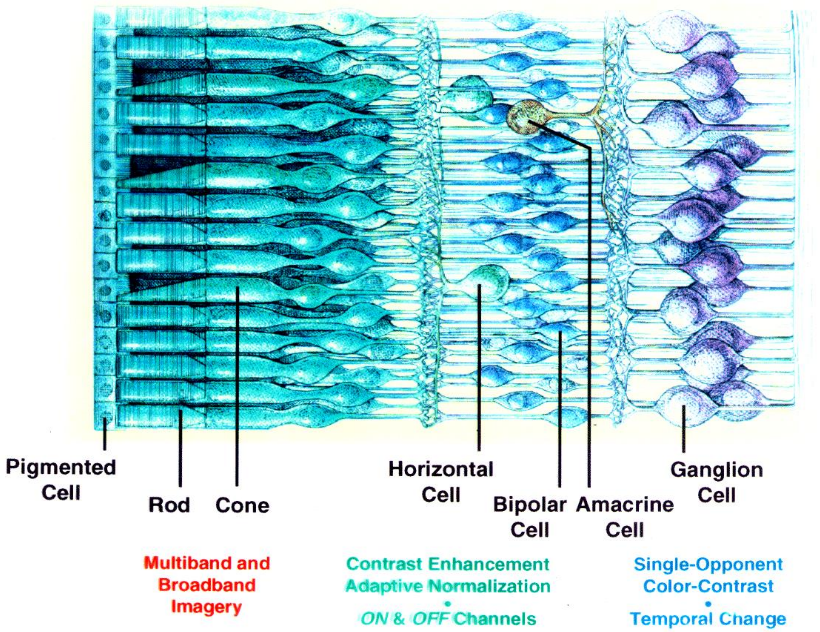


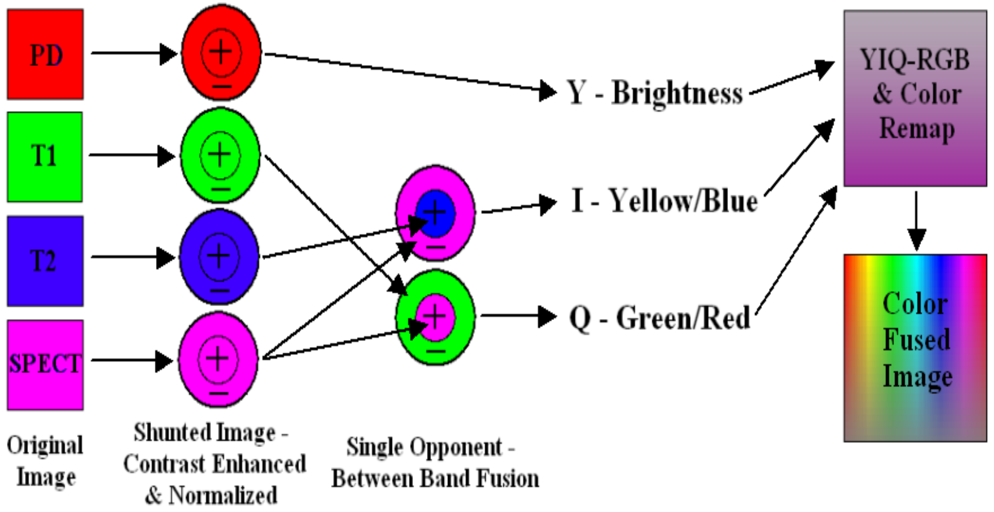
Open Competition Precision/Recall – 30/35
ORNL Current Precision/Recall – 60+/60+

Processing Street-Level Imagery (Jiangye Yuan)



Neurophysiologically-based imaged fusion





$$x'_{ij} = -Ax_{ij} + (B - x_{ij})[CI^c]_{ij} - (D + x_{ij})[G_s * I^S]_{ij}$$

Where:
A – decay rate
B – maximum activation level (set to 1)
D – minimum activation level (set to 1)
I^C – excitatory input
I^S – lateral inhibitory input
C and G_s are as follows:

$$G_{(x,y)} = \frac{1}{2\pi\sigma^2} e^{-\frac{(x^2+y^2)}{2\sigma^2}}$$

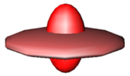
2D Shunt Operator Symbol

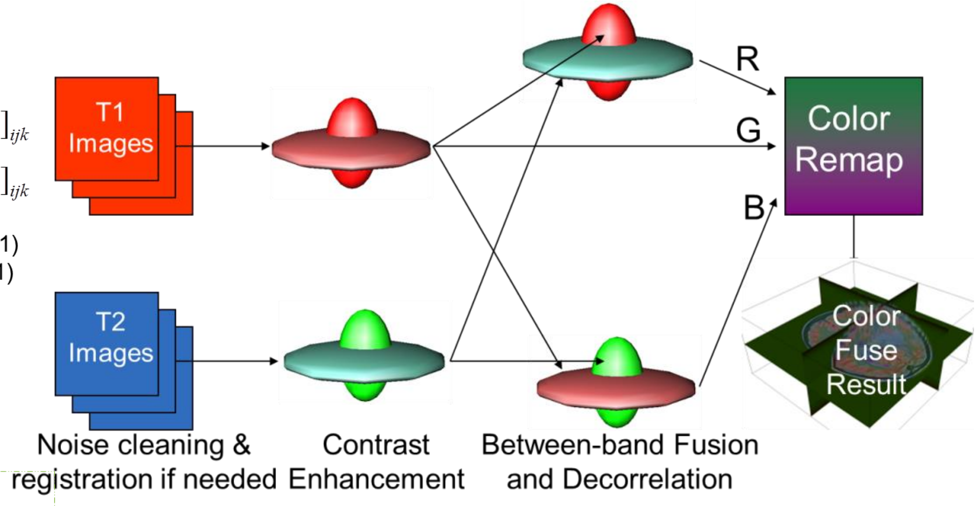
$$x'_{ijk} = -Ax_{ijk} + (B - x_{ijk})C[G_c * I^c]_{ijk} - (D + x_{ijk})[G_s * I^S]_{ijk}$$

Where:
A – decay rate
B – maximum activation level (set to 1)
D – minimum activation level (set to 1)
I^C – excitatory input
I^S – lateral inhibitory input
C, G_c and G_s are as follows:

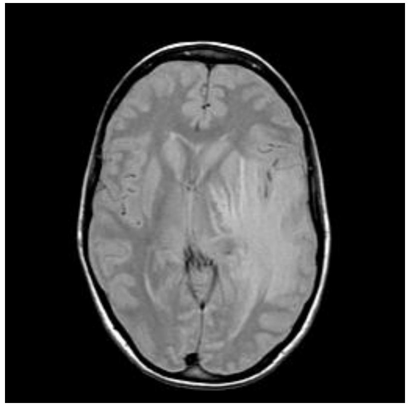
$$G_{(x,y,z)} = \frac{1}{4\pi^2\sigma^3} e^{-\frac{(x^2+y^2+z^2)}{2\sigma^2}}$$

3D Shunt Operator Symbol

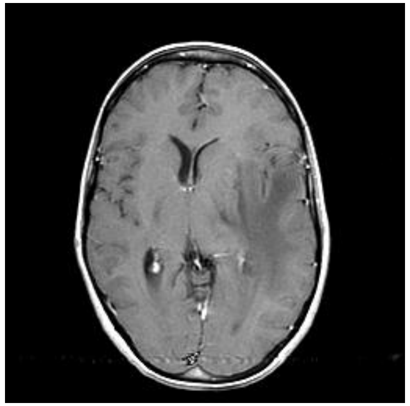




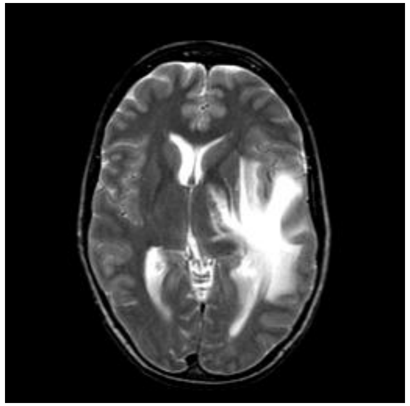
Field-deployed color night vision, armored tank detect



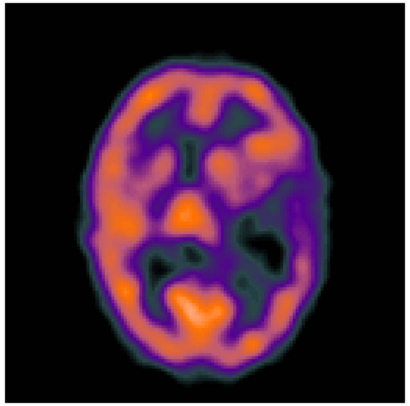
PD



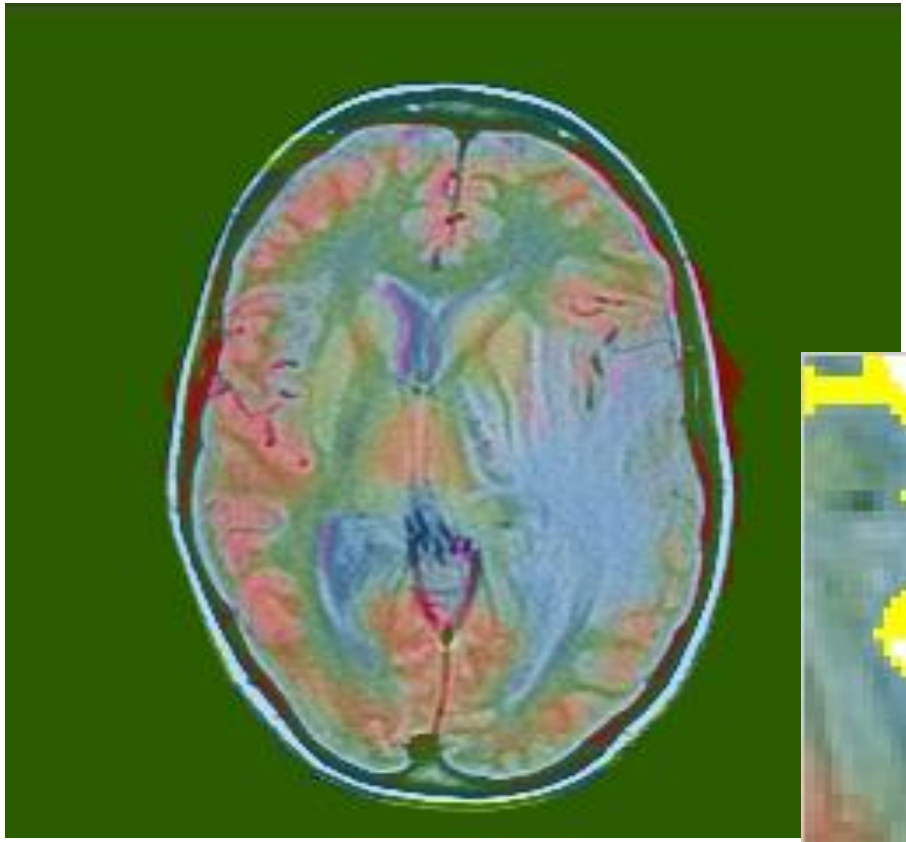
GAD



T2



SPECT



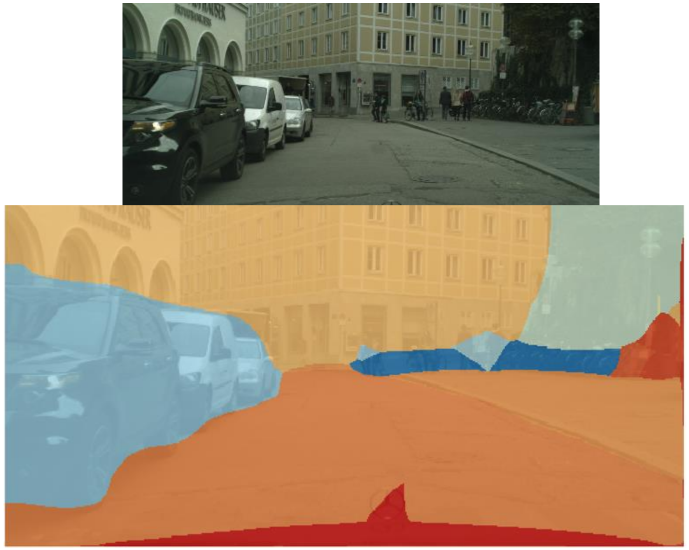
Color Fuse Result

Segmentation

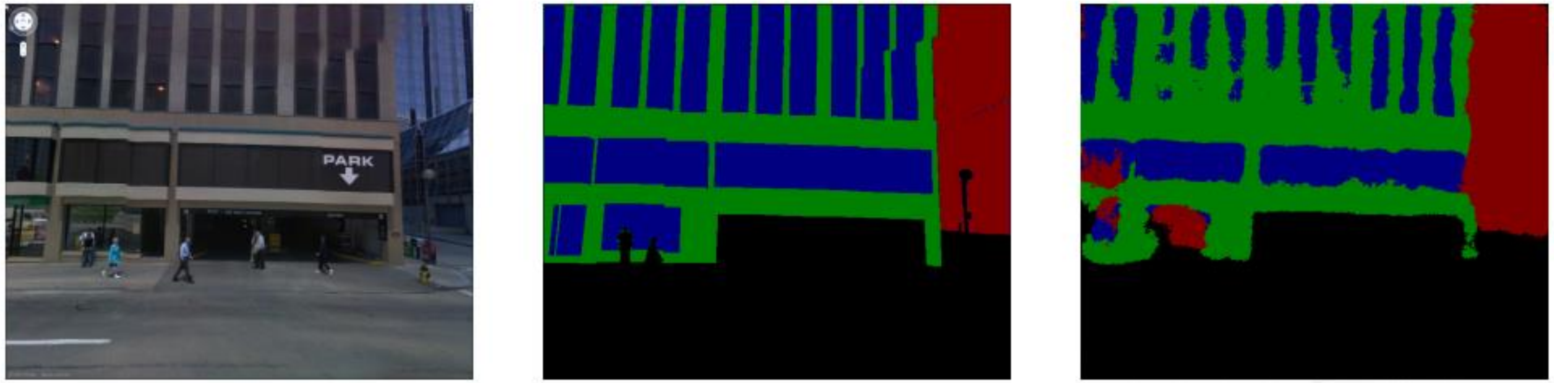
Oak Ridge National Laboratory

Street-level imagery (Lexie Yang)

Façade Type



Windows (blue)
Façade (green)
Street/open (black)
Other building (red)



Window-to-wall ratio

Input image Ground truth Model output

Platform capabilities – imagery updates

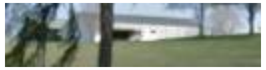
- StreetView processing for high-resolution details of Window-to-wall ratio and HVAC detection not currently feasible without higher-resolution data (aerial instead of highest-resolution satellite)

Window-to-Wall Ratio

2 views of the same

view_01_00	
Facade pixels:	54073
Window pixels:	21120
Ratio:	0.28087721
view_01_01	
Facade pixels:	63356
Window pixels:	27212
Ratio:	0.30045932

Worst cases



Building Footprints

Satellite-derived building footprints are irregular often must be simplified for modeling.

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Platform capabilities – imagery and population updates, challenges

Building Footprints

LiDAR acquisition date can lead to discrepancies

HVAC Detection

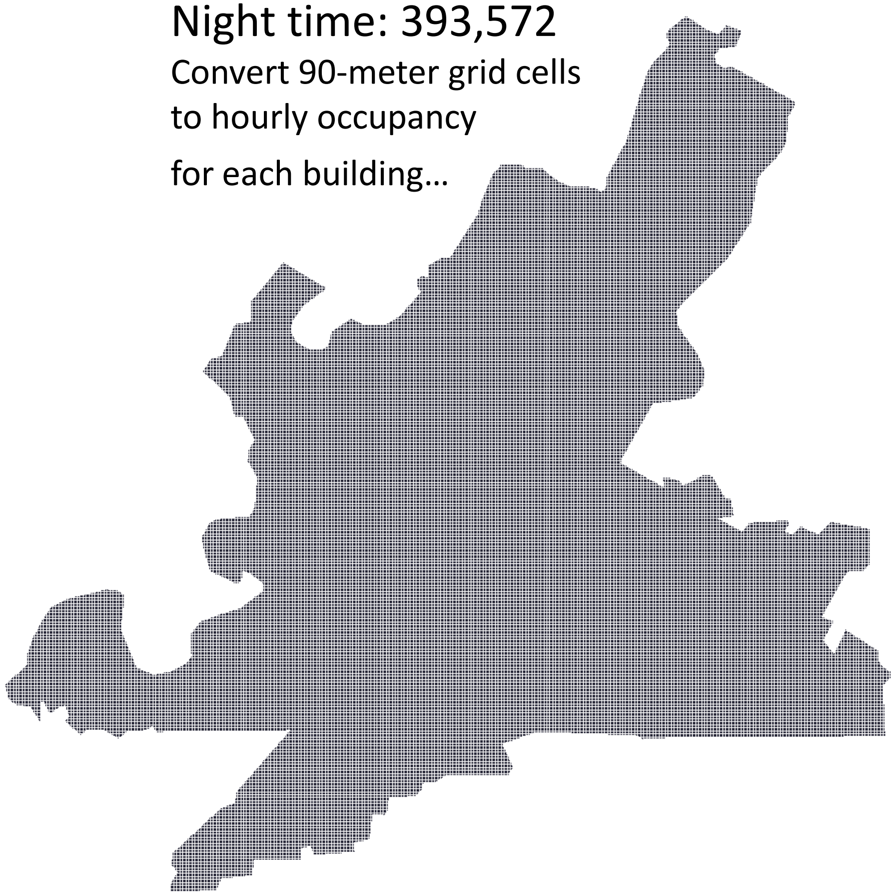
Aerial HVAC classification requires higher-resolution imagery (~10cm/pixel)

Population in Utility's Area

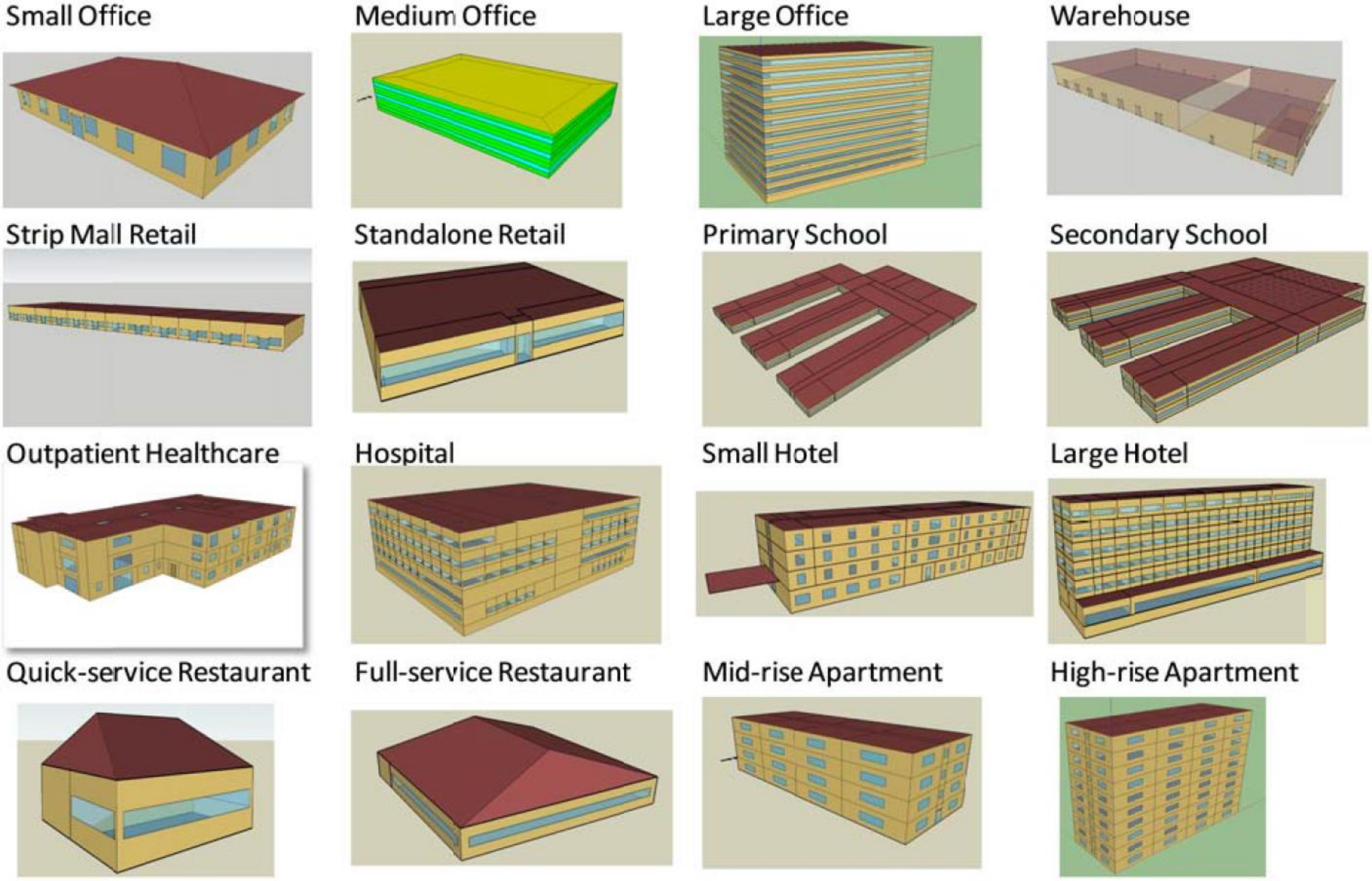
Day time: 434,725

Night time: 393,572

Convert 90-meter grid cells to hourly occupancy for each building…



Prototype Buildings



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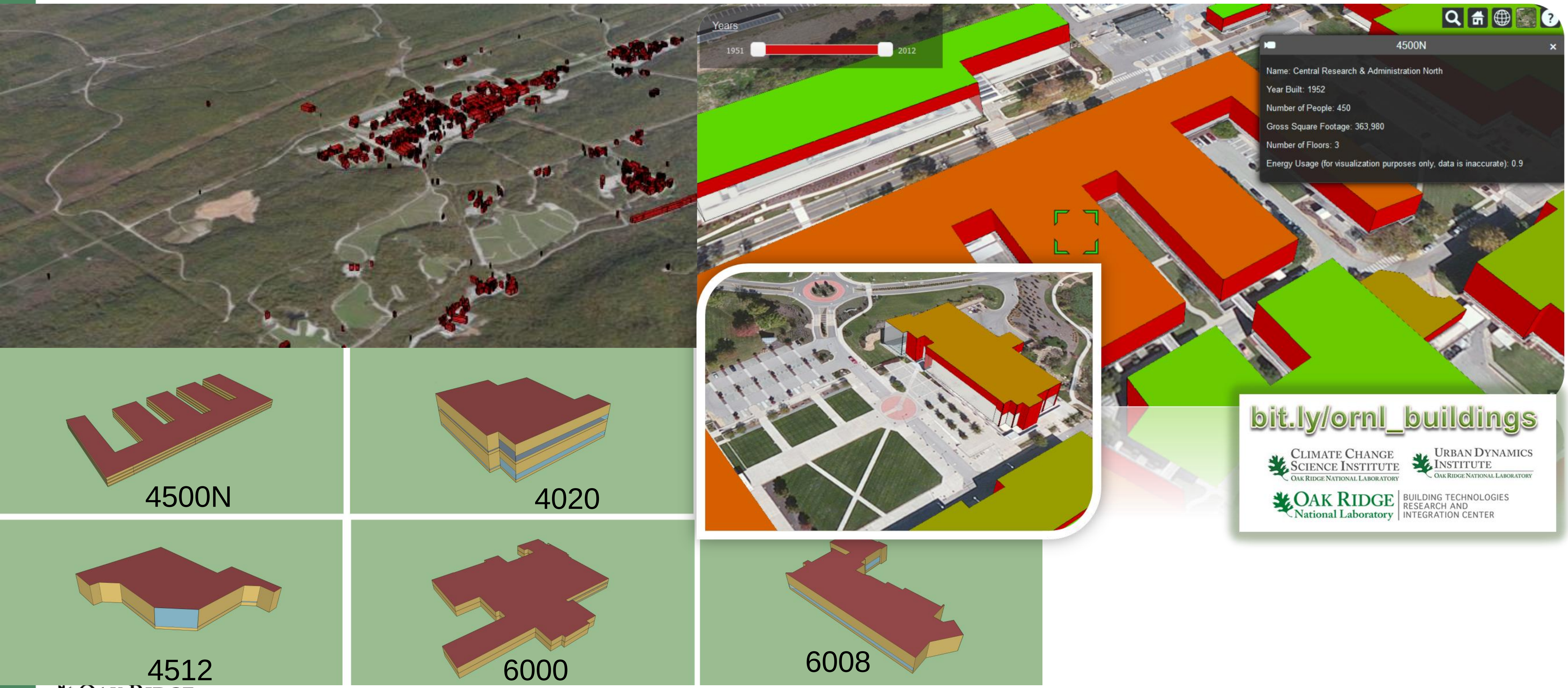

The University of Tennessee (2 days)

bit.ly/ut_buildings

CLIMATE CHANGE SCIENCE INSTITUTE
OAK RIDGE NATIONAL LABORATORY

URBAN DYNAMICS INSTITUTE
OAK RIDGE NATIONAL LABORATORY

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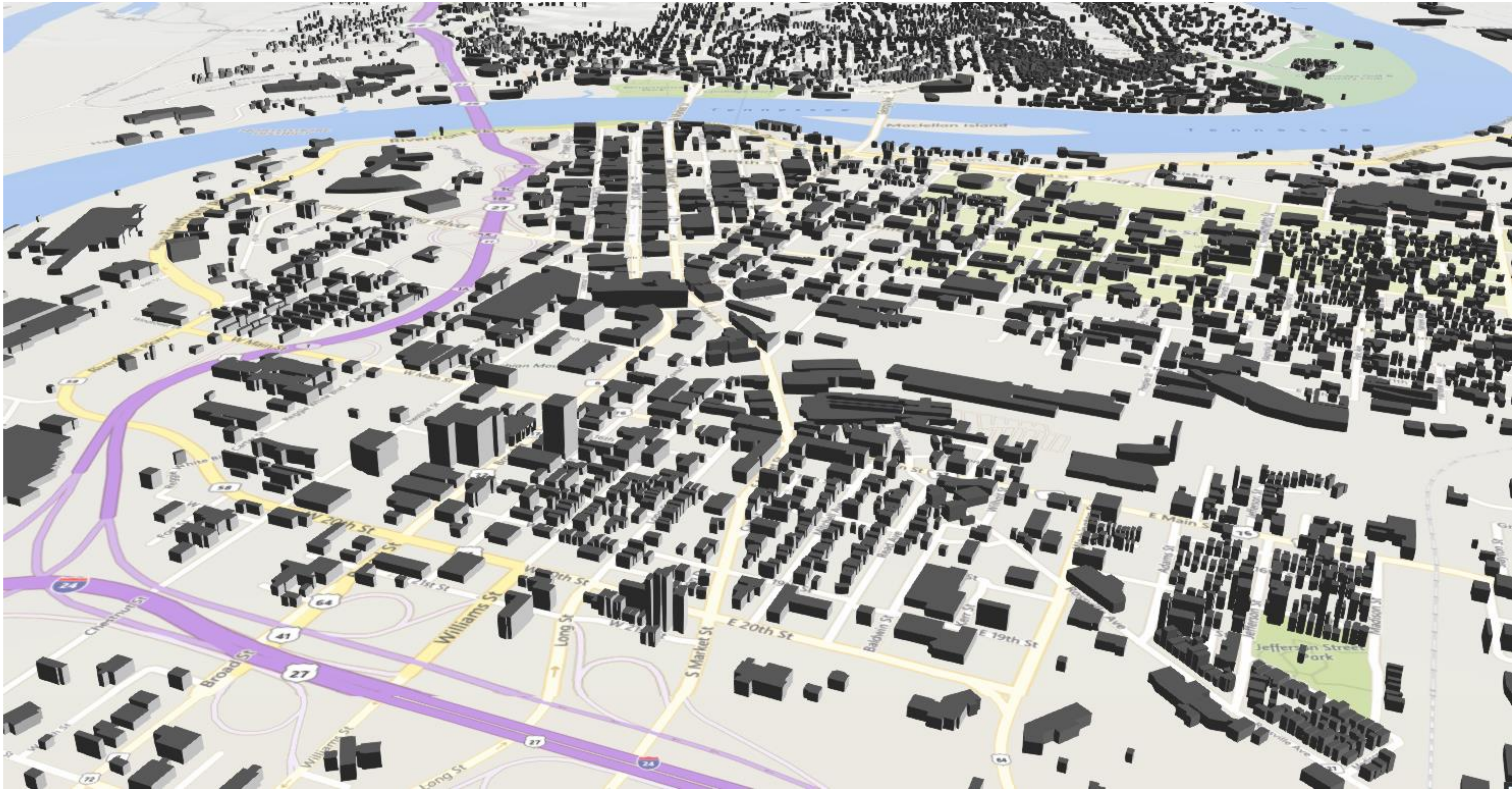
Digital Twin of a Utility



Use Case - Scenarios

- ***Preliminary*** building-specific estimates of energy, demand, and cost savings totaling **$11-$35 million per year** based on 9 scenarios prioritized by EPB.

1. **Peak Rate Structure**
   1. Scenario #1a, Peak contributions for each building
   2. Scenario #1b, Cost difference, in terms of dollars per year, for all building
2. **Demand Side Management**
   1. Scenario #2a, Monthly peak demand savings, annual energy savings, and dollar savings based on rate structure for all buildings.
   2. Scenario #2b, Location-specific deferral of infrastructure cost savings potential
3. **Emissions**
   1. Scenario #3a, Emissions footprints for each building
4. **Energy Efficiency**
   1. Scenario #4a, Optimal retrofit list of independent ECMs
   2. Scenario #4b, Optimal retrofit package of dependent ECMs
5. **Customer Education**
   1. Scenario #5a, Percentile ranking of each building's EUI by building type and vintage
   2. Scenario #5b, Monthly peak demand savings, annual energy savings, and dollar savings based on rate structure for all buildings compared to AMY weather file scenario.

The AutoBEM technology "axe"

135,481 building models have been created and matched to EPB's PremiseID

Limitations: limited building types, not calibrated, will improve quarterly

QA/QC: will show how close our simulations are to 15-min data

2.3 million EnergyPlus building energy models using AutoBEM technology, Titan, cloud, and local servers to produce and analyze 13 TB of simulation data.

1. Generate baseline building – OpenStudio (1.5-3h Amazon, 30h internal)
2. Run ECM measures – OS Measure (30 mins AWS, 2h internal), Custom (1m AWS, 5m intl.)
3. Copy data to Titan – 1 min (1.2GB tar.gz)
4. Submit to Titan – 0-2 hours in queue
5. EnergyPlus simulation time – 30-45 mins (5mins/sim = 1.4 years to simulate EPB on 1 core)
6. Data transfer – 40 mins (160GB tar.gz)
7. Uncompress – 10-15 mins
8. Reformat data – 20-30 mins
9. Analysis – 5-10 mins

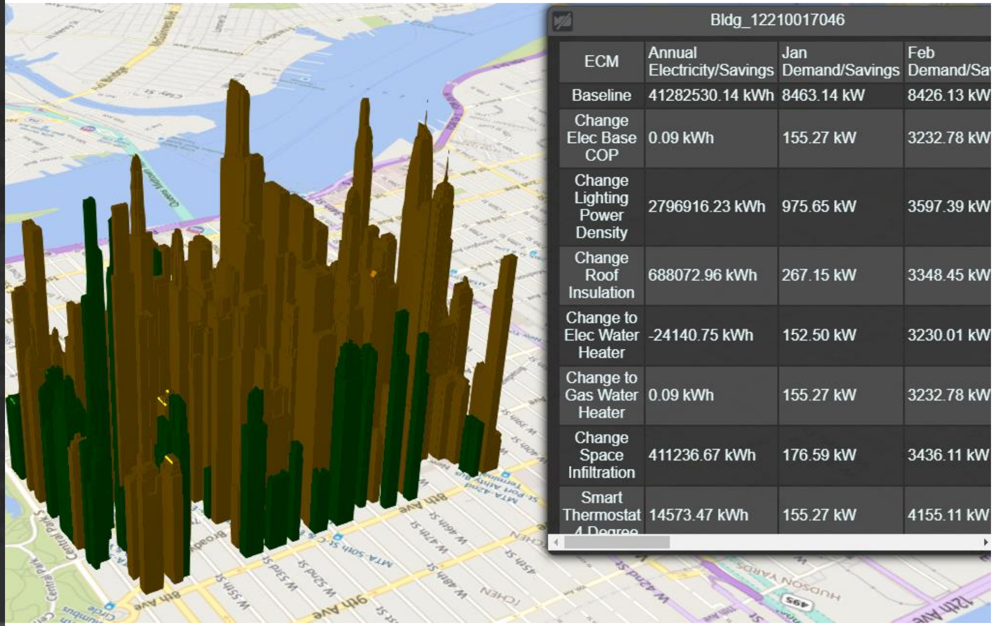
Time for creation, annual simulation, and analyzing "all" EPB buildings
6.5 hours (6.1h –36.5h)

Virtual Utility – interactive results

60246	
ID	60246
DOE Building Type	SmallOffice
Num Floors	3
Percentile	87.70 %
Estimated wholesale vs retail cost	$ 9797.07
CO_2 emissions	222052.32 lbs/year
Smart Thermostat - 4F cost savings	$ 1316.61
Smart Thermostat - 8F cost savings	$ 2325.84
TMY->AMY Smart Thermostat - 4F cost savings	$ 204.99
TMY->AMY Smart Thermostat - 8F cost savings	$ 103.41
HVAC Efficiency ECM	$ 1291.79
Gas HVAC ECM	$ 4276.69
Gas Water Heater ECM	$ 725.58
Heat Pump Water Heater ECM	$ 476.95
Insulation ECM	$ 736.27
Infiltration ECM	$ 1577.50
Lighting ECM	$ 2898.95

E=energy (MWh), D=demand (kW), [min,avg,max]

1. **Lighting Efficiency (0.85 W/ft^2)**
   E=[77, 784, 6757] D=[23, 999, 14410]
2. **Infiltration (reduce 25%)**
   E=[40, 774, 4648] D=[-0.8, 840, 14020]
3. **Insulation (R16.12 to R28.57)**
   E=[12, 204, 1600] D=[1.9, 817, 13928]
4. **Smart thermostat 2.2C (4F) pre-condition**
   E=[-72, 1.4, 525] D=[-938, 918, 13907]

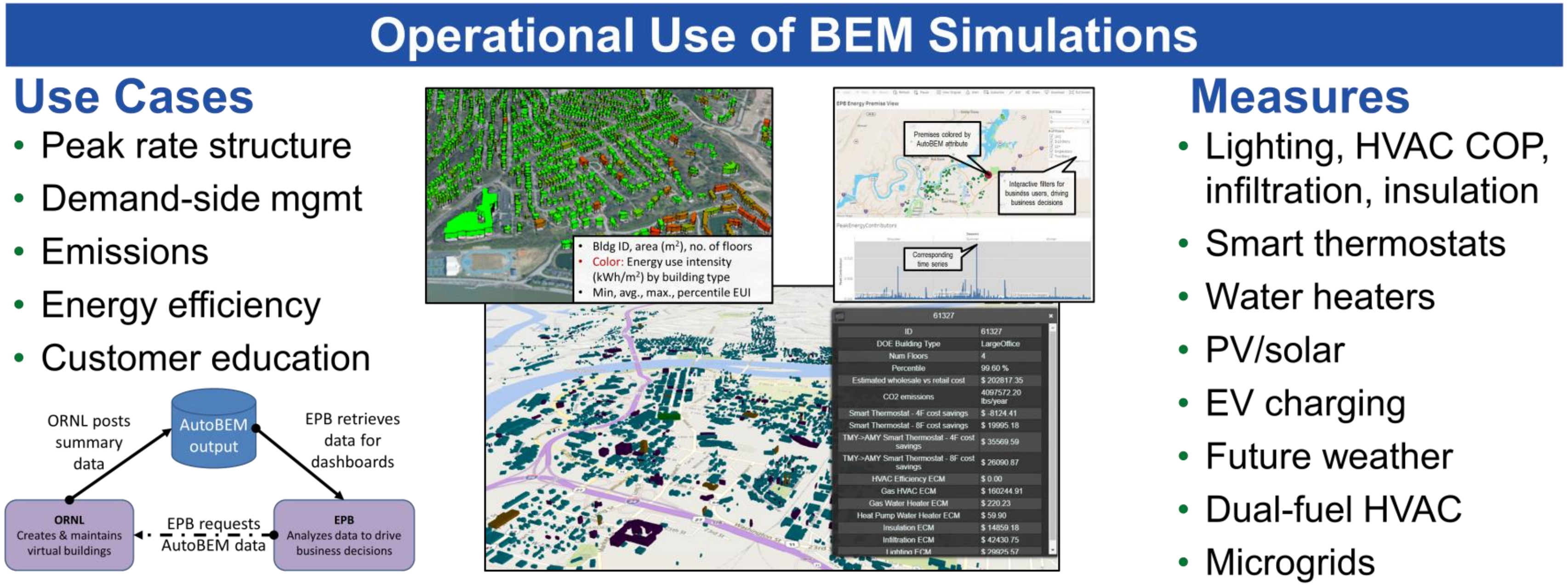


Bldg_12210017046

ECM	Annual Electricity/Savings	Jan Demand/Savings	Feb Demand/Sa
Baseline	41282530.14 kWh	8463.14 kW	8426.13 kW
Change Elec Base COP	0.09 kWh	155.27 kW	3232.78 kW
Change Lighting Power Density	2796916.23 kWh	975.65 kW	3597.39 kW
Change Roof Insulation	688072.96 kWh	267.15 kW	3348.45 kW
Change to Elec Water Heater	-24140.75 kWh	152.50 kW	3230.01 kW
Change to Gas Water Heater	0.09 kWh	155.27 kW	3232.78 kW
Change Space Infiltration	411236.67 kWh	176.59 kW	3436.11 kW
Smart Thermostat 4 Degree	14573.47 kWh	155.27 kW	4155.11 kW

Accuracy compared to real 15-minute data for each building

- Empirical Validation
  - 15-minute whole-building electrical for 178,368 bldgs
  - More accurate than BEM created by a human[1]
    - ½ error of the average manually-created BEM when compared to measured data



Result: $11–35 million/year in potential savings identified via simulation-informed data and valuation for *energy, demand, emissions, and cost impact* to EPB and each customer for each building under five use cases covering nine monetization scenarios

[1]Garrison, Eric, New, Joshua R., and Adams, Mark (2019). "Accuracy of a Crude Approach to Urban Multi-Scale Building Energy Models Compared to 15-min Electricity Use." Best PhD Student Paper award. In *Proceedings of the ASHRAE Winter Conference*, Atlanta, GA, Jan. 12-16, 2019. [PDF] [PPT]

Load Factor summary

Monthly AutoBEM Data

- **Premise Number**
- **Improvement Type**
- **Total Cost Savings ($)**
- **Monthly Costs Savings ($)**
- **Monthly Demand Svgs (KW**

~2.1M records per year, all bldgs

Join on Premise Number

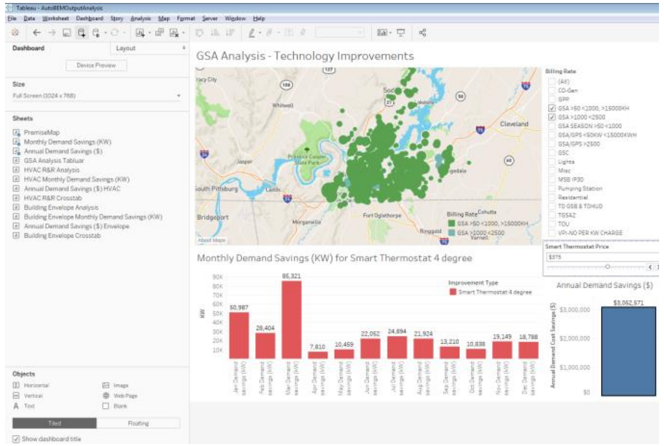
EPB System Attribute Data

- **Premise Number**
- **Service Address**
- **Latitude/Longitude**
- **XFMR information (bank, structure, etc.)**
- **Circuit, Substation, Feeder**

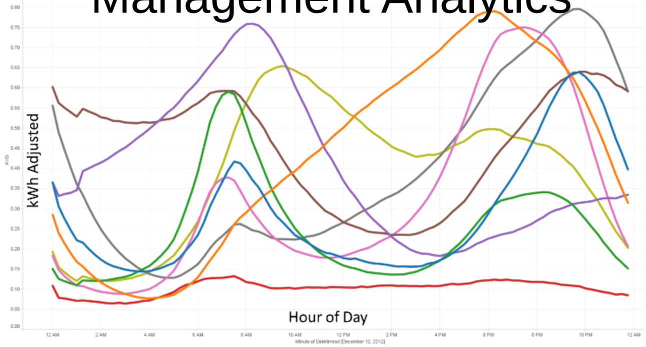
Data feeds to other EPB Systems

Distribution System Capacity Planning

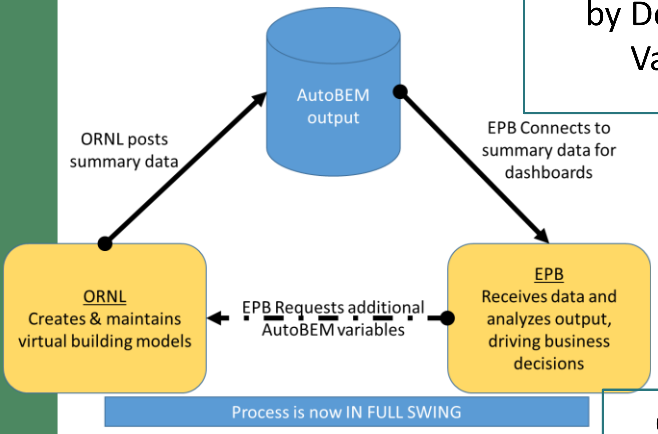
Data Visualization Tools



Customer Clustering & Demand Side Management Analytics



Virtual Utility integration



Map showing premises, sized by Demand Value

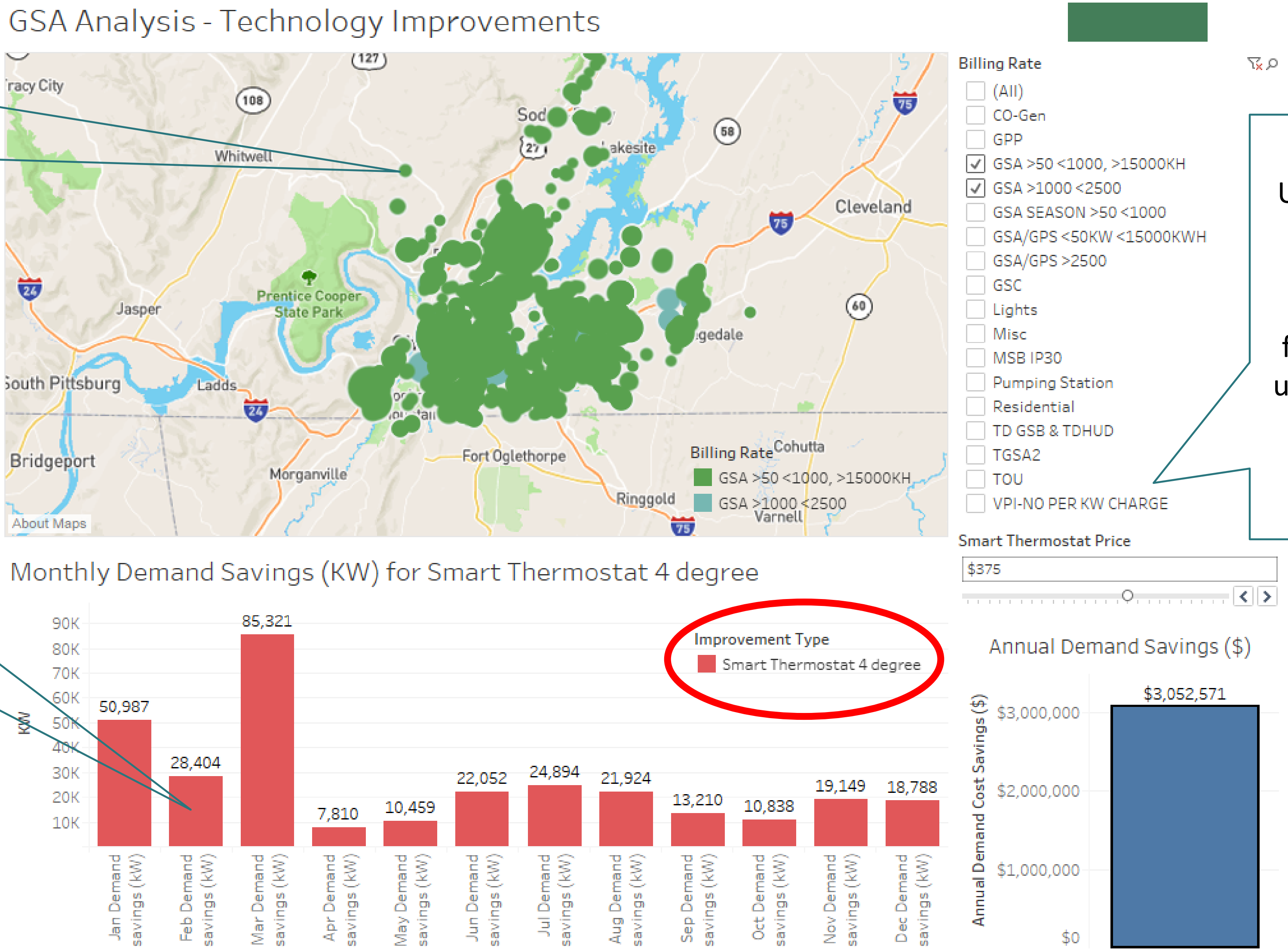


Chart showing monthly demand value

Use of filters create an interactive experience for business users, driving business decisions

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Tech Commercialization Fund with Google

- Environmental Insights Explorer
  - https://insights.sustainability.goo

ENVIRONMENTAL INSIGHTS EXPLORER

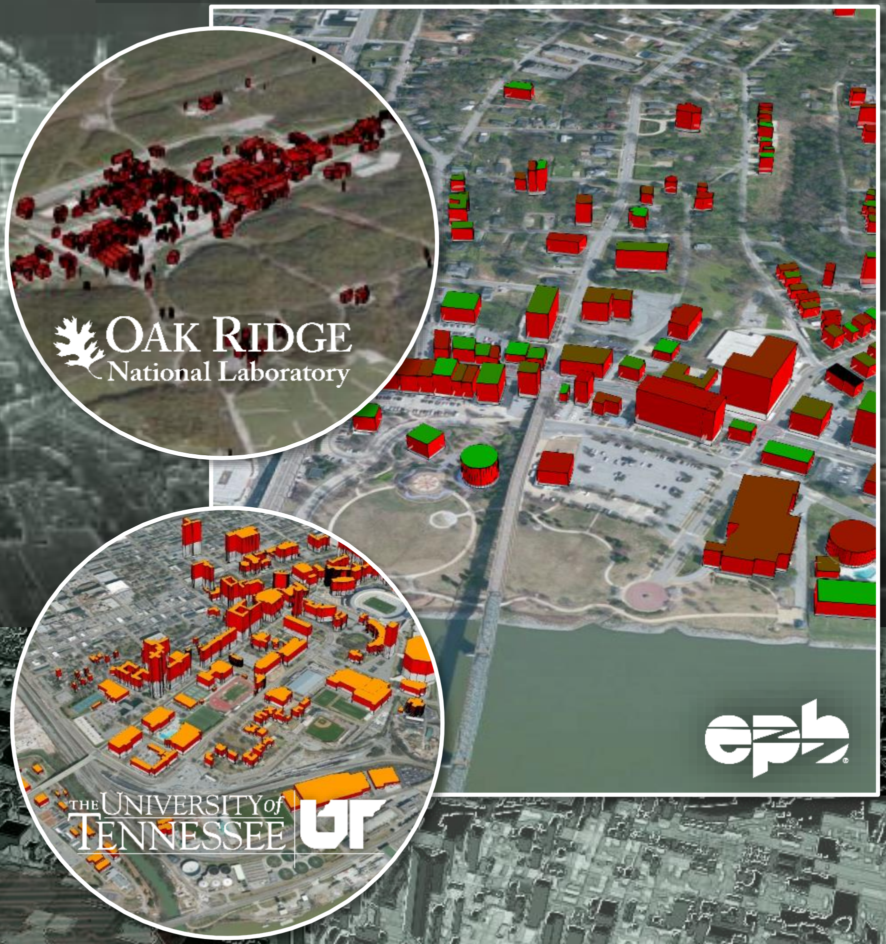
Impact begins with insights.
Explore data to make informed decisions and inspire action.

Discussion

Joshua New, Ph.D., CEM, PMP, CMVP, CSM
Subprogram manager for Software Tools & Models
Building Technologies Research and Integration Center (BTRIC)
Oak Ridge National Laboratory

newjr@ornl.gov

HPC Tools for Modeling and Simulation
Capturing building energy consumption



Automatic Detection and Building Energy Model Creation (AutoBEM)

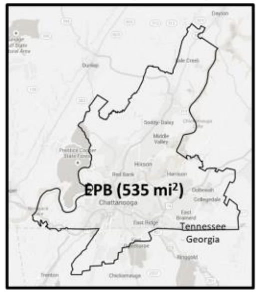
Data Sources

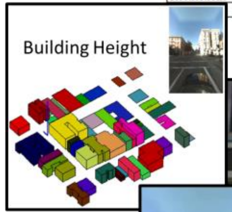
- Imagery (satellite, aerial)
- Street-level imagery
- Cartographic layers
  - Elevation, GIS
- Tax assessors
- Ranking of descriptors
  EE and Demand impacts
  (281–4,617 per building type)

Data comparison matrix

	Short Title
Summary	Satellite imagery, including panchromatic and multispectral images
Data type	Image
Company	
Website	
Temporal resolution	Cities - 3-11 times per week
Spatial resolution	0.3 m
Measure accuracy	
Cost	$11 per sq. km
Format	GeoTiff
Mapping to building input variables	Building footprints
Mapping to area properties	Vegetated areas, road surface, buildings, parking lots
Mapping to material properties	Road pavement materials (e.g., concrete, asphalt), parking lots (e.g., gravel, soil)
Coverage of US	Over 10 million km^2 of coverage of the contiguous US
Orientation	Aerial
Existing internal software	N/A
Existing expertise	Remote sensing data analysis tool
Restrictions	N/A

Occupancy

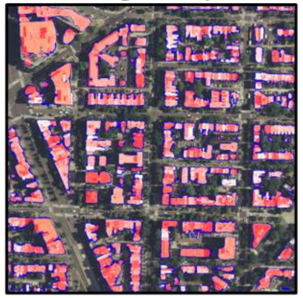




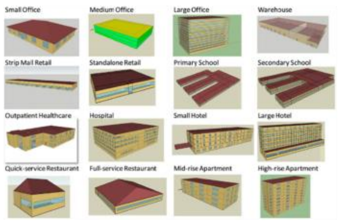
Street-level data

Window-to-wall ratio

Building footprints



Class	Object	Field	Default	Minimum	Maximum	Distribution	Type	Group	Constraint
Sizing:Parameters		Heating Sizing Factor	1.33	0.931	1.729	uniform	float		
Sizing:Parameters		Cooling Sizing Factor	1.33	0.931	1.729	uniform	float		
Lights	Core_bottom_Lights	Watts per Zone Floor Area	10.76	7.532	13.988	uniform	float	G0001	
Lights	Core_mid_Lights	Watts per Zone Floor Area	10.76	7.532	13.988	uniform	float	G0001	
Lights	Core_top_Lights	Watts per Zone Floor Area	10.76	7.532	13.988	uniform	float	G0001	
...	...	Watts per Zone Floor Area	10.76	7.532	13.988	uniform	float	G0001	
Lights	Perimeter_top_ZN_4_Lights	Watts per Zone Floor Area	10.76	7.532	13.988	uniform	float	G0001	
ElectricEquipment	Core_bottom_PlugMisc_Equip	Watts per Zone Floor Area	10.76	7.532	13.988	uniform	float	G0002	
...	...	Watts per Zone Floor Area	10.76	7.532	13.988	uniform	float	G0002	
ElectricEquipment	Core_bottom_Elevators_Equip	Design Level	32109.89011	22476.92	41742.86	uniform	float		
Exterior:Lights	Exterior Facade Lighting	Design Level	14804	10362.8	19245.2	uniform	float		
ZoneInfiltration:DesignFlowRate	FirstFloor_Plenum_Infiltration	Flow per Exterior Surface Area	0.000302	0.000211	0.000393	uniform	float	G0003	
...	...	Flow per Exterior Surface Area	0.000302	0.000211	0.000393	uniform	float	G0003	
ZoneInfiltration:DesignFlowRate	TopFloor_Plenum_Infiltration	Flow per Exterior Surface Area	0.000302	0.000211	0.000393	uniform	float	G0003	

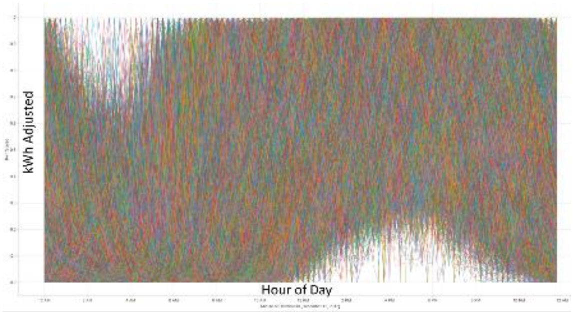


Software Tools

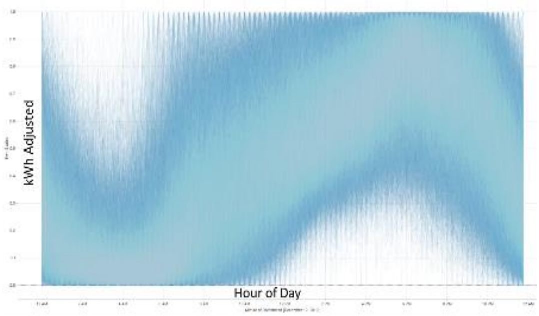
- Occupancy (every 90m)
- Aerial - best footprints
- Street - height, type, WWR
- LiDAR - geometry
- GIS - database API
- Building type
- Model generator
- Fastest buildings simulator
- Web-based visual analytics

Result: Simulated buildings for any area of interest that match 15-minute electrical data more accurately than most manually created models

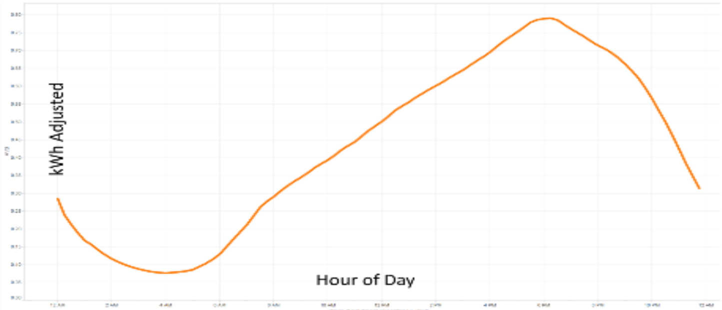
Clustering of (real) 15-min electrical data



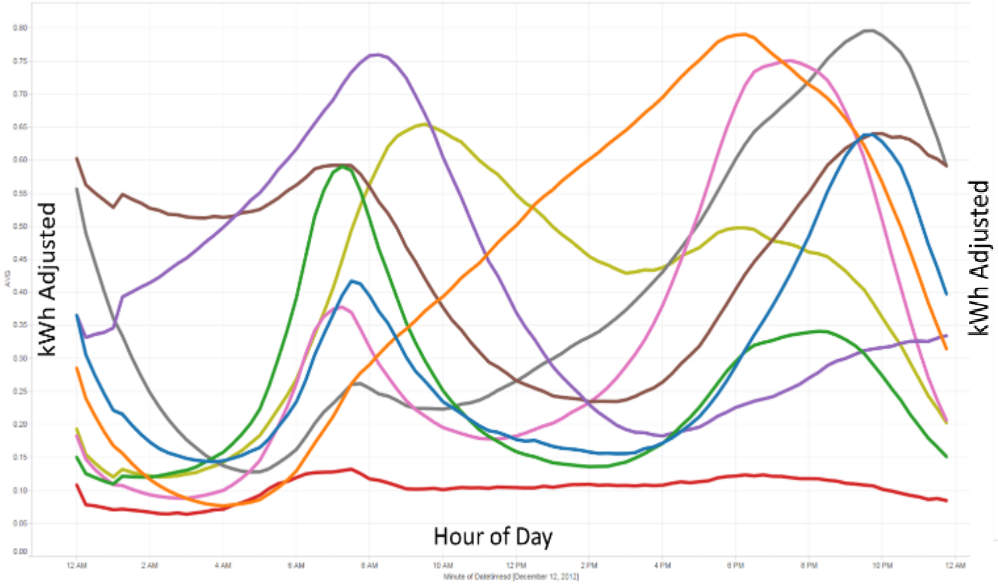
180,000 buildings measured
Whole-building electricity



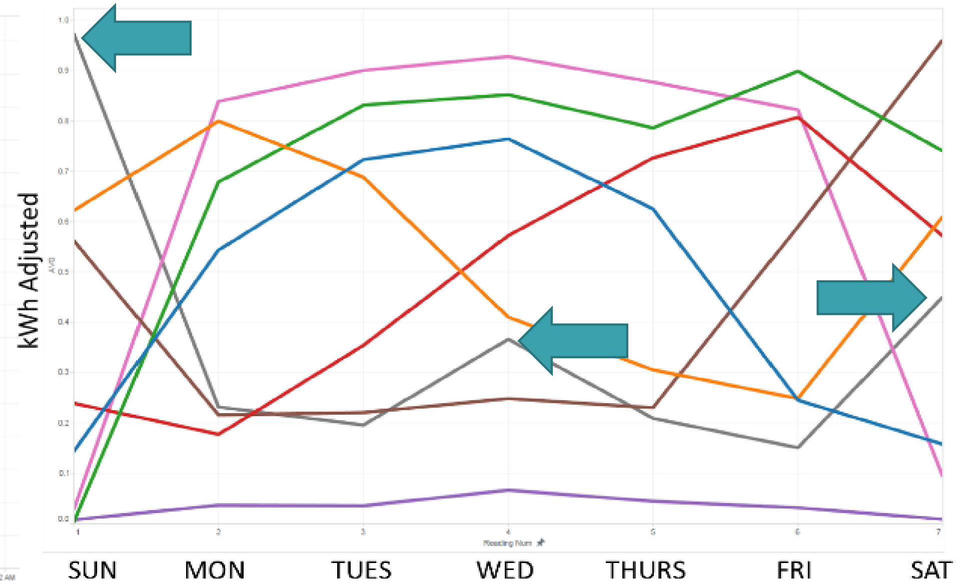
96d clustering (24h)



26,048 residential buildings with peaks typically between 5 and 7pm



9 residential clusters



8 commercial clusters (GSA1-3, 8am-5pm)

Load Factor summary

- Utility load factor $LoadFactor = Total(kWh)\ /\ (kWpeak * numHours)$
  - Close to 0, more opportunity for energy storage

	Vintage	Num Bldgs	% of all Bldgs	Avg. Load Factor
Residential	2006	16217	9.1%	0.170
	2009	6357	3.6%	0.177
	2012	149247	84.0%	0.163
Commercial	Pre-1980	670	0.4%	0.405
	1980-2004	1064	0.6%	0.296
	90.1-2004	1478	0.8%	0.255
	90.1-2007	268	0.2%	0.338
	90.1-2010	1224	0.7%	0.208
	90.1-2013	1808	1.0%	0.256

Building Type	Num Bldgs	% of all Bldgs	Avg. Load Factor
IECC Residential	171821	96.35%	0.164
Warehouse	799	0.45%	0.166
MidriseApartment	851	0.48%	0.261
SmallHotel	1557	0.87%	0.261
HighriseApartment	2068	1.16%	0.263
LargeHotel	408	0.23%	0.365
QuickServiceRest.	318	0.18%	0.380
Hospital	319	0.18%	0.399
Outpatient	59	0.03%	0.501

Superintelligence Considerations

- "AI has succeeded in being able to do everything that requires thinking, but still can not do what man does without thinking. Somehow, this is much harder." –Donald Knuth
- Societal doubling times – hunter/gatherer 224,00 years; farmers 909 years; industrial 6.3 years; next step would double every 2 weeks.
- Types of superintelligence: Speed (human brain but faster), Collective, Quality
  - Speed: Human neurons peak at 200 Hz, 2 billion Hz CPU is 10Mx faster
  - 10,000x faster read book in seconds, PhD dissertation in an afternoon, K-12 education in 2 weeks; 1Mx faster, millennium of work in 1 working day
- Strong AI would be the last invention makind would ever need make, assuming it was docile enough to tell us how to keep it under control
  - Human intelligence survey of experts: 10% think achievable by 2022, 2) 50% by 2040, 90% by 2075

Superintelligence Considerations

- Whole brain/world evolution – 5×10^{30} prokaryotes, 10^{19} insects, 10^{10} humans
  - Neuron simulation – simplest model 1k FLOPS, Hodgkin-Huxley model 1.2M FLOPS; 1 billion years of brain operation could be simulated for 10^{25} neurons in 10^{31}-10^{44} FLOPS; Summit=2×10^{17}
- Wilson, Minsky, McCarthy, and Windows support purpose of weak AI to maintain credibility
- Over 1 million industrial robots, over 10 million robots worldwide
- McCarthy's dictum – when something works, it is no longer called AI
- A sizable portion of our precious $1m^2$ of cortical real estate is zoned for image processing and starts in the eye.

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Surrogate Modeling (replace slow physics)

- "Constructing Large Scale Surrogate Models from Big Data and Artificial Intelligence." In *Journal of Applied Energy*, volume 202, pp. 685-699, September 2017.
  - Inputs: 7-156 (e.g. concrete slab thickness, thermal conductance of gypsum board)
  - Machine Learning Algorithms: FFNN and Lasso Regression
  - Prediction: 80-90 EnergyPlus outputs predicted
    - 35,040 values (15-min data)