Automatic Building Energy Modeling (AutoBEM) for Remote/Zero-Touch Audits

Presented at:

AEE Local Chapter

Knoxville, TN

Presented by:

Joshua New, Ph.D., C.E.M., PMP, CMVP
Building Technologies Research & Integration Center
Subprogram Manager, Software Tools & Models
Oak Ridge National Laboratory

June 13, 2018

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for the US Department of Energy

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Overview

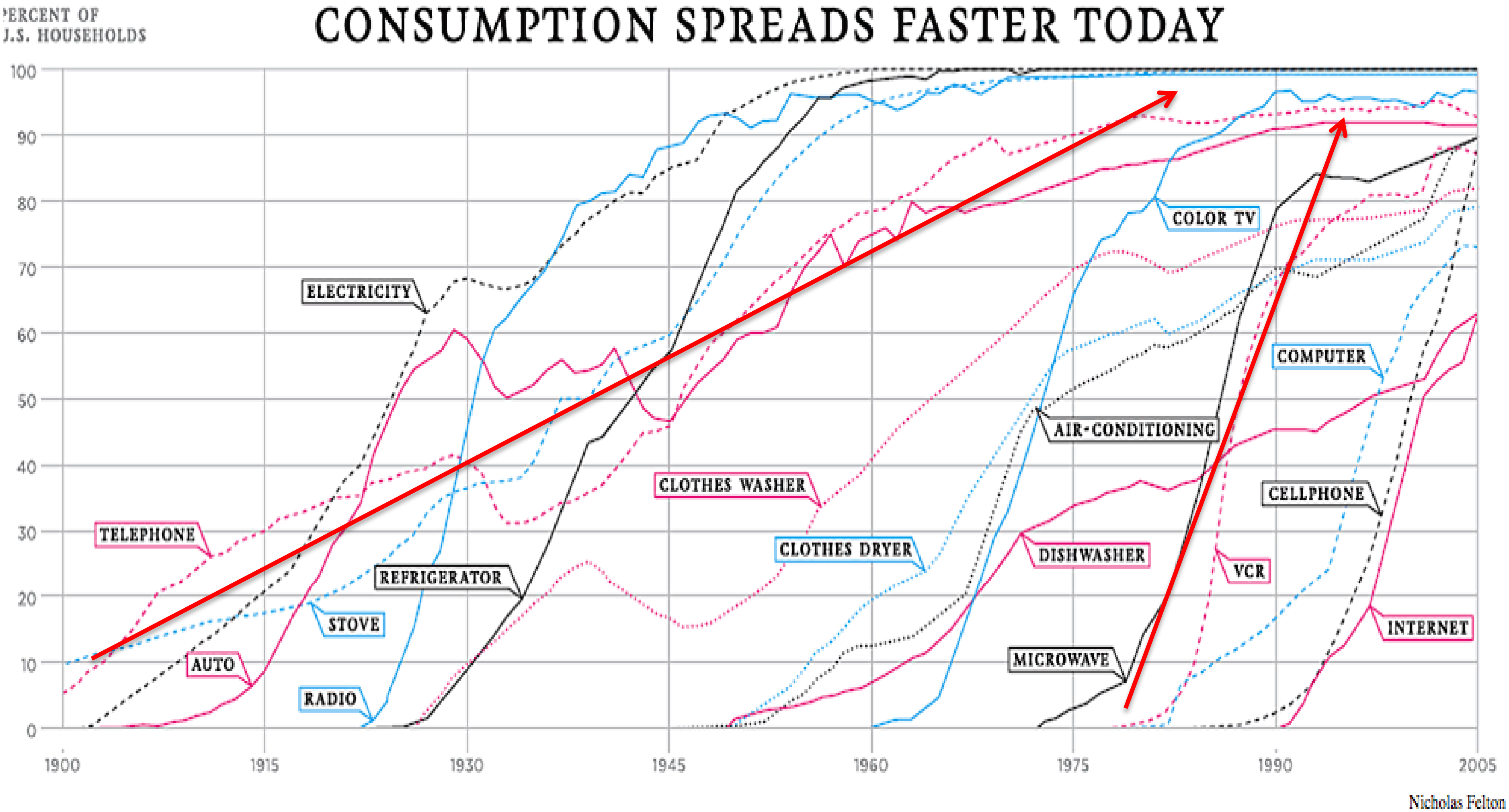
- Jim's vision for Utilities of the Future
- Introduction and Context
- 2 Nation-Scale Use Cases
  - Climate zone assessment
  - GEB market creation
- Urban-Scale modeling
  - Automatic Building detection and Energy Model creation (AutoBEM)
- Virtual EPB progress
  - Utility-prioritized use cases
  - Developed capabilities
  - Preliminary results

AUTOBEM: New Age Energy Security You Can Trust

Strategic Research

Jim Ingraham: EPB Vice President Strategic Research

Technology Adoption Rates Accelerate



Strategic Research

Wireless Broadband IoT Age Is Upon Us

Papal Conclave 2005

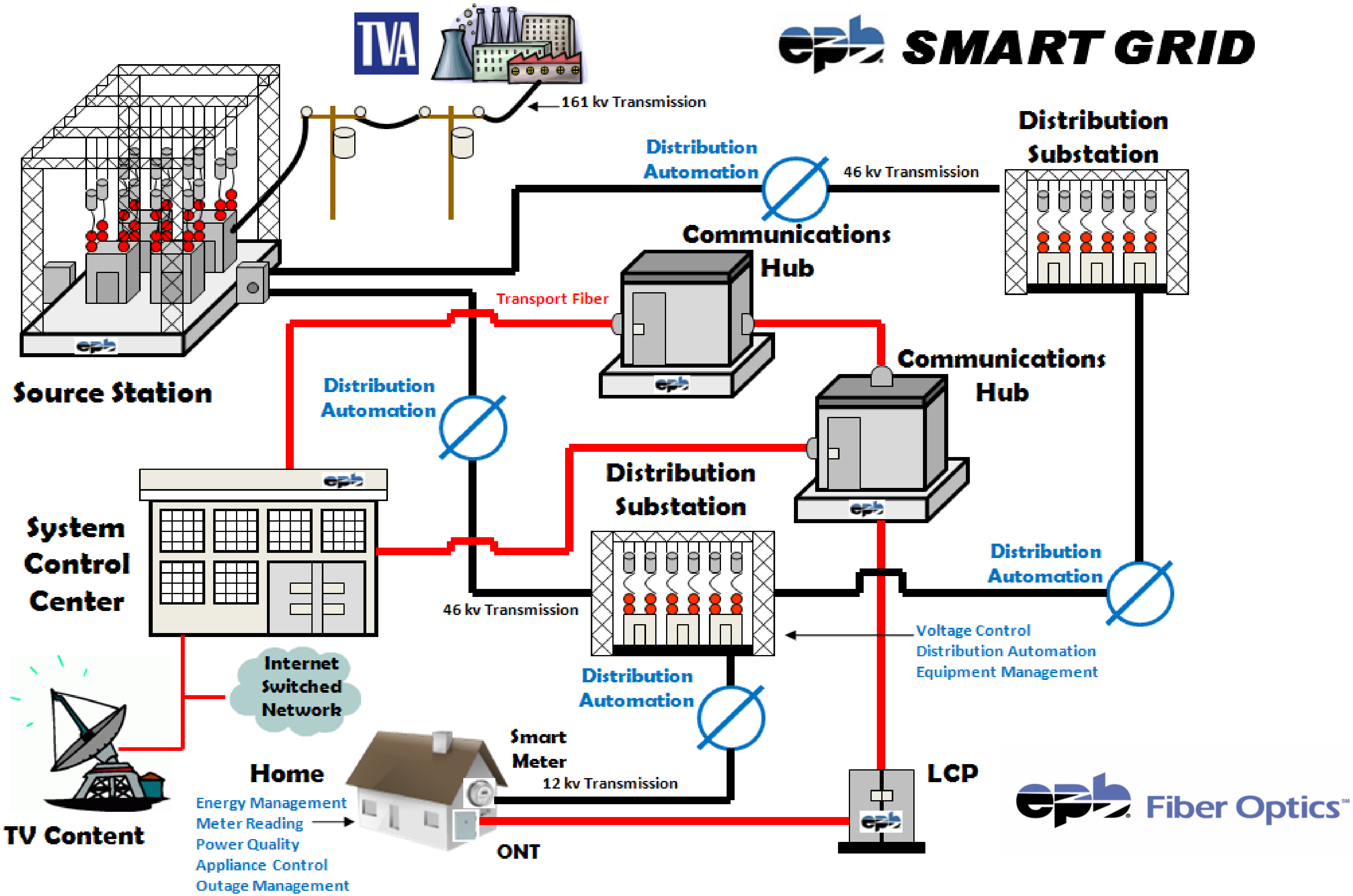
Strategic Research

Gigabit Speed Wireless Broadband Coming Soon in 2018-2019

Papal Conclave 2013

Strategic Research

ENERGY and INTERNET NETWORKS



A New Generation of Smart Energy Appliances

Strategic Research

2011

$250
Artificial Intelligence

2015

$5000
5KWh

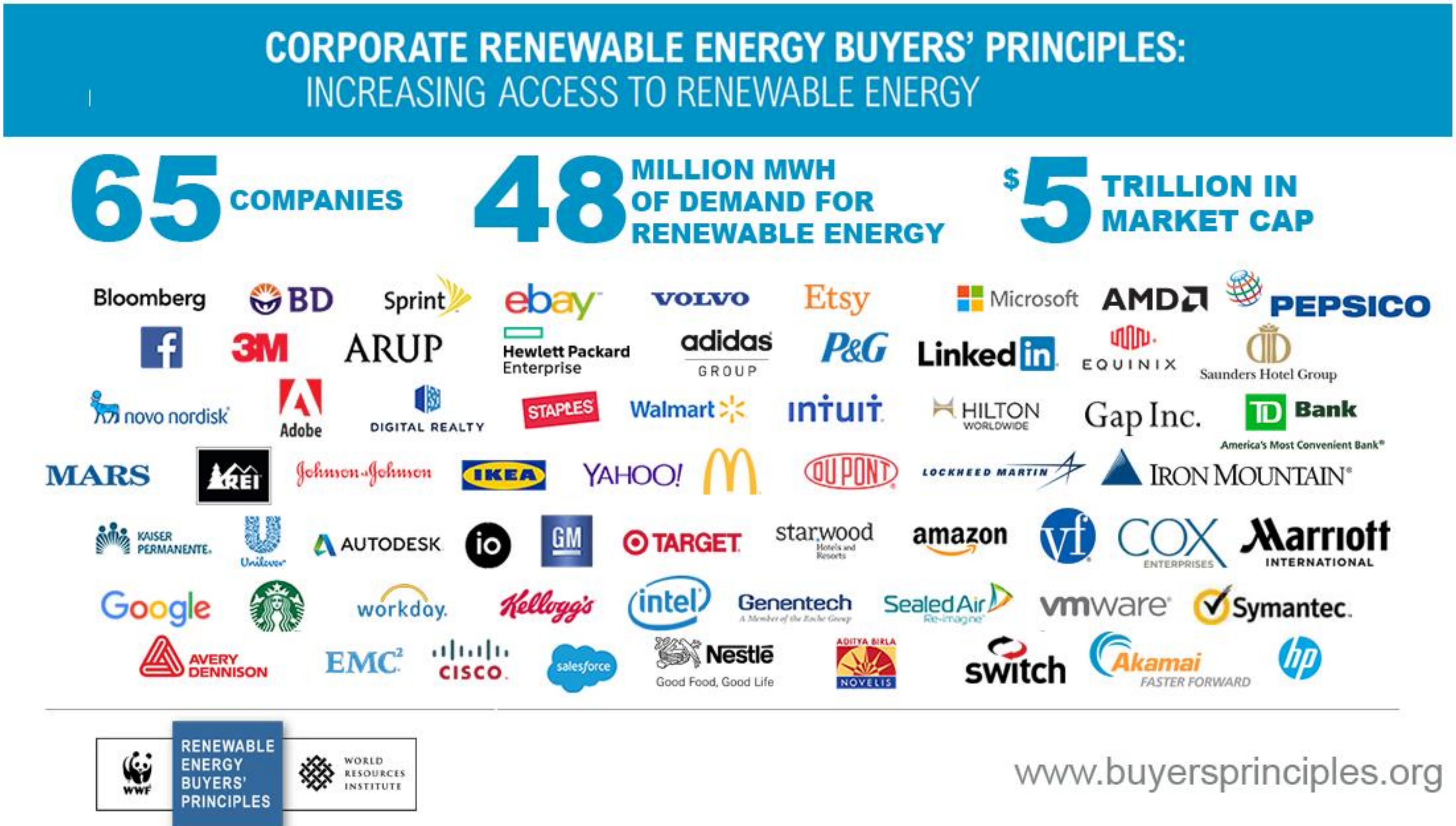
Residential Customer November 2016 Surprise

Why Tesla's new solar roof tiles and home battery are such a big deal

New Residential Customers Rising

epb
Strategic Research

The The Fortune 500 Is All In - Customer Demand



Some Partner With The Electric Company

Strategic Research

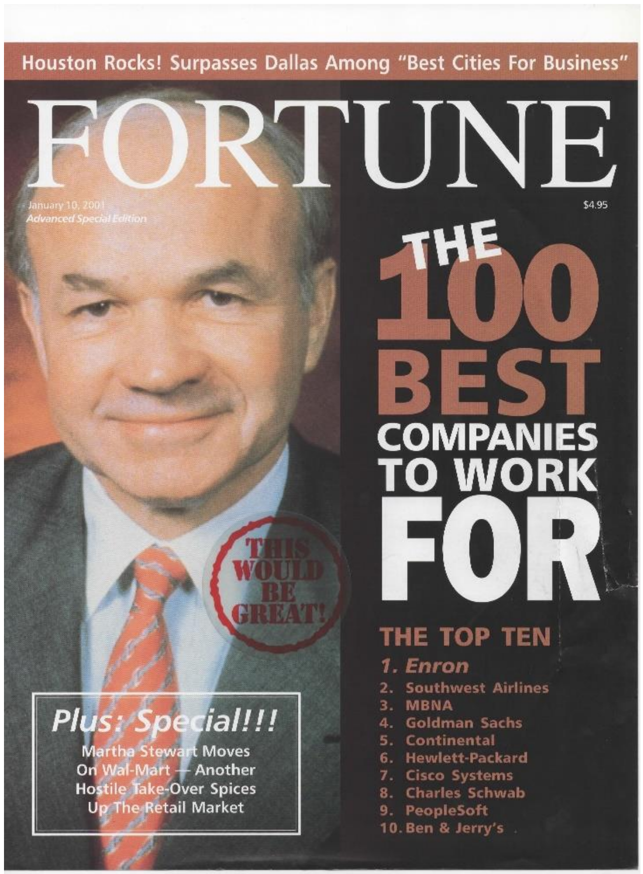
Strategic Research

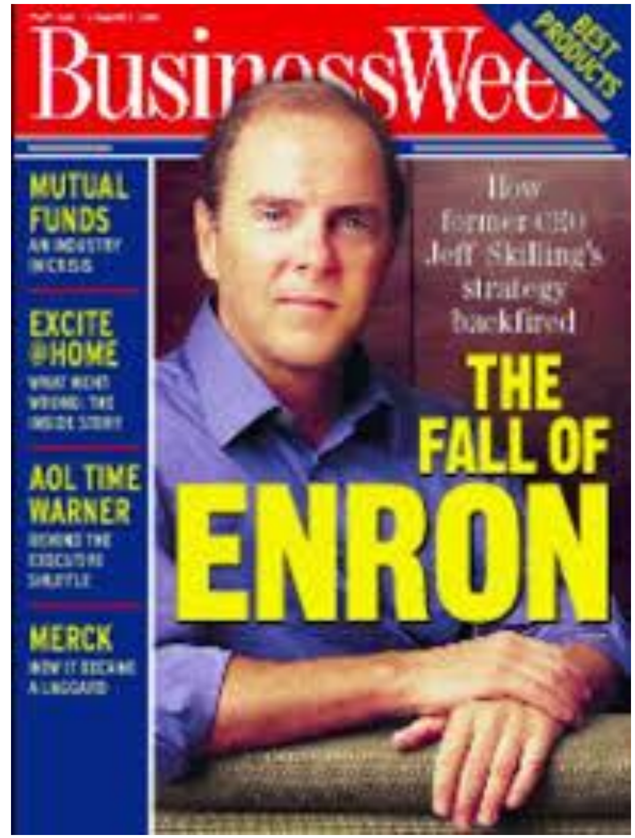
Some Do It On Their Own

SIGNAL ENERGY®
CONSTRUCTORS

WE HARNESS CREATIVE ENERGY

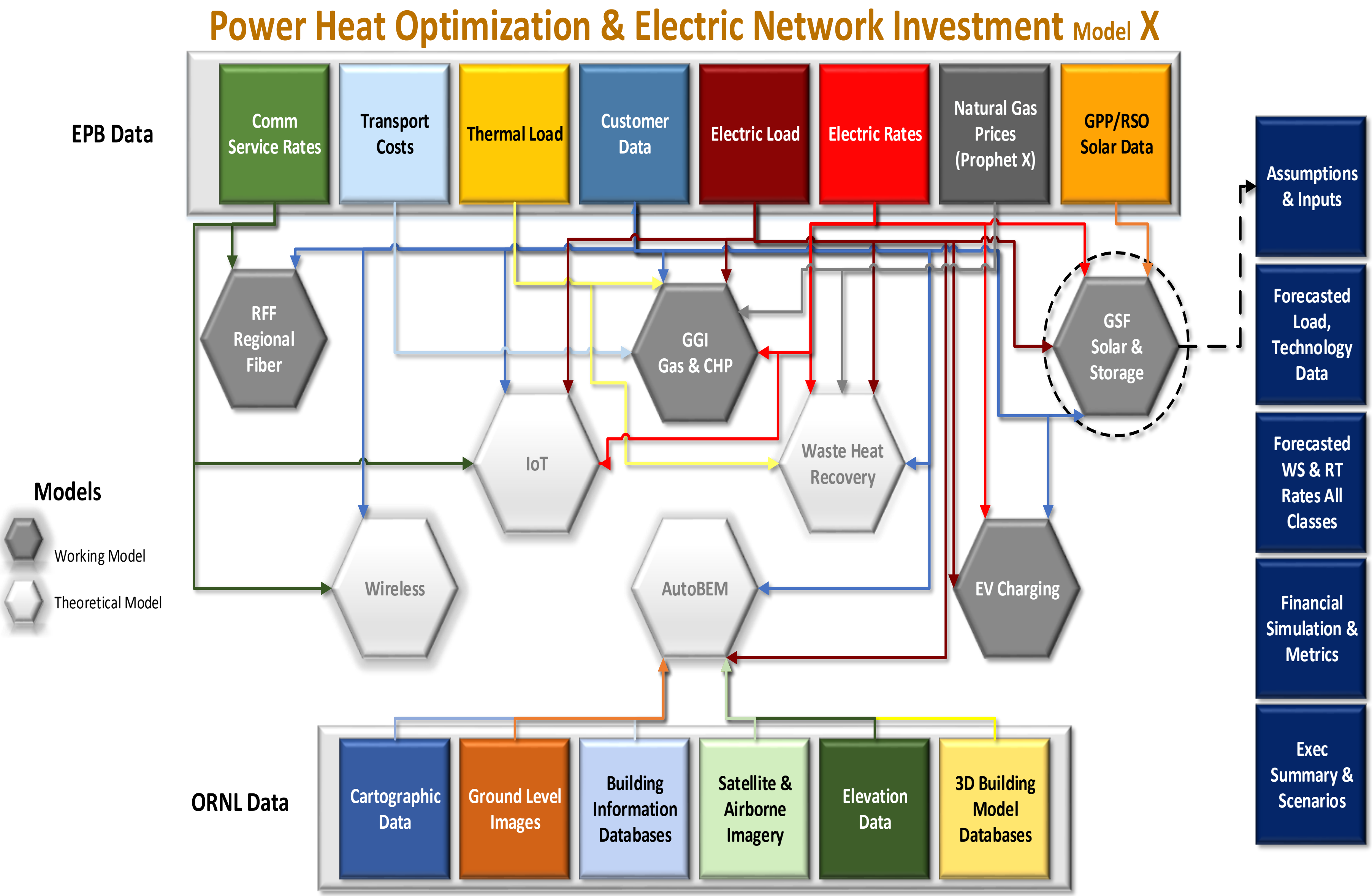
Energy Service Smoke And Mirrors Are Back





Who Can You Trust? DOE BTO AUTOBEM Can Be an Answer

AUTOBEM Integrated With EPB Appliance Models



Strategic Research

AUTOBEM Integrated With EPB Appliance Models

TESLA

POWERWALL

CERTIFIED INSTALLER

amazon echo

Where do Americans turn for answers we can trust?

DEPARTMENT OF ENERGY · UNITED STATES OF AMERICA

epb
Strategic Research

Who Will Die

Kodak

BlackBerry

TOWER RECORDS

BORDERS

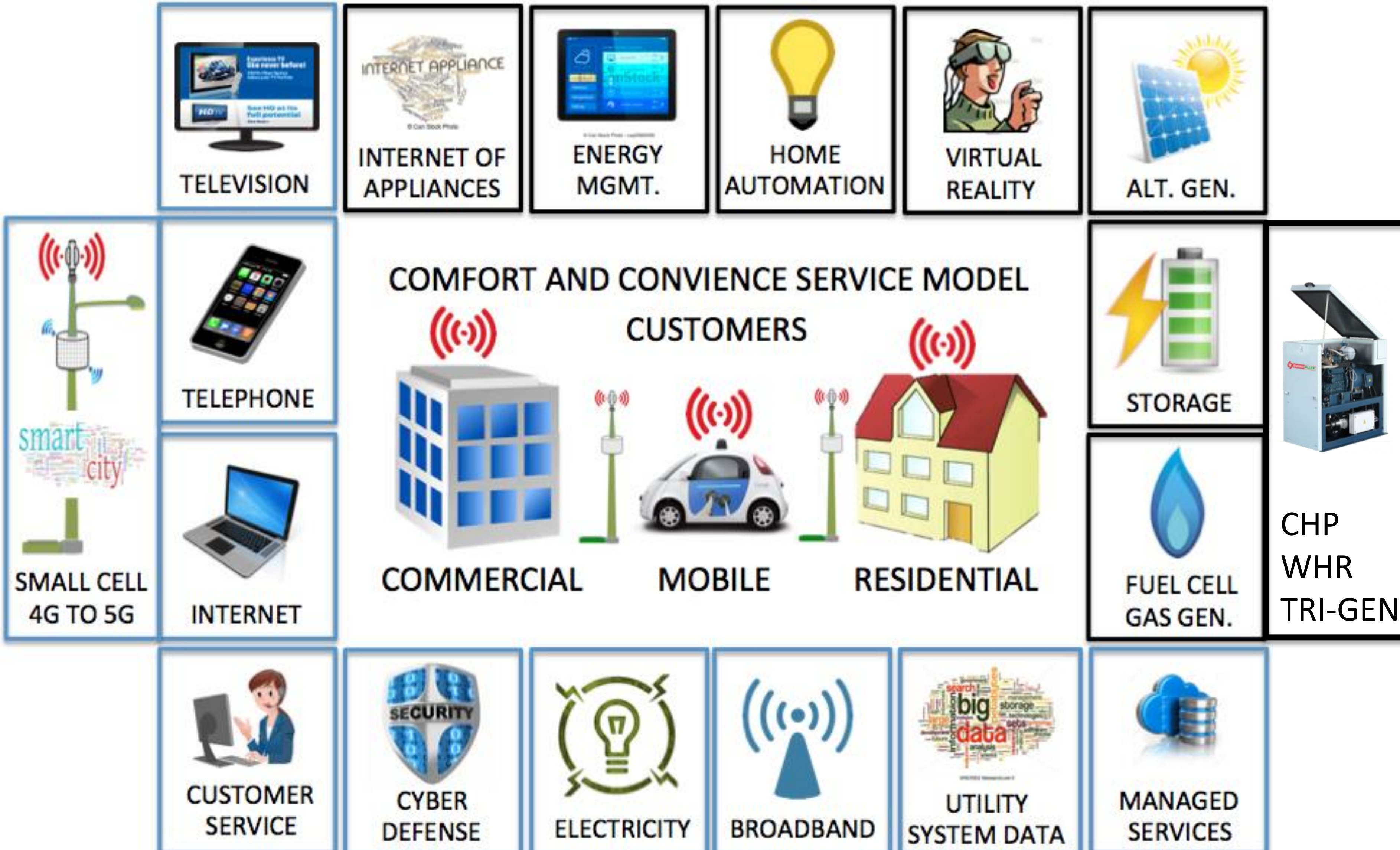
circuit city

BLOCKBUSTER VIDEO

SEARS

macy's

THE UTILITY OF THE FUTURE AT THE CUSTOMER PREMISE

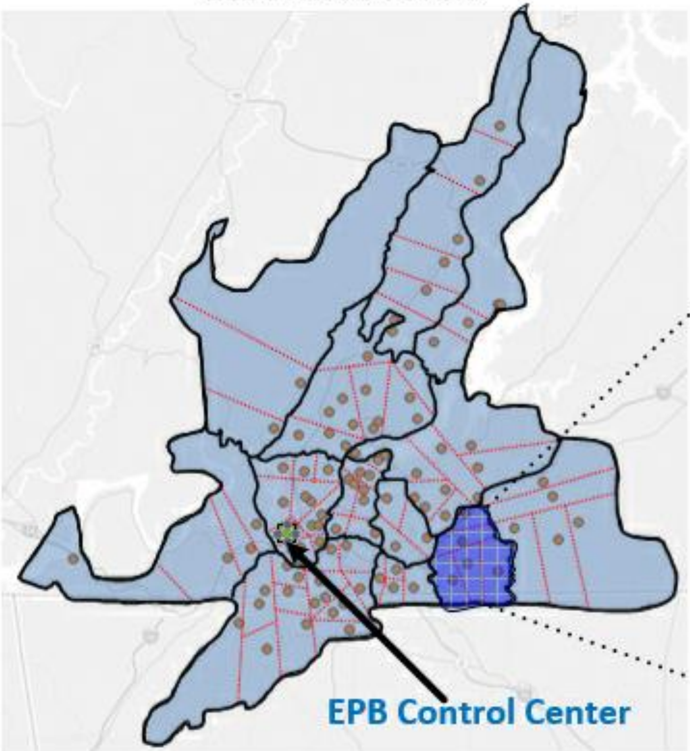


Control and Manage Load Factor Is The Key

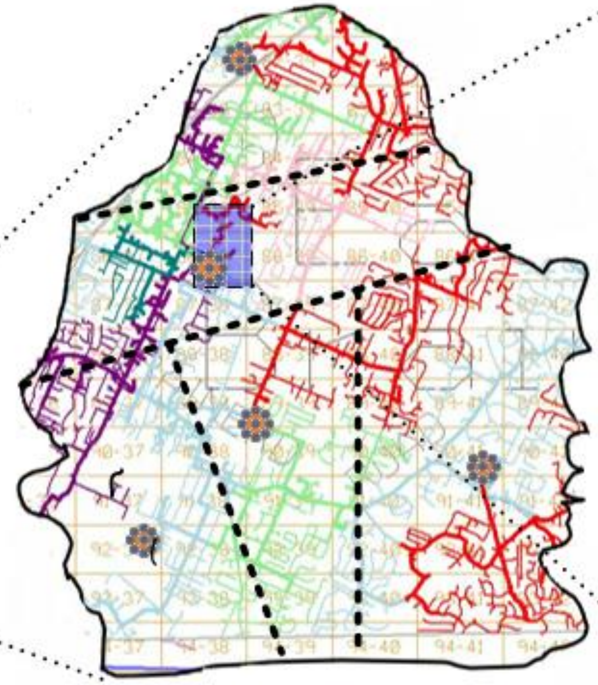
Strategic Research

AUTOBEM = MANAGE LOAD FACTOR

ELECTRIC SYSTEM



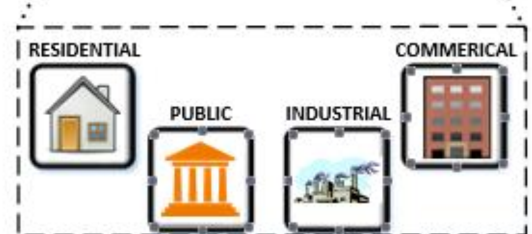
CIRCUITS



CUSTOMER

111 SUBSTATIONS
336 FEEDERS
166,000 BUILDINGS

MICROGRID
UTILITY SCALE
GENERATION/STORAGE/
ENERGY EFFICIENCY



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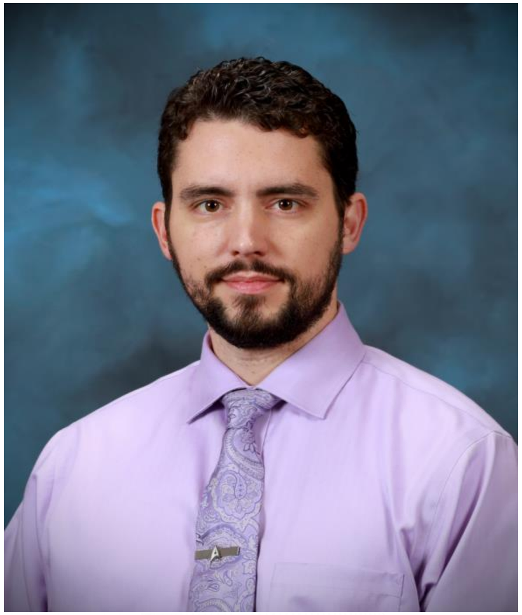
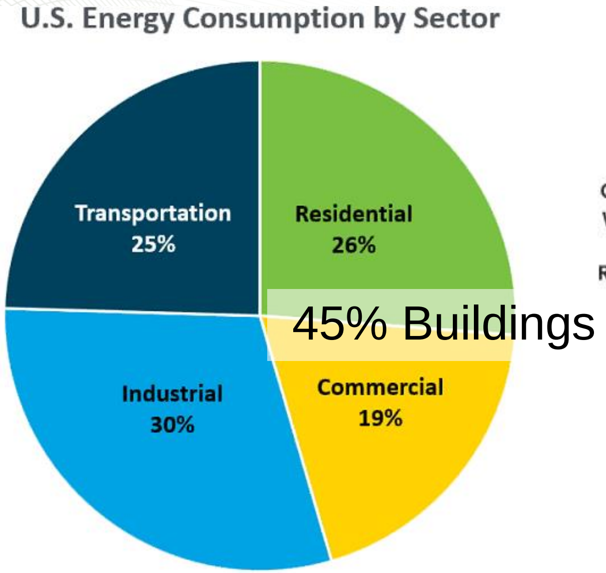
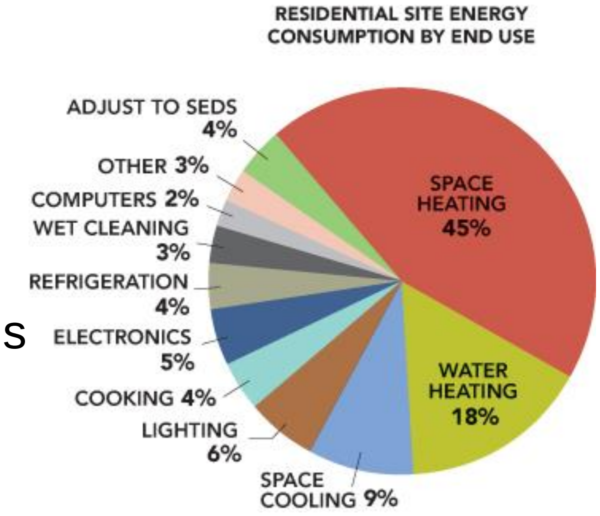
Joshua New, Ph.D., C.E.M., PMP

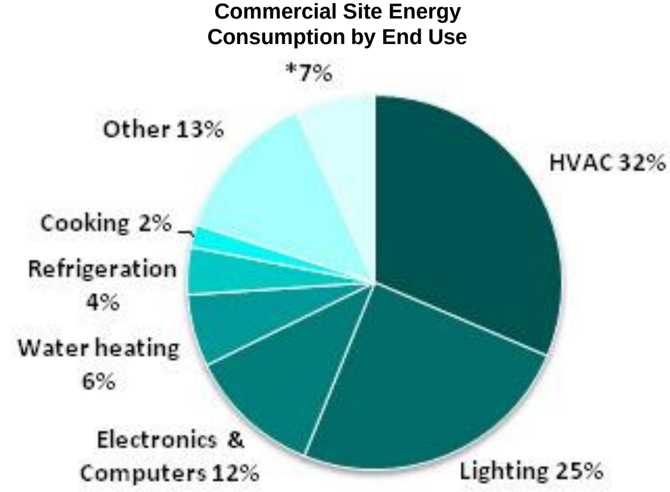
- **Career**
  - 2009+ Oak Ridge National Laboratory, R&D staff
    - ETSD, Building Technology Research & Integration Center (BTRIC), Building Envelope & Urban Systems Research Group (BEUSR)
  - 2012+ The University of Tennessee, Joint Faculty
- **Education**
  - The University of TN, (2004-2009), Knoxville; 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
  - ASHRAE, defines international building codes
    - TC1.5, Computer Applications, Voting member and officer
    - TC4.7, Energy Calculations, 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
    - SSPC140 and ASHRAE Guideline 14 involvement



Energy Consumption and Production







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.

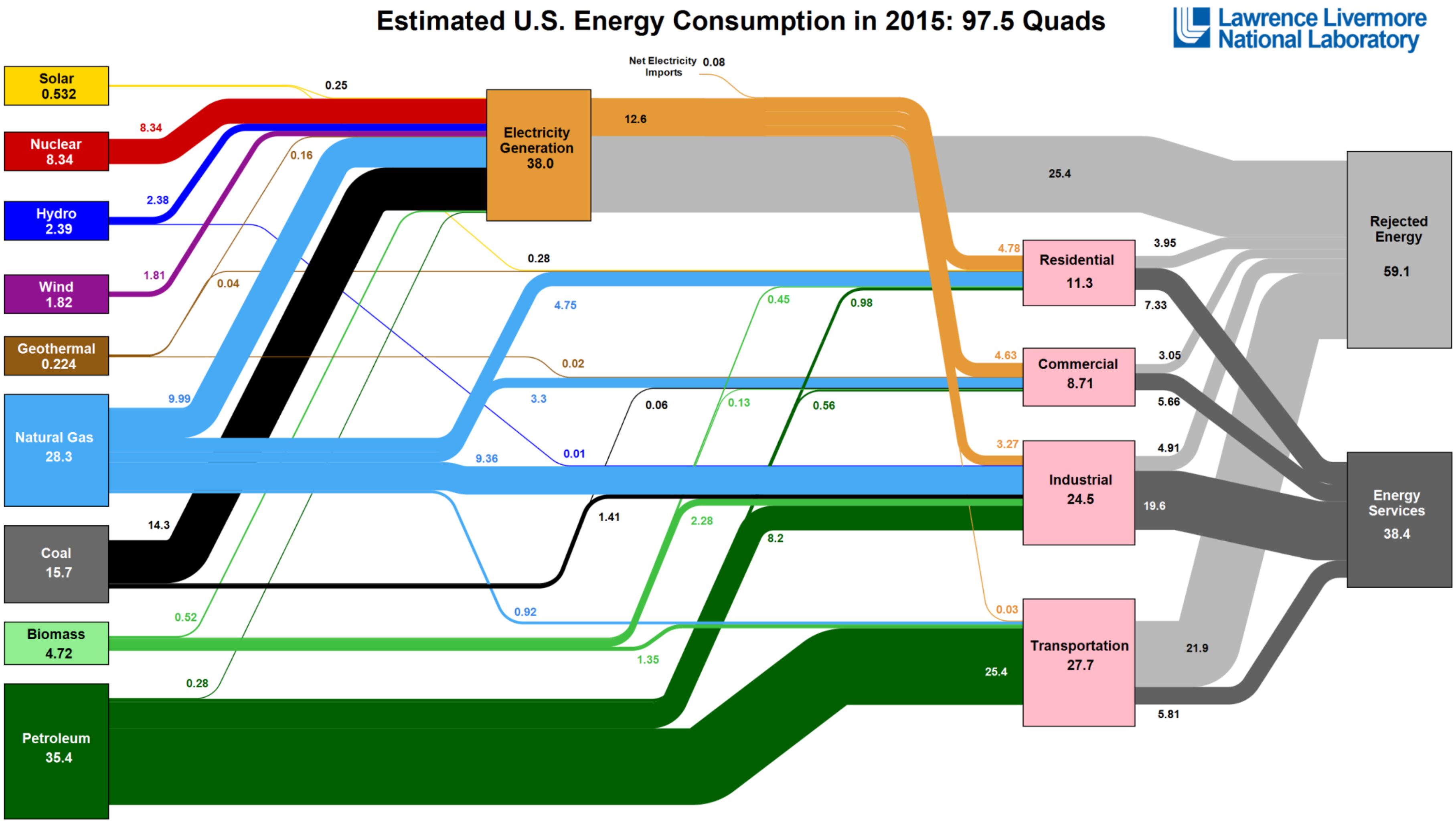
124 million U.S. buildings
$385 billion/yr energy bills

Goal of the DOE
Building Technologies Office:
45% energy reduction per sq. ft.
by 2030 compared to 2010 baseline

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

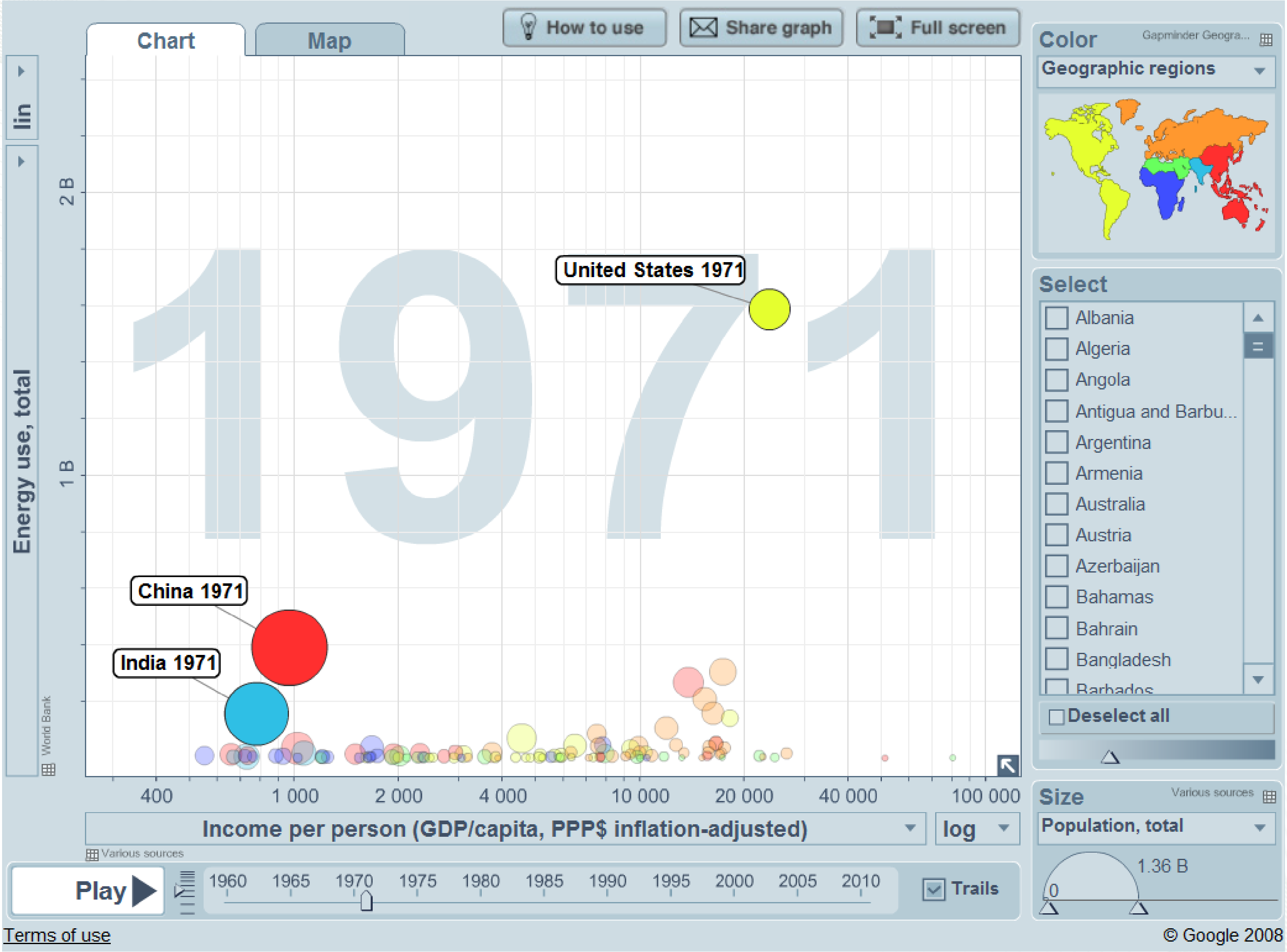
$9B/yr – ESCO; $7B/yr – utility EE
$14B/yr – DR management systems
0.3% modified, BEM < 10% of those

US Energy Consumption

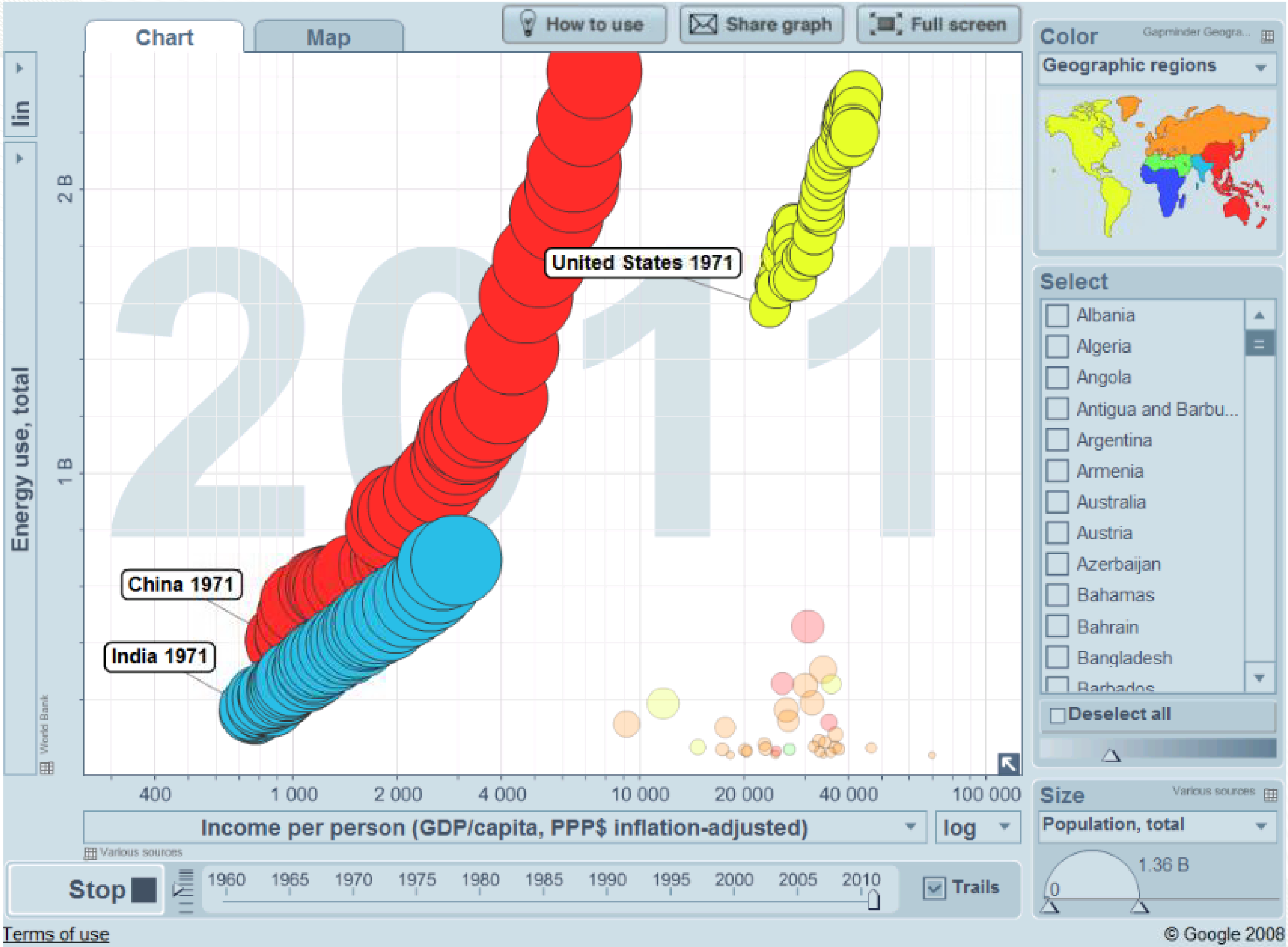


Source: LLNL March, 2016. Data is based on DOE/EIA MER (2015). If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. Distributed electricity represents only retail electricity sales and does not include self-generation. EIA reports consumption of renewable resources (i.e., hydro, wind, geothermal and solar) for electricity in BTU-equivalent values by assuming a typical fossil fuel plant heat rate. The efficiency of electricity production is calculated as the total retail electricity delivered divided by the primary energy input into electricity generation. End use efficiency is estimated as 65% for the residential sector, 65% for the commercial sector, 80% for the industrial sector, and 21% for the transportation sector. Totals may not equal sum of components due to independent Rounding. LLNL-MI-410527

40 Years: Energy and Quality of Life



A brief history of energy and life quality



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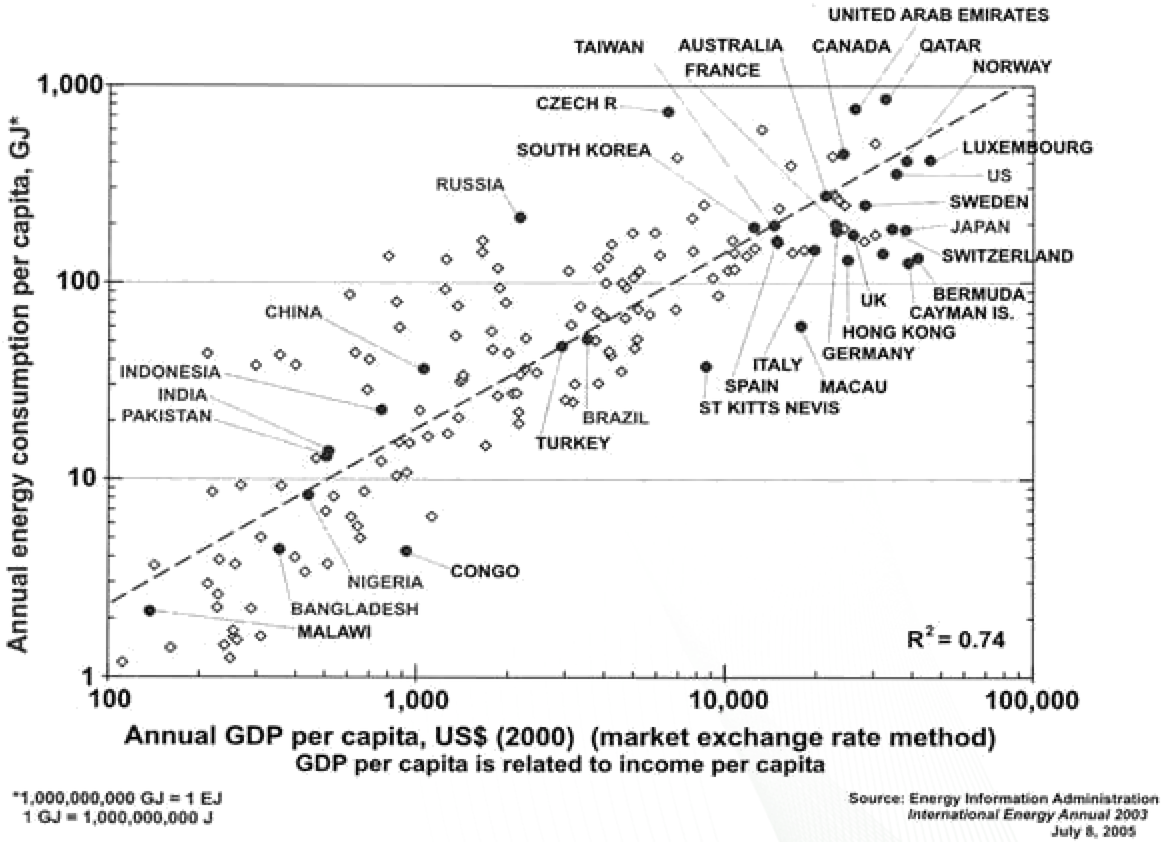
Energy Efficiency and Sustainability - global

- Buildings in U.S.
  - 45% of primary energy & CO_2; 74% of electricity
- Buildings in China
  - 60% of building floor space in 2030 has yet to be built
- Buildings in India
  - 67% of building floor space in 2030 has yet to be built



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Building Energy Modeling
+
Resilience of the Electric Grid
+
ASHRAE’s Changing Climate Zones

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ASHRAE Climate Zones

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

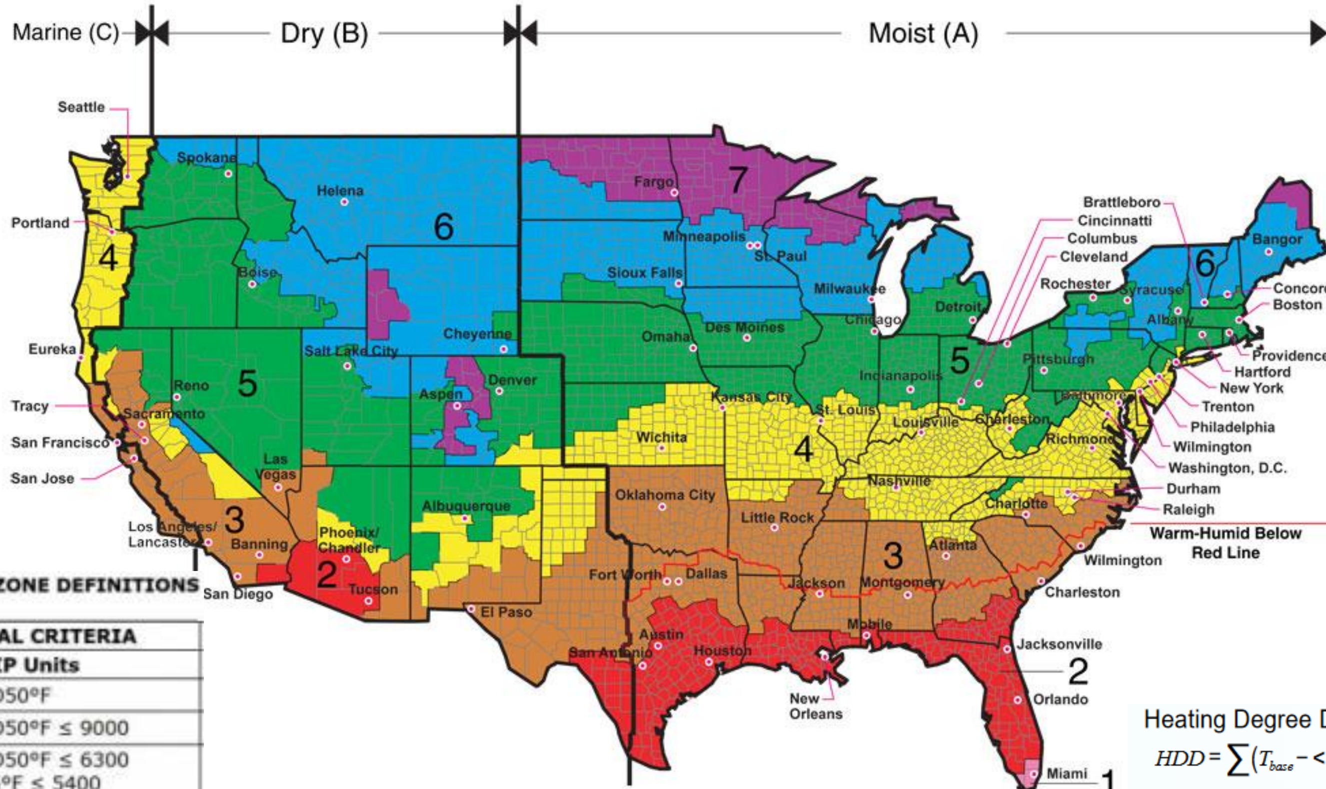


TABLE 301.3(2) INTERNATIONAL CLIMATE ZONE DEFINITIONS

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:

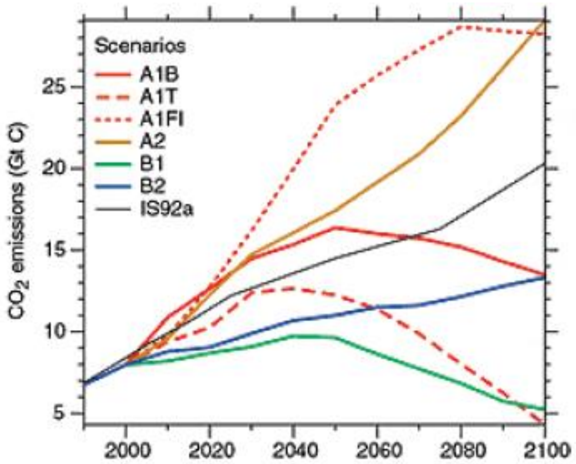
$$CDD = \sum (\langle T_i \rangle - T_{base})^{+}$$

T_{base} = 10°C (50°F)

Redefine CZs using model data

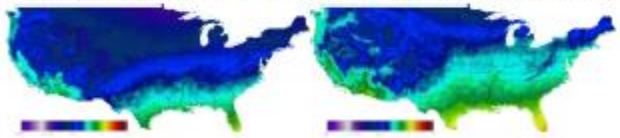
- Resolution: 2 km x 2 km grid cells
- Extent: Continental United States
- Present Conditions (1950-2000): WorldClim
- Future conditions (2050, 2100): PCM and Hadley GCMs; for multiple scenarios (IPCC AR4 A1FI, B1)

1. Precipitation during the hottest quarter
2. Precipitation during the coldest quarter
3. Precipitation during the driest quarter
4. Precipitation during the wettest quarter
5. Ratio of precipitation to potential evapotranspiration
6. Temperature during the coldest quarter
7. Temperature during the hottest quarter
8. Sum of monthly Tavg where Tavg >=5 deg C
9. Integer number of consecutive months where Tavg >= 5 deg C (Length of potential growing season)
10. Solar interception
11. Day/night diurnal temperature difference
12. Elevation



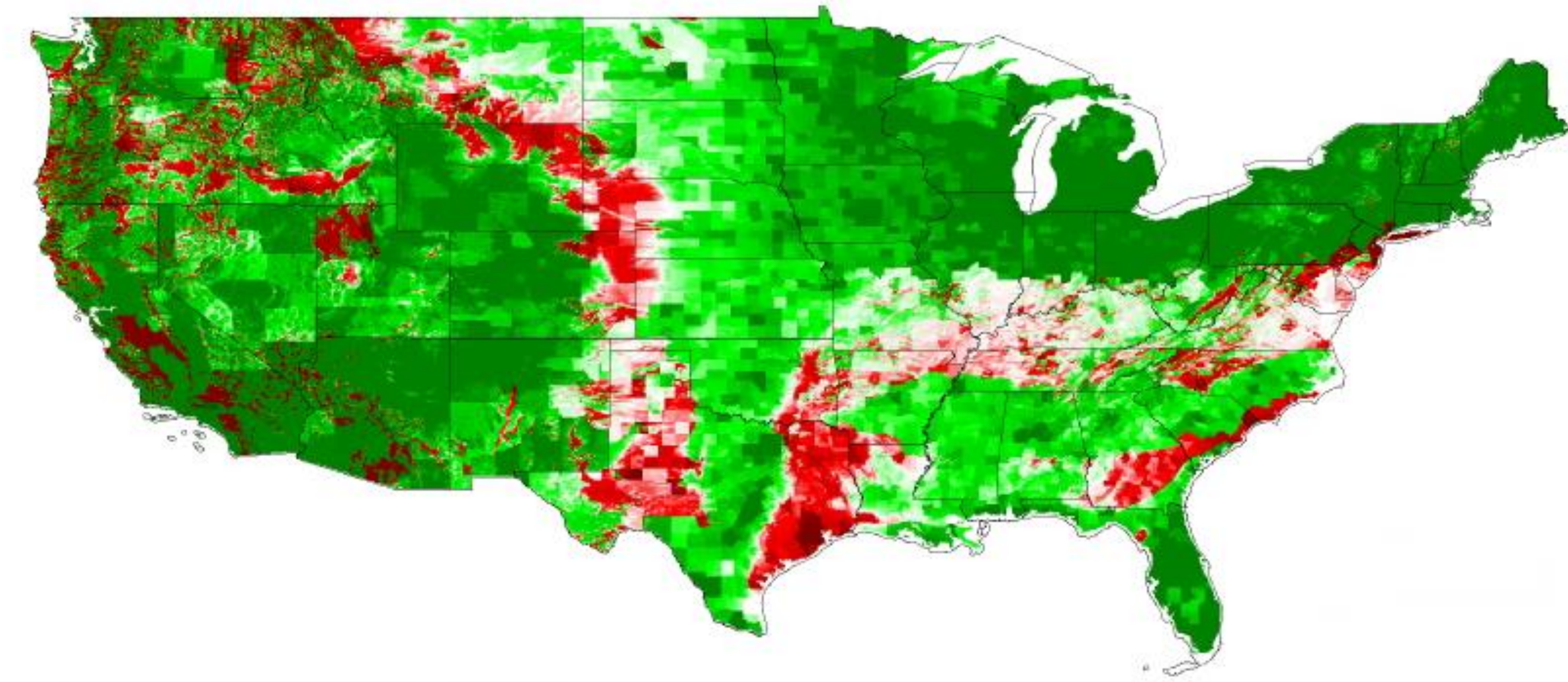
- 12 energy-related variables
  - Temperature
  - Humidity
  - Radiation
  - Elevation

Contemporary period (WorldClim)



Building-adjusted CZ improvement

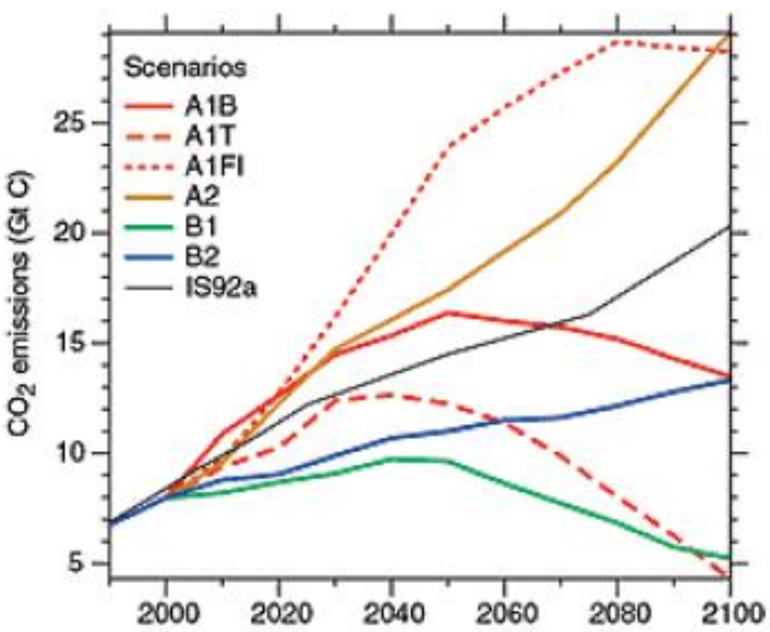
- What other (e.g. political) variables should be included?
- How could the nation's energy security and critical infrastructure resiliency be improved by incorporating future scenarios into the built environment?
- **How much energy and $ could be saved by having a forward-looking climate-aware building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

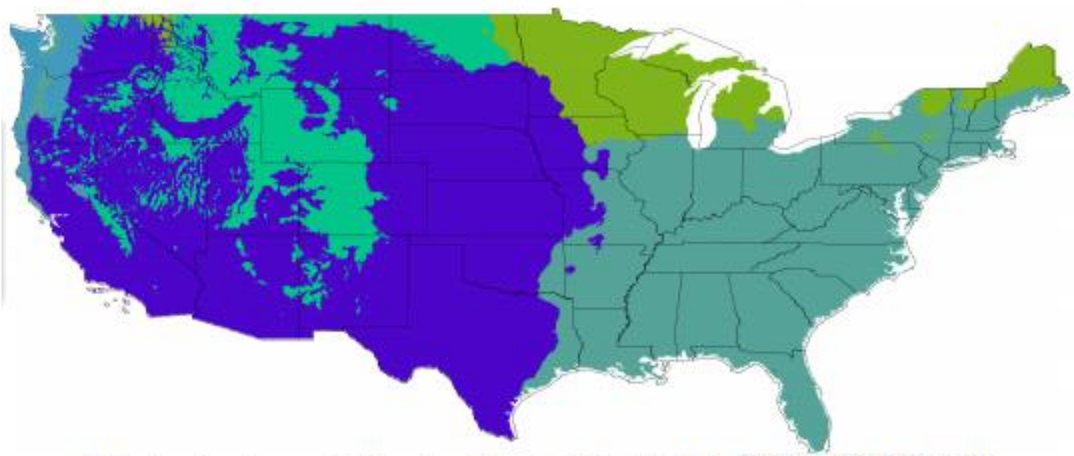


Climate Change Impacts

Contemporary Period

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





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

Building Energy Modeling
+
Grid-interactive Efficient Buildings
+
New Energy Market
(save x ± y at confidence level of z, time-sensitive value trades)

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HPC scalability for desktop software

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

>500k building simulations in <1 hour

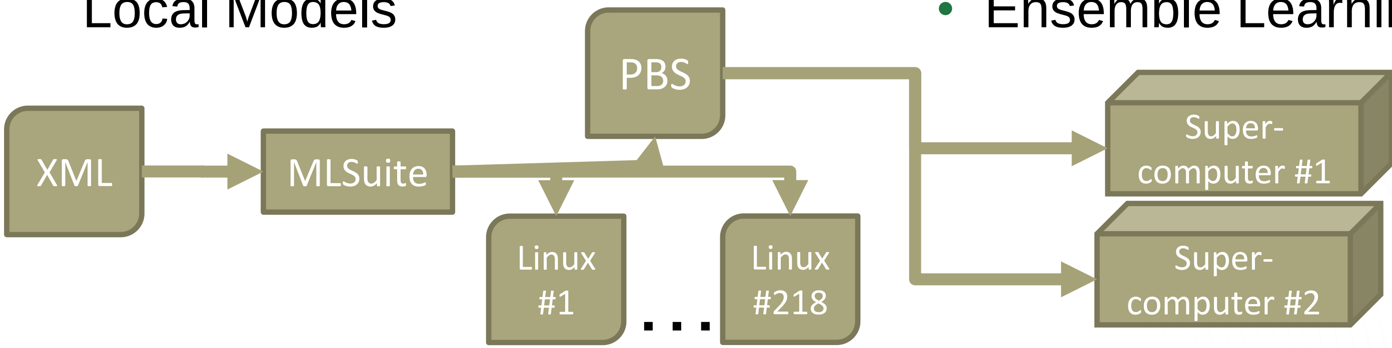
130M US buildings could be simulated in 2 weeks

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

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

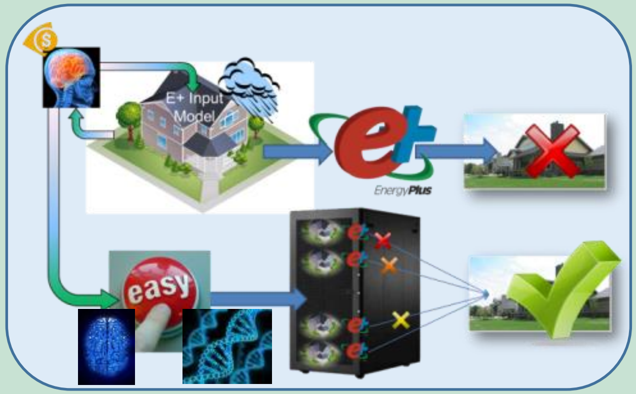


***Acknowledgment:* Dr. Lynne Parker (NSF Div. Dir. Info. and Intel. Systems); Dr. Richard Edwards (doctoral student, now Amazon’s ad analytics)**

Calibration Performance – automated M&V

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	Autotune Results
Monthly utility data	CVR	15%	1.20%
	NMBE	5%	0.35%
Hourly utility data	CVR	30%	3.65%
	NMBE	10%	0.35%

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

Energy I-Corps/Lab-Corps

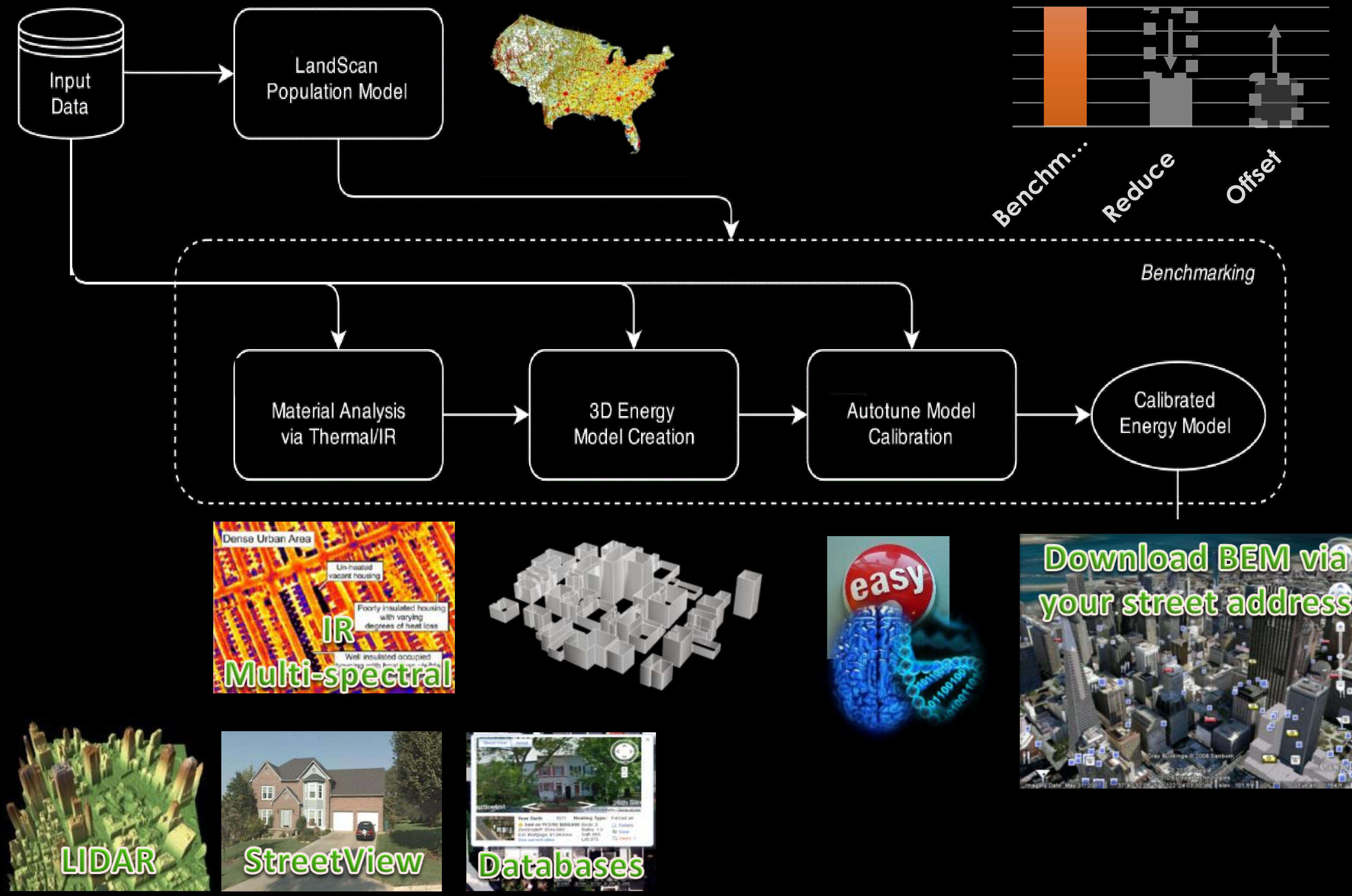
- Multiple organizations and countries using Autotune
- 6-week training program, commercialization of calibration software
  - Scientific method applied to the business model canvas
  - 115 interviews, evolve business model
  - Customer Segments: ESCOs and Utilities
    - Key technical gap:
      Utilities need a building energy model for every building in their service area

NTNU

parallel.works

organic think

Model America 2020 – calibrated BEM for every U.S. building



Building Energy Modeling
+
Automatic Building Energy Model creation (AutoBEM):
Reimagining BEM in a world with HPC, Imagery, and Advanced Metering Infrastructure

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Acknowledgements

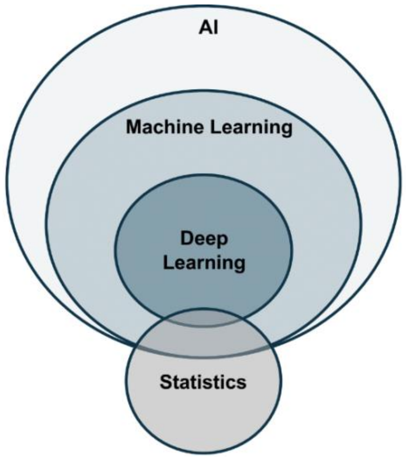
- U.S. Department of Energy
- National Nuclear Security Administration
- Oak Ridge National Laboratory
- Building Technologies Office
- Office of Electricity

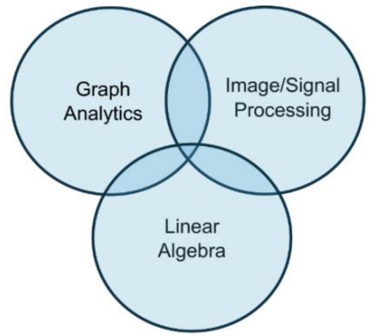
Data Sources

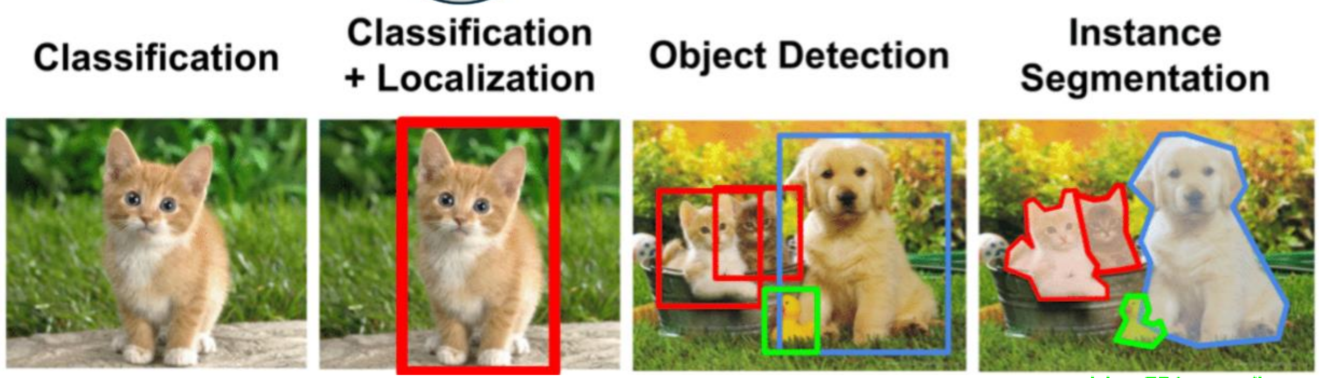
- Database and image sources for urban model generation
  - Satellite and airborne imagery
  - Cartographic data
  - Ground level images
  - Elevation data
  - Building information databases
  - 3D building model databases

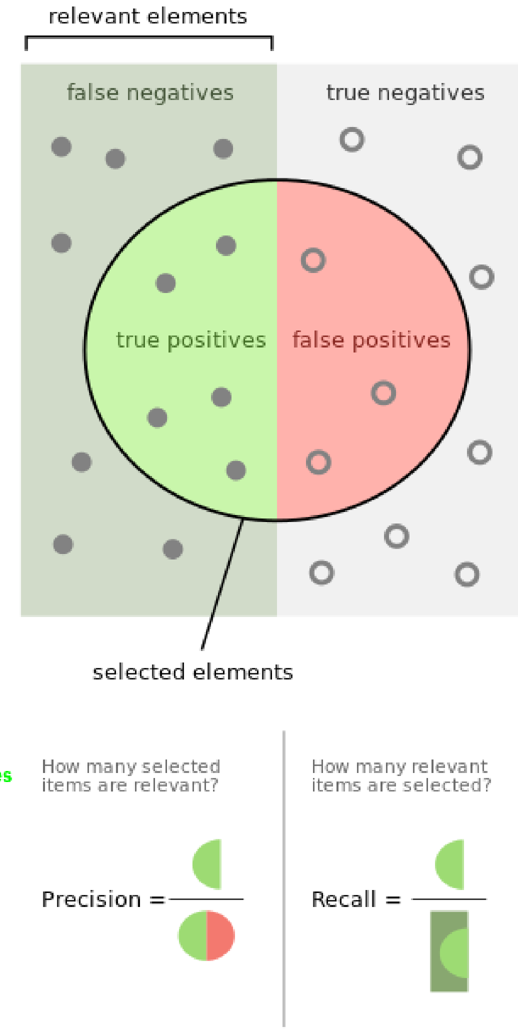
	Short Title
Summary	Satellite imagery, including panchromatic and multispectral images
Data type	Image
Company	
Website	
Temporal resolution	Cities - 3-11 times per week
Spatial resolution	0.3 m
Measure accuracy	
Cost	$11 per sq. km
Format	GeoTiff
Mapping to building input variables	Building footprints
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	

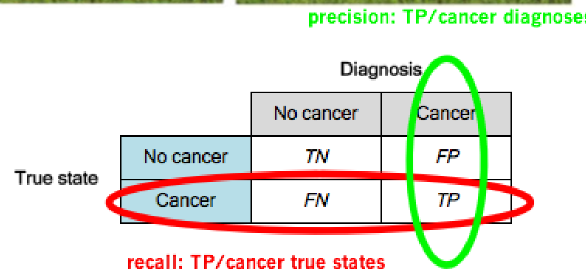
Computer Vision Overview



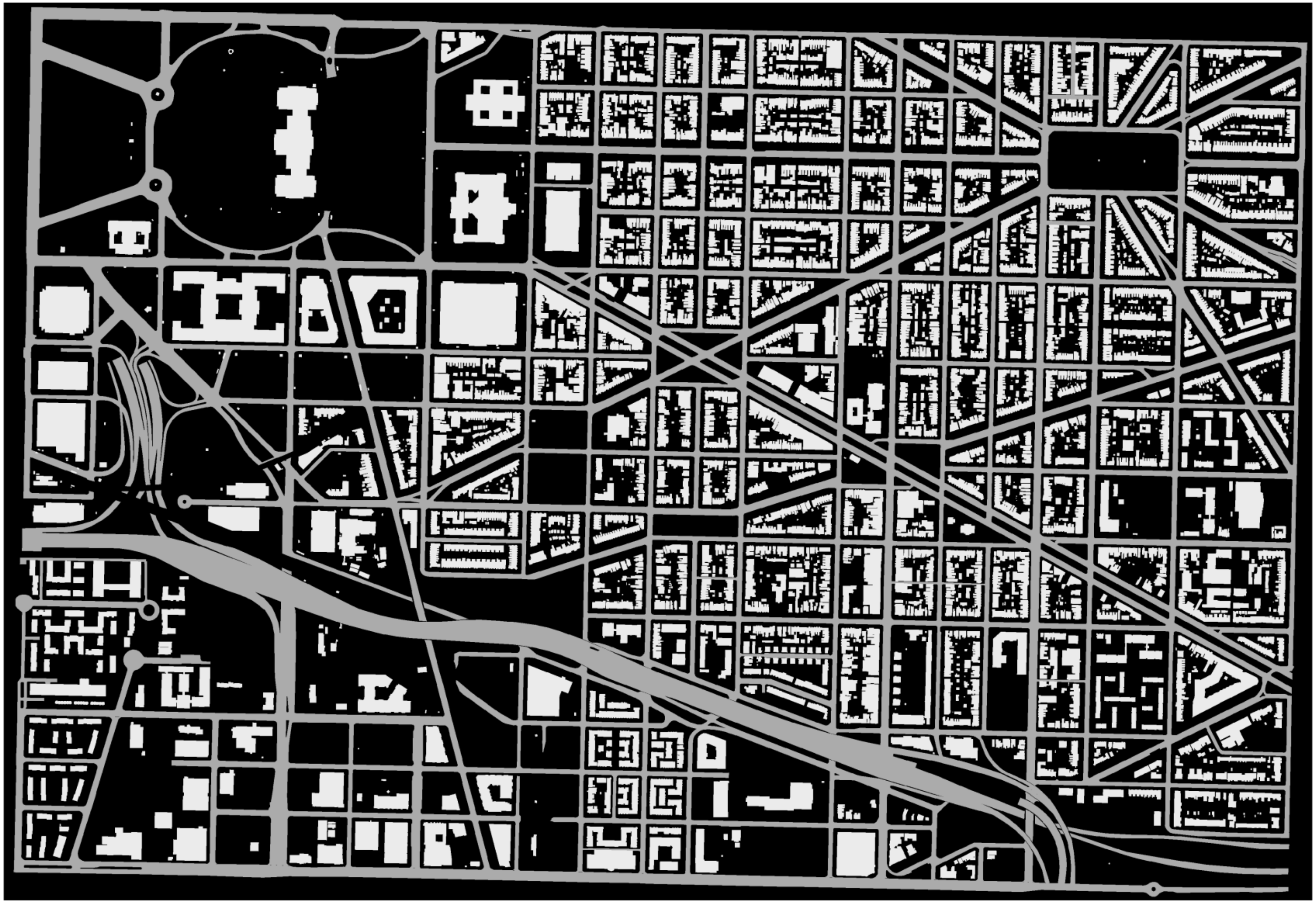




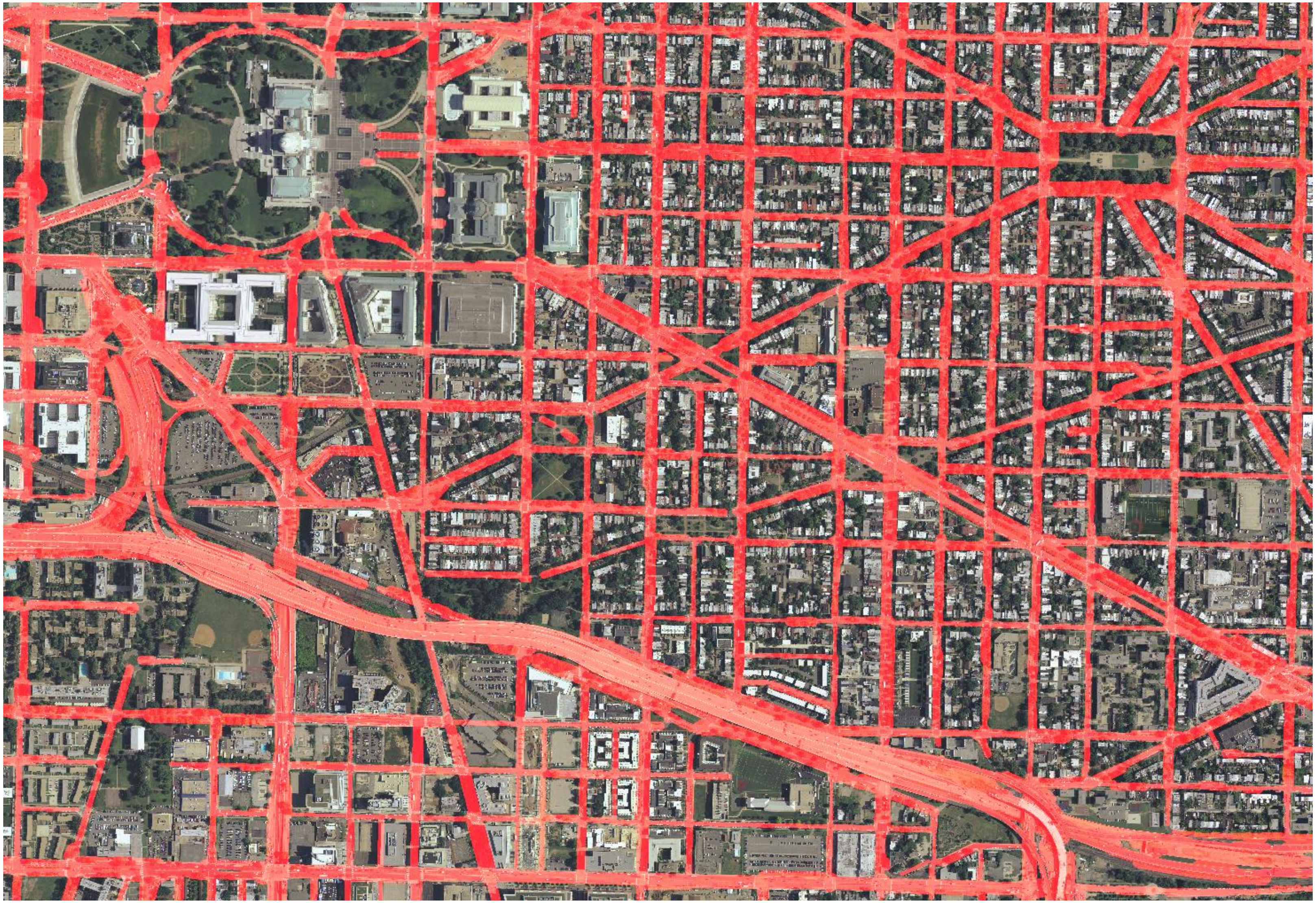




Manual Segmentation of DC



Automatic Road Extraction



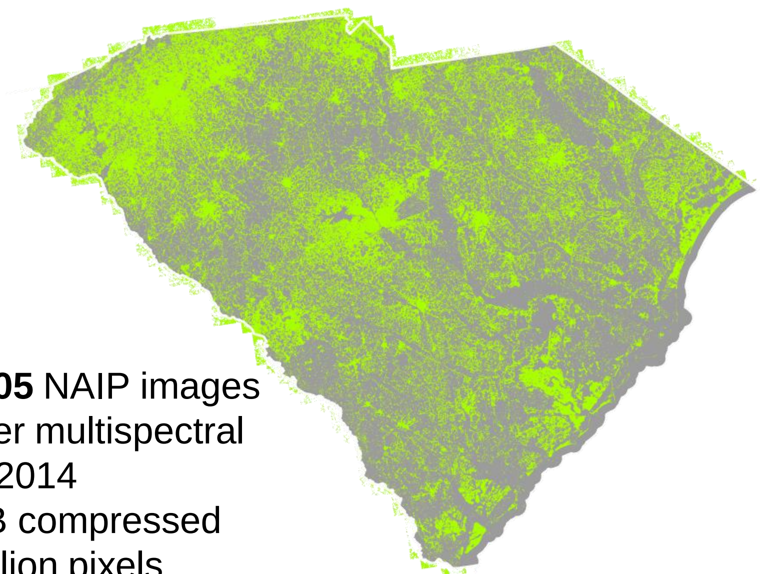
Automatic Building Footprint Extraction

Algorithm: Deep Learning extended and using GPUs for fast building footprint and area extraction over large geographical areas.

Multi-company Competition Precision/Recall – 30/35; Current Precision/Recall – 60+/60+

Automatic Building Footprint Extraction

- **220,005** NAIP images
- 1 meter multispectral
- 2012-2014
- 5.8 TB compressed
- 9.8 trillion pixels



Portland, OR (25,393 m²)
Imagery: June – July 2012
Lidar: September 2010

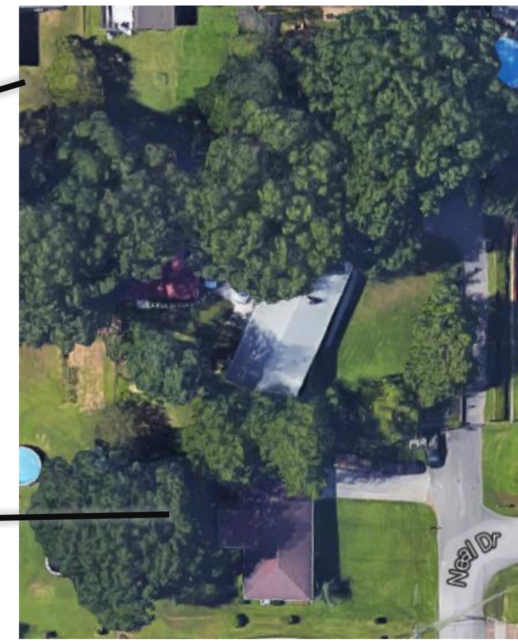
Frankfort, KY (14,801 m²)
Imagery: June 2012
Lidar: June 2011

Part of Knox County, TN (18,527 m²)
Imagery: June 2012
Lidar: October 2014

Comparison to canonical data sets

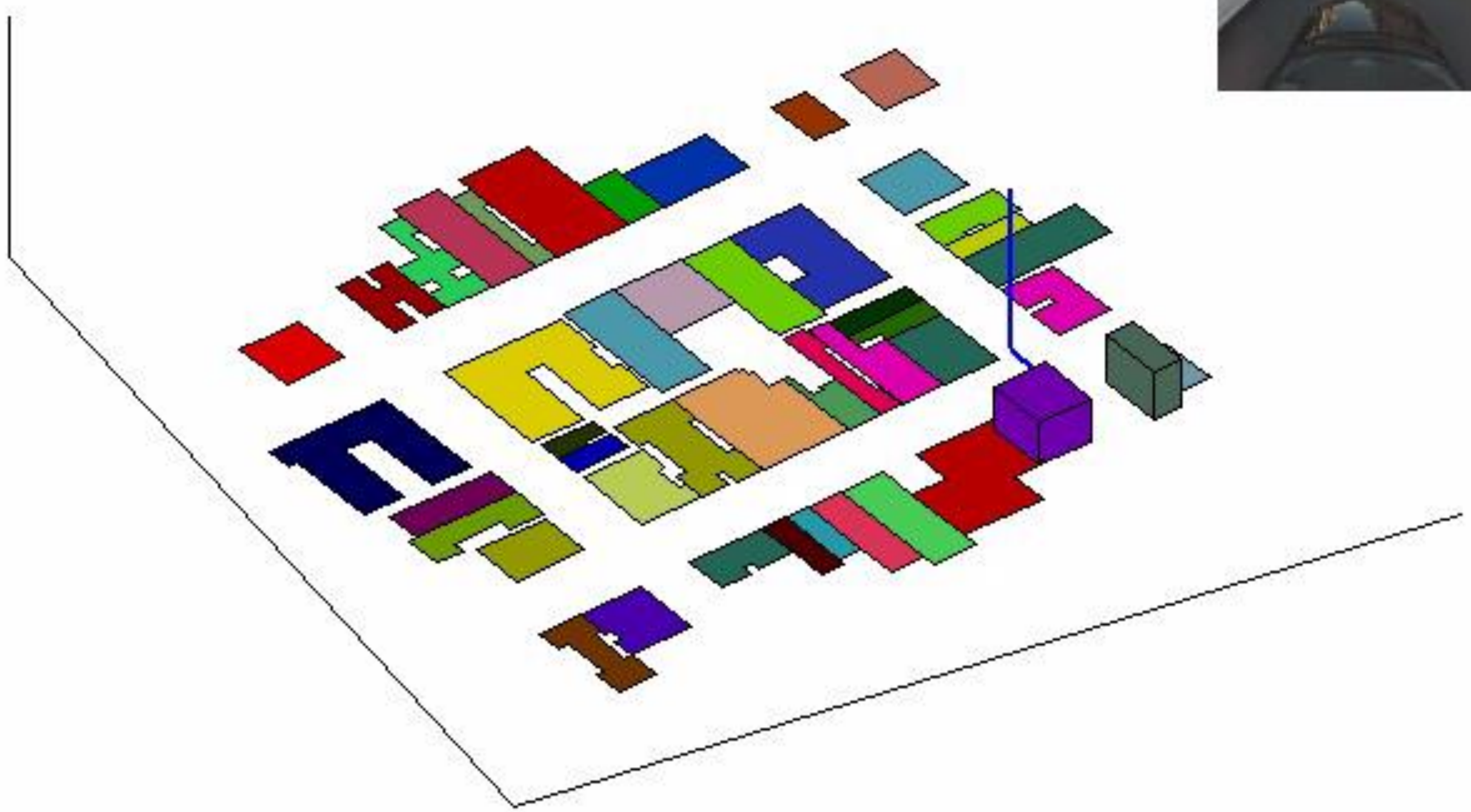
TNGIS Building Data

Lidar to Polygon

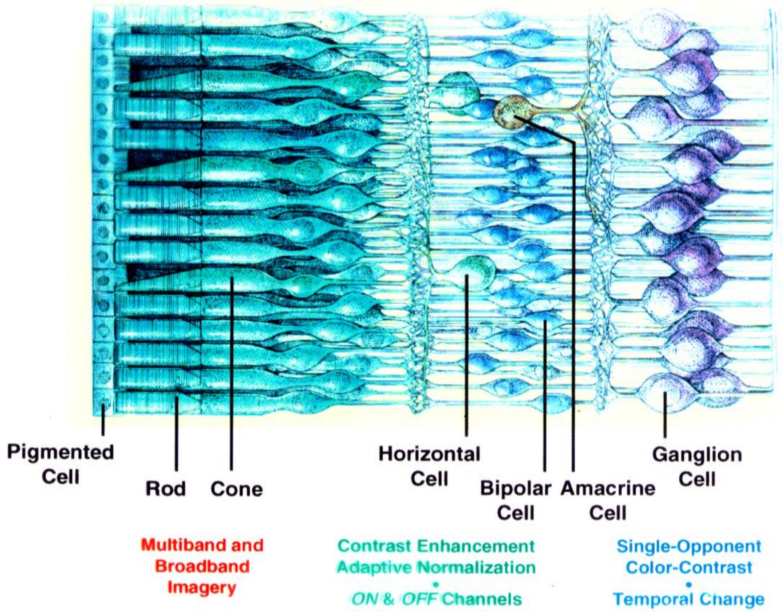


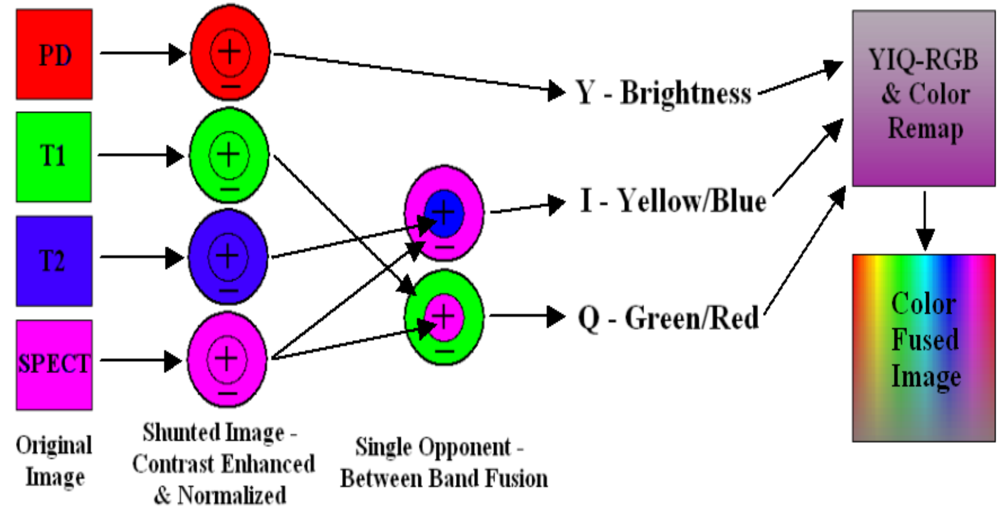
- Shapes are irregular.
- Trees block return hindering building classification by shape.

Processing Street-Level Imagery



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:

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

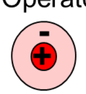
$$x'_{ijk} = -Ax_{ijk} + (B - x_{ijk})C[G_c * I^c]_{ijk}$$
$$- (D + x_{ijk})[G_s * I^S]_{ijk}$$

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:

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

2D Shunt Operator Symbol



3D Shunt Operator Symbol

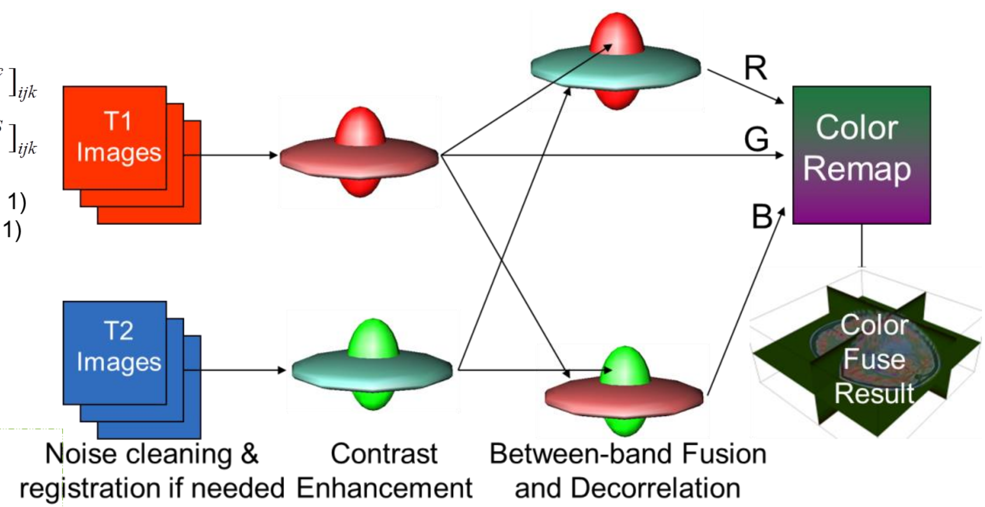
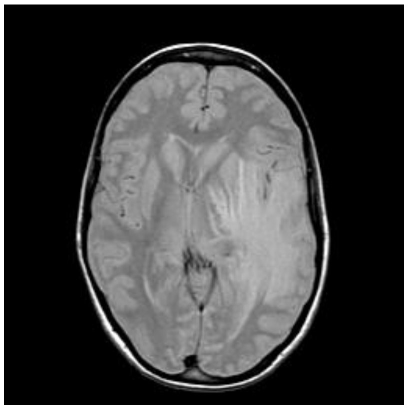
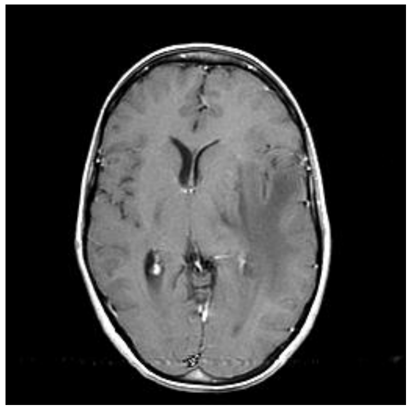


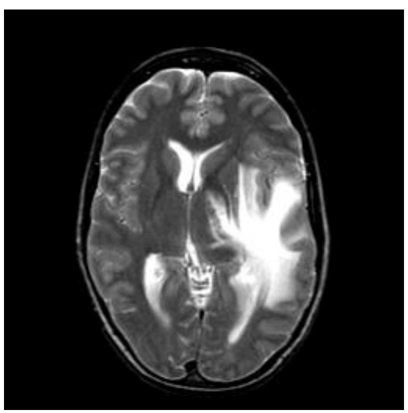
Image Fusion
(color night vision)



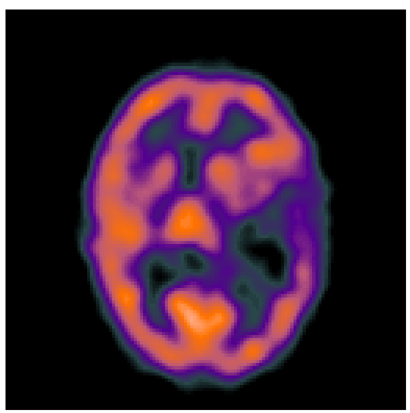
PD



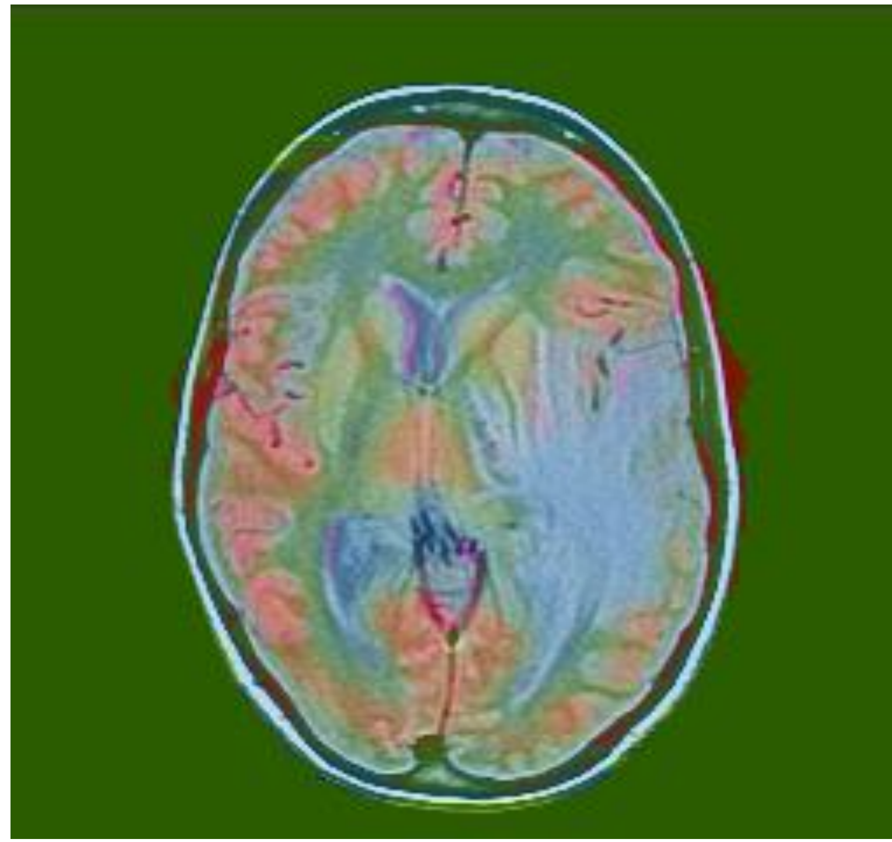
GAD



T2

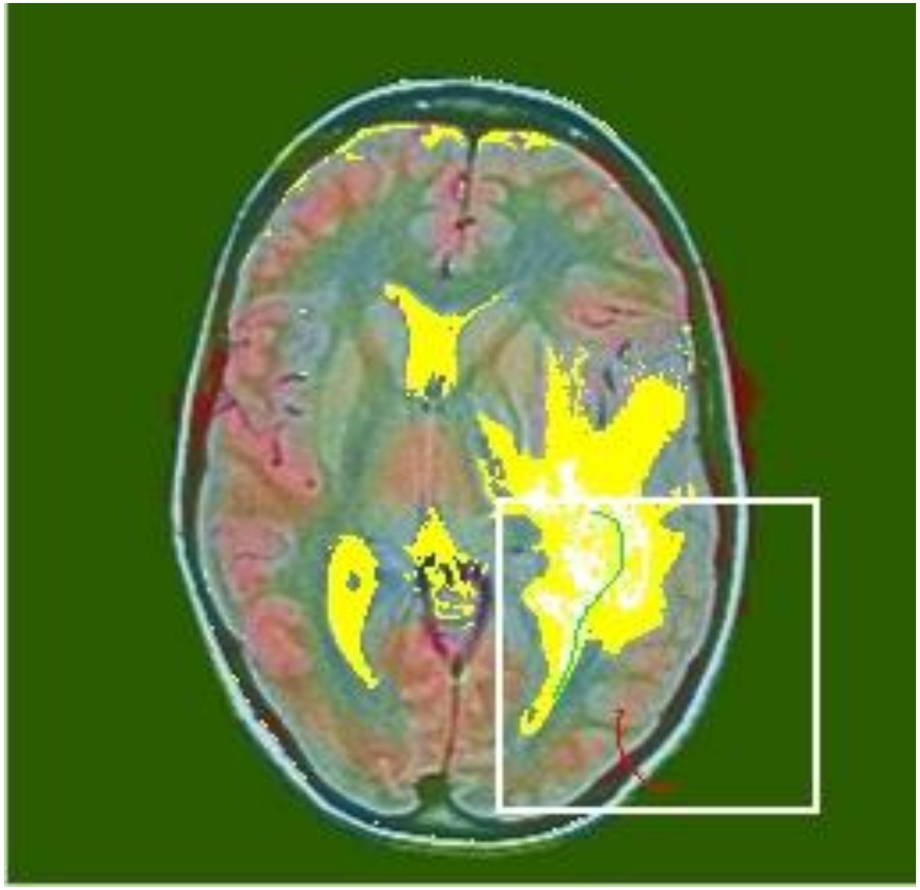


SPECT



Color Fuse Result

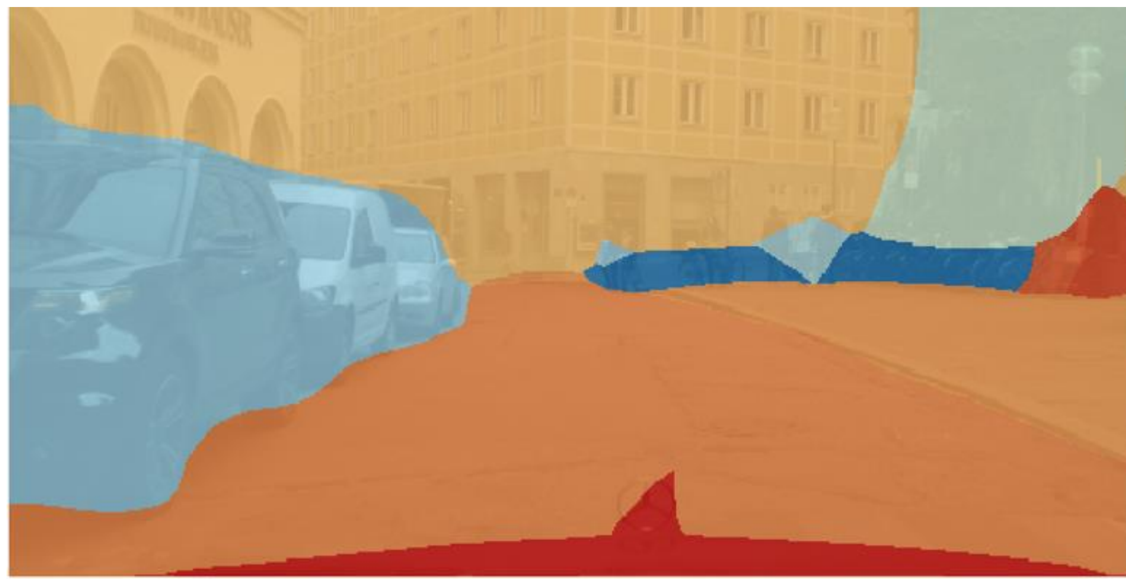
Retinal Fusion and Human/Computer Training (armored tank detection in satellite imagery)



Full Results

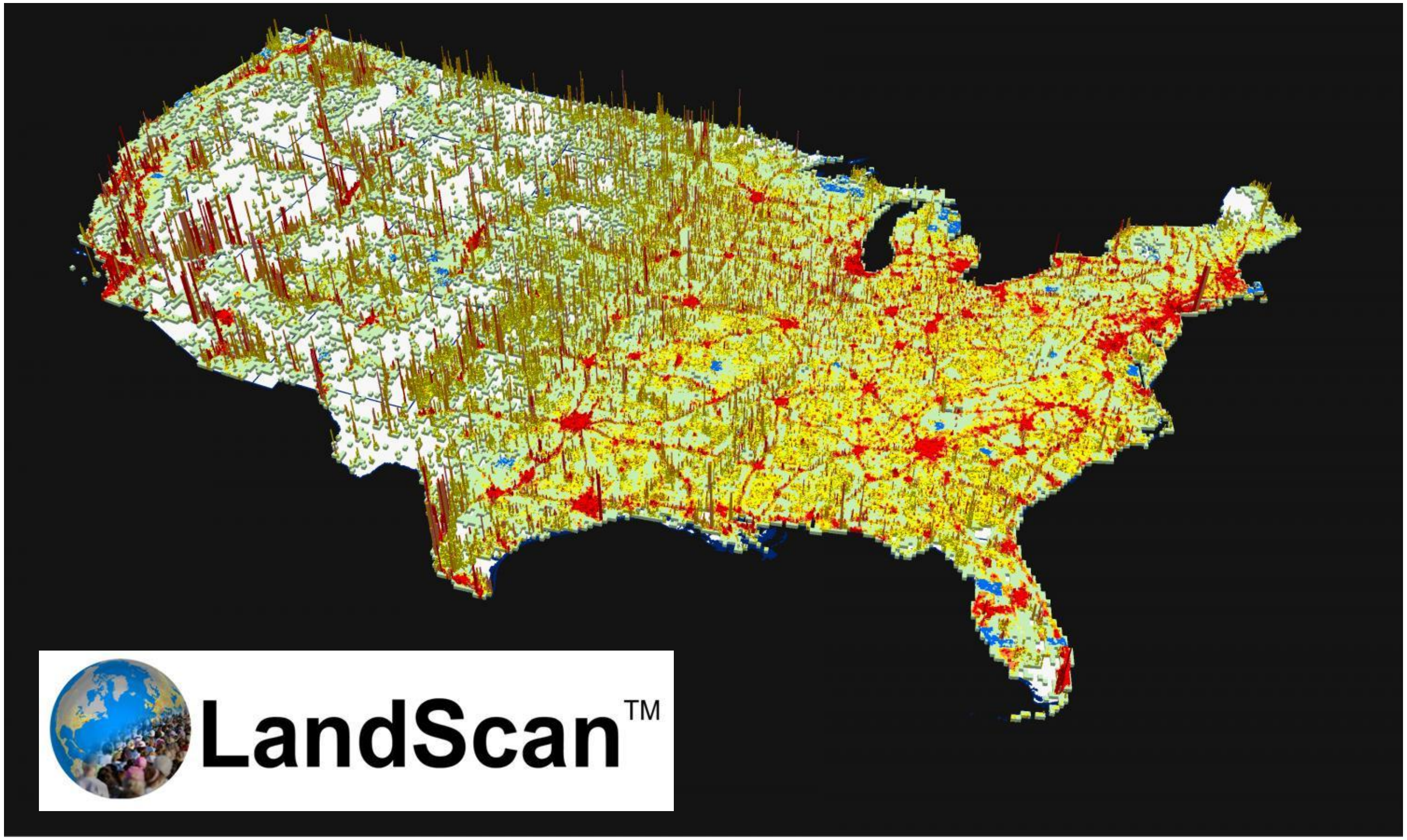
Detailed Results

Detection of Buildings (and properties) from StreetView imagery



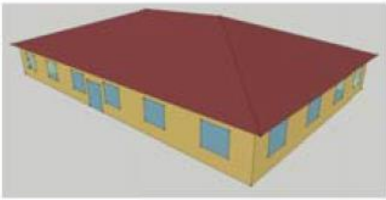
LandScan USA

- 90-meter grid of daytime (commercial) and night time (residential) population
  - ~14 different data sources (e.g. anonymized cell phone GPS)
  - Building occupancy and schedule adaptation

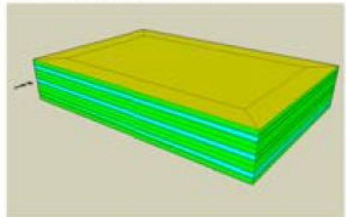


Prototype Buildings

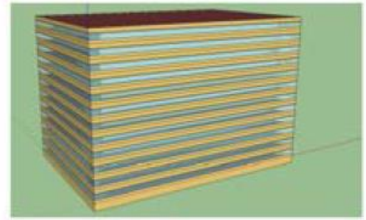
Small Office



Medium Office



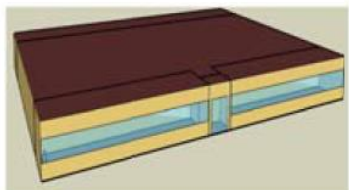
Large Office



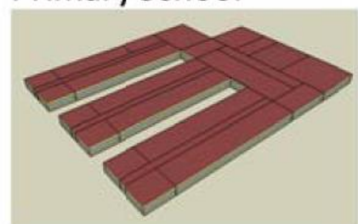
Warehouse

Strip Mall Retail

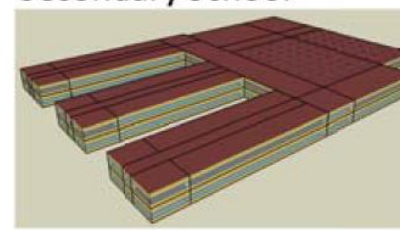
Standalone Retail



Primary School

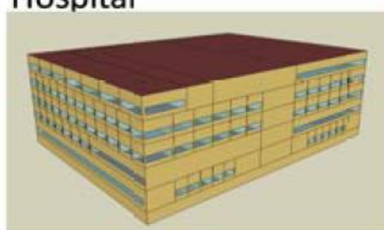


Secondary School



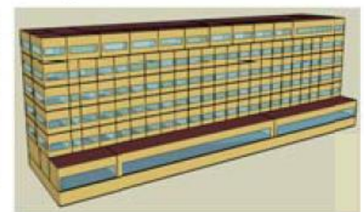
Outpatient Healthcare

Hospital

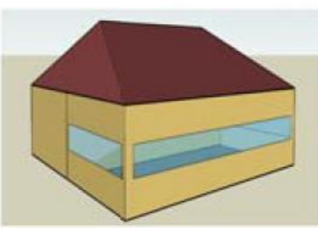


Small Hotel

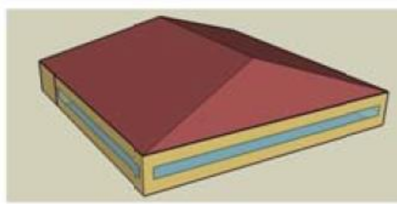
Large Hotel



Quick-service Restaurant

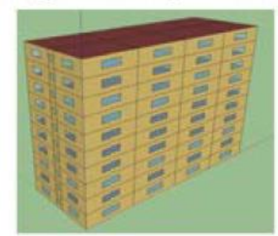


Full-service Restaurant



Mid-rise Apartment

High-rise Apartment

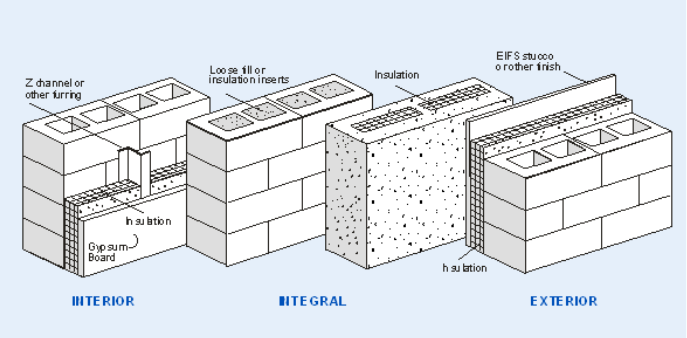


Prototype and Reference Building Updates

- 70, 80 → 90% of U.S. commercial floor space
- 16 types, 16 climate zones, 3 vintages = 768 buildings
  - 17-19+ types, 16-17 climate zones, 5-16+ vintages = 1,360-5,168 models
- ~3,000 avg. parameters per building
  - Square footage, HVAC layout, infiltration (i.e. airflow)
  - Construction (e.g. wall, layers of envelope)
  - Material properties (ASHRAE Handbook of Fundamentals)
  - Equipment and occupancy schedules

Table 3 Properties of Solids

Material Description	Specific Heat, Btu/lb·°F	Density, lb/ft³	Thermal Conductivity, Btu/h·ft·°F	Emissivity Ratio	Emissivity Surface Condition
Aluminum (alloy 1100)	0.214[b]	171[u]	128[u]	0.09[a]	Commercial sheet
				0.20[a]	Heavily oxidized
Aluminum bronze (76% Cu, 22% Zn, 2% Al)	0.09[u]	517[u]	58[u]		
Asbestos: Fiber	0.25[b]	150[u]	0.097[u]		
Insulation	0.20[t]	36[b]	0.092[b]	0.93[b]	"Paper"
Ashes, wood	0.20[t]	40[b]	0.041[b] (122)		
Asphalt	0.22[b]	132[b]	0.43[b]		
Bakelite	0.35[b]	81[u]	9.7[u]		
Bell metal	0.086[t] (122)				
Bismuth tin	0.040*		37.6*		
Brick, building	0.2[b]	123[u]	0.4[b]	0.93*	



AutoBEM – Automatic Building detection and Energy Model creation

- 19 underlying Intellectual Properties (granted or in process)
  - Range from classified to open-source
  - AutoBEM-LiDAR
  - AutoBEM-Aerial – world's best building footprint extractor
  - AutoBEM-Street
  - AutoBEM-3D DB
  - AutoBEM-Type
  - AutBEM-Gen – world's fastest BEM creator
  - AutoSIM – world's fastest buildings simulator
  - AutoDoEGen
  - AutoSTAT
  - Autotune – world's best calibration algorithm

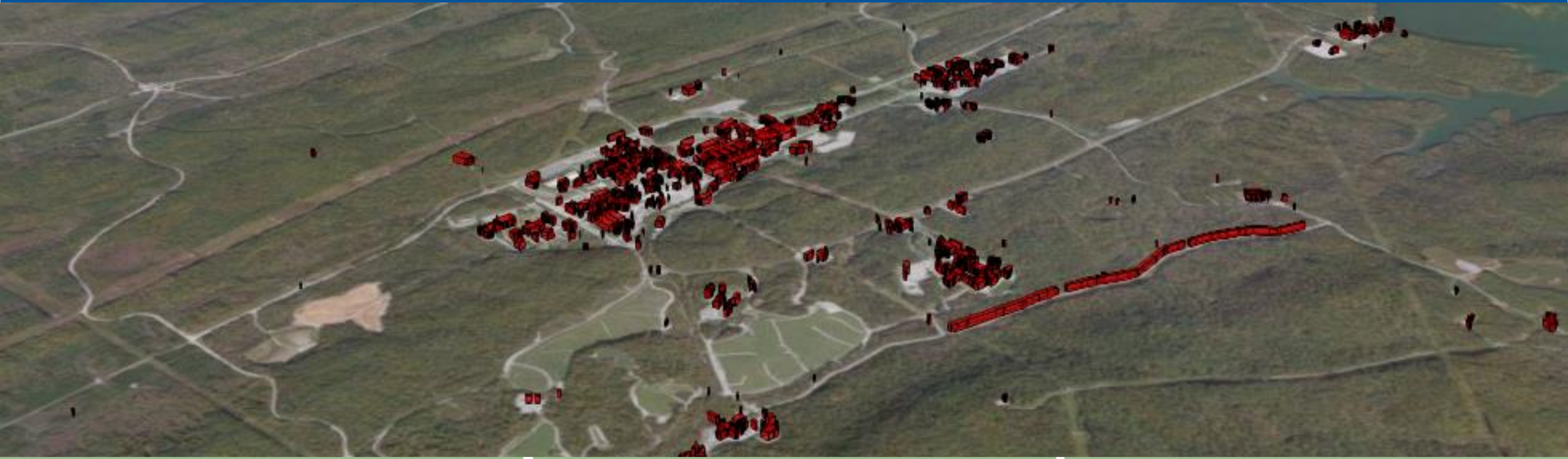
AutoBEM – ongoing work

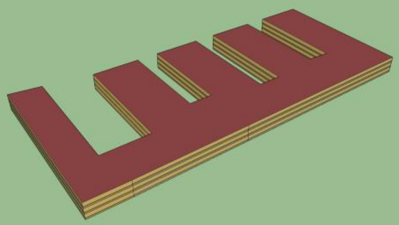
- AutoBEM-Aerial/HVAC
- AutoBEM-Aerial/Chiller
- AutoBEM-scrape

AutoBEM Façade

AutoBEM WWR

Oak Ridge National Laboratory





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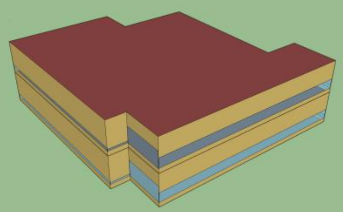

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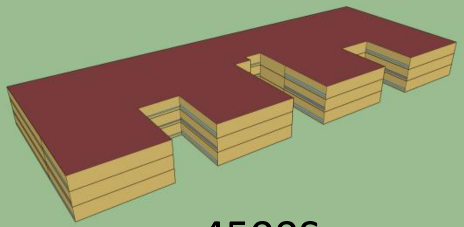

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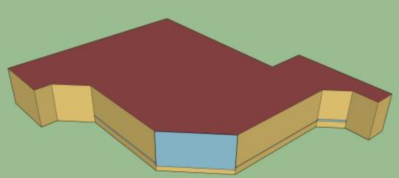

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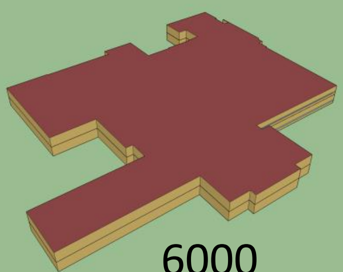
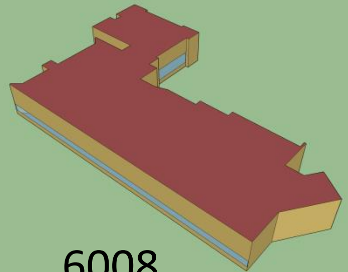


6000



6008

Oak Ridge National Laboratory (interactive)

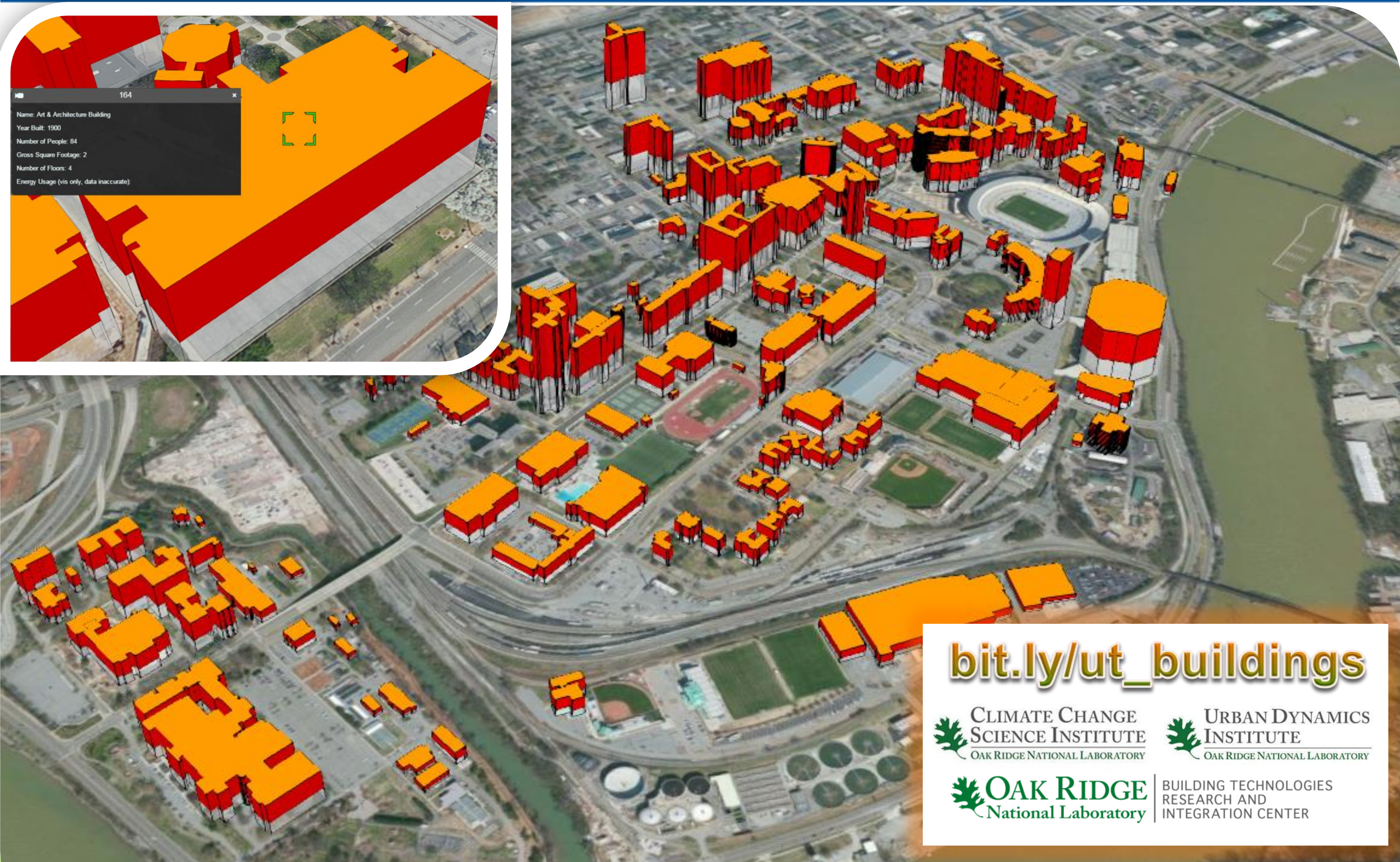
bit.ly/ornl_buildings

CLIMATE CHANGE SCIENCE INSTITUTE
OAK RIDGE NATIONAL LABORATORY

URBAN DYNAMICS INSTITUTE
OAK RIDGE NATIONAL LABORATORY

OAK RIDGE National Laboratory
BUILDING TECHNOLOGIES RESEARCH AND INTEGRATION CENTER

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

Oak Ridge National Laboratory

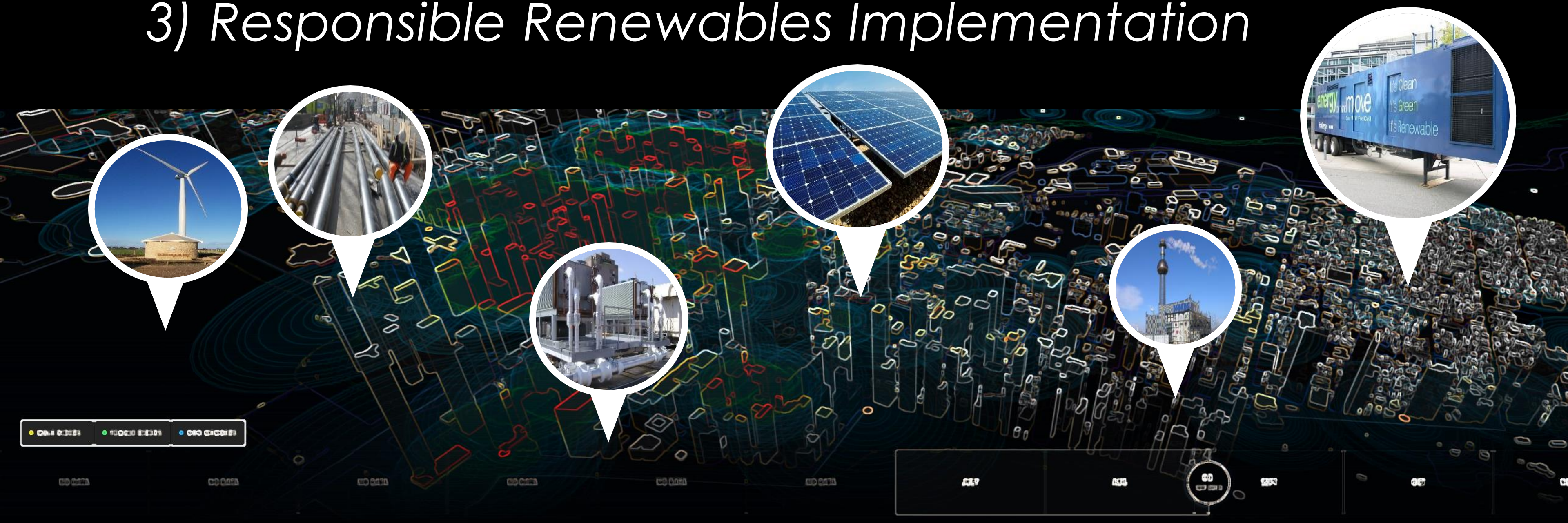
Building Technologies Research and Integration Center

Uses: Grid Modernization Load Models, Transactive Energy, Actionable Sustainability Plan, Carbon Neutrality, EE programs, Utility/Distributor Business Models (EaaS)

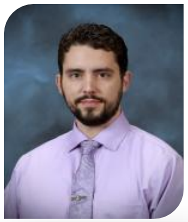
1) Demand-Side Building Efficiency

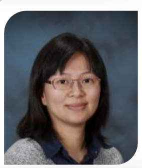
2) Distribution and Supply-Side Infrastructure Enhancements

3) Responsible Renewables Implementation



Virtual EPB – bios




- Joshua New, Ph.D., C.E.M., PMP
  - BTRIC "Software Tools & Models" responsible for development of DOE's building simulation tools, HPC, and AI for big data mining.
  - Led 62 projects (9.4/year) totaling $10M/$28M ($1.3M/yr)
    - 133/133 deliverables (44/yr) on-time and on-budget; 100+ publications (13.8/yr)
- James (Jim) Ingraham, B.S. Finance
  - EPB, VP of Strategic Research; electric utility and broadband communications; market research and data modeling
- William (Bill) Copeland, B.S. Economics, MBA
  - EPB, Director of Business Intelligence, EPB business systems, visual analytics
- Hsiuhan (Lexie) Yang, Ph.D. Civil Engineering
  - Computer vision specializing in aerial imagery
  - Machine learning for large data: NASA, AIST, NSF, DOE
- Mark Adams, M.S. Ag&Bio, Mechanical Engineering
  - Building simulation expert, EnergyPlus/OpenStudio developer

Virtual EPB Summary

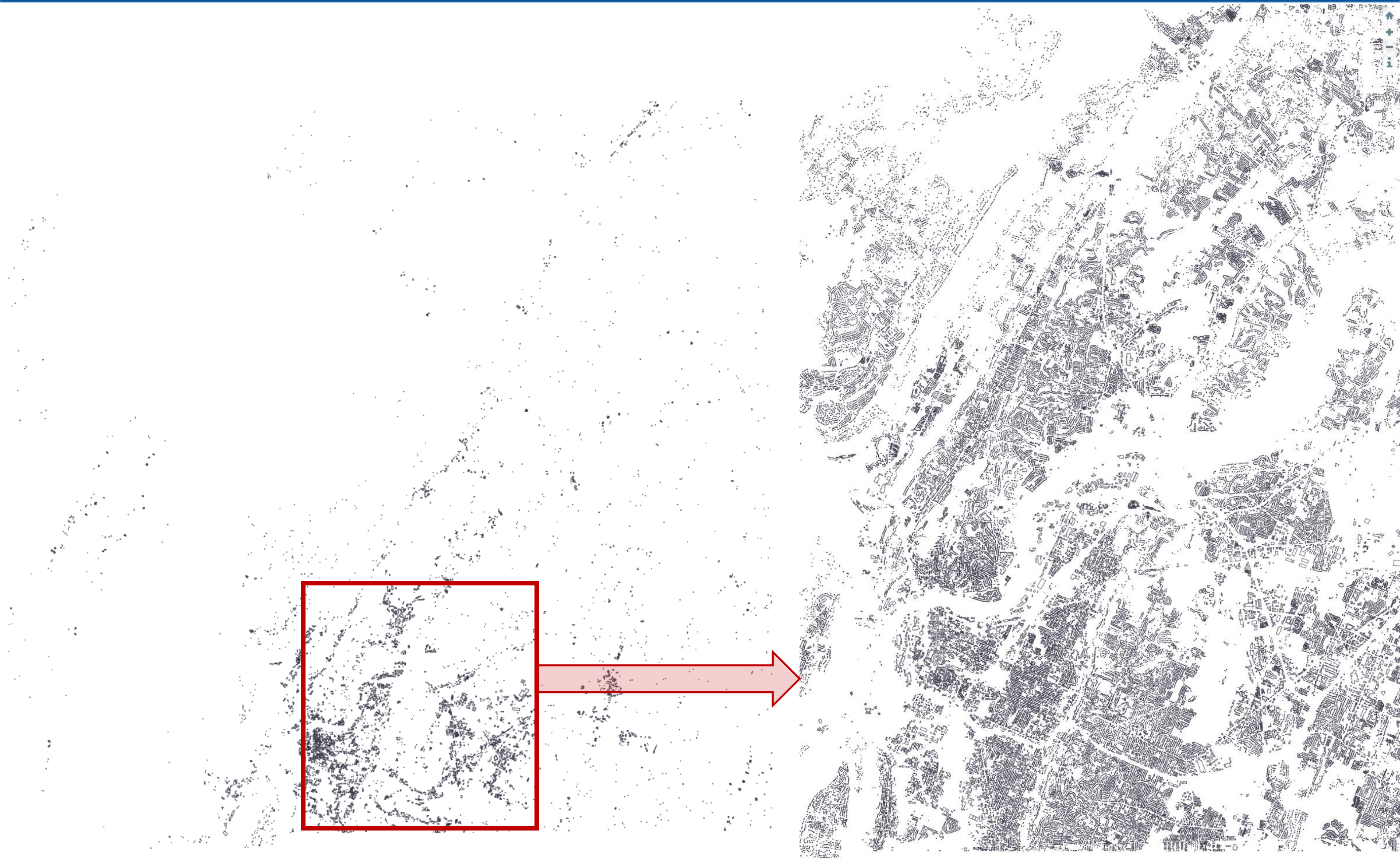
- Total - $700k (OE-$450k, 41 tasks; BTO-$250k, 15 tasks)
  - Final Deliverable: Simulation-informed data and valuation report for energy, demand, emissions, and $ impact to EPB for each building in EPB's service area for 5 prioritized use cases covering 9 monetization scenarios
- BTO ends 9/30/18 (WBS 2.5.1.31 "ORNL – OpenStudio – Virtual EPB")
  - FY18: 8 tasks, 6 quarterly milestones, 1 Go/No-Go (passed)
  - 7% ahead of schedule (SPI-1.07): 5 of 15 tasks completed (10 remaining)
  - 6% over budget (CPI-1.06)
- OE ends 4/1/19 ("Virtual EPB - Scalable Approach to Improve Load Models via Automated Building Creation and Autotune Calibration")
  - FY17: 10/10 tasks complete; 3 publications, 3 presentations
  - FY18+: 25 tasks, 6 milestones (10 remaining)
  - 100% on schedule (SPI-1.0): 15 of 18 tasks completed (3 remaining)
  - 1% over budget (CPI-1.01)

Utility Use Cases for Virtual EPB

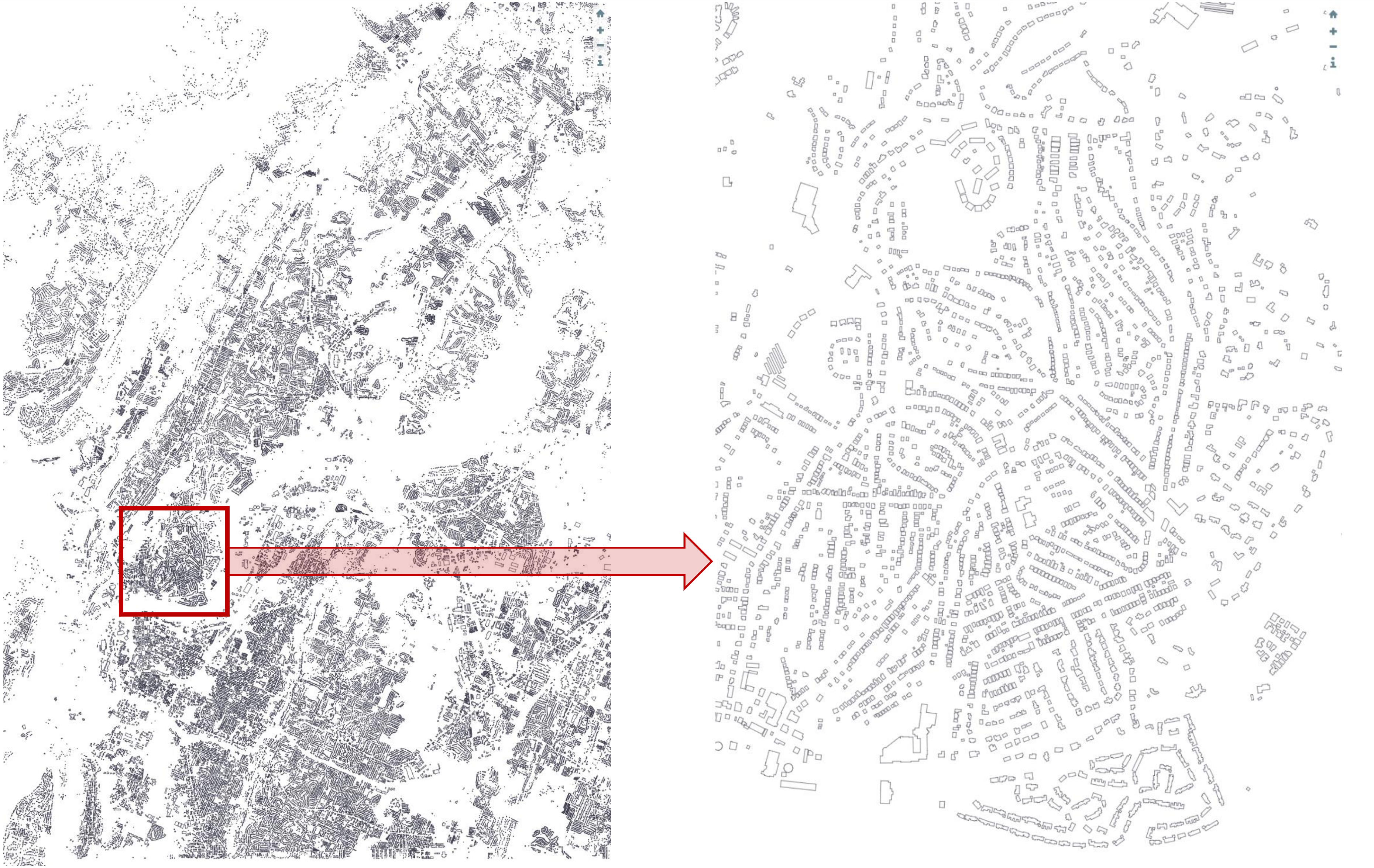
- **Peak Rate Structure** - model peak segment customers in aggregate as disproportionate contributors to electric utilities' wholesale demand charges for more equitable rate structures.
- **Demand Side Management** – identify DSM products and grid services for better distribution grid management that allow both utilities and rate-payers to share in peak reduction
- **Grid stability services** – quantify improved load models
- **Emissions** – accurately account for emissions contributed by each building, providing enhanced abilities for utilities to best comply with national emission policies.
- **Energy Efficiency** – accurate modeling/forecasting of every building energy profile virtually in a scalable fashion allows better follow-up and more targeted energy audits/retrofits.
- **Customer Education** - better understand building's energy usage as a function of weather to provide better information during customer billing enquiries.

Energy, Demand, Emissions, and $ for 9 scenarios (Customer->EPB, EPB->TVA)

EPB buildings in Tennessee (166,944)

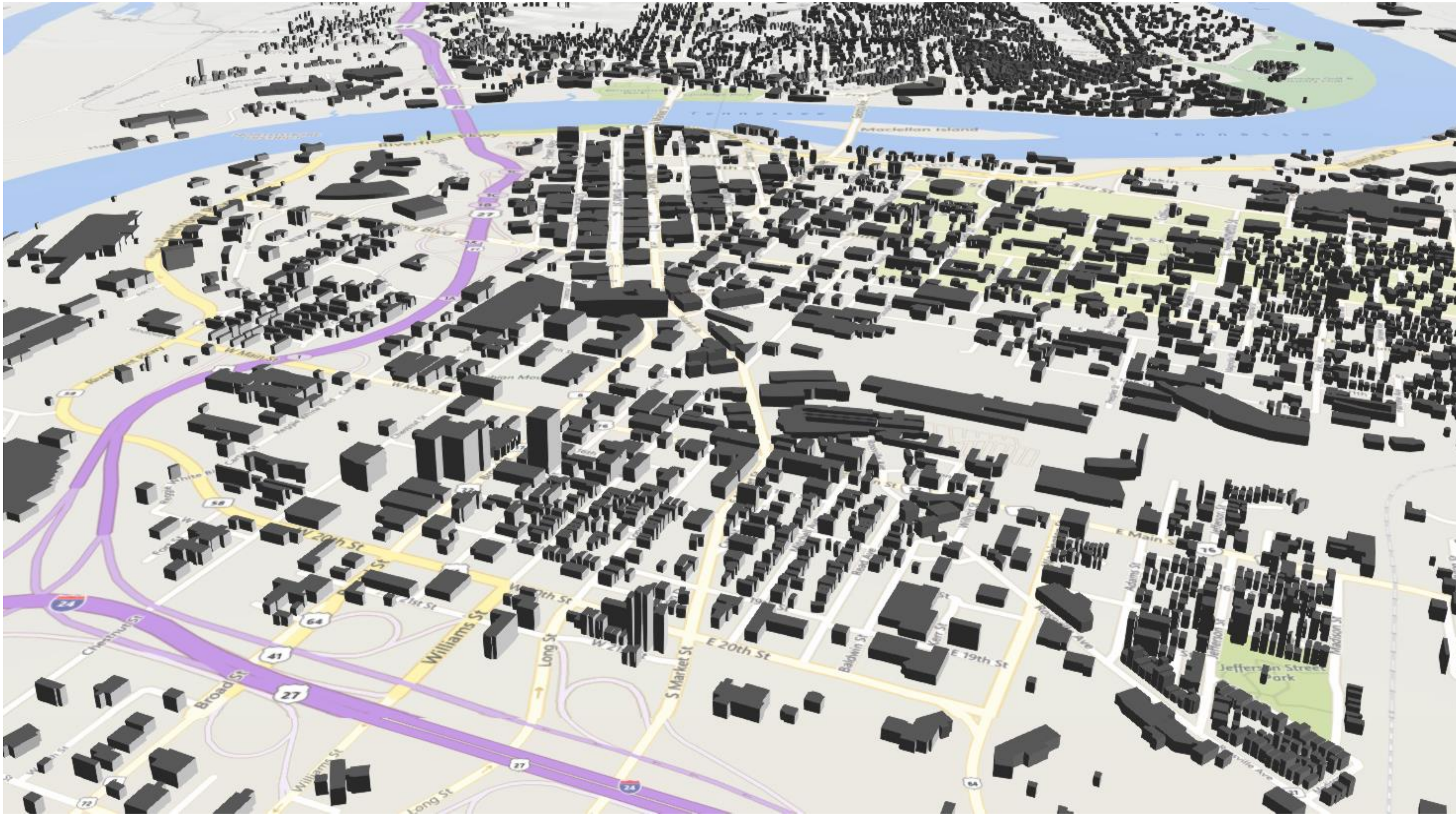


EPB buildings in Tennessee (166,944)



EPB buildings in Tennessee (166,944)

Chattanooga, TN (100,000+ buildings)



Completed Deliverables (Q1)

- 100+ page internal report NDA/OUO
  - New, Joshua R., Hambrick, Joshua, and Copeland, William A. (2017). "Assessment of Value Propositions for Virtual Utility Districts: Case Study for the Electric Power Board of Chattanooga, TN." ORNL internal report ORNL/TM-2017/512, December 15, 2017, 107 pages.
- 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

	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

  - 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 types

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

1.9 million EnergyPlus building energy models using AutoBEM technology, Titan, cloud, and local servers to produce and analyze 10.7 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)

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.

1a – Peak contribution percentile by type

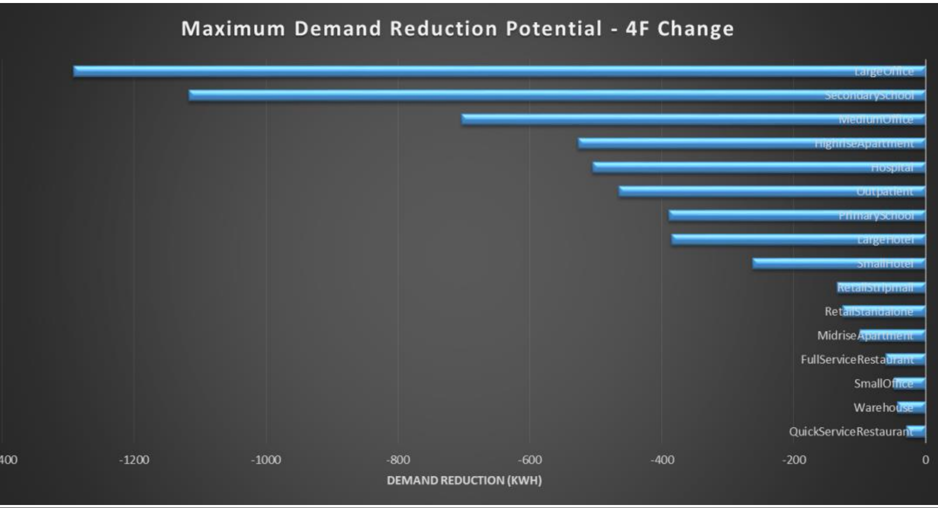
	A	B	C	D	E	F	G	H	I
1	building_id	cost_diffe	annual_energy (kWh)	retail_energy_cost ($)	wholesale_energy_cost ($)	annual_demand (kW)	retail_demand_cost ($)	wholesale_demand_cost ($)	
2	74861	5597.552	129749.1048	12157.49112		409.1261424	6501.014402		
3	113092	5415.594	127559.3297	11952.30919		383.8685745	6099.671648		
4	64129	5129.817	119339.2912	11182.09158		372.3913263	5917.298174		
5	103236	5572.164	129294.5828	12114.90241		406.4806789	6458.977987		
6	31936	4810.198	111343.3805	10432.87475		352.4933801	5601.11981		
7	82416	3269.327	76298.73286	7149.191269		235.9072173	3748.565684		
8	60724	3228.218	75268.60281	7052.668083		233.3579747	3708.058218		
9	54787	3592.691	82729.37285	7751.742236		265.8210192	4223.895994		
10	103004	3642.78	84572.18239	7924.41349		265.4617199	4218.18673		
11	33125	3450.992	80583.79881	7550.701949		248.7478345	3952.603091		
12	[illegible]	[illegible]	[illegible]	[illegible]		[illegible]	[illegible]		

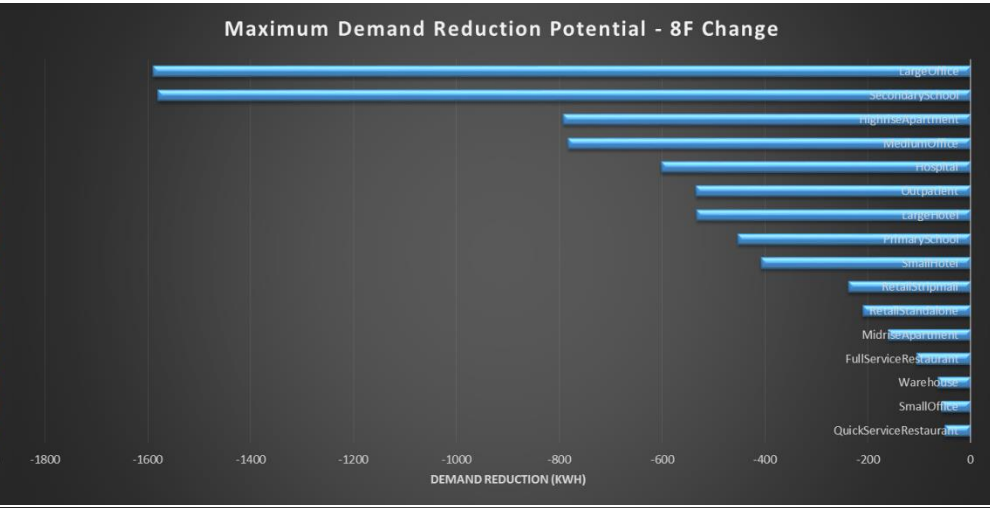
- Building ID
- Area (m^2)
- Number of Floors
- Color: Energy Use Intensity (kWh/m^2) by building type
- Min/Avg/Max by building type

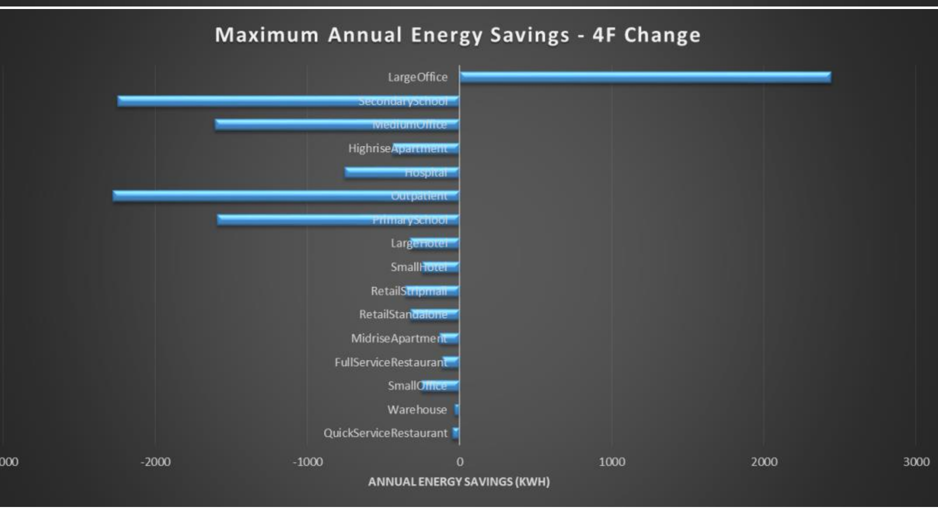
2a - Smart Thermostat

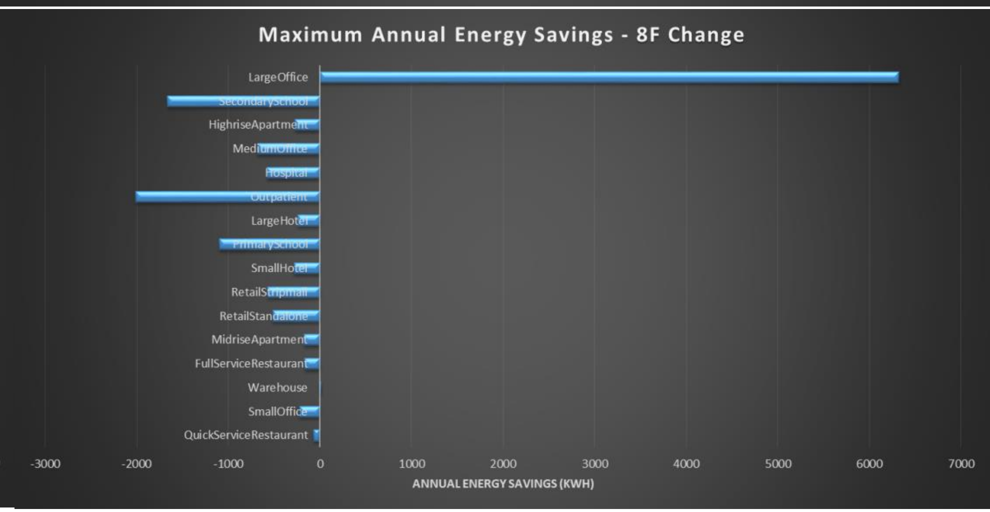
- Pre-heat/pre-cool 2 or 4 hours prior to peak demand hour each month
  - Single Heating or Single Cooling thermostat – up or down 4°F and 8°F
  - Dual Setpoint Thermostat – Average of baseline cooling and heating setpoints with a 0.5°C deadband
- Setback thermostat setpoint by 4°F or 8°F for peak demand hour and 4 hours after peak for each month
- Altered thermostat values affects 38 (1-4 per building type) thermostat schedules in 518 (3-118 per building type) thermal zones for 16 different building types
- The 4°F and 8°F runs are compared to baseline, unaltered simulation to determine demand reduction and energy savings potential

2a - Smart Thermostat: Maximum Demand and Energy Reduction Potential









Resiliency and Emissions Footprints

- **2b: Demand Side Management**
  - **Resiliency of critically-loaded feeders and substations**

Circuit: Customer Information

Circuit: **Circuit Count:**1
As of Date: **XFMR Count:** 146
Meter Count: 703

Circuit ID	Xfmr Structure Number - Compressed	Premise Number	Account Number - Formatted	Premise Service Address	Meter Number

- **3a: Emission Footprint for each building**
  - **Carbon footprint (CO_2)**
  - **Nitrogen oxides (NOx)**
  - **Sulfur Dioxide (SO_2)**
  - ***Methane (CH4)***
  - ***Nitrous Oxide (N2O)***

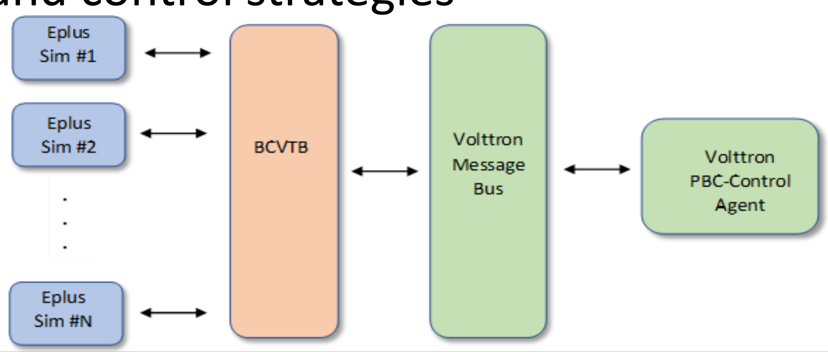
Demand and EE opportunities

- Energy, demand, emissions, savings (customer and utility) for every building every 15 minutes

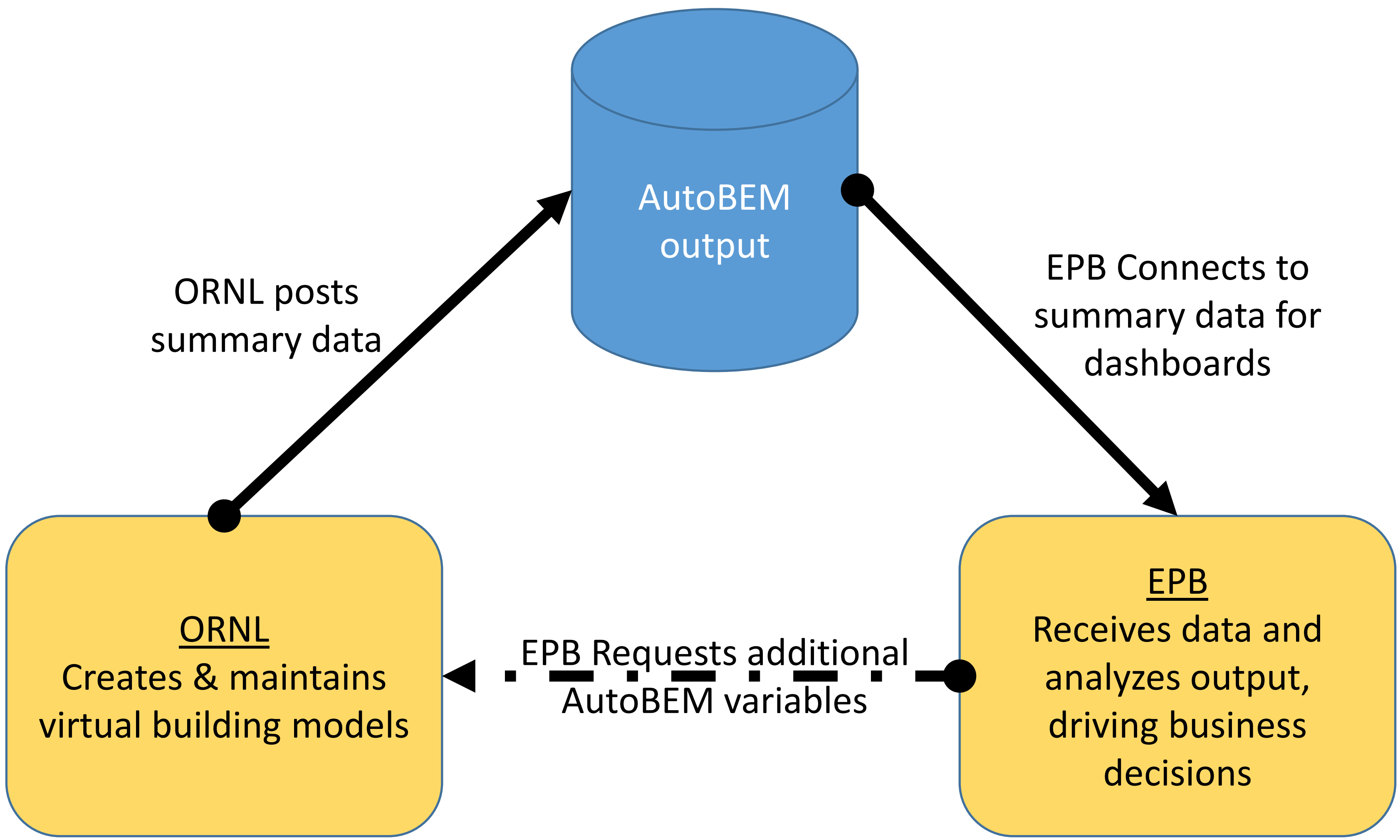
ECMs	Different Fields Calculated for Each ECM							
HVAC	Total	Annual	Energy	Annual	Annual	Annual	Annual	Total
Lighting	Cost	Electric	Cost	Electric	Demand	Demand	Demand	Cost
Infiltration	Savings	Savings	Savings		Savings	Cost		Savings
8F setback						Savings		
HVAC Efficiency	$	kWh	$	kWh	kW	$	kW	$
4F setback								
Insulation	Annual	Energy	Annual	Percent	Annual	Annual		
Water heater	Electric	Cost	Electric	Savings	Demand	Demand		
Heat pump	Savings	Savings			Cost Savings			
Smart WH	kWh	$	kWh	$	$	kW		

Related Work

- **Combined Heat and Power (CHP)**
  - Sizing micro-CHP based on heating, cooling, and electrical demands
- **Transactive HVAC Control**
  - EnergyPlus models for transactive control
- **Microgrid**
  - Simplified model replaced with EnergyPlus
  - Run for area within EPB for considering microgrid
- **VOLTTRON Deployment**
  - B2G services deployment of hardware and control strategies

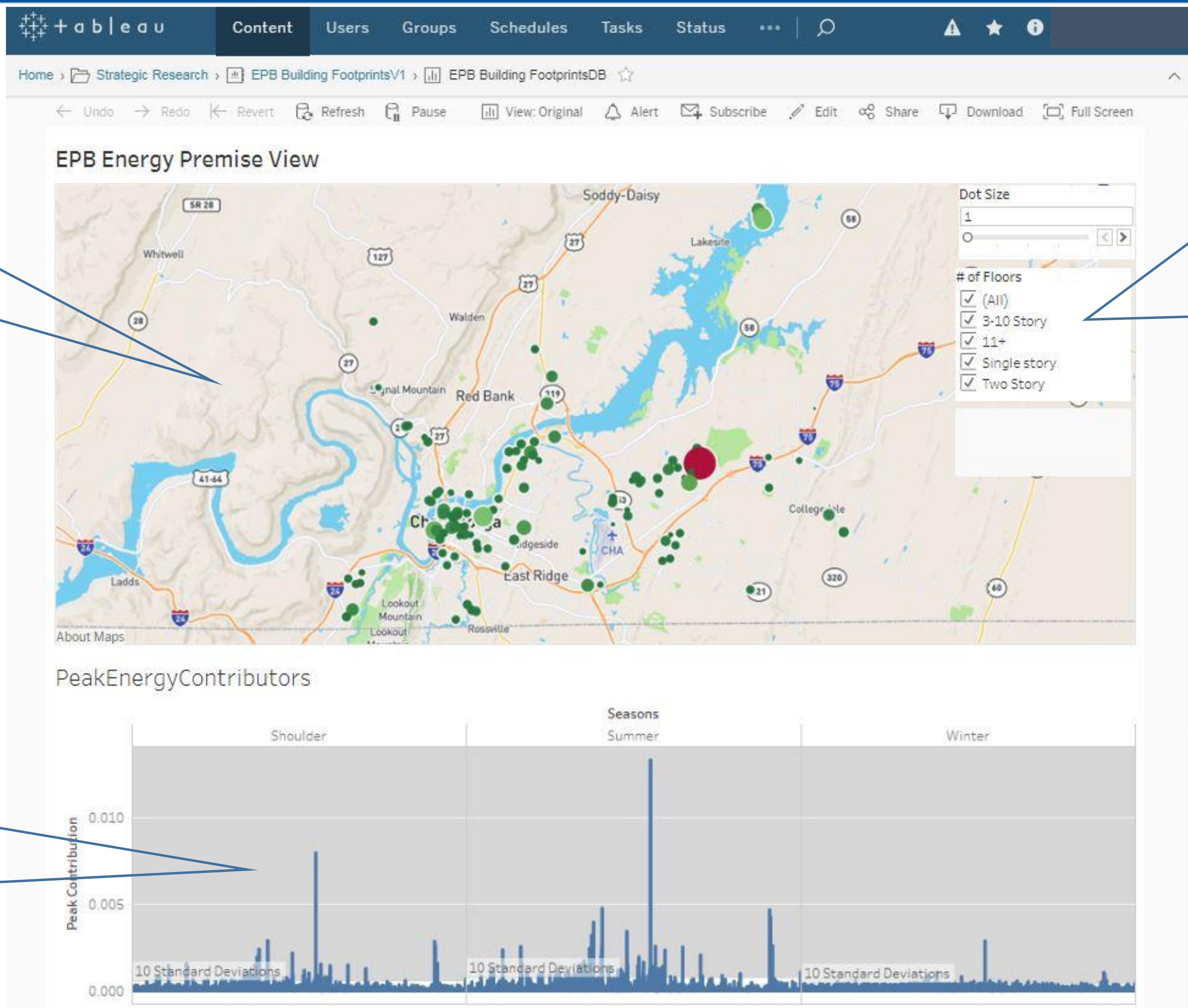


ORNL/EPB Coordination



EPB's operational systems

Map showing premises, colored by AutoBEM attribute



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

Chart showing same data, in time series format

Virtual EPB – 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

Exascale Computing Project

- Coupling:
  - Transportation (CommuterSim)
  - Weather (WRF, Nek5000)
  - Buildings (OpenStudio/EnergyPlus)
  - Population (LandScan)
  - Socio-economics
- Individual-person, agent-based models, fully-coupled simulations running on the fastest computers in the world

Argonne NATIONAL LABORATORY

OAK RIDGE National Laboratory

BERKELEY LAB

NREL NATIONAL RENEWABLE ENERGY LABORATORY

ECP EXASCALE COMPUTING PROJECT

Titan (ORNL), nation's fastest, 27 petaflops

Summit (ORNL), expected to be world's fastest, 207 PF

Aurora (ANL), ? (ORNL)

Exascale…

Discussion

Joshua New, Ph.D., CEM
BTRIC, Software Tools & Models
Oak Ridge National Laboratory

newjr@ornl.gov

HPC Tools for
Modeling and Simulation
Capturing building energy consumption