

Supercomputers (Titan!), Big Data Analytics, and Energy Efficient Robo-Homes

Joshua New, Ph.D.

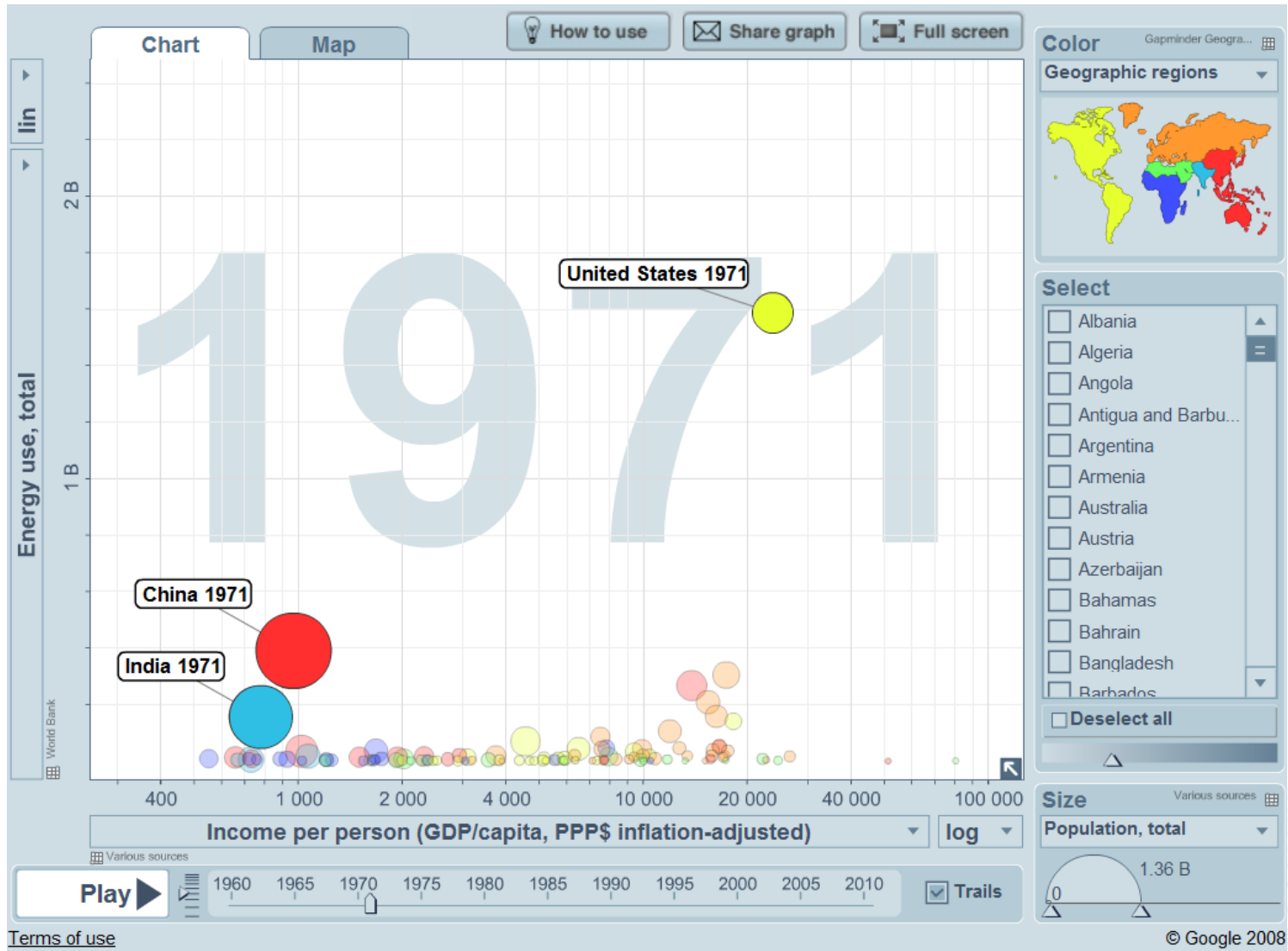
Building Technology Research
Integration Center (BTRIC)

Oak Ridge National Laboratory

newjr@ornl.gov

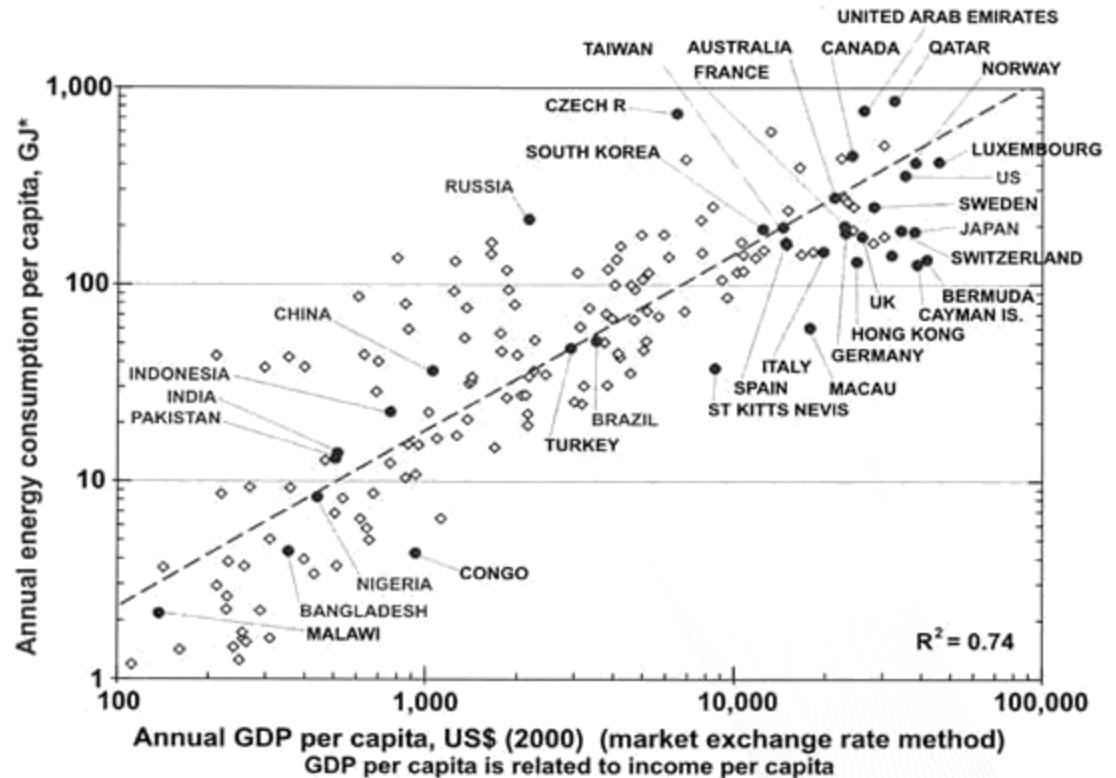


A brief history of energy and life quality



Sustainability is the defining challenge

- Buildings in U.S.
 - 41% of primary energy/carbon 73% of electricity, 34% of gas
- Buildings in China
 - 60% of urban building floor space in 2030 has yet to be built
- Buildings in India
 - 67% of all building floor space in 2030 has yet to be built

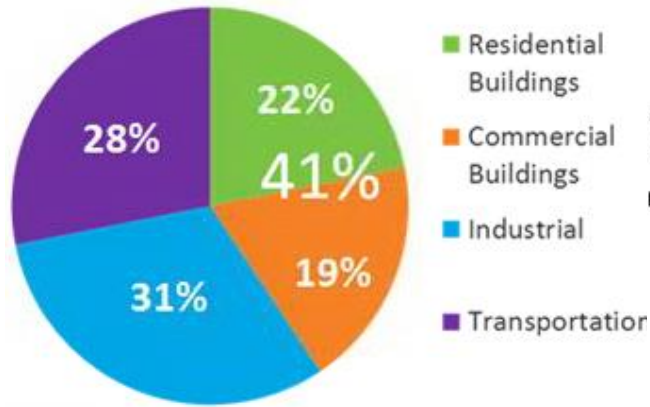


*1,000,000,000 GJ = 1 EJ
1 GJ = 1,000,000,000 J

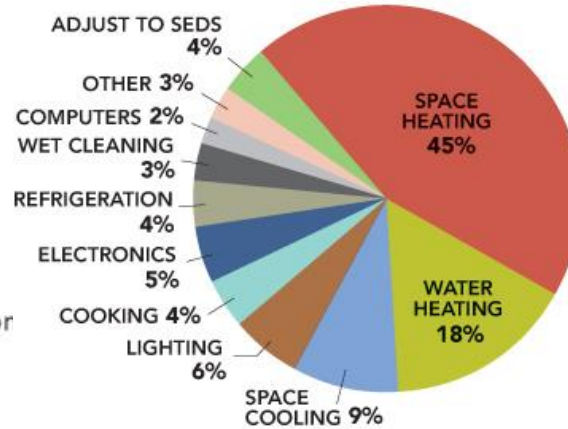
Source: Energy Information Administration
International Energy Annual 2003
July 8, 2005

Energy Consumption and Production

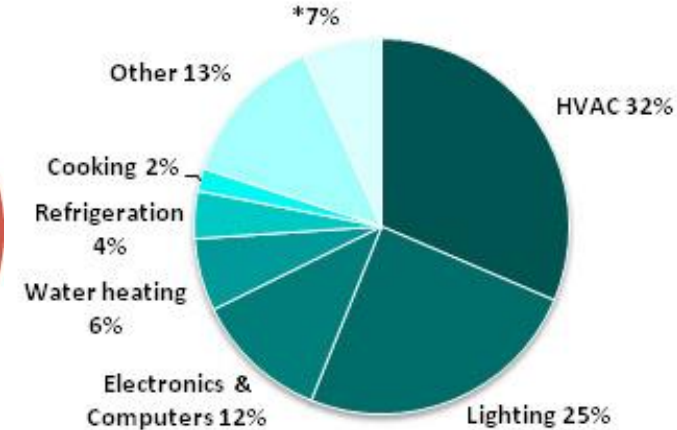
U.S. Primary Energy Consumption



RESIDENTIAL SITE ENERGY CONSUMPTION BY END USE

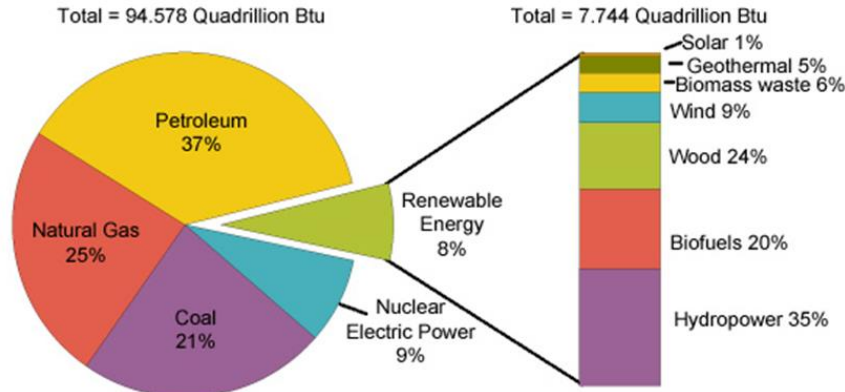


Commercial Site Energy Consumption by End Use



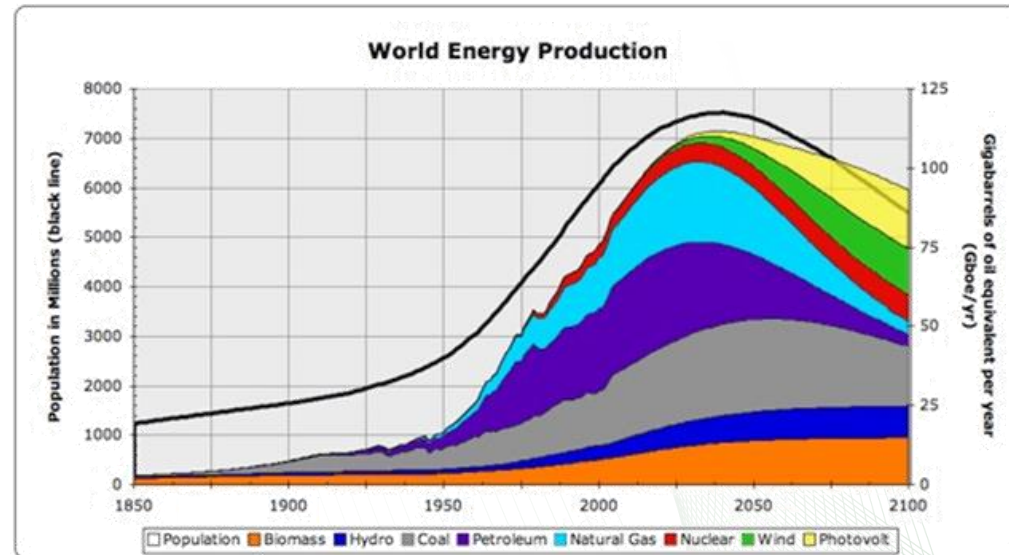
TN 2012 Electric Bill - \$1,533

The Role of Renewable Energy in the Nation's Energy Supply, 2009



Note: Sum of components may not equal 100% due to independent rounding.
 Source: U.S. Energy Information Administration, Annual Energy Review 2009, Table 1.3, Primary Energy Consumption by Energy Source, 1949-2009 (August 2010).

World Energy Production



Presentation summary

- Scientific Paradigms
- Roof Savings Calculator
- Visual Analytics
- Knowledge Work
- Autotune
- Example Data Tools
- Saving Money

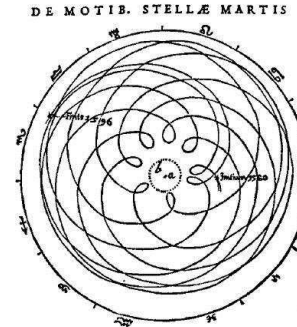
Presentation summary

- Scientific Paradigms (context)
- Roof Savings Calculator
- Visual Analytics
- Knowledge Work
- Autotune
- Example Data Tools
- Saving Money

4th Paradigm – The Science behind the Science

- Empirical – guided by experiment/ observation
 - In use thousands of years ago, natural phenomena
- Theoretical – based on coherent group of principles and theorems
 - In use hundreds of years ago, generalizations
- Computational – simulating complex phenomena
 - In use for decades
- Data exploration (eScience) – unifies all 3
 - Data capture, curation, storage, analysis, and visualization
 - Jim Gray, free PDF from MS Research

Tycho Brahe



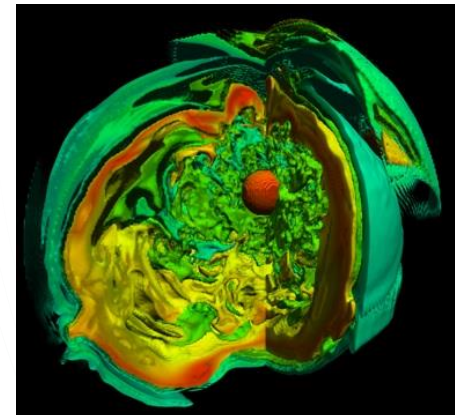
Johannes Kepler

$$\oint \mathbf{E} \cdot d\mathbf{A} = q / \epsilon_0$$

$$\oint \mathbf{B} \cdot d\mathbf{A} = 0$$

$$\oint \mathbf{E} \cdot d\mathbf{S} = -d\Phi_B / dt$$

$$\oint \mathbf{B} \cdot d\mathbf{S} = \mu_0 i + \mu_0 \epsilon_0 d\Phi_E / dt$$



4th Paradigm

Hierarchy Of Visual Understanding



David McCandless // v 0.1
InformationIsBeautiful.net

Presentation summary

- Scientific Paradigms
- **Roof Savings Calculator**
- Visual Analytics
- Knowledge Work
- Autotune
- Example Data Tools
- Saving Money

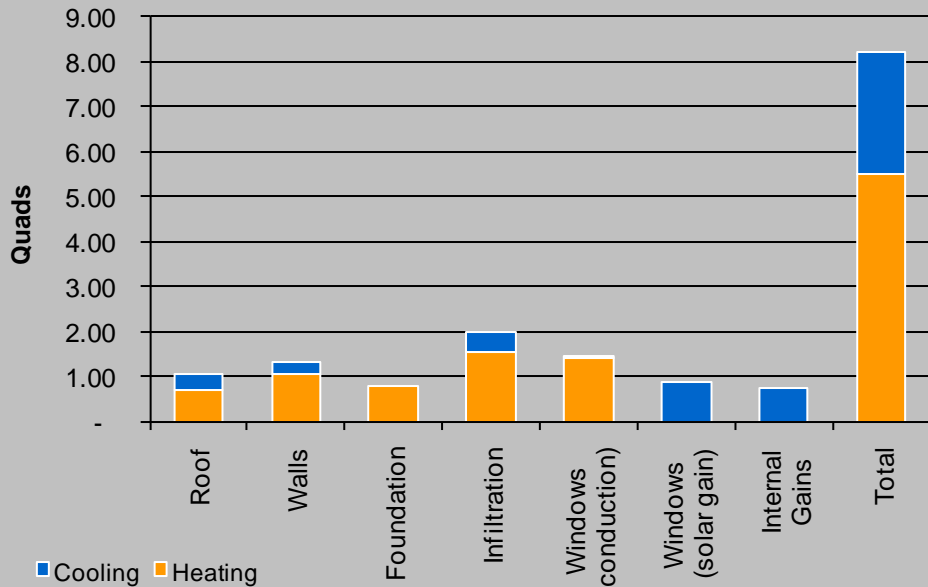
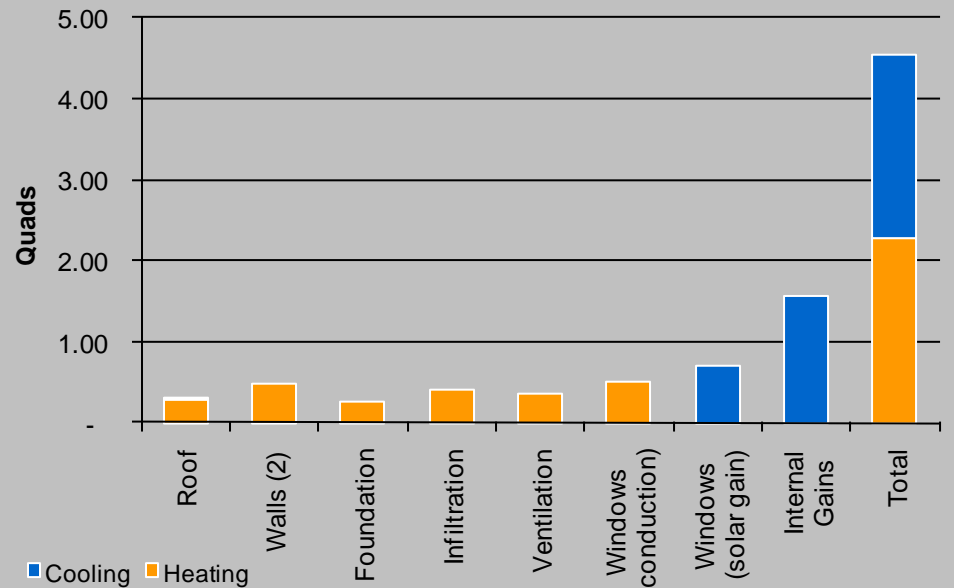


Figure 2. Residential energy loads attributed to envelope and windows

Source: Building Energy Data Book, U.S. DOE, Prepared by D&R International, Ltd., September 2008.

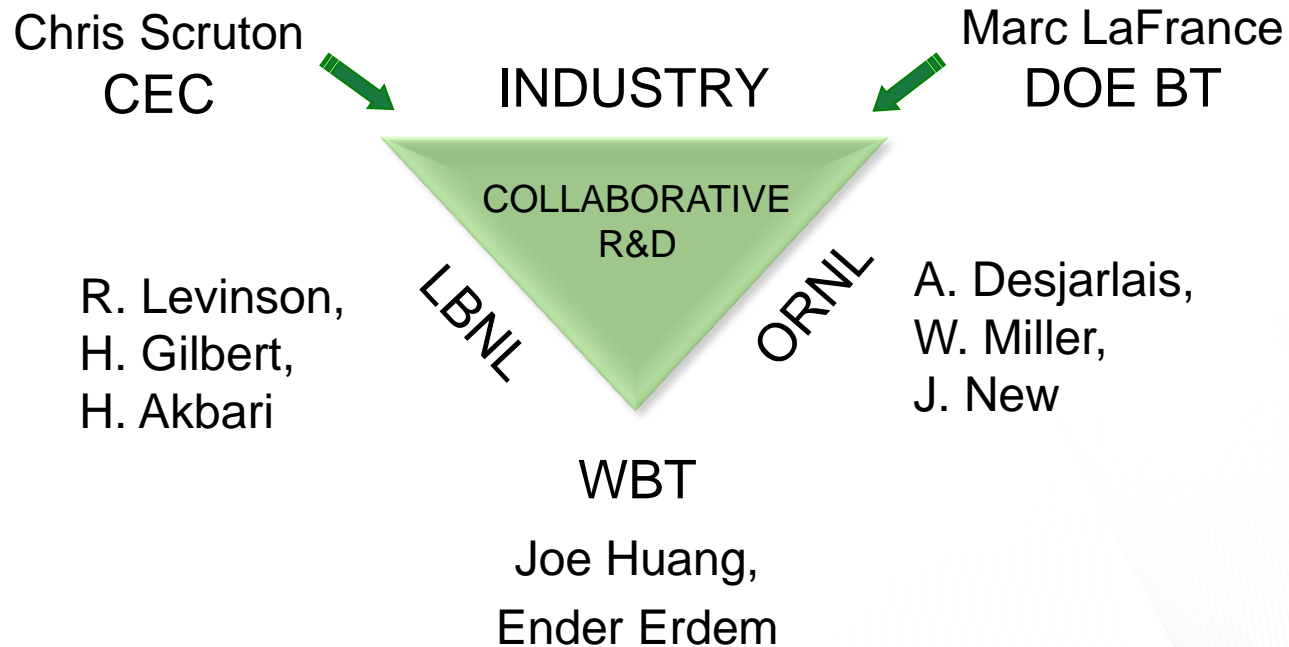
Figure 3. Commercial energy loads attributed to envelope and windows

Source: Building Energy Data Book, U.S. DOE, Prepared by D&R International, Ltd., September 2008.



Computer tools for simulating cool roofs

Roof Savings Calculator (RSC)



Roof Savings Calculator

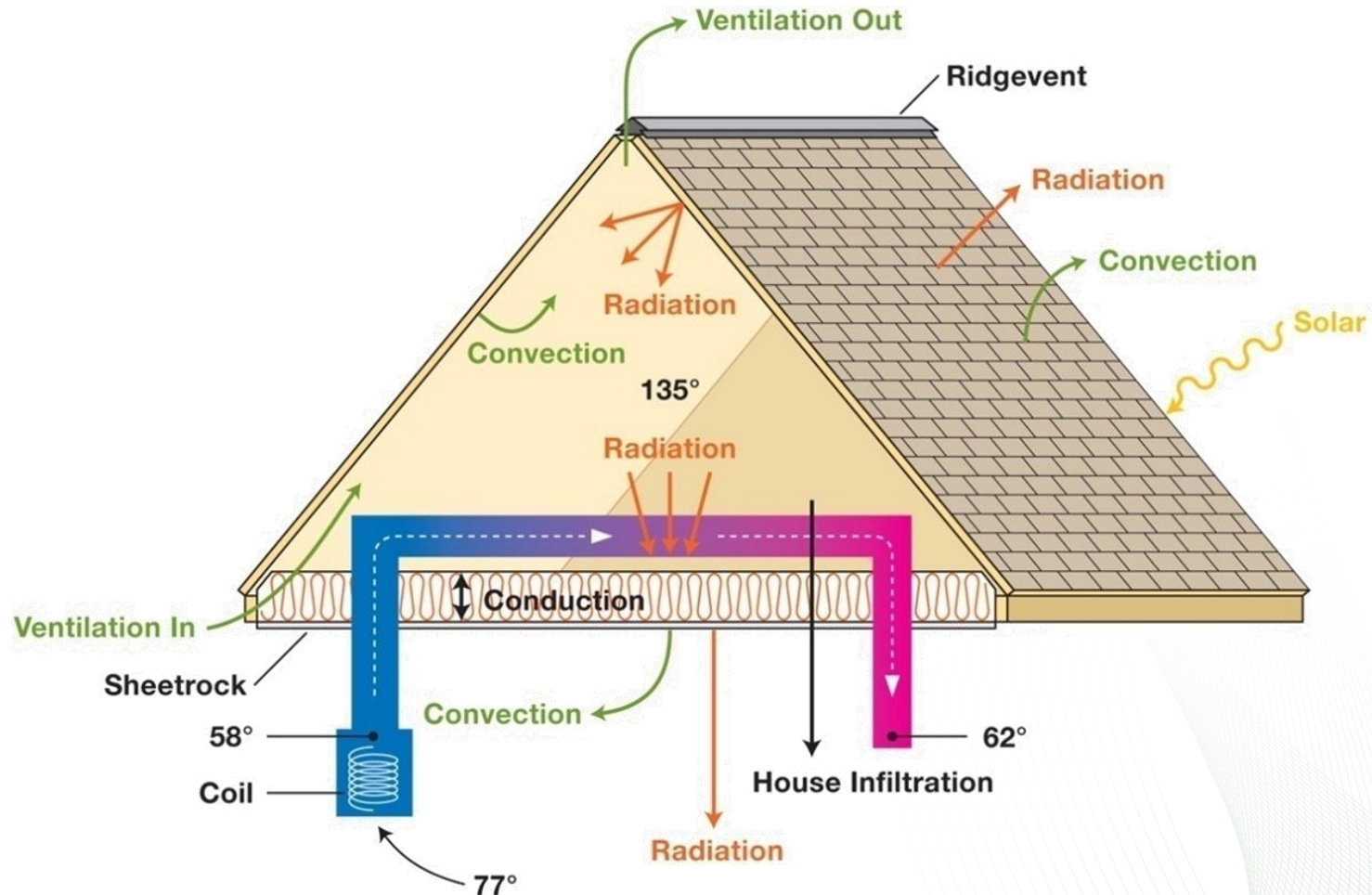
Calculator Input Comparison Chart

- Replaces:
 - EPA Roof Comparison Calc
 - DOE Cool Roof Calculator
- Minimal questions (<20)
 - Only location is required
 - Building America defaults
 - Help links for unknown information

	RSC ¹	PAC Slides ²	PAC QRpt ³	EPA ⁴	DOE ⁵
Building Type	✓	✓	✓	✓	
Location	✓	✓		✓	✓
Days of Operation per week		✓	✓	✓	
Building stock	✓	✓		✓	
Cooling system efficiency (SEER)	✓	✓	✓	✓	✓
Type of heating	✓	✓	✓	✓	✓
Heating system efficiency	✓	✓	✓	✓	✓
Duct location	✓	✓	✓		
Level of roof/ceiling insulation	✓	✓	✓	✓	✓
Above-sheathing ventilation	✓	✓			
Radiant barrier	✓	✓			
Roof thermal mass	✓	✓			
Roof solar reflectance	✓	✓	✓	✓	✓
Roof solar reflectance (black compare)	✓		✓	✓	
Roof thermal emittance	✓	✓	✓		✓
Roof thermal emittance (black compare)	✓		✓		
Internal load		✓			
Conditioned space under roof		✓			
Gas and electricity costs	✓	✓	✓	✓	✓
Inclination / Roof Area	✓			✓	
HVAC Schedule			✓		
Conditioned space (ft ²)	✓			✓	
Number of floors	✓				
Window-to-wall ratio	✓				

RSC = AtticSim + DOE-2.1E

AtticSim - ASTM C 1340 Standard For Estimating Heat Gain or Loss Through Ceilings Under Attics



Commercial building types

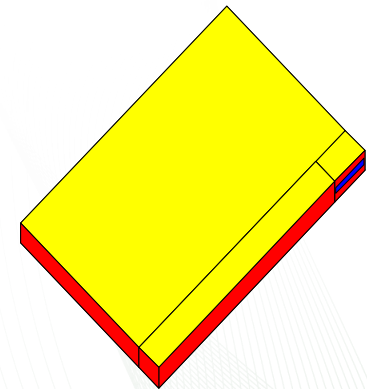
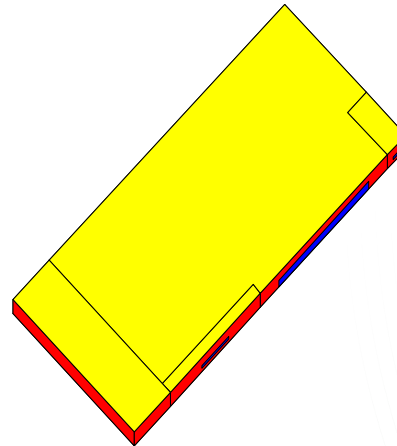
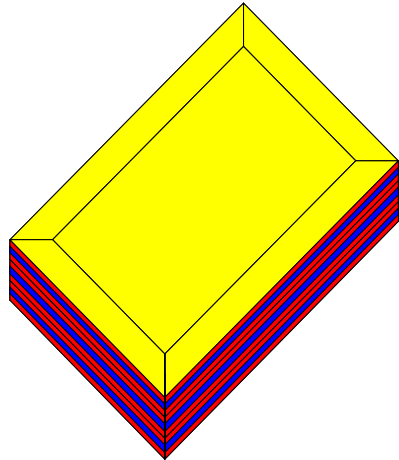
Office



“Big Box” Retail



Warehouse



Torcellini et al. 2008, “DOE Commercial Building Benchmark Models”, NREL/CP-550-43291, National Renewable Energy Laboratory, Golden CO.

Residential Roof Savings Calculator (RSC)

Go to: [Advanced Mode](#)

Building

1. Closest location (similar weather):

Select location

2. Building Type:

Residential

3. Conditioned floor area (ft²):

2025

4. Number of floors:

- 1
- 2

5. Year of construction:

- post-1990
- 1980-1990
- pre-1980



Heating/Cooling

6. Heating equipment:

- Electric heat pump
- Natural gas furnace
- Oil furnace

P1. Electricity price (cents per kWh):

11.68

P2. Natural gas price (dollars per 1000 ft³):

11.65

7. Heating system efficiency (AFUE):

- High-efficiency (90%)
- Mid-efficiency (83%)
- Low-efficiency (70%)
- Custom

8. Cooling system efficiency (SEER):

- High-efficiency (15)
- Mid-efficiency (13)
- Low-efficiency (10)
- Custom

Roof 1 - Existing Roof

9. Roof type:

- Tile
- Metal
- Asphalt shingle

10. Solar reflectance (aged 3 yrs):

- 60%
- 50%
- 40%
- 30%
- 20%
- 10%

11. Thermal emittance (aged 3 yrs):

- Acrylic Al-Zn coated steel (15%)
- Bare Al-Zn coated steel (20%)
- Metallic field-applied coating (50%)
- Painted steel (85%)
- Other materials (90%)

12. Above-sheathing ventilation:

- Yes
- No

13. Pitch (rise:run):

- High (slope > 8:12)
- Medium (2:12 < slope ≤ 8:12)
- Low (slope ≤ 2:12)

14. Radiant barrier present:

- Yes
- No

15. Attic insulation (hr ft² °F per Btu):

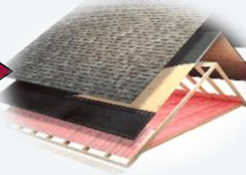
- R-50
- R-38
- R-19

16. Duct location:

- Conditioned space
- Attic

17. Duct leakage:

- Inspected (4%)
- Uninspected (14%)



Roof 2 - Cool Roof Comparison

18. Roof type:

- Tile
- Metal
- Asphalt shingle

19. Solar reflectance (aged 3 yrs):

- 60%
- 50%
- 40%
- 30%
- 20%
- 10%

20. Thermal emittance (aged 3 yrs):

- Acrylic Al-Zn coated steel (15%)
- Bare Al-Zn coated steel (20%)
- Metallic field-applied coating (50%)
- Painted steel (85%)
- Other materials (90%)

21. Above-sheathing ventilation:

- Yes
- No

22. Pitch (rise:run):

- High (slope > 8:12)
- Medium (2:12 < slope ≤ 8:12)
- Low (slope ≤ 2:12)

23. Radiant barrier present:

- Yes
- No

24. Attic insulation (hr ft² °F per Btu):

- R-50
- R-38
- R-19

25. Duct location:

- Conditioned space
- Attic

26. Duct leakage:

- Inspected (4%)
- Uninspected (14%)

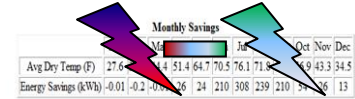


Calculate

Simulation Results

\$/yr
Energy Savings

Total	Cooling	Heating
\$93	\$95	-\$2
1163 kWh	1189 kWh	-0.25 kWh



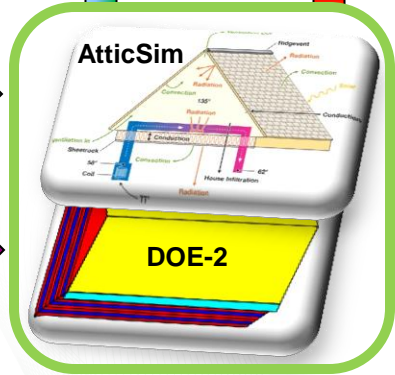
Retrofit Monthly Results

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Heating (kWh)	387.166	254.8	180.594	55.04	8.676	.104	0	0.552	2.645	28.728	139.31	280.123
Cooling (kWh)	0	0	0	4.739	82.222	131.746	246.844	338.529	79.026	50.816	0	0

Base-Case Monthly Results

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Heating (kWh)	387.156	254.8	180.584	75.04	8.676	.104	0	0.552	2.65	28.728	139.31	280.123
Cooling (kWh)	0	0	0	5.739	128.222	261.746	454.844	337.529	183.026	50.816	0	0

Downloads:
[Raw Input data](#)
[Raw Output data](#)



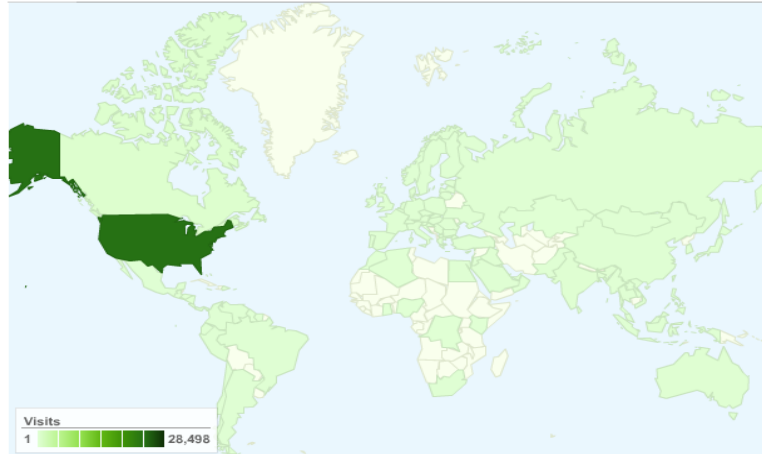
RoofCalc.com impact

Dashboard

Apr 20, 2010 - Feb 28, 2011

100,000+ visitors, 200+ user feedback,

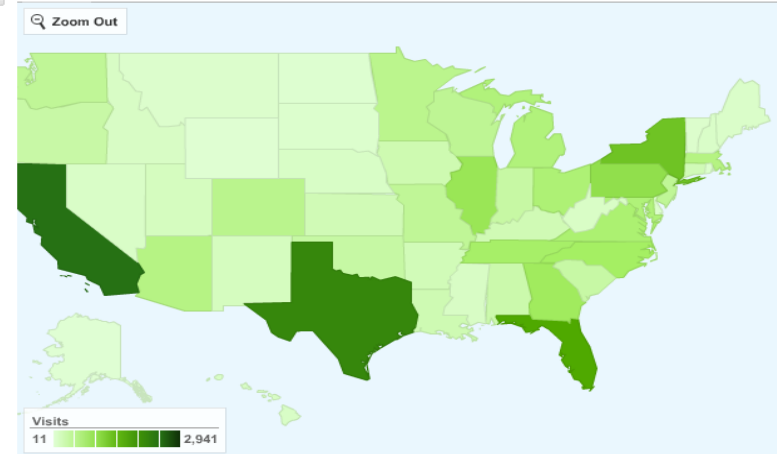
Average: ~81 visitors/day



30,752 visits came from 112 countries/territories

Detail Level: City | Country/Territory | Sub Continent/Region | Continent Dimension: None

Site Usage		Goal Set 1		Views: [Grid] [Line] [Table] [List]			
Visits	Pages/Visit	Avg. Time on Site	% New Visits	Bounce Rate			
30,752	1.42	00:01:25	88.26%	70.34%			
% of Site Total: 100.00%	Site Avg: 1.42 (0.00%)	Site Avg: 00:01:25 (0.00%)	Site Avg: 88.23% (0.04%)	Site Avg: 70.34% (0.00%)			
Detail Level: Country/Territory	Visits	Pages/Visit	Avg. Time on Site	% New Visits	Bounce Rate		
1. United States	28,498	1.42	00:01:25	88.35%	70.34%		
2. Canada	483	1.36	00:01:05	91.30%	73.08%		
3. India	156	1.42	00:01:08	80.77%	73.72%		
4. Australia	129	1.66	00:01:42	82.17%	66.67%		
5. United Kingdom	94	1.39	00:01:13	94.68%	65.96%		
6. South Korea	79	1.52	00:01:07	70.89%	68.35%		
7. Italy	66	1.61	00:01:33	89.39%	63.64%		



This country/territory sent 28,498 visits via 52 regions

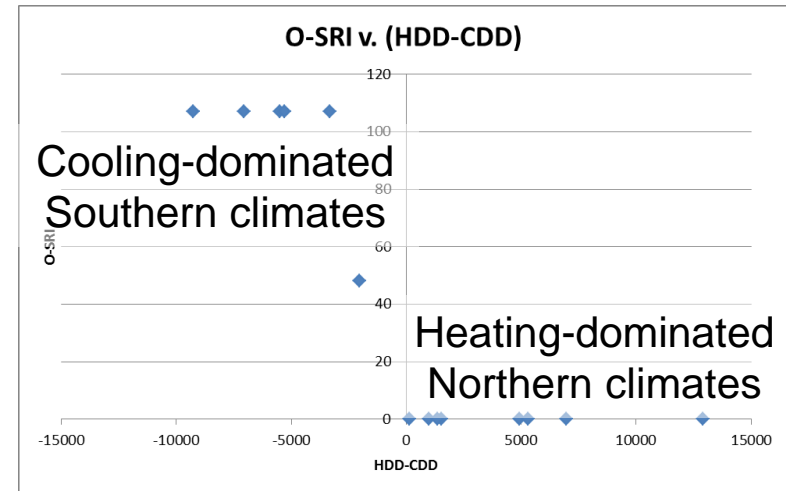
Detail Level: City | Region Dimension: None

Site Usage		Goal Set 1		Views: [Grid] [Line] [Table] [List]			
Visits	Pages/Visit	Avg. Time on Site	% New Visits	Bounce Rate			
28,498	1.42	00:01:25	88.35%	70.34%			
% of Site Total: 92.67%	Site Avg: 1.42 (-0.09%)	Site Avg: 00:01:25 (0.96%)	Site Avg: 88.23% (0.14%)	Site Avg: 70.34% (-0.00%)			
Detail Level: Region	Visits	Pages/Visit	Avg. Time on Site	% New Visits	Bounce Rate		
1. California	2,941	1.37	00:01:21	82.66%	73.95%		
2. Texas	2,558	1.43	00:01:26	90.30%	68.22%		
3. Florida	1,965	1.47	00:01:43	89.52%	68.09%		
4. New York	1,608	1.35	00:01:09	91.42%	73.45%		
5. Pennsylvania	1,206	1.39	00:01:20	91.04%	71.72%		
6. Illinois	1,114	1.36	00:01:12	89.41%	73.79%		
7. Georgia	1,032	1.40	00:01:18	90.50%	69.09%		

Nationwide results

Cost savings for offices - 14 cities,
local utility prices, 22 roof types

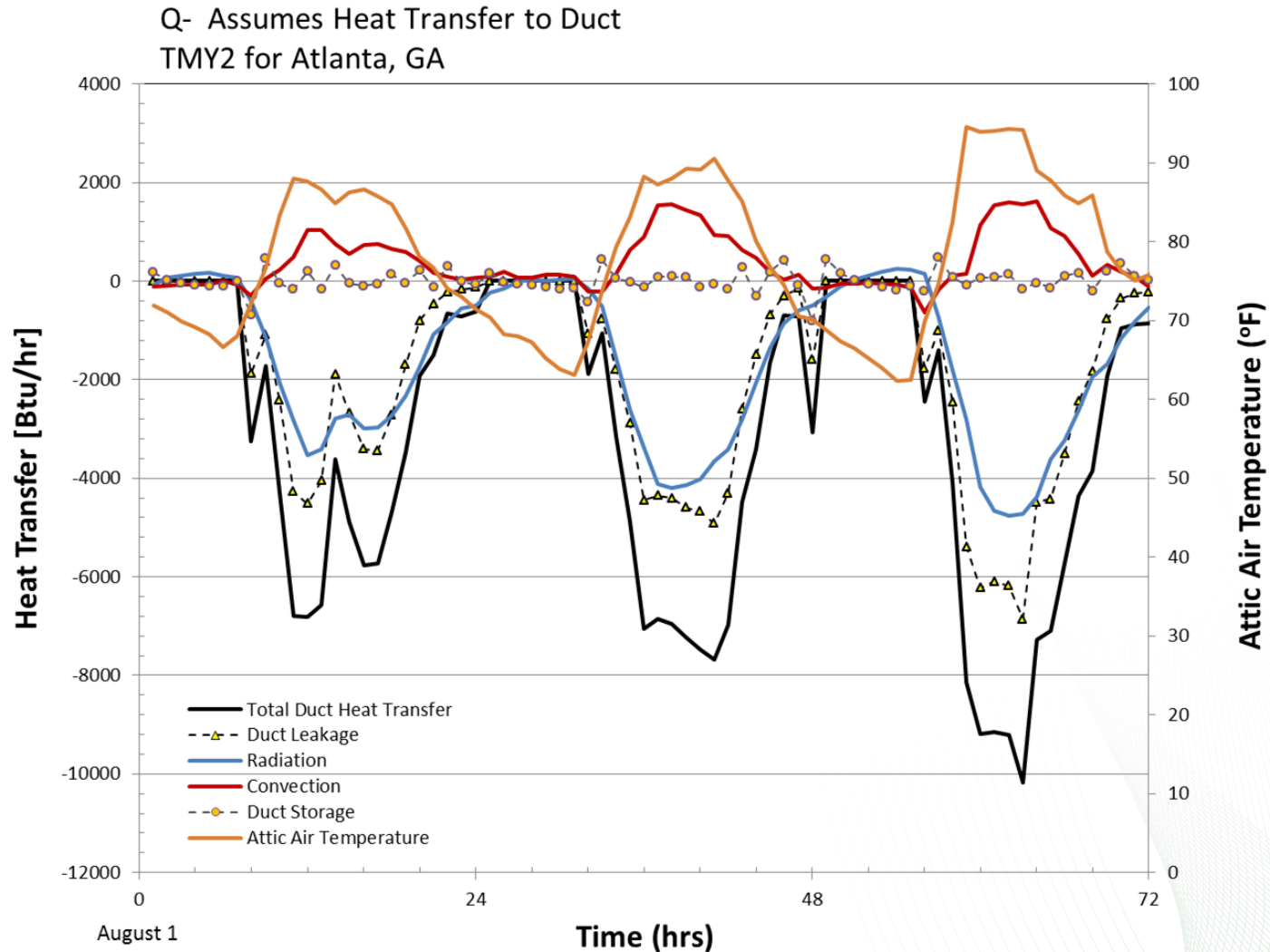
Description	Reflectance	Emisivity	SRI	Houston \$ saved	...13
BUR No Coating	10	90	6	42	
Mineral Mod Bit	25	88	25	103	
Single Ply	32	90	35	230	
Mineral Mod Bit	33	92	35	197	
Metal	35	82	35	60	
Aluminum Coating	43	58	35	279	
Mineral Mod Bit	45	79	55	291	
Coating over BUR	49	83	55	433	
Metal	49	83	55	208	
...14					



Location	Trend Desired SRI	Maximum Observed Savings, \$	Best Observed System	Related SRI	Slope Difference
Atlanta	107	1080	Aluminum Coating over BUR	65	Reversed
Austin	107	2680	Coating over BUR (White)	107	Same
Baltimore	107	1000	Single Ply /Coating over BUR	103.5	Reversed
Chicago	64.95	360	Aluminum Coating over BUR	48	Same
Fairbanks	42.68	680	Aluminum Coating over BUR	48	Same
Fargo	40.58	160	Aluminum Coating over BUR	48	Same
Houston	107	1840	Coating over BUR (White)	107	Same
Kansas City	107	800	Coating over BUR (White)	107	Reversed
Los Angeles	107	440	Aluminum Coating over BUR	65	Same
Miami	107	4440	Coating over BUR (White)	107	Same
Minneapolis	47.05	360	Aluminum Coating over BUR	48	Same
New York	107	560	Aluminum Coating over BUR	65	Reversed
Phoenix	107	3000	Coating over BUR (White)	107	Same
San Francisco	39.31	200	Aluminum Coating over BUR	48	Same

Mellot, Joseph W., New, Joshua R., and Sanyal, Jibonananda. (2013). "Preliminary Analysis of Energy Consumption for Cool Roofing Measures." In *RCI Interface Technical Journal*, volume 31, issue 9, pp. 25-36, October, 2013.

Summer operation of HVAC duct in ASHRAE climate zone 3



Enhanced RSC Site

Input Parameter GUI


Intro
Building Location
Building Details
WWR
HVAC Type
Heating / Cooling
Cool Roof
Roof Type

Roof Reflectivity
Roof Emittance
ASV
Roof Pitch
Radiant Barrier
Ceiling Insulation
Duct Location
Duct Leak


Roof Type

Select the roof type.


Current Roof:



Asphalt shingle




Metal




Tile


Hypothetical Cool Roof:




Asphalt shingle



Metal



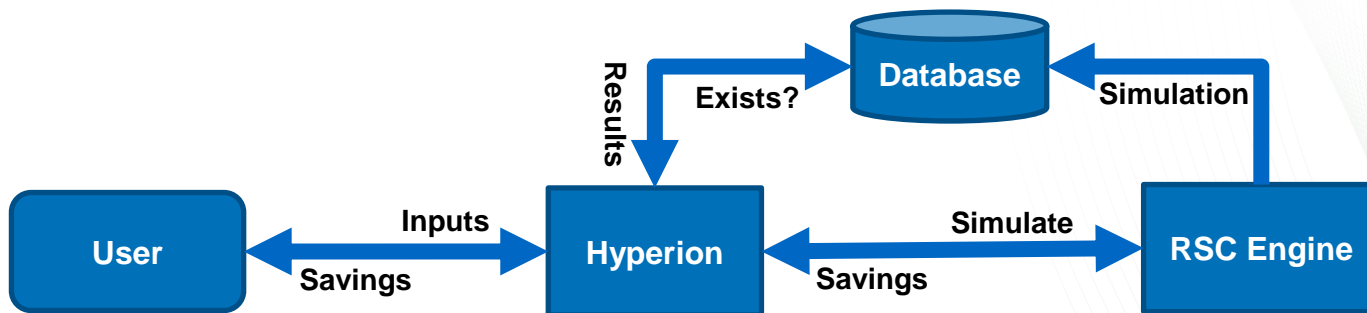
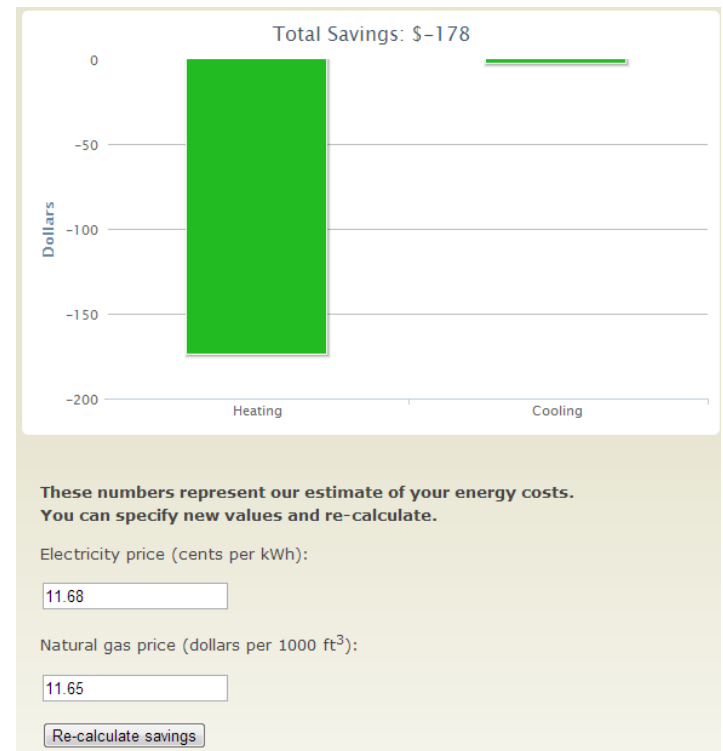
Tile



[Learn More](#)

Previous
Next
Calculate Savings

Result Output



Quote

“We speak piously of ... making small studies that will add another brick to the temple of science. Most such bricks just lie around the brickyard.”

–J.R. Platt, Science 1964, 146:347-53

RSC Service Example (Python)

```
client = suds.client.Client('URL/TO/WEB/SERVICE/rsc.wsdl')
print(client)
```

```
sm = client.factory.create('schema:soapmodel')
load_soap_model_from_xml('../examplemodel.xml', sm)
sr = client.service.simulate(sm)
print(sr)
```

```
sm = client.factory.create('schema:soapmodel')
load_soap_model_from_xml('../examplemodel.xml', sm)
print(sm)
contents = client.service.test(sm)
with open('pytest.zip', 'wb') as outfile:
    outfile.write(base64.b64decode(contents))
```

...download example building and batch script from rsc.ornl.gov/web-service.shtml

Update 1 line of code to change servers

```
1  import base64
2  import suds
3  import xml.dom.minidom
4  import logging
5
6
7  ⊕ def load_soap_model_from_xml(xmlfilename, soapmodel):
18
19  ⊕ def load_soap_results_from_xml(xmlfilename, soapresults):
34
35
36  logging.basicConfig()
37
38  test_type = ['simulate', 'test', 'upload', 'download']
39
40  print ("hello there, initializing client")
41  client = suds.client.Client('http://evenstar.ornl.gov/RSC/service/rsc.wsdl')
42  print ("printing client")
43  print(client)
44  raw_input('Press Enter to continue...'+'\n')
```

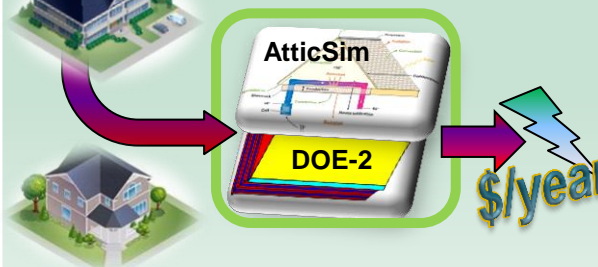
Millions of simulations visualized for DOE's Roof Savings Calculator and deployment of roof and attic technologies through leading industry partners

DOE: Office of Science

CEC & DOE EERE: BTO

Industry & Building Owners

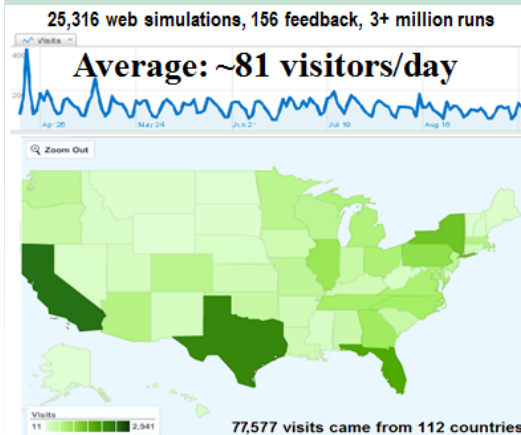
Engine (AtticSim/DOE-2) debugged using HPC Science assets enabling visual analytics on 3×10^6 simulations



Roof Savings Calculator (RSC) web site/service developed and validated [estimates energy and cost savings from roof and attic technologies]



CentiMark, the largest nation-wide roofing contractor (installs 2500 roofs/mo), is integrating RSC into their proposal generating system (20+ companies now interested)



Leveraging HPC resources to facilitate deployment of building energy efficiency technologies

Personal story behind one of DOE's RSC images

RoofCalc.com

14. Radiant barrier present:

- Yes
- No

15. Attic insulation (hr)

- R-50
- R-38
- R-19
- R-11
- R-7
- R-5
- R-3
- None

16. Duct location:

- Conditioned space
- Attic

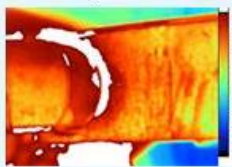
17. Duct leakage:

- Inspected (4%)
- Uninspected (14%)

Duct Leakage

Leaky ducts in unconditioned spaces are effectively costing you money to condition the planet, not your house. Commercial buildings have typical leakage rate of 10-20%; likewise, residential buildings typically have duct leakage rates near 14%. The CEC's Title 24 target leakage rate for inspected ducts is 4% and requires no greater than 6%. This calculator supports duct leakage rates of 4% and 14%.

Leaky Connection



Damaged Duct



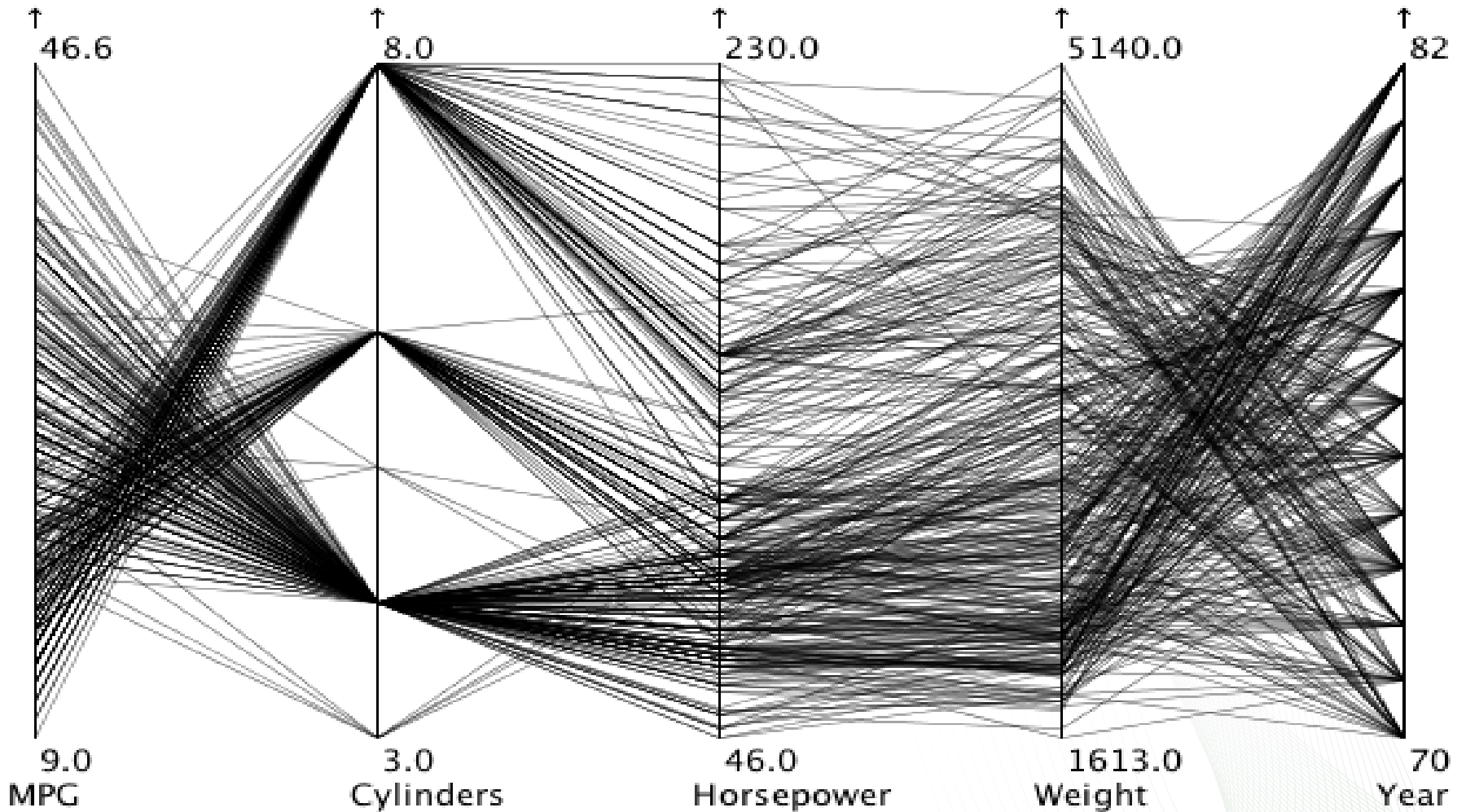
Sealed Ducts



Presentation summary

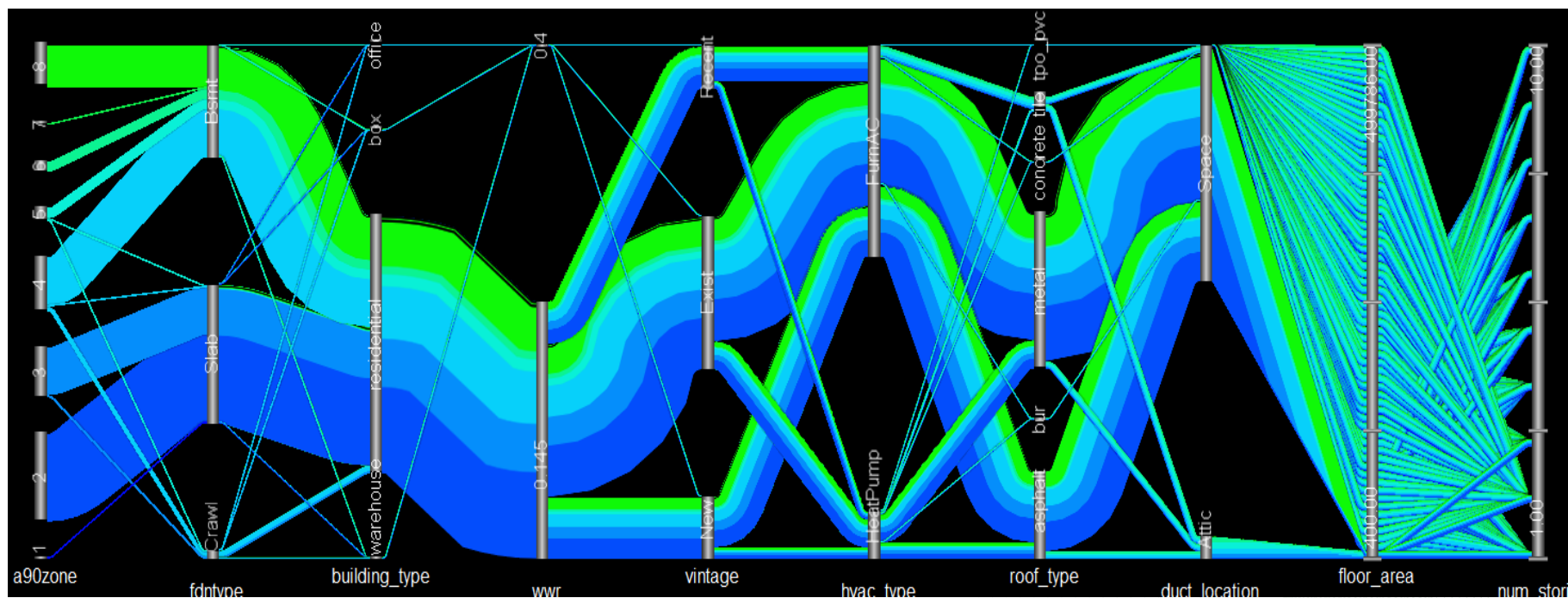
- Scientific Paradigms
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- Knowledge Work
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- Saving Money

PCP - car data set



PCP bin rendering

- Transfer function coloring:
 - Occupancy or leading axis



The power of “and” – linked views



Roof Savings Calculator

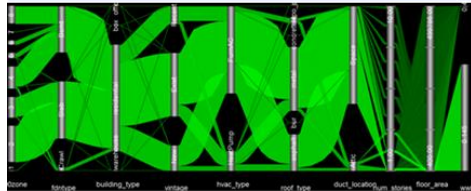
www.roofcalc.com

Dr. Joshua New (ORNL) and Chad Jones (UC-Davis)

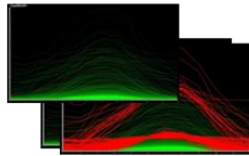
Dr. William A. Miller (ORNL), A. Desjarlais (ORNL), Yu Joe Huang (WhiteBox), Ender Erdem (WhiteBox)



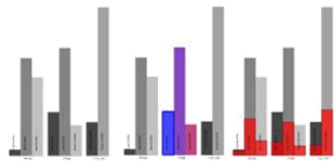
Multivariate Visualization of Large-Scale Parameter Sweeps



Parallel Coordinates Plots



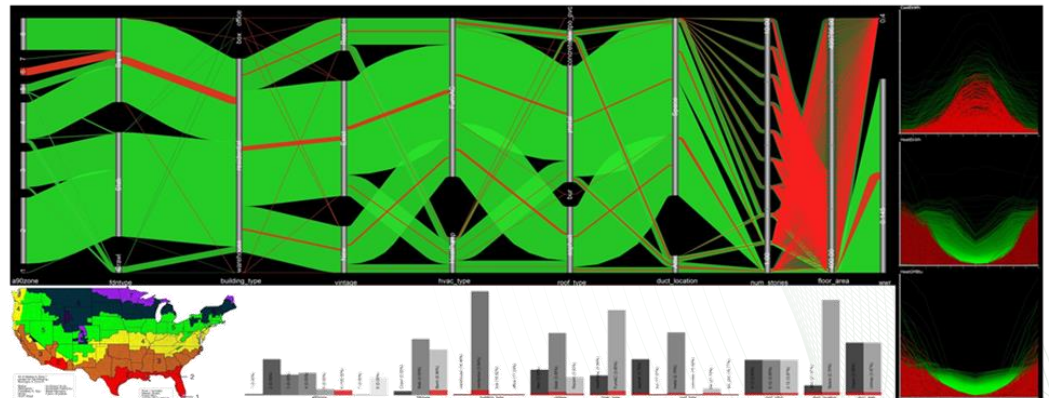
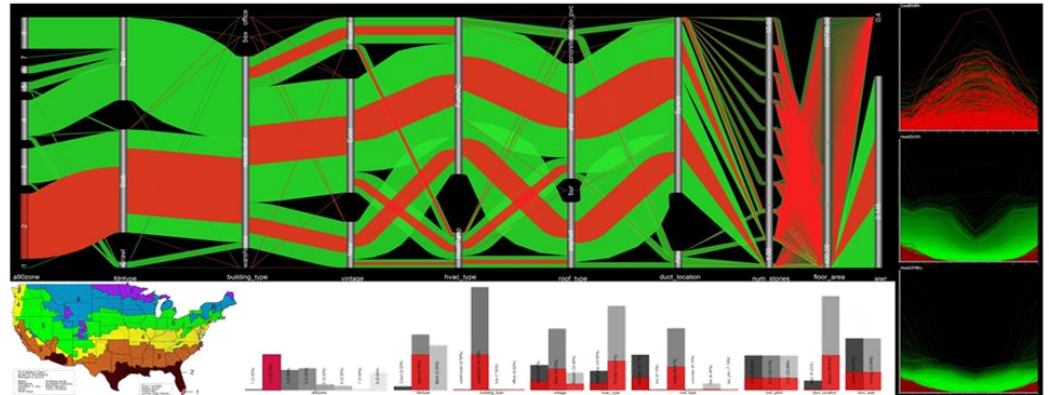
Time-variant Function Plots

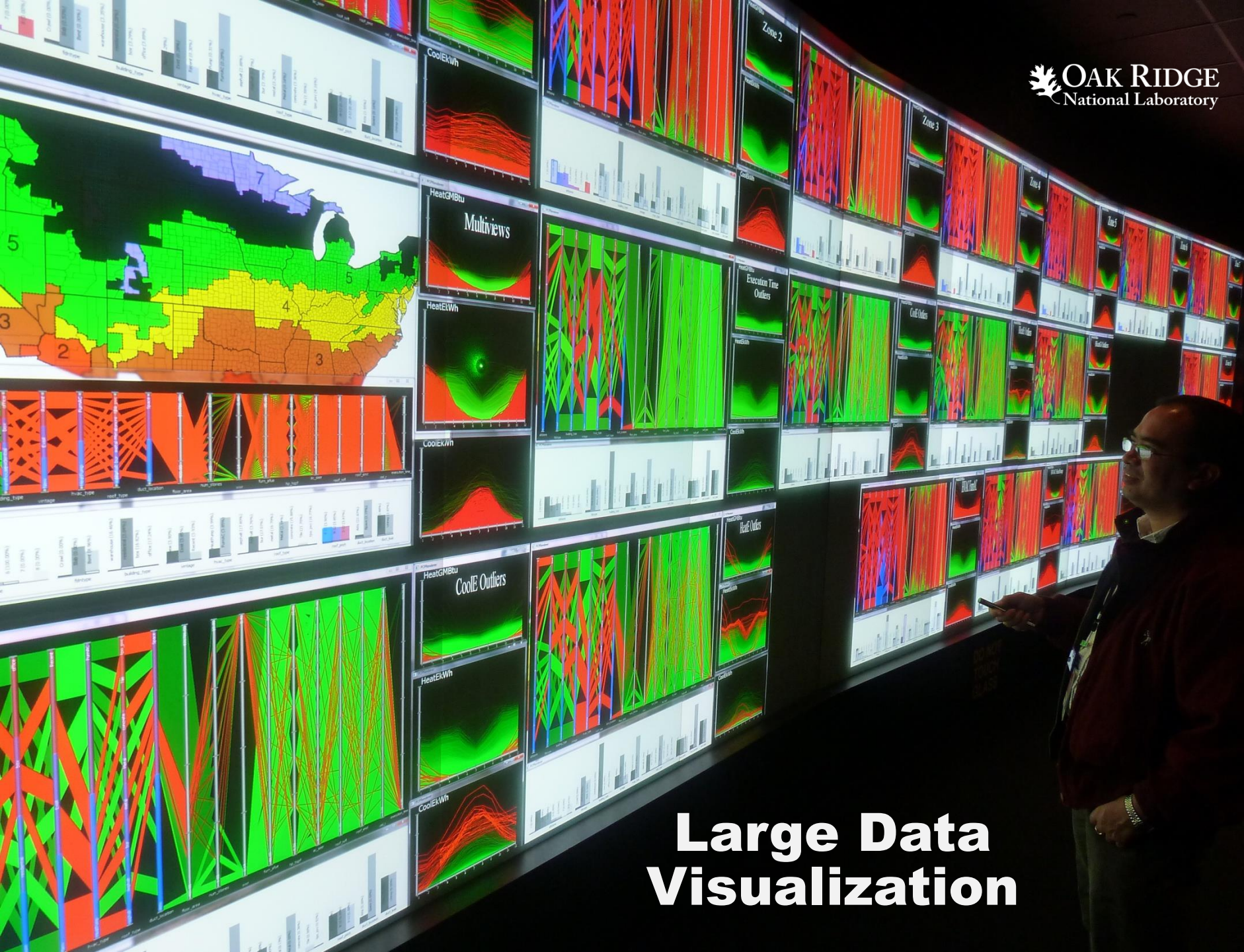


Category Charts



Climate Zone Map

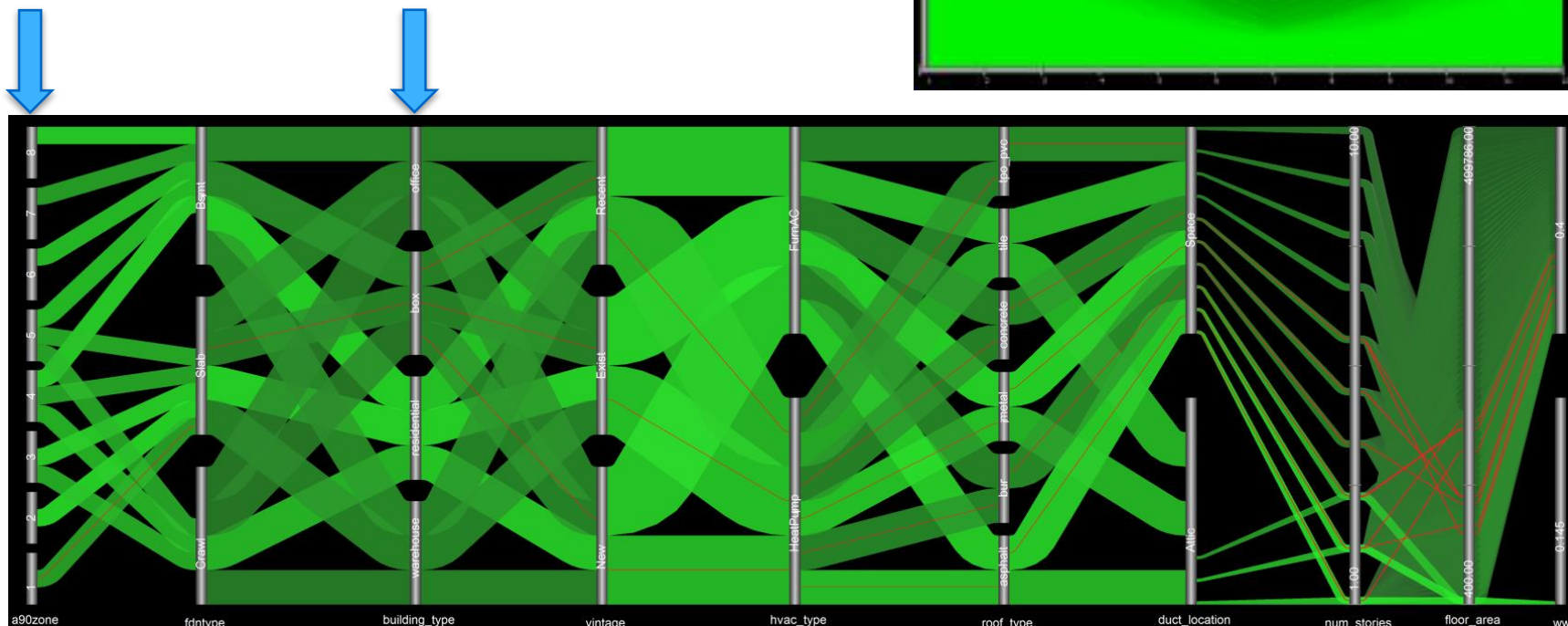
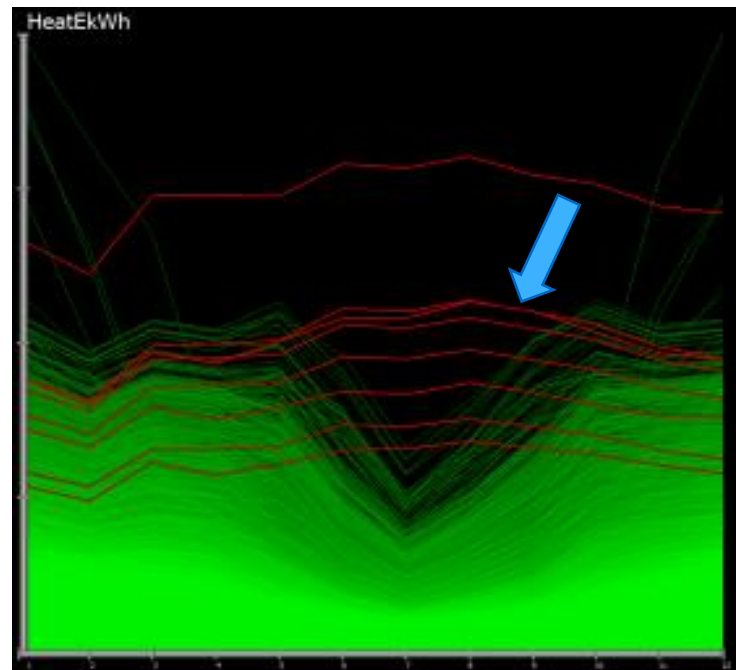




Large Data Visualization

Outliers (heating)

- Selection of heating outliers
- Find all have box building type and in Miami



Impact – RSC and Visual Analytics

12 Publications, 20+ organizations interested (licensing)

- New, Joshua R., Huang, Yu (Joe), Levinson, Ronnen, Mellot, Joe, Sanyal, Jibonananda, Miller, William A., and Childs, Kenneth W. (2013). "Analysis of DOE's Roof Savings Calculator with Comparison to other Simulation Engines" ORNL internal report ORNL/TM-2013/501, November 1, 2013, 63 pages.
- Mellot, Joseph W., Sanyal, Jibonananda, and New, Joshua R. (2013). "Preliminary Analysis of Energy Consumption for Cool Roofing Measures." Presented at the International Reflective Roofing Symposium, the American Coating Association's (ACA) conference, and in *Proceedings of the ACA's Coating Regulations and Analytical Methods Conference*, Pittsburgh, PA, May 14-15, 2013.
- Jones, Chad, New, Joshua R., Sanyal, Jibonananda, and Ma, Kwan-Liu (2012). "Visual Analytics for Roof Savings Calculator Ensembles." In *Proceedings of the 2nd Energy Informatics Conference*, Atlanta, GA, Oct. 6, 2012.
- Cheng, Mengdawn, Miller, William (Bill), New, Joshua R., and Berdahl, Paul (2011). "Understanding the Long-Term Effects of Environmental Exposure on Roof Reflectance in California." In *Journal of Construction and Building Materials*, volume 26, issue 1, pp. 516-26, August 2011.
- New, Joshua R., Miller, William (Bill), Desjarlais, A., Huang, Yu Joe, and Erdem, E. (2011). "Development of a Roof Savings Calculator." In *Proceedings of the RCI 26th International Convention and Trade Show*, Reno, NV, April 2011.
- Miller, William A., New, Joshua R., Desjarlais, Andre O., Huang, Yu (Joe), Erdem, Ender, and Levinson, Ronnen (2010). "Task 2.5.4 - Development of an Energy Savings Calculator." California Energy Commissions (CEC) PIER Project, ORNL internal report ORNL/TM-2010/111, March 2010, 32 pages.

Presentation summary

- Scientific Paradigms
- Roof Savings Calculator
- Visual Analytics
- Knowledge Work (context)
- Autotune
- Example Data Tools
- Saving Money

McKinsey Global Institute Analysis

Exhibit E3

Estimated potential economic impact of technologies from sized applications in 2025, including consumer surplus

\$ trillion, annual

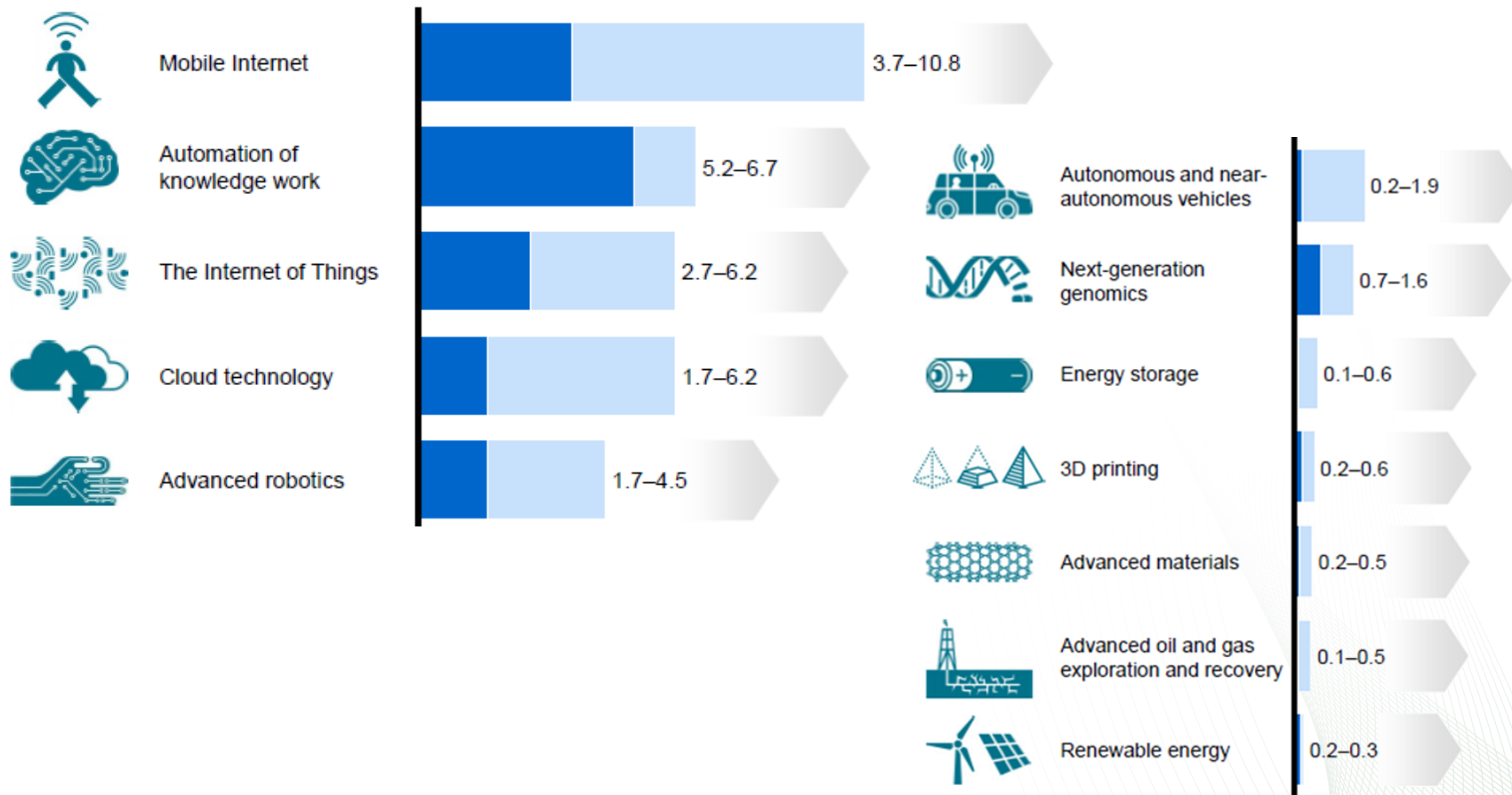
Range of sized potential economic impacts

Low

High

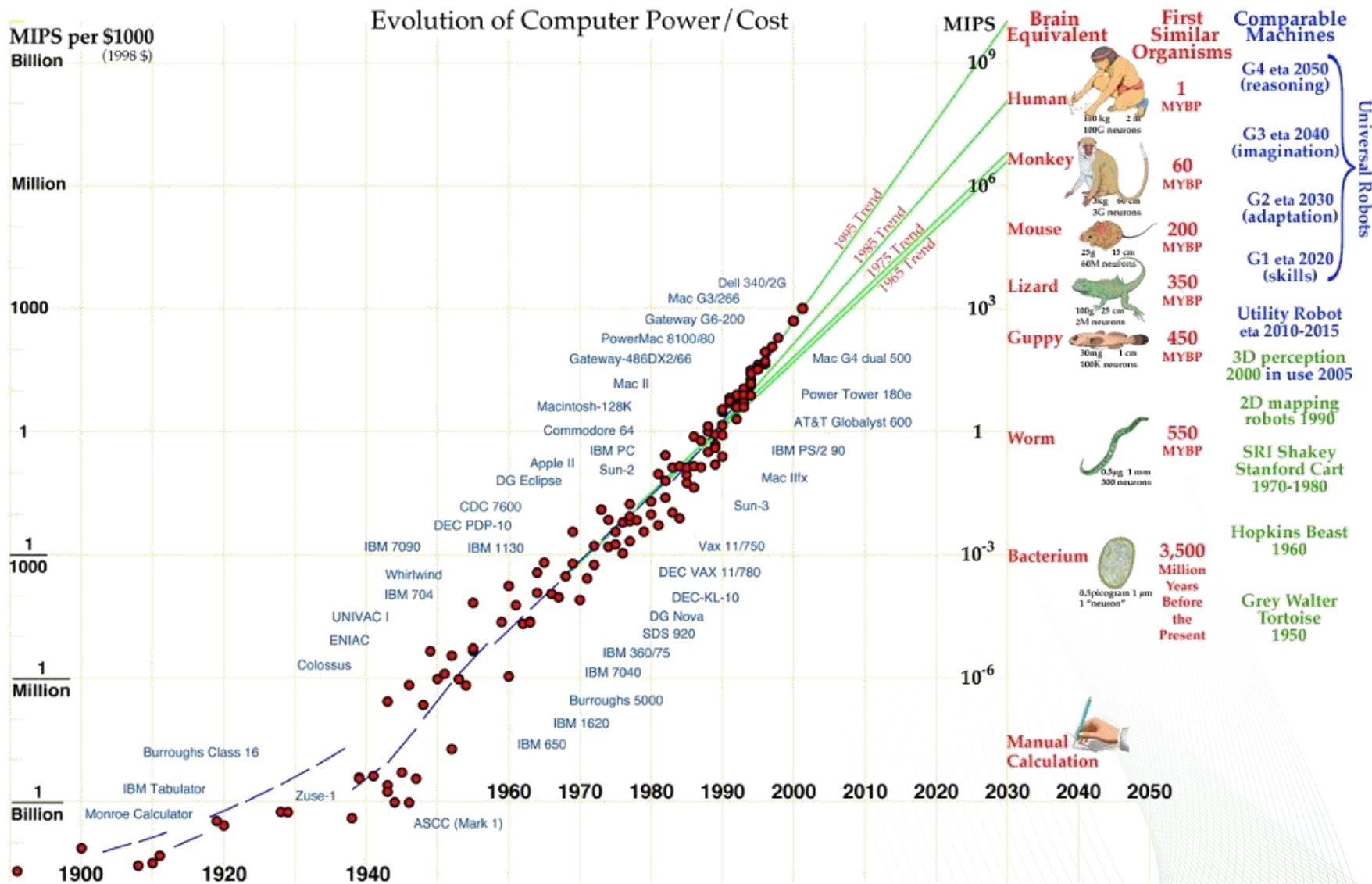
X-Y

Impact from other potential applications (not sized)

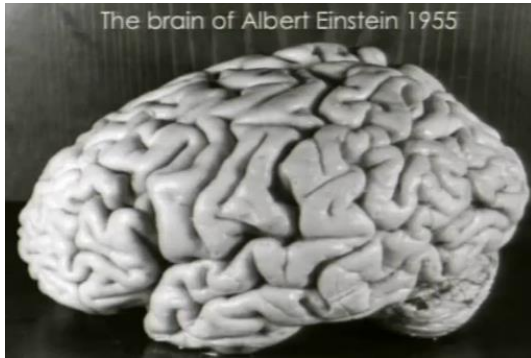


Source: McKinsey Global Institute analysis

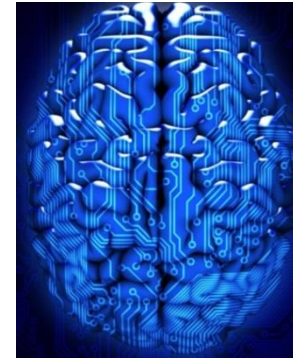
\$1000 machine helping meat machines



Humans and computers

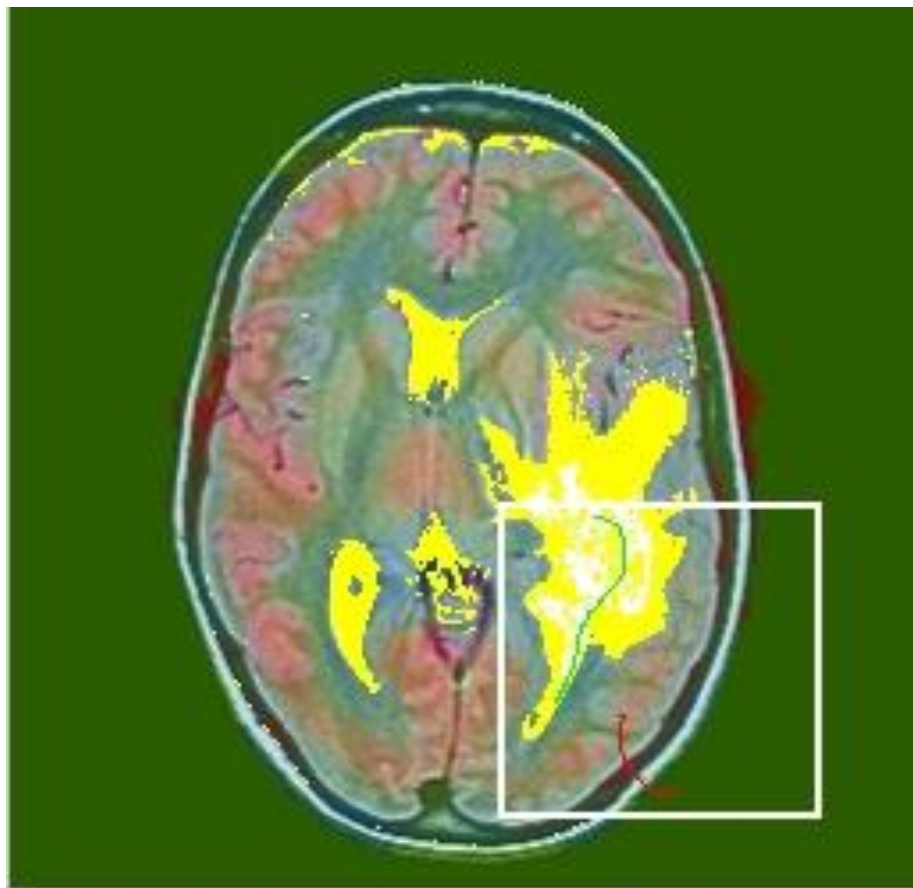


- 3 lbs (2%), 20 watts (20%)
- 120-150 billion neurons
- 100 trillion synapses
 - Firing time ~milliseconds
- 11 million bits/second input
 - Consciousness - 40 bits/second
- Working memory – 4-9 words
- Long-term memory – 1-1k TB
- Complex, self-organizing



- PC – 40 lbs, 500 watts
- 4 cores
- 3 billion Hz
 - Firing time ~nanoseconds
- 100 million bits/second
 - Not yet
- 62,500,000 words
- Disk – 3TB, perfect recall
- “Dumb”, Artificial Intel.

Learning associations



Full Results

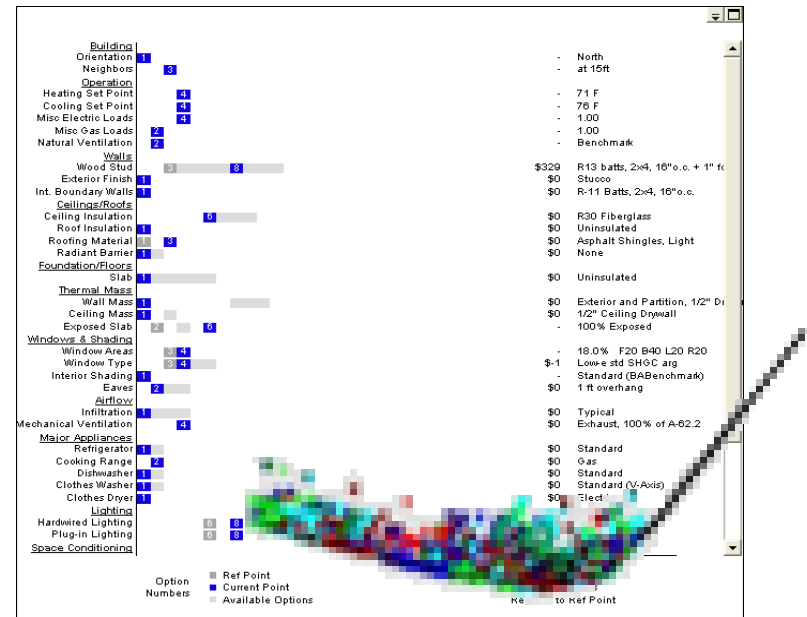
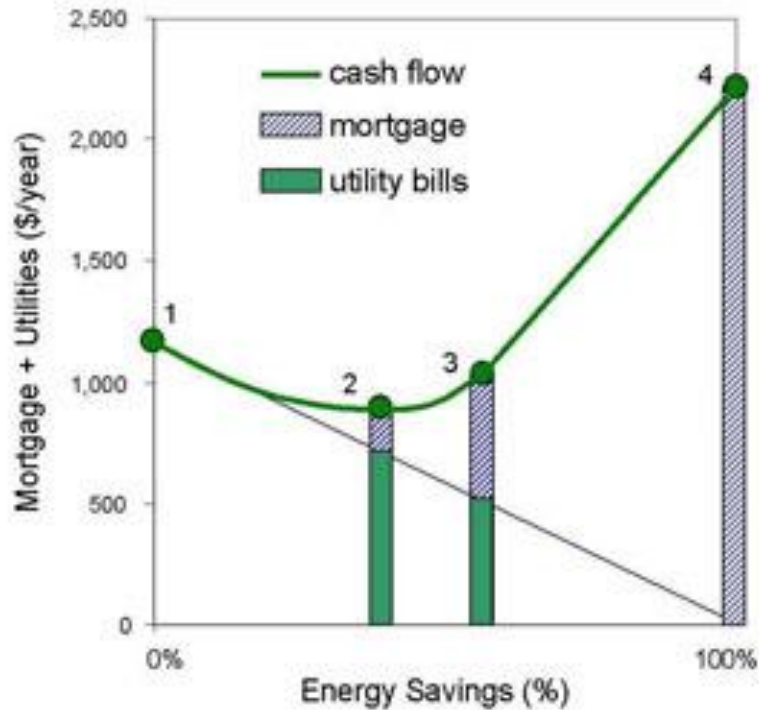


Detailed Results

Presentation summary

- Scientific Paradigms
- Roof Savings Calculator
- Visual Analytics
- Knowledge Work (context)
- **Autotune**
- Example Data Tools
- Saving Money

Existing tools for retrofit optimization



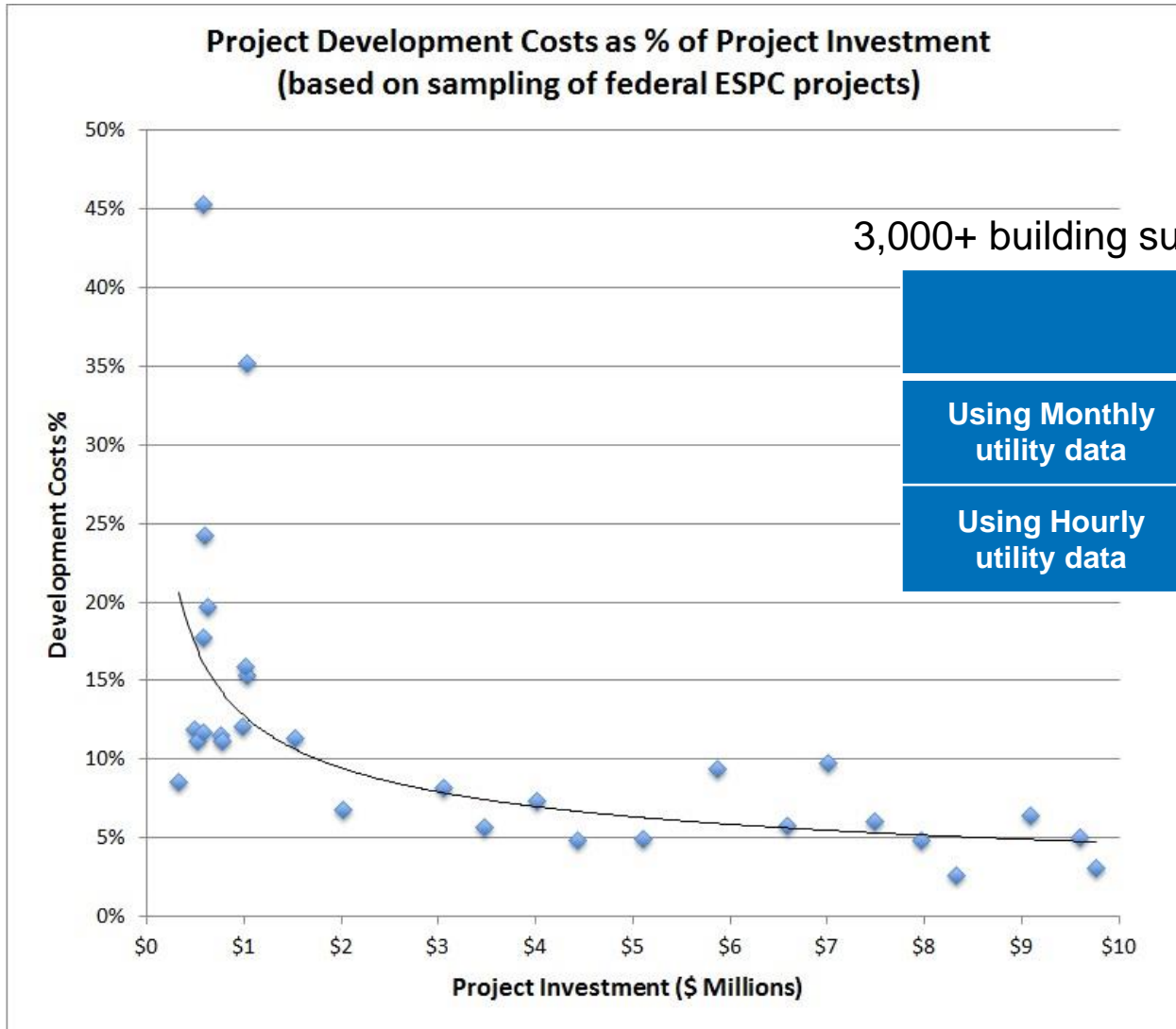
Simulation Engine
DOE-\$65M (1995-?)



API



Business limitations for M&V

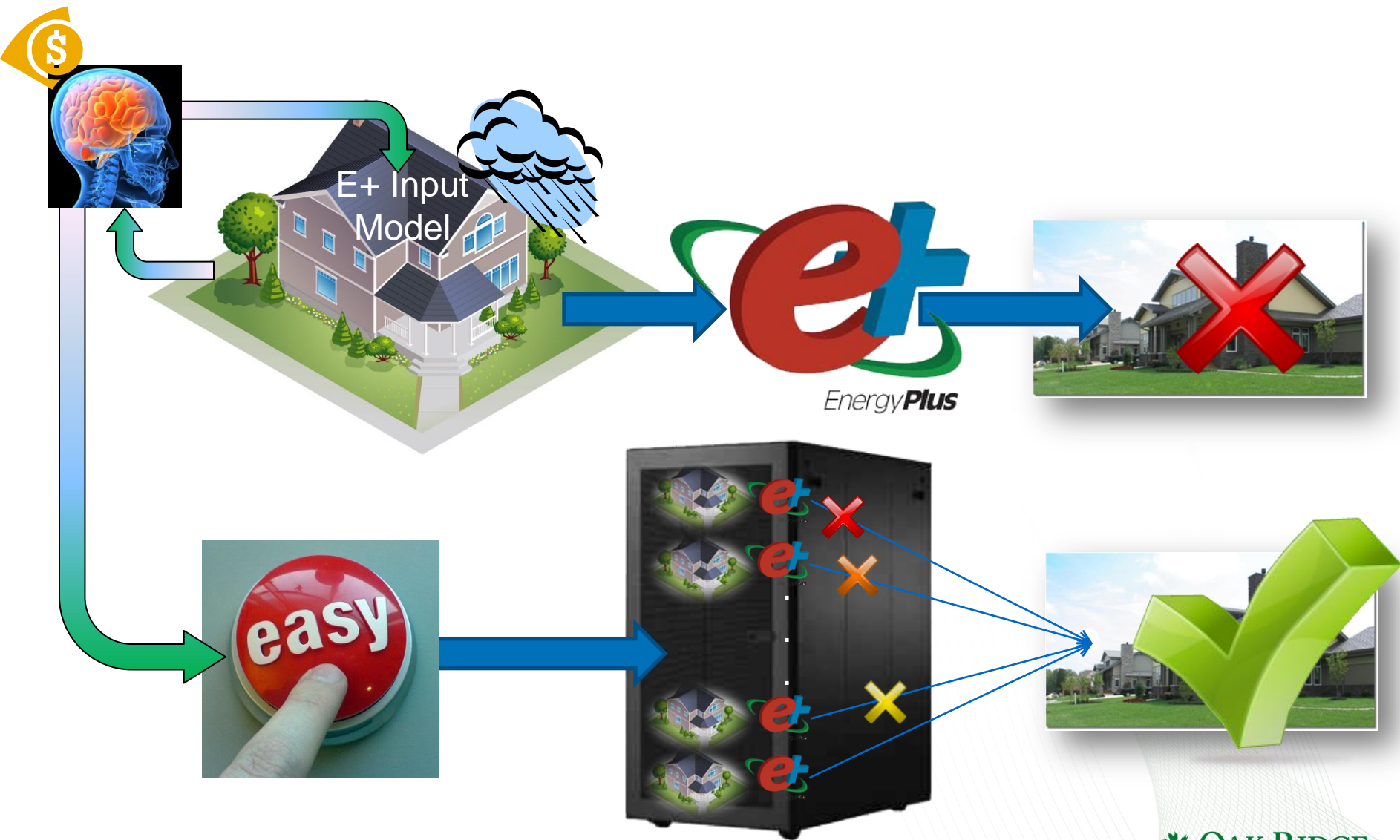


3,000+ building survey, 23-97% monthly error

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

The Autotune Idea

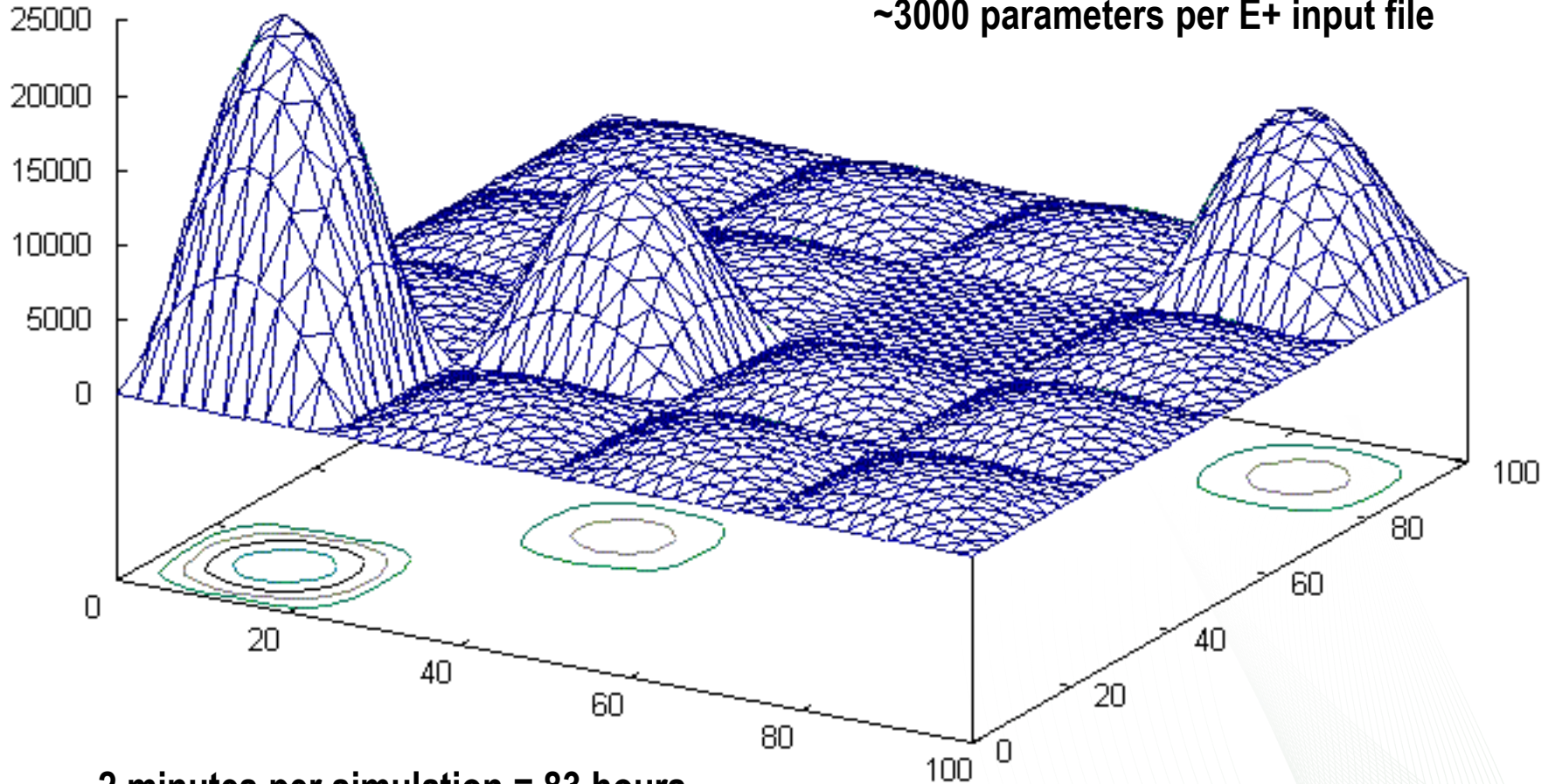
Automatic calibration of software to data



The search problem

Problem/Opportunity:

~3000 parameters per E+ input file



ORNL High Performance Computing Resources

INTRODUCING TITAN

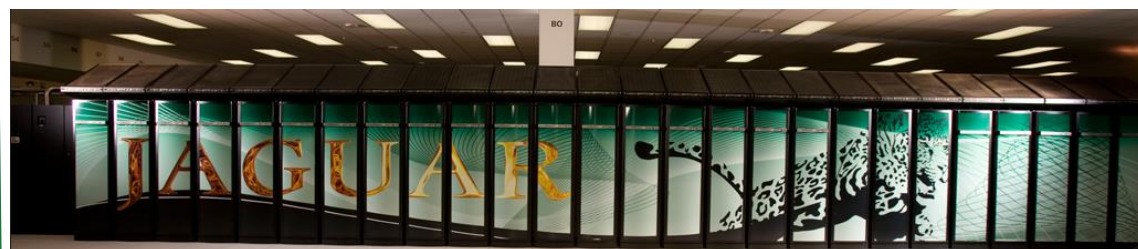
Advancing the Era of Accelerated Computing



Titan:
299,008 CPU cores
18,688 GPU cores
710TB memory, distributed

Jaguar:
224,256 cores
360TB memory

Nautilus:
1024 cores
4TB shared-memory



Kraken:
112,896 cores



Gordon:
12,608 cores
SSD



HPC scalability for desktop software

- EnergyPlus desktop app
- Writes files during a run
- Uses RAMdisk
- Balances simulation memory vs. result storage
- Works from directory of input files & verifies result
- Bulk writes results to disk

Acknowledgment: Jibo Sanyal, ORNL R&D Staff

8 Million EnergyPlus Simulations

270TB dataset of energy data for buildings

No of Processors	E+ Tasks	Wall-clock Time (mm:ss)
64	256	18:34
128	512	18:22
256	1024	20:30
512	2048	20:43
1024	4096	21:03
2048	8192	21:11
4096	16384	20:00
8192	32768	26:14
16384	65536	26:11
65536	262144	44:52
131072	524288	45TB 68:08

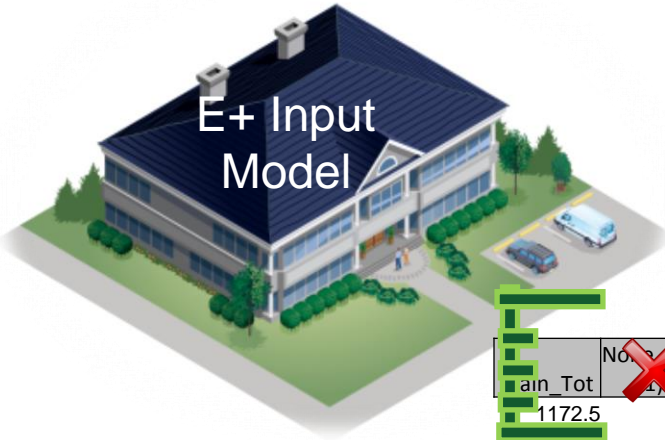
Scalability on Titan



Computational complexity

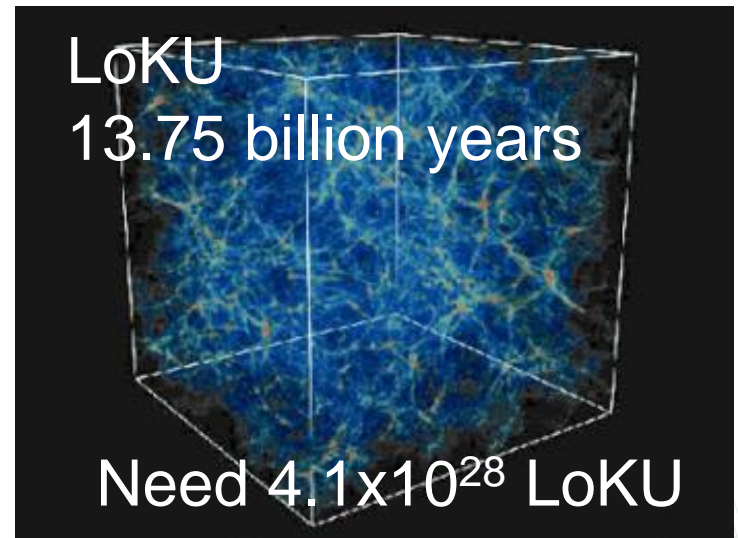
Problems/Opportunities:

Domain experts chose to vary 156
 Brute-force = 5×10^{52} simulations



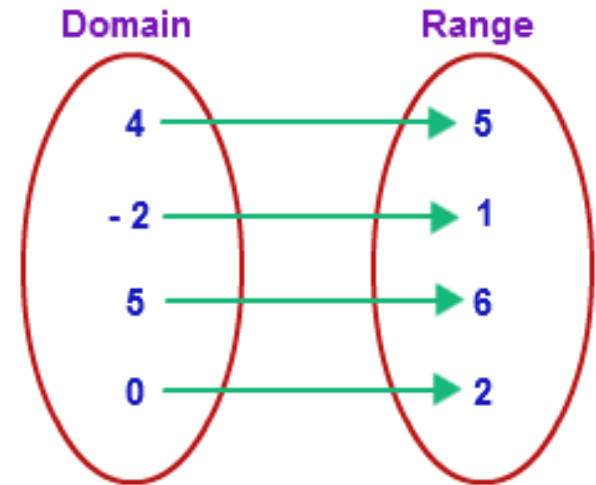
E+ parameters

1172.5	0	0	6.75	18.75	0	0	0	6.75	18	0	0
main_Tot	No. of Tot	(one_Tot(1_in_Tot	1_out_Tot	HP_black	HP_fa	HP_comp	HP_in_Tot	HP_out	HP_black	HP_fa



What is artificial intelligence?

- Give it (lots of) data
- It maps one set of data to another
- Paradigms
 - Unsupervised (clustering)
 - Reinforcement (don't run into wall)
 - Supervised (this is the real answer)
- Methods for doing that...
biologically motivated or not



act human	act rational
think human	think rational

MLSuite: HPC-enabled suite of machine learning algorithms

- 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: UTK computer science graduate graduate Richard Edwards, Ph.D. (advisor Dr. Lynne Parker); now Amazon




Applications of machine learning

- EnergyPlus – 2-10 mins for an annual simulation

```
!- ALL OBJECTS IN CLASS
Version,
    7.0;      !- Version

!- SIMULATION CONTROL
SimulationControl,
    No, !-Do Zone Sizing Calculation
    No, !-Do System Sizing Calculation
    ...
```



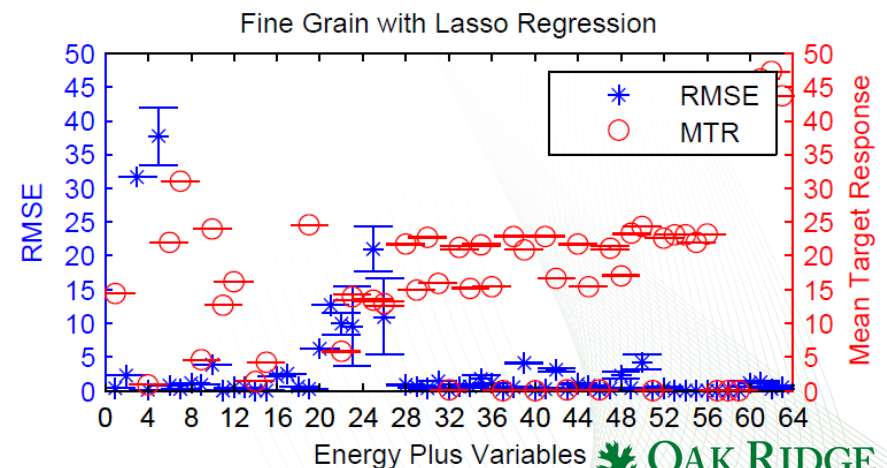
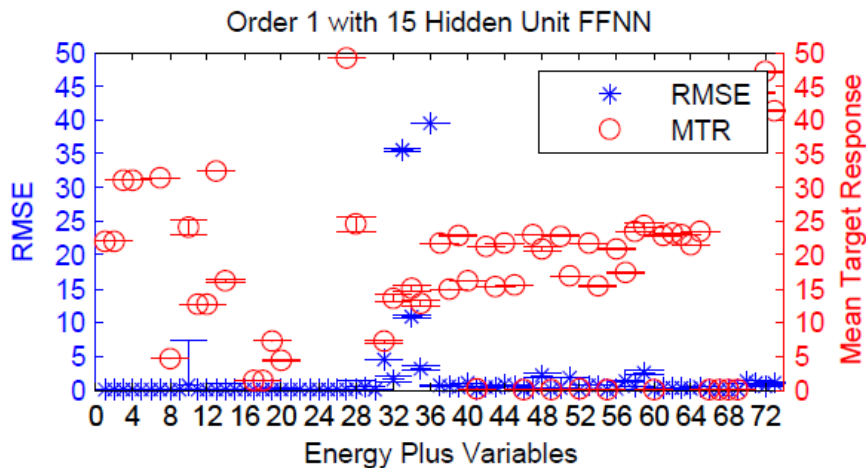
et
EnergyPlus

Date/Time	Environment	Environment	Environment
01/01 00:15:00	-1.77	99.75	98595
01/01 00:30:00	4.9	97	98595
01/01 00:45:00	4.825	95.75	98595
01/01 01:00:00	4.75	94.5	98595
01/01 01:15:00	4.675	93.25	98595

Input.id

Output.csv

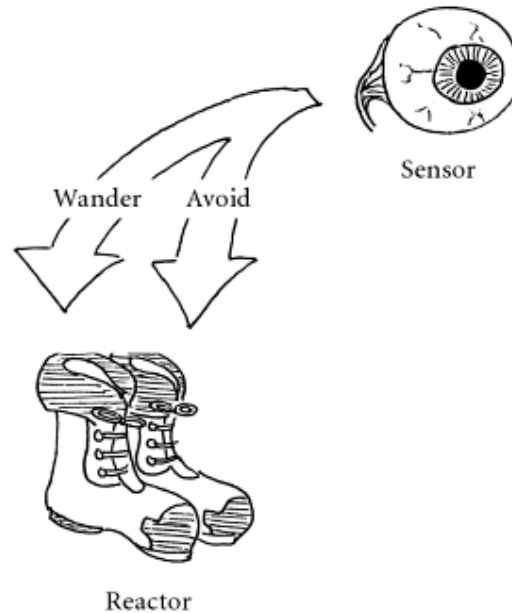
- ~E+ - 4 seconds AI agent as surrogate model, 90x speedup, small error, brittle



Quote

**“the world is the best model
of itself.”**

–Rodney Brooks, 1990, Elephants and nouvelle AI



Nouvelle AI. A robot should sense and then move according to simple rules such as “Avoid collisions” or “Wander.”

Source of Input Data

- 3 Campbell Creek homes (TVA, ORNL, EPRI)
- ~144 sensors/home, 15-minute data:
 - Temperature (inside/outside)
 - Plugs
 - Lights
 - Range
 - Washer
 - Radiated heat

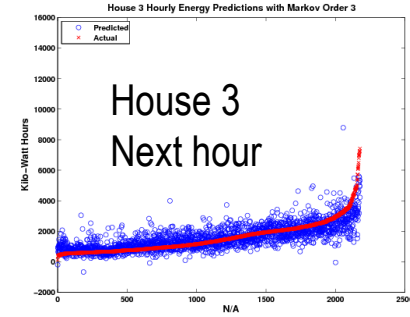
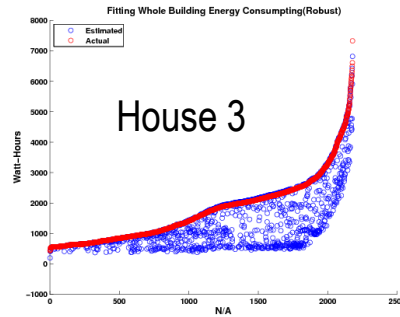
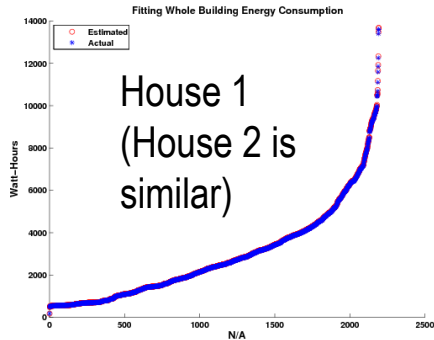


- Dryer
- Refrigerator
- Dishwasher
- Heat pump air flow
- Shower water flow
- Etc.



Applications of machine learning

- Linear Regression predicting whole building energy use



- Accuracy Metrics for best subset of sensors

▶ Root Mean Squared Error(RMSE):

$$RMSE = \sqrt{\frac{1}{N-1} \sum_{i=1}^N (y_i - p_i)^2}$$

▶ Mean Absolute Percentage of Error(MAPE):

$$MAPE = \frac{1}{N} \sum_{i=1}^N \frac{|y_i - p_i|}{y_i}$$

▶ Coefficient of Variance(CV):

$$CV = \frac{RMSE}{y_{mean}} \times 100$$

▶ Mean Bias Error(MBE):

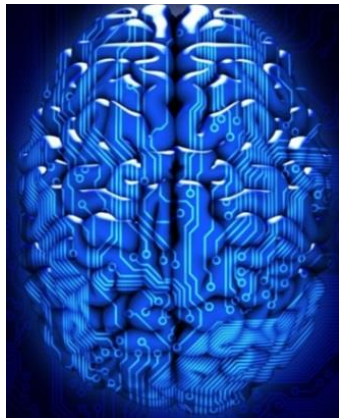
$$MBE = \frac{\frac{1}{N-1} \sum_{i=1}^N (y_i - p_i)}{y_{mean}} \times 100$$

	HME FFNN	HME LS-SVM	SVR	FCM
RMSE(Watt-Hours)	569.96±50.13	582.61±33.97	603.85±40.55	581.87±41.67
MAPE(%)	17.07±1.19	15.94±0.92	15.48±0.87	17.37±1.02
CV(%)	20.14±1.65	20.59±1.12	21.32±1.32	20.56±1.37
MBE(%)	0.42±1.17	-0.07±0.89	-1.50±0.80	0.01±0.99

	Best Four Sensors	Best Model	Top 10 Sensors
RMSE	1127.88±33.00	942.25±26.14	1129.04±32.38
MAPE	41.17±1.12	30.53±1.03	40.4483±1.29
CV	39.76±1.02	33.21±0.73	39.80±0.96
MBE	-0.04±0.90	-0.06±0.92	-0.05±1.05
ICOMP(IFIM)	2166.3±1.54	1845.88±21.25	2125.50±2.72

MLSuite: HPC-enabled Suite of Machine Learning algorithms

- 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



Evolutionary computation

How are offspring produced?

	Thickness	Conductivity	Density	Specific Heat
Bldg1	0.022	0.031	29.2	1647.3
Bldg2	0.027	0.025	34.3	1402.5
$(1+2)_1$	0.0229	0.029	34.13	1494.7
$(1+2)_2$	0.0262	0.024	26.72	1502.9

- Average each component
- Add Gaussian noise
- ... “AI inside of AI”

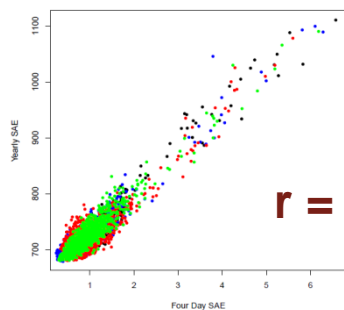
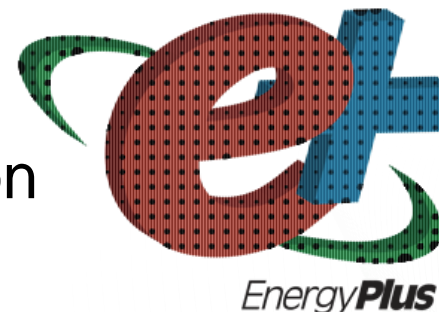


Getting more for less

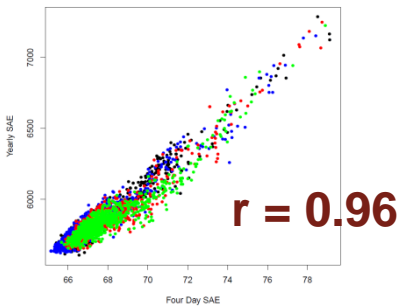
- EnergyPlus is slow
 - Full-year schedule
 - 2 minutes per simulation



- Use abbreviated 4-day schedule instead
 - Jan 1, Apr 1, Aug 1, Nov 1
 - 10 – 20 seconds per simulation

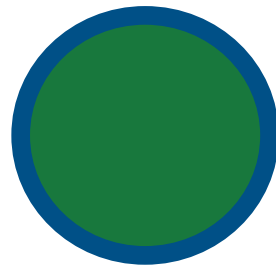


Monthly Electrical Usage



Hourly Electrical Usage

Evolutionary combination

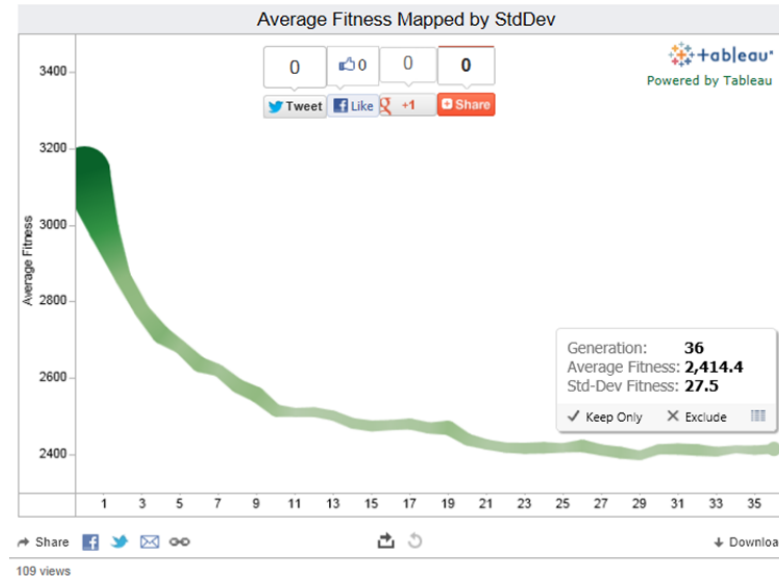


Island Hopping



4 of 19 experiments

1. Surrogate Modeling
2. Sensor-based Energy Modeling (sBEM)
3. Abbreviated Schedule
4. Island-model evolution




Automated M&V process Autotune calibration of simulation to measurements

XSEDE and DOE Office of Science

DOE-EERE BTO


Industry and building owners



Nautilus

No of Processors	No of E+ sims	Wall-clock Time (h:mm:ss)	Time/E+ task (mm:ss)
32	32	0:02:08	2:08
64	64	0:03:04	3:04
128	128	0:04:11	4:11
128	1024	0:34:24	4:18
256	2048	1:25:17	10:40
512	1024	0:18:05	9:02


Scalability on Nautilus



Gordon


No of Processors	E+ Tasks	Wall-clock Time (mm:ss)
64	256	18:34
128	512	18:22
256	1024	20:30
512	2048	20:43
1024	4096	21:03
2048	8192	21:11
4096	16384	20:00
8192	32768	26:14
16384	65536	26:11
65536	262144	44:52
131072	524288	45TB 68:08

Scalability on Titan



Kraken

8 million building sims
270TB dataset!
(0.5M, 45TB, 1hr)





- Features:**
- Works with “any” software
 - Tunes 100s of variables
 - Customizable distributions
 - Matches 1+ million points

Commercial Buildings

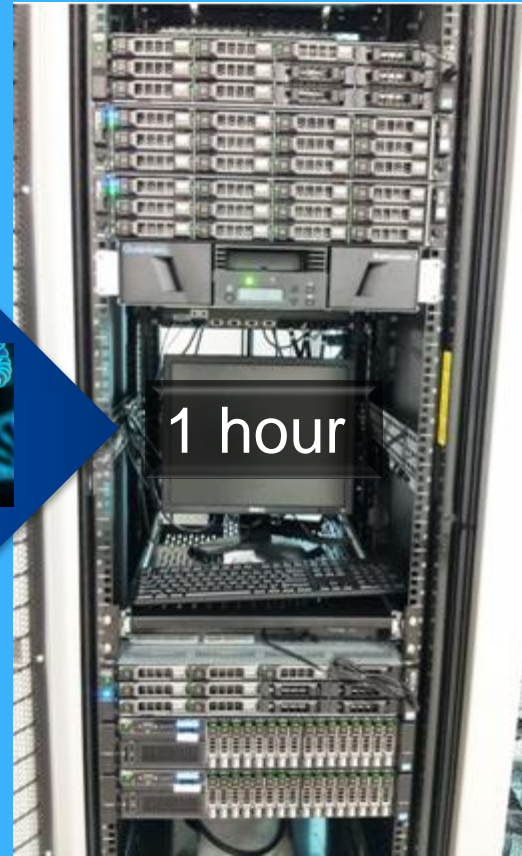
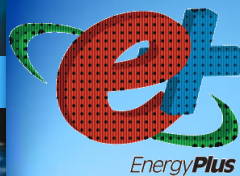
		ASHRAE G14 Requires	Autotune Results
Monthly utility data	CVR	15%	0.32%
	NMBE	5%	0.06%
Hourly utility data	CVR	30%	0.48%
	NMBE	10%	0.07%

Residential home	Tuned input avg. error
Within 30¢/day (actual use \$4.97/day)	Hourly – 8% Monthly – 15%

10+ companies interested

Leveraging HPC resources to calibrate models for optimized building efficiency decisions

HPC-informed algorithmic reduction... to commodity hardware



LoKU

13.75 billion years

Need 4.1×10^{28} LoKU

Science of how Autotune works

Communications (33+ related publications):

- 1) Autotune Overview (2)
- 2) Large Ensemble Simulations and Big Data Challenges (2)
- 3) Machine Learning Techniques – on sensor data (2),
MLSuite scalability on HPC (5)
- 4) Machine Learning applied to Calibration – Surrogate modeling (1), inverse modeling (1), PhD dissertation (1)
- 5) Fixing time-series (sensor) data (6), weather data (1)
- 6) Provenance for tracking sensor data usage (3)
- 7) Autotune System Results – residential ZEBRAAlliance (3), comparison to manual M&V (2), commercial buildings (2), high-resolution calibration (2), and “trinity testing” (2)

Autotune

[Home](#)

[About](#)

[Contact Us](#)

Introduction to Autotune

Autotune can save time, effort, and money in modeling a building. Autotune uses a rough estimate of the building and real data to create models that more closely represent the building. All you have to do is get started with one of the setups and you can soon have models of your building.

About This Website

Autotune is designed to make the modeling process easier. You can start designing your model through the basic or advanced setup. If you have already completed the setup, you can enter your tracking number into the tracking box to review the progress of your order or download models if any are available.

Enjoy the simplistic power of Autotune!

Create a model for your building

Basic Setup

The basic setup is designed with simplicity in mind. If you have only the basic knowledge of the building, this is the choice of setup for you.

[Get Started](#)

Advanced or Experienced Setup

The advanced setup is for those who are very knowledgeable with the specifications of the building. This setup will provide the most customized model and will result in quicker, more accurate results.

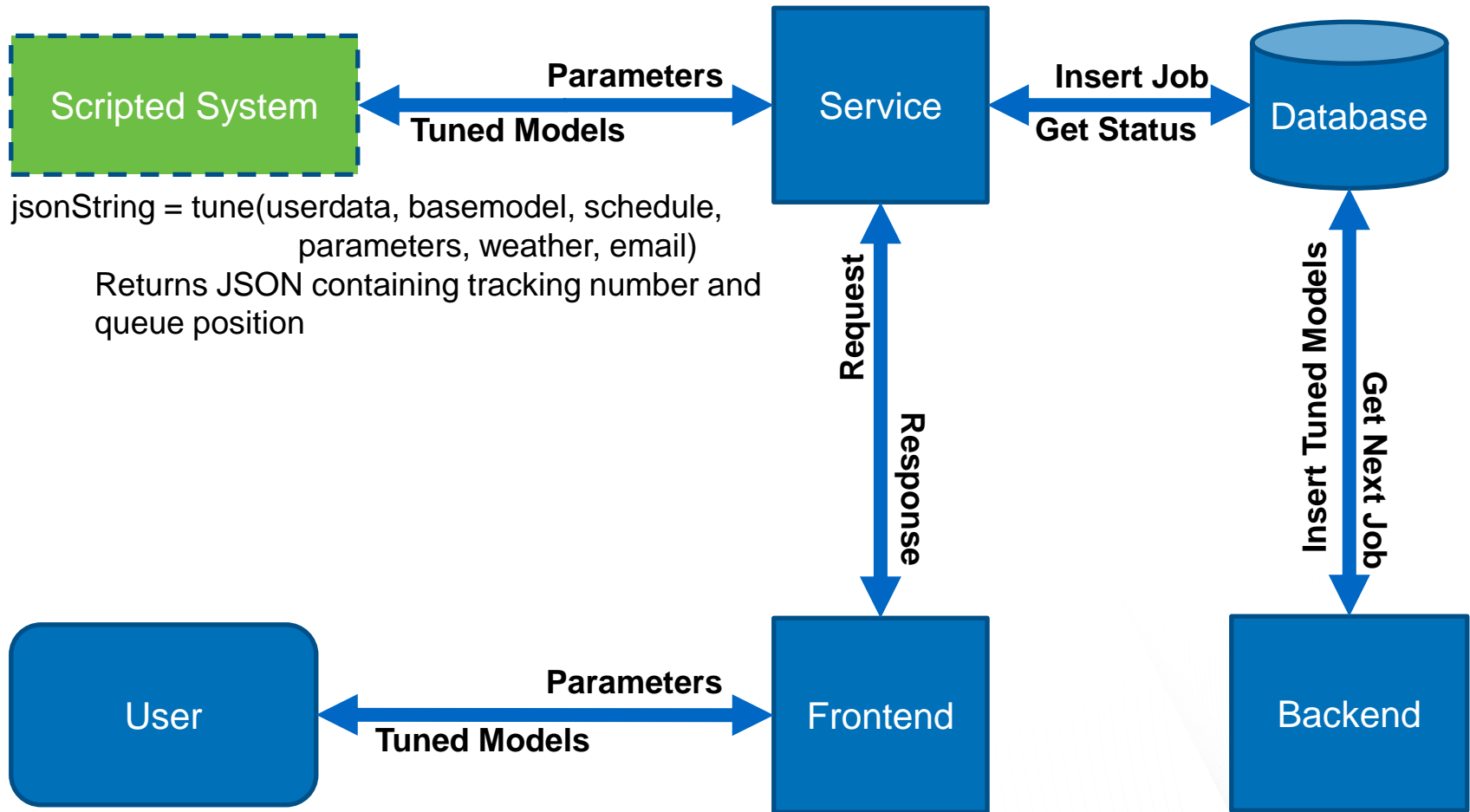
[Advanced Setup](#)

Track Progress of Your Model

Check on your model

[Review](#)

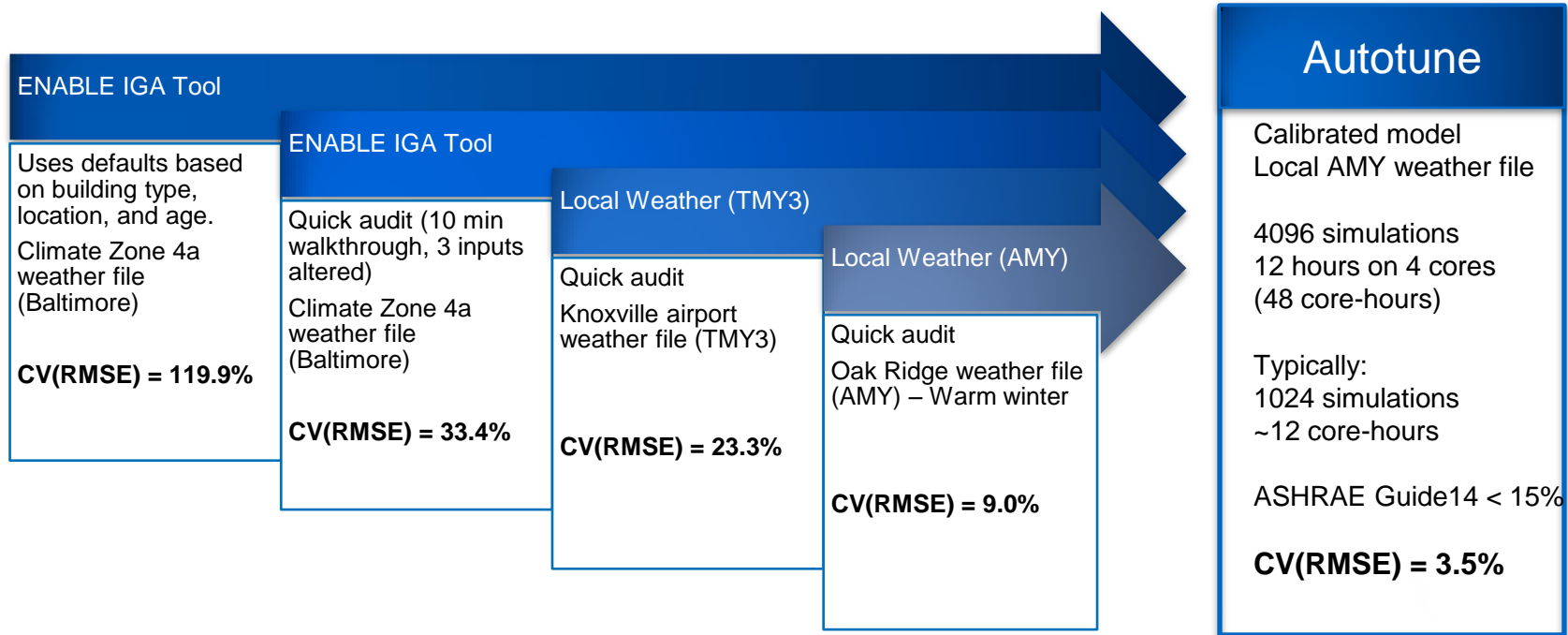
Website



```
jsonString = tune(userdata, basemodel, schedule,  
                  parameters, weather, email)  
Returns JSON containing tracking number and  
queue position
```

10 companies interested, 3 have provided data

Building 3147 Autotune results



	15 Minute	Hourly	Daily	Monthly
Defaulted (climate zone TMY3)	155.55%	154.14%	129.11%	119.87%
Quick audit (climate zone TMY3)	72.48%	71.33%	52.25%	33.43%
Quick audit (local TMY3)	63.89%	62.60%	41.08%	23.33%
Quick audit (local AMY)	43.30%	41.64%	22.18%	9.03%
Tuned (local AMY)	38.12%	35.99%	17.75%	3.50%

The Autotune Team

Jibo Sanyal

Mahabir Bhandari

Som Shrestha

Joshua New

Aaron Garrett

Buzz Karpay

Richard Edwards



<http://autotune.roofcalc.com>

“Big Ideas”

Model US – SimCity for all US Buildings

Data integration and computer vision for low-fidelity, wide-area software models of all existing buildings with eventual calibration and simulation

Technology/Approach Summary

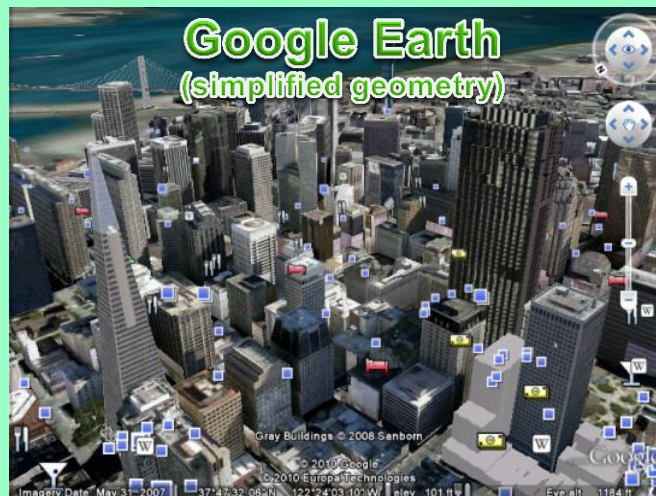
- Consolidate building imagery for box-plot models
- Classify imagery via machine learning for layering box-plot models with material and equipment properties
- Create building database for year constructed, square footage, no. of beds and baths, heating type in public database, etc. for use by industry partners
- Create models with methods similar to LDRD
- CoNECT used on 220,000 Knox-county buildings
- HPC for annual energy simulations of all US buildings (requires avg. INCITE allocation of 127M core hours)
- Data sources have identified databases covering 100+ million buildings, surpassing the largest DOE’s Building Technology Office database of ~30,000.

Technology/Approach Impact

- Light commercial support \$5-9 billion industry
- ESCO revenue in 2008 was \$4.1 billion, with the market served being 9% residential (public utility programs and public housing)
- At 96% of the building stock, ESCO uptake could be a \$12 billion dollar industry with 75% of revenue from EE

Data Integration, Mining, and Modeling

Model US – 125.1 million buildings



Presentation summary

- Scientific Paradigms
- Roof Savings Calculator
- Visual Analytics
- Knowledge Work
- Autotune
- Example Data Tools
- **Saving Money**

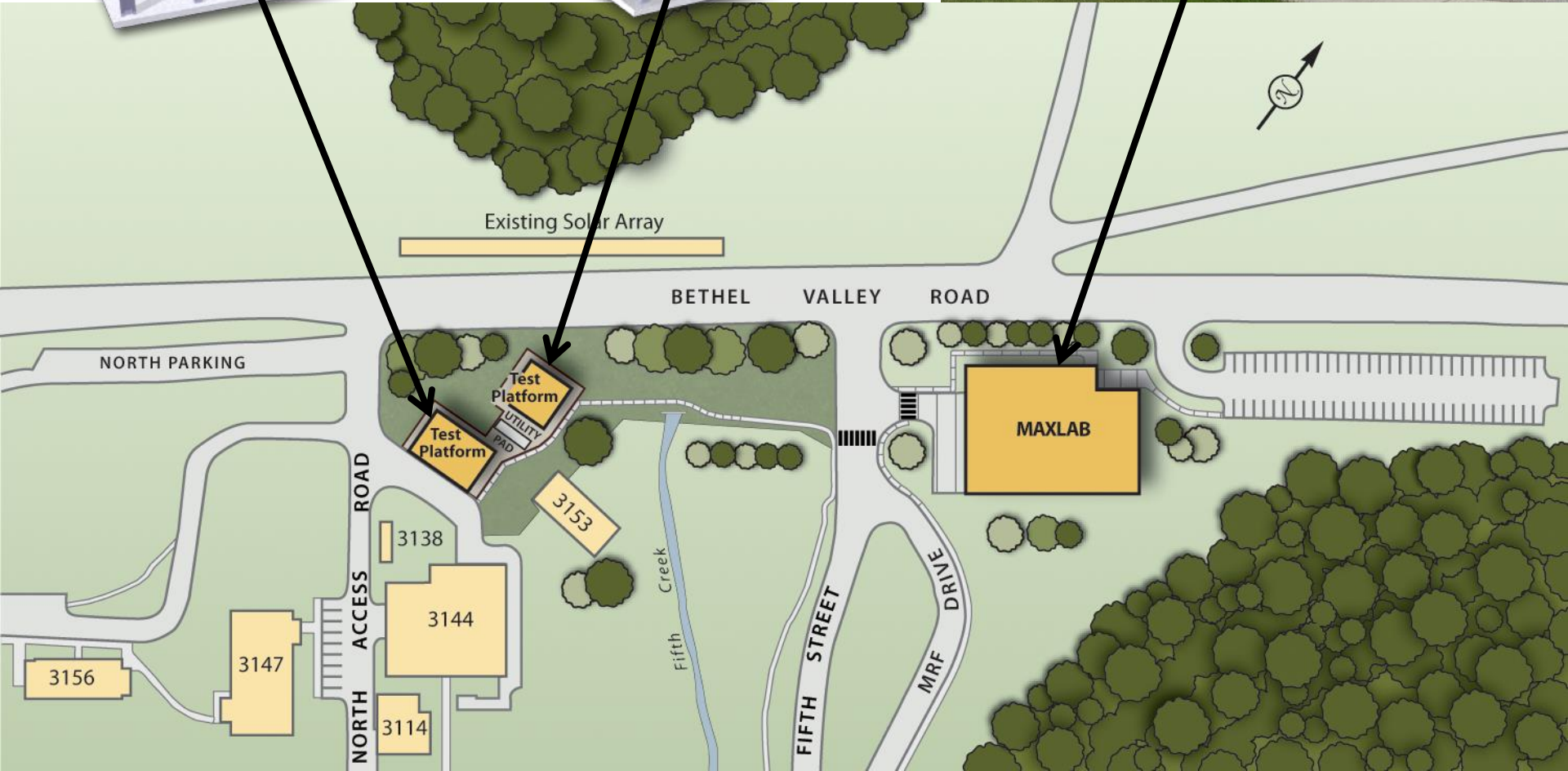
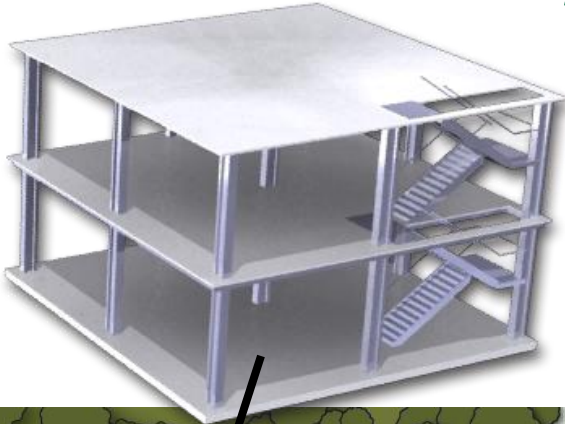
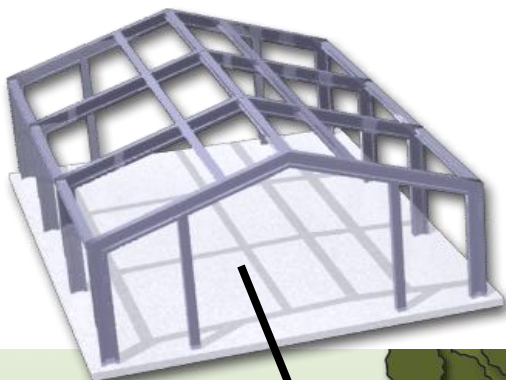
Campbell Creek Robo-Homes

- 3 residential homes, Campbell Creek Energy Efficient Homes Project
- Campbell Station Rd Knoxville, TN



- **Home 1:** control home, uses building techniques typical in Tennessee Valley
- **Home 2:** typical house, but retrofitted with energy efficiency technologies
- **Home 3:** uses latest construction technologies, including photovoltaic panels and solar water heating

MAXLAB Project



FRP1 Sensors



Refrigerant Mass Flow



Natural Gas Flow



Electrical Power



Refrigerant Temp and Press



Airflow

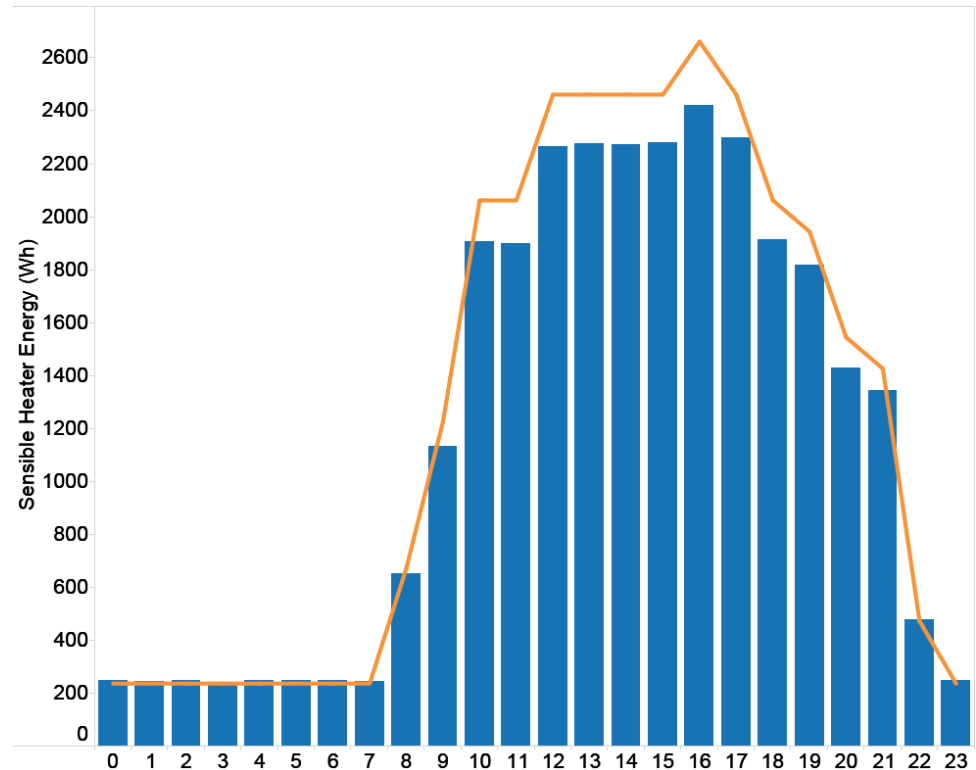


Air Temp And RH

Automatic filling of humidifiers

- Water lines installed for humidifier auto-fill in FRP2
- Float valves installed for auto-fill
- System includes flood protection

National Averages defined by Building America benchmarks (dishwasher, shower, occupancy, location, heat, moisture, etc.)





YOU NEVER KNOW WHO'S WATCHING...
(NEVER SHARE PRIVATE INFORMATION ONLINE.)



IT

Tape Backup

Elessar

EVENSTAR

Sensor Correction

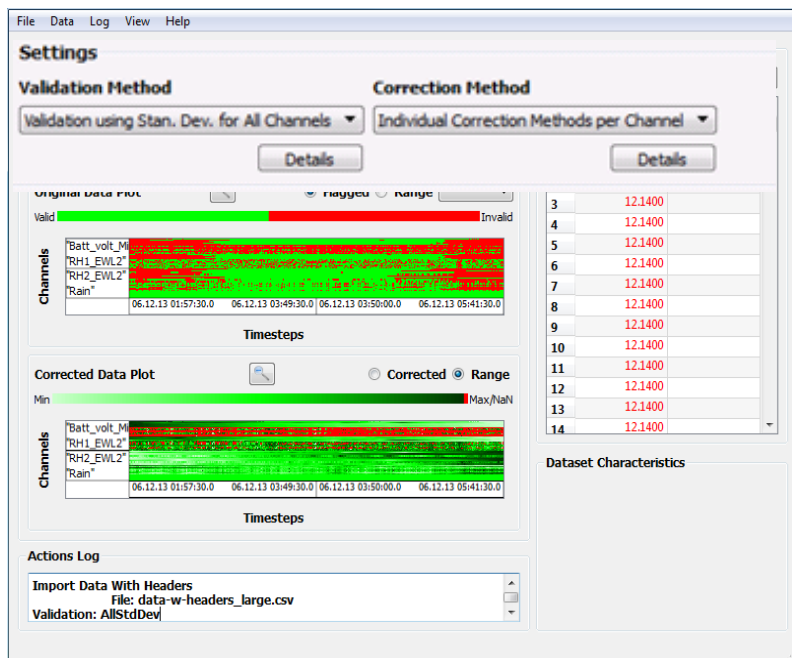


Table 2. Summary of Testing Results for the Filtering Correction Algorithms (Castello et al. 2013)

	Kalman				LPC			
	w	AE	RE	$RMSE$	w	AE	RE	$RMSE$
Temperature	12	3.6%	5.3%	2.75	96	7.0%	10.0%	11.17
Humidity	96	5.2%	8.9%	5.35	96	9.2%	15.1%	14.36
Energy	48	9.7%	468.5%	13.75	4	9.6%	109.1%	12.92
Pressure	12	3.5%	74.0%	0.22	96	12.0%	22.5%	91.76
Airflow	4	0.6%	0.3%	0.00	48	0.6%	66.0%	0.98

Table 1. Summary of Testing Results for the Statistical Correction Algorithms (Castello and New. 2012)

	Temperature				Humidity				Energy			
	w	AE	RE	$RMSE$	w	AE	RE	$RMSE$	w	AE	RE	$RMSE$
LS	12	4.2%	6.4%	3.44	24	5.4%	9.5%	6.10	24	12.3%	890.0%	24.66
MLE	12	3.1%	4.6%	2.49	12	4.8%	8.2%	4.71	96	7.6%	391.3%	10.92
SA	48	12.9%	15.8%	10.25	6	8.6%	21.2%	8.09	6	7.4%	340.5%	9.93
TB ($\epsilon=1$)	6	2.6%	3.9%	1.94	6	4.2%	7.3%	3.93	6	7.3%	241.3%	10.19
TB ($\epsilon=2$)	6	2.5%	3.8%	1.92	6	3.9%	6.7%	3.62	12	7.3%	355.3%	9.99
TB ($\epsilon=3$)	6	2.5%	3.8%	1.93	6	3.9%	6.7%	3.64	6	7.4%	369.9%	9.83

Provenance – sensor lineage



ProvDMS Provenance Data Management System

Home New Experiment My Experiments Others Experiments Interactive 3D Documentation

Data Loggers FRP1-1

Source Channels

Channel	Units
T1m	
T24h	
T30s	
T60m	
FRP1-2	
T1_EWL1	degF
T2_EWL1	degF
T1_EWL2	degF
T1_NWL1	degF

FRP 1 - 1

1 min

T1m-T1_EWL1
T1m-T2_EWL1
T1m-T1_EWL2
T1m-T1_EWL2

15 min

T15m-T1_EWL1
T15m-T2_EWL1
T15m-T1_EWL2
T15m-T1_EWL2

60 min

T60m-T1_EWL1
T60m-T2_EWL1
T60m-T1_EWL2
T60m-T1_EWL2

Select Channels →

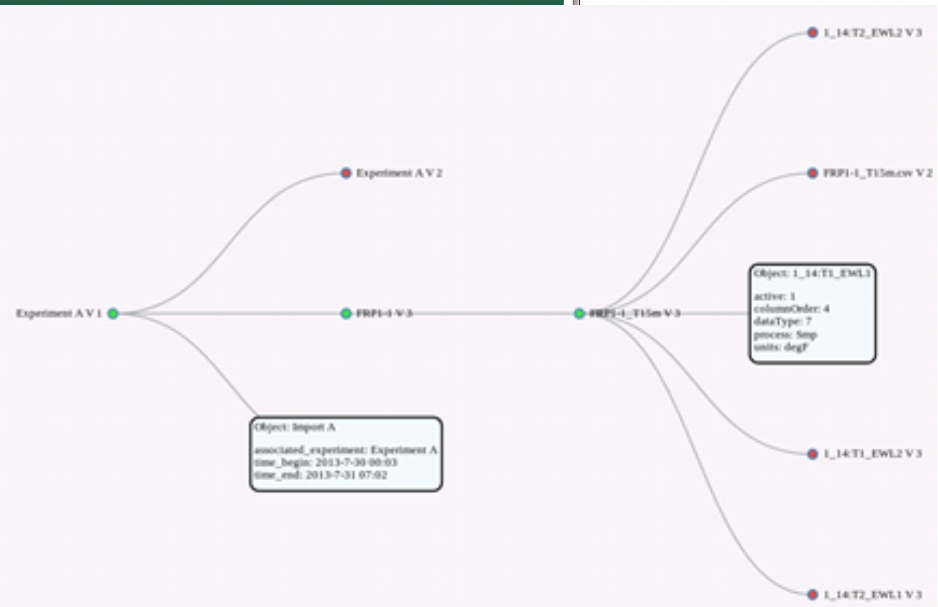
Channel	T1_EWL2	Station	FRP1-1
Units	degF	Logger	T15m
Process	Smp	Column Order	6
Data Type	7		
Active	1		

← Deselect Channels

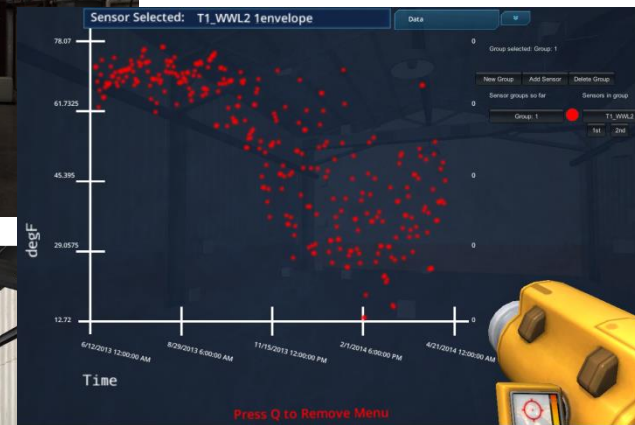
Save New Experiment

Name:

Save



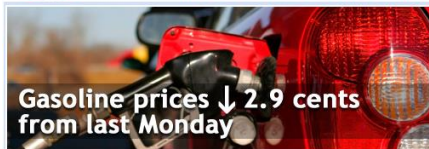
Unity Game for Sensor Data



Presentation summary

- Scientific Paradigms
- Roof Savings Calculator
- Visual Analytics
- Knowledge Work
- Autotune
- Saving Money

Information Sources



Features:

- Latest U.S. Gasoline Prices
- Latest U.S. Diesel Prices
- Careers at EIA
- State Energy Profiles
- Updated Country Brief

A - Z Topics

A B C D E F G H I
J K L M N O P Q R
S T U V W XYZ

Latest Data

Crude Futures Price - 9/23/2010
\$75.18 /bbl wk chg: +0.61 yr chg: +6.21

Retail Gasoline Price - 9/20/2010
\$2.723 /gal wk chg: +0.002 yr chg: +0.171

Energy Sources

- Petroleum**
Crude oil, gasoline, heating oil, diesel, propane, jet fuel, and other petroleum products...
- Natural Gas**
Exploration and reserves, storage, imports and exports, production, prices, sales...
- Electricity**
Sales, revenue and prices, power plants, fuel use, stocks, generation, trade, demand & emissions...
- Coal**
Reserves, production, prices, employment and productivity, distribution, stocks, imports and exports...
- Renewable & Alternative Fuels**
Includes hydropower, solar, wind, geothermal, biomass and ethanol...
- Nuclear**
Uranium fuel, nuclear reactors, generation, spent fuel...

Topics

- Forecasts & Analysis**
Monthly and yearly energy forecasts, analysis of energy topics, financial analysis, Congressional reports...
- Environment**
Greenhouse gas data, voluntary reporting, electric power plant emissions...
- Households, Buildings & Industry**
Energy use in homes, commercial buildings, manufacturing and transportation...
- Geography**
- International**
Country energy information, detailed and overviews...
- State & U.S. Historical Data Overview**
Monthly and yearly energy statistics allow for comparison across all fuels and sectors...

Most Requested

Latest Market Updates

- On-Highway Retail Diesel Prices
- Gasoline and Diesel Fuel Update
- Natural Gas Storage Report
- This Week in Petroleum
- Weekly Petroleum Status Report

Forecasts

- Annual Energy Outlook
- Short-Term Energy Outlook
- International Energy Outlook

State and Country Information

- Country Energy Profiles
- State Energy Profiles

Other Resources:

- All Reports and Products
- EIA Survey Forms
- 2010 EIA Conference
- Sign Up for Email Updates
- EIA RSS Feeds
- EIA on Twitter

What's New

- Sep 21: Libya Country Analysis Brief
- Sep 21: Financial News for Independent Energy Companies, Second Quarter 2010
- Sep 20: Monthly Flash Estimate

[More What's New...](#)

Press Room

Press releases, Congressional testimony.

Basic Information

Energy Explained | Energy in Brief | FAQs

Your Guide To Understanding Energy

- What Is Energy?
- Units & Calculators
- Petroleum
- Natural Gas
- Coal
- Nuclear
- Use of Energy
- Energy & the Environment
- Hydropower
- Biofuels: Ethanol & Biodiesel
- Wind
- Geothermal



www.dsireusa.org/

DSIRE™
Database of State Incentives for Renewables & Efficiency

U.S. DEPARTMENT OF ENERGY Energy Efficiency & Renewable Energy
North Carolina Solar Center
IREC

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DSIRE SOLAR
solar policy information

DSIRE is a comprehensive source of information on state, local, utility and federal incentives and policies that promote renewable energy and energy efficiency. Established in 1995 and funded by the U.S. Department of Energy, DSIRE is an ongoing project of the N.C. Solar Center and the Interstate Renewable Energy Council.

Choose one or both databases:

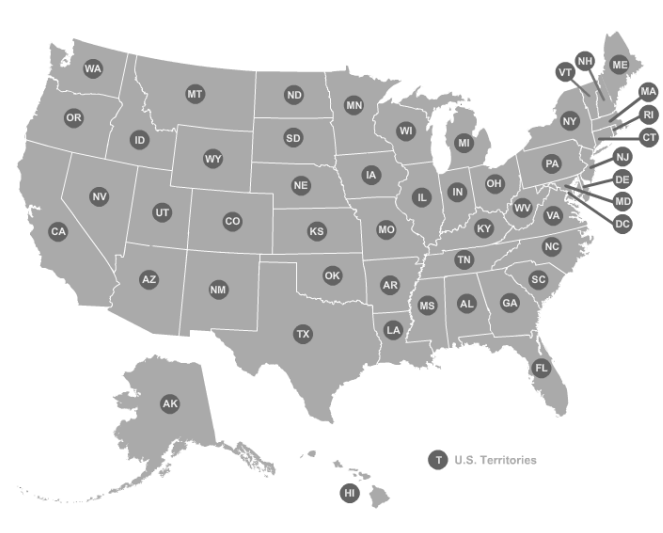
Renewable Energy Energy Efficiency

Federal Incentives

Resources

- Summary Maps
- Summary Tables
- Library
- Search
- What's New?

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NC STATE UNIVERSITY

Disclaimer: The information presented on the DSIRE web site provides an unofficial overview of financial incentives and other policies. It does not constitute professional tax advice or other professional financial guidance, and it should not be used as the only source of information when making purchasing decisions, investment decisions or tax decisions, or when executing other binding agreements. Please refer to the individual contact provided below each summary to verify that a specific financial incentive or other policy applies to your project.

Scalability of utility data access

Google powermeter

Discontinued

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Discontinued – May 31st [Go](#)

Tennessee (38314)

Average Energy Home Cost = \$3,175/yr

Savings with Hohm = **\$1648/yr**

Average Hohm Score=47

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Sign up, It's free

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TAKE ACTION TO KEEP THE PLANET COOL

WELCOME TO COOLCALIFORNIA.org, our goal is to provide resources to all Californians in order to reduce their environmental impact and take action to stop climate change. Realizing local governments, businesses, schools and individuals have different needs, we have customized pages for each audience. Click the tabs above to find:

What's New

- Financial Resources
- Eco-Driving
- Climate Action Planning

Simulation for your home

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Energy Assessment Tool for Home Professionals

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Building ID: Home
 Location: Knoxville, Tennessee
 Zip Code: 37934
 Session: 2114321

HESPro.Ibl.gov

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UPGRADE RECOMMENDATIONS

What efficiency level would you like to model for the initial selection of upgrades?

What simple payback period would you like to use for selecting upgrades?

RECALCULATE

Rows that are dimmed are not included in the calculated values for the retrofit package. To include them check their boxes and recalculate.

Potential Yearly Savings

Money: **\$1,614**
 Energy: **18,357 kWh**
 0 Therms
 Emissions: **27,727 lb. CO₂**

This reduction in greenhouse-gas emissions is like taking 2.4 car(s) off the road.



[Will I make a difference?](#)

[Existing Home Configuration](#)

You have visited 1 (4%) and completed 0 of the 23 possible forms.

Add/Remove	Upgrade	Upgrade Choice & Description	Yearly Savings	Estimated Added Cost	How Much is Too Much?	Simple Payback Time	Estimated Return on Investment	Avoided Emissions (lbs. CO₂)
<input type="checkbox"/>	Check/Uncheck All Upgrades	Total for Selected Upgrades:	\$1,614	\$5	\$16,140	4	27%	27,727
<input checked="" type="checkbox"/>	Thermostat	ENERGY STAR-labeled progra	\$150	\$ 320	\$1,500	2	47%	2,568
<input checked="" type="checkbox"/>	Windows	2-pane/solar-control low-E/argc	\$278	\$ 648	\$2,780	2	43%	4,779
<input checked="" type="checkbox"/>	Indoor lights	CFLs in high-use fixtures	\$45	\$ 88	\$450	2	42%	1,417
<input checked="" type="checkbox"/>	Clothes washer	MEF=1.42 WF=9.5 ENERGY :	\$61	\$ 180	\$610	3	33%	762
<input checked="" type="checkbox"/>	Wall insulation	R-11 wall + R-5 exterior foam s	\$371	\$ 1183	\$3,710	3	31%	6,376
<input checked="" type="checkbox"/>	Duct Sealing	Reduce leakage to 6% of total	\$263	\$ 890	\$2,630	3	29%	4,520
<input checked="" type="checkbox"/>	Electric water heater	EF=0.95	\$45	\$ 195	\$450	4	22%	767
<input checked="" type="checkbox"/>	Air sealing	25% air leakage reduction	\$157	\$ 850	\$1,570	5	18%	2,701
<input checked="" type="checkbox"/>	Floor insulation	R-25	\$274	\$ 1534	\$2,740	6	18%	4,697
<input type="checkbox"/>	Heat pump	SEER=14 HSPF=8.2 ENERGY	\$66	\$ 739	\$660	11	1%	1,136
<input type="checkbox"/>	Attic insulation	R-49	\$204	\$ 2615	\$2,040	13	7%	3,498
<input type="checkbox"/>	Refrigerator	15% better than standard ENE	\$6	\$ 87	\$60	14	6%	110
<input type="checkbox"/>	Duct Insulation	R-6	\$53	\$ 910	\$530	17	NCE	918
<input type="checkbox"/>	Dishwasher	EF=0.68 ENERGY STAR	\$20	\$ 360	\$200	18	NCE	307

Money for homeowners

TVA energyright solutions

www.energyright.com

SOLUTIONS ENERGY EVALUATION LIGHTING HEAT PUMPS WATER HEATERS NEW HOMES ENERGY SAVING TOOLS

FOR YOUR HOME
SAVE MONEY.
SAVE ENERGY.
START NOW.

- > LIGHTING
- > HEAT PUMPS
- > NEW HOMES
- > ENERGY-SAVING TOOLS

Complete a free online energy evaluation, and for more in-depth information, schedule an in-home energy evaluation, conducted by a TVA-certified evaluator.

- > [Take the online energy evaluation](#)
- > [Schedule an in-home energy evaluation](#)

FEDERAL TAX CREDITS
Find out about tax credits you can receive for installing energy-efficient products and technologies in your home.
> [Read More](#)

ENERGY LIBRARY
This online library of energy information can help you learn about energy use in your home.
> [Read More](#)

MONEY SAVING MINUTES

tvakids.com
One of the best ways to promote energy efficiency is to get kids involved. At TVAkids.com, kids can find out what to do at home and at school to help reduce the consumption of electricity.
> [Read More](#)

TENNESSEE OFFERS ENERGY EFFICIENCY REBATES
Tennesseans can get a rebate of up to \$250 on their energy efficient home heating and cooling systems through the Tennessee Energy Efficient Appliance Rebate Program (TEEARP).
> **Air source heat pumps - \$250 rebate**
> **Central air conditioners - \$250 rebate**
> **Room air conditioners - \$40 rebate**
> **Gas furnaces - \$150 rebate**
> [Read the fact sheet](#)
> [Get an application online](#)

TIP of the WEEK
Replace incandescent bulbs with compact fluorescents - they use 75% less energy and last 10 times longer.

You pay \$150 for energy audit

Auditor provides list of recommendations

You pay up to \$1000 for subset of recommendations

TVA give you \$650 (reimburses \$150 fee and pays 50% of cost up to \$500)

Discussion

Oak Ridge National Laboratory

EESD – Martin Keller

ETSD – Johney Green

BTRIC – Patrick Hughes

WBCI – Melissa Lapsa

Joshua New, Ph.D.

newjr@ornl.gov

