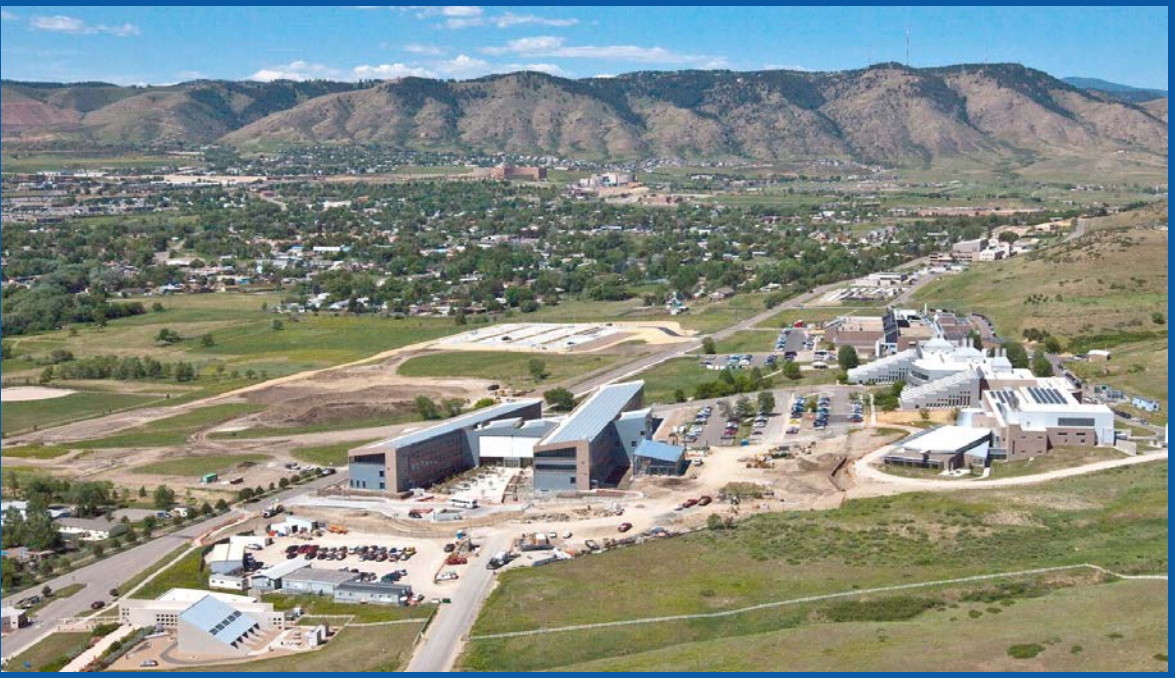
NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Improving the Accuracy of Software-Based Energy Analysis for Residential Buildings



Ben Polly

The Energy & Environmental Building Alliance (EEBA) Conference

September 14, 2011

Las Vegas, Nevada

NREL/PR-5500-52745

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Learning Objectives

1. Understand the **basic components** of software-based energy analysis for residential buildings

2. Explore the **concepts of "error" and "accuracy"** when analysis predictions are compared to measured data

3. Learn how NREL is working to **continuously improve** the accuracy of energy analysis methods

4. **Calibrate expectations** for the accuracy of residential energy analysis methods

Presentation Outline

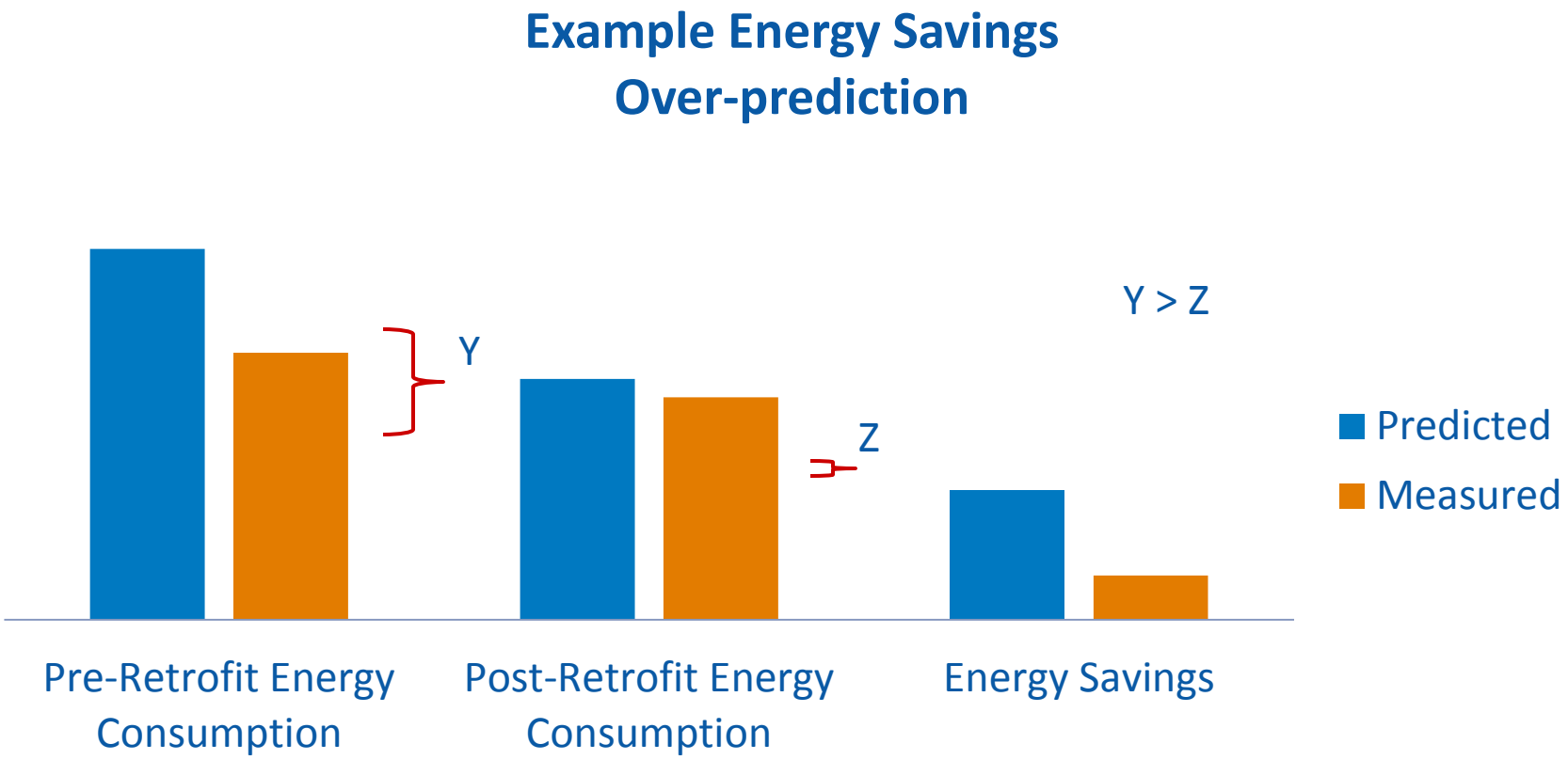
A. Motivation and Goals
B. Basics and Terminology
C. NREL Efforts To Improve Accuracy
    1. Building America House Simulation Protocols
    2. National Residential Efficiency Measures Database
    3. Field and Laboratory Systems Test Support
    4. BESTEST
    5. BEopt Diagnostic Test Suite
    6. Addressing Potential Issues
    7. Field Data Repository
    8. Comparative Analysis
    9. Uncertainty Analysis

Focus for this talk

D. Final Remarks

Motivation and Goals

Motivation and Goals

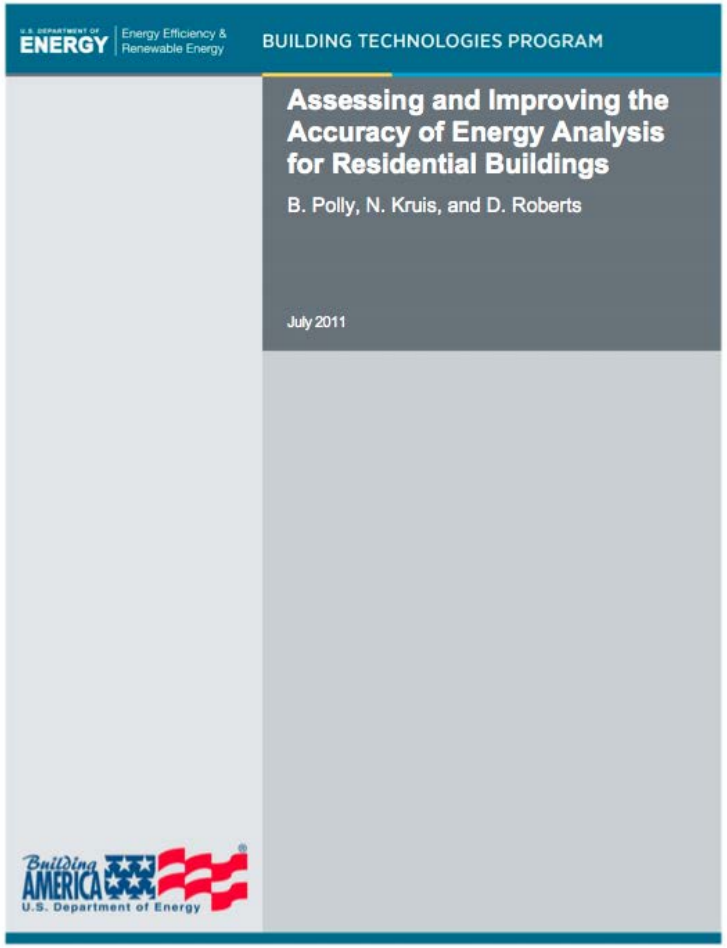


Motivation and Goals

Motivation:

- Stakeholders rely on accurate predictions
- Previous research indicates that analysis methods tend to **overpredict** energy use for poorly insulated leaky homes

  (see Appendix A of report →)
- Inaccuracy ⟹ Risk



Motivation and Goals

Goals of NREL Analysis Accuracy R&D:

- **Provide industry with the tools and technical information** needed to improve the accuracy and consistency of analysis methods
- **Reduce the risks** associated with purchasing, financing, and selling energy efficiency upgrades
- **Enhance software and input collection methods** considering impacts on accuracy, cost, and time of energy assessments

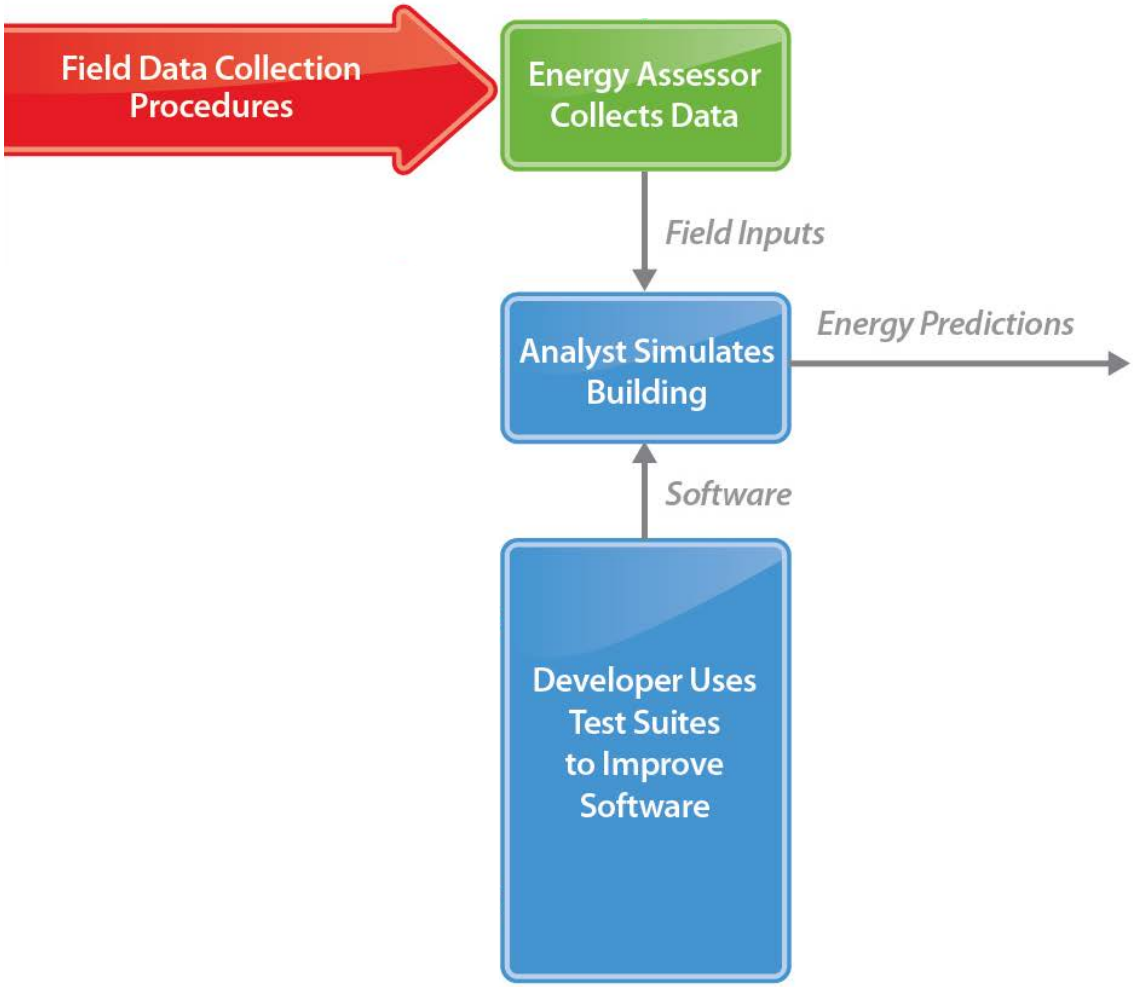
Basics and Terminology

Basics and Terminology

- Analysis methods and tools are available at various “levels”
  - Single component
  - Whole-building 
  - Community
- Whole-building energy analysis is used in the residential sector for many purposes:
  - Design energy-efficient homes
  - Produce labels, scores, and ratings
  - Predict energy and cost savings from energy efficiency upgrades
  - Determine cost and performance criteria for new energy-efficiency technologies
  - Provide quantitative analysis and data to support programmatic and policy-related decisions.

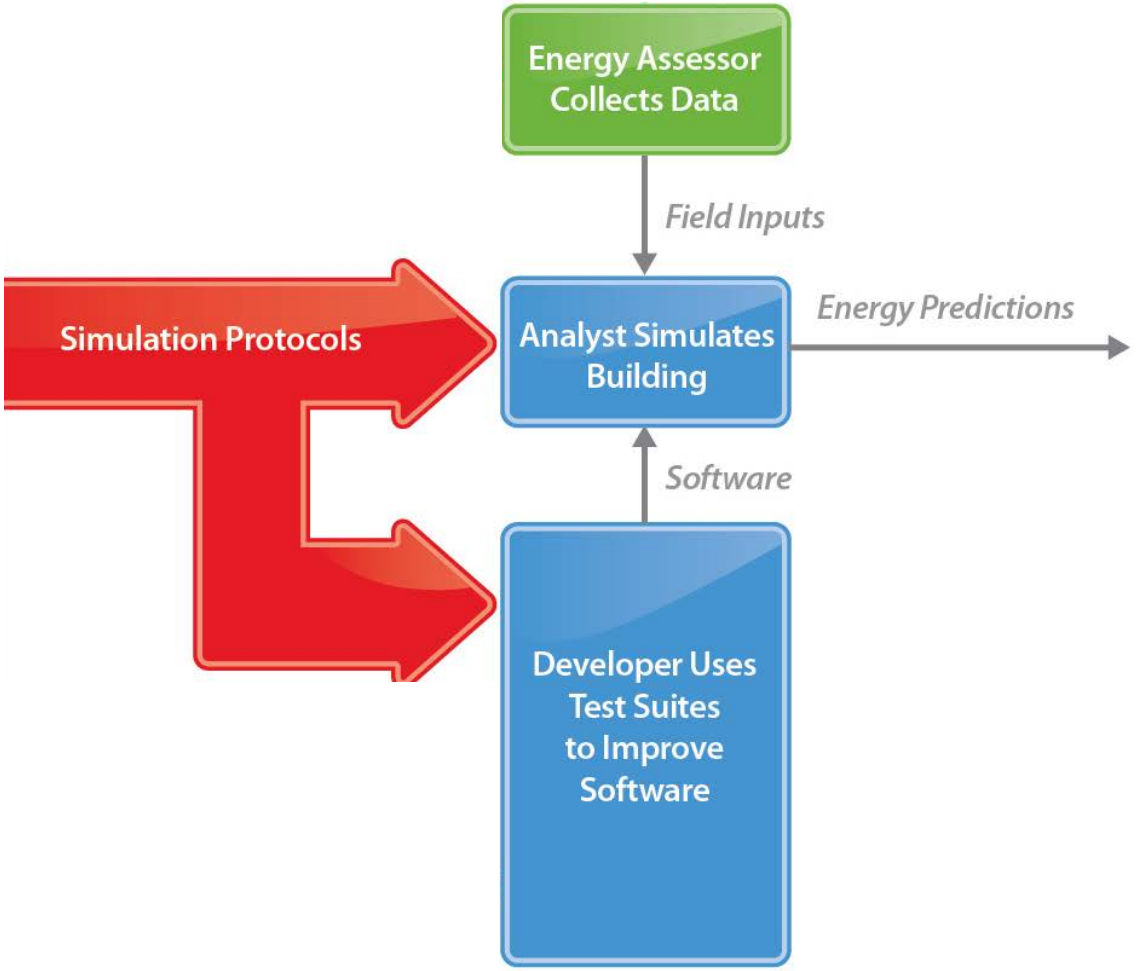
Basics & Terminology

Field Data Collection Procedures: Published recommendations for collecting data from a house through measurement and observation.



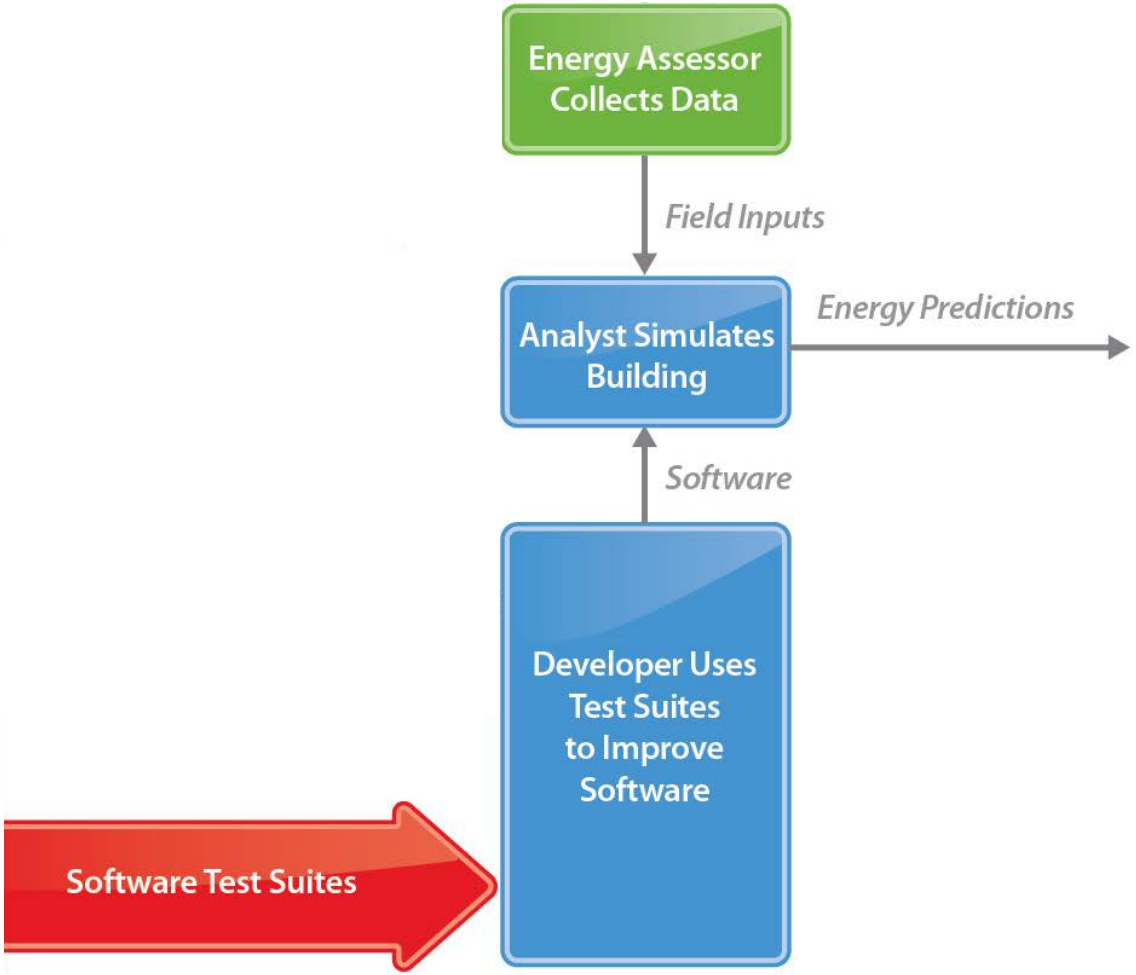
Basics & Terminology

Simulation Protocols: Published defaults and assumptions for simulation inputs that are not directly measured or observed in the field.

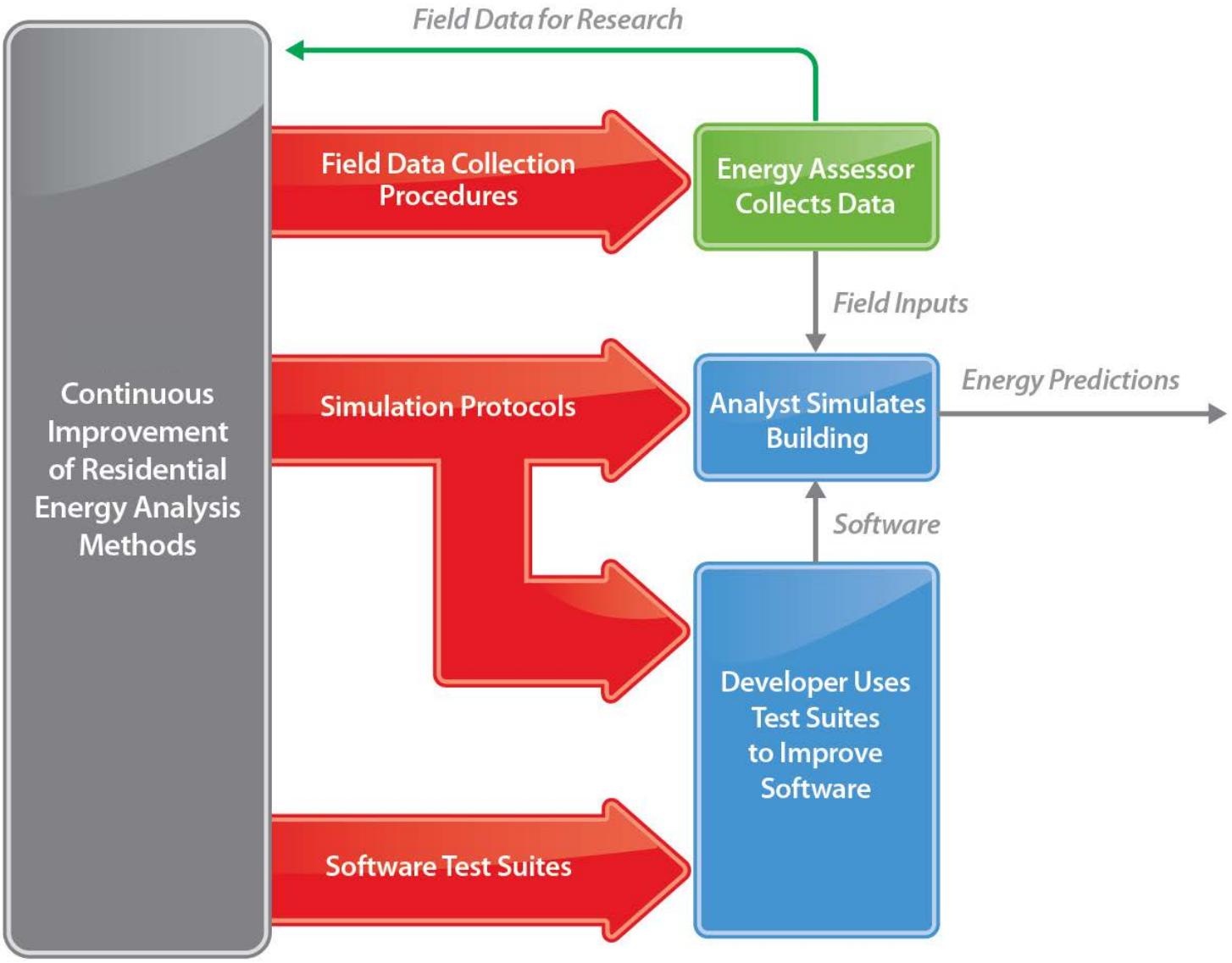


Basics & Terminology

Software Test Suites:
Published suites of tests through which commercial vendors can compare their software results to those of reference software, analytical solutions, and empirical data.



Basics & Terminology



Basics and Terminology

A range of perspectives:

One Home — Many Homes

- House-specific
- Unique occupant behavior
- “Operational” mode

- Average
- Standard occupant behavior
- “Asset” mode

Operational Analysis: Specific occupants are considered.

Asset Analysis: Standard occupants are considered.

Basics and Terminology

Compare predicted energy use to measured energy use:

$$"error" = predicted - measured$$

Simulated energy use

Measured energy use based on utility billing data

Basics and Terminology

Many Metrics for Accuracy!

- Mean error
- Median error
- Mean percent error
- Median percent error
- Mean absolute error
- Median absolute error
- Mean absolute percent error
- Median absolute percent error
- Standard deviation of the errors
- Root mean squared error
- Realization rate
- And more..

Basics and Terminology

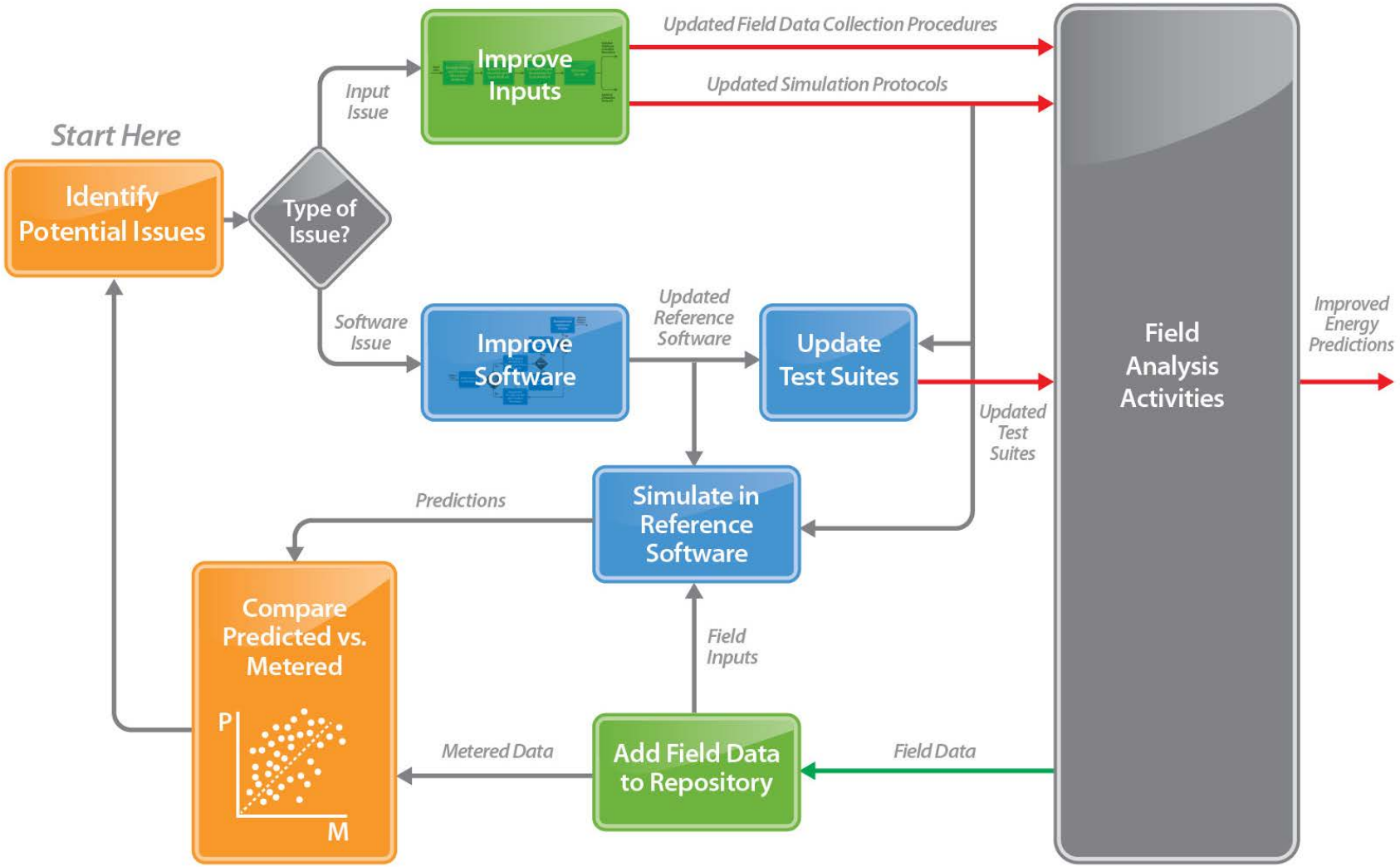
How accurate should a software tool be for a single home (let's say, yours)?

- Example: 30% predicted utility bill savings; what range of actual savings would you accept?
  - 29%–31%?
  - 25%–35%?
  - 20%–40%?
  - 0%–60%?

On average for a large number of homes?

NREL Efforts To Improve Accuracy

NREL Efforts To Improve Accuracy



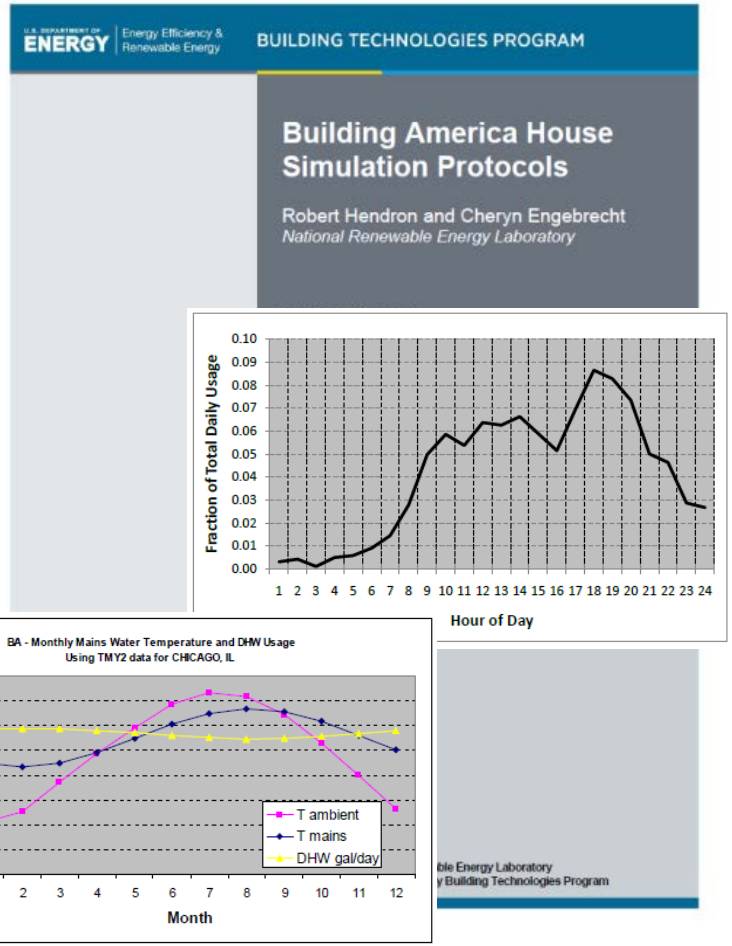
NREL Efforts To Improve Accuracy

1. Building America House Simulation Protocols
2. National Residential Efficiency Measures Database
3. Field and Laboratory Test Support
4. BESTEST
5. BEopt Diagnostic Test Suite
6. Addressing Potential Issues
7. **Field Data Repository**
8. **Comparative Analysis**
9. **Uncertainty Analysis**

1. Building America House Simulation Protocols

Objective: *Improve inputs for asset (non-operational) assessments.*

- Provides detailed, standardized operational information
- Based on 15+ years of Building America research
- Used in BEopt optimization software
- Available to broader energy assessment community

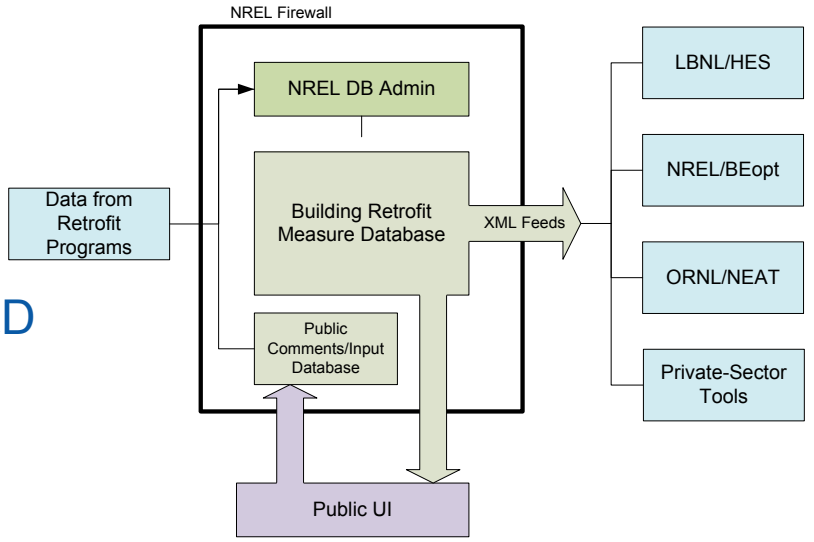


2. National Residential Efficiency Measures Database

Objective: *Improve inputs.*

- Provides detailed and standardized resource of information for residential energy efficiency measures
  - Measures list
  - Performance parameters (U-value, SEER, etc.)
  - Costs
  - Standardized format
  - Improve technical consistency and accuracy
  - Support external building science R&D
  - Enhance public transparency

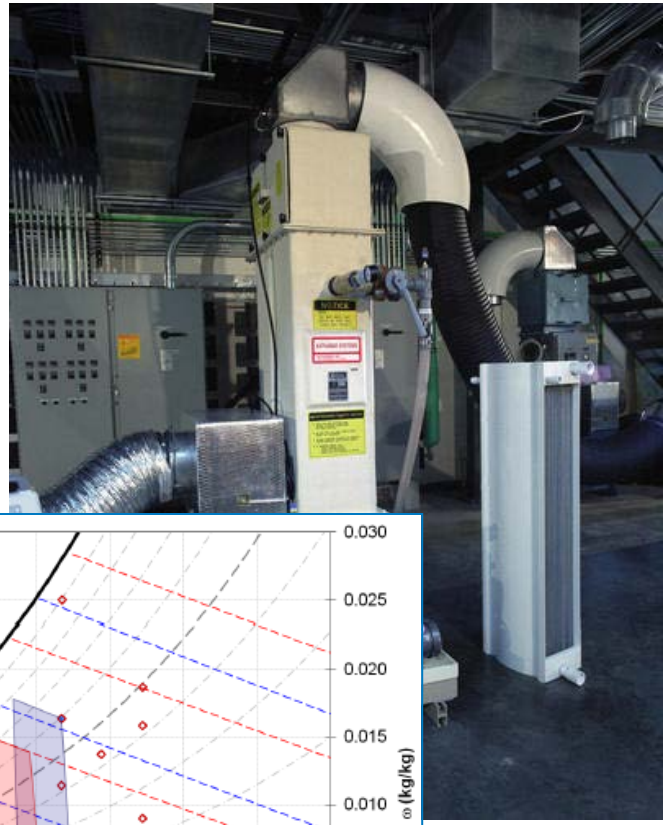




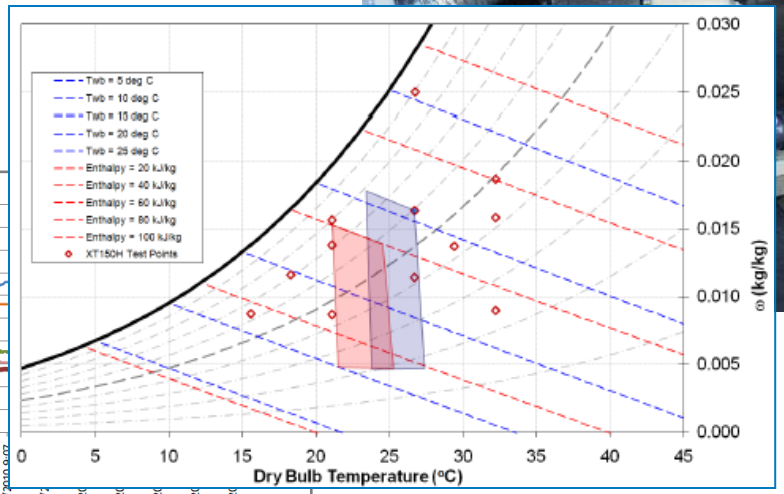
3. Field and Laboratory Systems Test Support

Objective: *Improve inputs and models.*

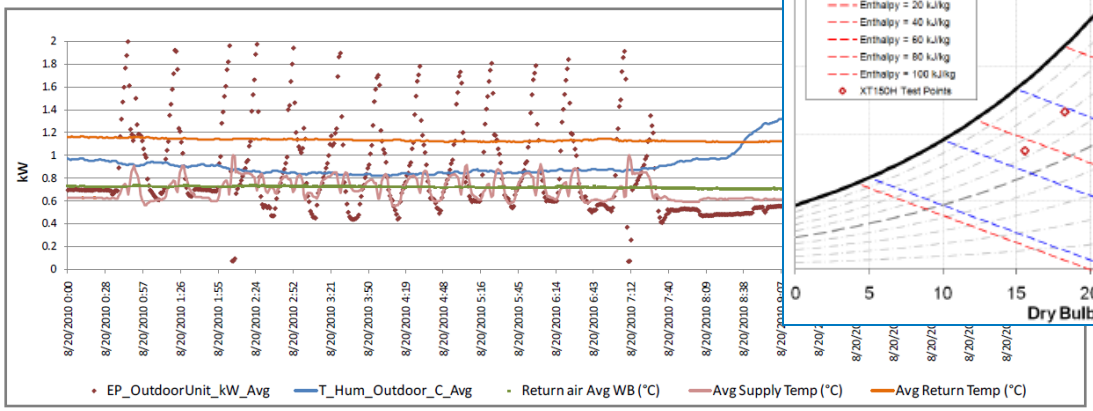
- Building America and BetterBuildings
- Empirical validation of systems models
  - Bench testing in laboratory
    - Full range of operation
  - In situ testing in home
    - Installed performance
    - Interaction



PIX #11459



Source: NREL TP-5500-47215

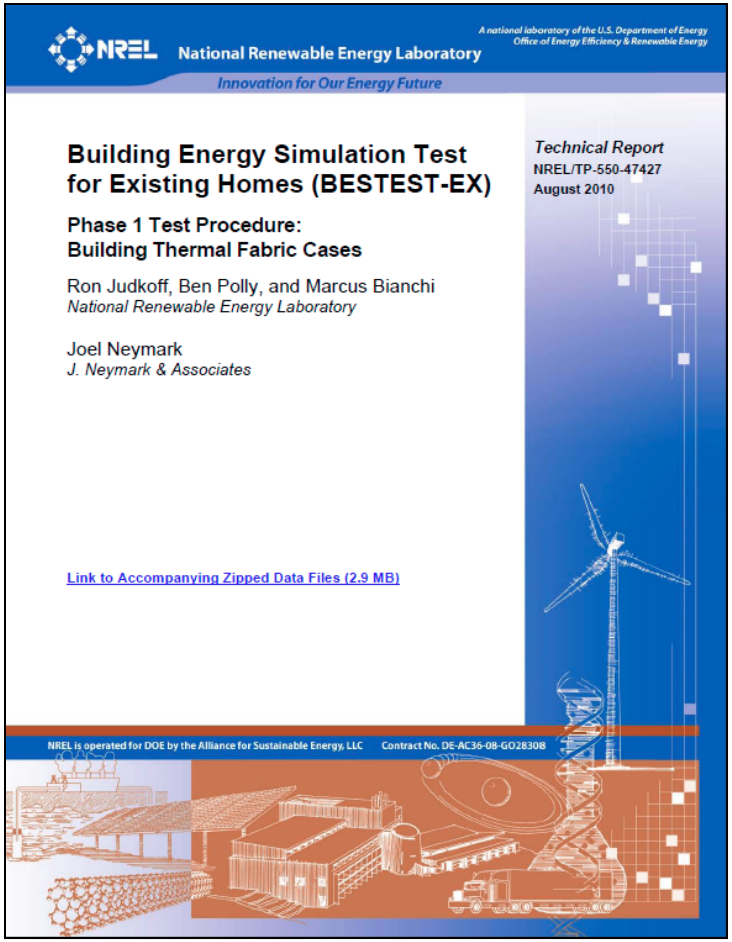


Source: NREL TP-5500-49881

4. BESTEST

Objective: *Provide tools for developers to improve the accuracy of their software.*

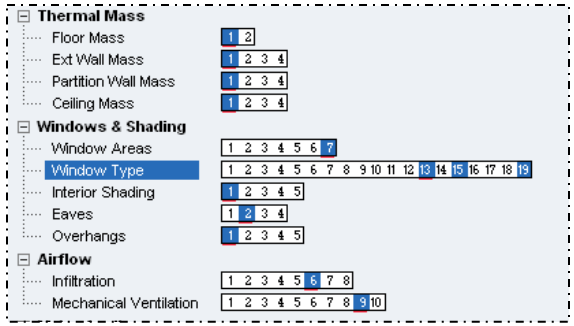
- Test suites can be comparative, analytical, or empirical
- Current focus is on developing empirical test suites
- Classes of empirical data include:
  - Laboratory and field data for isolated building systems
  - Building characteristics and utility bill data
- Test suites should be diagnostic

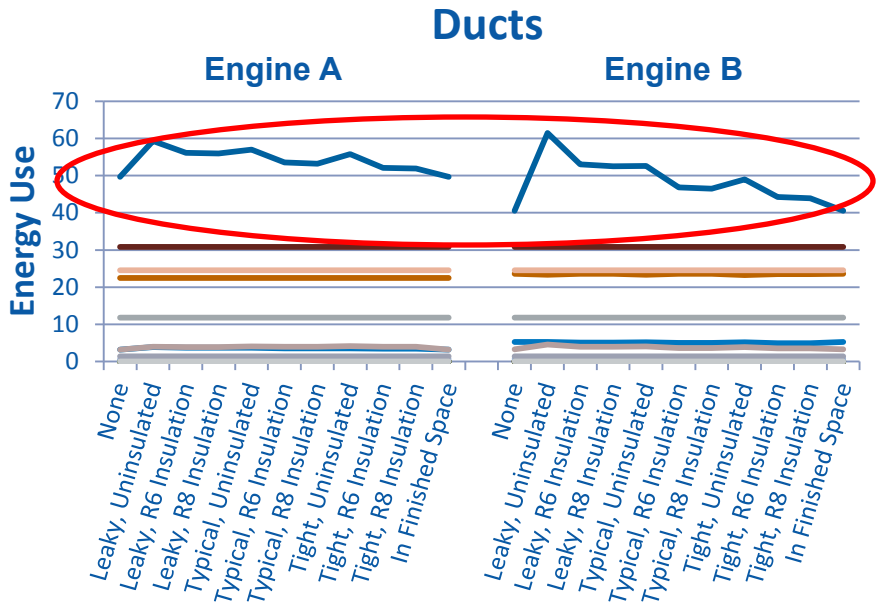


5. BEopt Diagnostic Test Suite

Objective: *Identify and understand differences between commonly used building energy simulation engines.*

- BEopt has many categories and options within each category
- Test suite automatically sweeps through many options/categories using each simulation engine
- Goal is to provide equivalent inputs
- Output can be compared to identify bugs and physical modeling differences

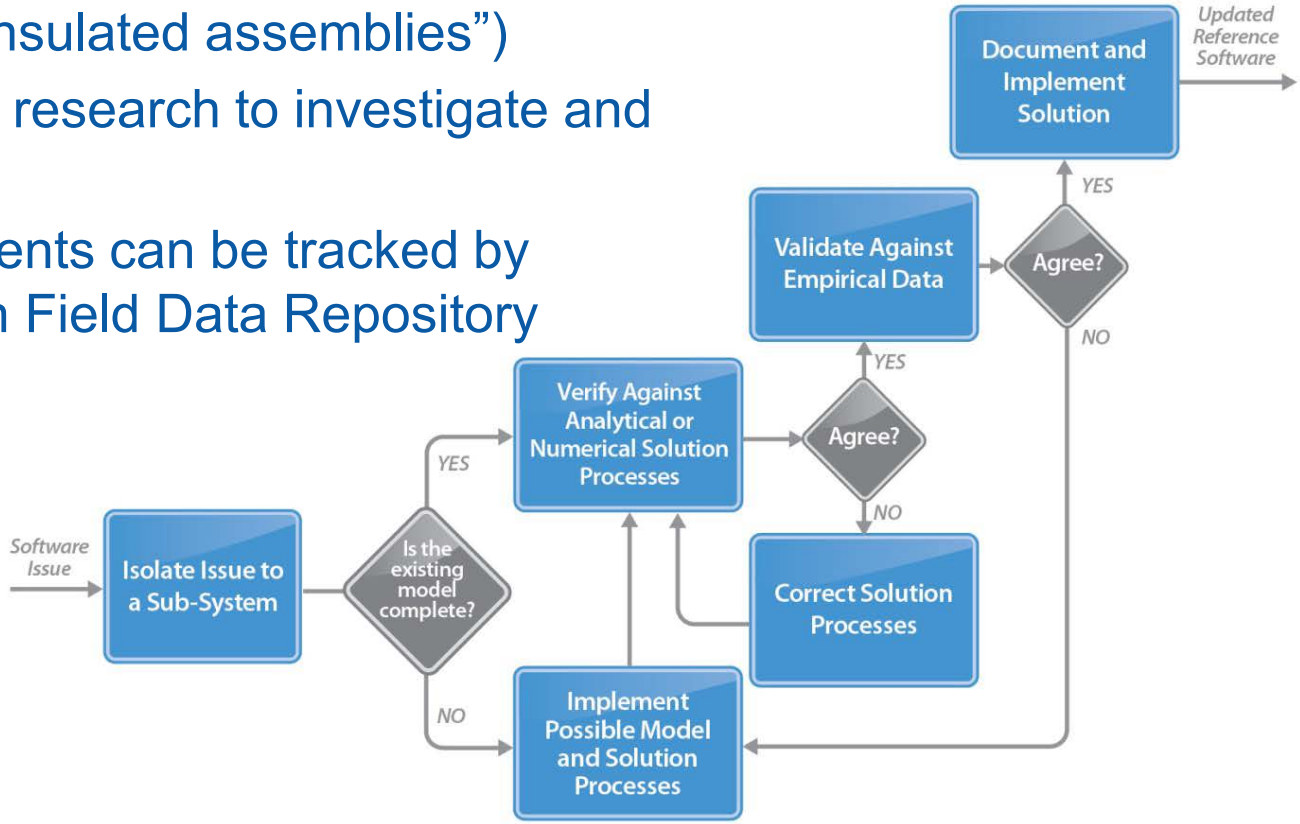




6. Addressing Potential Issues

Objective: *Identify, investigate, and correct input and software issues.*

- Developed initial list of potential issues (e.g., "temperature variation room-to-room," "performance of uninsulated assemblies")
- Conducting focused research to investigate and resolve issues
- Impact of improvements can be tracked by simulating houses in Field Data Repository



NREL Efforts To Improve Accuracy

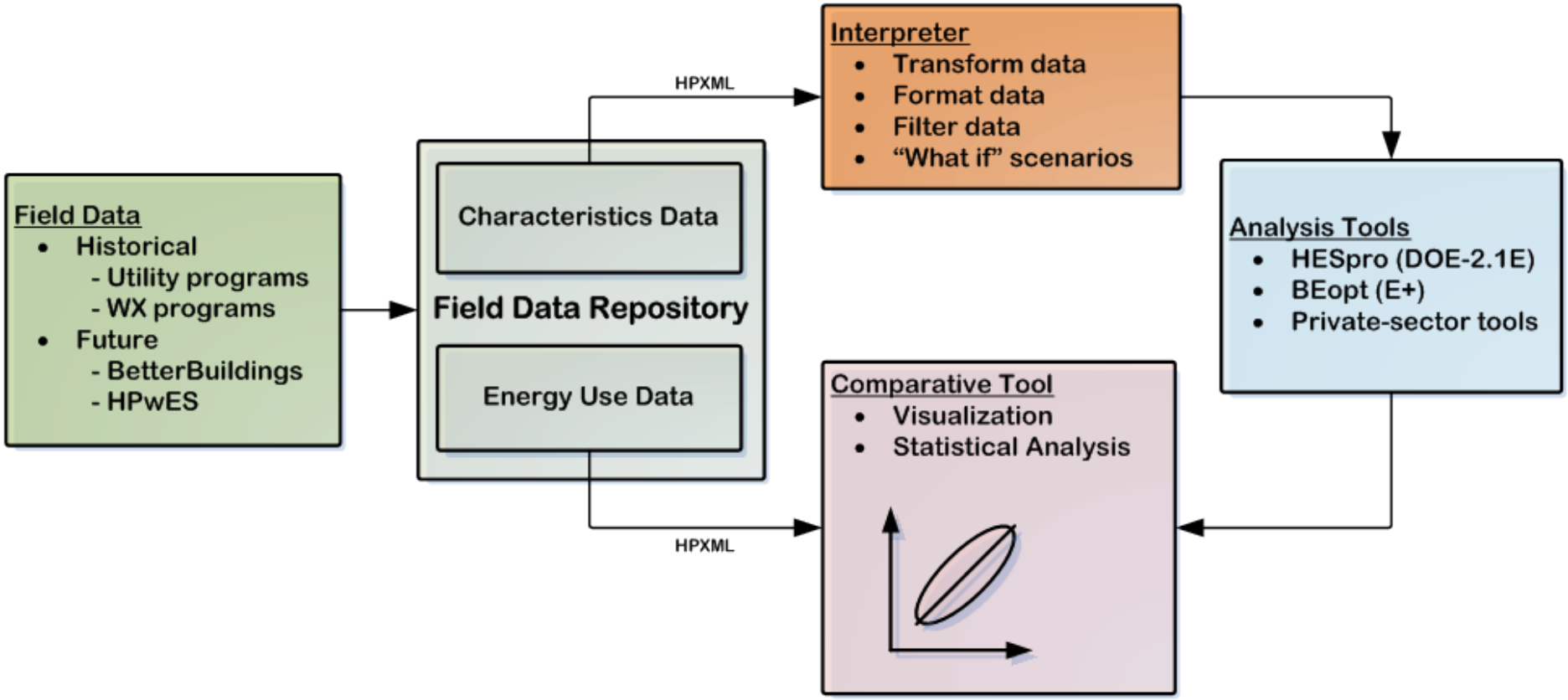
1. Building America House Simulation Protocols
2. National Residential Efficiency Measures Database
3. Field and Laboratory Test Support
4. BESTEST
5. BEopt Diagnostic Test Suite
6. Addressing Potential Issues
7. **Field Data Repository**
8. Comparative Analysis
9. Uncertainty Analysis

7. Field Data Repository

Objective: *Develop infrastructure for comparing software predictions to measured data.*

- Collect, organize, and leverage historical and emerging robust datasets of residential building characteristics and measured energy use
- Develop capabilities that facilitate connecting database to reference and industry software to automate process of simulating homes
- Develop visualization and statistical tools for comparing predictions to measured data

7. Field Data Repository: Process



7. Field Data Repository: Data Collection

In hand (as of 9/14/11)

Number of homes	Characteristics	Billing	Post Upgrade	Locations
2970	Full	Full	Yes	CO, IA
1295	Full	Full	No	MN, NC, NY, OR, TX, WI
2200	Full	None	No	VT
1670	Limited	Full	Limited	CA
14276	Limited	Limited	No	CO

In process

Full characterization and utility bills for:

- 950 newer homes in Florida
- Up to 18,000 older homes in the Northeast

Planned

Collection of assessment tool input files (full characterization) from a subset of BetterBuildings grantees with facilitation from assessment tool providers

- These will augment data collected in BBIS
- Potentially hundreds of thousands of homes

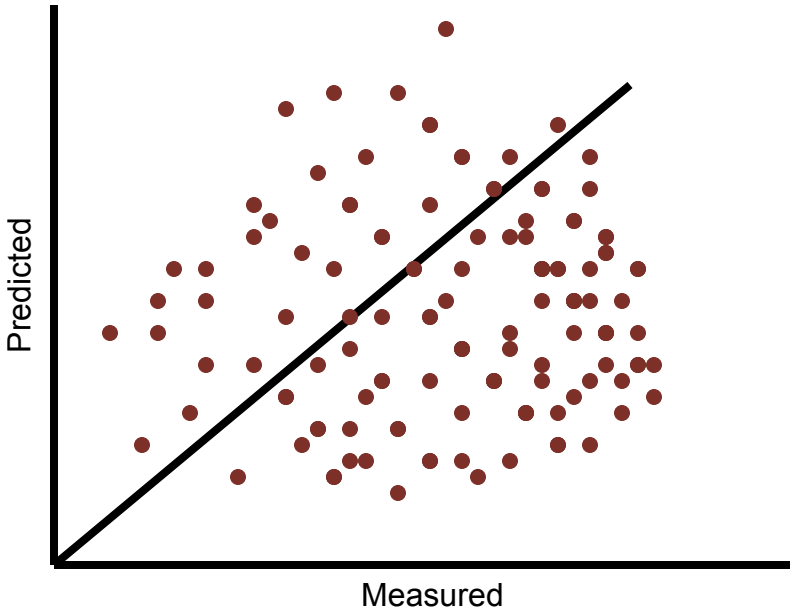
NREL Efforts to Improve Accuracy

1. Building America House Simulation Protocols
2. National Residential Efficiency Measures Database
3. Field and Laboratory Test Support
4. BESTEST
5. BEopt Diagnostic Test Suite
6. Addressing Potential Issues
7. Field Data Repository
8. **Comparative Analysis**
9. Uncertainty Analysis

8. Comparative Analysis

Objective: *Improve inputs and models.*

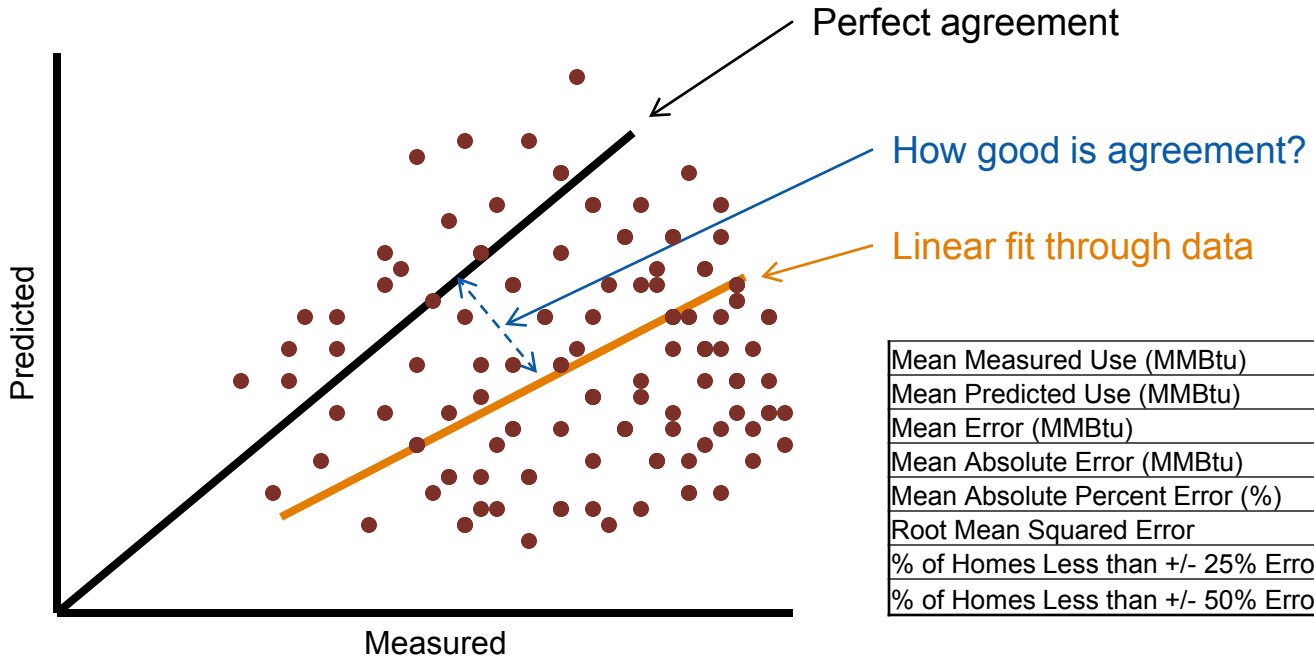
- Utilize Field Data Repository
- Investigate differences and possible explanatory factors
  - Review methods and assumptions
  - Test impacts by parametrically "toggling" inputs
  - Look for "drivers" affecting error



8. Comparative Analysis

Automated, comparative analysis for large populations of homes

- Graphical
- Statistical
- Tool-to-measured (utility bill)
- Tool-to-tool

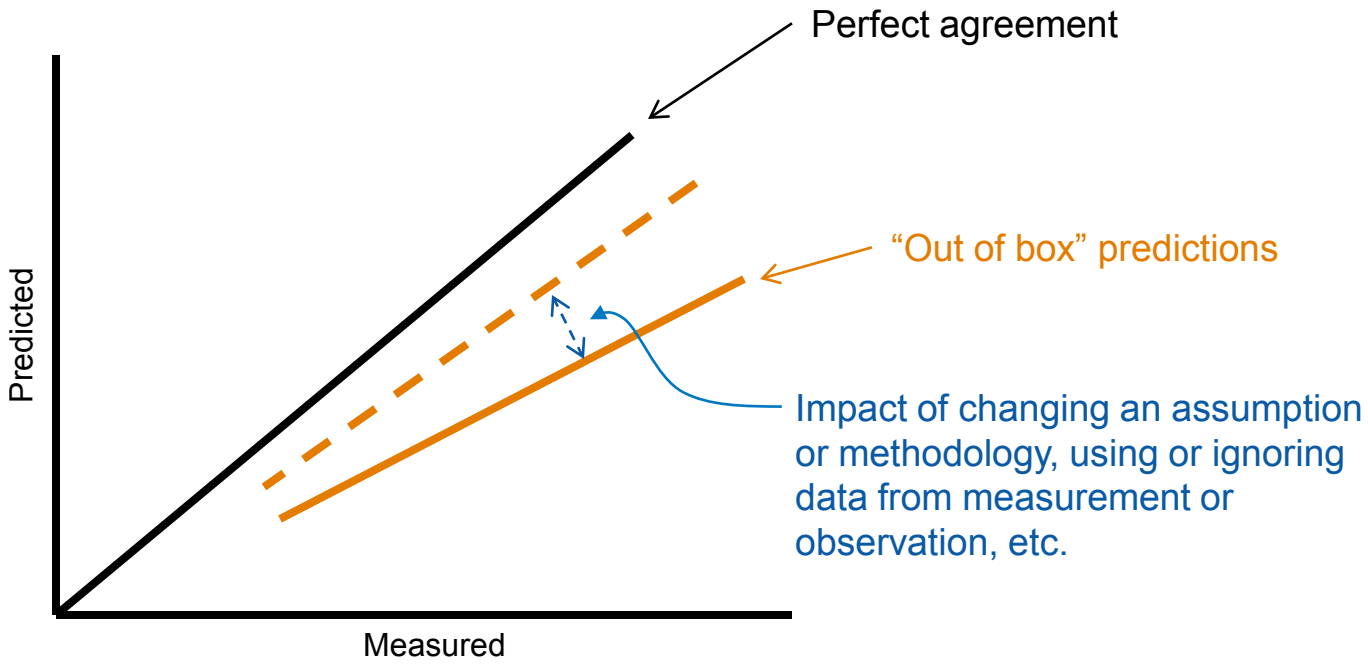


Mean Measured Use (MMBtu)	112.7
Mean Predicted Use (MMBtu)	111.0
Mean Error (MMBtu)	-1.7
Mean Absolute Error (MMBtu)	15.8
Mean Absolute Percent Error (%)	15.2
Root Mean Squared Error	20.7
% of Homes Less than +/- 25% Error	82
% of Homes Less than +/- 50% Error	100

8. Comparative Analysis

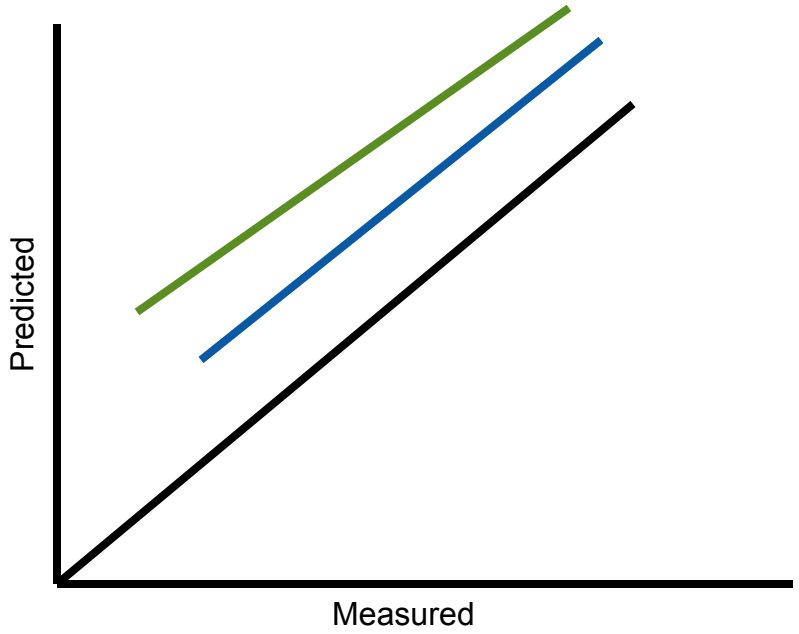
Investigate differences and possible explanatory factors

- Review methods and assumptions
- Test impacts by parametrically "toggling" inputs
- Look for "drivers" affecting error



8. Comparative Analysis

More or fewer data?





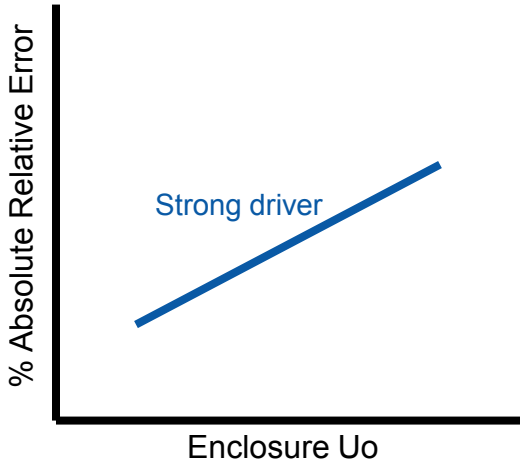
PIX #15073

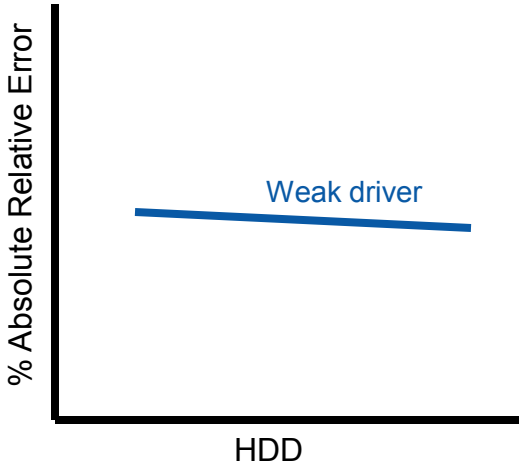
Example: with versus without blower door

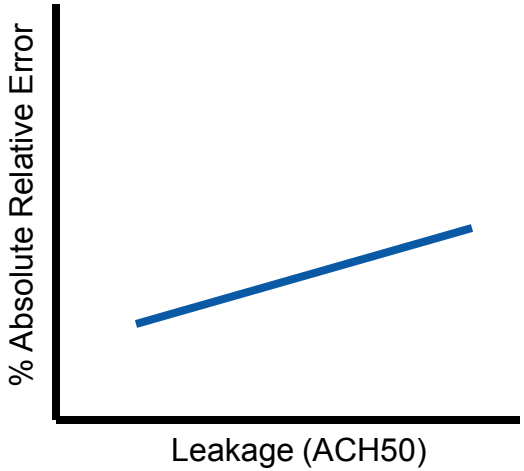
8. Comparative Analysis

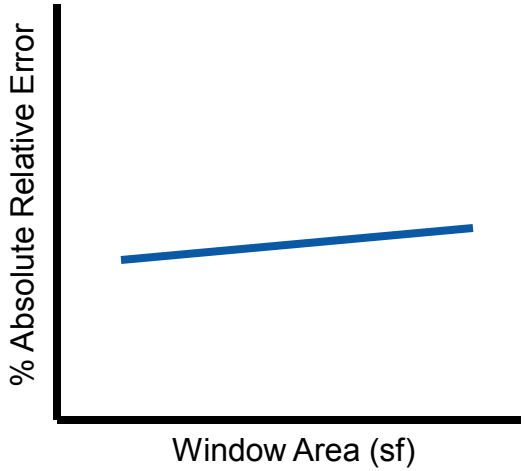
What's driving the "error"?

*Examples Only

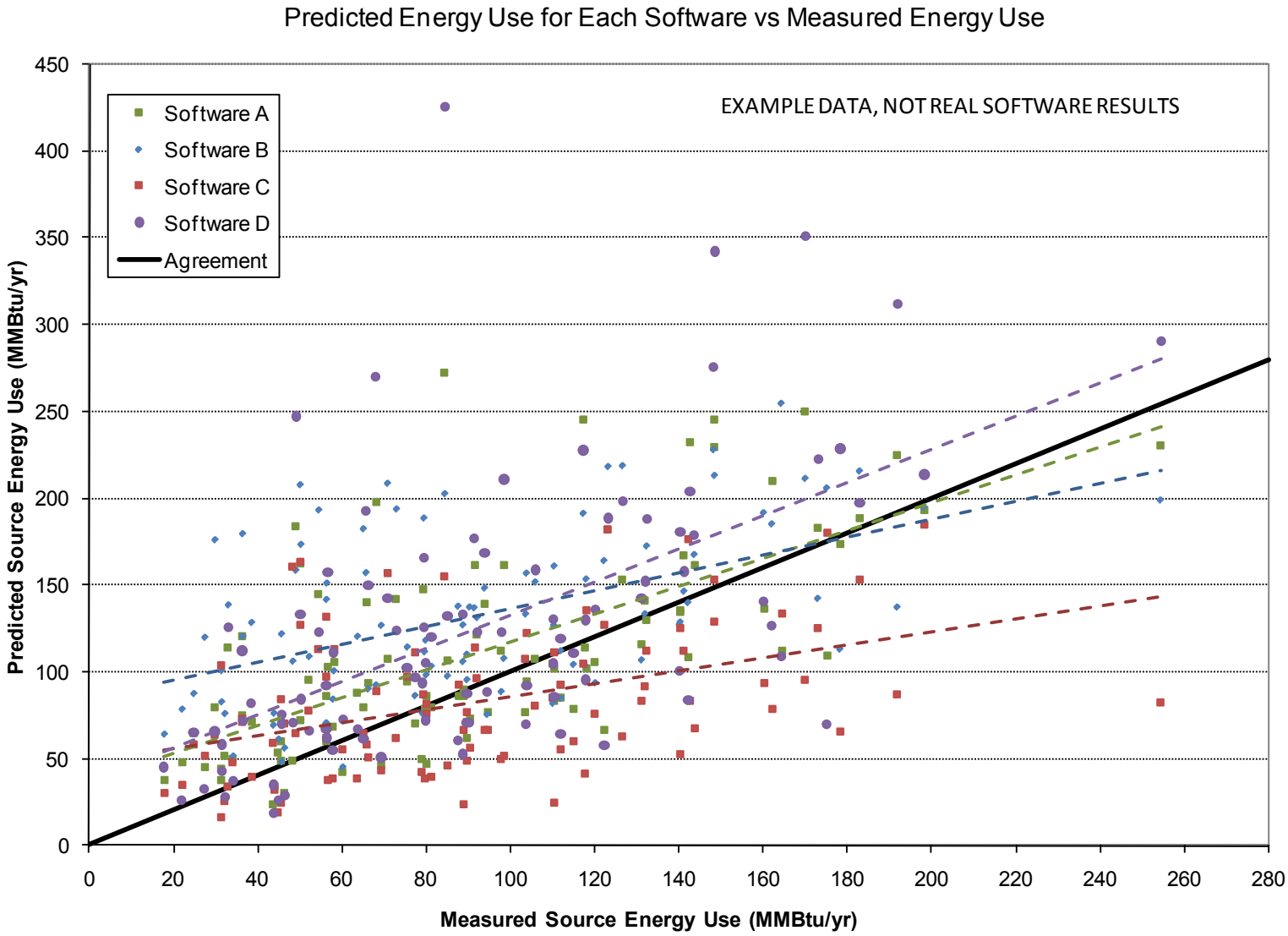






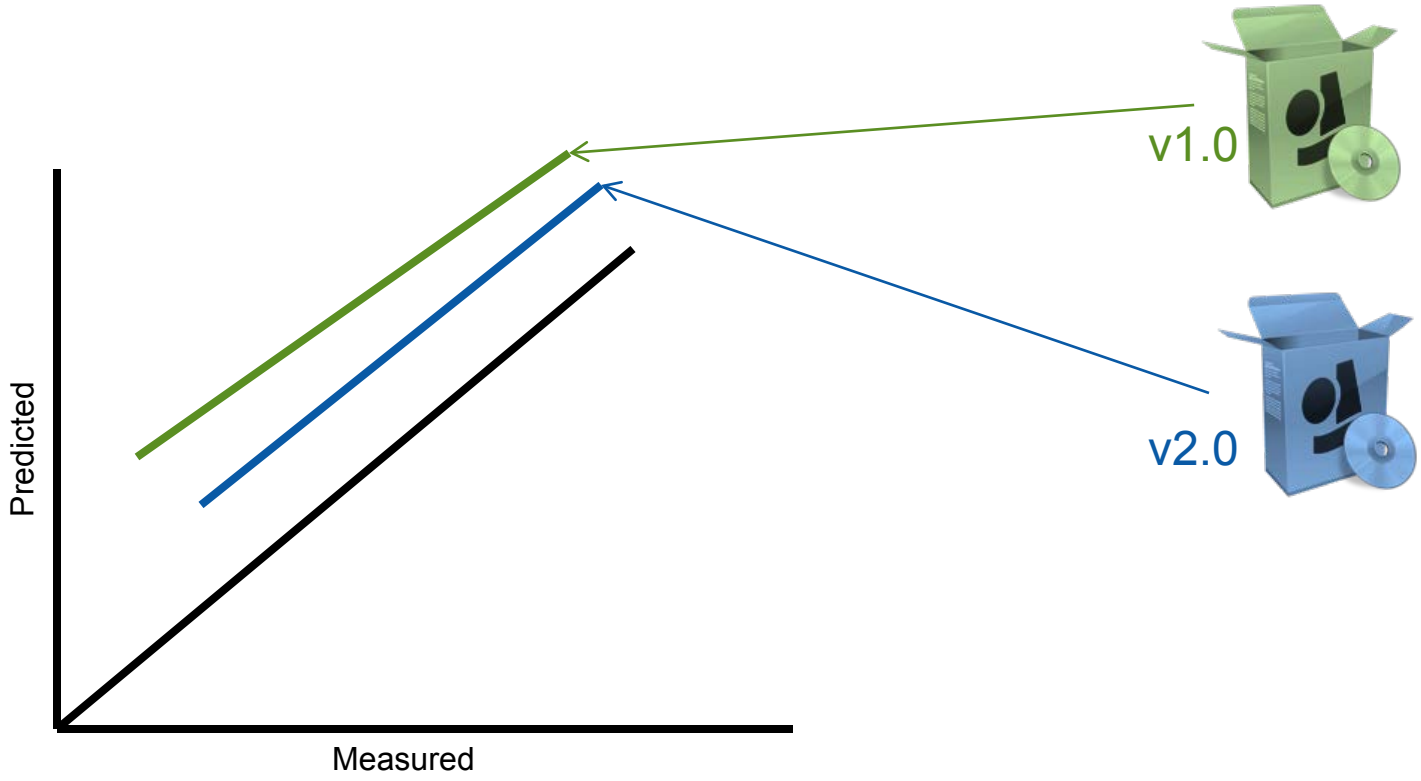


8. Comparative Analysis



8. Comparative Analysis

Impact of assessment tool improvements



8. Comparative Analysis

- NREL researchers are working to connect various software tools to the Field Data Repository
- Preliminary comparative analysis has helped improve DOE's Home Energy Saver software
- Data transfer standard will improve accessibility and usefulness

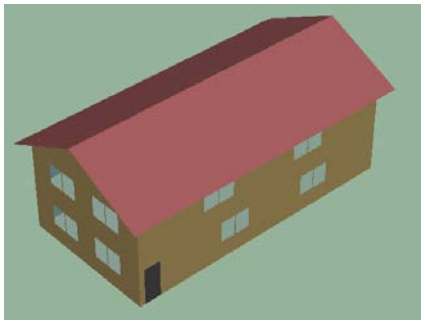
NREL Efforts to Improve Accuracy

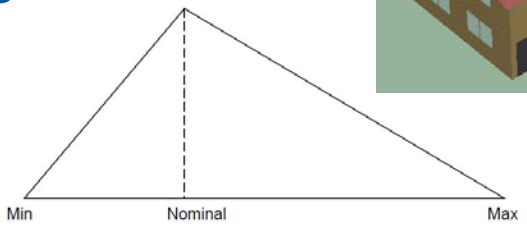
1. Building America House Simulation Protocols
2. National Residential Efficiency Measures Database
3. Field and Laboratory Test Support
4. BESTEST
5. BEopt Diagnostic Test Suite
6. Addressing Potential Issues
7. Field Data Repository
8. Comparative Analysis
9. **Uncertainty Analysis**

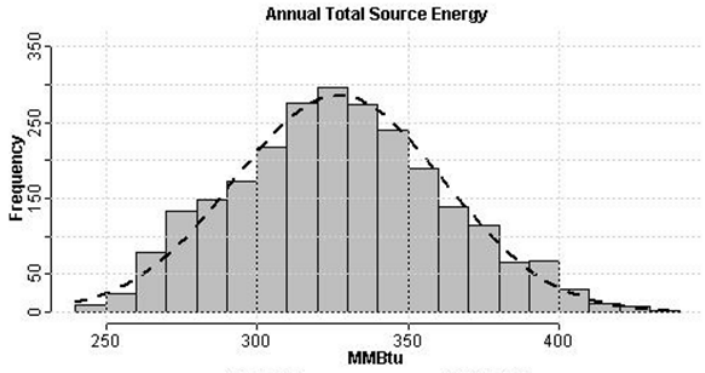
9. Operational Uncertainty Analysis

Objective: *Estimate the uncertainty in software predictions due to uncertainty in input information.*

- Requires estimates of uncertainty in input parameters
- Monte Carlo simulations performed using BEopt to generate distribution of simulation output
- Provides estimates of range of expected disagreement between predicted and actual energy uses
- Helps identify most important information to collect in energy assessments







9. Operational Uncertainty Analysis

- Whether an input is defaulted, estimated, or measured, there is some uncertainty as to how closely the input value matches the “true” value
  - e.g., heating set point = 68 ± X °F

- Errors in input propagate through a building energy simulation program to produce errors in output
  - e.g., predicted annual source energy use = 250 ± Y MMBtu

Research Goal: Establish uncertainty ranges around software predictions.

9. Operational Uncertainty Analysis

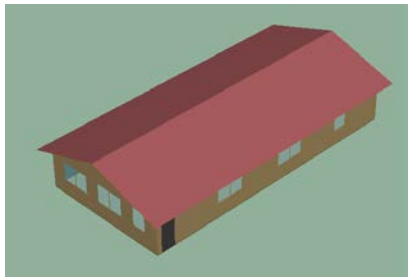
Types of Input Error:

- **Building Inputs.** Building geometry, material physical properties, and characteristics of mechanical equipment.
- **Occupant Inputs.** Descriptions of occupant behavior and occupant-controlled equipment settings.
- **Site Inputs.** Local weather, soil properties, and adjacent structures/vegetation.

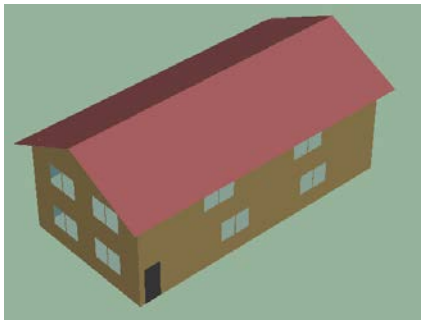
Research Question: In an asset evaluation, where specific occupant information is NOT collected, what is the uncertainty in energy use predictions due to uncertainty and variability in occupancy?

9. Operational Uncertainty Analysis

House A: 1,539 ft^2, one story, inefficient home, representative of 1960s-era construction



House B: 2,500 ft^2, two story, more efficient home, representative of new construction



Category	House A	House B
Orientation	Front of house faces north	Front of house faces north
Dimensions	North and south walls = 57 ft East and west walls = 27 ft One story	North and south walls = 50 ft East and west walls = 25 ft Two story
Garage	None	None
Bedrooms/Baths	3/2	3/2
Neighbors	15 ft away on east and west	15 ft away on east and west
Eave Depth	2 ft	2 ft
Vented Crawlspace	2.0 ACH, R-11 between joists	2.0 ACH, R-19 between joists
Exterior Walls	2 × 4, 16”o.c., no cavity insulation (R-1.2 air gap)	2 × 6, 21”o.c., R-19 cavity insulation
Unfinished Attic	2 × 6 joists, R-11 insulation	2 × 6 joists, R-49 insulation
Window Type	Single pane, U = 0.774, SHGC = 0.679	Low-e double pane, U = 0.318 , SHGC = 0.302
Window Area/Distribution	20% of exterior wall area, 20% of total window area on front, 40% on back, and 20% on each side	20% of exterior wall area, 20% of total window area on front, 40% on back, and 20% on each side
Gas Furnace	78% AFUE	92.5% AFUE
Air Conditioner	SEER 10 (9.31 EER)	SEER 13 (11.09 EER)
Ducts	Uninsulated, in crawlspace, leakage fraction = 0.300	R-6 insulation, in crawlspace, leakage fraction = 0.075
Living Space SLA	0.000886	0.000360
Mechanical Ventilation	Spot vent only	Spot vent and ASHRAE 62.2 (including infiltration credit)
Water Heater	Gas, energy factor = 0.59, in living space	Gas, energy factor = 0.67, in living space
Major Appliances	Refrigerator, electric range, dishwasher, clothes washer, electric clothes dryer.	Refrigerator, electric range, dishwasher, clothes washer, electric clothes dryer.

9. Operational Uncertainty Analysis

Technical Approach:

1. Identify operational inputs accessible in the BEopt input file and select a subset of key inputs for variation
2. Define probability distributions representing the uncertainty ranges for each key input
3. Randomly select values from probability distributions for each key input and simulate energy use for that “realization” of inputs
4. Repeat Step 3 for many realizations to generate a range of simulation output using BEopt/EnergyPlus
5. Analyze the distributions of simulated energy uses.

9. Operational Uncertainty Analysis

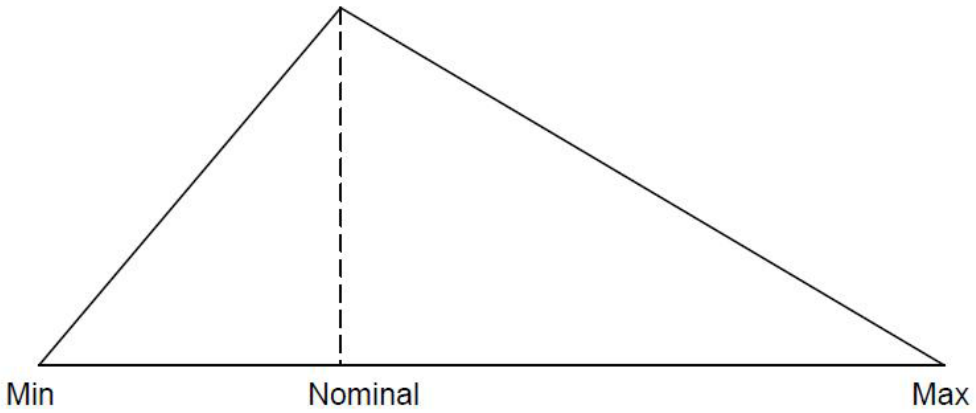
Technical Approach:

For preliminary analysis, assume inputs are either independent or (1:1)

- e.g., select heating set point and refrigerator multiplier independently
- e.g., use same selected value for clothes washer/dryer multipliers

Select inputs from triangular probability distributions

- Require estimates of minimum, nominal, and maximum values
- Allow for non-symmetric distributions





PIX # 07726

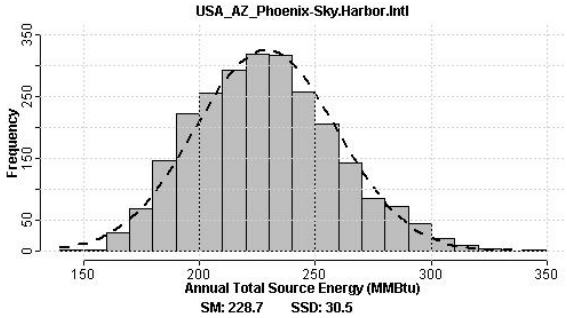
9. Operational Uncertainty Analysis

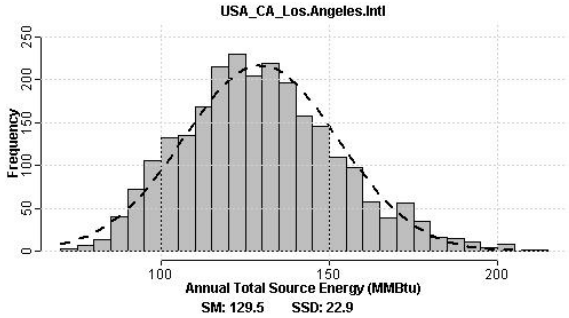
Operational Inputs Perturbed in Analysis

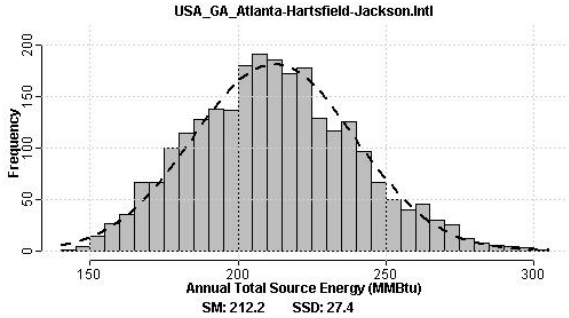
Input	Minimum	Nominal	Maximum
Space Heating Set Point (°F)	60	68	75
Space Cooling Set Point (°F)	71	78	86
Miscellaneous Electric Loads Multiplier	0.2	0.8	2.0
Miscellaneous Gas Loads Multiplier	0.2	0.8	2.0
Miscellaneous Hot Water Loads Multiplier	0.2	0.8	2.0
Interior Shading Multiplier	0.5	0.6	1.0
Interior Lighting Multiplier	0.2	0.8	2.0
Exterior Lighting Multiplier	0.2	0.8	2.0
Furniture Conductivity (Btu-in./hr-ft^2-°F)	0.64	0.80	0.96
Furniture Density (lb/ft^3)	32	40	48
Furniture Specific Heat (Btu/lb-°F)	0.232	0.290	0.348
Furniture Area Fraction	0.1	0.3	0.5
Furniture Weight (lb/ft^2)	2	8	14
Furniture Solar Absorptance	0.4	0.6	0.8
Refrigerator Multiplier	0.7	1.0	1.3
Range/Dishwasher Multiplier	0.2	0.8	2.0
Clothes Washer/Dryer Multiplier	0.2	0.8	2.0
Fraction of Total Window Area Open	0.00	0.04	0.14
Water Heater Set Point (°F)	110	125	140

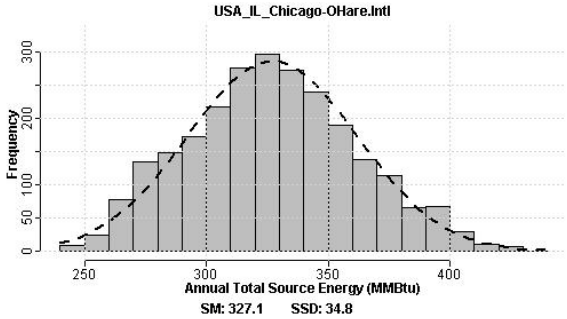
9. Operational Uncertainty Analysis

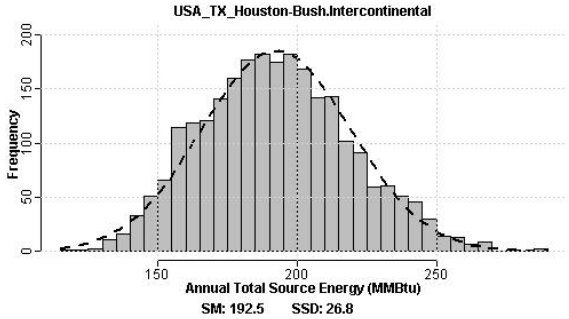
Example Preliminary Results: Existing home annual source energy use by climate.

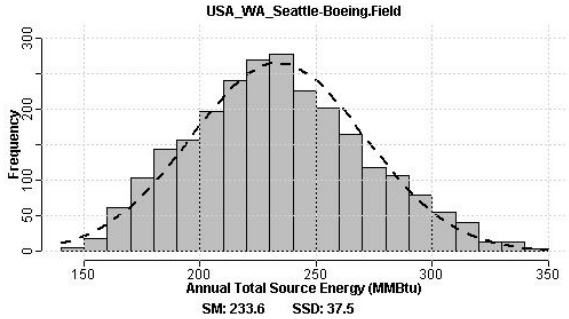












9. Operational Uncertainty Analysis

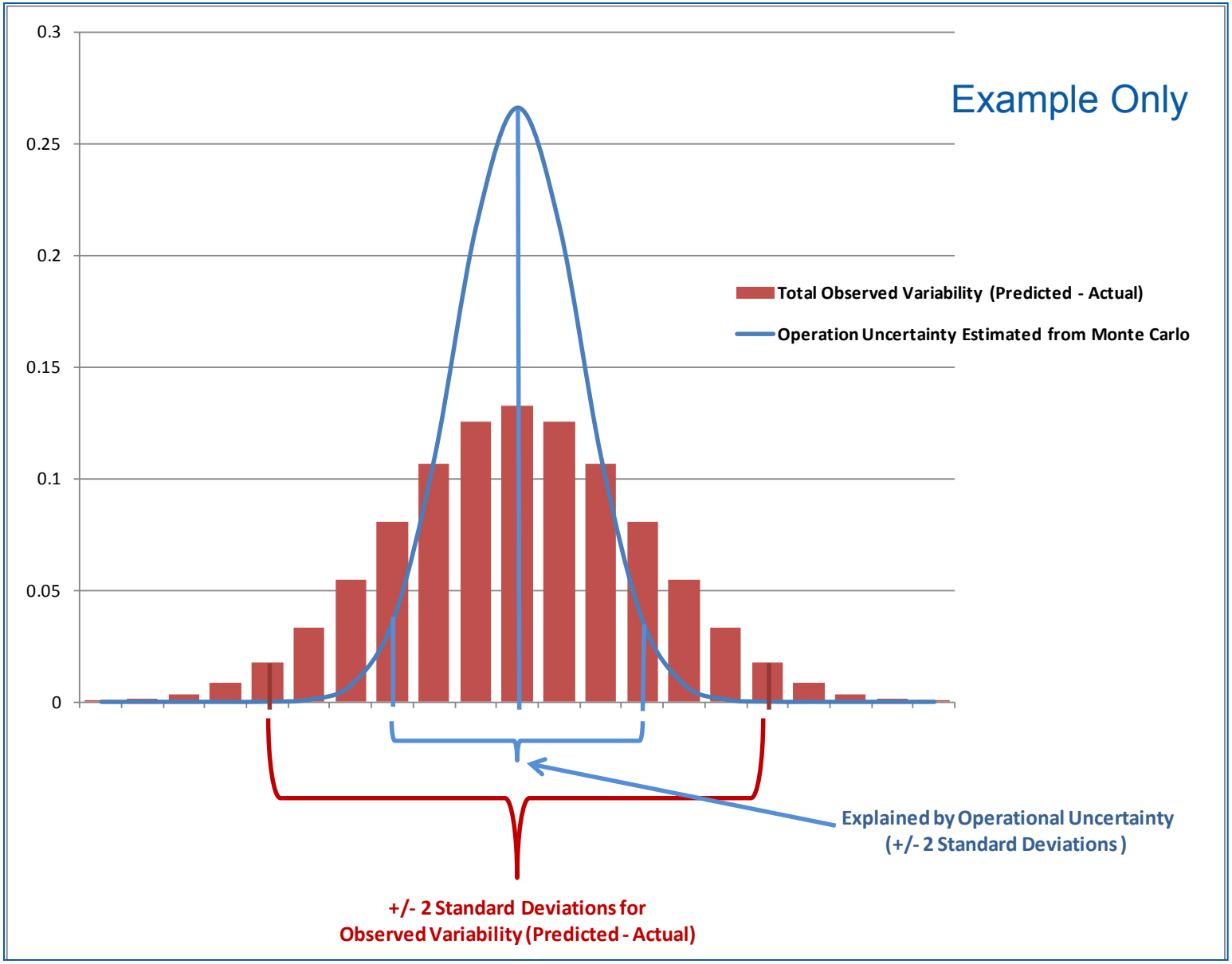
Summary of Preliminary Results: Annual source energy by climate.

	HOUSE A			HOUSE B		
	MEAN	**SD**	**SD/MEAN**	**MEAN**	**SD**	**SD/MEAN**
Atlanta, GA	212.2	27.4	0.13	146.5	19.8	0.14
Chicago, IL	327.1	34.8	0.11	193.8	20.4	0.11
Houston, TX	192.5	26.8	0.14	142.9	21.2	0.15
Los Angeles, CA	129.5	22.9	0.18	111.4	18.1	0.16
Phoenix, AZ	228.7	30.5	0.13	157.6	22.4	0.14
Seattle, WA	233.6	37.5	0.16	148.7	19.4	0.13
City Average	**220.6**	**30.0**	**0.14**	**150.1**	**20.2**	**0.14**

Preliminary Conclusions:

- Variability in occupant behavior causes considerable uncertainty in predictions for an asset evaluation
- Approximately ± 20%-35% for total source energy use, may be more if input correlation is considered

9. Operational Uncertainty Analysis



Final Remarks

Final Remarks

- Stakeholders rely on accurate predictions
- Analysis methods tend to over-predict energy use for poorly insulated, leaky homes
- NREL is following a well-defined process to identify, investigate, and resolve potential issues
- Various projects support overall effort
    1. Building America House Simulation Protocols
    2. National Residential Efficiency Measures Database
    3. Field and Laboratory Test Support
    4. BESTEST
    5. BEopt Diagnostic Test Suite
    6. Addressing Potential Issues
    7. **Field Data Repository**
    8. **Comparative Analysis**
    9. **Uncertainty Analysis**

Focus for this talk

References

Hendron, R.; Engebrecht, C. (2010). *Building America House Simulation Protocols.* Golden, CO: National Renewable Energy Laboratory. NREL/TP-550-49246.

Judkoff, R.; Neymark, J. (2006). "Model Validation and Testing: The Methodological Foundation of ASHRAE Standard 140." *ASHRAE Transactions* 112(2):367–376. Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers.

Judkoff, R.; Wortman, D.; O'Doherty, B.; Burch, J. (2008). *A Methodology for Validating Building Energy Analysis Simulations.* Golden, CO: National Renewable Energy Laboratory. NREL/TP-550-42059. Based on unpublished report of 1983 with same authors and title, previously referenced as SERI/TR-254-1508.

More Information

- More information can be found in a recently published report:

  Polly, B.; Kruis, N.; Roberts, D. 2011. *Assessing and Improving the Accuracy of Energy Analysis Methods for Residential Buildings*. Golden, CO: National Renewable Energy Laboratory. DOE/GO-102011-3243.

- Questions?