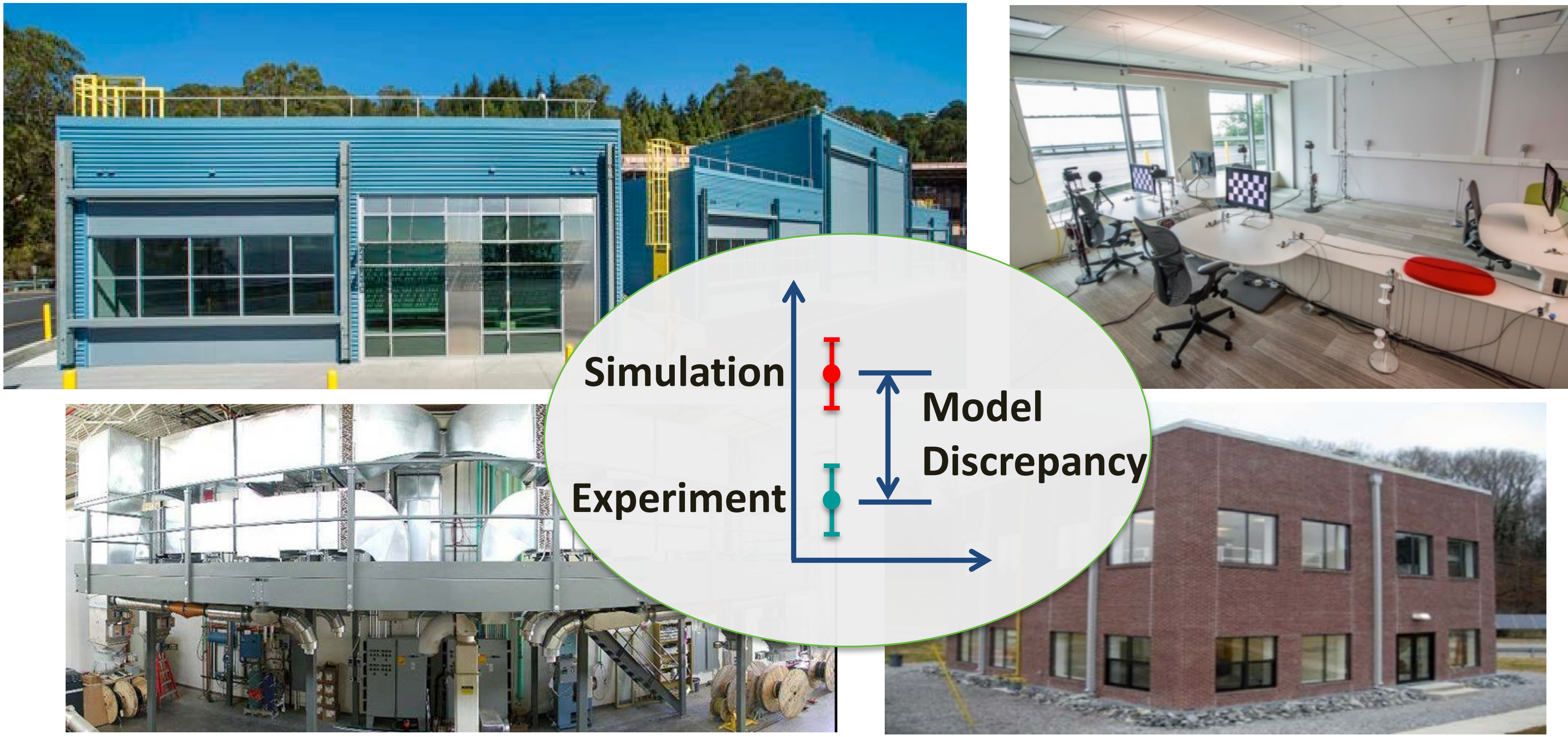
U.S. DEPARTMENT OF ENERGY

Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

Validation and Uncertainty Characterization for Energy Simulation



Lawrence Berkeley National Lab

Argonne National Lab, National Renewable Energy Lab, Oak Ridge National Lab

Project Summary

Timeline:

Start date: 10/1/2015

Planned end date: 9/30/2018

Key Milestones:

First full submission to SSPC 140; 5/31/2018

Budget:

Total Project $ to Date:

- DOE: $2,200,000
- Cost Share: $250,000

Total Project $:DOE: $2,700,000

- Cost Share: $260,000*
  **de facto* cost-share from Southern California Edison.

Key Partners:

ASHRAE SSPC 140
Southern California Edison

Project Outcome:

Provide empirical data for ASHRAE Standard 140 *Standard Method of Test for the Evaluation of Building Energy Analysis Computer Programs* to enable improved accuracy of BEM engines and improved characterization of their accuracy, leading to:

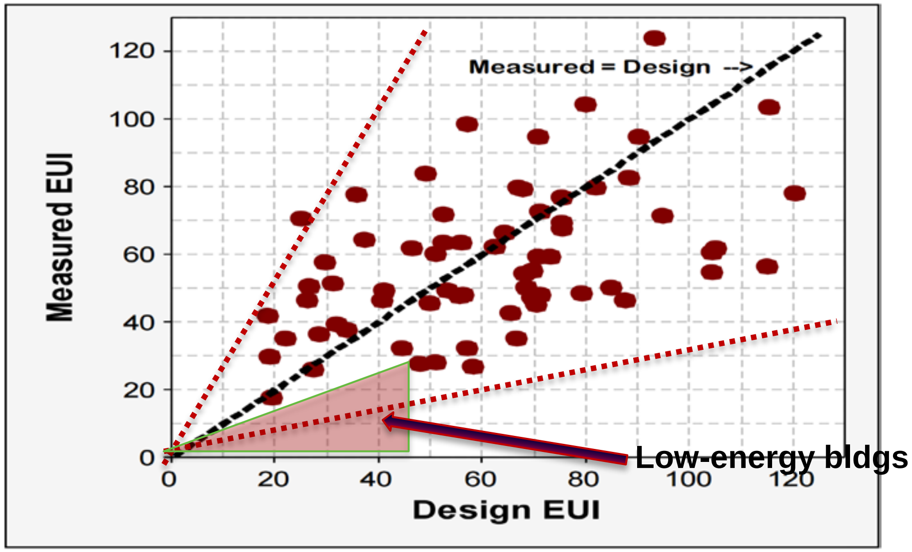
- More accurate BEM engines
- Consistent and validated products
- Confidence in all BEM tools, → greater adoption and influence on design decisions → more efficient buildings

Team Roles

- **LBNL**: FLEXLAB measurements of space cooling and heating loads
- **ORNL**: FRP measurements of a multi-zone VAV system
- **NREL**: performance mapping of small RTU's
- **ANL**: uncertainty characterization for experimental measurements and propagation from simulation inputs to simulation outputs

- **TAG**: vendors, practitioners and researchers: review plans and results – one to two meetings per year
- **ASHRAE** Standing Standard Project Committee 140 *Standard Method of Test for the Evaluation of Building Energy Analysis Computer Programs*: review of submissions for inclusion in Standard 140

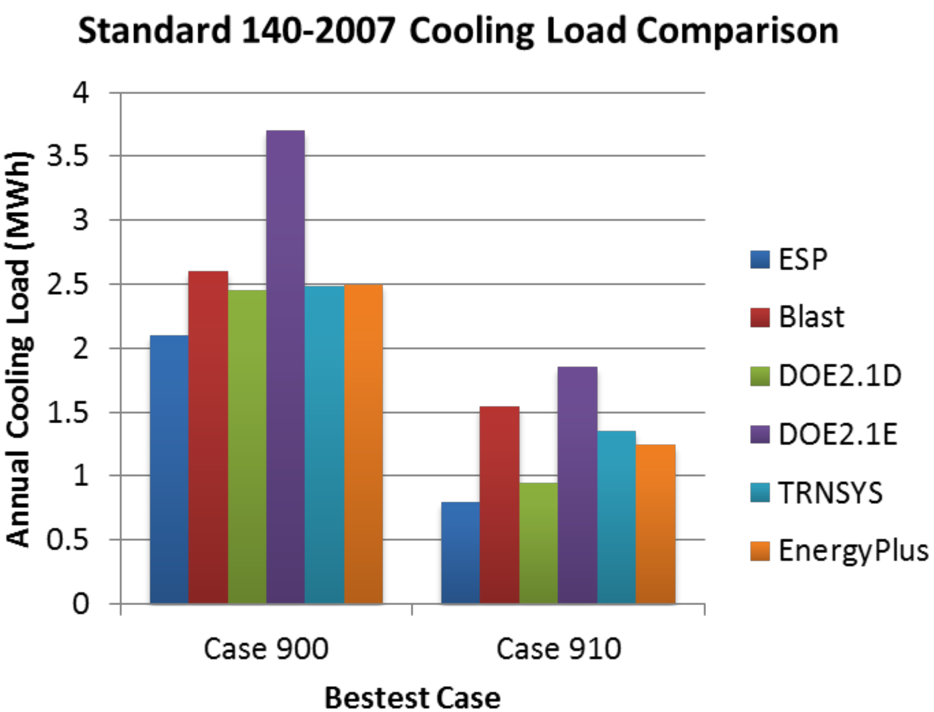
Context and Problem Characterization



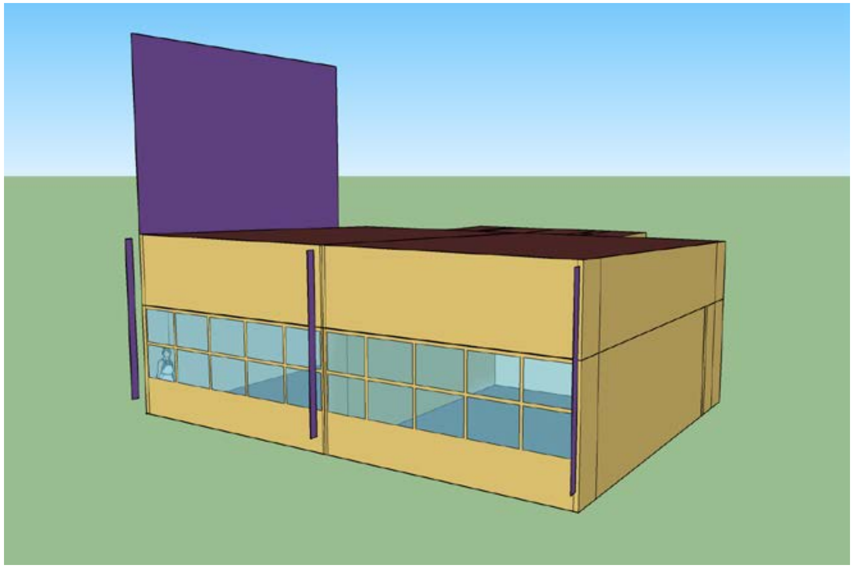
Sources of differences between simulated and actual performance:

- **Uncertainty**
  - o **Algorithms**
  - o Input parameters
  - o Modeler decisions
- **Variability**
  - o Weather
  - o Occupancy
  - o Operation

- The Standard 140 framework accommodates empirical tests but does not yet include any
- We now have facilities to make cost-effective empirical testing possible:
  - – LBNL FLEXLAB
  - – ORNL FRP
  - – NREL HVAC



Zone Heating and Cooling Loads



Lawrence Berkeley National Lab – Philip Haves – phaves@lbl.gov

Baptiste Ravache
Mehry Yazdanian

Darryl Dickeroff
Xiufeng Pang

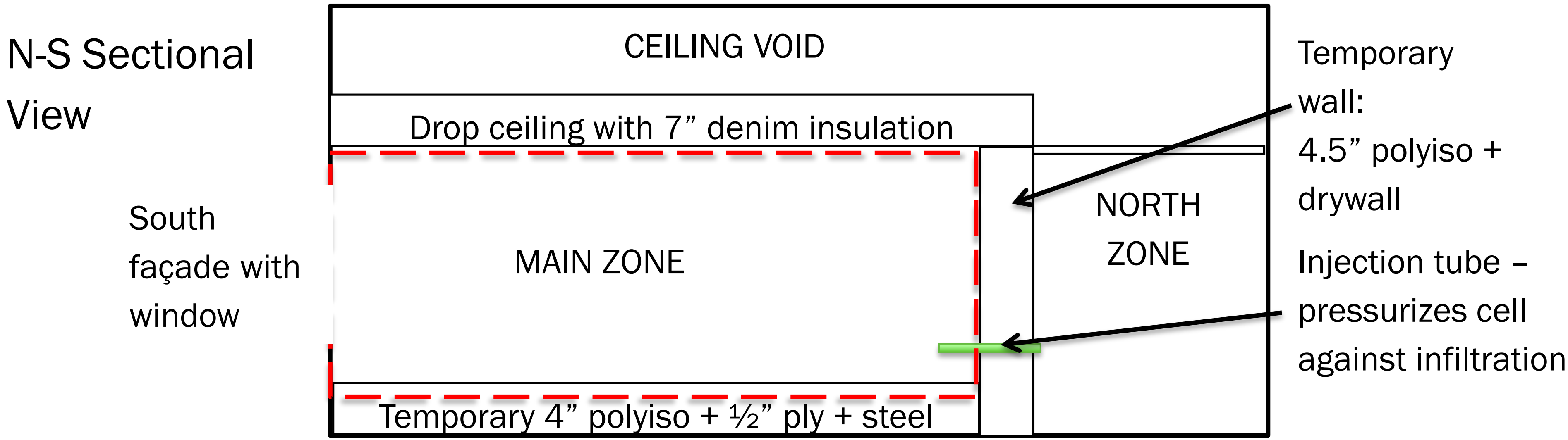
LBNL – FLEXLAB testing approach

Focus on heat transfer in occupied spaces

- Space conditioning:
  - Mixing ventilation
  - Radiant panels and slabs
- Ideal vs realistic conditions:
  - **Ideal**: model assumptions: no furniture, ideal internal heat sources, good mixing
  - **Realistic**: furniture, lights, simulated occupants, imperfect mixing
- Zone type:
  - Interior: no fenestration, ~adiabatic walls
  - Exterior: window, opaque part of window wall has lower R-value

FLEXLAB Configuration and Tests

N-S Sectional View



Test cells reconfigured to have a simple main zone that can be modeled by programs having limited modeling capabilities:

- insulated drop ceiling
- temporary north wall

Decouple main zone from construction complexities in ceiling void and north zone

Tests performed:

- Low mass (insulation covering slab)
- High mass (exposed floor slab)
- Constant zone temperature
- Night set-back

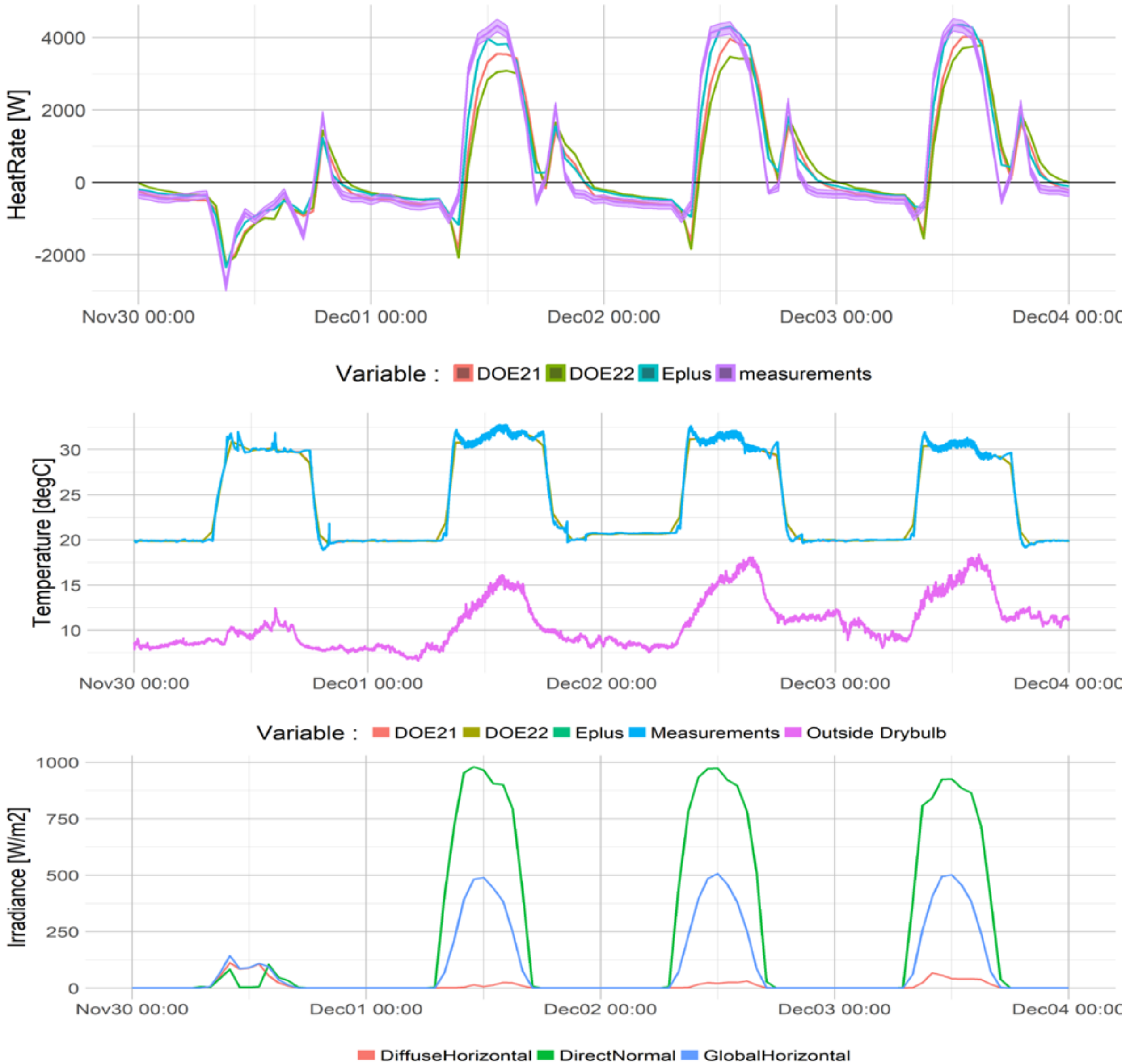
Cooling/heating load measured on air-side

Outcomes

- 17 documented tests of 7 different physical and operational configurations – stress tests of conventional overhead mixing ventilation ⟶ SSPC 140:
  - Construction: as-builts ...
  - Instrumentation
  - Measurements – 10 min averages of 1 sec samples, ~200 points:
    - Weather – solar on horiz and S vert, air and sky temps, wind
    - Rate of cooling/heating delivered (airflow, supply-return ΔT)
    - Air temperatures (41 per test cell)
    - Surface and slab temperatures (106) and heat fluxes (23)
- Comparisons with EnergyPlus and DOE-2 for QA
- Extended shakedown of new construction and instrumentation ⟶ well prepared to make further measurements efficiently

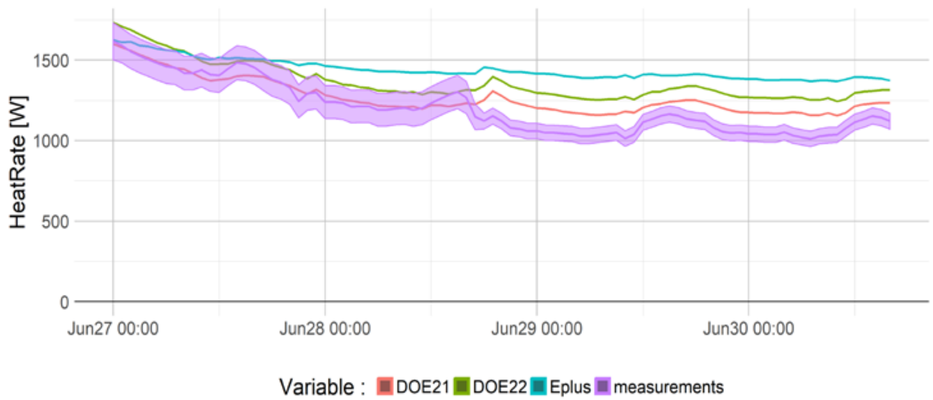
Sample (good) result and presentation format:

Scenario 11:06: Low Mass, Exposed Windows, No Int Gain, Var Set-point (20C / 30C)

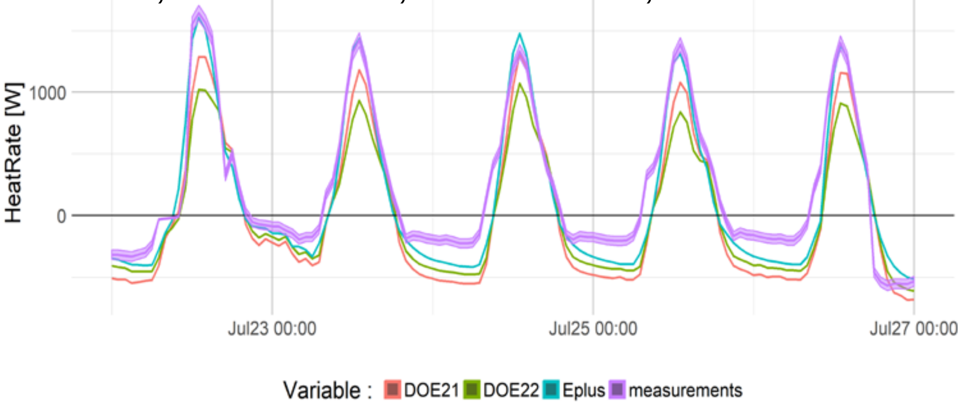


Results with (as yet) unresolved problems

High Mass, Covered Windows, Constant 1430 W Internal Gains, Constant Set-point



Low Mass, Exposed Windows, No Internal Gains, Constant Set-point



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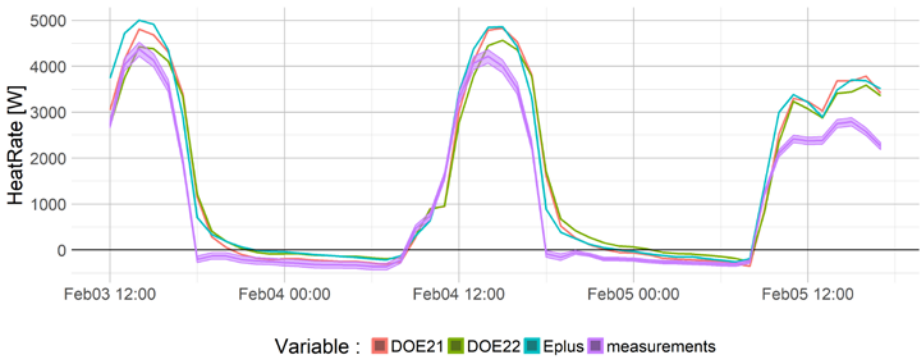
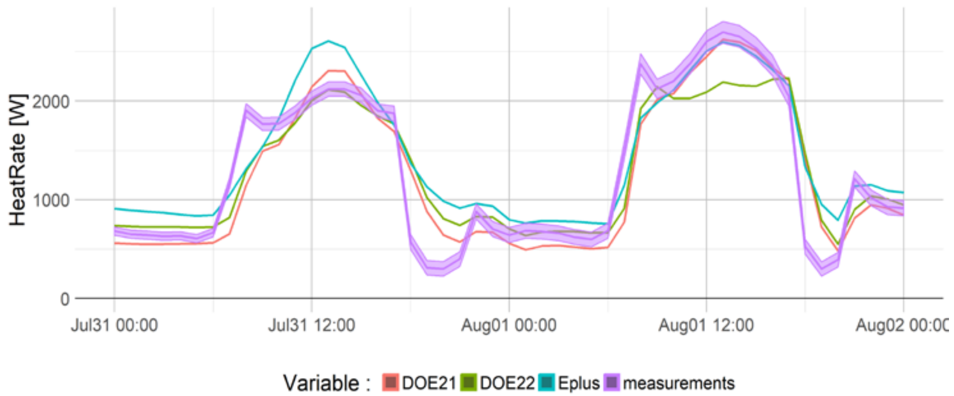


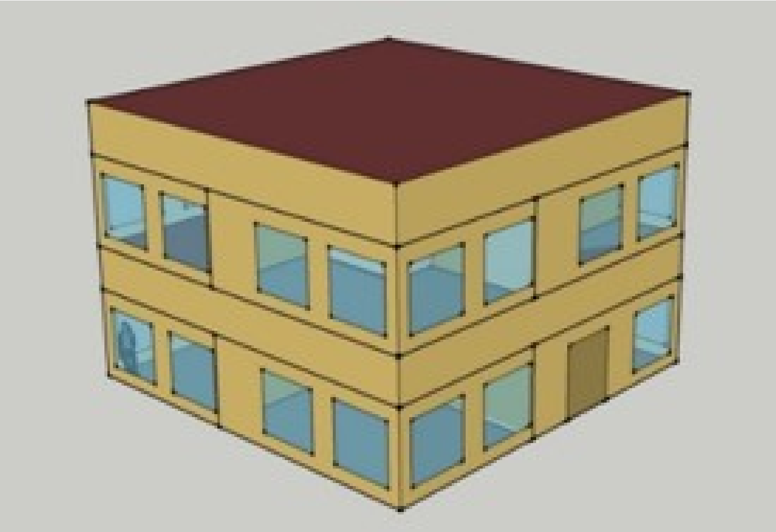
Low Mass, Exposed Windows, High Internal Gains, Var Set-point



Immediate next steps:

- Quasi-real-time, component-level, measured heat balance for diagnosis
- Real-time EnergyPlus – compare measured and expected performance for automated discrepancy detection and localization

Multizone HVAC System Validation using ORNL's Flexible Research Platform



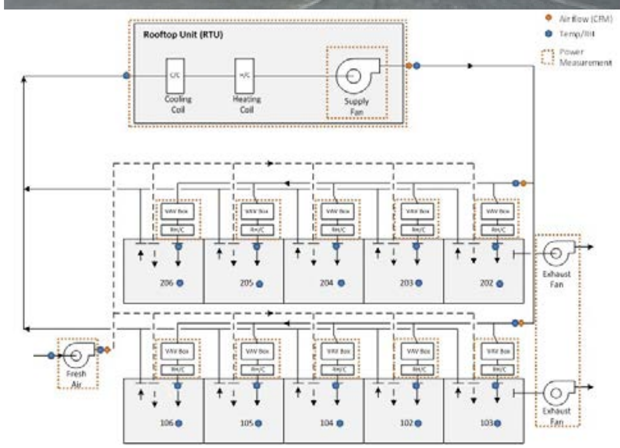
Oak Ridge National Laboratory

Joshua New– newjr@ornl.gov

Piljae Im– imp1@ornl.gov

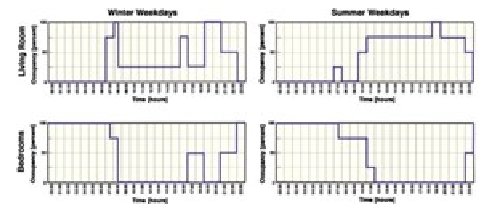
Validation of Multi-Zone HVAC System Modeling – Test Facility

Multizone HVAC - RTU with VAV Reheat

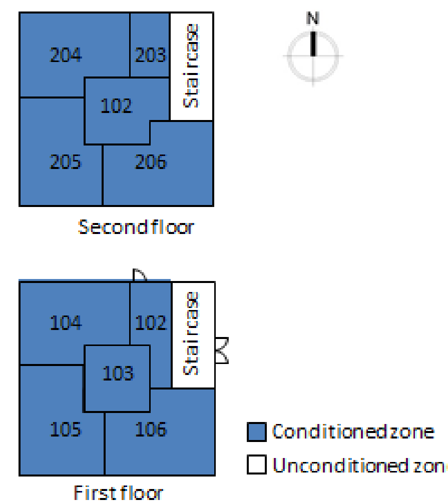


Weather Station

Simulated Occupancy



Flexible Research Platform (FRP)



- Flexible Research Platform (FRP): 2 story small office building (40’ x 40’) with 10 thermal zones.
- Multizone HVAC system: Rooftop Packaged Unit with Variable Air Volume (VAV) Reheating
- Occupancy emulation: occupancy is emulated by process control of lighting, humidifiers for human-based latent loading, and a heater for miscellaneous electrical loads (MELs).

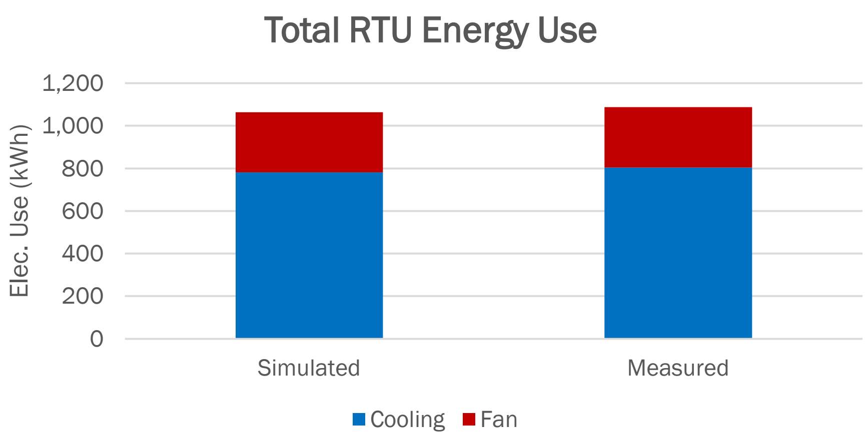
Outcomes

- Multiyear test plan
- 5 documented tests (3 for cooling seasons and 2 for heating seasons)
  - Experimental plan was set based on ASHRAE Standard 140
  - Each test was performed for at least 1 week
- Modeling input documents
- Comparison analysis with EnergyPlus results

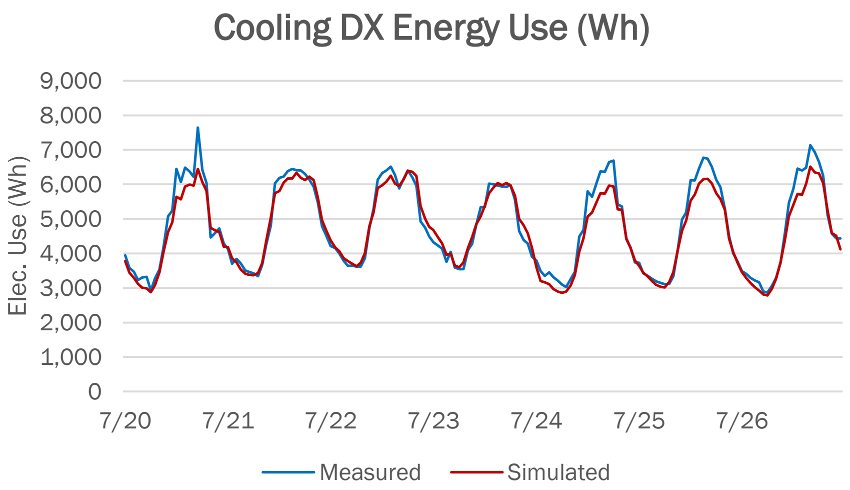
Sample Results - I

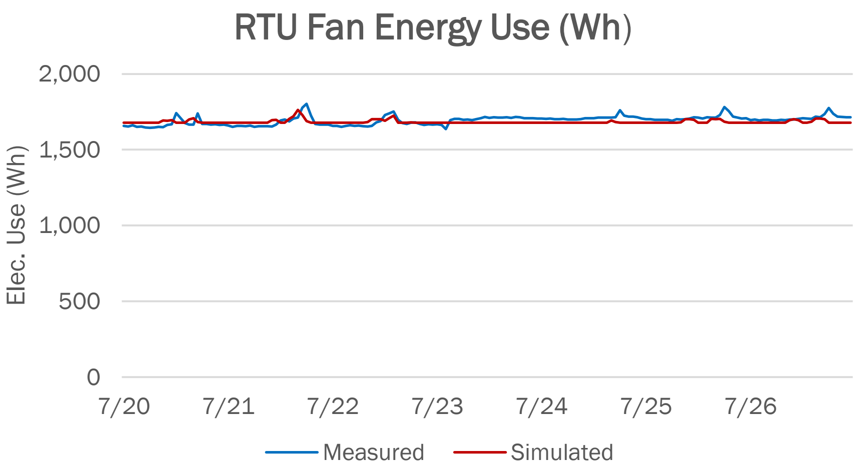
Test 1: Cooling Baseline :

- No occupancy emulation
- All internal lights are turned off; no internal loads
- Fixed discharge temperature of 55ºF and no Outdoor air ventilation or exhaust air
- No humidity control and no heating (including no reheating)
- Fixed zone set point temp of 72ºF



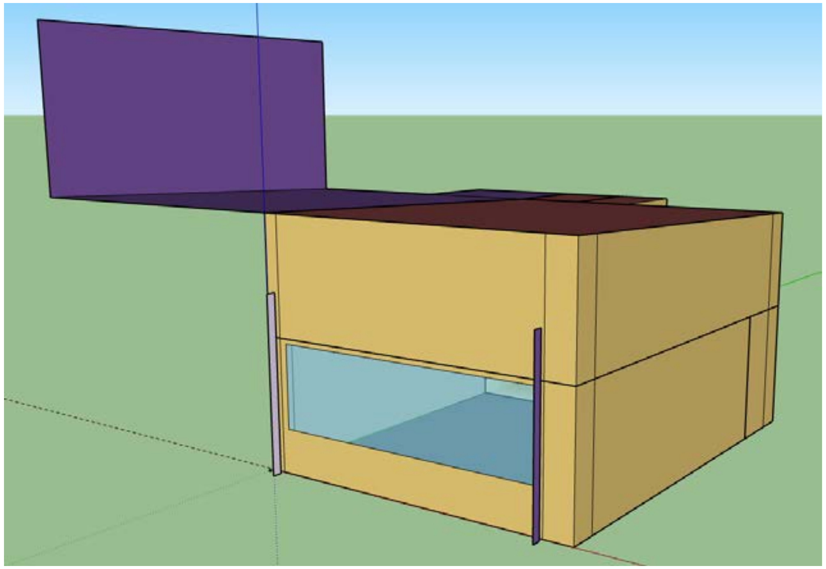
Measured HVAC Energy use is 2.2% higher than simulated

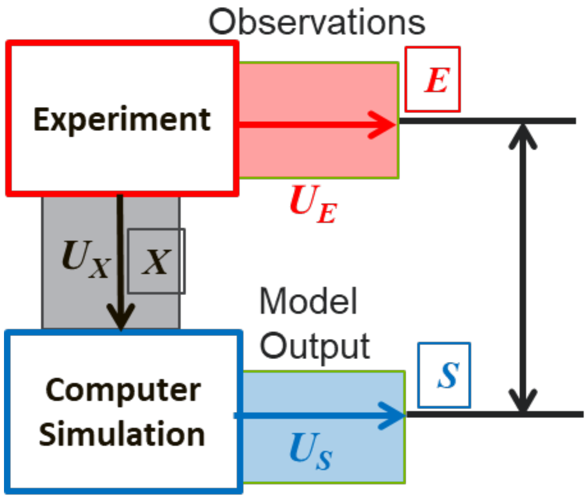




Hourly NMBE and CV(RMSE) for HVAC total energy use are about 2.2%, and 4.9%, respectively.

Uncertainty Characterization



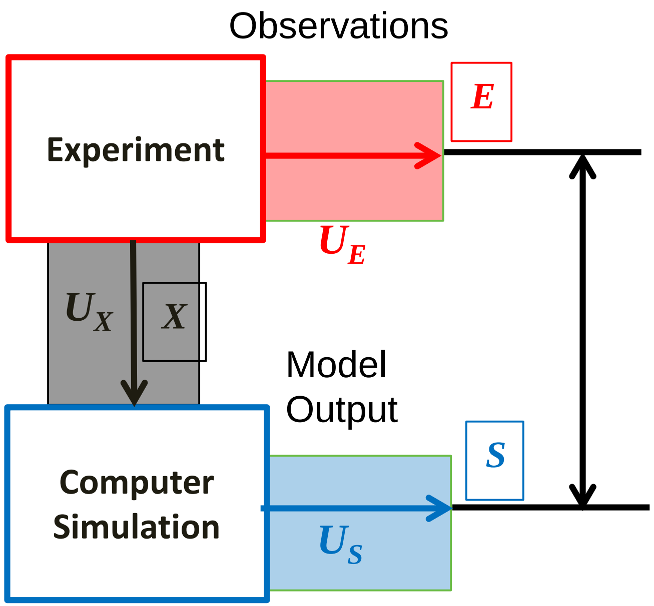


Argonne National Laboratory – Ralph Muehleisen – rmuehleisen@anl.gov

Qi Li

Uncertainty Analysis Goals

1. Characterize the uncertainty in the experiments
2. Characterize the values and the uncertainty in model inputs given detailed description of the experiments and facilities
3. Develop a standard method for propagation of uncertainty
4. Develop discrepancy metrics for comparing experiment to simulations when there is uncertainty



Metrics for model validation under uncertainty

- Continuous Ranked Probability Score (CRPS) **(Gneiting and Raftery 2007)**

$$CRPS(F_Y, Y') = \int_{-\infty}^{\infty} \left(F_Y(y) - \mathbb{1}(y - Y')\right)^2 dy$$

F_Y and Y' : A predicted distribution and an observation of random variable Y respectively

$F_Y(y)$: The cumulative distribution function (CDF) of F_Y
$F_Y(y) = P(Y \le y)$, i.e. the probability that Y takes a value less than y according to F_Y

$\mathbb{1}(y - Y')$: The CDF reflected by the observation Y', $\mathbb{1}(y - Y') = \begin{cases} 0 & if\ y < Y' \\ 1 & otherwise \end{cases}$

- CRPS reduces to absolute error when F_Y becomes a deterministic prediction, i.e. $F_Y = \hat{Y}$ and $F_Y(y) = \mathbb{1}\left(y - \hat{Y}\right)$.

$$CRPS\left(\hat{Y}, Y'\right) = \int_{-\infty}^{\infty} \left(\mathbb{1}\left(y - \hat{Y}\right) - \mathbb{1}(y - Y')\right)^2 dy = \left|\hat{Y} - Y'\right|$$

Gneiting, Tilmann, and Adrian E Raftery. 2007. "Strictly Proper Scoring Rules, Prediction, and Estimation." *Journal of the American Statistical Association* 102 (477):359–78. https://doi.org/10.1198/016214506000001437.

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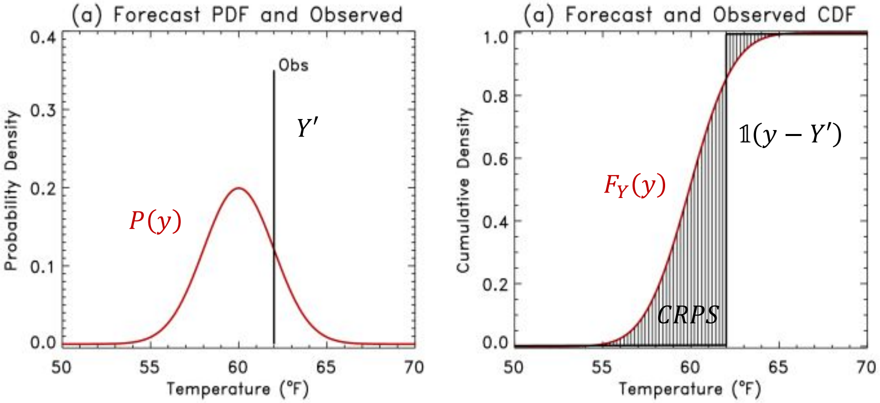
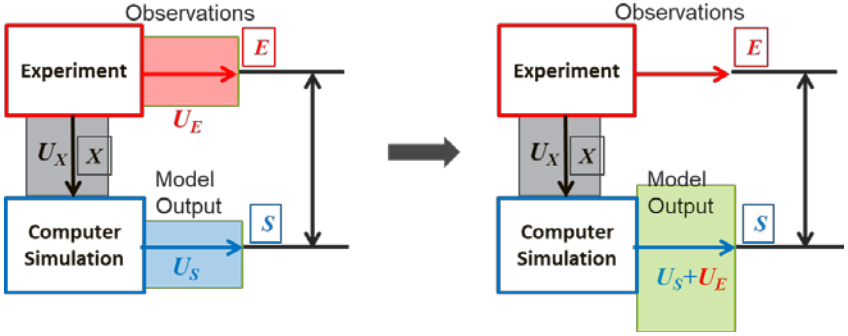
- An illustrative example:



http://www.met-learning.eu/pluginfile.php/5277/mod_resource/content/6/www/resource/msg/verification/images/Graph_cdf_pdf.jpg

- Use perturbed-ensemble method to include observation uncertainty **(Anderson, 1996)**

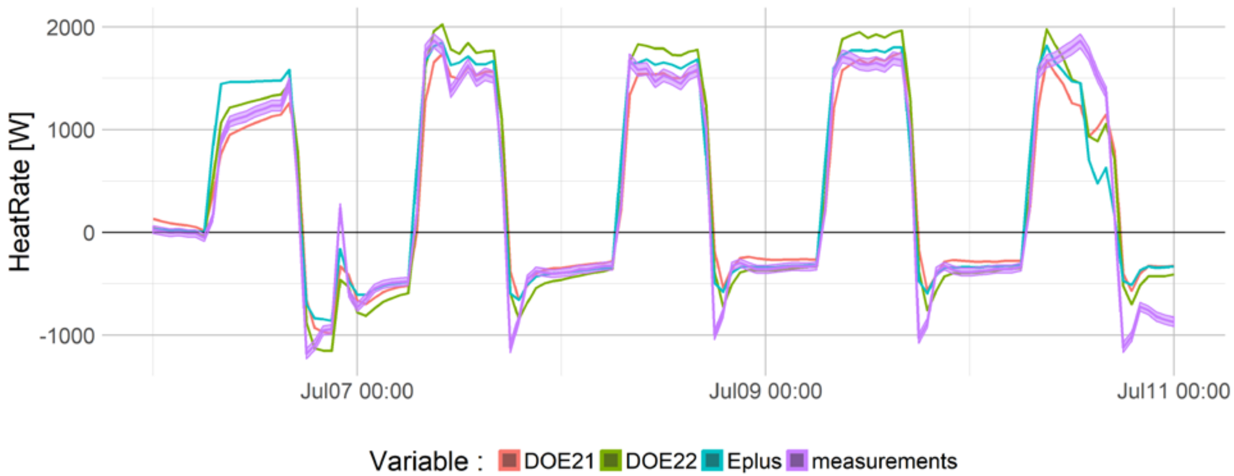


Anderson J. 1996. A method for producing and evaluating probabilistic forecasts from ensemble model integrations. *J. Climate* 9:1518–1530.

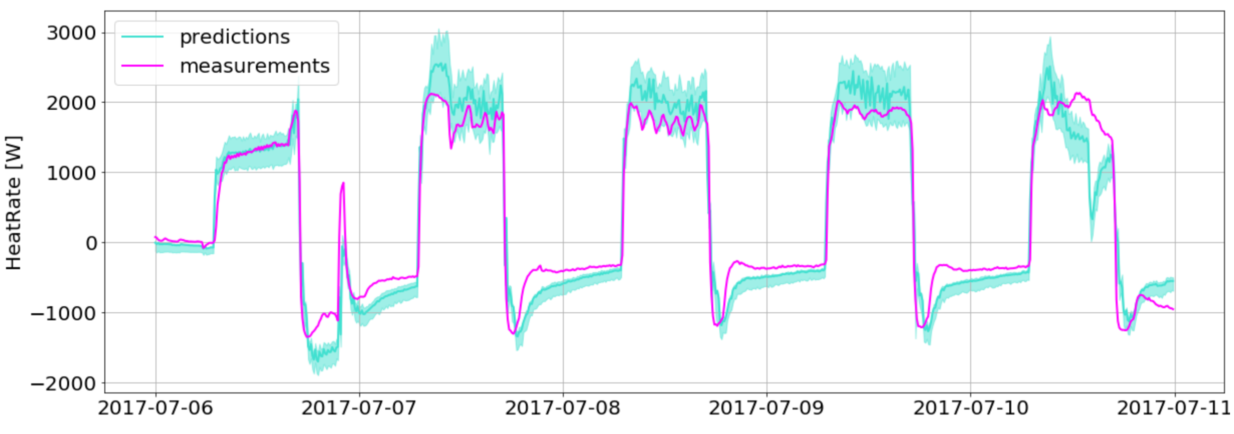
Modeling and uncertainty quantification

- An independent ANL model to avoid biases and test the construction information

LBNL comparison result (hourly output): RNMBE 0.80%

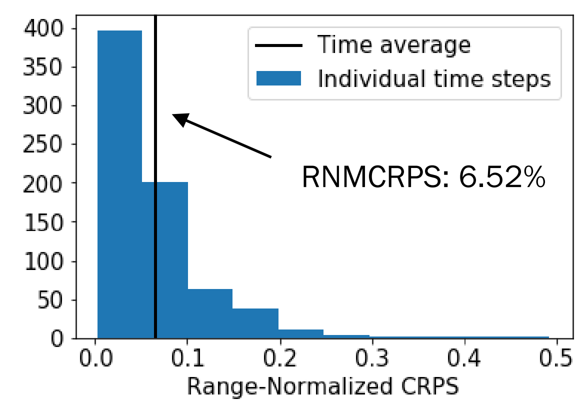


ANL comparison result (10-min output): RNMCRPS 6.52%



Considered uncertainties:

- Envelope material properties
- Room air stratification
- Non-uniform slab temperature
- Sensor error in model inputs:
  - weather conditions
  - internal load
  - test cell temperatures
- Sensor error in measurements:
  - Heat rate



Performance Mapping of Small Roof Top Units: NREL HVAC Test Loop

National Renewable Energy Lab - Ron Judkoff <ron.judkoff@nrel.gov>

NREL: Performance Mapping of RTUs

Full Performance Mapping of a 5 ton SEER 17 and a 6 ton IEER 23 Completed and Data Entered into the DOE Technology Performance Exchange (TPEX)

- 5 Ton Seer 17 (90 test conditions measured & full factorial for 387)
  - Multi-stage scroll compressor R-410A and single speed condenser fan
  - Direct drive variable supply air fan with high efficiency motor
  - Low Leak Dampers
  - Hot gas re-heat advanced humidity control
  - Economizer
- 6 Ton IEER 23 (90 test conditions measured)
  - Variable speed compressor, evaporator fan, and condenser fan
  - Direct drive compressor using R-410A
  - On board controls optimized for lowest lift & dehumidification mode not requiring re-heat
- Data will be used in the future to provide an empirical basis to HVAC BESTEST 1 and 2 in ASHRAE Standard 140 so that the tests include realistic part load behavior for testing BEMs

(TPEX: https://www.tpex.org/content/generic-rtu-6ton-23ieer-1scrollvariable-testdata)

Work in Remainder of FY18

All

- Submit draft documentation of current tests to SSPC 140

LBNL

- Begin extension to include furniture and radiant systems, as resources permit

ORNL

- Complete documentation of measurements and modeling

NREL

- Produce a paper on the issues associated with performance mapping and modeling the latest generation of variable highly efficient equipment
- Continue leading the NREL formal liaison role with SSPC-140

ANL

- Continue model development with better quantification of uncertainty through detailed measurement data.
- Establish a validation framework based on CRPS.

Potential Future Work

All

- Iterate with SSPC 140 on documentation of current project submissions

LBNL

- Extend overhead mixing to include furniture and different types of internal gains
- Extend to radiant systems: ceiling panels, floor slabs

ORNL

- Extend to different supervisory control strategies for multi-zone VAV
- Further measurements on envelope for building loads
- Extend to occupancy-emulated residential buildings at ORNL

NREL

- Develop a hybrid tabularized approach for complex performance maps
- Include fully performance-mapped equipment as part of whole building empirical validation experiments to reduce uncertainty from HVAC performance

ANL

- Expand uncertainty framework to support IESVE, TRNSYS, etc

REFERENCE SLIDES

Project Budget

Project Budget: Originally \$3M, then reduced to \$2.7M, followed by further, substantial cuts – now restored to \$2.7M

Additional Funding: Informal cost shared from complementary project, funded by Southern California Edison, to use FLEXLAB measurements to adjudicate between 2.2/eQuest and EnergyPlus.

Budget History					
FY 2016 (past)		FY 2017 (past)		FY 2018 (current)	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
\$700k	\$60k	\$1,000k	\$100k	\$1,000k	\$90k

Project Plan and Schedule

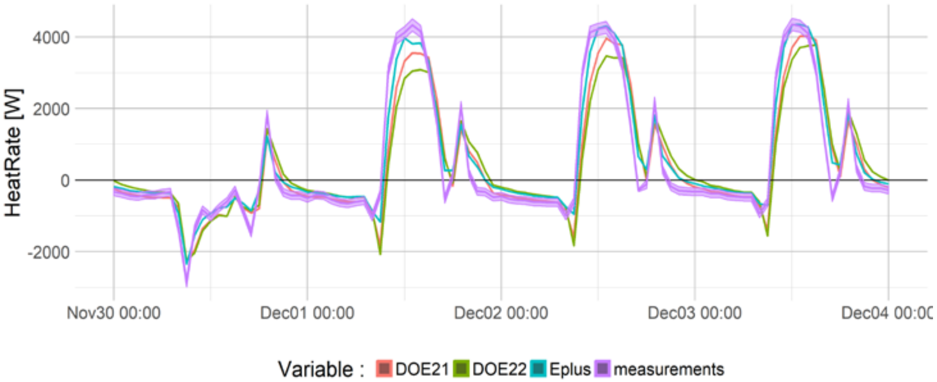
Project Schedule		
Project Start: Oct 1, 2016		Completed Work
Projected End: Sep 30, 2018		Active Task (in progress work)
		Milestone/Deliverable (Originally Planned) use for missed
		Milestone/Deliverable (Actual) use when met on time

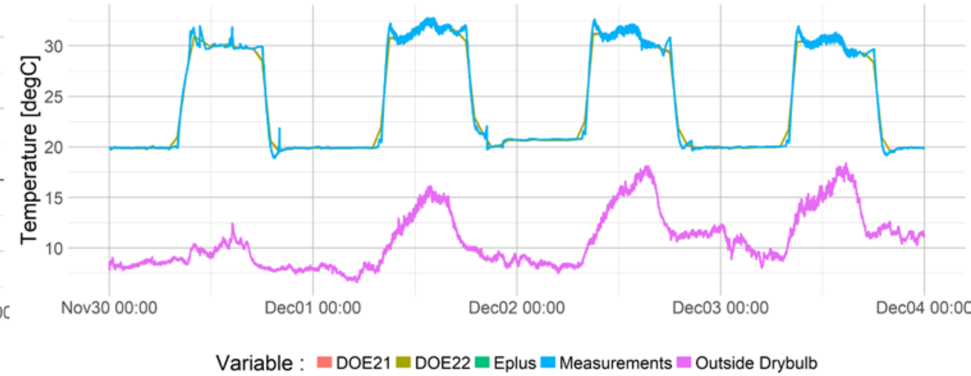
	FY2016				FY2017				FY2018			
Task	Q1 (Oct-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Oct-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Oct-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)
Draft project plan and experimental designs												
Completed Development of Validation Metric(s)												
First EnergyPlus validation with FRP data												
First EnergyPlus validation with FLEXLAB data												
Documented data for mixing ventilation (F/L)												
Completed Heating/Cooling Tests & Analyses(FRP)												
Complete Validation of FLEXLAB and FRP Experiments												
SEER 17 & IEER 23 mapped, data in TPEX, paper												

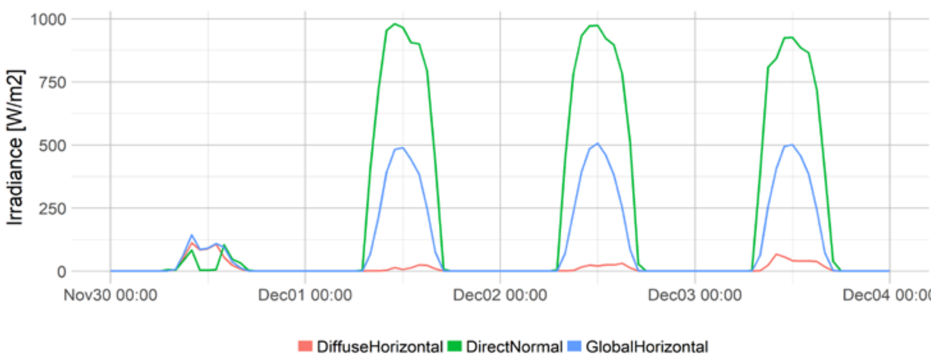
(Extra slide if needed for discussion)

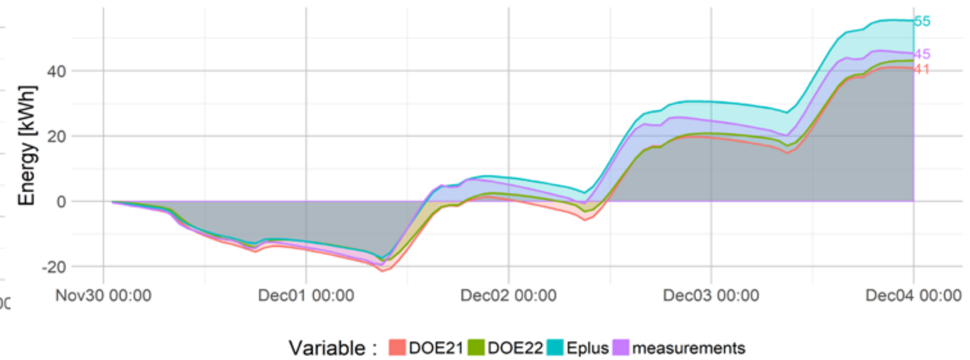
Sample (good) result and presentation format:

Scenario 11:06: Low Mass, Exposed Windows, No Int Gain, Var Set-point (20C / 30C)









	Day			Night		
	EplustoMeas	**DOE21toMeas**	**DOE22toMeas**	**EplustoMeas**	**DOE21toMeas**	**DOE22toMeas**
RNMBE	0.53%	-2.79%	-5.56%	2.13%	0.88%	3.44%
RNCVRMSE	7.36%	12.80%	15.50%	3.65%	4.25%	5.67%

RNMBE = Range-Normalized Mean Bias Error

RNCVRMSE = Range-Normalized Coefficient of Variation of the RMS Error