Energy Modeling of Dedicated Outdoor Air Systems for a Small Commercial Pilot Project

BUILDING ENERGY SIMULATION FORUM, AUGUST 17, 2016

AMY MONTGOMERY, MASc, P.Eng.

RDH BUILDING SCIENCE

Overview

- Pilot project: energy efficient replacement options for end-of-life packaged rooftop units on small commercial buildings
  - Dedicated Outdoor Air Systems (DOAS) with Heat Recovery Ventilation (HRV)
- Energy modeling as a tool to quantify savings
- Share progress and lessons learned

Pilot Project Overview

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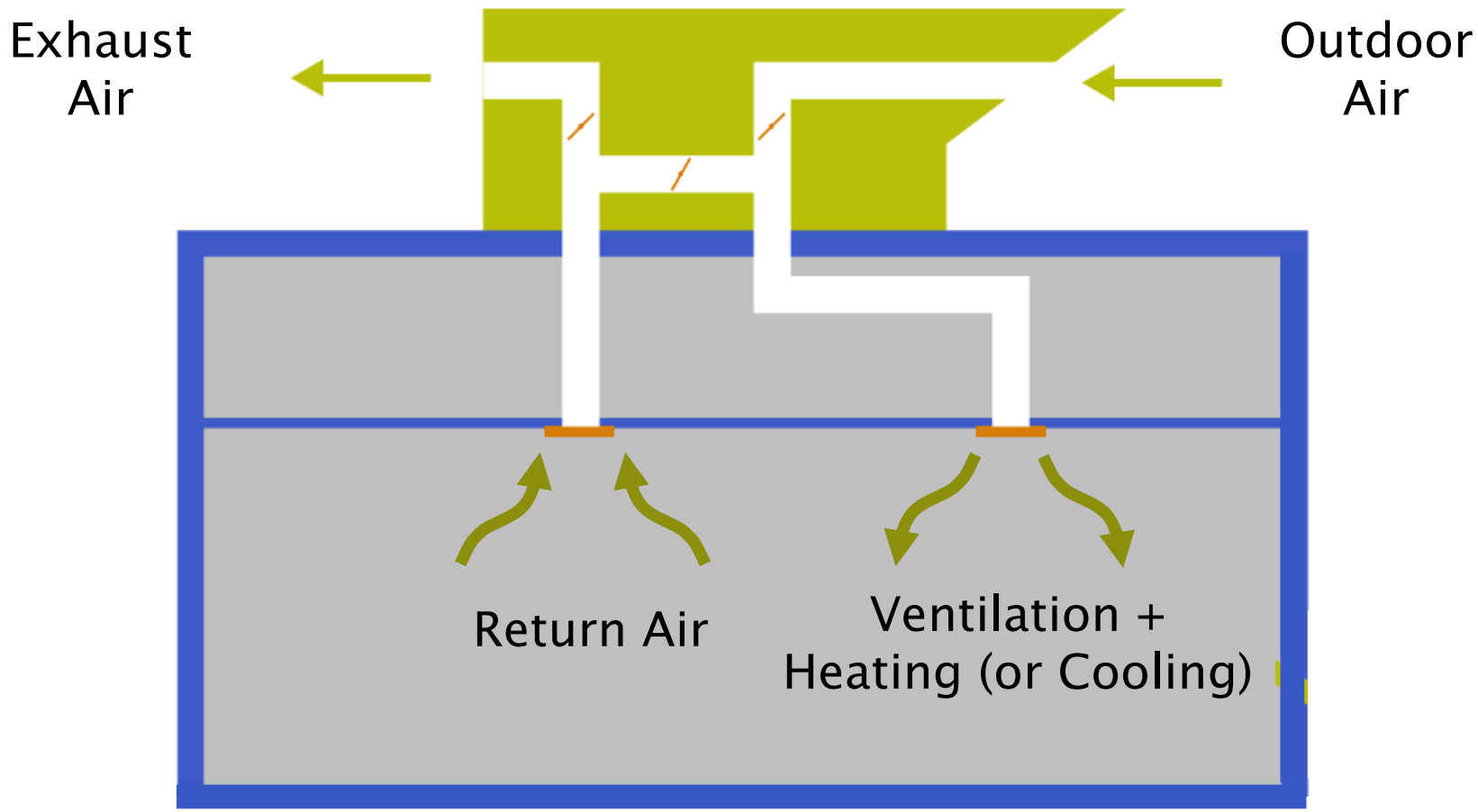
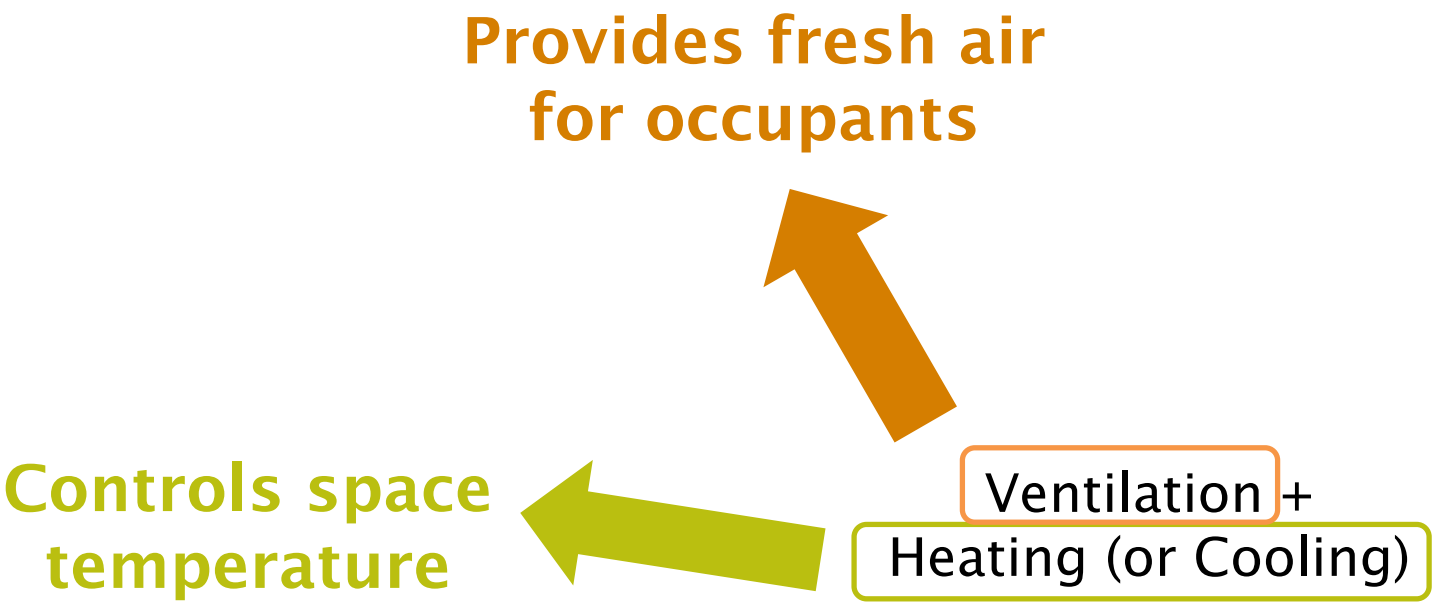
- Target Building Sector:
  - Small commercial (< 25,000 ft^2)
  - Includes small office, retail, schools, restaurants, small assembly
  - Makes up approx. half of the commercial building floor area in the Pacific Northwest.
  - Smaller HVAC systems; typically not engineered.

Pilot Project Overview

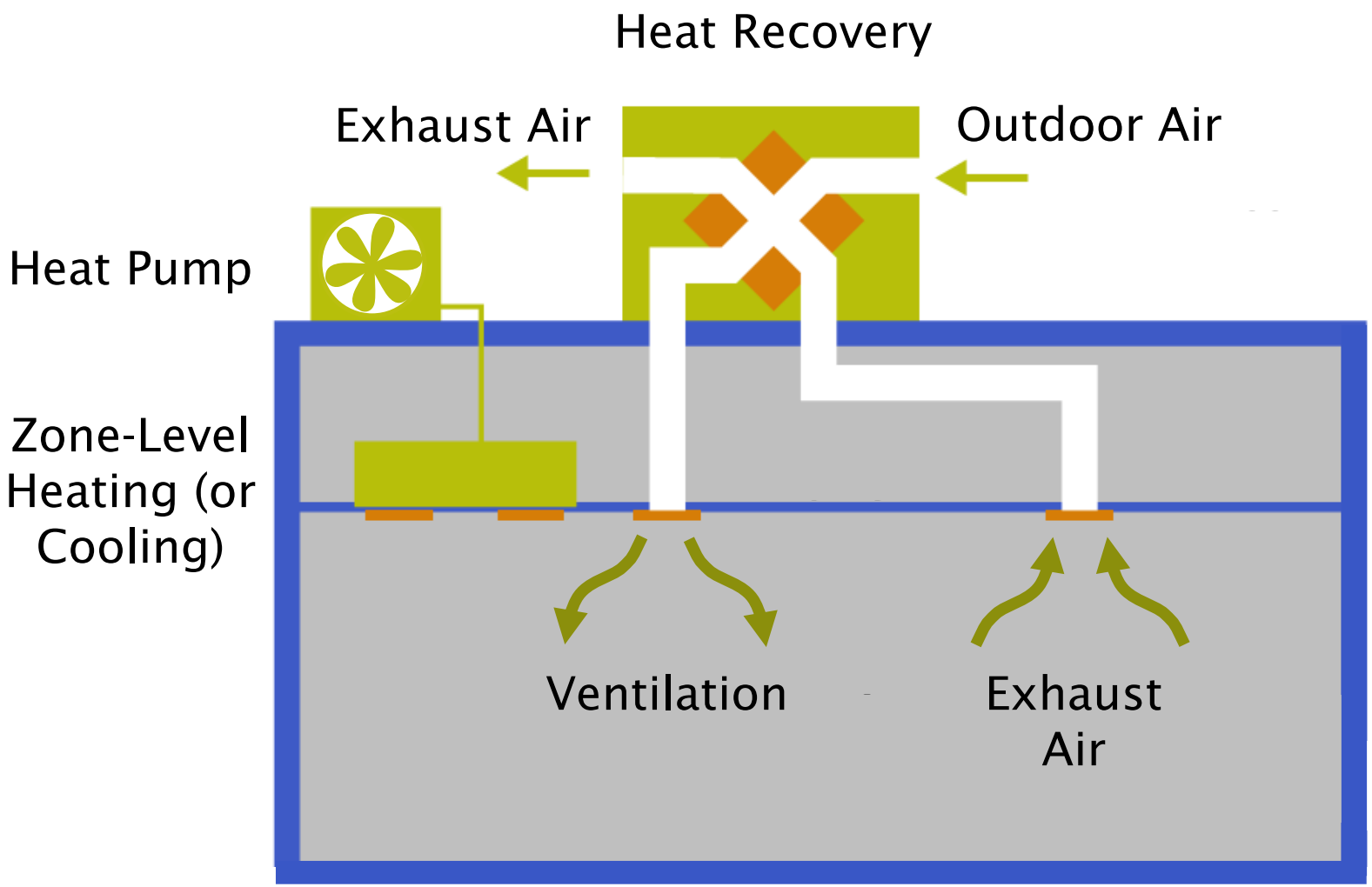


Packaged Rooftop Unit

Pilot Project Overview



Pilot Project Overview



Dedicated Outdoor Air System

Pilot Project Overview

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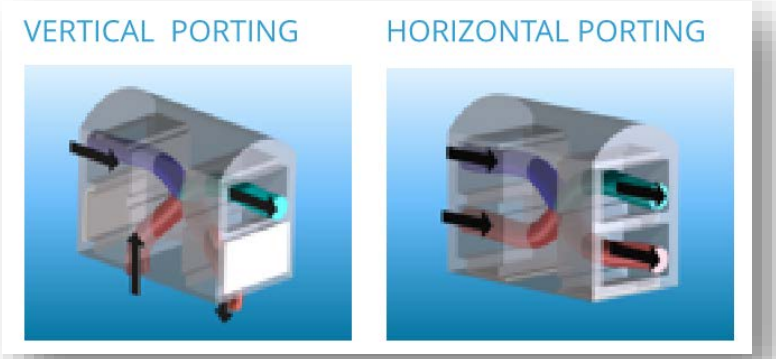
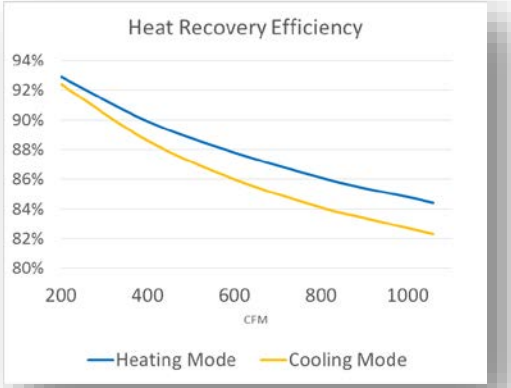
- Dedicated Outdoor Air System (DOAS) with Heat Recovery in Small Commercial Building Sector
  - Successful DOAS conversion depends on several factors, including:
    - Reduction in ventilation air volumes; demand controlled ventilation (DCV)
    - Very low ventilation fan power (0.5 Watts/cfm or less)
    - **Very high ventilation heat/energy recovery efficiency**
  - Minimal uptake due to lack of a cost-effective high efficiency ventilation solution

Pilot Project Overview

RDH

- Early pilot work funded by the Northwest Energy Efficiency Alliance (NEEA)
  - New high efficiency Heat Recovery Ventilation (HRV) unit
  - Vertical mounting for existing RTU ductwork
  - 1000 cfm max flow
  - Greater than 80% sensible heat recovery efficiency





Pilot Project Overview

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→ **PART 1:** Establish Baseline Conditions

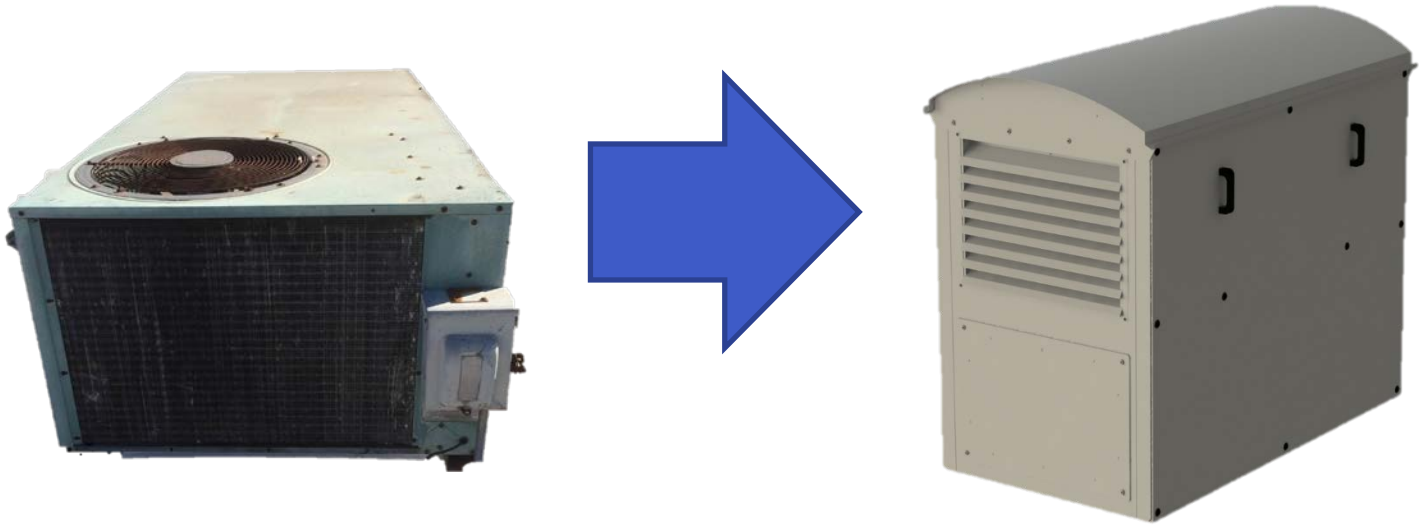
→ **PART 2:** Calibrated Baseline Energy Model

→ **PART 3:** DOAS Conversion

→ **PART 4:** Establish Post-Conversion Conditions

→ **PART 5:** Calibrated Post-Conversion Energy Model

Savings



Pilot Project Overview

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→ **PART 1:** Establish Baseline Conditions

- → Site Review
- → Baseline Air Leakage Testing
- → Installation of Monitoring Equipment

Pilot Project Overview

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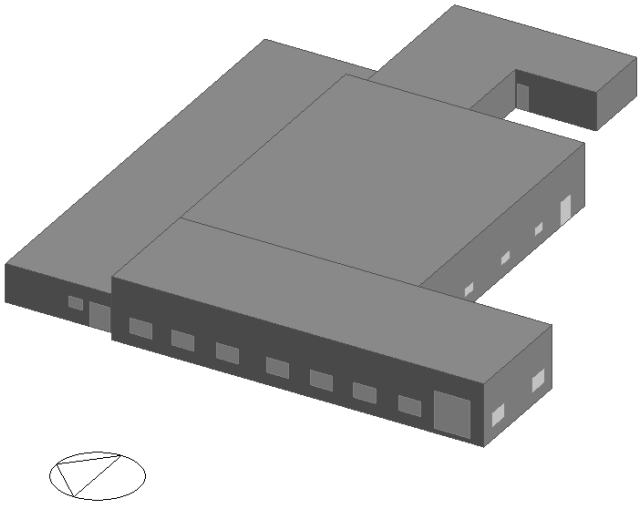
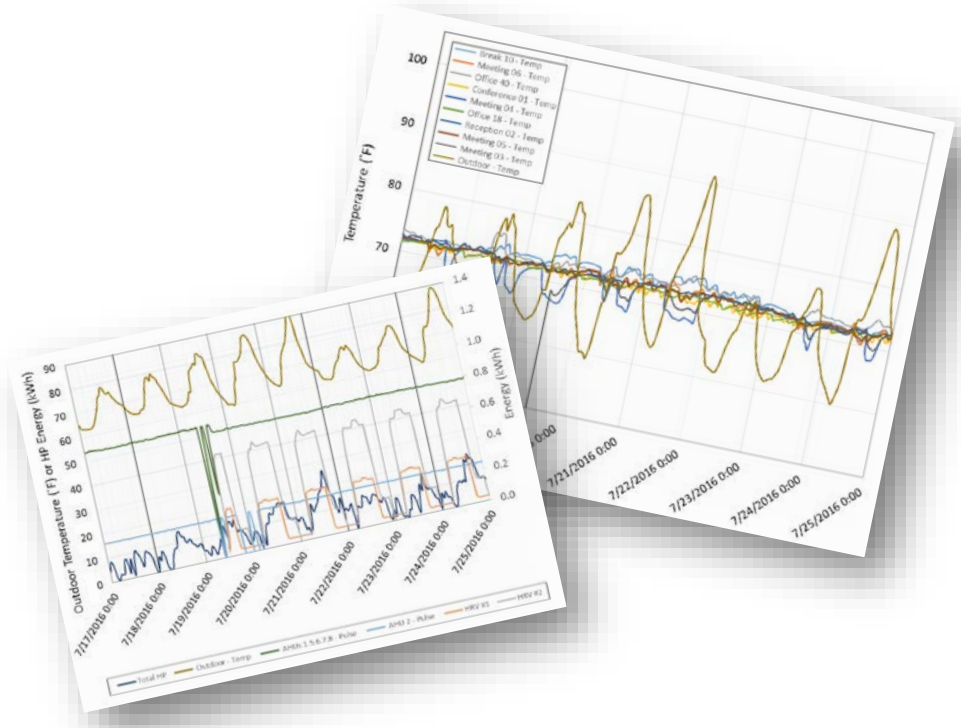
- **PART 2:** Calibrated Baseline Energy Model
  - Actual Operating Conditions (occupancy, schedules, heating and cooling setpoints, etc.)
  - Baseline Air Tightness
  - Monitoring Data
  - Historic Utility Data





Pilot Project Overview

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- **PART 3:** DOAS Conversion
  - New HRV unit
  - Zone-level heating and cooling
  - Local design teams and contractors

Pilot Project Overview

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→ **PART 4:** Establish Post-Conversion Conditions

- → Site Review
- → Post-Conversion Air Leakage Testing
- → Additional Monitoring Equipment

Pilot Project Overview

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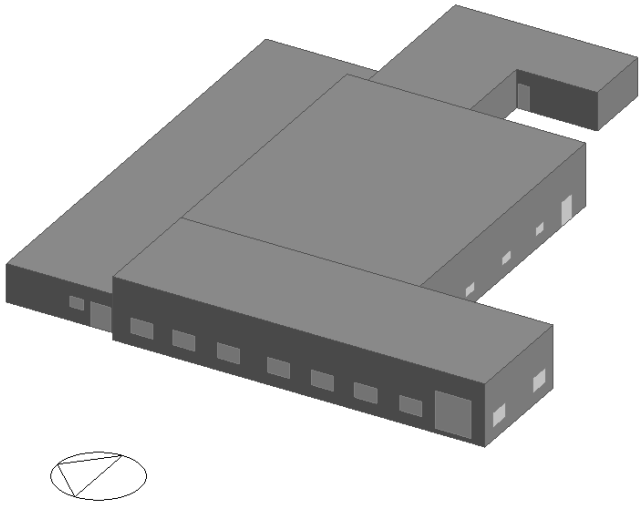
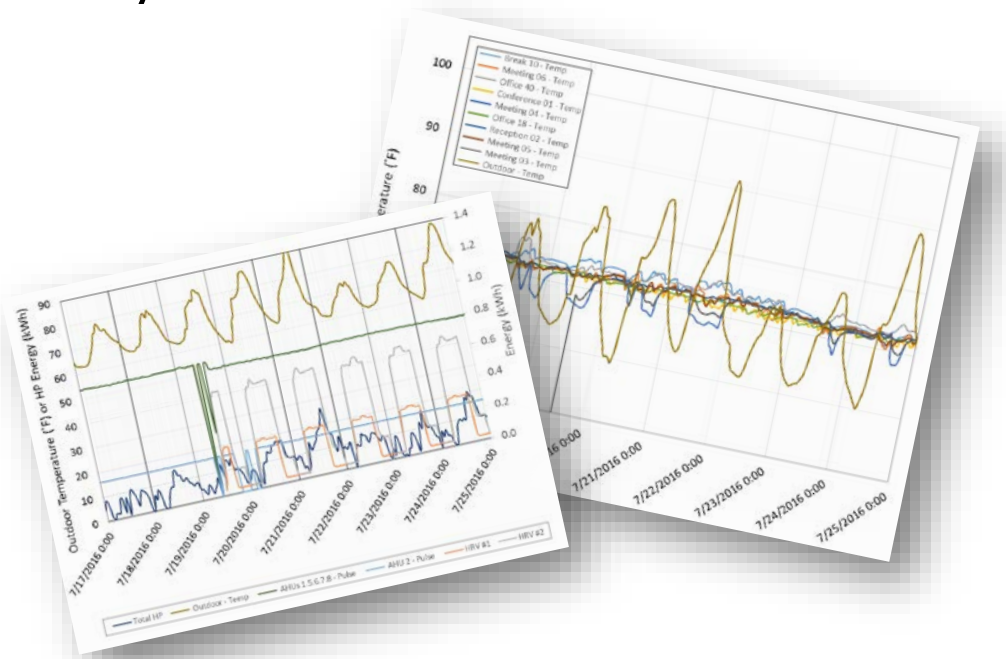
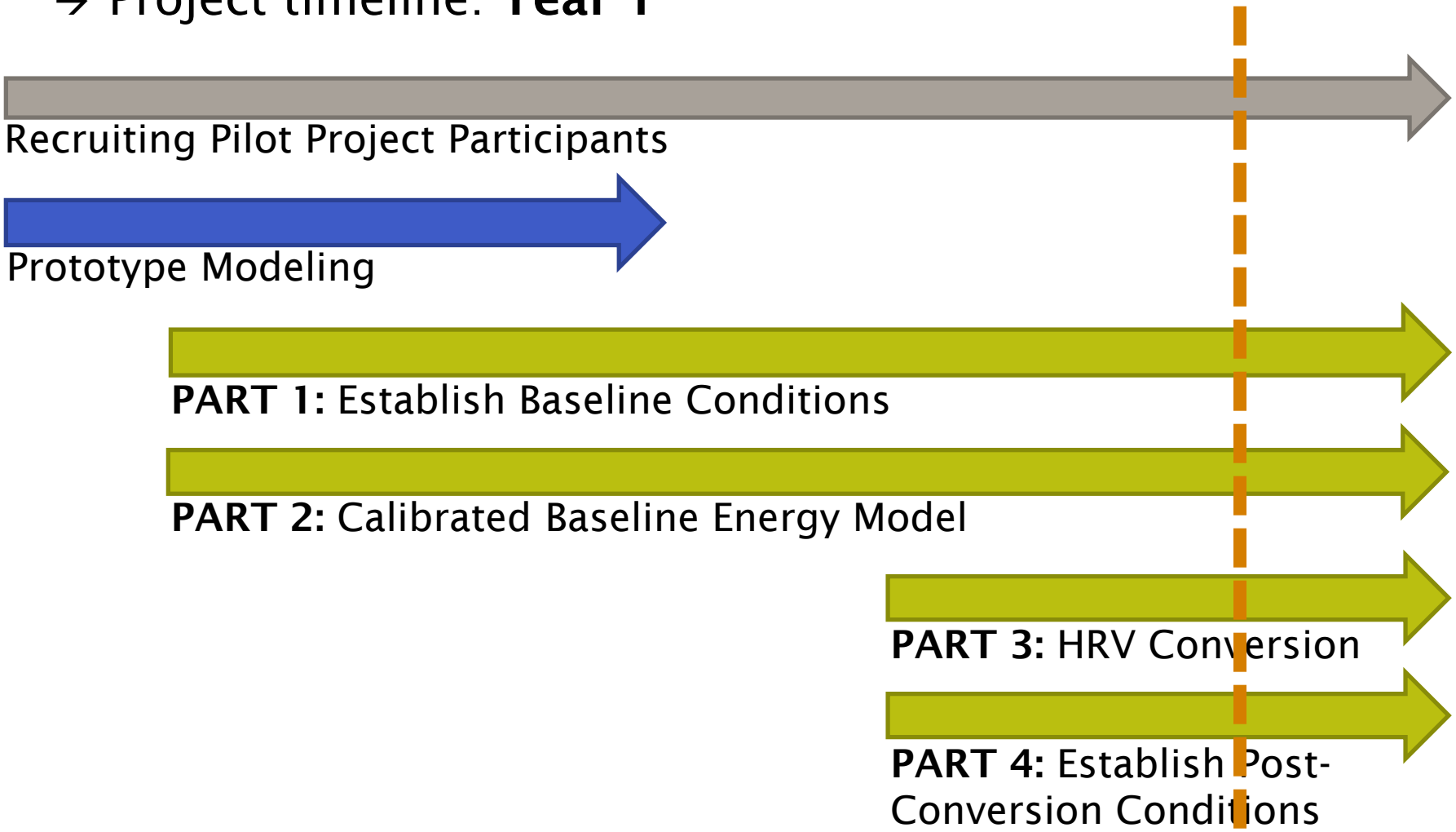
- **PART 5:** Calibrated Post-Conversion Energy Model
  - Maintain Baseline Operating Conditions
  - Post-Conversion Air Tightness
  - Monitoring Data
  - 1 Year Post Conversion Utility Data





Pilot Project Overview

→ Project timeline: **Year 1**



Pilot Project Overview

→ Project timeline: **Year 2**

PART 1: Baseline

PART 2: Baseline Model

PART 3: HRV Conversion

PART 4: Establish Post-Conversion Conditions

PART 5: Calibrated Post-Conversion Energy Model

Prototype Modeling

Prototype Modeling

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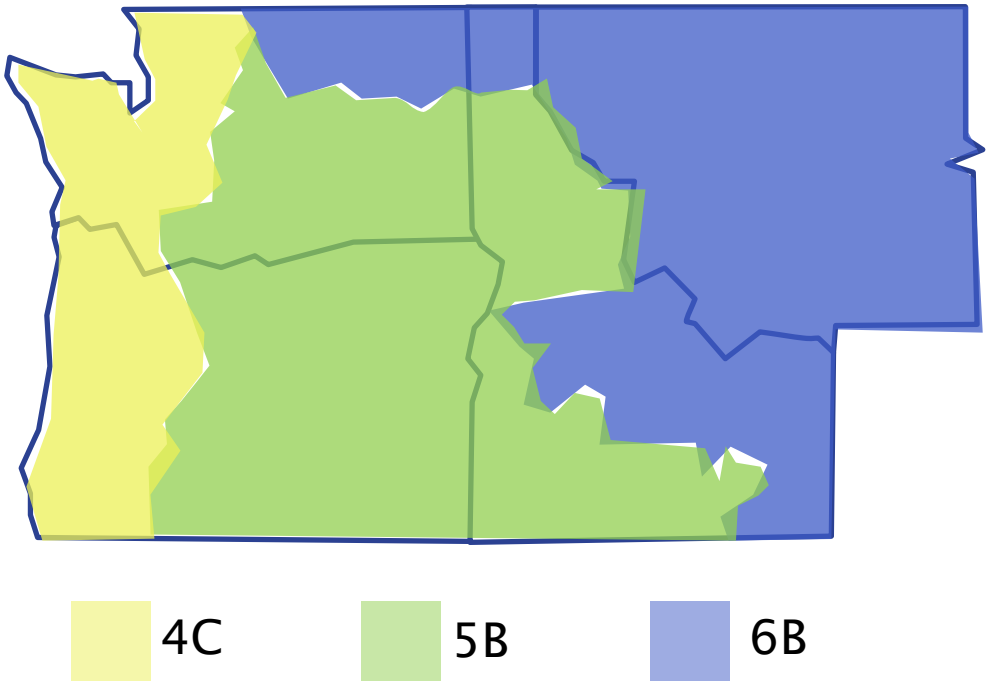
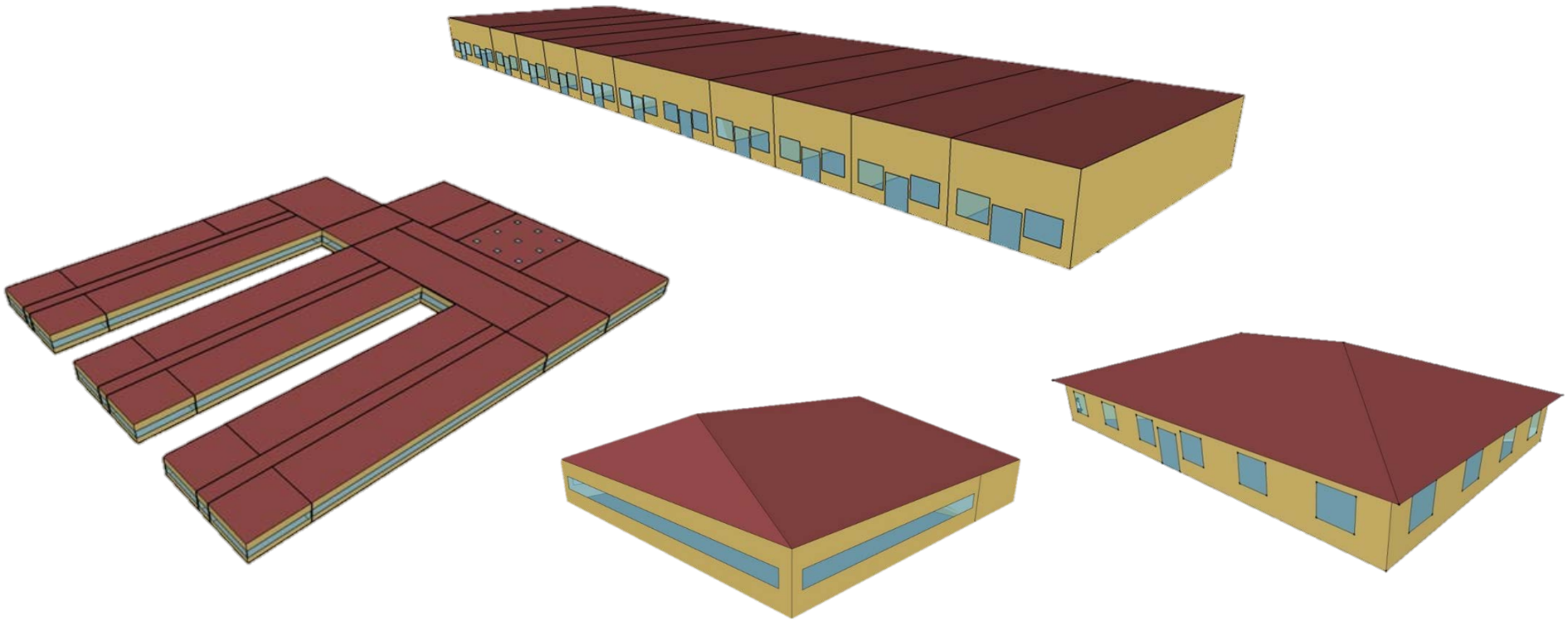
- Perform energy modeling of small commercial building prototypes to demonstrate savings potential
  - Prototype buildings
    - Office
    - Retail
    - School
    - Restaurant
  - Climate zones
    - CZ4C Portland OR
    - CZ5B Boise ID
    - CZ6B Helena MT



Prototype Modeling

RDH

- A few notes on prototypes:
  - Geometry and majority of operating inputs from DOE Commercial Prototype Building Models

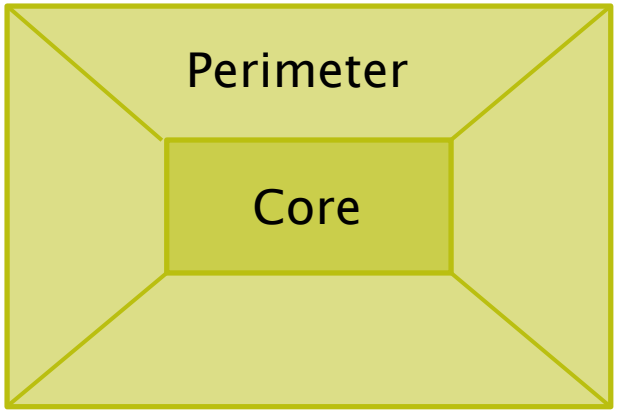


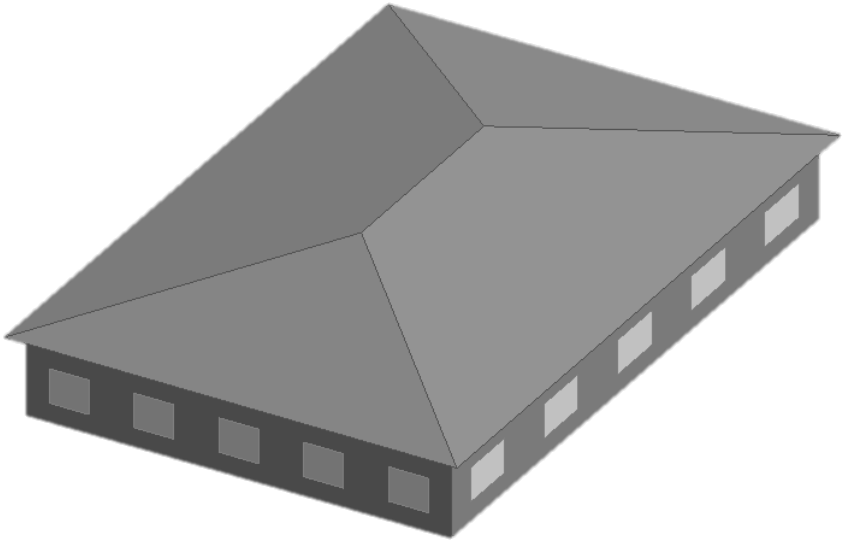
Prototype Modeling

- A few notes on prototypes:
  - How to reflect existing small commercial building stock?
    - DOE Pre-1980s Building enclosure inputs (4C/5B/6B)
      - R-5/R-6/R-7 walls
      - R-11/R-14/R-17 roof
      - U-0.55 windows
    - Downgraded baseline equipment efficiencies by 10%
    - No motorized damper controls on baseline rooftop units
      - Fixed damper position at 20%

Prototype Modeling

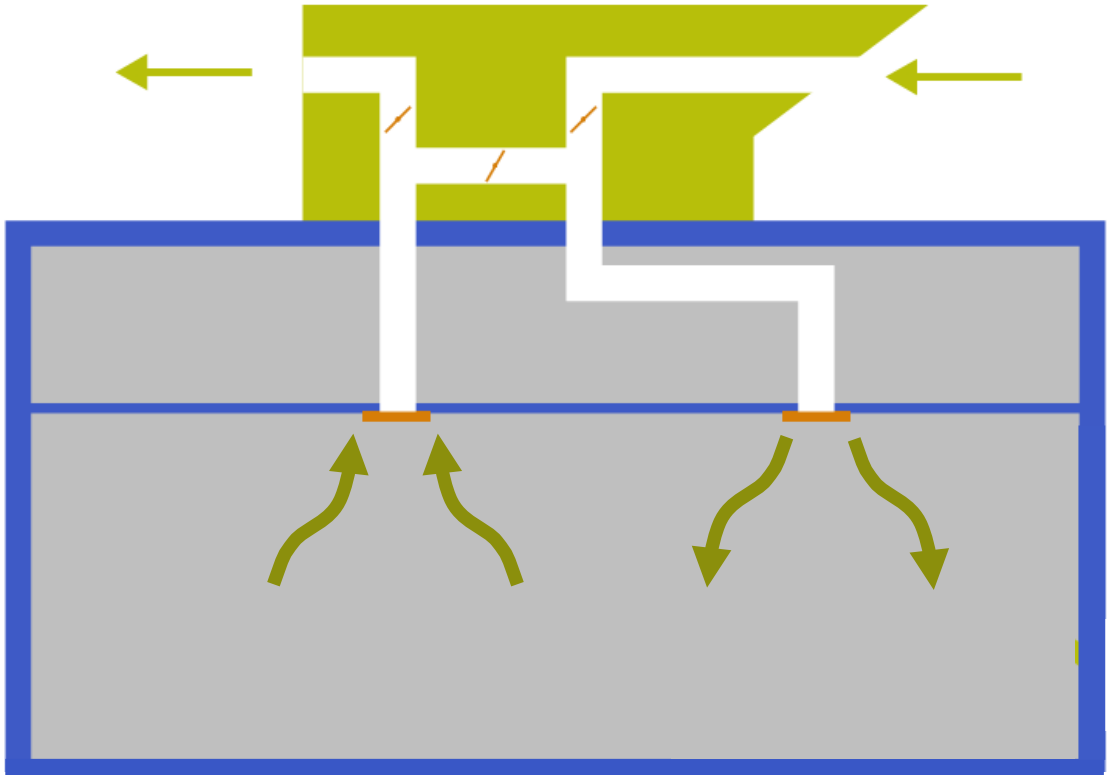
- Office Building
  - 5,500 ft^2
  - Defined as perimeter (70%) and core (30%) areas





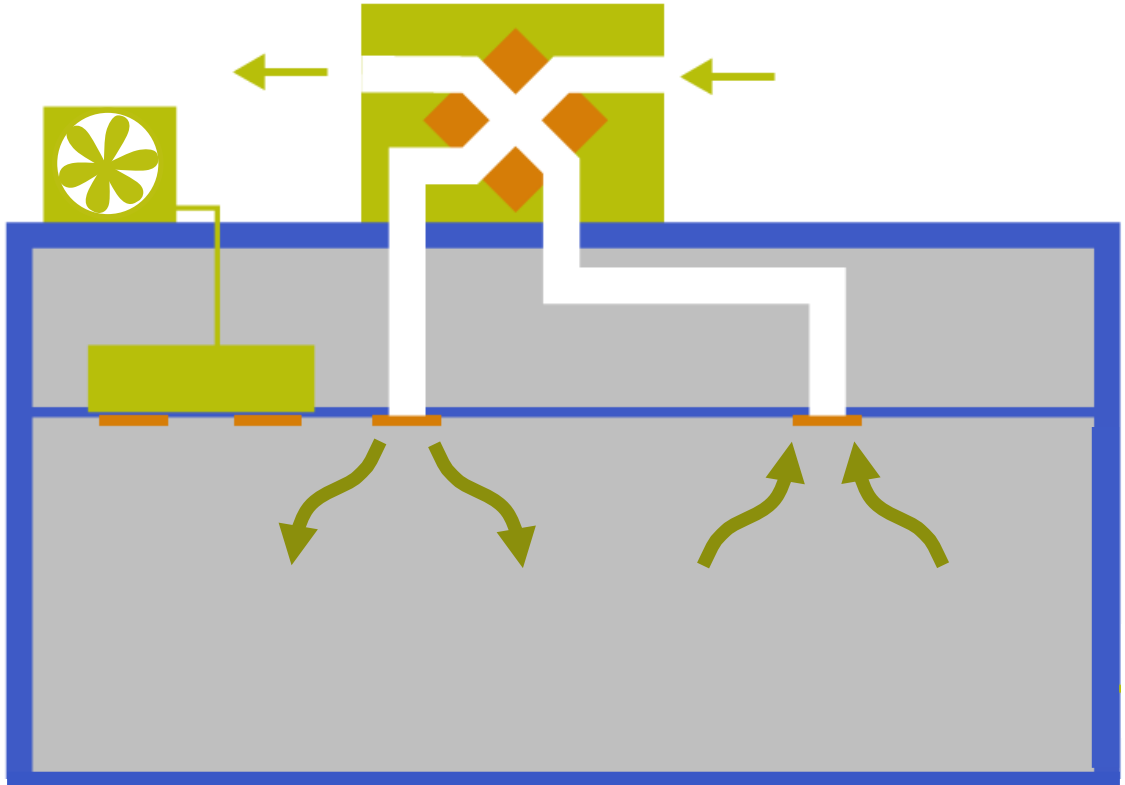
Office Baseline

→ Rooftop Unit (RTU) with Gas-Fired Heating and DX Cooling



Office Conversion

→ Dedicated Outdoor Air System (DOAS) with Heat Recovery Ventilation (HRV) and Zone-Level Heat Pumps

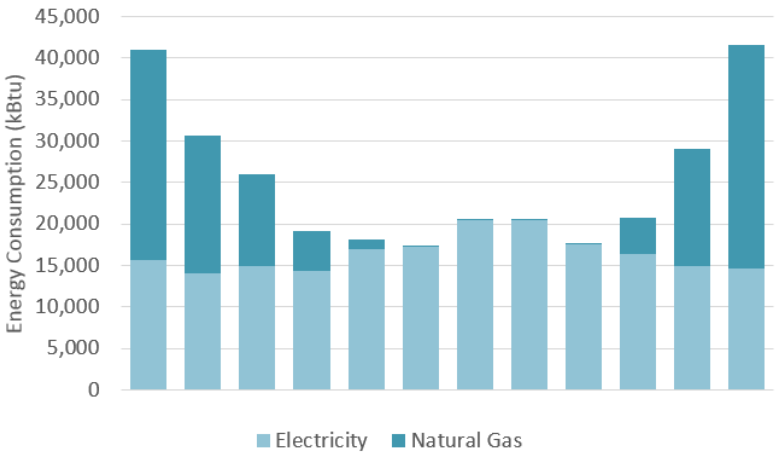


Prototype Modeling

→ Office Prototype Results

Baseline

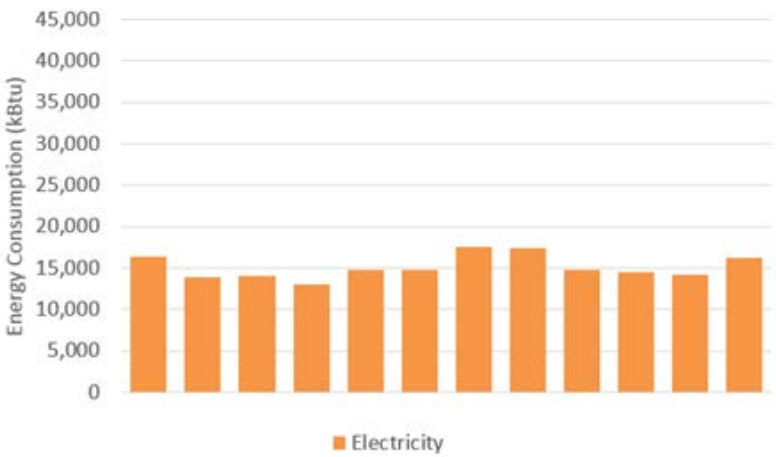
Annual Energy Consumption Profile



Whole building modeled EUI of **55 kBtu/ft²**.

Conversion

Annual Energy Consumption Profile



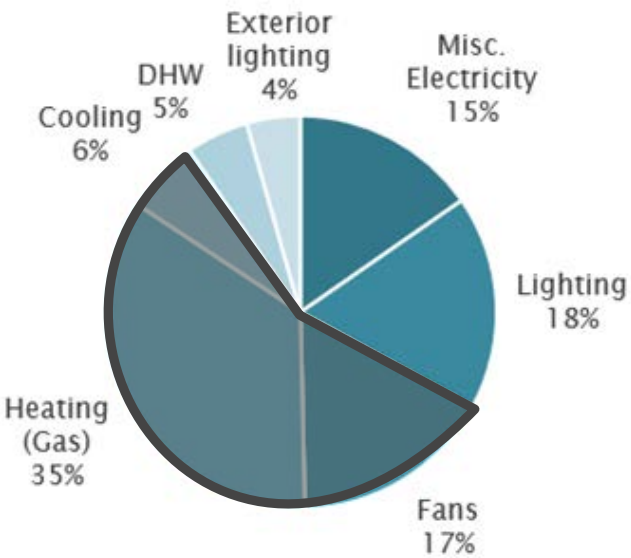
Whole building modeled EUI of **33 kBtu/ft²**. Results in **22 kBtu/ft² energy savings** over the baseline model.

Prototype Modeling

→ Office Prototype Results

Baseline

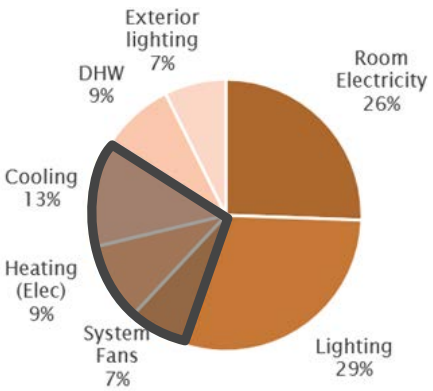
Annual Energy Consumption Profile



HVAC systems represent **57%** or **32 kBtu/ft²** of the overall energy use.

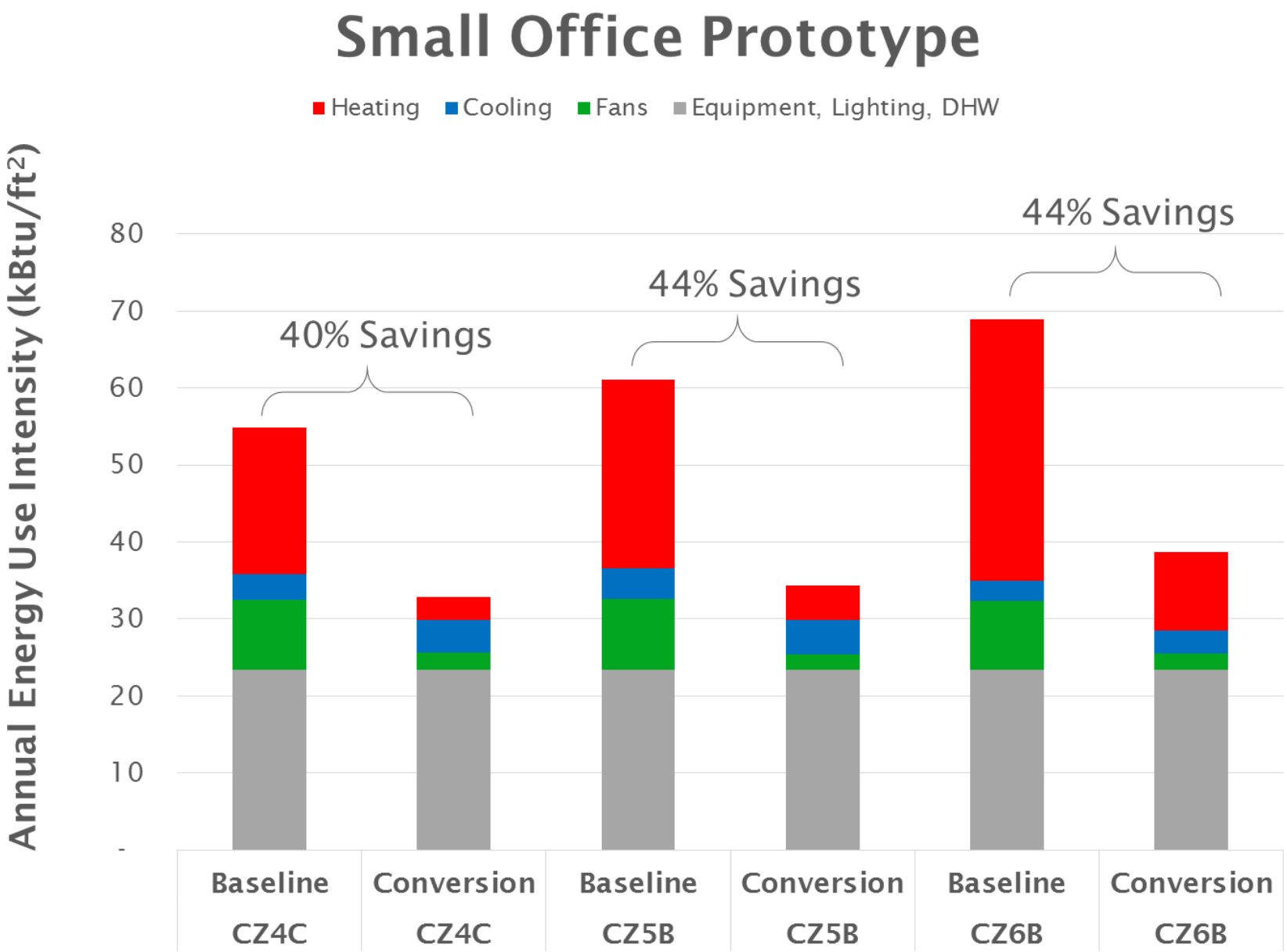
Conversion

Annual Energy Consumption Profile



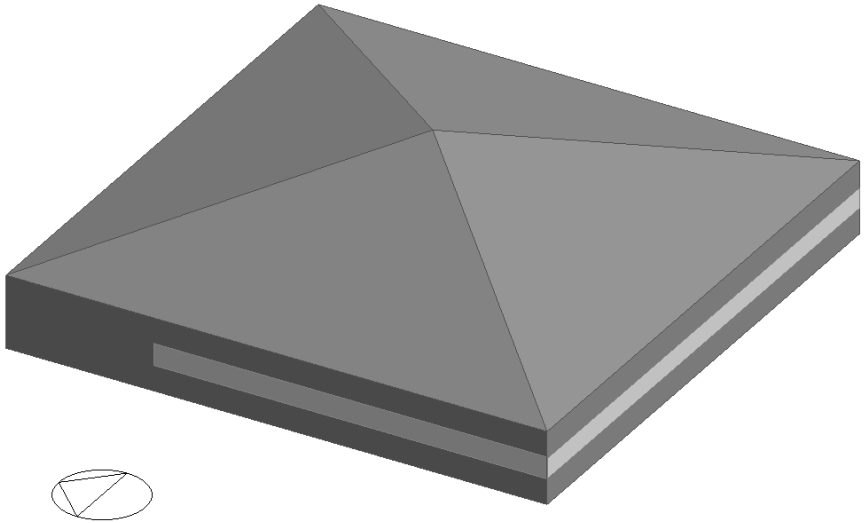
HVAC systems represent **29%** or **10 kBtu/ft²** of the overall energy use.

Prototype Modeling



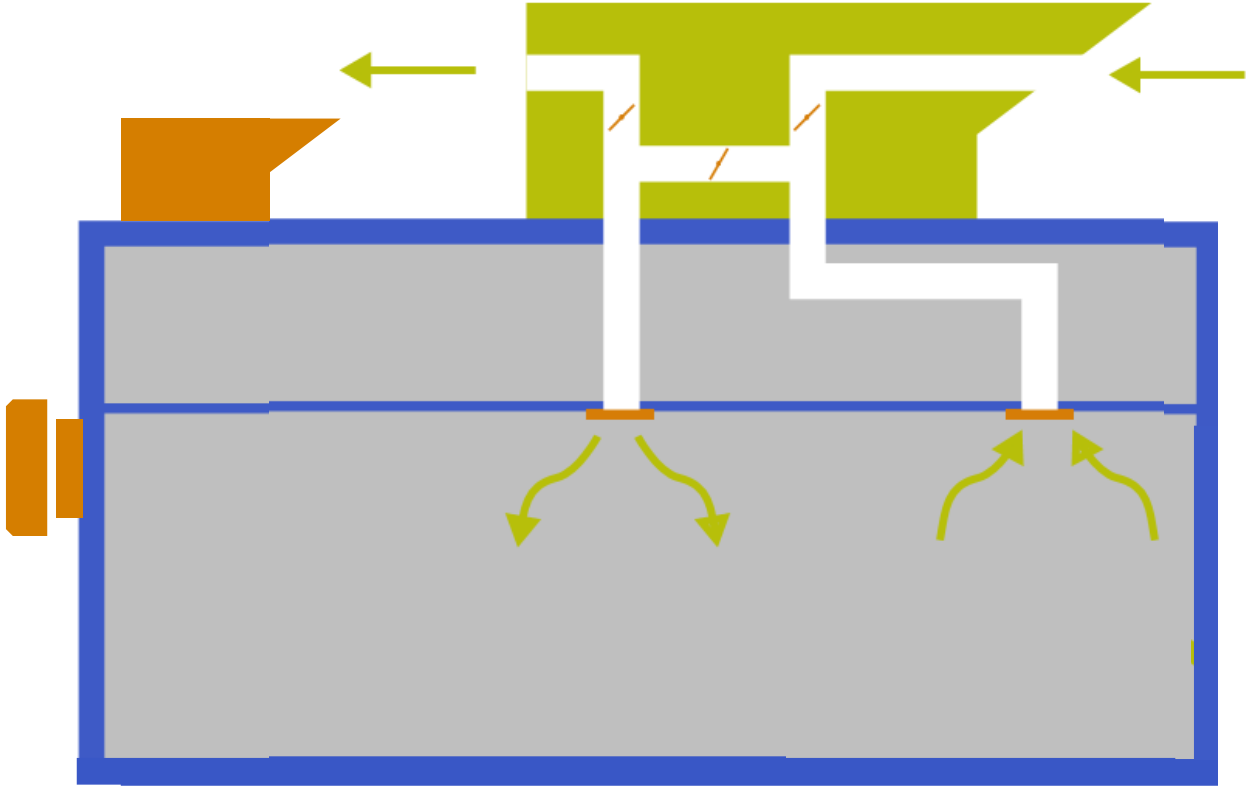
Prototype Modeling

- Sit-Down Restaurant
  - 5,500 ft^2 floor area
  - Includes dining area (73%) and kitchen (27%)



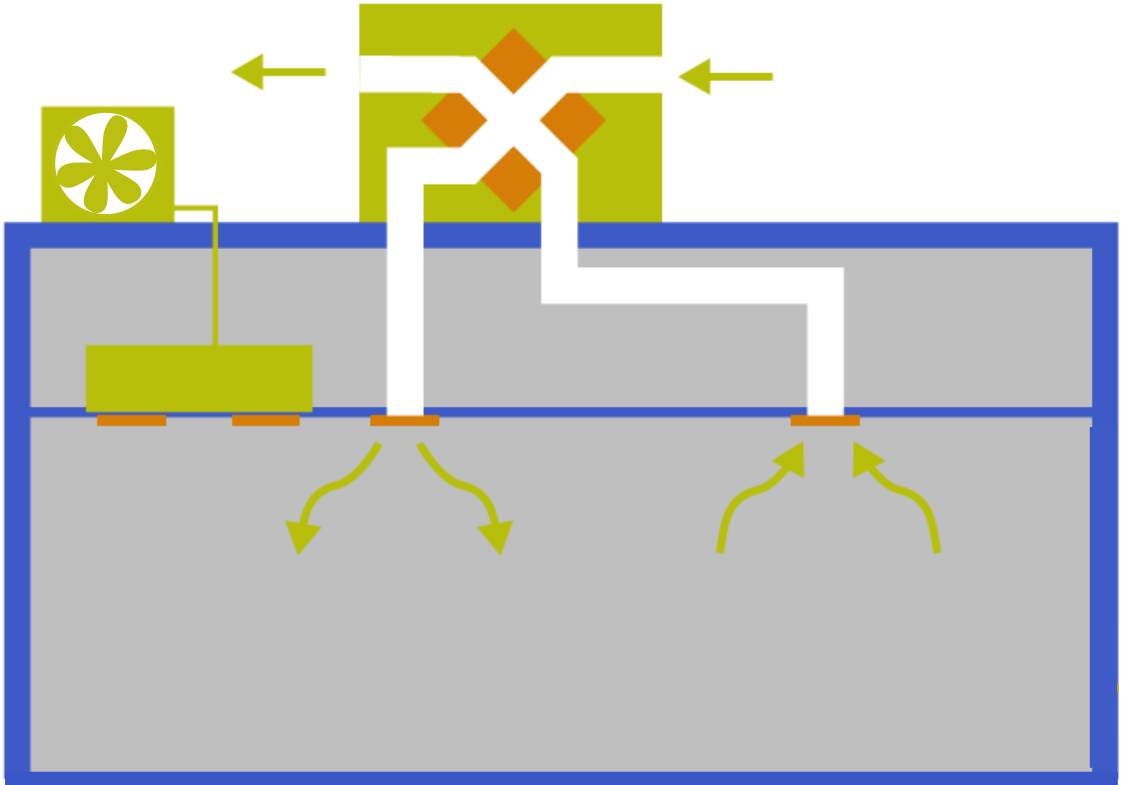
Sit-Down Restaurant Baseline

→ Rooftop Unit (RTU) with Gas-Fired Heating and DX Cooling; Kitchen Exhaust with 100% Outdoor Air Make-up



Sit-Down Restaurant Conversion

→ Dedicated Outdoor Air System (DOAS) with Heat Recovery Ventilation (HRV) and Zone-Level Heat Pumps; Kitchen Exhaust Heat Recovery

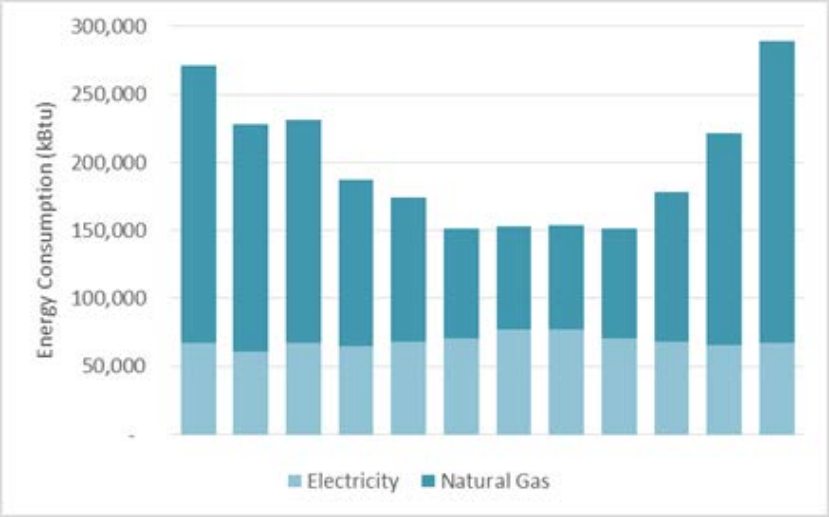


Prototype Modeling

→ Sit-Down Restaurant Prototype Results

Baseline

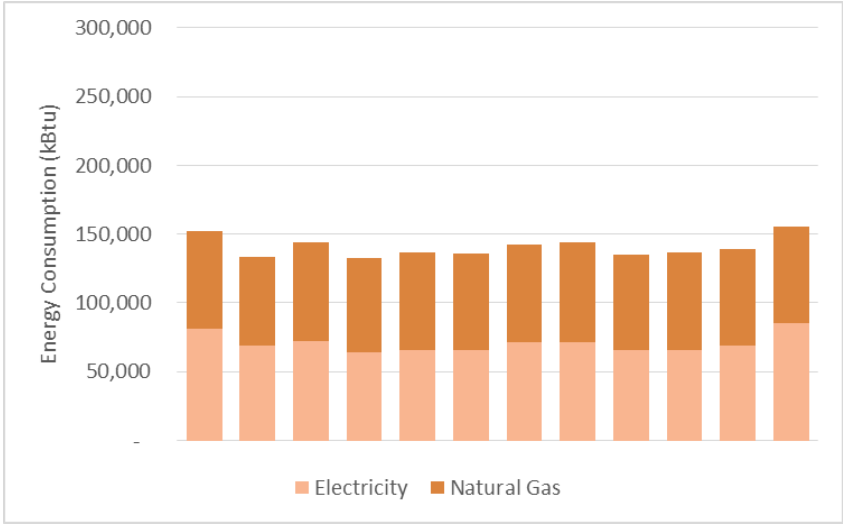
Annual Energy Consumption Profile



Whole building modeled EUI of **435 kBtu/ft²**.

Conversion

Annual Energy Consumption Profile



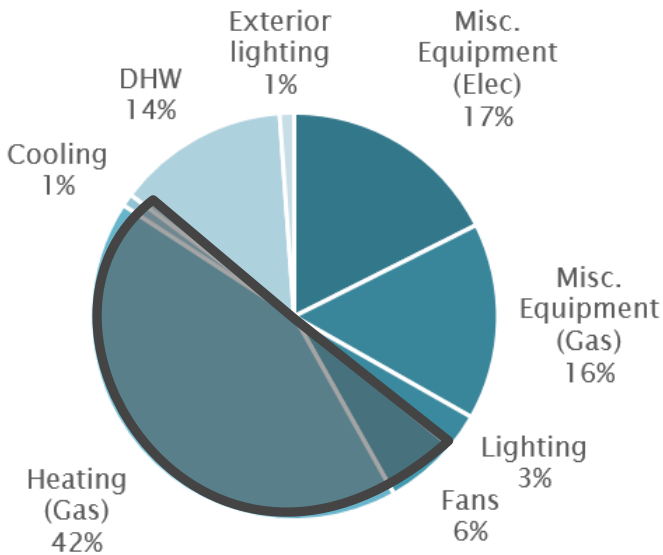
Whole building modeled EUI of **307 kBtu/ft²**. Results in **128 kBtu/ft² energy savings** over the baseline model.

Prototype Modeling

→ Sit-Down Restaurant Prototype Results

Baseline

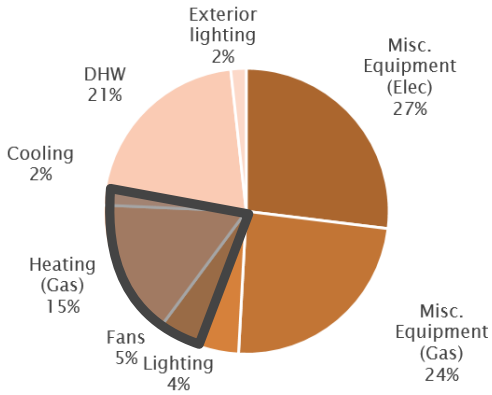
Annual Energy Consumption Profile



HVAC systems represent **39%** or **169 kBtu/ft²** of the overall energy use.

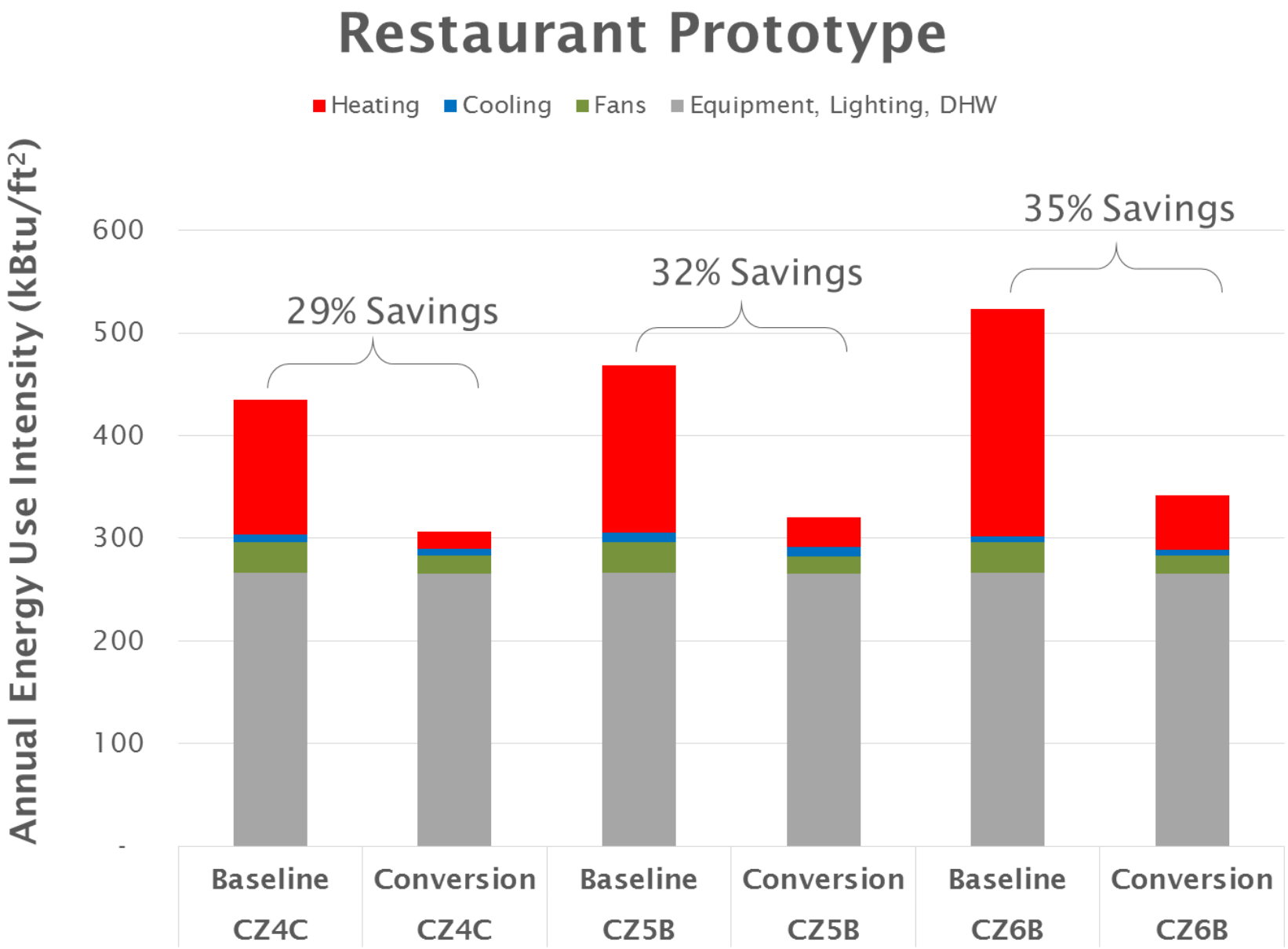
Conversion

Annual Energy Consumption Profile



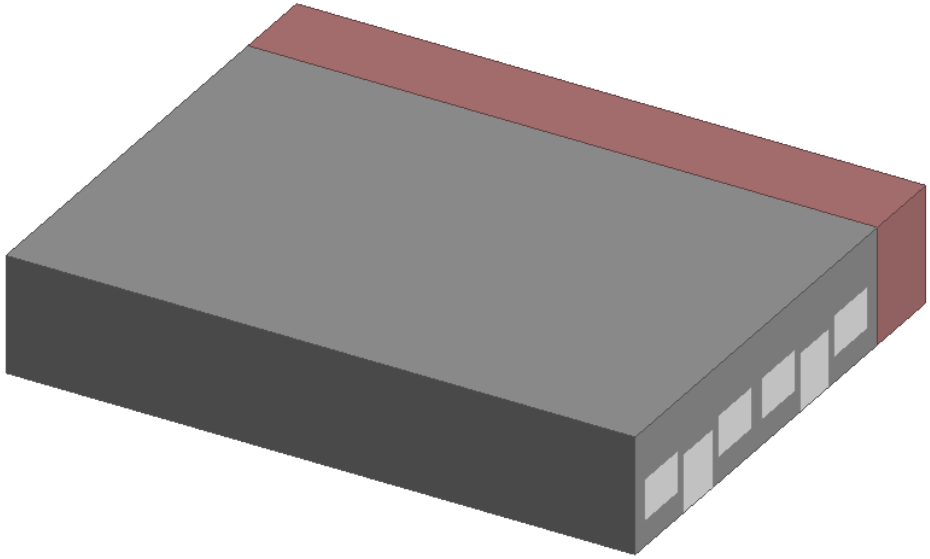
HVAC systems represent **13%** or **41 kBtu/ft²** of the overall energy use.

Prototype Modeling



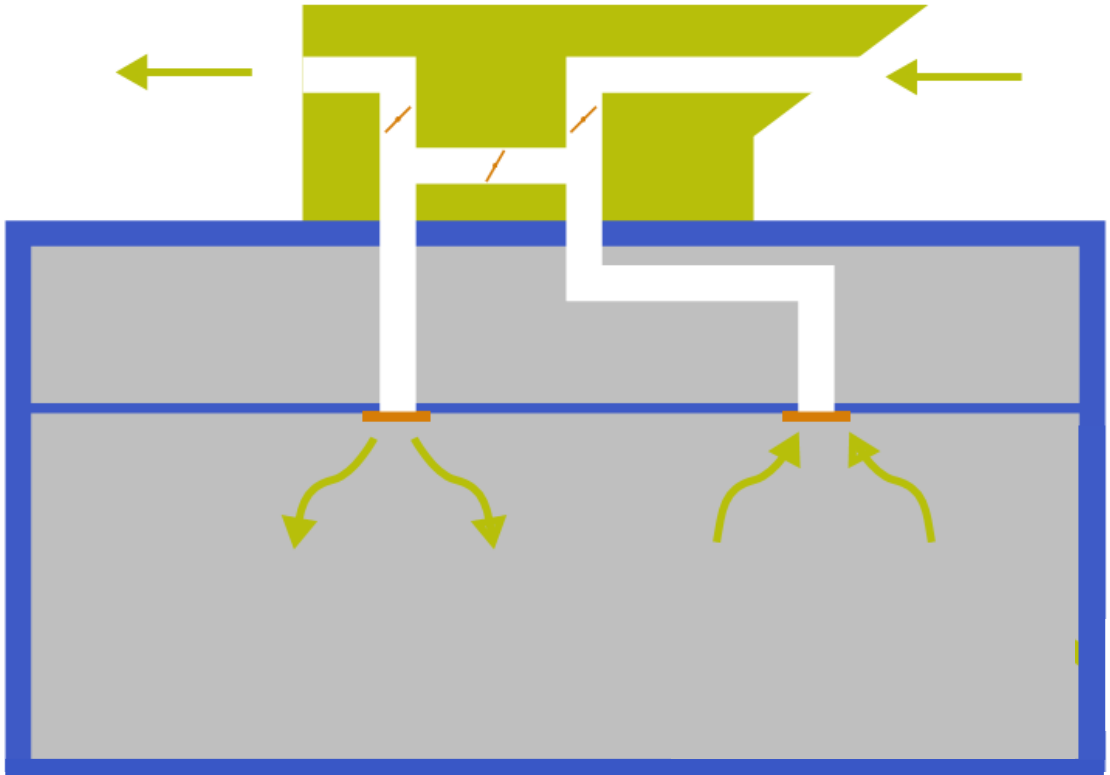
Prototype Modeling

- Retail
  - 3,750 ft^2
  - End unit of strip mall
  - 100% retail space



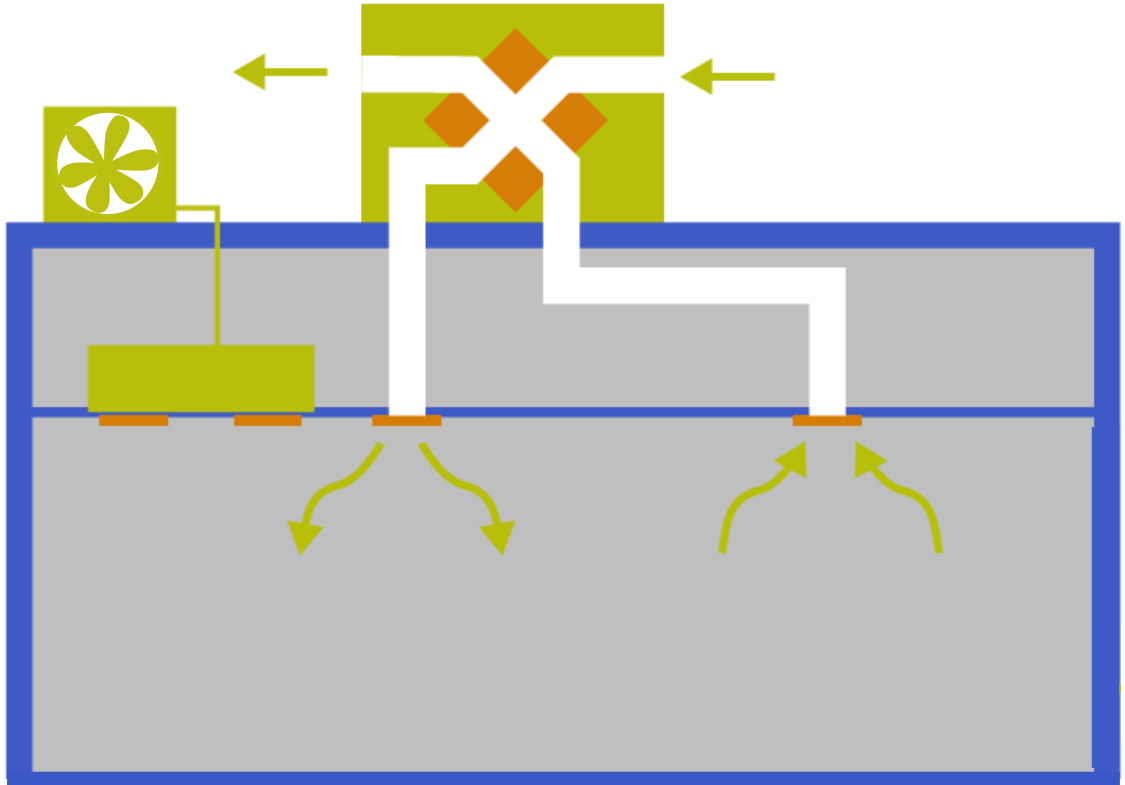
Retail Baseline

→ Rooftop Unit (RTU) with Gas-Fired Heating and DX Cooling



Retail Conversion

→ Dedicated Outdoor Air System (DOAS) with Heat Recovery Ventilation (HRV) and Zone-Level Heat Pumps

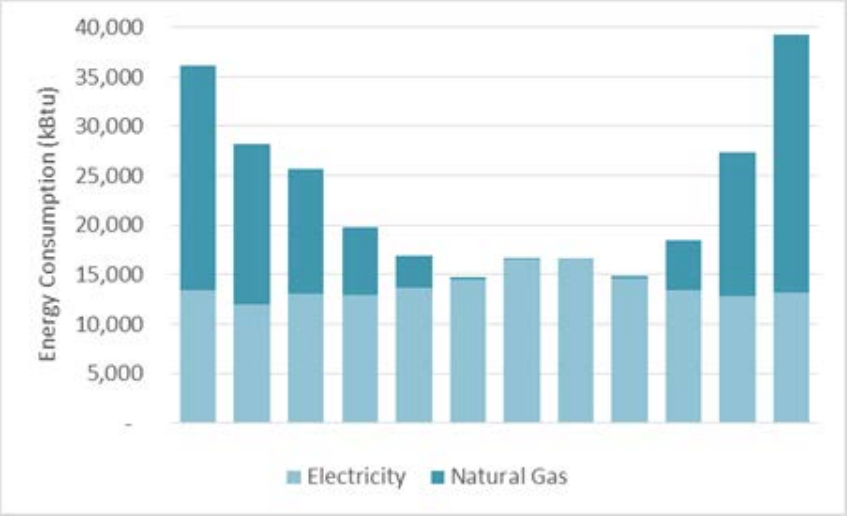


Prototype Modeling

→ Retail Prototype Results

Baseline

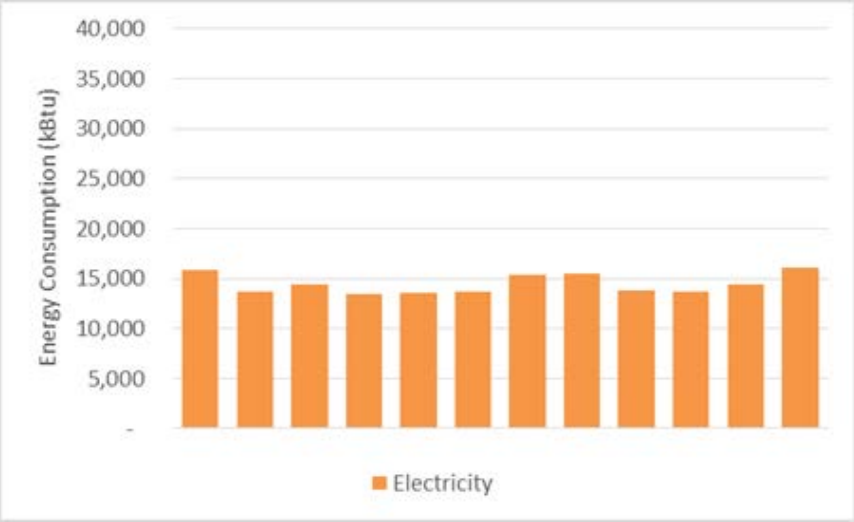
Annual Energy Consumption Profile



Whole building modeled EUI of **71 kBtu/ft²**.

Conversion

Annual Energy Consumption Profile



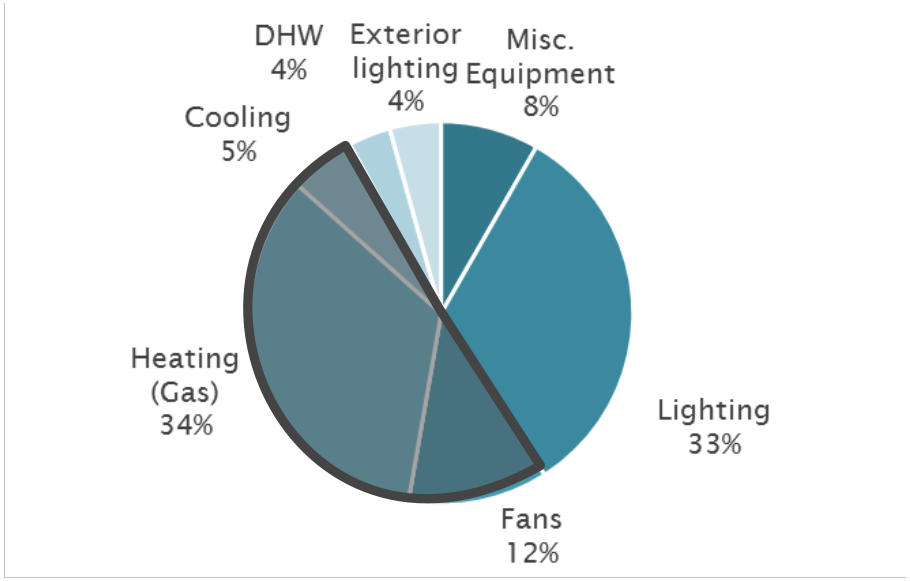
Whole building modeled EUI of **44 kBtu/ft²**. Results in **27 kBtu/ft² energy savings** over the baseline model.

Prototype Modeling

→ Retail Prototype Results

Baseline

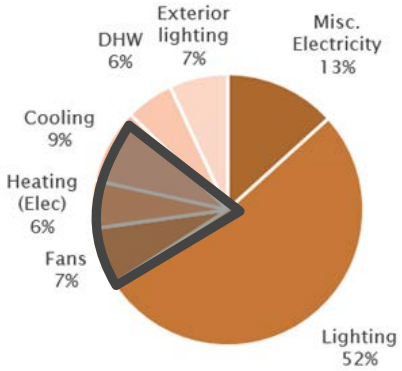
Annual Energy Consumption Profile



HVAC systems represent **52%** or **37 kBtu/ft²** of the overall energy use.

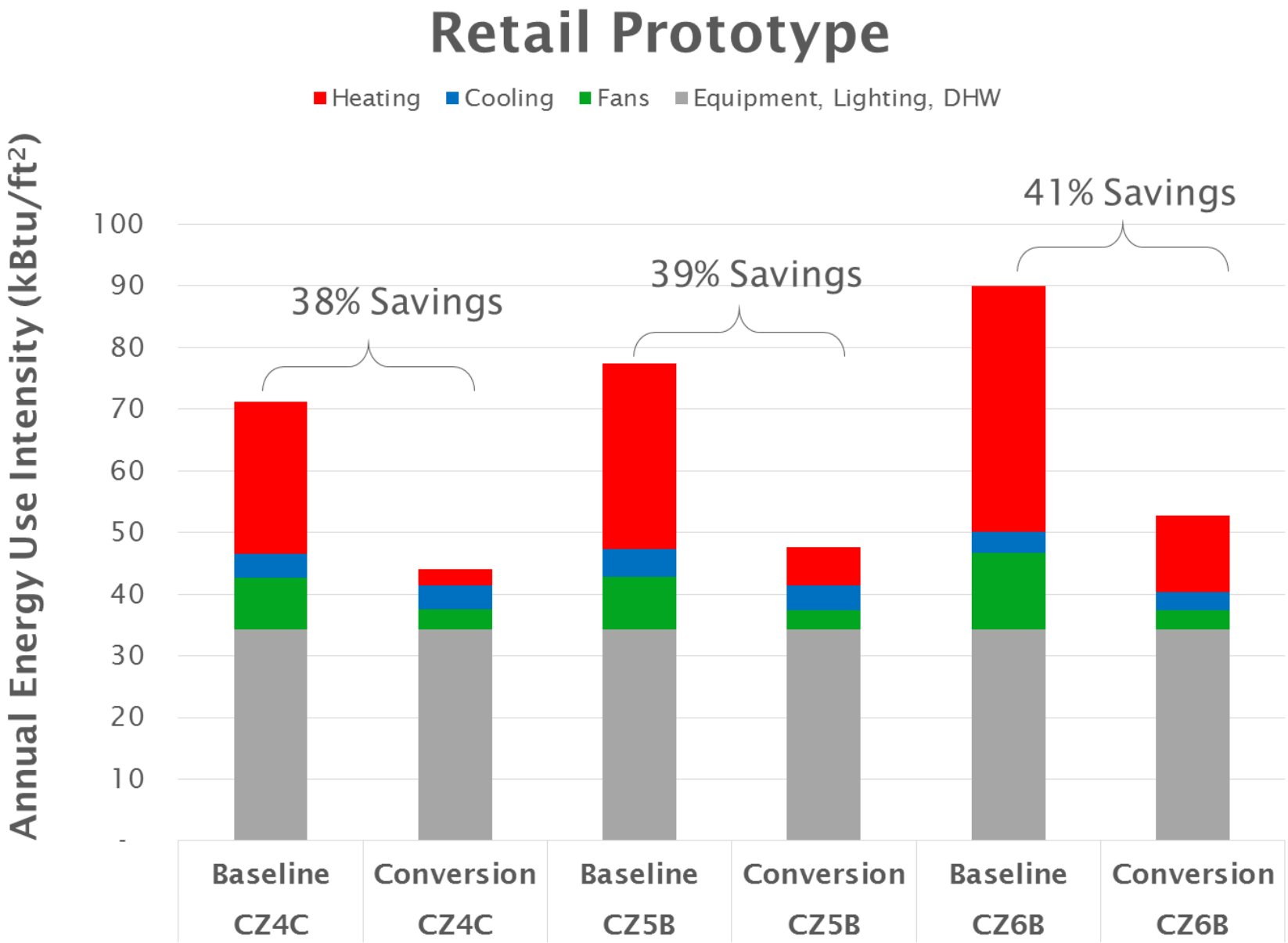
Conversion

Annual Energy Consumption Profile



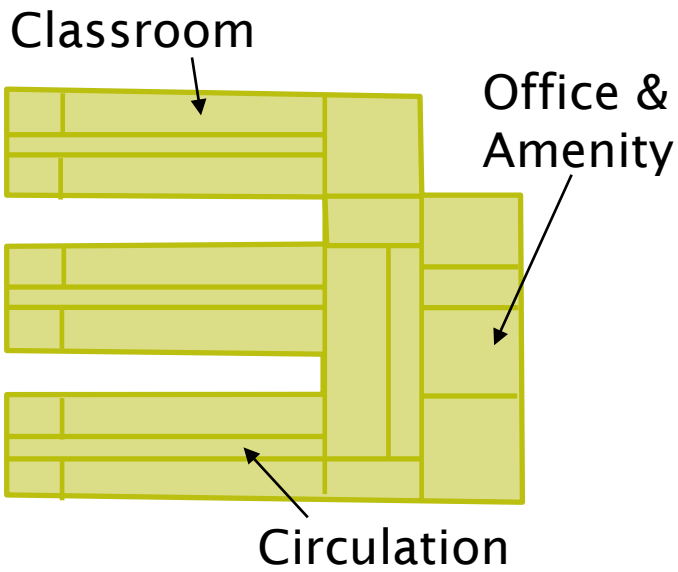
HVAC systems represent **22%** or **10 kBtu/ft²** of the overall energy use.

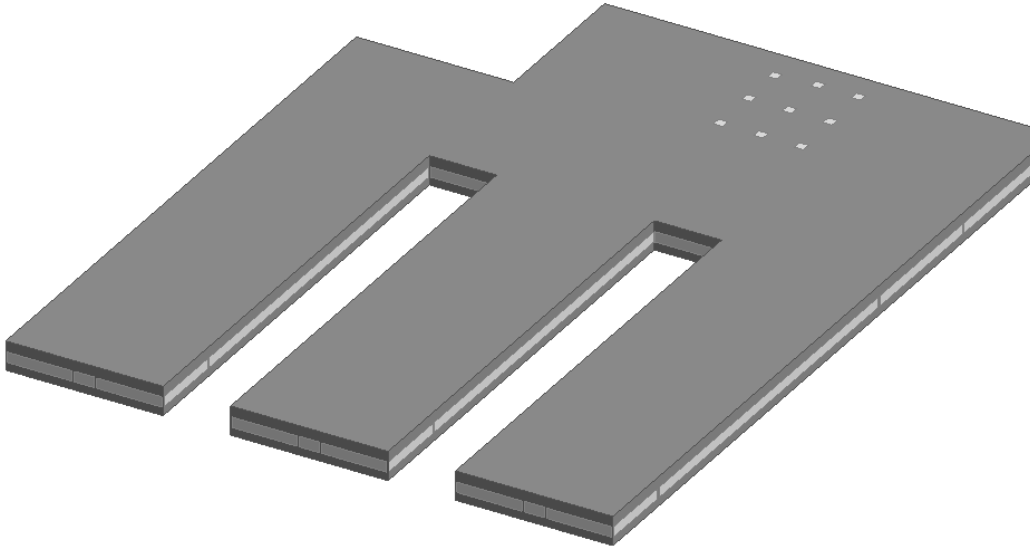
Prototype Modeling



Prototype Modeling

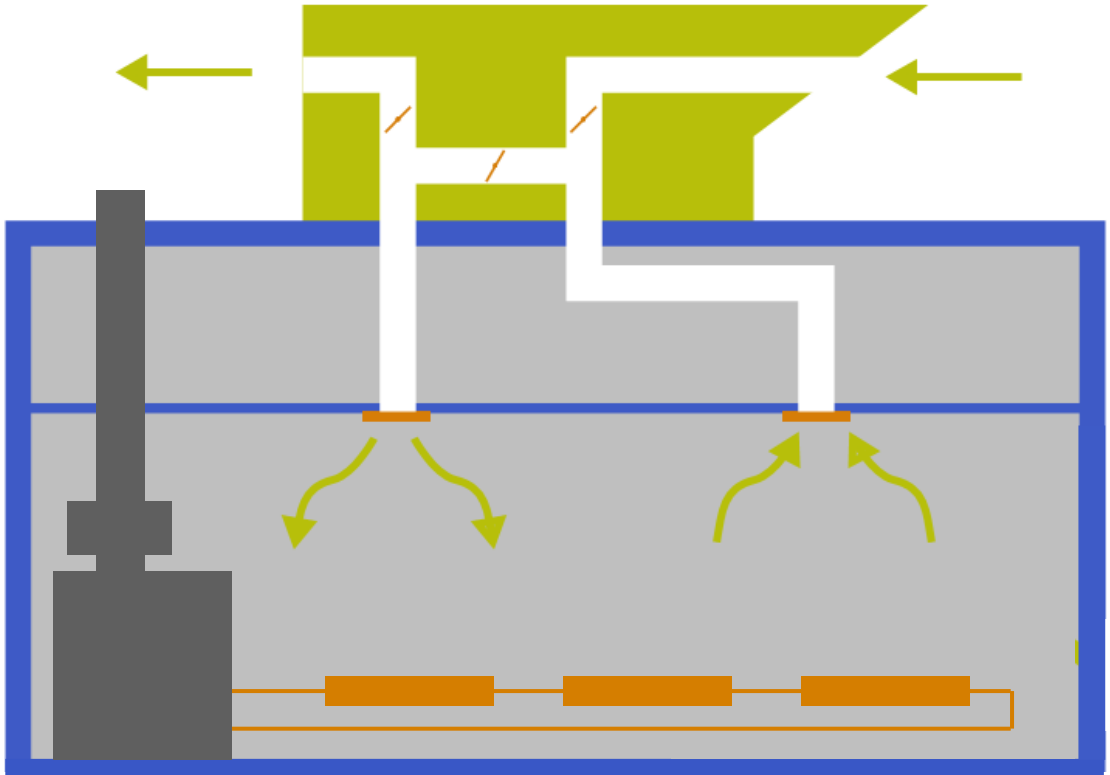
- Primary School
  - 74,600 ft^2
  - Includes classrooms (50%), office & amenity (27%), and circulation and service areas (23%)





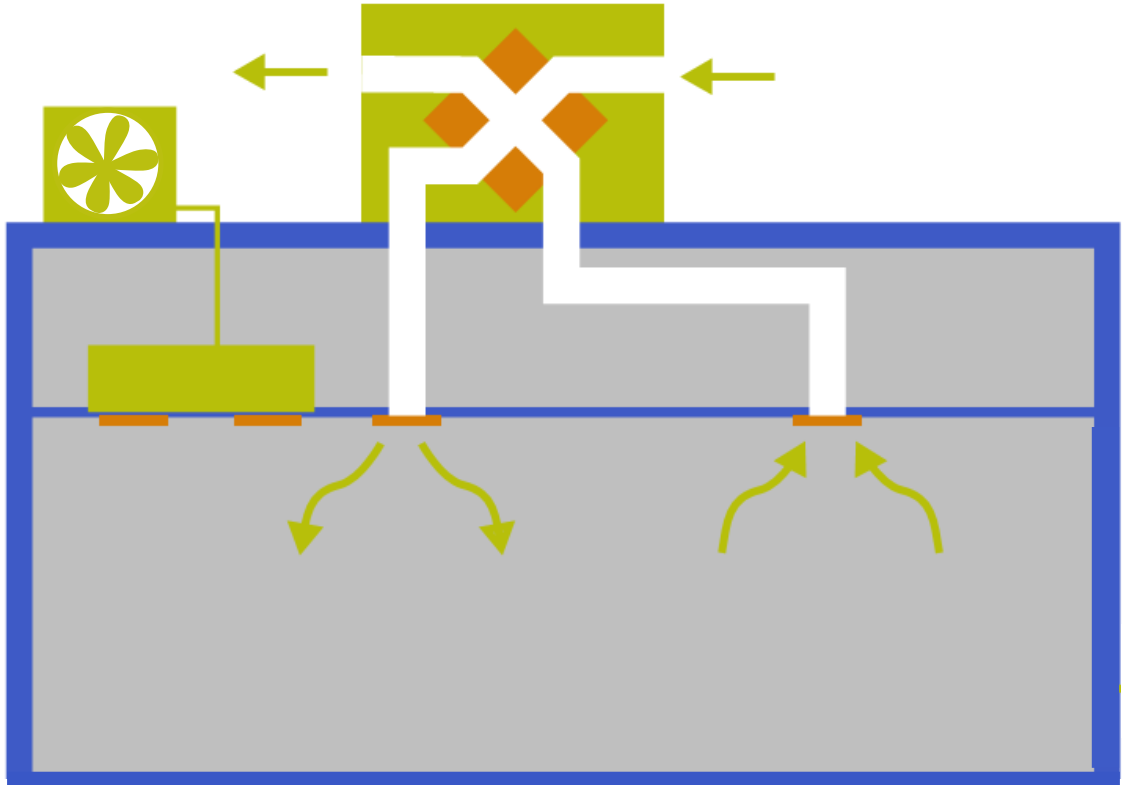
Primary School Baseline

→ Gas-Fired Boiler, Rooftop Unit (RTU) with Hydronic Heating and DX Cooling, and Zone-Level Hydronic Re-Heating



Primary School Conversion

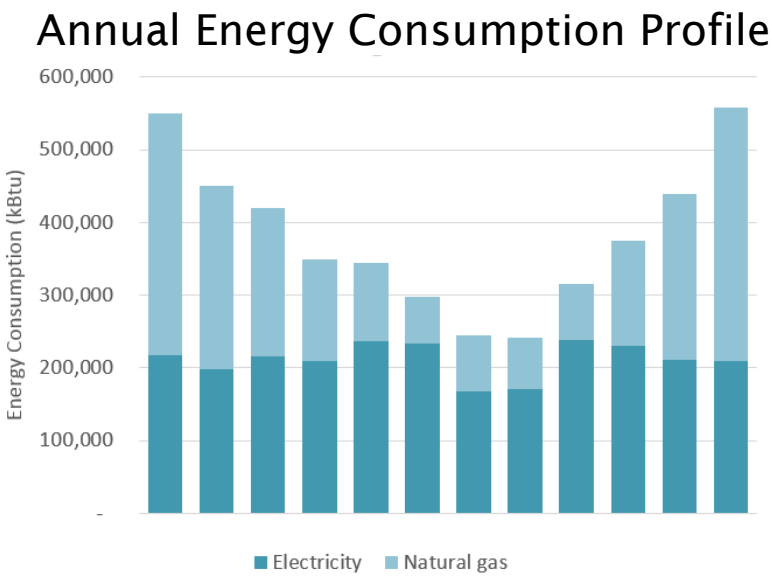
→ Dedicated Outdoor Air System (DOAS) with Heat Recovery Ventilation (HRV) and Zone-Level Heat Pumps



Prototype Modeling

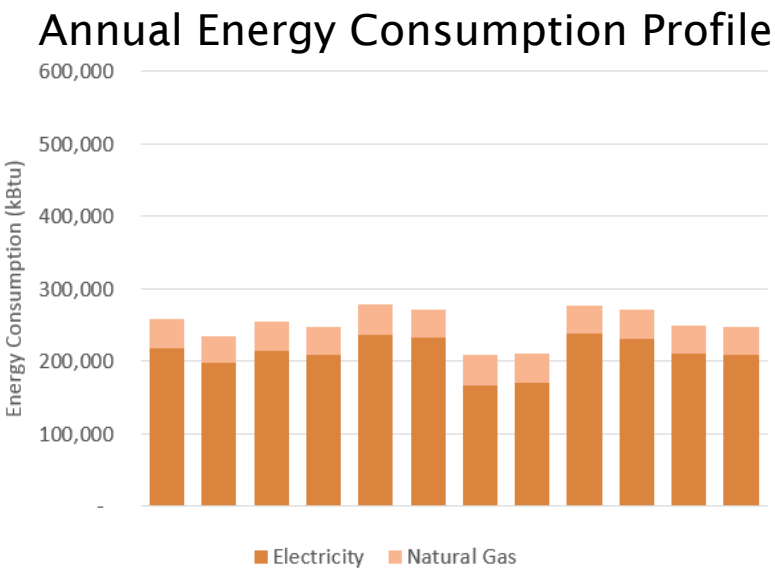
→ Primary School Prototype Results

Baseline



Whole building modeled EUI of **61 kBtu/ft²**.

Conversion



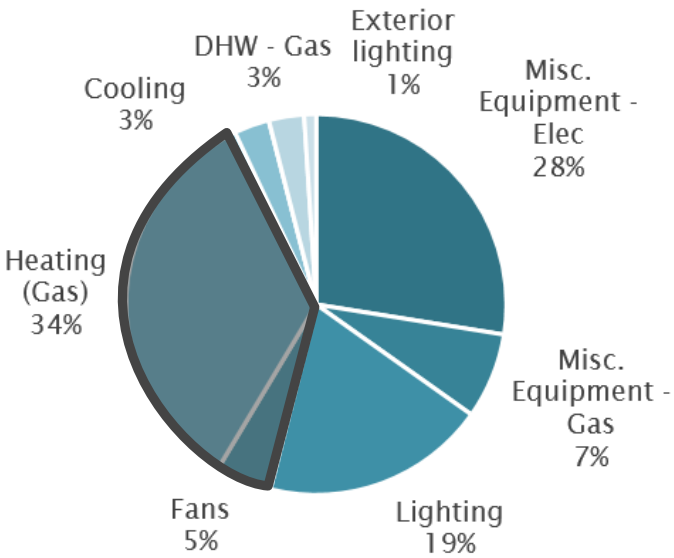
Whole building modeled EUI of **41 kBtu/ft²**. Results in **20 kBtu/ft² energy savings** over the baseline model.

Prototype Modeling

→ Primary School Prototype Results

Baseline

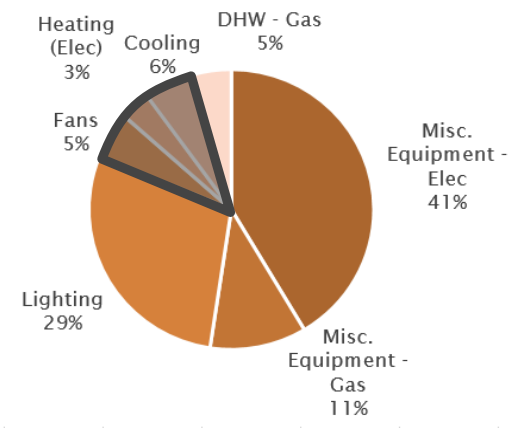
Annual Energy Consumption Profile



HVAC systems represent **42%** or **26 kBtu/ft²** of the overall energy use.

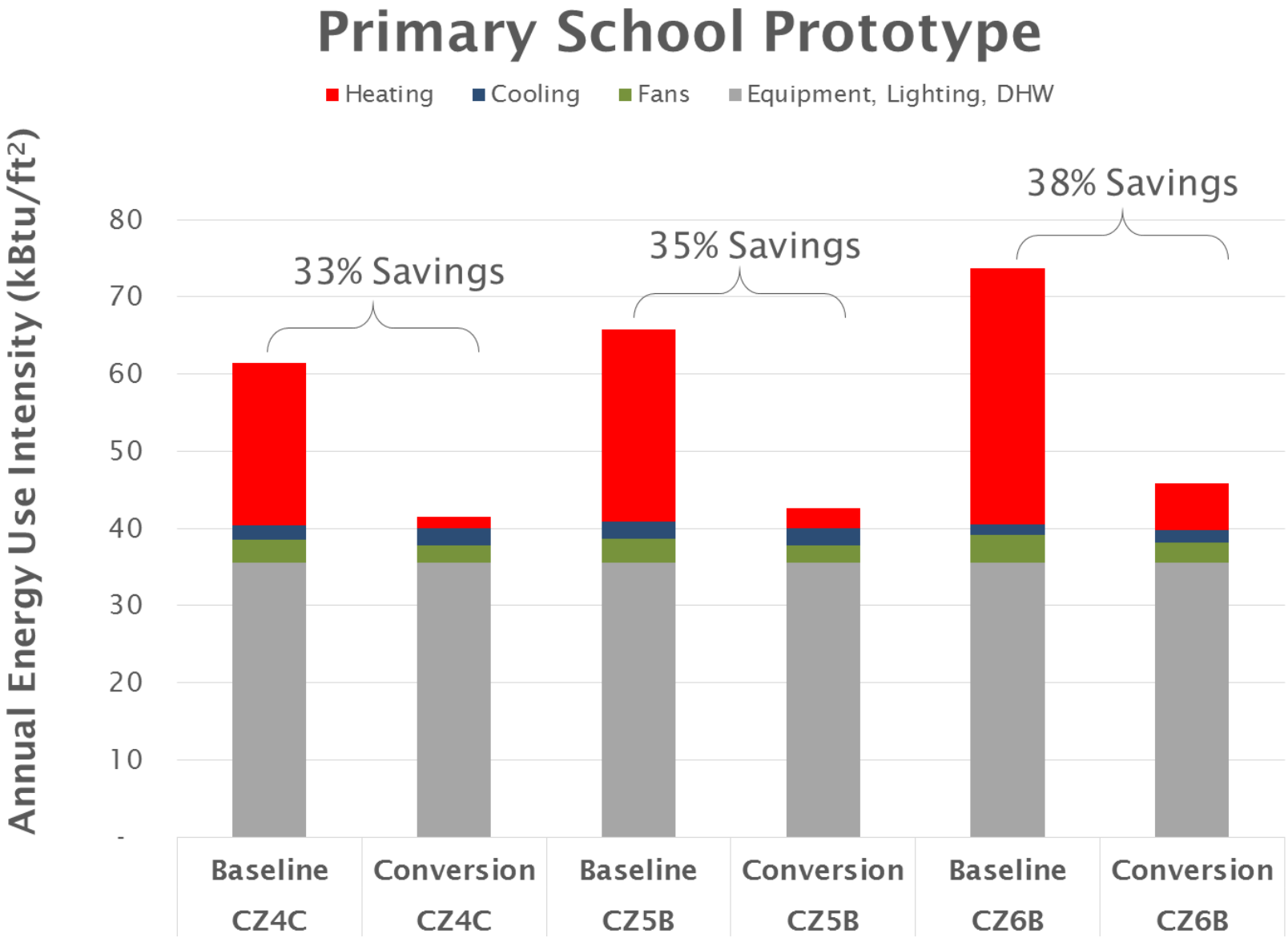
Conversion

Annual Energy Consumption Profile



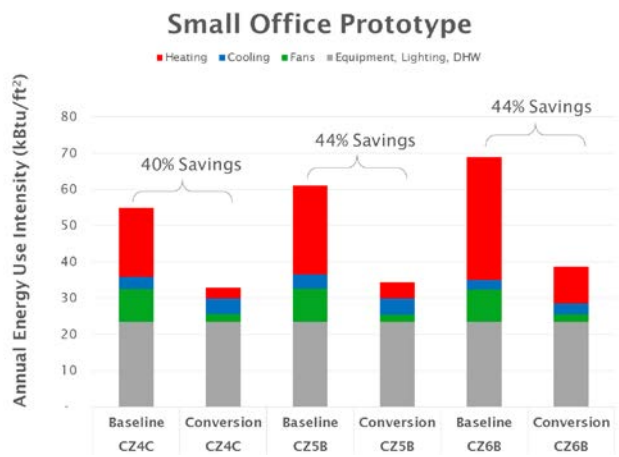
HVAC systems represent **14%** or **6 kBtu/ft²** of the overall energy use.

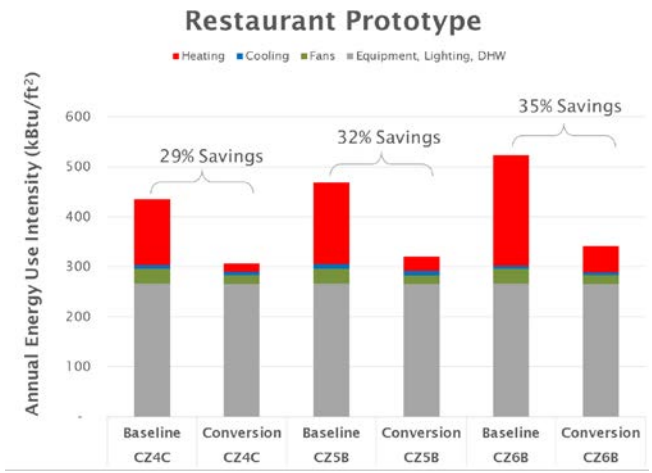
Prototype Modeling

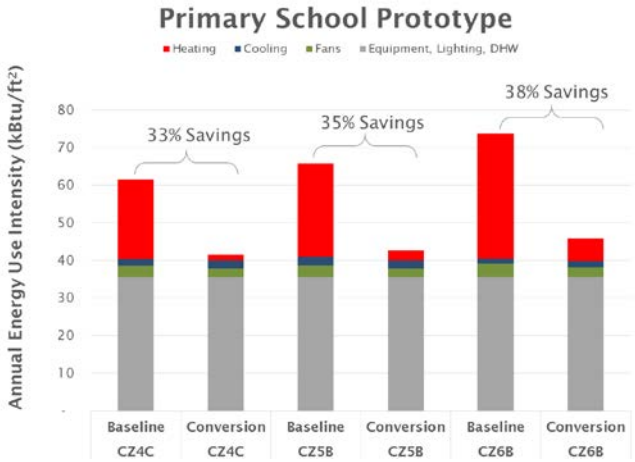


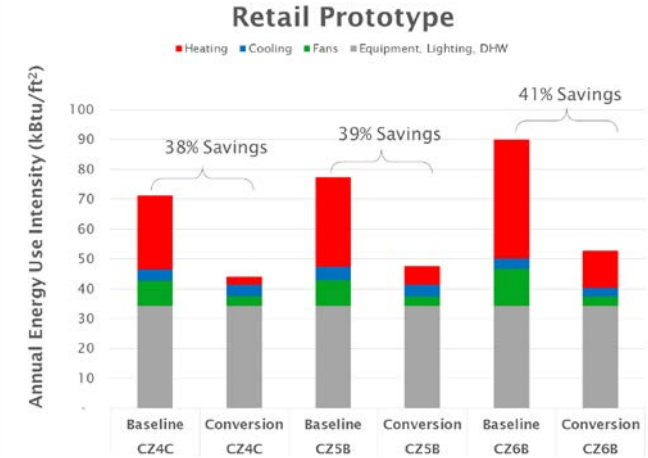
Prototype Modeling

→ 30% to 40% predicted whole building savings for DOAS conversion





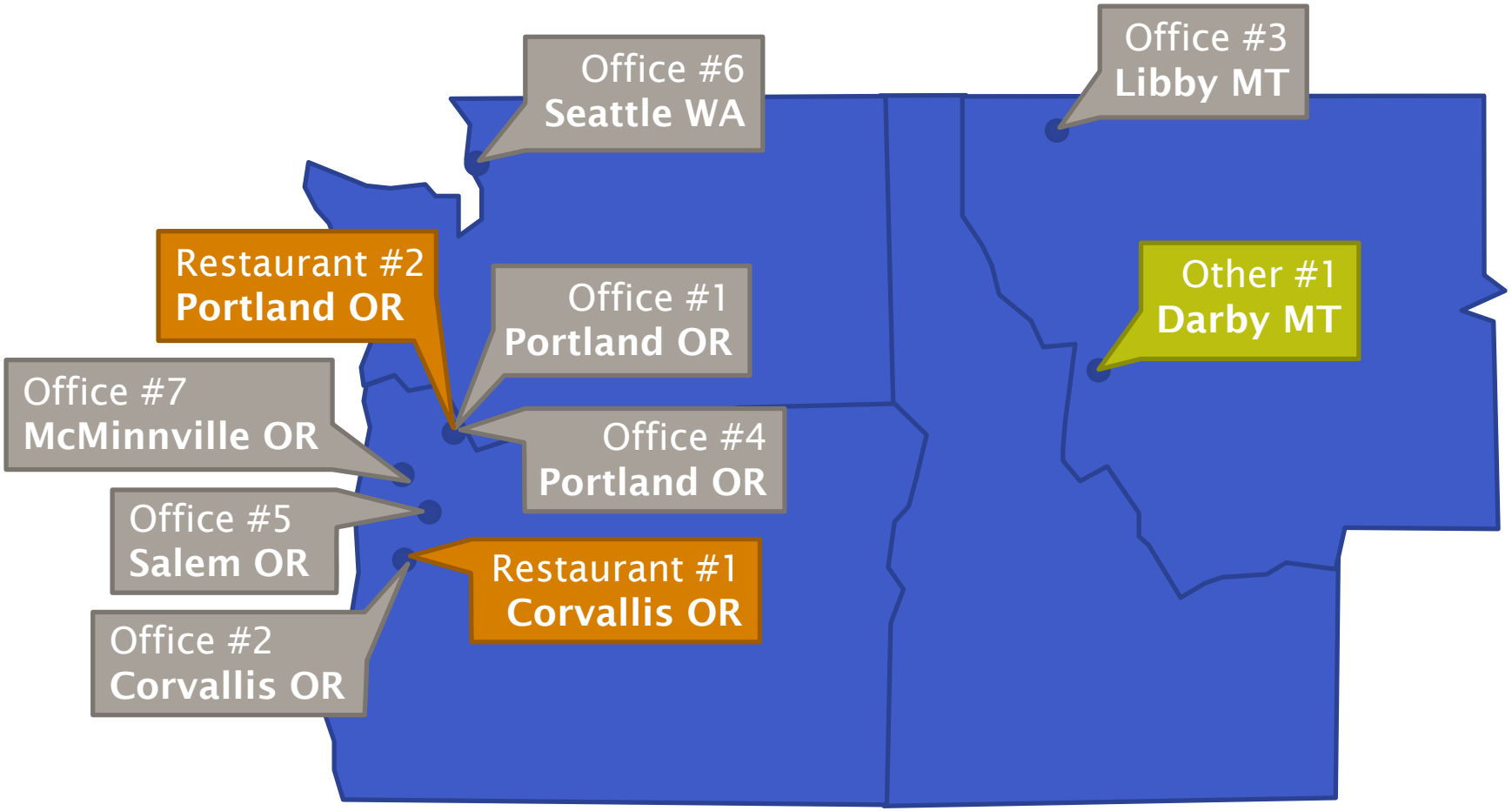




Pilot Projects

Pilot Projects

→ 10 pilot projects to date



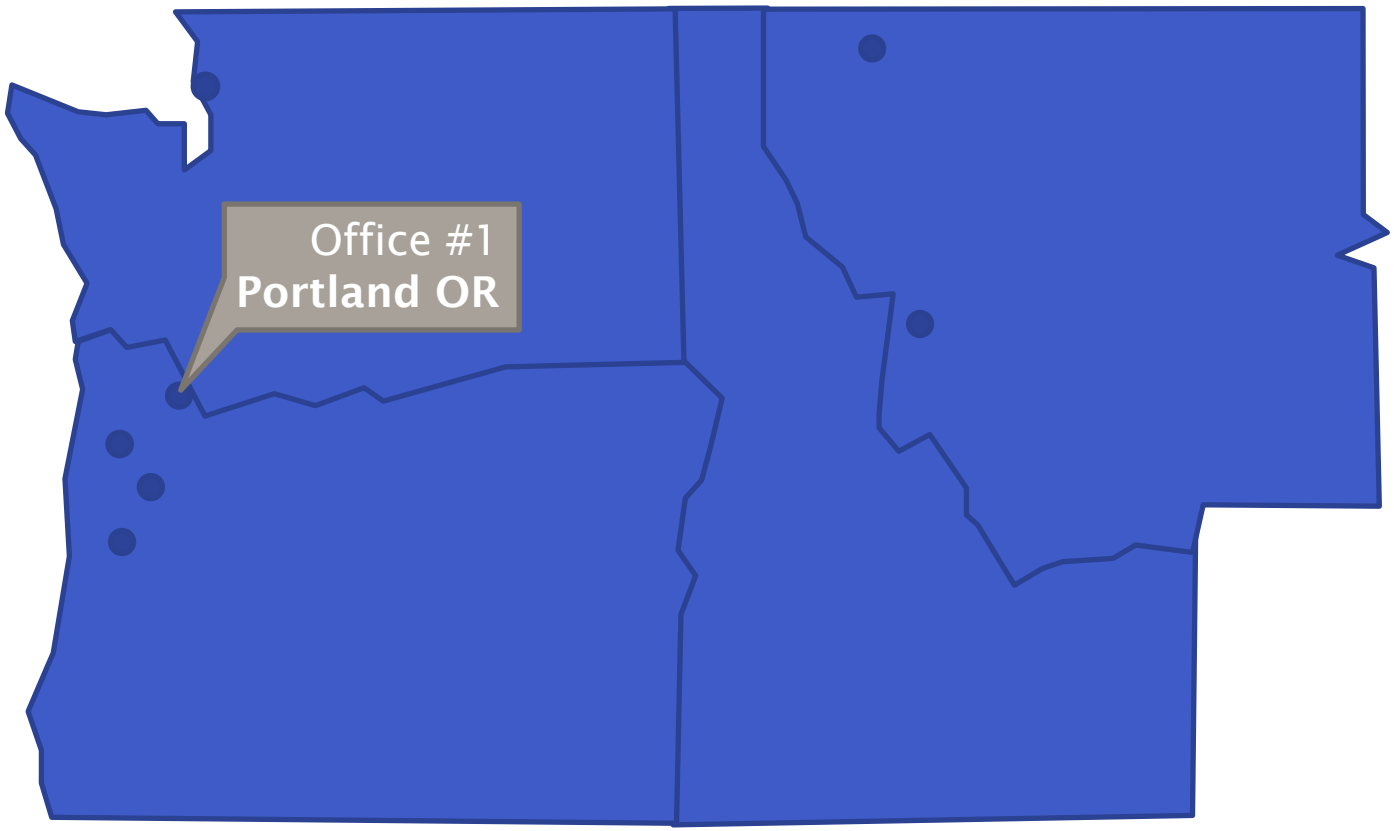
Pilot Projects

RDH

- Highlight first pilot projects
  - Office 1, Portland OR
  - Office 2, Corvallis, OR
  - Office 3, Libby, MT
  - Restaurant 1, Corvallis, OR

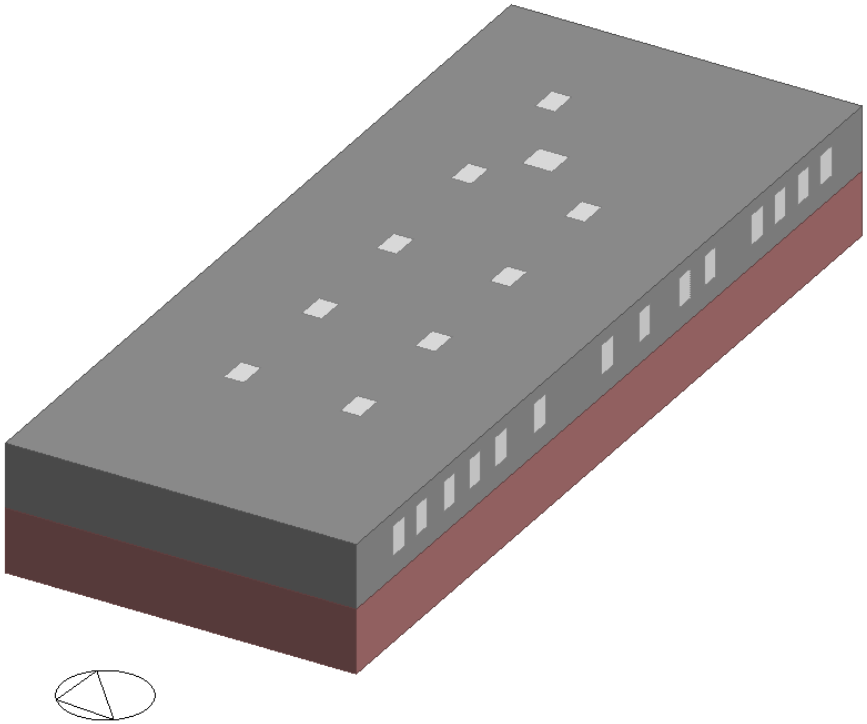
- Progress report
- General lessons learned to reconcile energy model and in-service energy performance

Pilot Projects

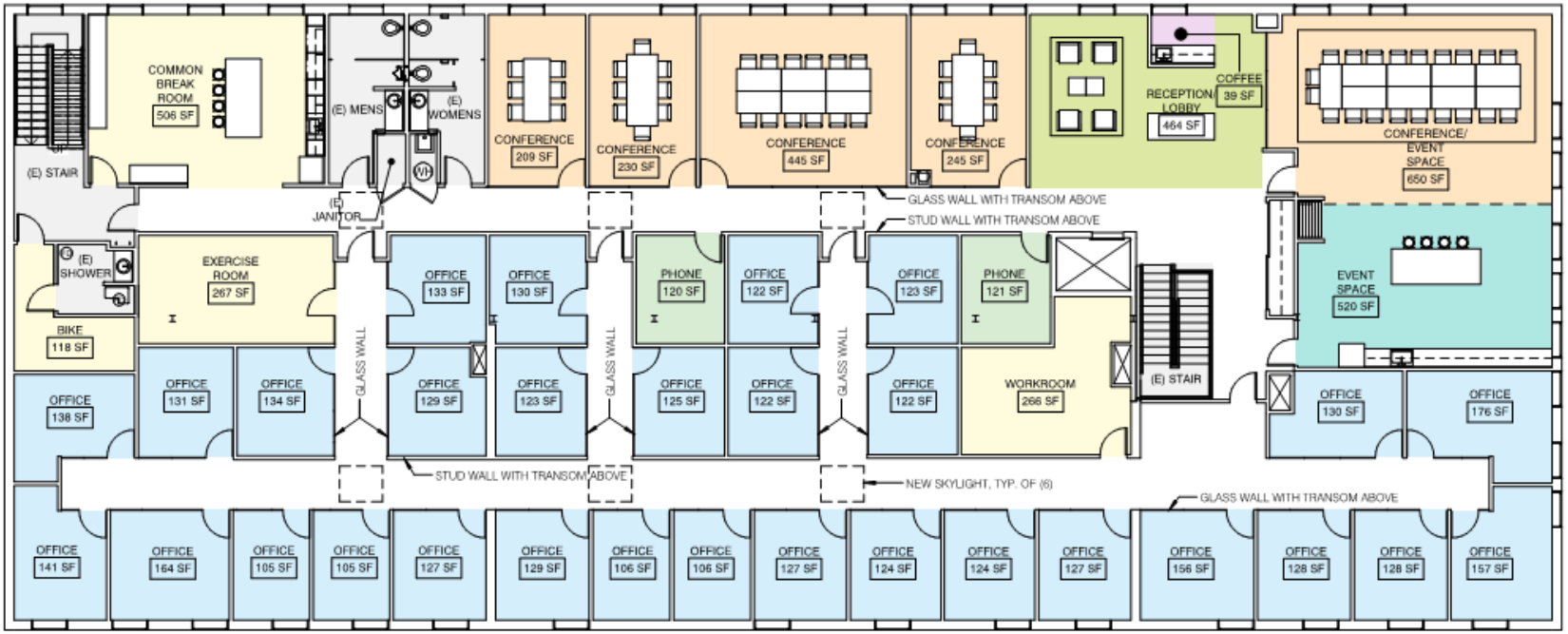


Pilot Projects

- → **Office 1**
- → Existing heritage building
- → Second floor of a 2 storey building
- → Private offices
- → Intermittent occupancy in meeting and conference rooms
- → Monday through Friday day time operation



Pilot Project



Pilot Project

RDH

- → **Office 1**
- → Baseline
  - → 9 RTUs, total 35 tons cooling, 650,000 Btu/h heating
- → Conversion
  - → 4 HRVs
  - → 8 zone-level VRF fan coil units, tons cooling, 215,000 Btu/h heating


Weathermaker
AC 7
FILTER SECTION

Pilot Project

RDH

- **Office 1**
- Pre-Conversion Air Leakage Testing
  - Air Leakage Test Result: 0.616 cfm/ft^2 at 75 Pa
    - Air leakage noted at operable windows, HVAC dampers, and mechanical chases between floors.

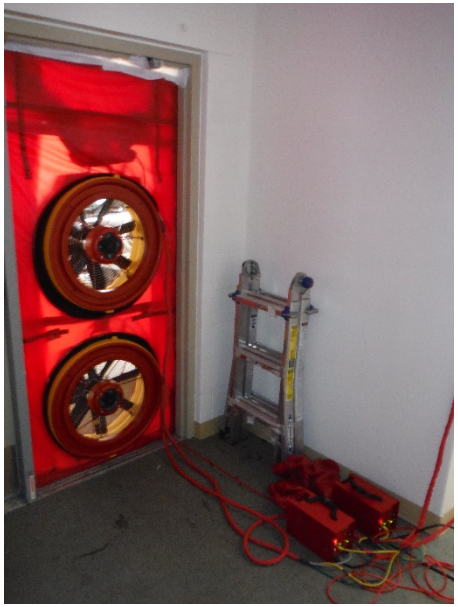
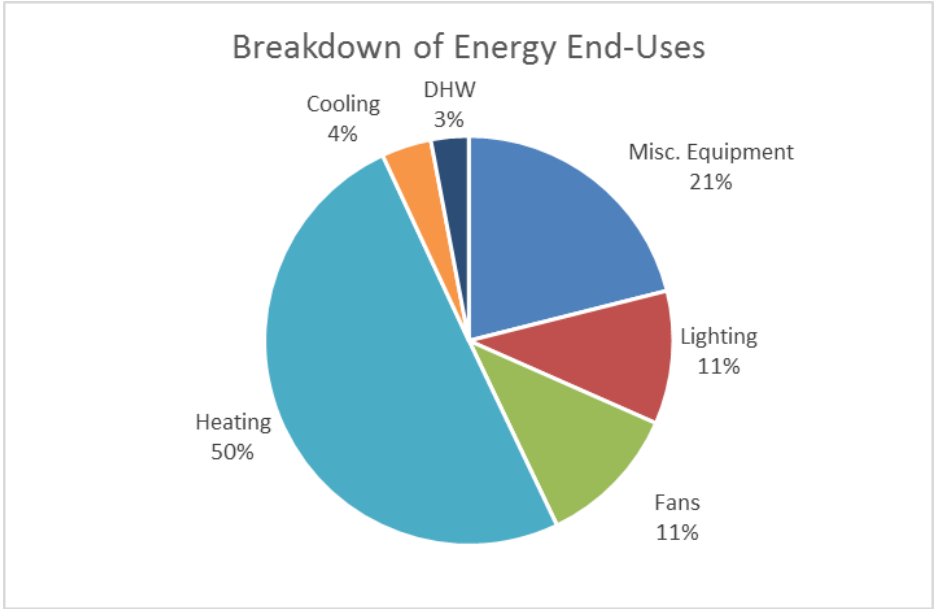
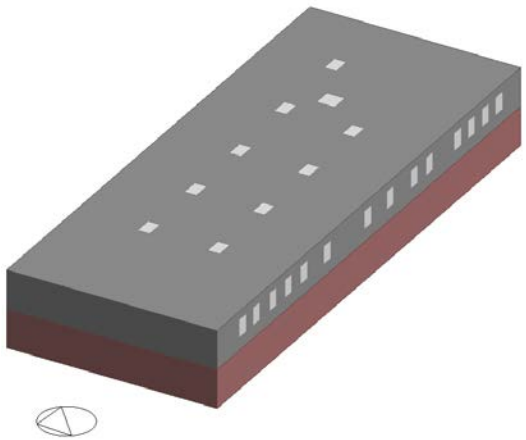


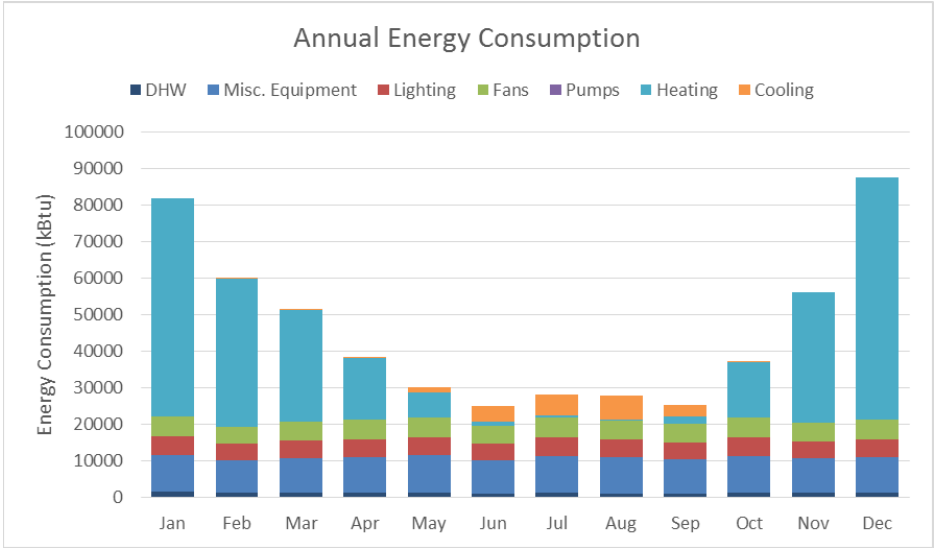
TABLE 1– SUMMARY OF AIR LEAKAGE TEST RESULTS			
Test Condition	Depressurize	Pressurize	Average
Enclosure Airtightness [cfm/ft^2@75Pa]	0.615	0.617	0.616
Equivalent Leakage Area [ft^2 @ 75Pa]	14.9	15.0	14.95
Air Changes [per Hour @ 50Pa]	5.71	5.84	5.77
Air Leakage Test Coefficient (C) [cfm/Pa^n]	1431.3	1761.1	N/A
Flow Exponent (n) [dimensionless]	0.611	0.564	N/A
Squared Correlation Coefficient (r^2) [dimensionless]	0.9964	0.9977	N/A

Pilot Project

- → **Office 1**
- → Preliminary baseline modeling results
  - → EUI 51 kBtu/ft^2








FRONT
35
44

Pilot Project

RDH

- → **Office 1**
- → Post-Conversion Air Leakage Testing
  - → Air Leakage Test Result: 0.506 cfm/ft^2 at 75 Pa

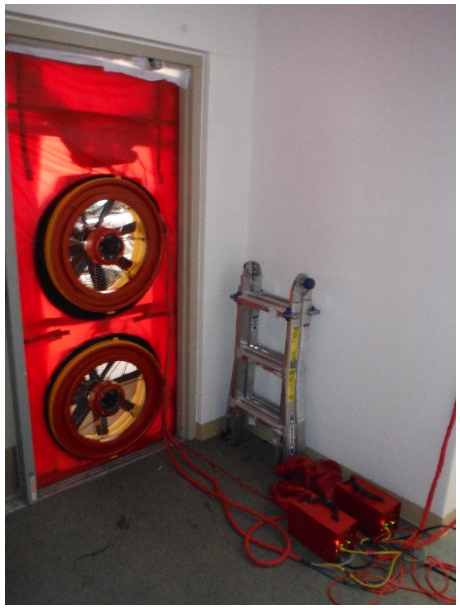
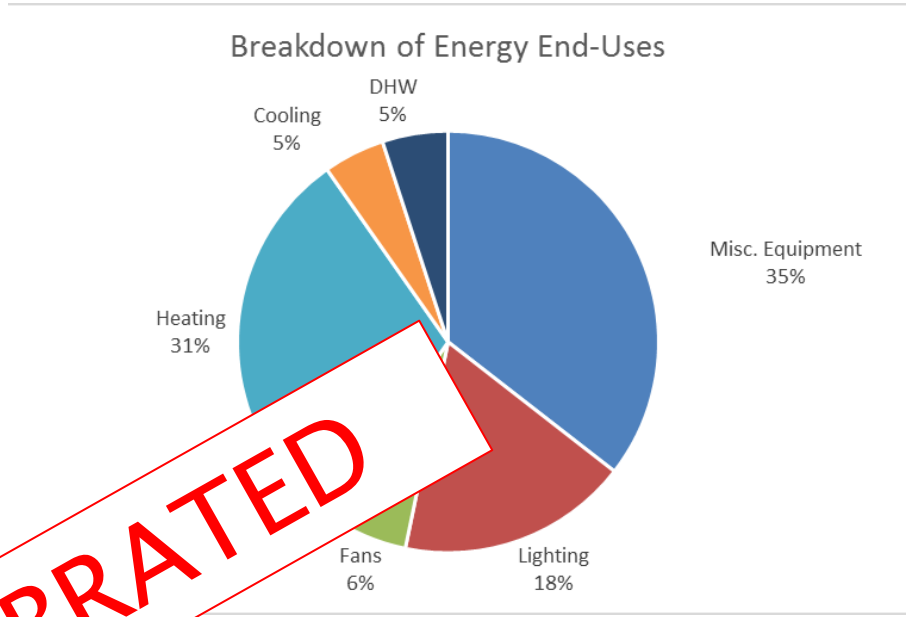


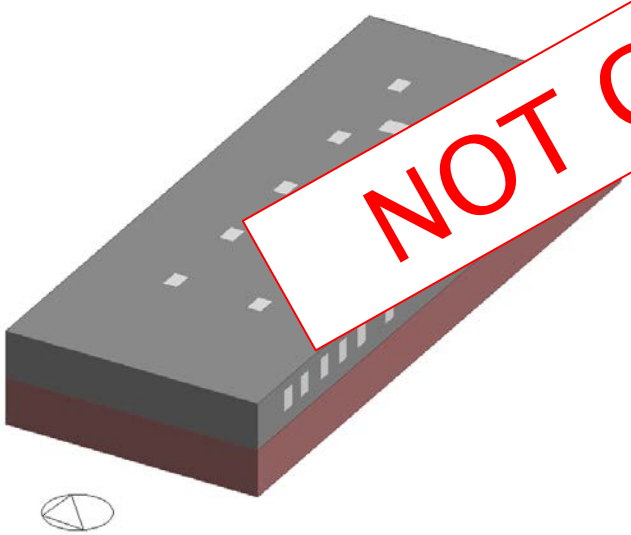
TABLE 1 – SUMMARY OF AIR LEAKAGE TEST RESULTS			
Test Condition	Depressurize	Pressurize	Average
Enclosure Airtightness [cfm/ft^2@75Pa]	0.481	0.531	0.506
Equivalent Leakage Area [ft^2 @ 75Pa]	11.87	12.72	12.30
Air Changes [per Hour @ 50Pa]	4.53	4.96	4.74
Air Leakage Test Coefficient (C) [cfm/Pa^n]	1299.4	1306.5	N/A
Flow Exponent (n) [dimensionless]	0.577	0.598	N/A
Squared Correlation Coefficient (r^2) [dimensionless]	0.9956	0.9980	N/A

Pilot Project

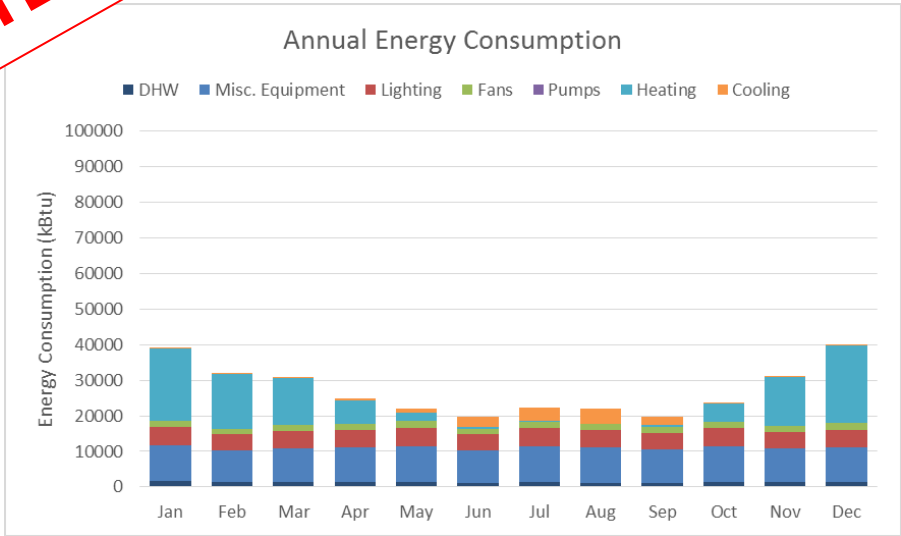
RDH

- **Office 1**
- Preliminary DOAS conversion modeling results
  - EUI 30 kBtu/ft^2
  - ~ 40% savings





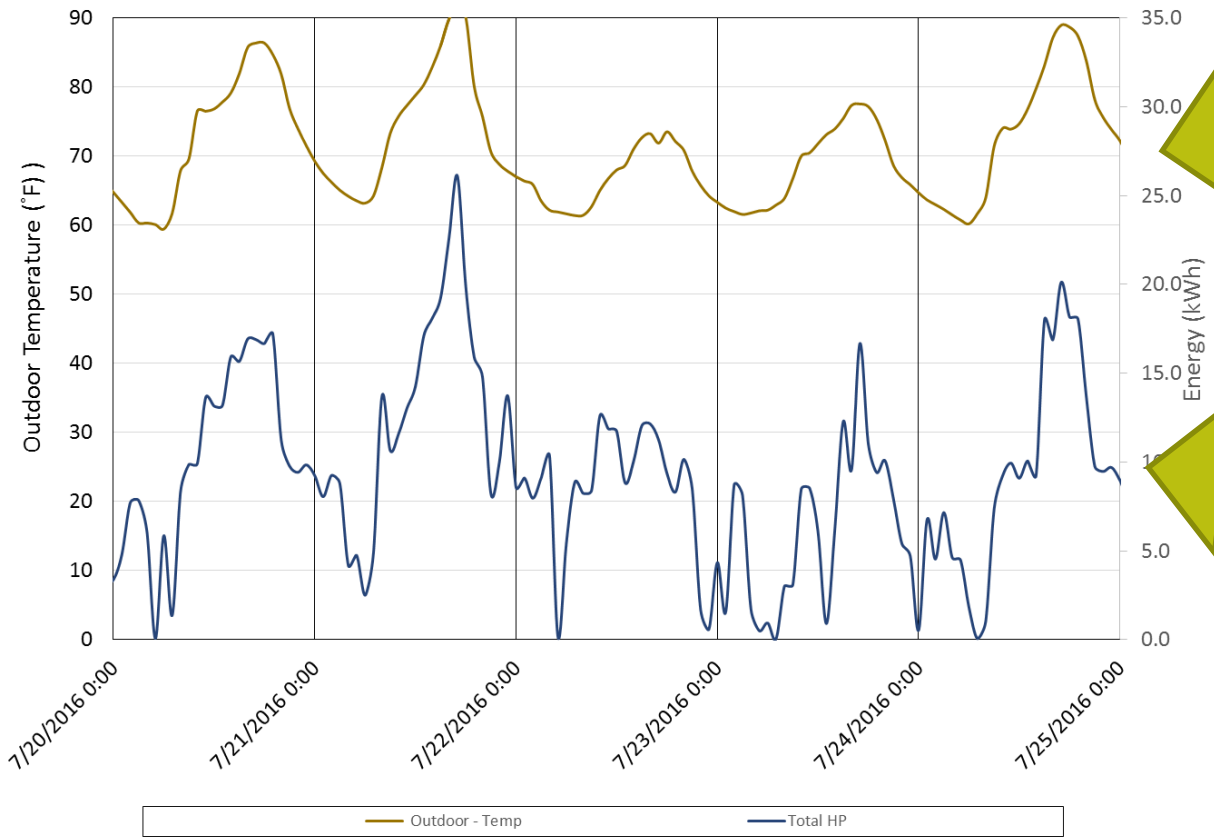
NOT CALIBRATED



Pilot Project

→ **Office 1**

→ Preliminary Monitoring Data



Outdoor Air Temperature

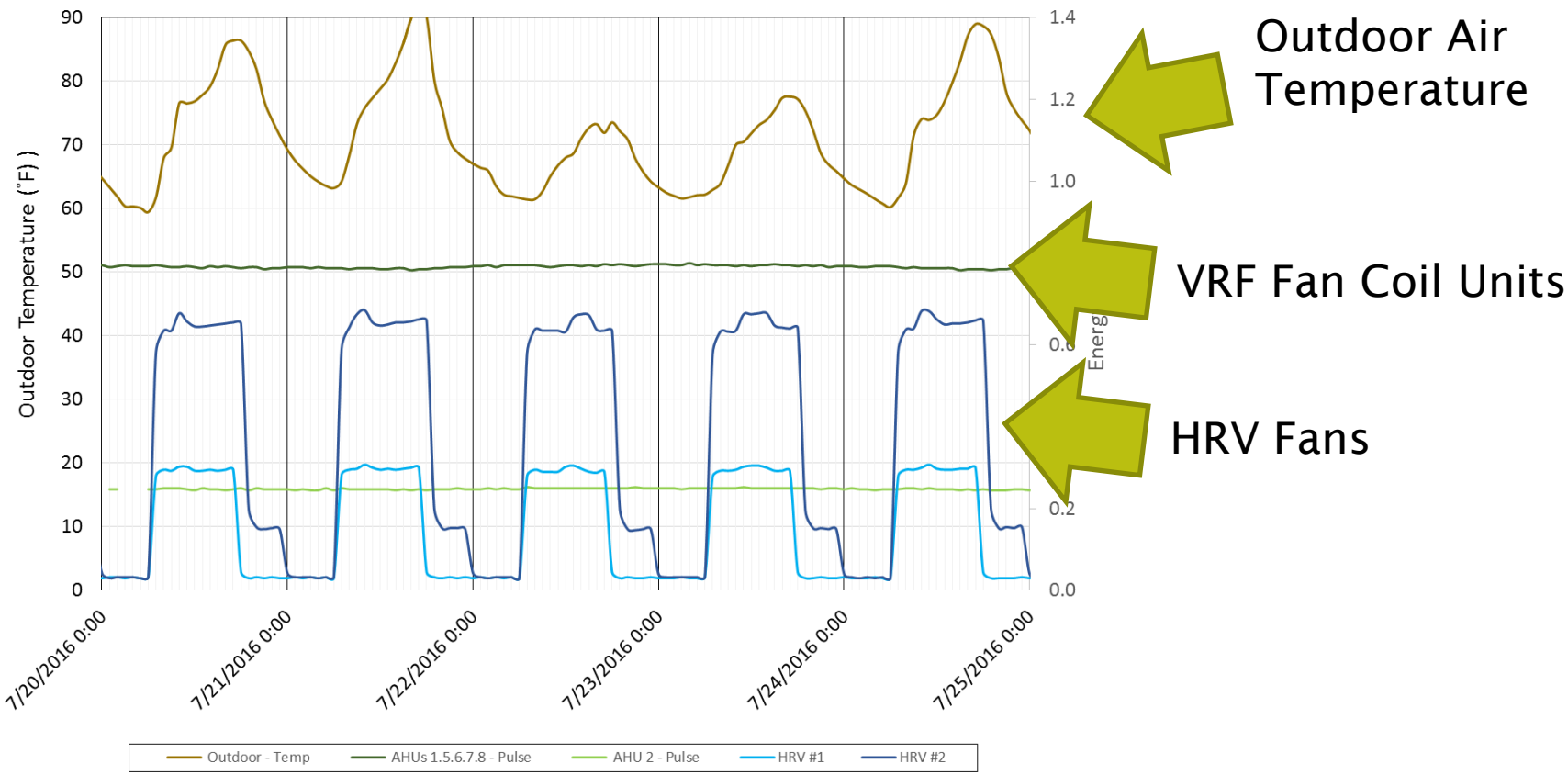
Heat Pump Energy

(Cooling Mode)

Pilot Project

→ **Office 1**

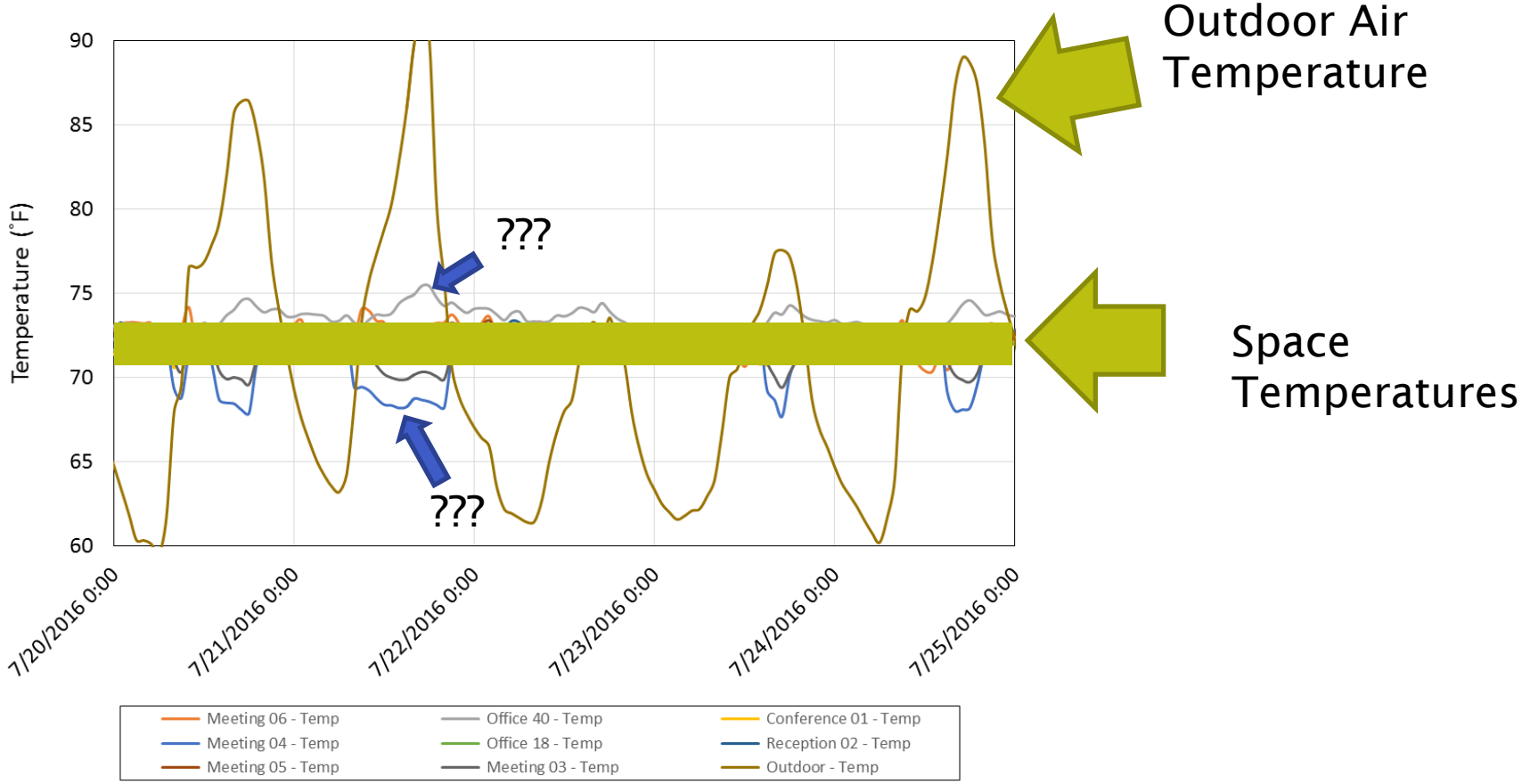
→ Preliminary Monitoring Data



Pilot Project

→ **Office 1**

→ Preliminary Monitoring Data



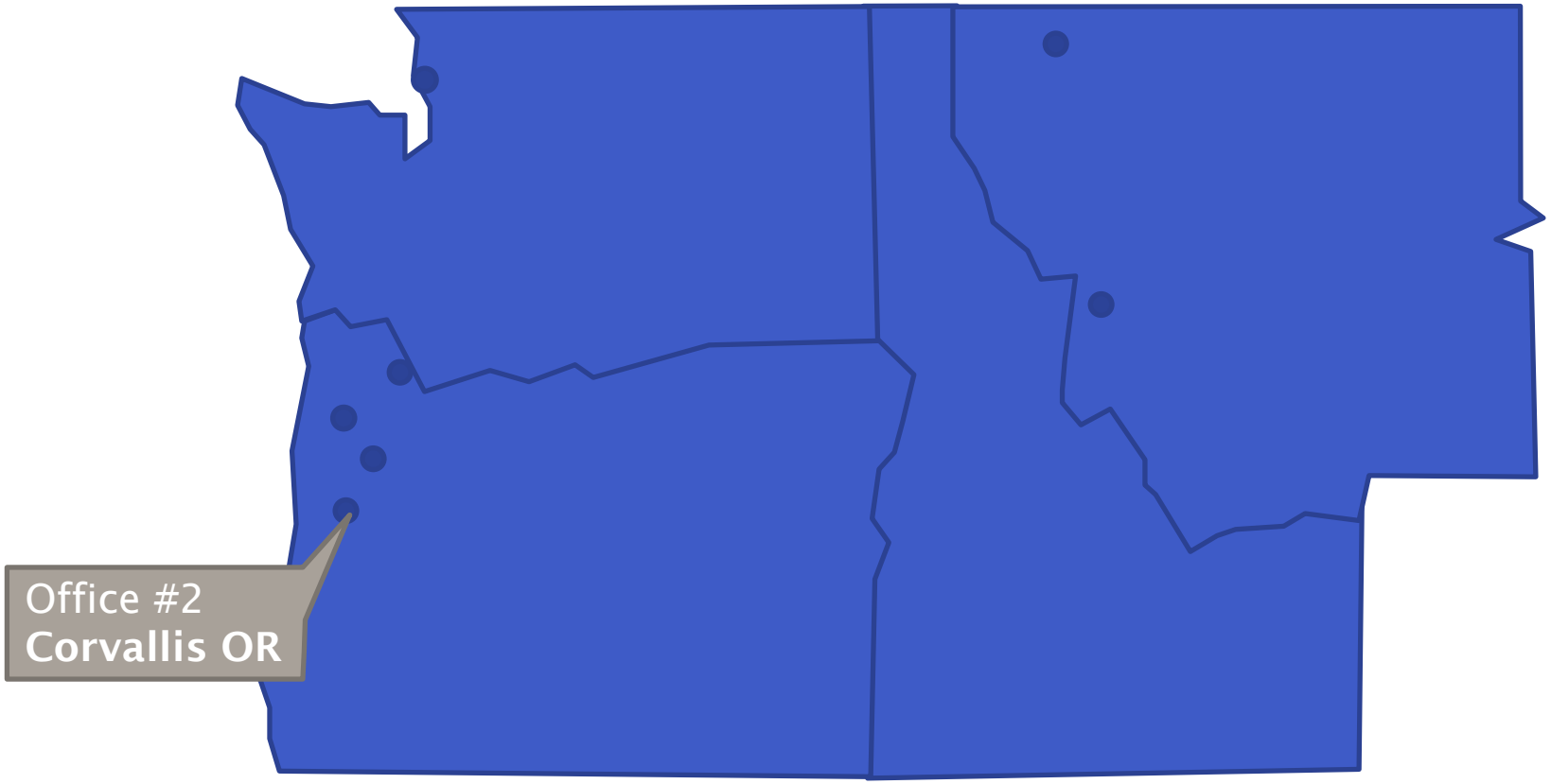
Pilot Project

RDH

- **Office 1**
- What's next?
  - Fine tuning DOAS conversion
  - Collect more utility data and monitoring data
  - Calibrate DOAS conversion model

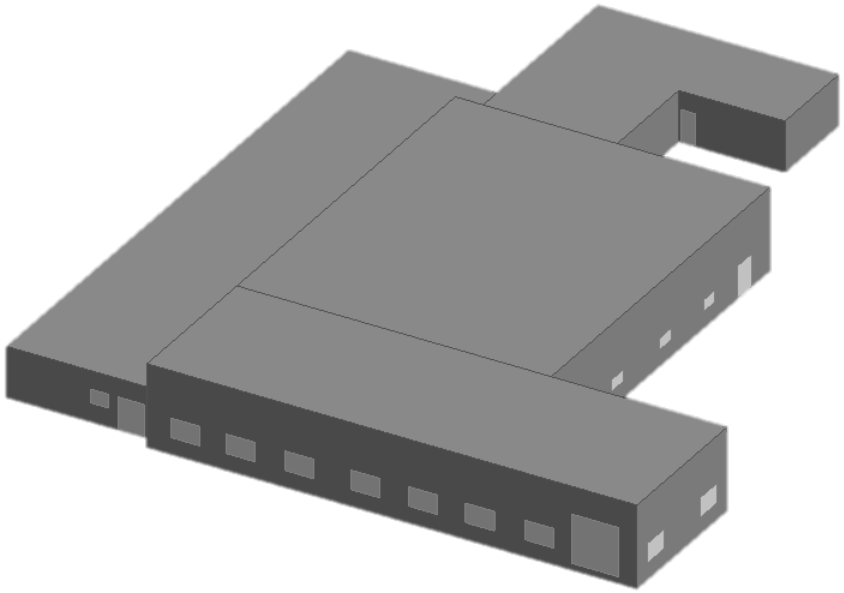
- General "lessons learned" for reconciling metered and modeled energy performance:
  - Commissioning matters!
  - Expect and mitigate anomalies in monitoring data

Pilot Projects

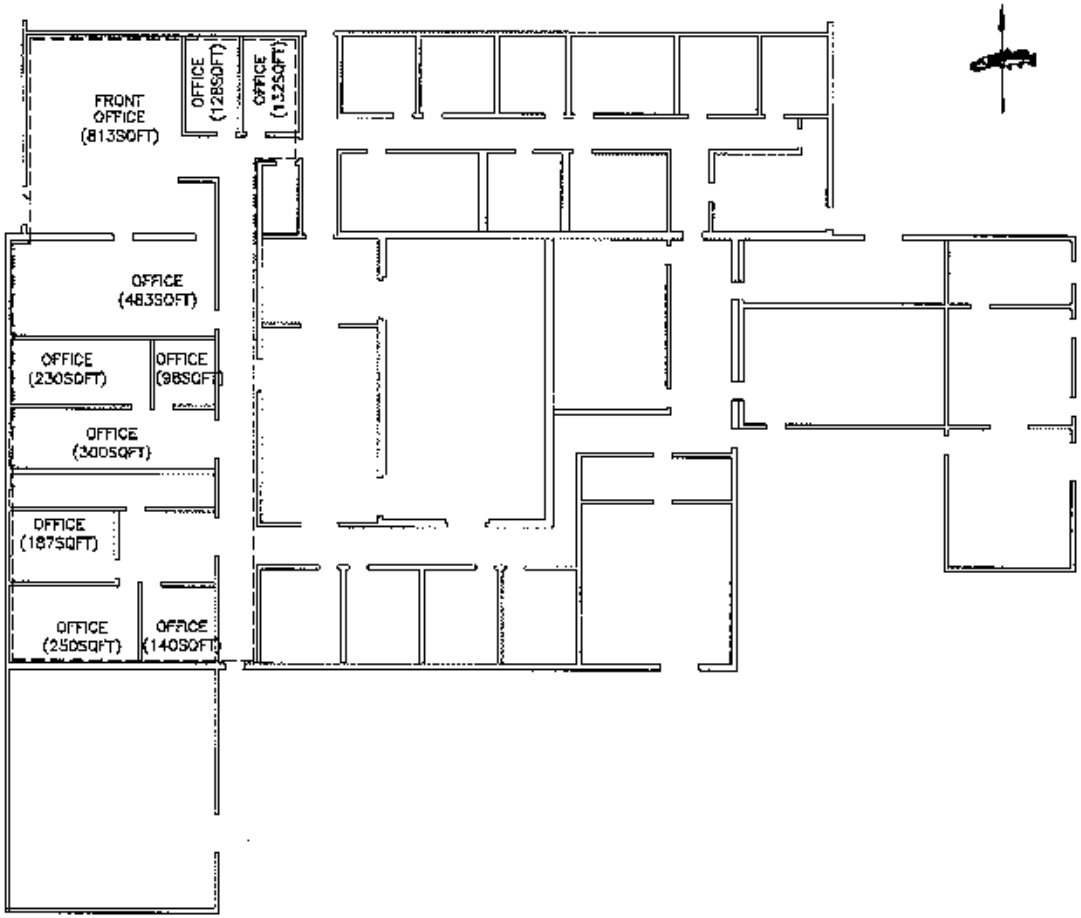


Pilot Projects

- → **Office 2**
- → Single storey office building
- → Private offices, conference room, storage & library
- → Monday through Friday day time operation
- → DOAS conversion for 2 out of 5 zones



Pilot Projects



Pilot Project

- **Office 2**
- Baseline
  - 5 RTUs, total 20 tons cooling, 227,000 Btu/h heating
- Conversion
  - 3 RTUs remain, total 14 tons cooling, 152,000 Btu/h heating
  - 1 HRV
  - 2 zone-level multi-split indoor units and 1 outdoor unit, 4 tons cooling, 54,000 Btu/h heating

Pilot Project

RDH

- **Office 2**
- Pre-Conversion Air Leakage Testing
  - Air Leakage Test Result: 0.295 cfm/ft^2 at 75 Pa
    - Air leakage noted at office entry doors, operable windows, exhaust fans with gravity dampers (under positive pressure).

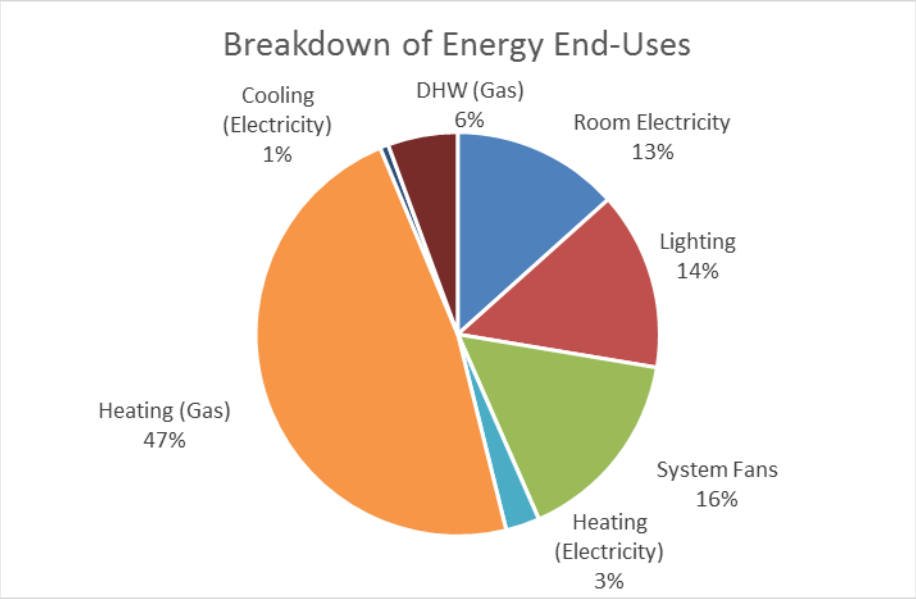
TABLE 21– SUMMARY OF AIR LEAKAGE TEST RESULTS

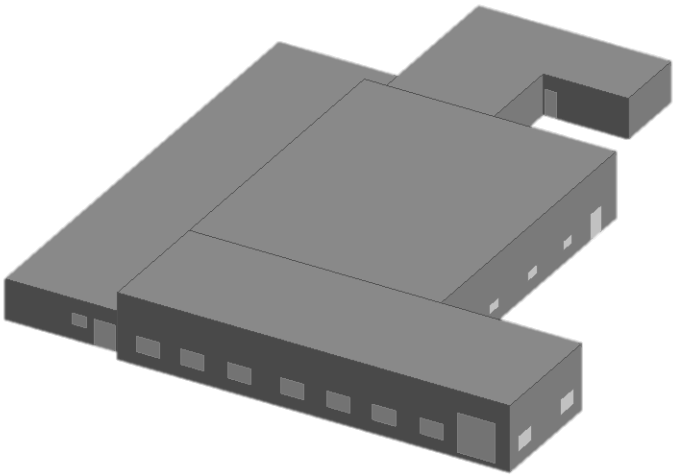
Test Condition	Depressurize	Pressurize	Average
Enclosure Airtightness [cfm/ft^2@75Pa]	0.231	0.358	0.295
Equivalent Leakage Area [ft^2 @ 75Pa]	5.93	9.16	7.54
Air Changes [per Hour @ 50Pa]	1.81	2.74	2.27
Air Leakage Test Coefficient (C) [cfm/Pa^n]	579.7	722.5	N/A
Flow Exponent (n) [dimensionless]	0.606	0.656	N/A
Squared Correlation Coefficient (r^2) [dimensionless]	0.999	0.999	N/A

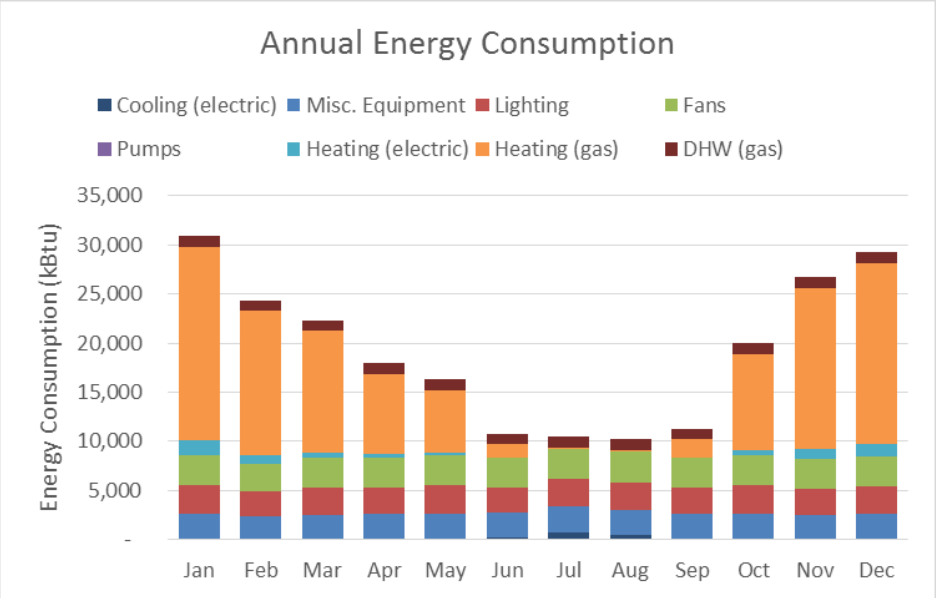
Pilot Projects

RDH

- → **Office 2**
- → Preliminary baseline modeling results
  - → EUI 60 kBtu/ft^2







Pilot Projects

→ **Office 2**

→ DOAS conversion in spring/summer 2016

Pilot Project

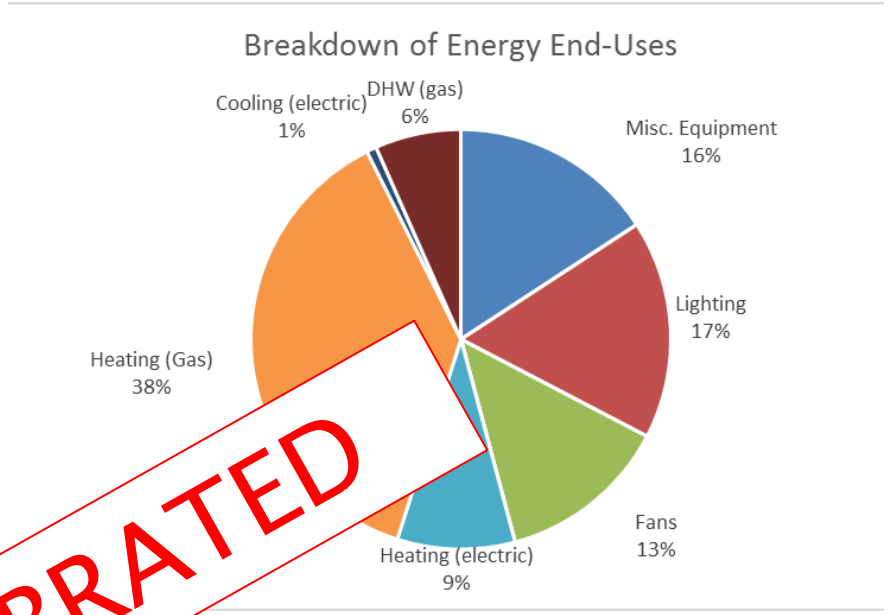
RDH

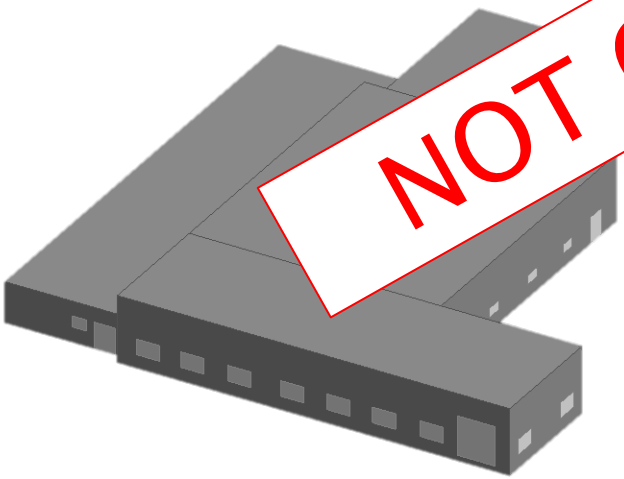
- → **Office 2**
- → Post-Conversion Air Leakage Testing
  - → Air Leakage Test Result: 0.266 cfm/ft^2 at 75 Pa

TABLE 21– SUMMARY OF AIR LEAKAGE TEST RESULTS			
Test Condition	Depressurize	Pressurize	Average
Enclosure Airtightness [cfm/ft^2@75Pa]	0.203	0.328	0.266
Equivalent Leakage Area [ft^2 @ 75Pa]	5.264	8.483	6.875
Air Changes [per Hour @ 50Pa]	1.61	2.58	2.09
Air Leakage Test Coefficient (C) [cfm/Pa^n]	515.72	779.27	N/A
Flow Exponent (n) [dimensionless]	0.606	0.621	N/A
Squared Correlation Coefficient (r^2) [dimensionless]	0.999	0.998	N/A

Pilot Projects

- → **Office 2**
- → Preliminary DOAS conversion modeling results
  - → EUI 50 kBtu/ft^2





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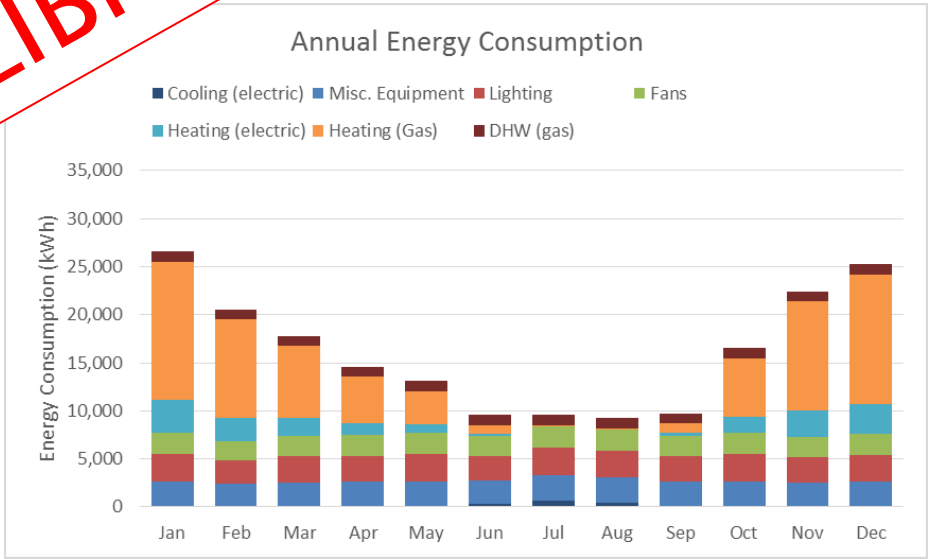
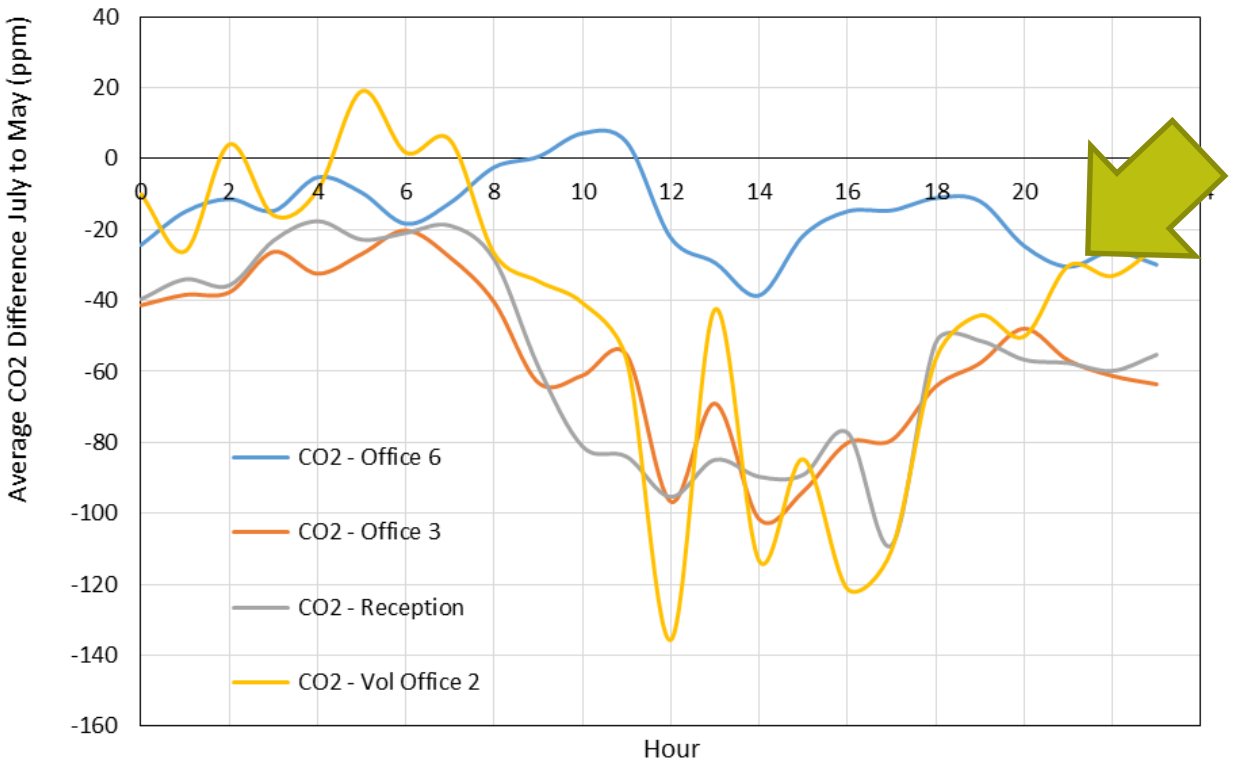


Pilot Projects

→ **Office 2**

→ Preliminary Monitoring Data



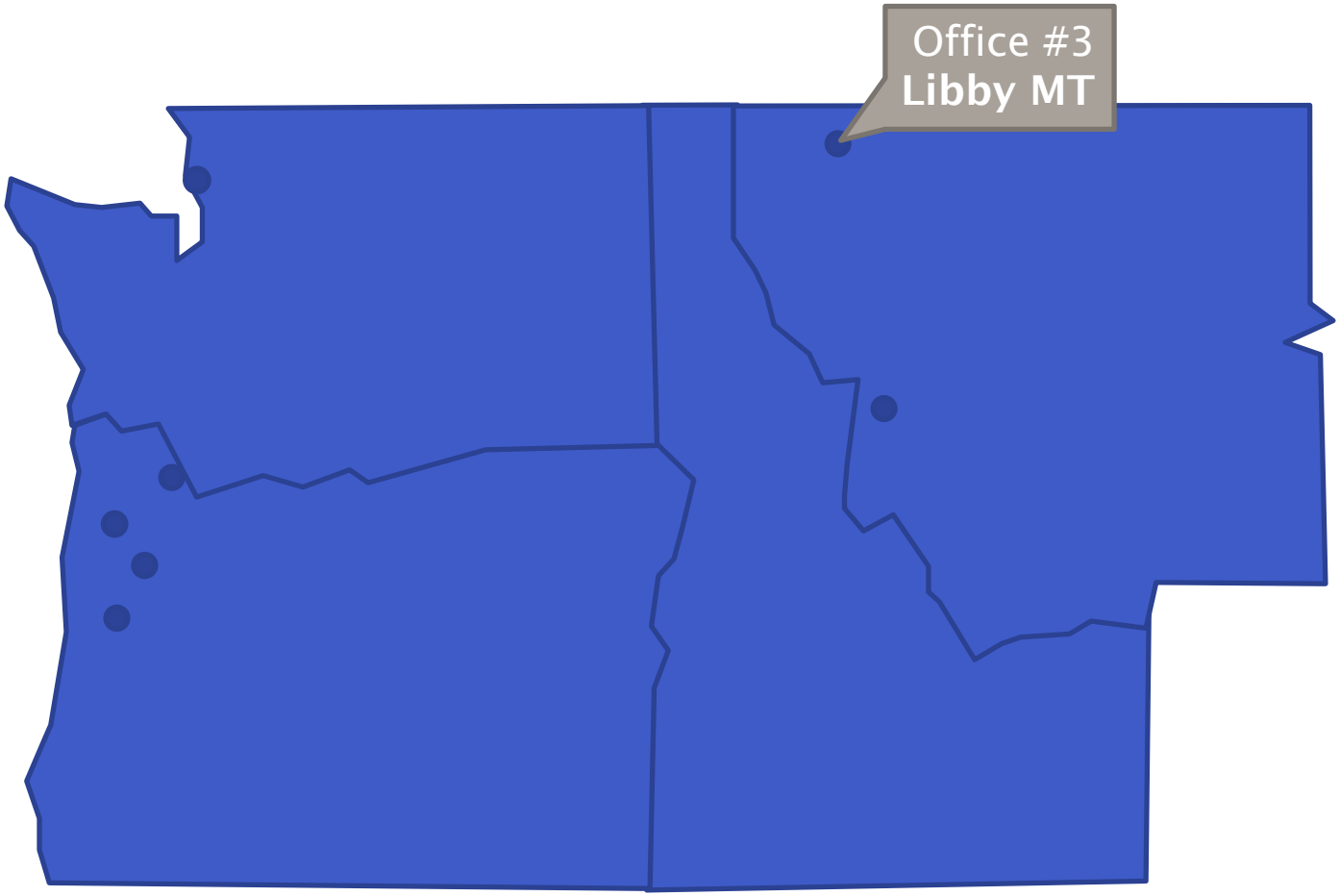
24 hour period showing time averaged difference between post-conversion CO_2 levels and pre-conversion CO_2 levels.

Pilot Project

- **Office 2**
- What's next?
  - Collect more utility data and monitoring data
  - Calibrate DOAS conversion model

- General "lessons learned" for using energy modeling as a tool to evaluate performance:
  - Modeling evaluates energy consumption; don't forget the non-energy benefits.

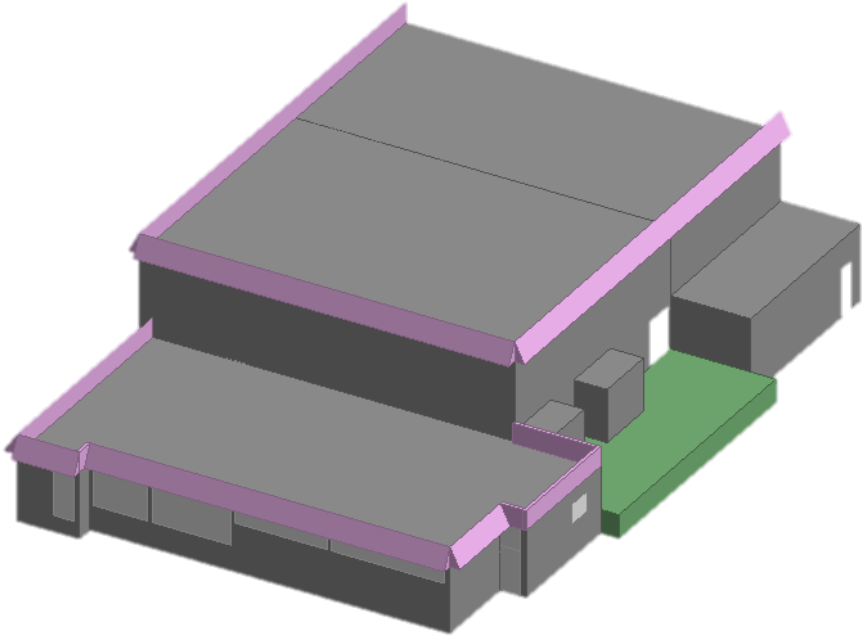
Pilot Projects



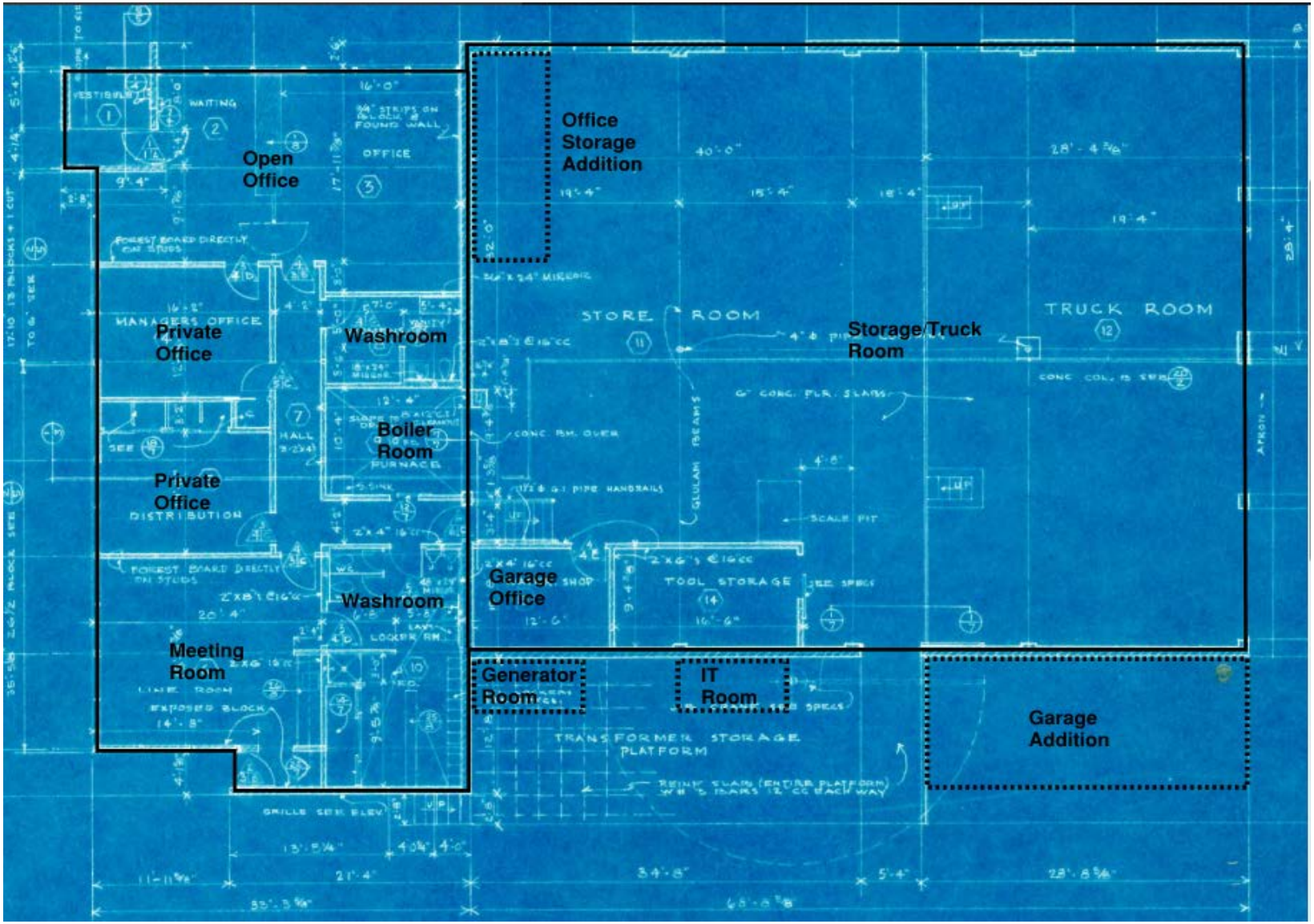
Pilot Projects

RDH

- → **Office 3**
- → Single storey office with attached garage + shop area
- → Monday through Friday day time schedule



Pilot Projects



Pilot Project

- **Office 3**
- Baseline
  - 1 RTU, total 7 tons cooling, 76,000 Btu/h heating
  - Hydronic heating (electric)
- Conversion
  - 1 HRV
  - 9 zone-level multi-split indoor units and 2 outdoor units, 4 tons cooling, 54,000 Btu/h heating


FLATHEAD
ELECTRIC
COOPERATIVE

Pilot Project

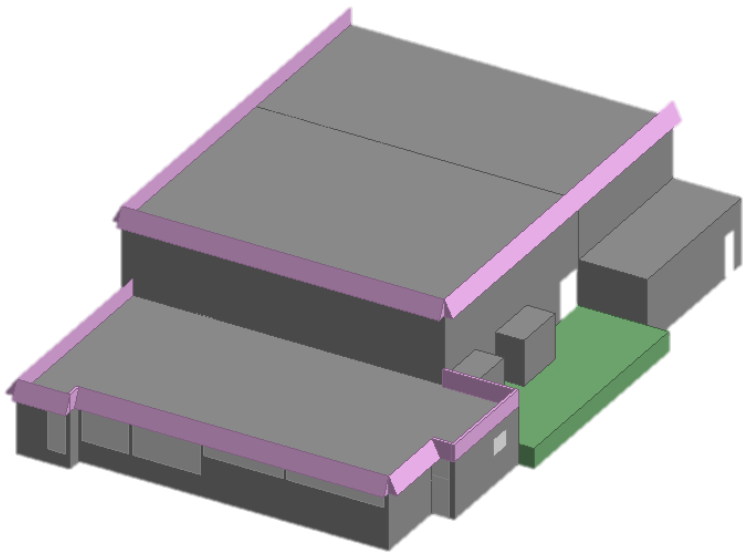
RDH

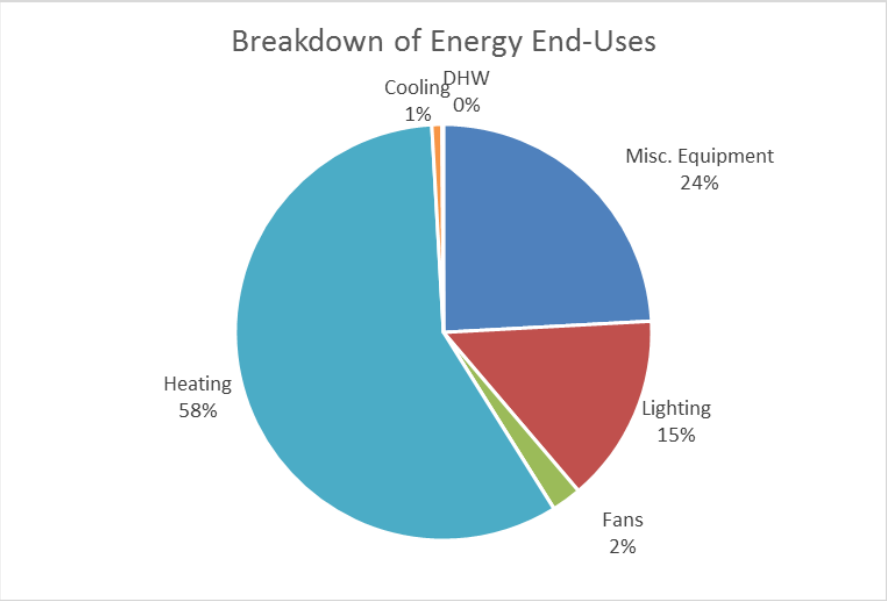
- **Office 3**
- Pre-Conversion Air Leakage Testing
  - Air Leakage Test Result: 0.746 cfm/ft^2 at 75 Pa
    - Air leakage noted at roof to wall joints in garage, operable windows and overhead sectional doors in garage, ductwork.

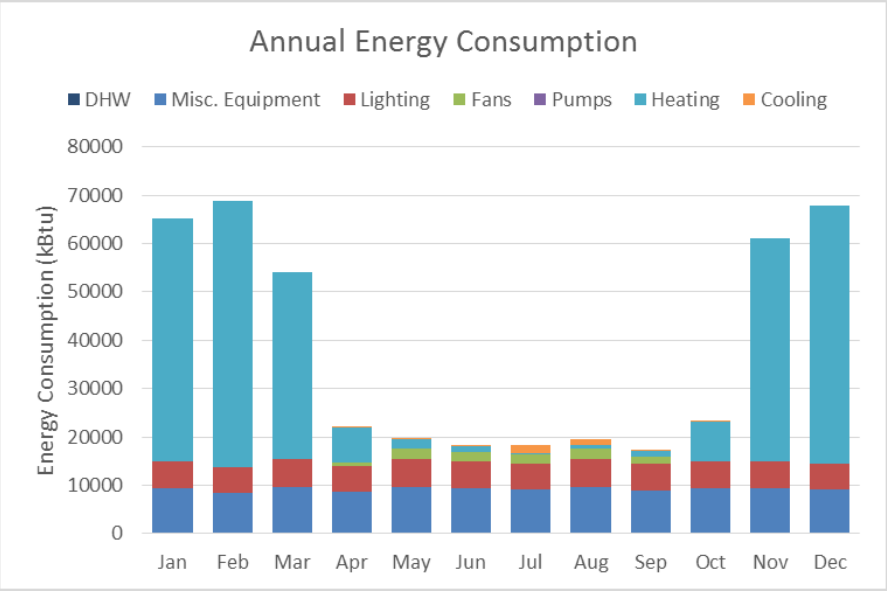
TABLE 21– SUMMARY OF AIR LEAKAGE TEST RESULTS			
Test Condition	Depressurize	Pressurize	Average
Enclosure Airtightness [cfm/ft^2@75Pa]	0.769	0.723	0.746
Equivalent Leakage Area [ft^2 @ 75Pa]	11.15	10.48	10.82
Air Changes [per Hour @ 50Pa]	6.31	6.07	6.19
Air Leakage Test Coefficient (C) [cfm/Pa^n]	1080	1312	N/A
Flow Exponent (n) [dimensionless]	0.609	0.549	N/A
Squared Correlation Coefficient (r^2) [dimensionless]	0.999	0.999	N/A

Pilot Projects

- → **Office 3**
- → Preliminary baseline modeling results
  - → EUI 79 kBtu/ft^2







Pilot Projects

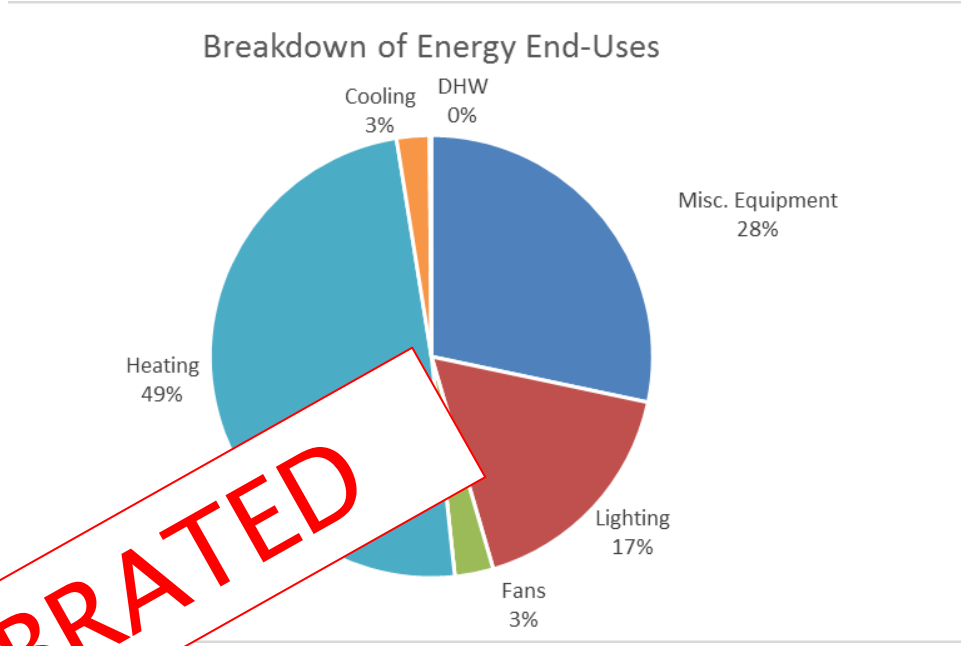
→ **Office 3**

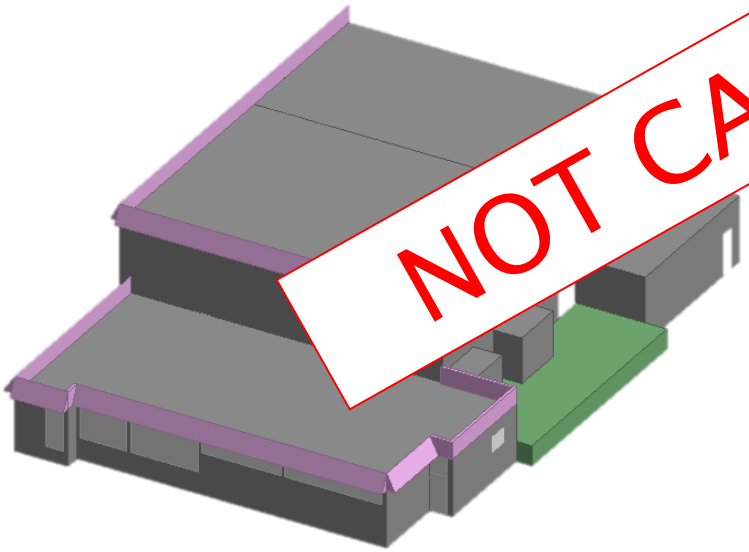
→ DOAS conversion scheduled for summer 2016

Pilot Projects

RDH

- → **Office 3**
- → Preliminary DOAS conversion modeling results
  - → EUI 67 kBtu/ft^2





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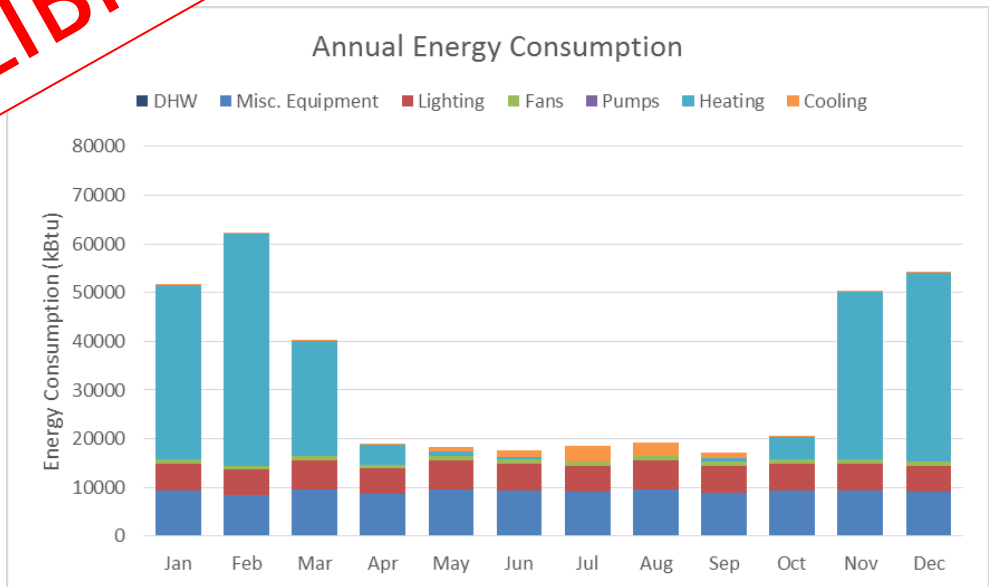
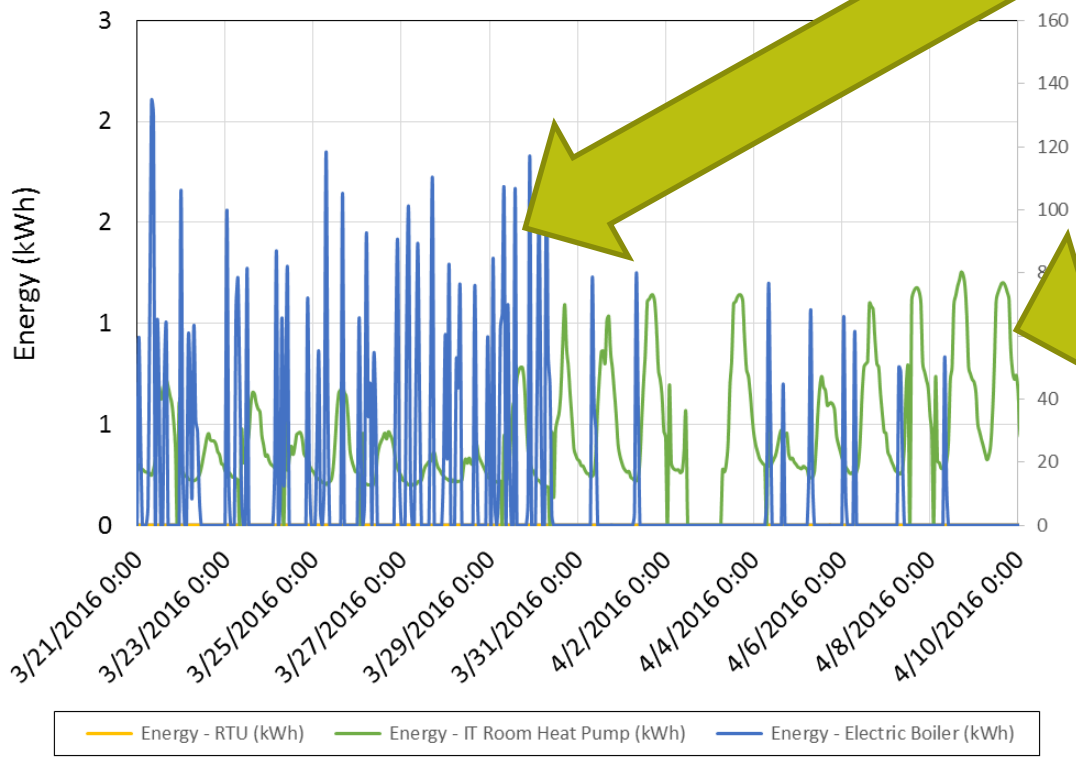


Pilot Projects

→ **Office 3**

→ Preliminary Monitoring Data

Electric boiler energy consumption (secondary axis)



IT room heat pump (primary axis)

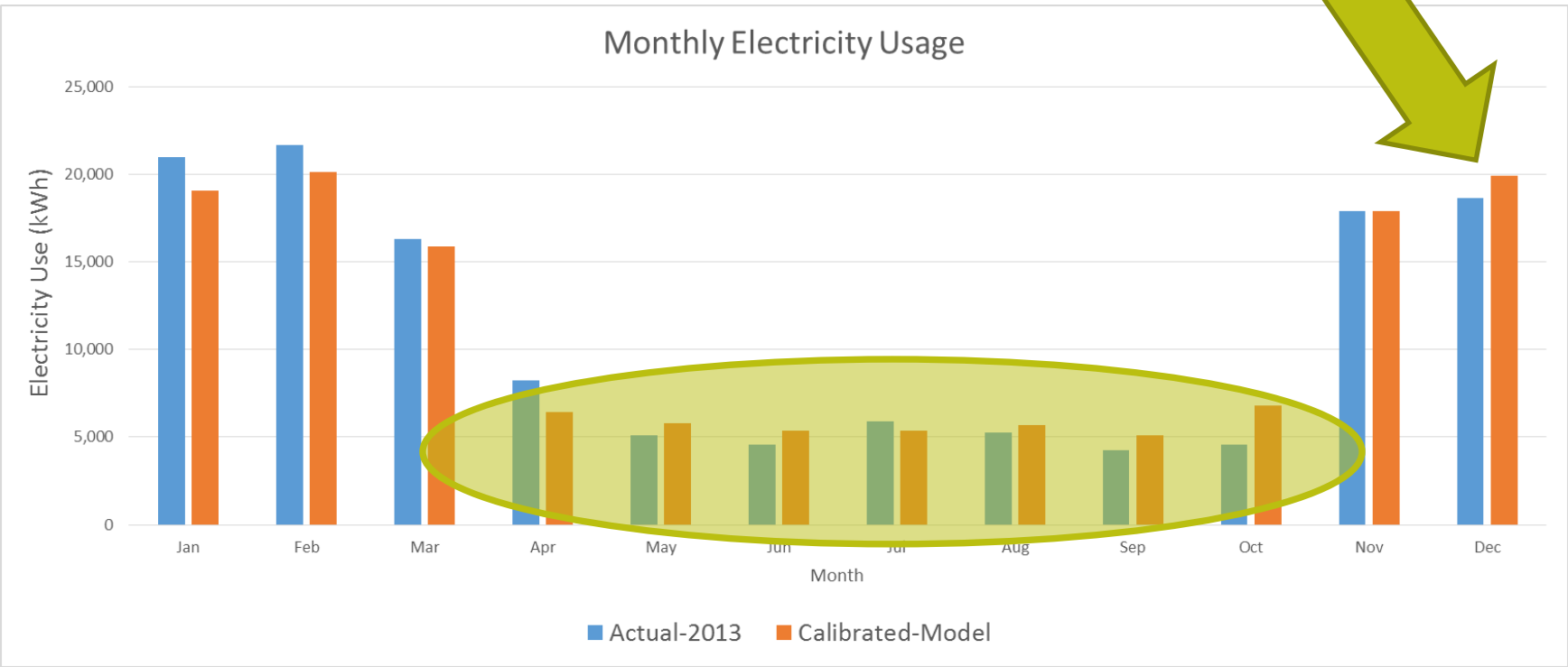
RTU???

Pilot Projects

→ **Office 3**

→ Preliminary Monitoring Data

Actual electricity consumption and modeled electricity consumption per month for the year 2013.

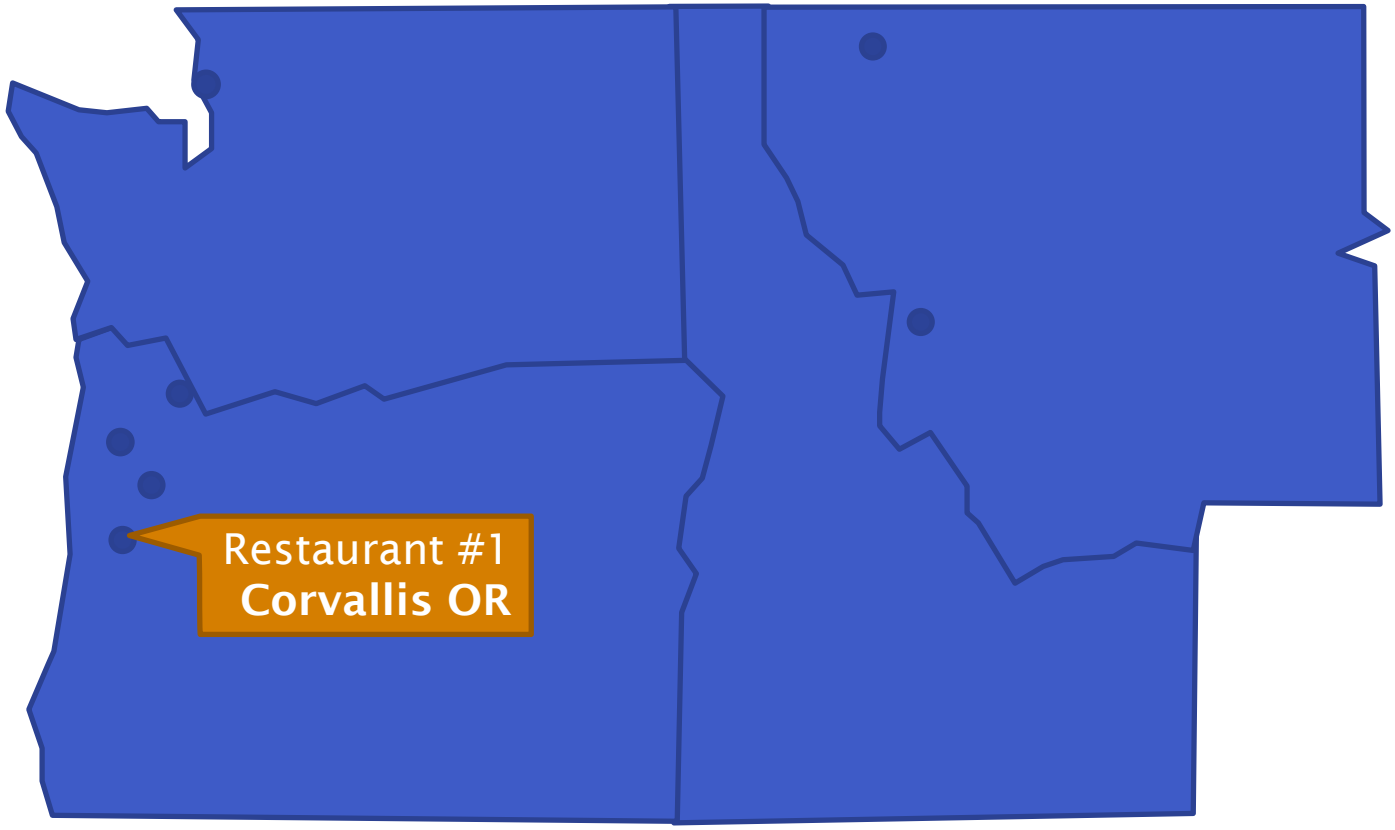


Pilot Project

- **Office 2**
- What's next?
  - Install DOAS conversion
  - Post-conversion air leakage testing and monitoring equipment install
  - Collect more utility data and monitoring data
  - Calibrate DOAS conversion model

- General "lessons learned" for reconciling metered and modeled energy performance :
  - Expect and incorporate seasonal and other building-specific operating characteristics.

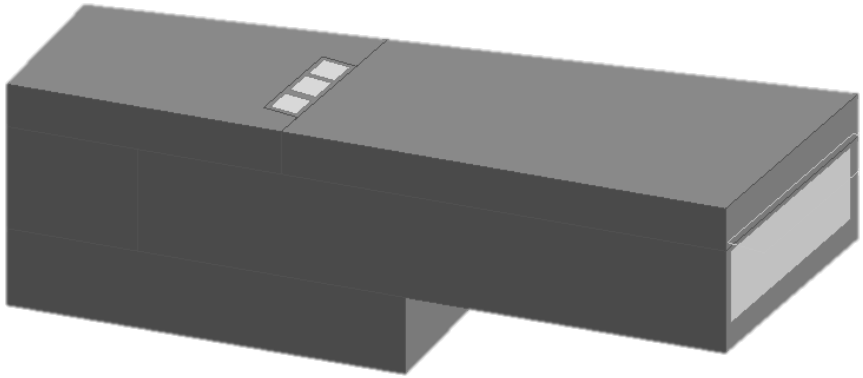
Pilot Projects



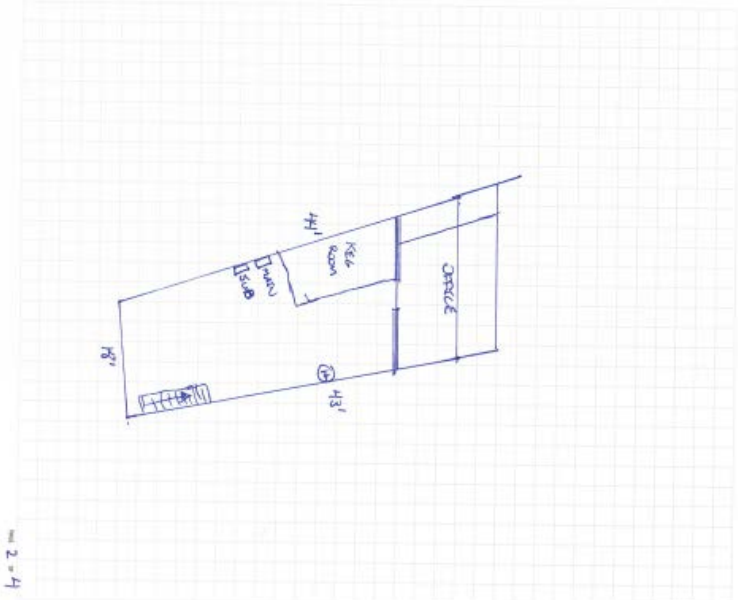
Pilot Projects

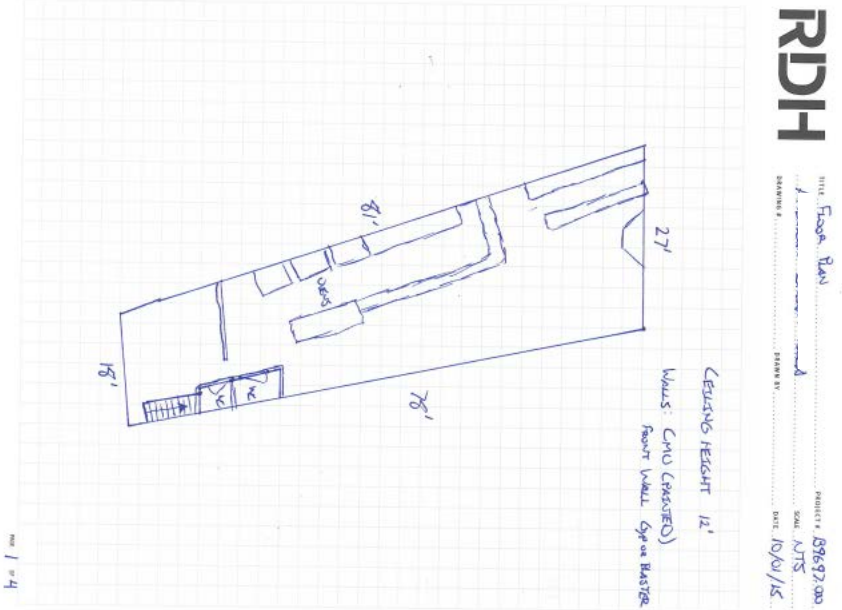
RDH

- → **Restaurant 1**
- → Busy sit-in & take-out restaurant
- → Dining area, kitchen, basement storage
- → Operating hours from 9AM to midnight, daily



Pilot Project





Pilot Project

- **Restaurant 1**
- Baseline
  - Dining area:
    - Previously had 1 RTU, 7.5 tons cooling, 88,000 Btu/h heating
    - Currently no ventilation
    - Ductless split heat pumps for heating and cooling
- Conversion
  - Dining area:
    - Install 1 HRV to reinstate ventilation at low energy penalty
    - Use existing ductless split heat pumps for heat and cooling


757-7221
GO BEAVS
2525
TAKE A SEAT AND GET THE HEAT!
KNOCK HERE FOR BEER!

Pilot Project

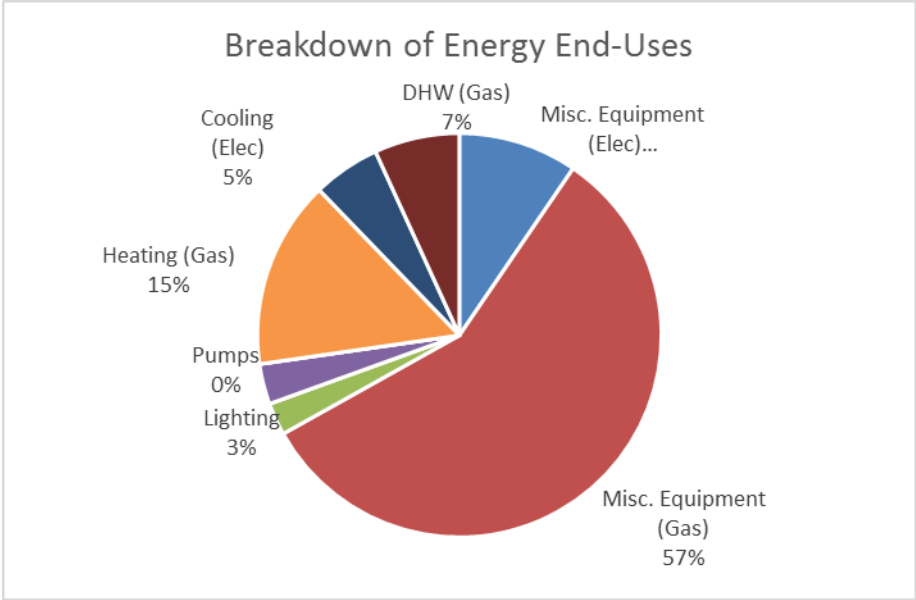
- **Restaurant 1**
- Pre-Conversion Air Leakage Testing
  - Air Leakage Test Result: 1.634 cfm/ft^2 at 75 Pa
    - Air leakage noted at existing RTU supply and return registers, around doorway to basement, exhaust fans.

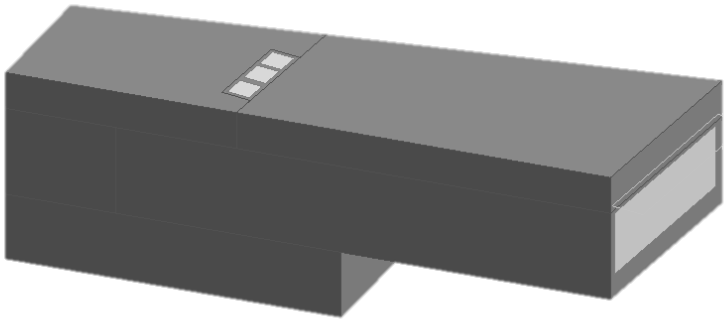
TABLE 21– SUMMARY OF AIR LEAKAGE TEST RESULTS

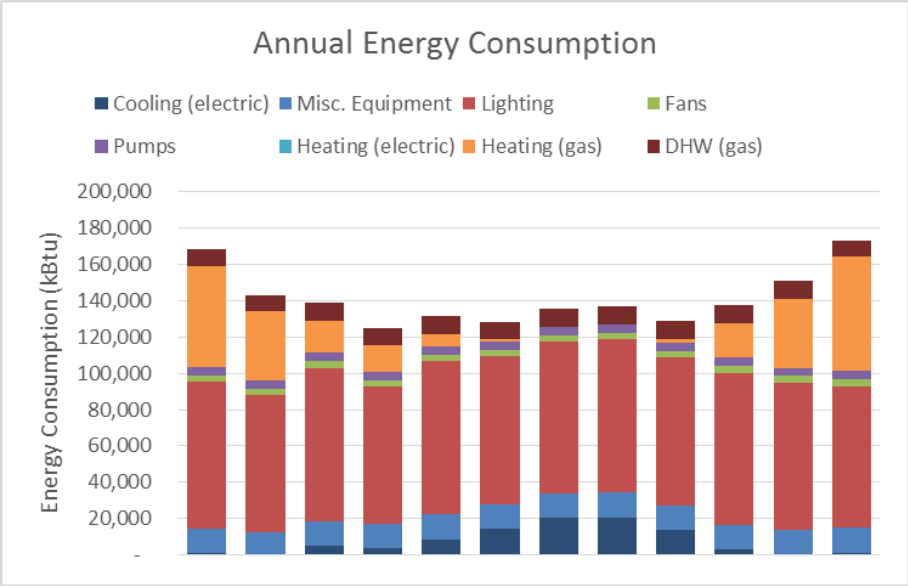
Test Condition	Depressurize	Pressurize	Average
Enclosure Airtightness [cfm/ft^2@75Pa]	1.635	1.633	1.634
Equivalent Leakage Area [ft^2 @ 75Pa]	8.614	8.607	8.610
Air Changes [per Hour @ 50Pa]	19.4	19.95	19.68
Air Leakage Test Coefficient (C) [cfm/Pa^n]	1209.7	1617.3	N/A
Flow Exponent (n) [dimensionless]	0.523	0.455	N/A
Squared Correlation Coefficient (r^2) [dimensionless]	0.9991	0.993	N/A

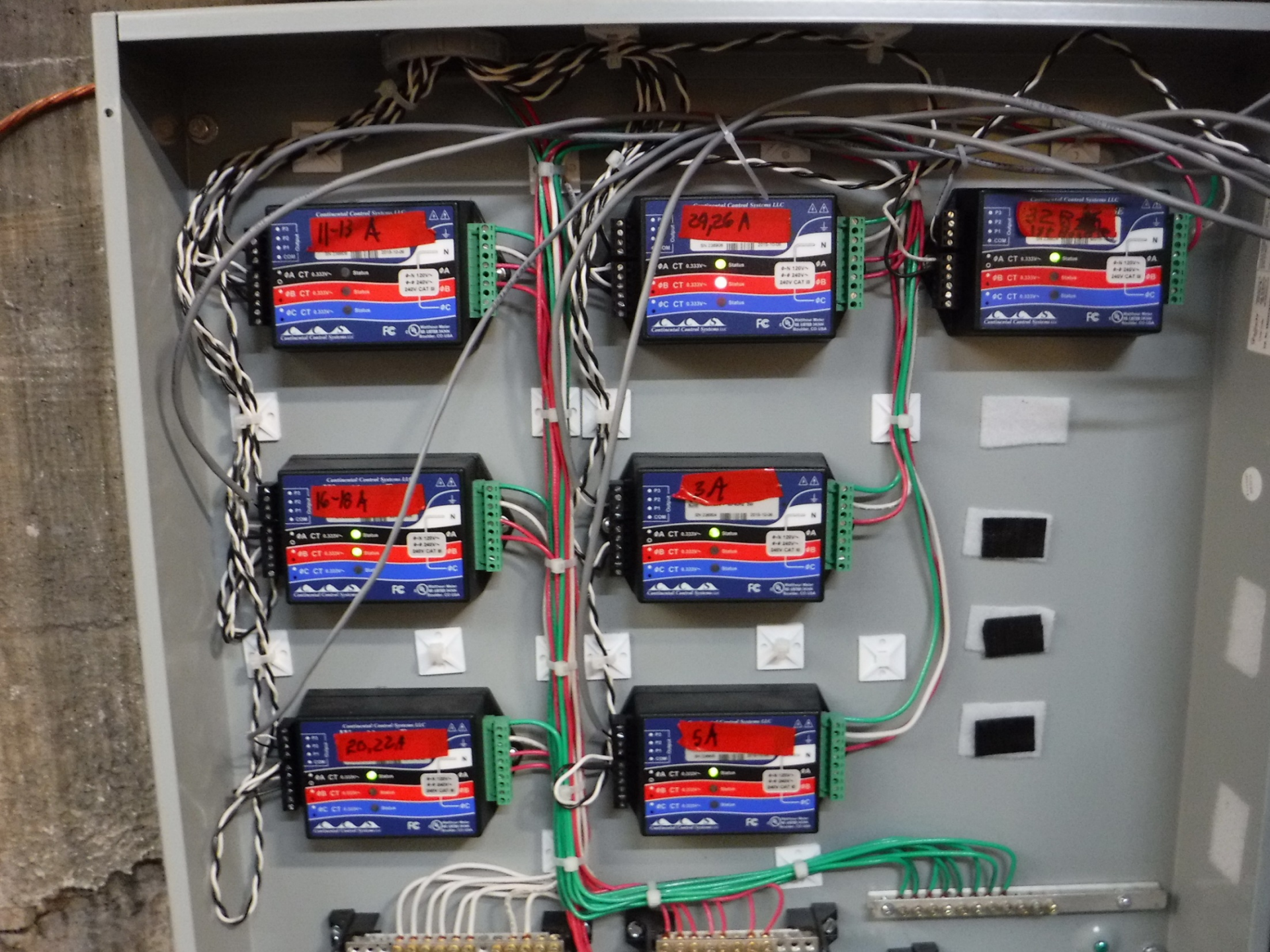
Pilot Project

- → **Restaurant 1**
- → Preliminary baseline modeling results
  - → EUI 651 kBtu/ft^2








11-13 A
29,26 A
16-18 A
3A
20,22A
5A

Pilot Project

RDH

- → **Restaurant 1**
- → Post-Conversion Air Leakage Testing
  - → Air Leakage Test Result: 1.644 cfm/ft^2 at 75 Pa

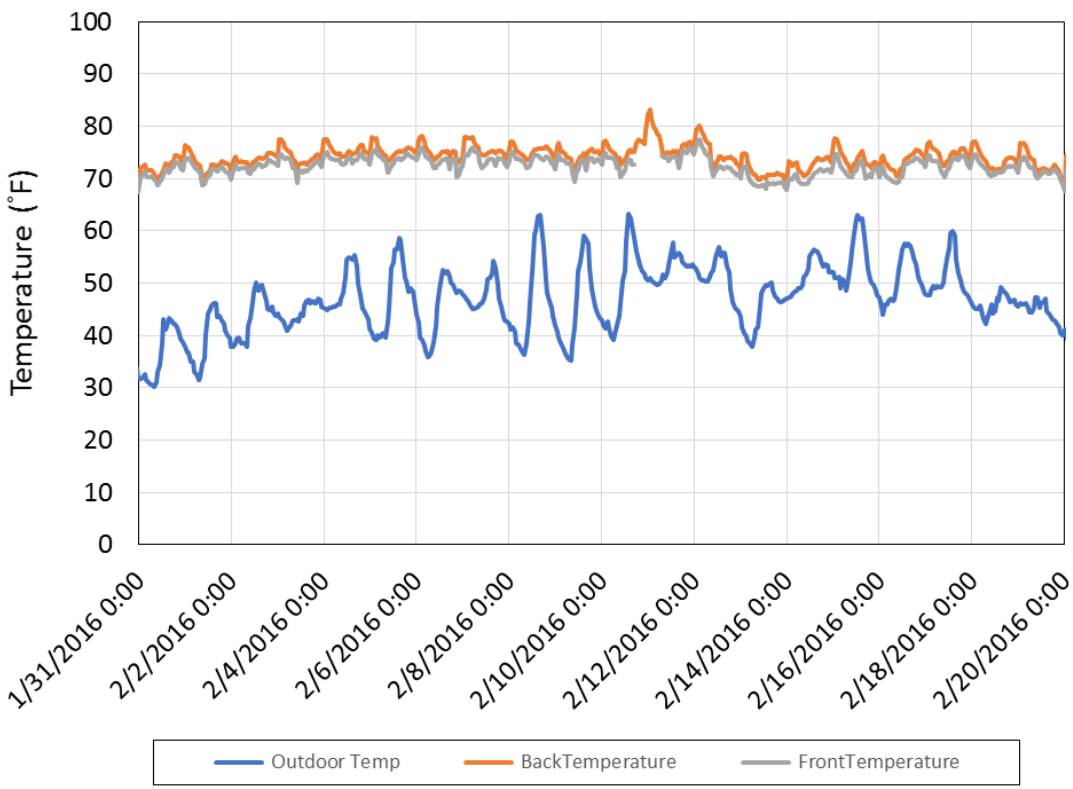
TABLE 1 – SUMMARY OF AIR LEAKAGE TEST RESULTS

Test Condition	Depressurize	Pressurize	Average
Enclosure Airtightness [cfm/ft^2@75Pa]	1.616	1.673	1.644
Equivalent Leakage Area [ft^2 @ 75Pa]	8.517	8.815	8.665
Air Changes [per Hour @ 50Pa]	19.28	19.92	19.60
Air Leakage Test Coefficient (C) [cfm/Pa^n]	1246.1	1267.4	N/A
Flow Exponent (n) [dimensionless]	0.513	0.517	N/A
Squared Correlation Coefficient (r^2) [dimensionless]	0.999	0.999	N/A

Pilot Project

→ **Restaurant 1**

→ Preliminary Monitoring Data



Interior Air Temperature (front and back)

Outdoor Air Temperature

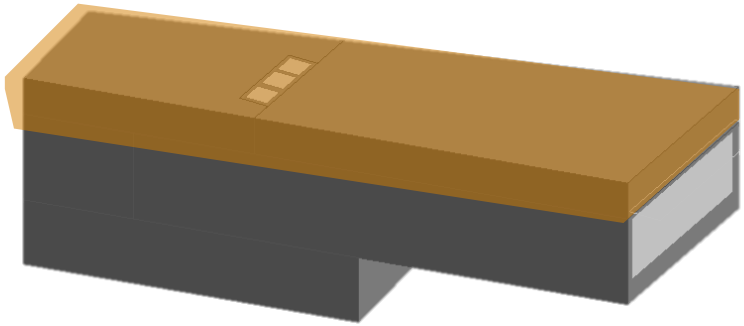
Pilot Project

RDH

→ **Restaurant 1**

→ Preliminary Monitoring Data

Interior Air Temperatures ≠ Temperature at HRV Exhaust Inlet



Duct Leakage in Unconditioned Attic

Pilot Project

- **Restaurant 1**
- What's next?
  - Collect more utility data and monitoring data
  - Create and calibrate DOAS conversion model

- General "lessons learned" for reconciling metered and modeled energy performance:
  - Expect and mitigate system losses.

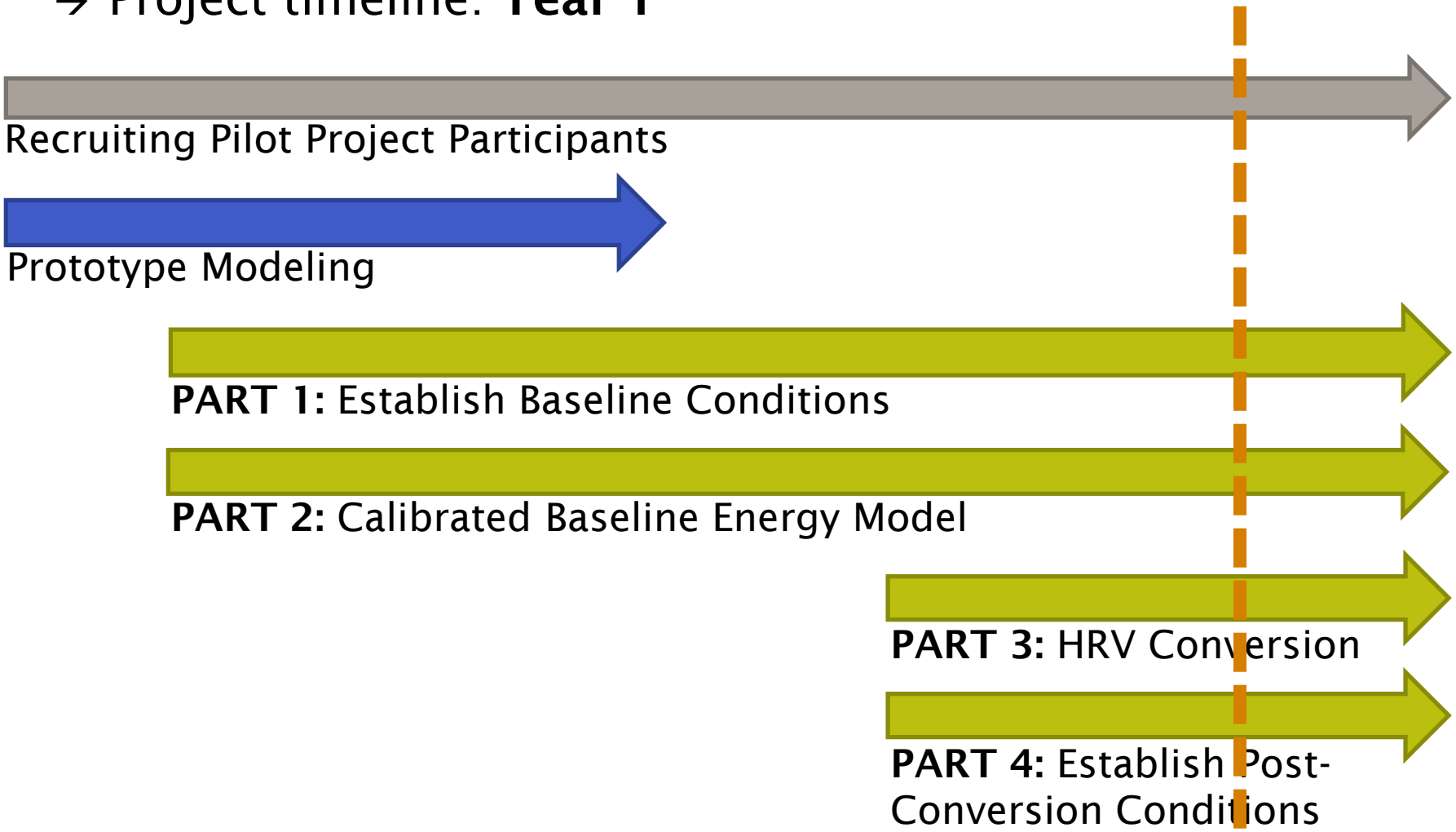
Summary and Next Steps

Summary and Next Steps

→ Summary – progress thus far

Summary and Next Steps

→ Project timeline: **Year 1**



Summary and Next Steps

- Summary – some early lessons learned for connecting modeled energy performance with in-service building performance
  - Commissioning matters!
  - Expect and mitigate anomalies in monitoring data.
  - Expect and incorporate building-specific and seasonal operational schedules.
  - Expect and mitigate system losses.
  - Also, don't forget the non-energy benefits.

Summary and Next Steps

→ Project timeline: **Year 2**

PART 1: Baseline

PART 2: Baseline Model

PART 3: HRV Conversion

PART 4: Establish Post-Conversion Conditions

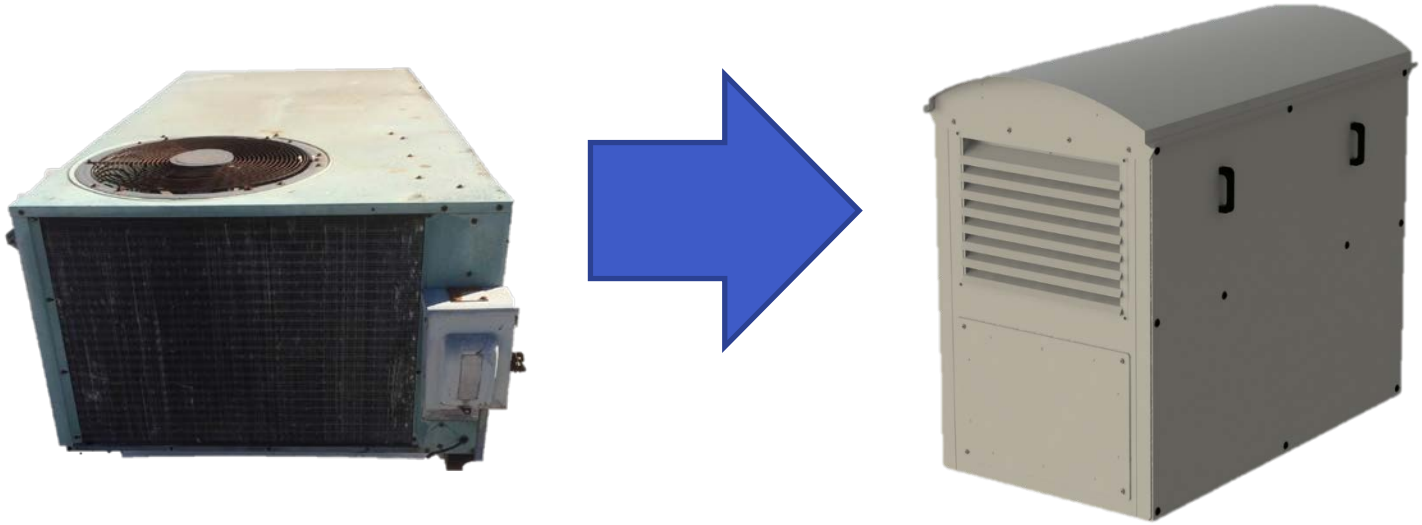
PART 5: Calibrated Post-Conversion Energy Model

Summary and Next Steps

RDH

- → ~~**PART 1:** Establish Baseline Conditions~~
- → **PART 2:** Calibrated Baseline Energy Model
- → **PART 3:** DOAS Conversion
- → ~~**PART 4:** Establish Post Conversion Conditions~~
- → **PART 5:** Calibrated Post-Conversion Energy Model

Reliably Estimate and Validate Savings



Market Transformation

Discussion + Questions

FOR FURTHER INFORMATION PLEASE VISIT

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RDH BUILDING SCIENCE

RDH Building Engineering Ltd. and Building Science Consulting Inc. have merged. Effective November 1, 2015, we now operate as one integrated firm. The merger brings two of the leading building science firms in North America together to provide a combination of cutting-edge research with leading design and implementation capabilities. The result is a unique offering for our clients–an ability to explore new and innovative ideas based on science and our practical knowledge of what can be built. We are excited about the possibilities as we launch the new firm.