Evidence-Based Best Practices for IAQ in High Performance Homes

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Energy & Environmental Building Alliance
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Atlanta GA
Learning Objectives

• Best practices to reduce IAQ risk
  -> IAQ Scoring Tool

• Interim findings IAQ study in new, California homes

• Building America study of IAQ in new US homes

• Low-cost IAQ monitors for residential PM$_{2.5}$

• Florida Solar Energy Center demonstration of smart ventilation for energy savings and comfort
Acknowledgements

CEC
Public Interest Research Programs

EPA
Indoor Environments Division

HUD
Office of Healthy Homes and Lead Hazard Control

Rengie Chan  Woody Delp  Yang-Seon Kim  Brennan Less  Vi Rapp  Max Sherman  Iain Walker
What is good indoor air quality?

- Pollutant concentrations at safe levels
- No dampness & mold issues
- Allergens minimized
- No unpleasant odors
- Comfortable temperature and humidity
- Air seems “fresh” and pleasant
Best practices to minimize IAQ risk

• Start with Indoor airPLUS / Energy Star
  – Water tight, robust drainage
  – Robust ventilation for kitchen, bath, laundry, dwelling
  – Low-emitting materials
  – Commissioning and pre-ventilation

• Moisture and comfort managed; dehumidification and humidification as needed

• Airtight and well-insulated envelope

• Filtration for fine and ultrafine particles (≥MERV13)

• Minimize potentially hazardous SVOC*

• Build for changing climate: resilient to storms & floods

*www.sixclasses.org
Best practices for IAQ performance

Occupants aware, educated, and empowered
• Aware of indoor pollutant sources and controls
• Manuals describing equipment, use, required maintenance

Robust control equipment:
• Minimal maintenance and/or service contracts
• Automated fault detection

Sensors:
• Aid awareness
• Closed loop control
• Fault detection
NOT Best Practices

• Unvented gas heater / fireplace
• Built on a flood plane, former wetland, etc.
• Inattention to radon risk
• Inadequate kitchen exhaust / recirc range hood
• Build tight and leave ventilation to the occupant
IAQ Score – Example New Home

### IAQ hazards

**Indoor Pollutants**
- Allergens
- PM$_{2.5}$
- UFP
- Form.
- VOC
- SVOC
- NO$_2$
- CO

**Outdoor Pollutants**
- PM$_{2.5}$
- UFP
- Ozone
- NO$_2$
- VOC
- Radon

**Moisture & humidity**
- Indoor moisture
- Outdoor moisture

**Odors**

### Sources

- Indoor: Allergens, PM$_{2.5}$, UFP, Form., VOC, SVOC, NO$_2$, CO
- Outdoor: PM$_{2.5}$, UFP, Ozone, NO$_2$, VOC, Radon

### Controls

- Indoor: Allergens, PM$_{2.5}$, UFP, Form., VOC, SVOC, NO$_2$, CO
- Outdoor: PM$_{2.5}$, UFP, Ozone, NO$_2$, VOC, Radon

- Moisture & humidity: Indoor, Outdoor

- Odors: Indoor, Outdoor
IAQ Score Framework

- Rates the home as found
- Considers typical IAQ hazards and risks
  - Includes typical occupant activities
- Adds house-specific risks
  - Nearby outdoor source, mold contamination, etc.
- Quantifies severity of hazard and effectiveness of control
- Value of each control depends on severity of hazard
- Considers control robustness, ease of use, durability, etc.
Concerns about IAQ in California New Homes

• 2004-5: Surveyed ~1500 new homeowners by mail\(^1\)
  – Few opened windows in winter; many did not ventilate all year
  – Kitchen and bath ventilation not used regularly

• 2007-8: Measured pollutants & ventilation in 108 new homes\(^2\)
  – 9 of 16 homes with ducted mechanical ventilation had grossly insufficient flow
  – Many homes did not use windows for ventilation; 67% below code requirement
  – Majority of homes exceeded formaldehyde health guidelines

• 2008: California Building Code requires mech. ventilation

• 2014: Healthy Efficient New Gas Homes study begins
  – Funded by Public Interest Natural Gas Research program

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\(^1\)Price and Sherman, 2006; \(^2\)Offermann, 2009; \(^3\)hengh.lbl.gov
California New Home Study

**Goal**: Characterize ventilation equipment and IAQ in homes built to 2008 code, which required mechanical ventilation per ASHRAE 62.2

- Web-based survey to update knowledge about ventilation practices and IAQ perceptions
- Field study in occupied homes:
  - Characterize ventilation equipment, measure flows
  - One-week monitoring of ventilation and indoor air quality; occupants log activities that impact IAQ
  - LBNL designed protocols and analyzing data
  - GTI collecting data with help from PG&E and SoCalGas
Californians* in more satisfied with IAQ than outdoor air quality

Homes built since 2002

Survey Responses (%)

- Very Dissatisfied (-4)
- 3
- 2
- Neutral
- 1
- 2
- Very Satisfied (4)

IAQ  n=2765
OAQ  n=2766
Californians recognize that recirculating range hoods not as effective as venting hoods

(a) Range hood use
- Extracting (1974; 86%)
- Recirculating (329; 14%)

(b) Reasons for not using it
- Extracting (1837; 83%)
- Recirculating (389; 17%)
California New Home Study

<table>
<thead>
<tr>
<th>Data from first 21 homes</th>
<th>Mean</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size (ft^2)</td>
<td>2818</td>
<td>1363 – 4975</td>
</tr>
<tr>
<td># of Bedrooms</td>
<td>3.8</td>
<td>3 – 5</td>
</tr>
<tr>
<td># of Full Bathrooms</td>
<td>3.0</td>
<td>2 - 5</td>
</tr>
<tr>
<td>Year Built</td>
<td>2014</td>
<td>2011- 2015</td>
</tr>
<tr>
<td>Number of Occupants</td>
<td>3.1</td>
<td>1 - 8</td>
</tr>
<tr>
<td>Density (ft^2 / occupant)</td>
<td>1149</td>
<td>387 - 2127</td>
</tr>
</tbody>
</table>
Dwelling unit mechanical ventilation meets code in most homes, exceeds in many

![Airflow Rate (CFM) Diagram](image_url)
Range hood exhaust flows have sufficient flow*

*Also code requirement for sound
Measured bath & toilet exhaust fans meet code

<table>
<thead>
<tr>
<th>Flowrate (CFM)</th>
<th>Master Bathroom</th>
<th>Toilet</th>
<th>Bathroom 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td></td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>1.2</td>
<td>1.2</td>
<td>1.2</td>
</tr>
</tbody>
</table>
Envelope air tightness

Mean of first 17 homes (5 ACH50) is slightly higher than homes in LBNL Air Leakage Database (resdb.lbl.gov)*
Nitrogen dioxide very low in first 21 homes

- **EPA Annual Exposure**
- **Previous California New Home**

- **Living room**
  - Mean: 0.8
  - Mullen et al. 2016
  - Mean = 17

- **Outdoor**
  - Mean = 17
  - Mean Kitchen = 23

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Mullen et al. 2016

Mean outdoor = 17

Mean Kitchen = 23
Formaldehyde lower than in prior CA study

Mean

OEHHA 8-Hour Inhalation REL

Previous California New Home Study

Formaldehyde Concentration (ppb)

Living room

Master Bedroom

Outdoor

0

10

20

30

40

50
Formaldehyde decreases with air exchange rate.

Data from new California homes

Air exchange rate estimated based on mechanical ventilation operation

(h⁻¹)
Formaldehyde may not decrease over time

Data from new California homes
Building America New Home IAQ Study Goals

• **Collect baseline data**
  
  – Measure indoor air pollutants and humidity, characterize mechanical system designs and performance in a diverse sample of new homes (2013 or later) and climates.

• **Inform standards and technology development**
  
  – Analyze data to assess impacts of current building practices, codes and standards on IAQ, to inform future standards and technology development needed to ensure acceptable IAQ in new homes.
Study Scope

• Target 32 homes per CZ:
  ~50% with 62.2-compliant mechanical ventilation (MV)

• Characterize home, mechanical equipment

• Survey occupants about activities, satisfaction

• Monitor ventilation, IAQ, activities for 1 week; repeat for 2nd week in 8 homes / CZ

All of Alaska is in Zone 7 except for the following boroughs in Zone 8:
Project Team

- **DOE Building America**
  - Project direction and management for impact

- **Lawrence Berkeley National Lab**
  - Design field study procedures
  - Create & manage database
  - Analyze data to inform standards & technology development

- **Florida Solar Energy Center (FSEC), Pacific NW National Lab (PNNL)**
  - Recruit and collect field data
  - Quality assurance and upload data
  - Analysis by climate zone
  - Enhancements
Measurements

• Diagnostic testing
  – Envelope & duct airtightness
  – Mechanical ventilation equipment rated and measured flows

• One-week monitoring
  – Use of ventilation equipment and activities
  – Pollutants & environment
    (Outdoor, Indoor, Bedroom)
    • PM$_{2.5}$: O, I*, B*
    • CO$_2$: I, B
    • NO$_2$, NO$_X$: O, I, B
    • Formaldehyde: O, I, B
    • T, RH: O, I, B, baths

• Dwelling unit ventilation system
• Most frequently used bath fans
• Kitchen exhaust
• Clothes dryer
• Water heater in conditioned space
• Heating/cooling equipment
• Standalone (de)humidification equipment
• Standalone air cleaner
• Cooktop, oven, and toaster oven use
• Fireplace use

*Low-cost monitor used in this location
Low-Cost / Consumer Grade Indoor Air Quality Monitors
What’s available to measure PM?
Packaged devices ~$200

- A pleasing box that may have a display or glow according to the perceived IAQ
- May have additional sensors (CO₂, VOC, ...)
- Cloud storage
- Possibility of controlling things

<table>
<thead>
<tr>
<th>Amazon Echo</th>
<th>ecobee</th>
<th>Honeywell</th>
</tr>
</thead>
<tbody>
<tr>
<td>IFTTT</td>
<td>nest</td>
<td>LUX</td>
</tr>
</tbody>
</table>
Low Cost Devices Evaluated ~ $200-300

- **AirBeam**: PM, T, RH
- **AirVisual Node**: PM2.5, PM10, T, RH, CO2
- **AirQualityEgg V2**: PM, T, RH
- **AWAIR**: PM, T, RH, CO2, VOC
- **Dylos DC1700**: Counts (Small, Large)
- **Foobot**: PM, T, RH, CO2, VOC
- **PurpleAir V2**: PM1, PM2.5, PM10, T, RH
- **Speck V2**: Count, PM, T, RH
For what do we need IAQ monitors?

• Measure things we can’t see or smell

• Hazard identification

• Closed loop control

• Assess benefits of controls or retrofits

• Track performance over time

• Quantify IAQ
For what do we need IAQ monitors?

• Measure things we can’t see or smell

• Hazard identification
  Reliable: see every important event
  Some “false positives” OK.
  Reversible: recovers after a spike
  Quantitative not essential
  Drift okay if relating rise to recent

• Closed loop control
For what do we need IAQ monitors?

- Measure things we can’t see or smell
- Assess benefits of controls or retrofits
- Track performance over time
  - Quantitative; Limited drift
  - Not varying with environmental conditions
- Quantify IAQ
## What do we want to measure?

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Identify hazard</th>
<th>Activate controls</th>
<th>Evaluate benefits</th>
<th>Track over time</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Satisfaction</strong></td>
<td></td>
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<tr>
<td>T/RH/CO₂</td>
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<tr>
<td><strong>Smell it</strong></td>
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<tr>
<td>Odors</td>
<td></td>
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<tr>
<td><strong>Smell or see it</strong></td>
<td></td>
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<tr>
<td>Dampness and mold</td>
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<tr>
<td><strong>Misleading</strong></td>
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<tr>
<td>TVOC</td>
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<tr>
<td>Formaldehyde, Radon</td>
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<tr>
<td>Carbon Monoxide (CO)</td>
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<tr>
<td>Acrolein, NO₂</td>
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<tr>
<td><strong>Mostly indoor sources</strong></td>
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<tr>
<td>PM$<em>{2.5}$, PM$</em>{10}$</td>
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<tr>
<td>Ultrafine particles</td>
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<tr>
<td>Irritants / Allergens</td>
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<td><strong>Indoor and outdoor sources</strong></td>
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<td>Diesel PM / Black carbon</td>
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<td></td>
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<td>✔️</td>
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<td>✔️</td>
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<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
</tr>
<tr>
<td>Ozone ($$)</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
</tr>
</tbody>
</table>
Some information on the web

• EPA: mostly focusing on outdoors
  https://www.epa.gov/air-sensor-toolbox

• South Coast AQMD: outdoor and chamber tests
  http://www.aqmd.gov/aq-spec/home

• Carnegie Mellon (chambers)
  https://explorables.cmucreatelab.org/explorables/air-quality-monitor-tests/

• Air quality in China (outdoors)
  http://aqicn.org/sensor/
Low-cost IAQ monitors for residential PM$_{2.5}$

- Most of the existing evaluations of low-cost particle monitors done outdoors or with ideal aerosols
- Particles emitted in homes vary with the source, and may differ greatly from outdoor aerosols

**Question:**
Do any of the available low-cost IAQ monitors provide quantitative data or reliably track reference monitors?

**Study:**
In lab, generate particles from typical indoor activities and compare low-cost to research and reference monitors.
Evaluation of low-cost particle monitors

Experiments conducted in a 120-m³ room
Sources to evaluate low-cost particle monitors

The sources

General

Burning / Heated
Sources to evaluate low-cost particle monitors

Cooking
Reference Instruments ~ $35000 each

Thermo-Scientific TEOM-1405DF

Grimm miniWRAS

Aerosol Spectrometer
Particle size distribution in 41 channels from 10nm up to 35μm

Direct Mass readings
PM$_{2.5}$, PM$_{Coarse}$
Research Instruments ~ $4000-7000

Light scattering devices
PM$_{2.5}$ ~1$\mu$g $\cdot$ m$^{-3}$ to 100+ mg $\cdot$ m$^{-3}$

BT-645

Met One Instruments, Inc.
Ratio of Reference to Low-Cost Response

Pearson's ρ

- < 0.6
- ≥ 0.6 < 0.8
- ≥ 0.8

* Integrations

Mass Median Diameter
None of the devices were quantitative across all or even most of the sources. If sources vary, cannot use low-cost monitors to quantify pollutant exposures.

Several “saw” most of the sources; could be used to control filtration and ventilation to reduce in-home exposures.

All of the low-cost devices failed to see sources dominated by ultrafine particles.

Need another way to detect UFP for control. VOC sensors could partially fill this gap.
Variable Capacity Comfort Systems and Smart Ventilation Systems in High-Performance Homes

Panelists
Eric Martin, Chuck Withers, Danny Parker, and Karen Fenaughty – Florida Solar Energy Center

October 3, 2017
Smart Mechanical Ventilation Systems

- Systems optimize energy consumption and comfort while maintaining IAQ by varying fan operation.

- Systems ventilate more during periods that provide energy, comfort, and/or IAQ advantages and less during periods that provide a disadvantage.

- System operation controlled in response to differing control variables, such as outdoor temperature, outdoor moisture, occupancy, etc.
• Procedures for evaluation of time-varying ventilation

• Occupant exposure to pollutants relative to continuous ventilation

• Average (annual) relative exposure = 1 (chronic exposure)

• Peak exposure < 5 for any time step (acute exposure)

• No existing system varies flow rate while maintaining relative exposure
Real-Time Weather-Based Smart Ventilation

Vary mechanical ventilation airflow with an algorithm that interprets measurements of current and 24-hour historical outdoor temperature and moisture.

\[
RSS = \sqrt{(\Delta T \times X_{\downarrow T})^2 + (\Delta W \times X_{\downarrow W})^2}
\]

Hourly Fan Flow = (Target Fan Flow * (Average RSS$_1$:RSS$_{23}$/RSS$_{24}$))

<table>
<thead>
<tr>
<th>Period (defined by hourly outdoor T)</th>
<th>Parameter</th>
<th>Phase I Scheme Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cooling</td>
<td>Outdoor temp range for cooling period target</td>
<td>&gt; 71.5°F</td>
</tr>
<tr>
<td></td>
<td>Cooling period target fan flow</td>
<td>55 cfm</td>
</tr>
<tr>
<td>Heating</td>
<td>Outdoor temp range for heating period target</td>
<td>&lt; 60°F</td>
</tr>
<tr>
<td></td>
<td>Heating period target fan flow</td>
<td>75 cfm</td>
</tr>
<tr>
<td>Floating</td>
<td>Outdoor temp range for floating period target</td>
<td>&lt;= 71.5°F; &gt;= 60°F</td>
</tr>
<tr>
<td></td>
<td>Floating period target fan flow</td>
<td>138 cfm (fan limit)</td>
</tr>
<tr>
<td>All</td>
<td>Indoor temperature</td>
<td>64.4°F</td>
</tr>
<tr>
<td></td>
<td>Delta-temperature weight ($X_T$)</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Indoor moisture ($W$)</td>
<td>12g/m$^3$</td>
</tr>
<tr>
<td></td>
<td>Delta-moisture weight ($W_W$)</td>
<td>1</td>
</tr>
</tbody>
</table>
Phase I Simulated Results

Phase I Scheme Simulated Smart Ventilation Algorithm, TMY3 Orlando
Fan Flow (79 CFM) and Relative Exposure (1.08)

Phase I Scheme Simulated Smart Ventilation Algorithm, TMY3 Orlando
Hourly Flow and Relative Exposure for July
## Phase II

<table>
<thead>
<tr>
<th>Period</th>
<th>Parameter</th>
<th>Phase I Scheme Values</th>
<th>Phase II Scheme Values</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><strong>Outdoor temp for cooling period target</strong></td>
<td>&gt; 71.5°F</td>
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</tr>
<tr>
<td>Cooling</td>
<td><strong>Cooling period target fan flow</strong></td>
<td>55 cfm</td>
<td>75 cfm</td>
</tr>
<tr>
<td></td>
<td><strong>Outdoor temperature for fan override</strong></td>
<td>n/a</td>
<td>&gt;= 88°F</td>
</tr>
<tr>
<td>Heating</td>
<td><strong>Outdoor temp for heating period target</strong></td>
<td>&lt; 60°F</td>
<td>&lt; 50°F</td>
</tr>
<tr>
<td></td>
<td><strong>Heating period target fan flow</strong></td>
<td>75 cfm</td>
<td></td>
</tr>
<tr>
<td>Floating</td>
<td><strong>Outdoor temp for floating period target</strong></td>
<td>&lt;= 71.5°F; &gt;= 60°F</td>
<td>&lt;= 71.5°F; &gt;= 50°F</td>
</tr>
<tr>
<td></td>
<td><strong>Floating period target fan flow</strong></td>
<td>138 cfm (fan limit)</td>
<td>209 cfm (fan limit)</td>
</tr>
<tr>
<td></td>
<td><strong>Outdoor W to adjust floating period target</strong></td>
<td>n/a</td>
<td>&gt;= 15g/m3</td>
</tr>
<tr>
<td></td>
<td><strong>Floating period target adjusted for W</strong></td>
<td>n/a</td>
<td>75 cfm</td>
</tr>
<tr>
<td>All</td>
<td><strong>Indoor temperature (T)</strong></td>
<td>64.4°F</td>
<td>64.4°F</td>
</tr>
<tr>
<td></td>
<td><strong>Delta-temperature weight (X_T)</strong></td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td><strong>Indoor moisture (W)</strong></td>
<td>12g/m3</td>
<td>12g/m3</td>
</tr>
<tr>
<td></td>
<td><strong>Delta-moisture weight (X_W)</strong></td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

### Graph

**Phase II Scheme Simulated Smart Ventilation Algorithm, TMY3 Orlando**

- **Fan Flow (96 CFM) and Relative Exposure (1.01)**
  - Constant Flow
  - Hourly Smart Fan Flow
  - Daily Avg. RE
FSEC FRTF Labs

- 1,536 ft², 2.2 ACH50
- Supply ventilation
- ASHRAE 62.2-2016

\[ Q_{\text{total}} = Q_{\text{fan}} + \phi Q_{\text{inf}} = 76.1 \text{ cfm} \]

\[ \phi = 1, \quad Q_{\text{fan}} = 66 \text{ cfm} \]

\[ \phi \neq 1, \quad Q_{\text{fan}} = 75 \text{ cfm} \]
Key findings

• Potential to use broadband weather to drive Smart Vent.

• Accurate sensing of local outdoor temperature is
  – Air temperature higher near ground & varies w/ time of day
  – Ideal summer ventilation outdoor target temp not 75, but ~65°F

• Hi-outlet to interior temps emphasize SV comfort potential
Phase I Experimental Results

Smart Ventilation Algorithm: October Average Daily Profile
7% Reduction to cooling (47 kWh); Minor change in interior humidity; RE = 1.25

Average Smart Fan Flow: 66 CFM
Control Fan Flow: 73 CFM

Smart RH
Control RH
OA Inlet Temp
Control AC Power
Smart AC Power

Fan Flow (CFM), RH (%), Temperature (F)

1  2  3  4  5  6  7  8  9  10  11  12  13  14  15  16  17  18  19  20  21  22  23  24

1,800
1,500
1,200
900
600
300

100
90
80
70
60
50
40
30

-
## Phase I vs. Phase II Experimental Results

### Phase I: Summer

<table>
<thead>
<tr>
<th>Month</th>
<th>Cooling Energy (kWh)</th>
<th>Fan Energy (kWh)</th>
<th>Total (kWh)</th>
<th>% Savings</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fixed</td>
<td>Smart</td>
<td>Savings</td>
<td>Fixed</td>
</tr>
<tr>
<td>Aug</td>
<td>1,312</td>
<td>1,295</td>
<td>16</td>
<td>29</td>
</tr>
<tr>
<td>Sep</td>
<td>1,011</td>
<td>1,013</td>
<td>(2)</td>
<td>29</td>
</tr>
<tr>
<td>Oct</td>
<td>671</td>
<td>624</td>
<td>47</td>
<td>29</td>
</tr>
</tbody>
</table>

### Phase II: Summer

<table>
<thead>
<tr>
<th>Month</th>
<th>Cooling Energy (kWh)</th>
<th>Fan Energy (kWh)</th>
<th>Total Energy (kWh)</th>
<th>% Savings</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fixed</td>
<td>Smart</td>
<td>Savings</td>
<td>Fixed</td>
</tr>
<tr>
<td>May</td>
<td>719</td>
<td>630</td>
<td>89</td>
<td>29</td>
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<tr>
<td>Jun</td>
<td>822</td>
<td>749</td>
<td>73</td>
<td>29</td>
</tr>
<tr>
<td>Jul</td>
<td>1,011</td>
<td>924</td>
<td>87</td>
<td>29</td>
</tr>
</tbody>
</table>
Smart Ventilation (SV) Conclusions

- **10% summer cooling energy savings can be achieved**
  - Potential for greater savings with enthalpy heat recovery and optimization of fan energy (var. speed motor)
  - Certainty of improved comfort & likely acceptability
  - Reduction in fan power critical to positive ann. savings
  - Need evaluation of SV control method across climates

For more information:
- [www.fsec.ucf.edu](http://www.fsec.ucf.edu)
- [www.bapirc.org](http://www.bapirc.org)

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