Building America

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Energy Savings from Window Attachments: Please Mind the Gap

Moderator:

Nicole Harrison– National Renewable Energy Laboratory

Panelists:

Katherine Cort – Pacific Northwest National Laboratory

Thomas Culp – Birch Point Consulting

Joseph Petersen– Pacific Northwest National Laboratory

October 28, 2015

PNNL-SA-114072

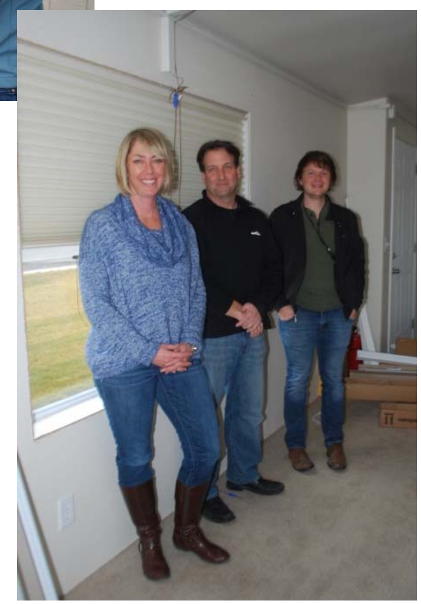
Katherine Cort, Project Lead, Pacific Northwest National Laboratory

- Katherine "Katie" Cort is an economist with PNNL and team lead of Building America's Window Attachments Program. Ms. Cort has over 15 years of experience analyzing energy-efficiency programs, technologies, and research and provides technical support for the U.S. Department of Energy's (DOE) Building Technologies Program.

Key Staff and Partnerships

Pacific Northwest National Laboratory

- Katie Cort
- Joe Petersen
- Sarah Widder
- Jessie Melvin
- Massine Merzouk
- Jessica Weber
- Jake Knox
- Graham Parker



Partners

- Thomas Culp, Birch Point Consulting
- Greg Sullivan, Efficiency Solutions
- Consortium for Energy Efficiency (CEE)
- Todd Stratmoen, Larson Manufacturing Company
- Quanta Technology
- Hunter Douglas
- Northwest Energy Efficiency Alliance, Energy Trust of Oregon

2015 Joint Funding for Experiments

Northwest Energy Efficiency Alliance (NEEA)

- Alliance is made up of more than 140 Northwest utilities and energy efficiency organizations working on behalf of more than 13 million energy consumers in the Northwest.
- Dedicated to accelerating both electric and gas energy efficiency.
- Leverages regional partnerships to advance the adoption of energy-efficient products, services, and practices.
- Mobilizing the market toward energy efficiency is the most cost-effective way to meet our future energy needs.

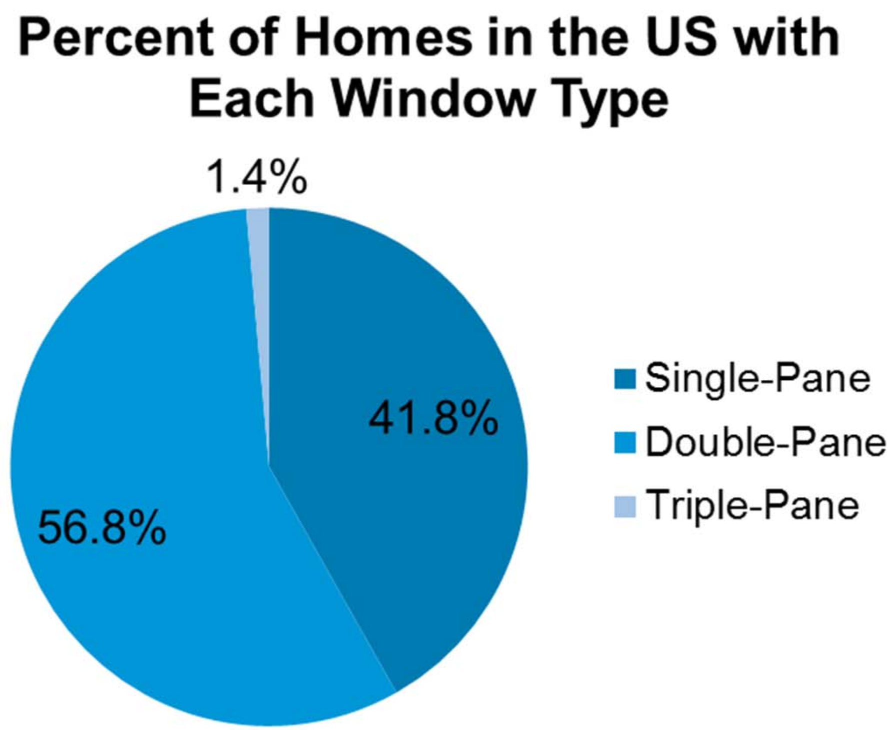
Window Attachments

LEGEND
- ● "Greatest benefit"
- ◐ "Moderate benefit"
- ○ "Neutral or average"
- ⊙ "Potential detriment or weak point"

	Insulation	Airtightness	Solar Heat Control	Winter Comfort	Summer Comfort	Condensation Resistance	Ventilation	Maintains View	Daylighting	Glare Control	Privacy	Low Product Cost	Low Installation Cost[9]	Durability/Service Life[10]	Adjustability	Protection for Window	Noise Control	Egress	Security
Exterior Attachments																			
Low-e storms windows	●	◐	○[1]	●	○[1]	◐	●	●	◐	○	○	○	○	●	◐	●	◐	○	◐
Awnings	○	○	●	○	●	○	●	◐[2]	◐	●	○	○	⊙[3]	◐	◐[4]	◐	○	●	○
Roller shades	○	○	●	○	●	○	◐	○	○	◐	●	◐	◐	○	◐	◐	○	○	○
Roller shutters	◐	○	●	○	●	○	○	⊙	⊙	●	●	⊙	⊙	●	◐	●	◐	○	●
Interior Attachments																			
Conventional roller shades	○	○	◐	◐	◐	○	○	○	◐	◐	●	●	●	○	◐	○	○	○	○
Conventional drapes	○	○	◐[5]	◐	◐	○	○	○	○	◐	●	●	●	○	◐	○	○	○	○
Louvered blinds	○	○	◐	○	◐	○	◐	◐	●	●	●	●	●	○	●	○	○	○	○
Insulated window panels	◐[6]	◐	○[1]	◐	○[1]	◐	⊙	●	◐	○	○	◐[7]	●	○	⊙	○	◐	⊙	◐
Insulated cellular shades[8]	●	◐	◐	●	◐	⊙	○	○	◐	◐	●	○	◐	◐	●	○	◐	○	○
Window quilts	●	◐	◐	●	◐	⊙	⊙	⊙	⊙	○	●	○	⊙	○	◐	○	◐	○	○
Surface-applied films	○	○	◐	○	◐	○	○	◐	◐	◐	◐	◐	◐	○	○	○	◐	●	◐
Other																			
Existing window rehab	○	◐	○	◐	○	○	●	●	◐	○	○	●	⊙	◐	●	◐	◐	◐	○
Solar Screens	○	○	●	○	◐	○	◐	⊙	⊙	◐	○	◐	●	◐	⊙	○	○	○	○
Seasonal single-use	◐	●	○	◐	○	●	⊙	◐	◐	○	○	●	●	⊙	⊙	○	○	○	○

Window Retrofit Opportunities

- 19 billion ft^2 of existing residential windows
- ~47 million homes with single glazing, another
- ~46 million with double pane clear[1]



[1]Cort (2013) and DOE-EIA

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Window Retrofit Opportunity

Existing buildings

- 25-30% of heat losses in building are through the window (infiltration and conduction)

New buildings (residential)

- Windows account for 60% of heat losses[1]

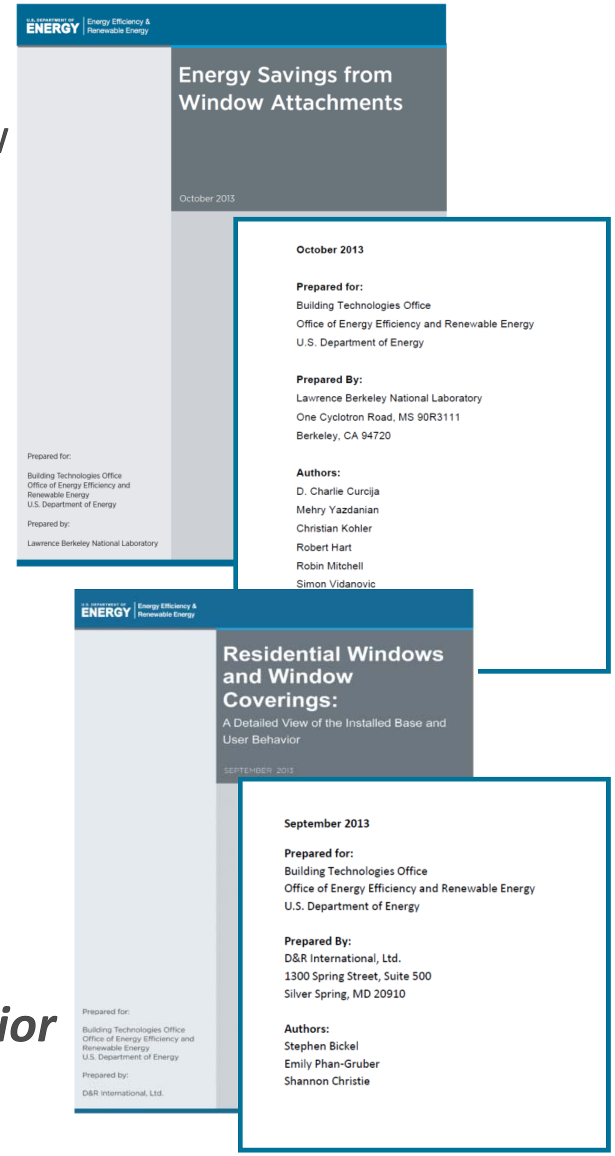
Opportunity

- Window attachments can offer affordable solutions to insulating and air sealing existing windows
- Applicable to existing homes and buildings
- Meets savings-to-investment ratio payback threshold for most weatherization and utility programs
- Easy to install

[1] Source: Huang et al. 1999

Energy Savings Potential of Window Attachment Products

- Comprehensive energy-modeling study that examined 11 different typical residential window attachments including:
  - shades
  - blinds
  - storm window panels
  - surface-applied films
- Baseline with 4 types of houses, 3 types of windows, in 12 climate zones
- Operation assumptions based on DRI study
- For most attachments examined, energy savings significant, but results depend on type of attachment, season, climate, and operation.
- *In heating-dominated climates in north/central zones, **low-e insulating storm panels (both interior and exterior) and insulating cellular shades** are the most effective at reducing HVAC .*



Market Assessment

Barrier	Strategy/Pathway to Overcoming Barriers
Identity Crisis	CEE, Weatherization programs, Utilities, Codes and rating organizations
Stigma (storm windows)	Utilities, CEE, WAP, and Federal agencies
Not recognized by rating systems	Codes and rating organizations: AERC, Building America's CSI team, ENERGY STAR (EPA/DOE), BEOPT, Home Energy Score (DOE)
Do-it-yourself (or not)	Weatherization programs, Home Performance with ENERGY STAR, Federal Energy Management Program (FEMP)
Permanence and Persistence (utility programs)	Utilities, CEE, follow-up on field studies (e.g., Chicago study follow-up)

Addressing Market Barriers

- DOE's Attachments Energy Rating Council (AERC) effort to help develop fenestration attachment rating system. See http://aercnet.org/ for more information.
- Working with CEE to develop tools and resources related to efficient window attachments for energy-efficiency programs.
- Low-e storm windows integrated in FEDS model (supports most Federal building energy audits).
- Working directly with utility and weatherization programs to provide technical assistance. July 2015 Bonneville Power Administration's Regional Technical Forum (RTF) adopted low-e storm windows as "proven" measure. http://rtf.nwcouncil.org/meetings/2015/07/

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Other Resources

Tom Culp, Owner, Birch Point Consulting, LLC

Thomas Culp is the owner of Birch Point Consulting, LLC which provides engineering and strategic consulting services in the areas of energy efficient window performance, building code development, glass performance, and glass coatings.

The New Look of Low-E Storms: Inside and Out

- Cost is about one-third of the cost of full window replacement!

Images courtesy of Larson Manufacturing Company and QUANTAPANEL

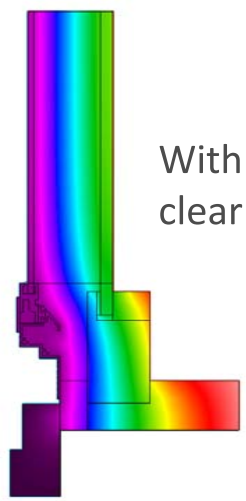
- Aesthetically pleasing
- Operable
- Adds comfort
- Similar energy savings to full window replacement

Low-E Storm Windows: Concept

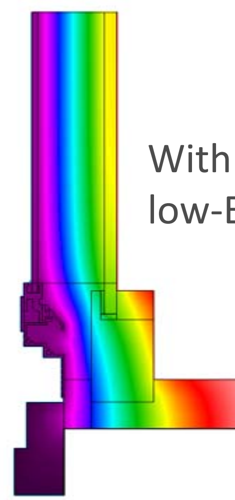
In late 90's, LBNL suggested that low-e storm windows could be a cost-effective **insulating** and **sealing** measure for existing windows:

- Air Sealing of Prime Window
  - Case studies show 10% reduction in overall home air leakage
- Creation of "Dead Air Space"
  - Reduce Conduction and Convective losses across prime window
- Reflection of Radiant Heat: Low-E Glass
  - 35% increased performance over clear glass

Fixed wood window, single glazed



With exterior storm, clear glass

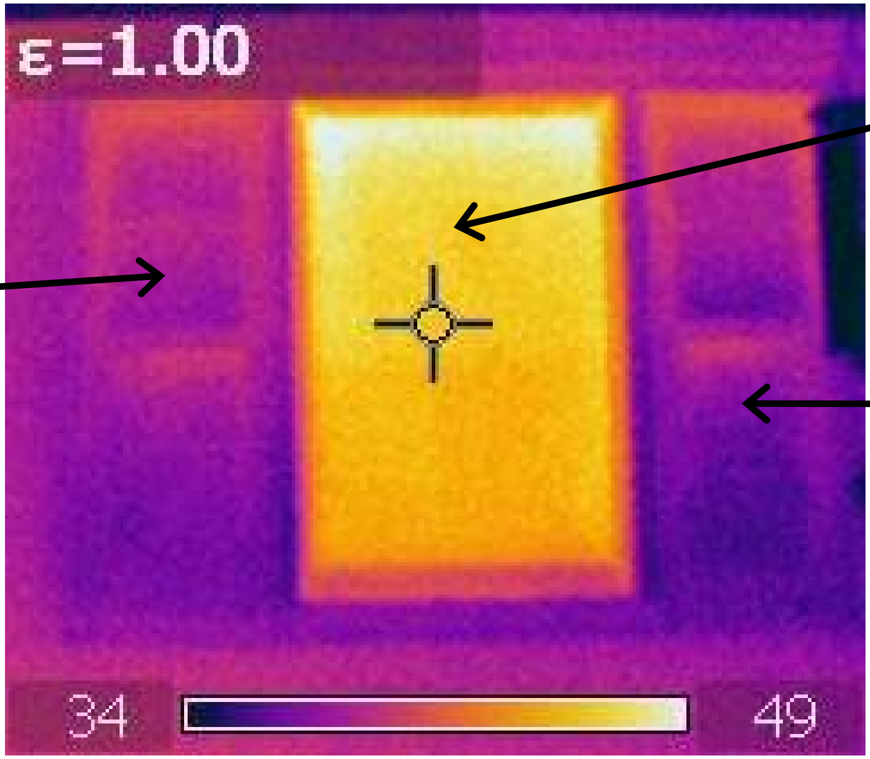


With exterior storm, low-E glass

Low-E Storm Windows: Concept

- IR field images show obvious heat loss reducation:

With Low-E Storm Window



Original single-pane window

With Low-E Storm Window

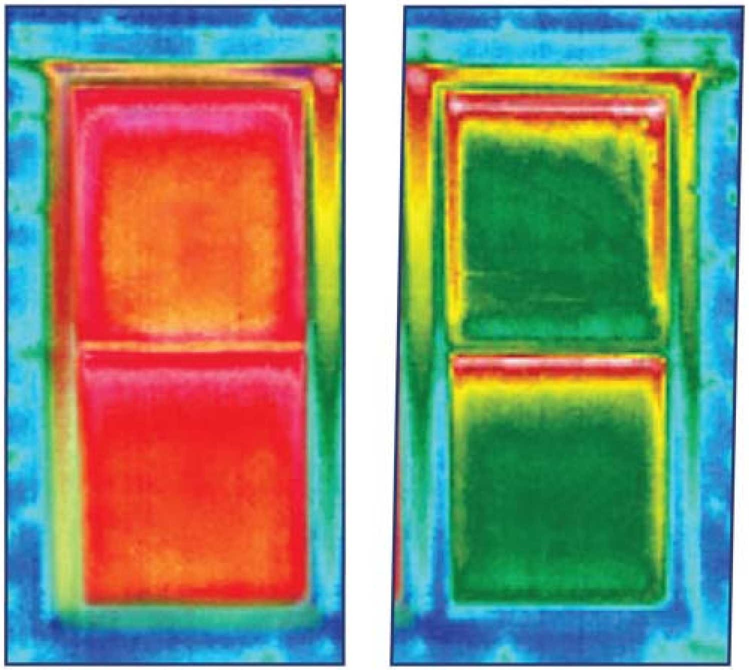
Image taken from the exterior.
Light colors show heat loss.

Insulated Cellular Shades

- Aesthetically pleasing
- Operable
- Adds comfort and privacy
- Significant heating and cooling energy savings
- Home resale value increase

Images of Hunter Douglas Duette Architella Trielle shades. Courtesy of Hunter Douglas.

Insulated Cellular Shades: Concept



No window covering

Duette® Architella™ honeycomb shades

Heating Savings

- Approximately half of a home's heating energy goes out the window.
- Energy-efficient window coverings can reduce heat loss through windows by 40% or more.
- Equates to 20% heating energy savings.
- Assumes proper operation.

Cooling Savings

- With standard double-pane windows, approximately 76% of incident sunlight enters the windows to become heat.
- Cellular shades can reduce unwanted solar heat through windows by up to 80%, reducing the total solar gain to 15% or less.

Window Properties with Low-E Storm Windows

Over *single pane* windows, U-factor decreased 59-64% with low-E panel

Over *double pane* windows, U-factor decreased 43-57% with low-E panel

SHGC reduced by 17-28%
(more with solar control low-E glass, not shown)

Base Window	Storm Type	U-Factor	SHGC	VT
Wood Double Hung, Single Glazed	--	0.88	0.61	0.66
	Clear, Exterior	0.47	0.54	0.57
	Clear, Interior	0.46	0.54	0.59
	Low-e, Exterior	**0.36**	**0.46**	0.52
	Low-e, Interior	**0.34**	**0.50**	0.54
Wood Double Hung, Double Glazed	--	0.51	0.57	0.61
	Clear, Exterior	0.34	0.49	0.53
	Clear, Interior	0.32	0.51	0.55
	Low-e, Exterior	**0.28**	**0.42**	0.48
	Low-e, Interior	**0.26**	**0.47**	0.50
Wood Fixed, Single Glazed	--	0.87	0.64	0.69
	Clear, Exterior	0.46	0.58	0.62
	Clear, Interior	0.45	0.56	0.62
	Low-e, Exterior	**0.34**	**0.50**	0.56
	Low-e, Interior	**0.34**	**0.52**	0.57
Wood Fixed, Double Glazed	--	0.47	0.60	0.64
	Clear, Exterior	0.32	0.53	0.57
	Clear, Interior	0.32	0.54	0.58
	Low-e, Exterior	**0.27**	**0.46**	0.52
	Low-e, Interior	**0.25**	**0.50**	0.53

Culp et al, 2015
PNNL-24444

Window Properties with Low-E Storm Windows

Over *single pane* windows, U-factor decreased 59-64% with low-E panel

Over *double pane* windows, U-factor decreased 43-57% with low-E panel

SHGC reduced by 17-28%
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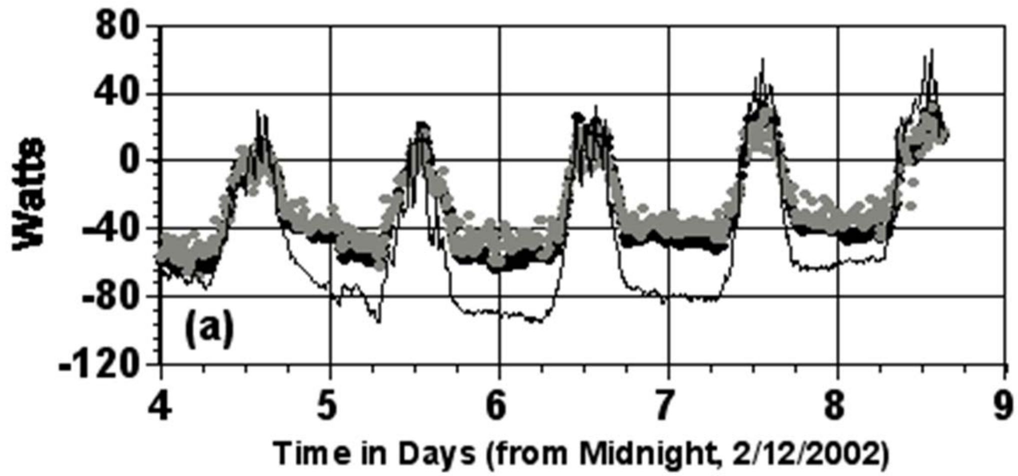
Culp et al, 2015
PNNL-24444

Base Window	Storm Type	U-Factor	SHGC	VT
Aluminum Double Hung, Single Glazed	--	1.12	0.61	0.65
Worst case mounting	Clear, Exterior	0.67	0.56	0.58
Thermally broken mounting (recommended)	Clear, Exterior	0.58	0.56	0.59
	Clear, Interior	0.53	0.53	0.59
Worst case mounting	Low-e, Exterior	0.57	0.47	0.53
Thermally broken mounting (recommended)	**Low-e, Exterior**	**0.44**	**0.48**	0.54
	Low-e, Interior	**0.41**	**0.50**	0.54
Aluminum Double Hung, Double Glazed	--	0.75	0.58	0.60
Worst case mounting	Clear, Exterior	0.55	0.51	0.54
Thermally broken mounting (recommended)	Clear, Exterior	0.45	0.52	0.55
	Clear, Interior	0.41	0.51	0.55
Worst case mounting	Low-e, Exterior	0.49	0.44	0.49
Thermally broken mounting (recommended)	**Low-e, Exterior**	**0.36**	**0.44**	0.50
	Low-e, Interior	**0.32**	**0.47**	0.50
Aluminum Fixed, Single Glazed	--	1.06	0.72	0.77
Worst case mounting	Clear, Exterior	0.62	0.59	0.62
Thermally broken mounting (recommended)	Clear, Exterior	0.55	0.61	0.65
	Clear, Interior	0.51	0.60	0.66
Worst case mounting	Low-e, Exterior	0.51	0.50	0.57
Thermally broken mounting (recommended)	**Low-e, Exterior**	**0.42**	**0.52**	0.59
	Low-e, Interior	**0.38**	**0.56**	0.60
Aluminum Fixed, Double Glazed	--	0.62	0.67	0.71
Worst case mounting	Clear, Exterior	0.47	0.54	0.58
Thermally broken mounting (recommended)	Clear, Exterior	0.40	0.56	0.60
	Clear, Interior	0.36	0.57	0.61
Worst case mounting	Low-e, Exterior	0.42	0.47	0.52
Thermally broken mounting (recommended)	**Low-e, Exterior**	**0.33**	**0.48**	0.55
	Low-e, Interior	**0.29**	**0.53**	0.56

Initial Testing

- 2000-2002: side-by-side testing in LBNL's MoWITT facility.
- Demonstrated low-e storm window + primary window performed same as new double-pane low-e replacement window.[1]

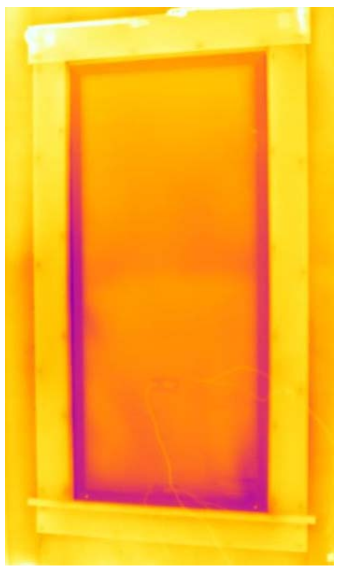


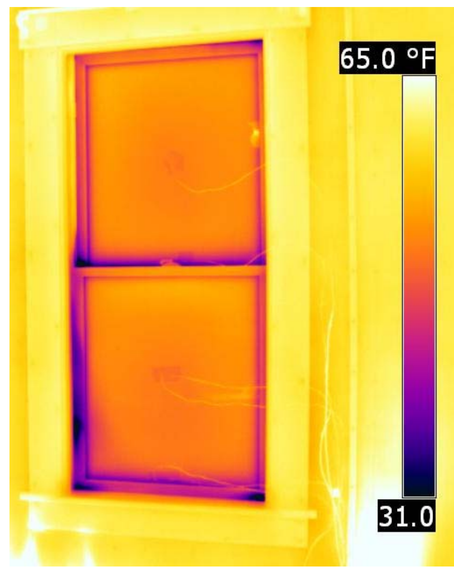
[1] Klems, 2003

IR Imaging with LBNL, Building Green

- Interior low-e storm panel showed comparable performance as replacement sashes with low-e + argon
- Improvement from low-e glass and very good air tightness

interior low-e panel over "vintage" single-pane wood frame window





Single-pane replaced with dual glazed low-e + argon sash inserts

Vermont winter night. Image taken from the interior. Dark colors show heat loss.

P. Yost, Building Green; H. Goudy and D.C. Curcija, LBNL

Demonstration Case Studies

2003-2006 Chicago field study

(DOE, HUD, NAHB Research Center, LBNL)[1]

- Energy monitoring on 6 weatherization homes with single glazing
- Low-e storm installation (all windows)
- Reduced heating load of the home by 21%
- Simple payback of 4.5 years
- Overall home air infiltration reduced by 6-8% (15 cfm_{50} reduction per window)

[1] Drumheller, 2007

Demonstration Case Studies

2011-13 Atlanta field study
(NAHB Research Center, Larson Manufacturing, QUANTAPANEL)[1]

- 10 older homes with single glazing
- Low-e storm window installation over all windows
- Approx 15% heating savings, 2-30% cooling savings (large variability)
- Overall home air leakage reduced by 17% (3.7 ACH50)
- Occupants ranked other benefits:
  - improved home appearance
  - reduced drafts
  - improved comfort
  - reduced noise

[1] Culp et al, 2013

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Demonstration Case Studies

2012-13 Philadelphia multifamily field study

(NAHB Research Center, QUANTAPANEL, Larson Manufacturing)[1]

- Two large 3-story apartment buildings (101 apartments)
- Replaced old clear storm windows over single glazing with new low-E storm windows (interior)
- 18-22% reduced heating energy use
- 9% reduced cooling energy use
- Apartment air leakage reduced by 10%

[1] Culp et al, 2013

Real-World Examples

Photos courtesy of QUANTAPANEL

Success Stories - Weatherization

- 2009: Ability to include low-E storm windows added to NEAT / Weatherization Assistant software
- 2010: With DOE support, low-E storm windows added to Pennsylvania's Weatherization Measure Priority List for single-family homes[1]
  – NEAT analysis for 37 home types in 4 cities
  – SIR 1.4-2.2 over single-pane windows
  – SIR 1.3-2.1 over metal-framed dual-pane windows
  – SIR much higher when using propane fuel

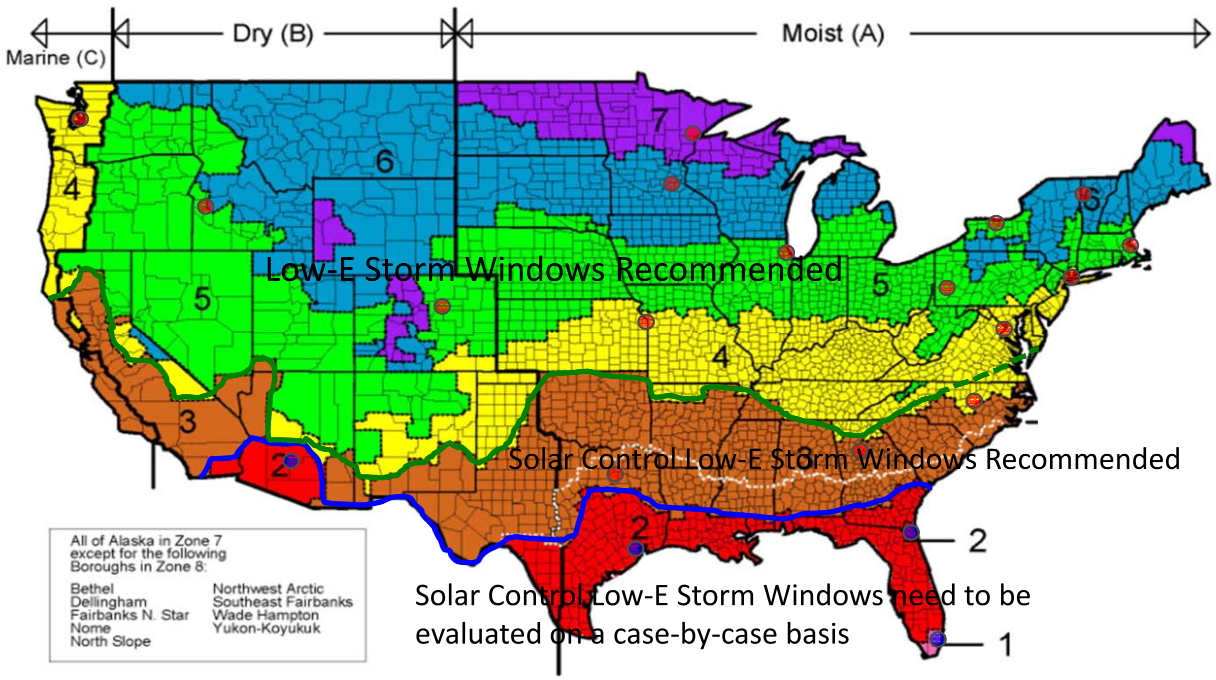
SIR = Savings-to-Investment Ratio. Must be > 1 to qualify.

[1] Zalis et al, 2010

Success Stories - Weatherization

Expanded NEAT and RESFEN analysis to 22 cities across all 8 climate zones.[1]

Over all single pane windows and double-pane metal-framed windows:



Cost effective in climate zones 3-8 with SIR 1.2 – 3.2

[1] Culp et al. 2014 and 2015. PNNL-22864 rev2 and PNNL-24826

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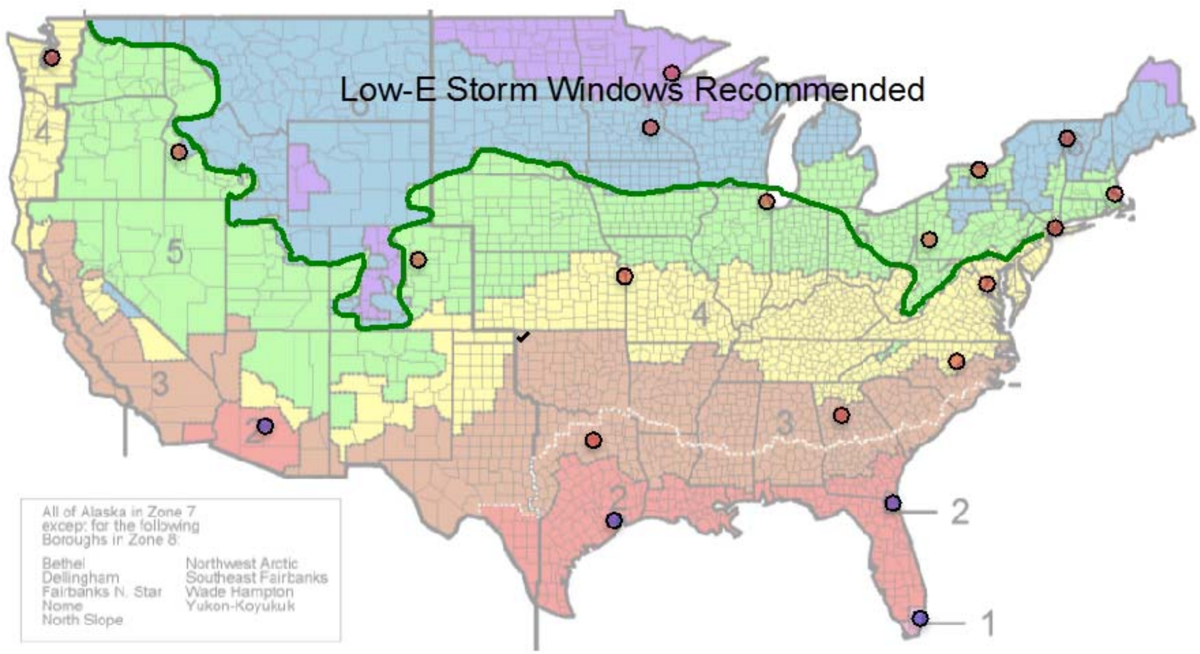
Success Stories - Weatherization

Expanded NEAT and RESFEN analysis to 22 cities across all 8 climate zones.[1]

Over double-pane wood or vinyl-framed windows:



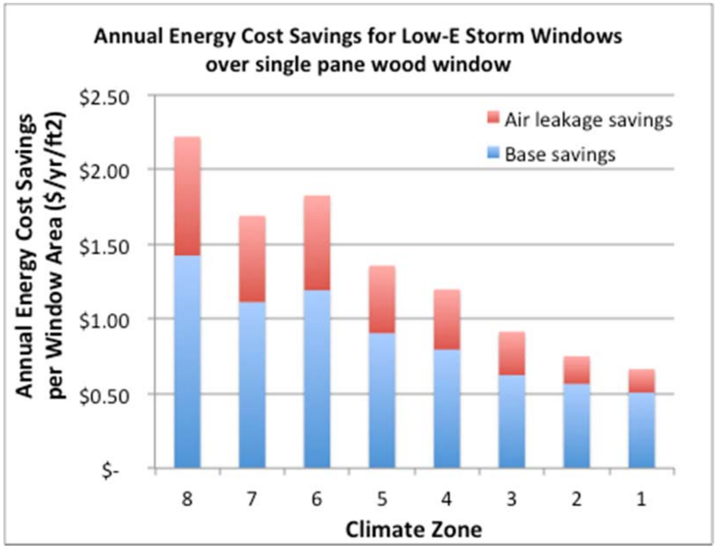
Cost-effective in climate zones 6-8 and eastern part of zone 5 with SIR 1.1 – 1.9.

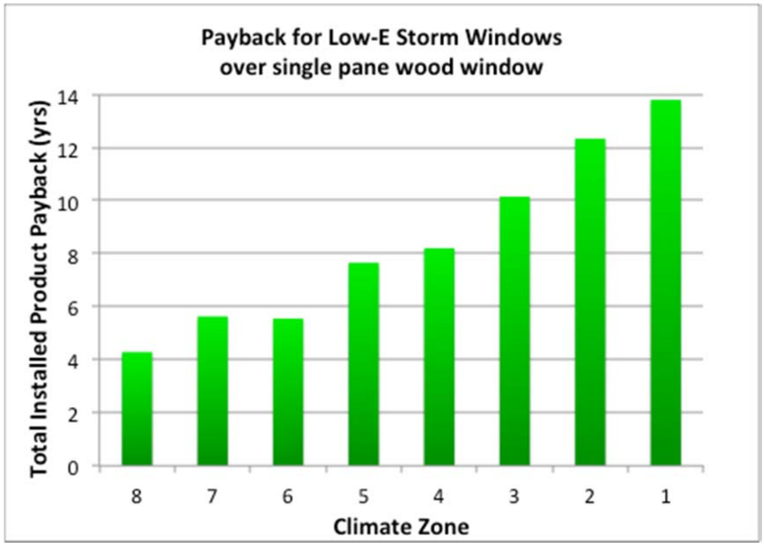
Recommended over even larger range with propane or electrical resistance heat.

[1] Culp et al. 2014 and 2015.
PNNL-22864 rev2 and PNNL-24826

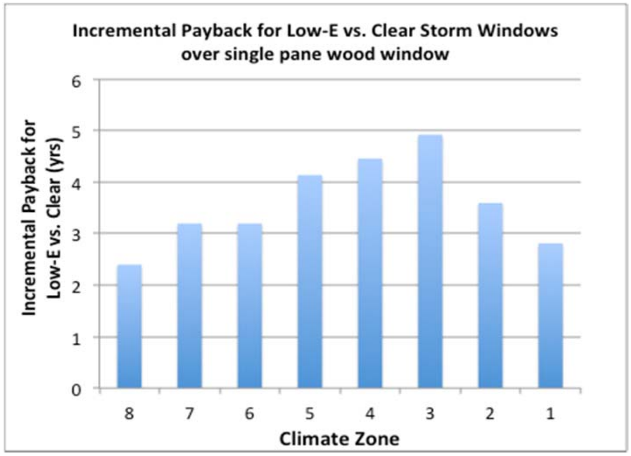
Cost Effectiveness of Low-E vs. Clear Glass Storm Windows

- Energy cost savings of low-E Storms obviously highest in coldest climates.





- Incremental cost of using low-E glass versus clear glass has short payback periods in *all* climate zones, over *all* window types



Culp, et. al. 2015
PNNL-24826

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Joe Petersen, Engineer, Pacific Northwest National Laboratory

- **Joe Petersen** joined PNNL in 2012. He serves as the primary technical lead and point of contact for work done within the PNNL Lab Homes. He has a master’s degree in electrical engineering and completed his thesis on Lab Home research techniques to simulate human occupancy in a controlled experimental setting.

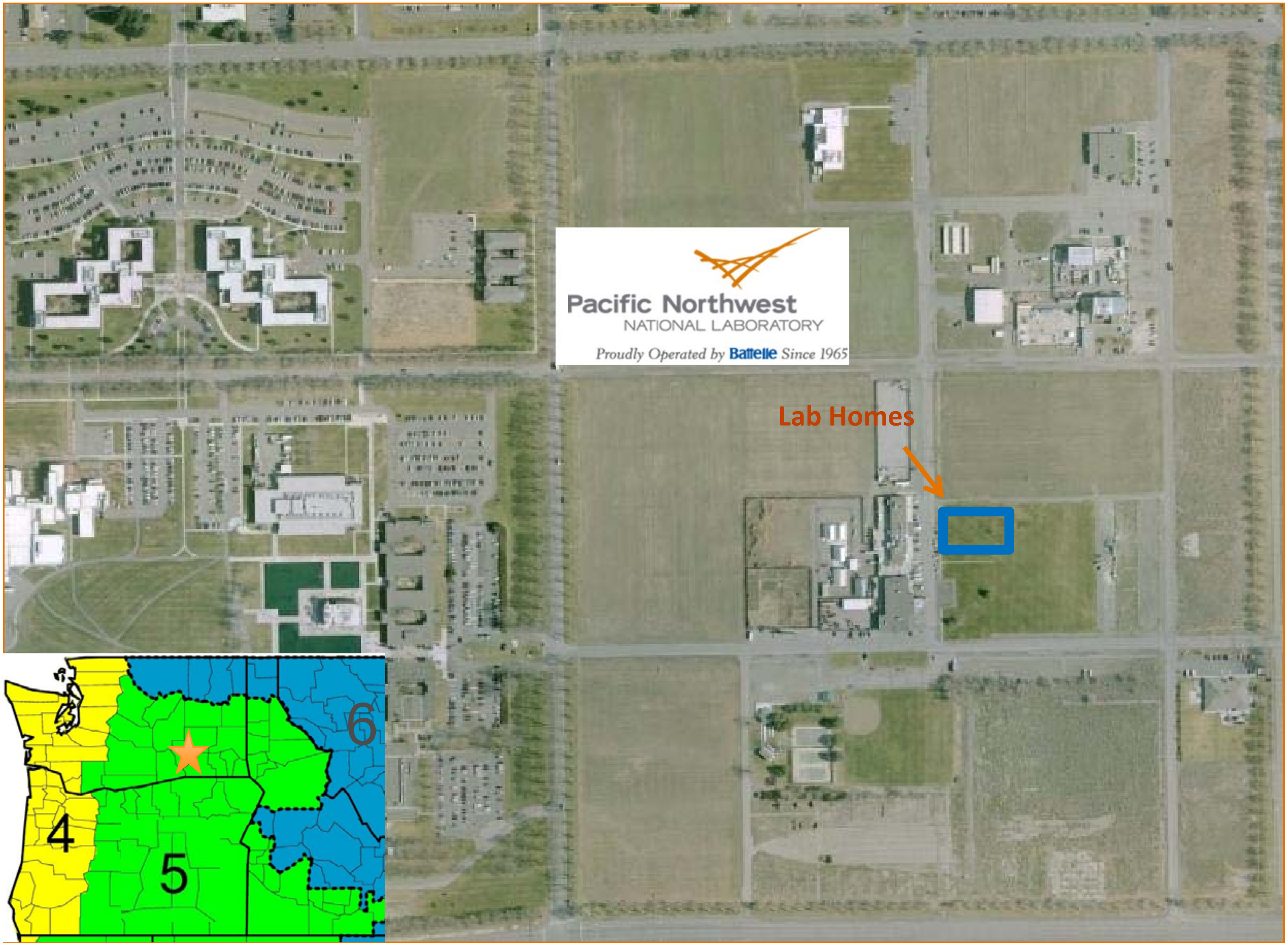
PNNL Lab Homes Field Testing

Side-by-side simulated field environment provides a unique platform for efficiently and cost-effectively demonstrating new energy-efficient and grid-responsive technologies.

Lab Homes Partners

- Initial Partners
  - DOE/BTO/Building America-ARRA
  - DOE/BT/Windows and Envelope R&D
  - Bonneville Power Administration
  - DOE/OE
  - PNNL Facilities
  - Tri Cities Research District
  - City of Richland
  - Northwest Energy Works
  - WSU-Extension Energy Program
  - Battelle Memorial Institute (made land available)

Sited Within the Tri-Cities Research District in Richland, WA



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Lab Homes Characteristics

- Specified to represent existing manufactured and stick-built housing
  - 3 BR/2BA 1493-ft^2 double-wide, factory-built to HUD code.
  - All-electric with 13 SEER/7.7 HSPF heat pump central HVAC + alternate Cadet fan wall heaters throughout
  - R-22 floors, R-11 walls & R-22 ceiling with composition roof
  - **195.7-ft2 (13% of floor) window area**
    - **74% coverage for a total 144.8-ft^2**
  - Wood siding
  - Incandescent lighting
  - Bath, kitchen, whole-house exhaust fans
  - Carpet + vinyl flooring
  - Refrigerator/range/washer/dryer/dishwasher
  - All electric

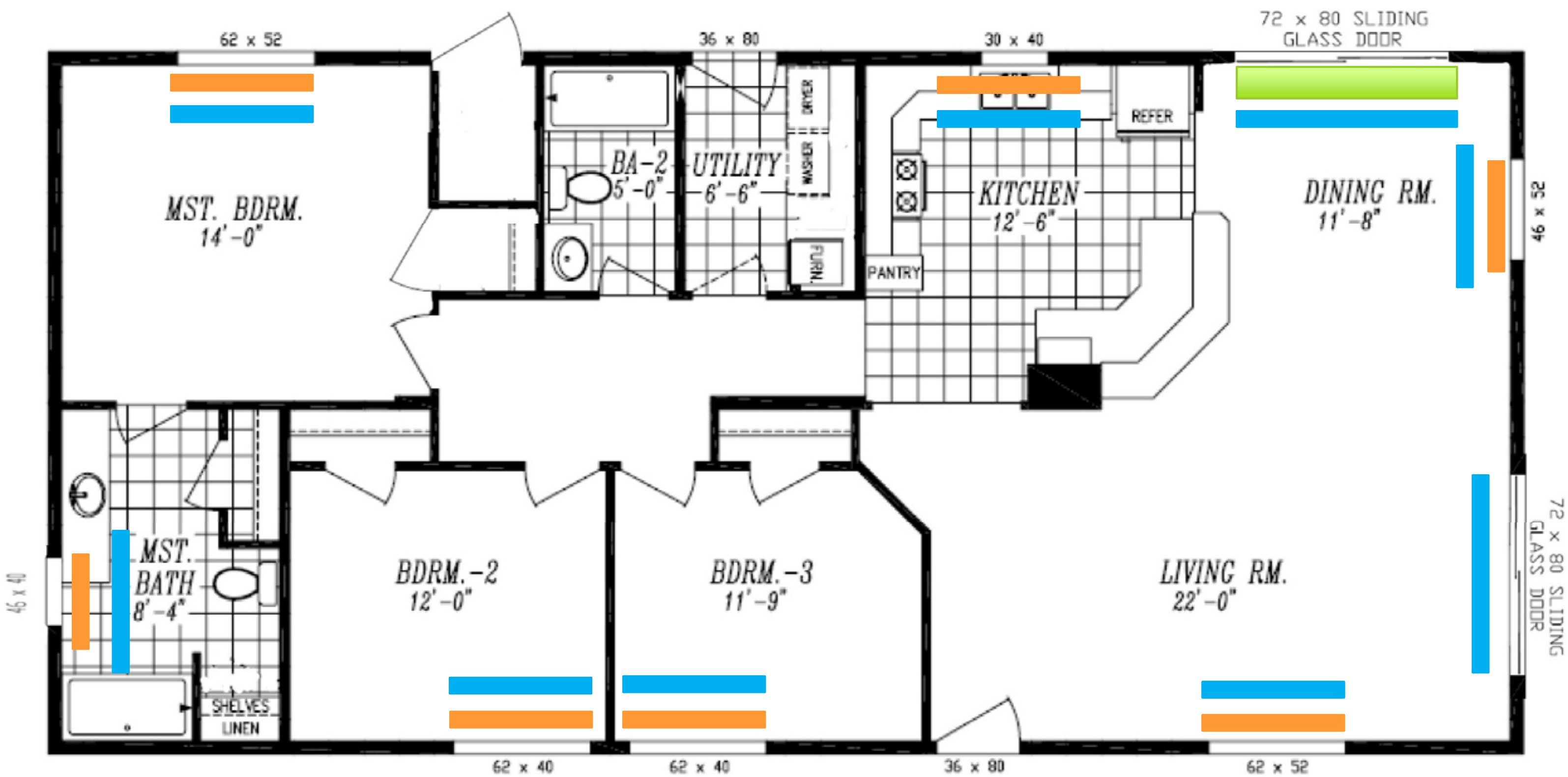
- Modifications include end-use metering, sensors, weather station, and three electric vehicle charging stations

Lab Homes Floor Plan

Sliding Glass Door Retrofit

Interior Storm Window

Hunter Douglas Cellular Shades



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Metering and Monitoring

- Energy metering
  - 42 individually controllable breakers
  - Itron smart billing meter
- Temperature and relative humidity
  - 15 interior room temperature thermocouples
  - 22 interior and exterior glass surface temperature thermocouples
  - 2 room relative humidity sensors
  - 2 mean radiant temperature sensors
- Water and environment
  - Controllable water flows at fixtures
  - Solar insolation (pyranometer) inside home
  - Site weather station
- Data collection via 2 Campbell Scientific data loggers/home
  - 1 minute, 15 minute, and hourly




Window Characteristics

- Baseline primary windows in each home are double-pane, clear glass window with an aluminum frame.

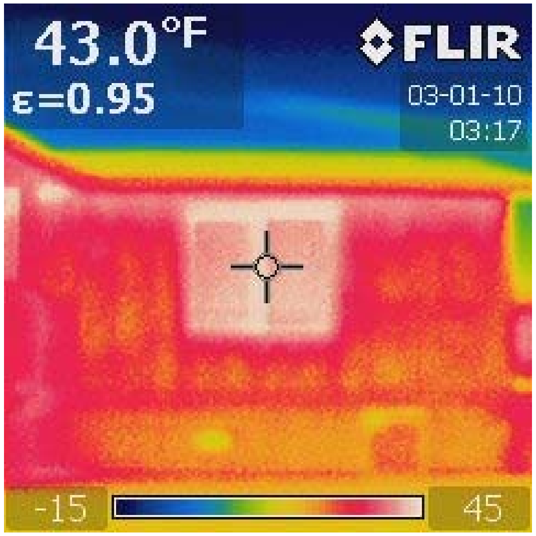
	Baseline Windows		Baseline Windows with Low-E Storms[1]		Highly Insulating Windows[2]	
	Windows	Patio Doors	Windows	Patio Doors	Windows	Patio Doors
U-factor	0.68	0.66	0.32	0.31	0.20	0.20
SHGC	0.7	0.66	0.57	0.53	0.19	0.19
VT	0.73	0.71	0.61	0.59	0.36	0.37

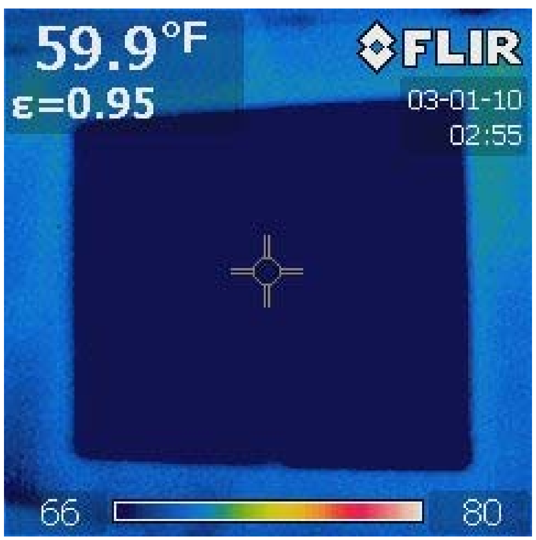
[1] Culp et al, 2015. *Low-E Retrofit Demonstration and Education Program*. Final Report, U.S. DOE project #DE-E E0004015, Quanta Technologies, Malvern, Pennsylvania.
[2] Widder et al, 2012. *Side-by-Side Field Evaluation of Highly Insulating Windows in the PNNL Lab Homes*. PNNL-21678, Pacific Northwest National Laboratory, Richland, WA.

Interior Installation

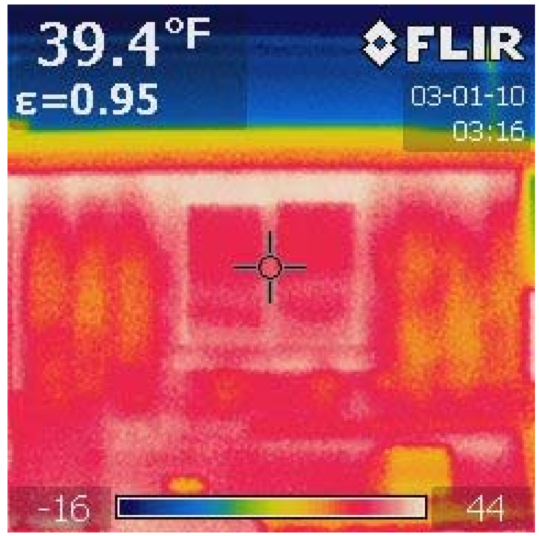
Infrared Images – Interior Storm Windows

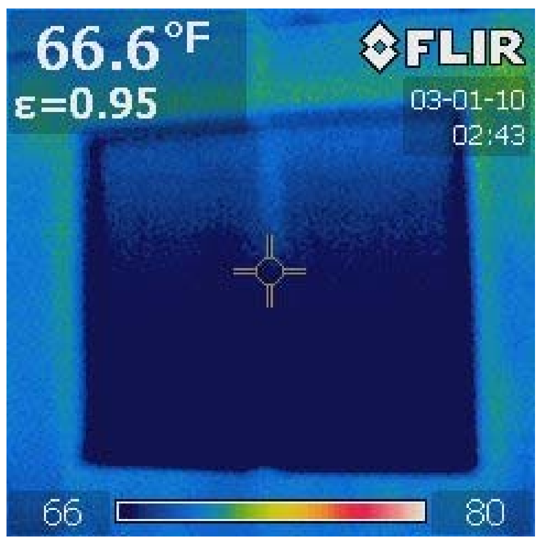
Baseline Home





Experimental Home





Low-e storm panels installed in Experimental Home

Exterior Master Bedroom – ΔT between the two surfaces is 3.6°F

Interior Master Bedroom – ΔT between the two surfaces is 6.7°F

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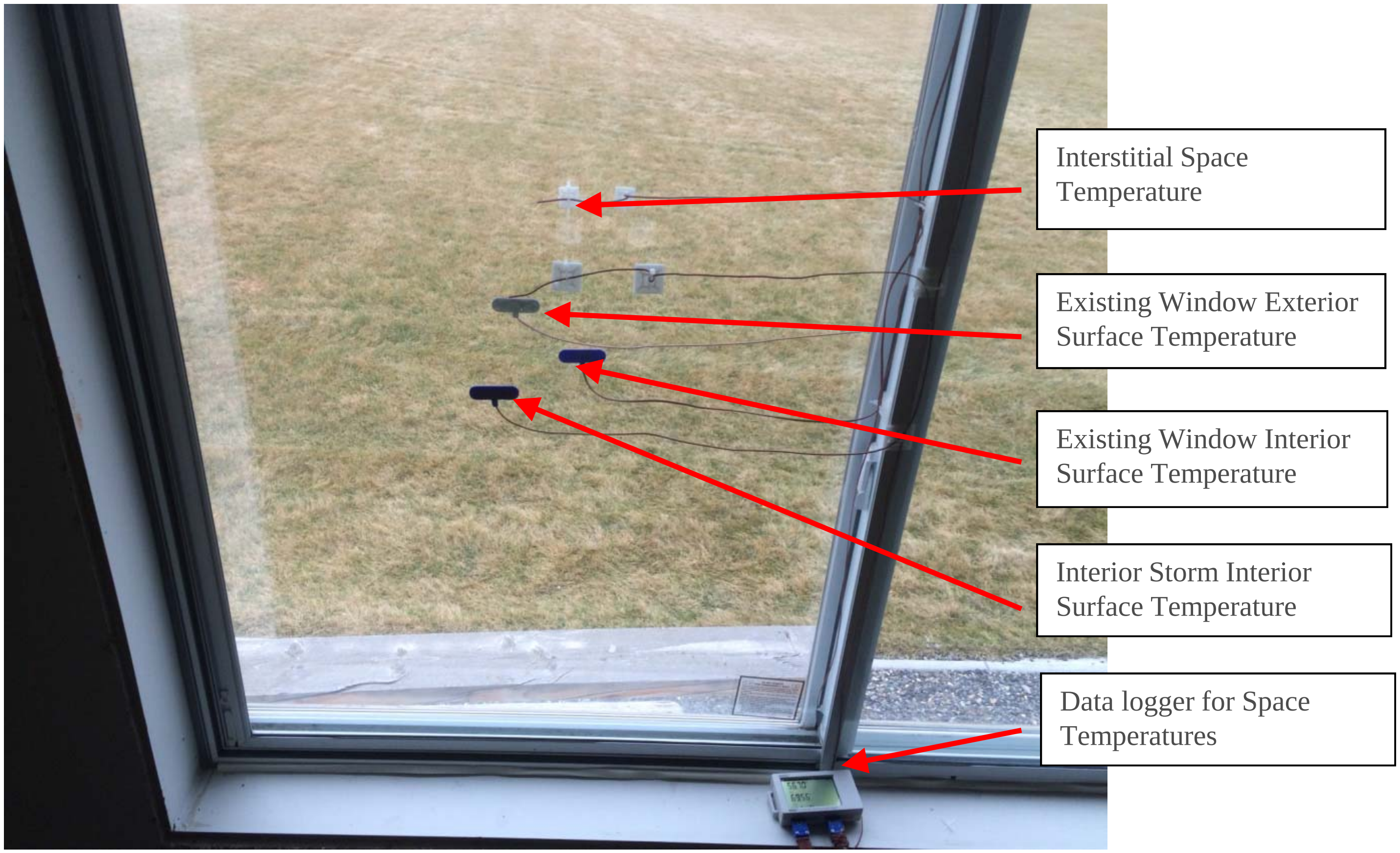
Temperature Profile – Interior Storm Windows

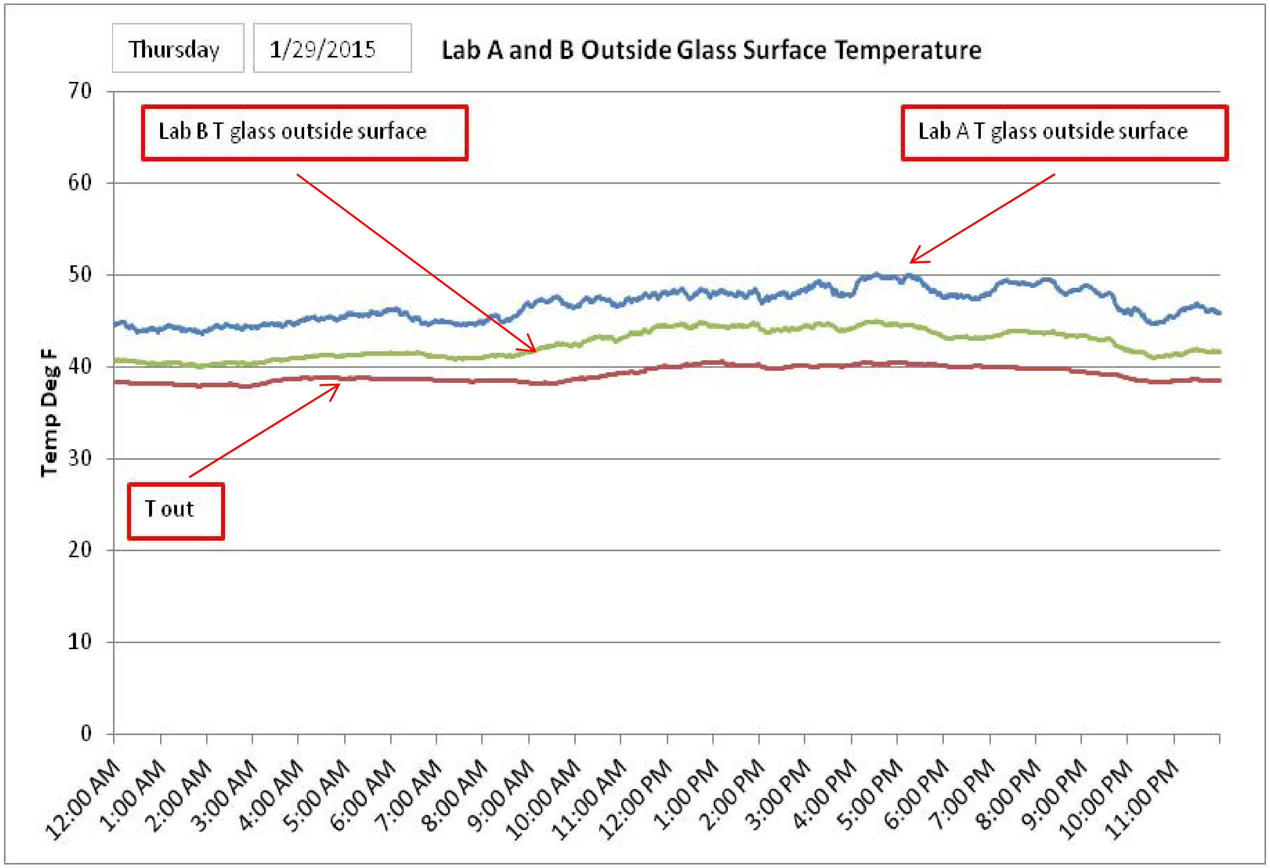
Can infrared pictures be validated with our metering equipment?



Temperature Profile – Interior Storm Windows

Exterior glass temperature comparison during the heating season

- Average Outdoor Air Temperature (OAT) = 40°F
- Baseline home (Lab A) is consistently 5–6 ˚F warmer than the experimental home (Lab B).



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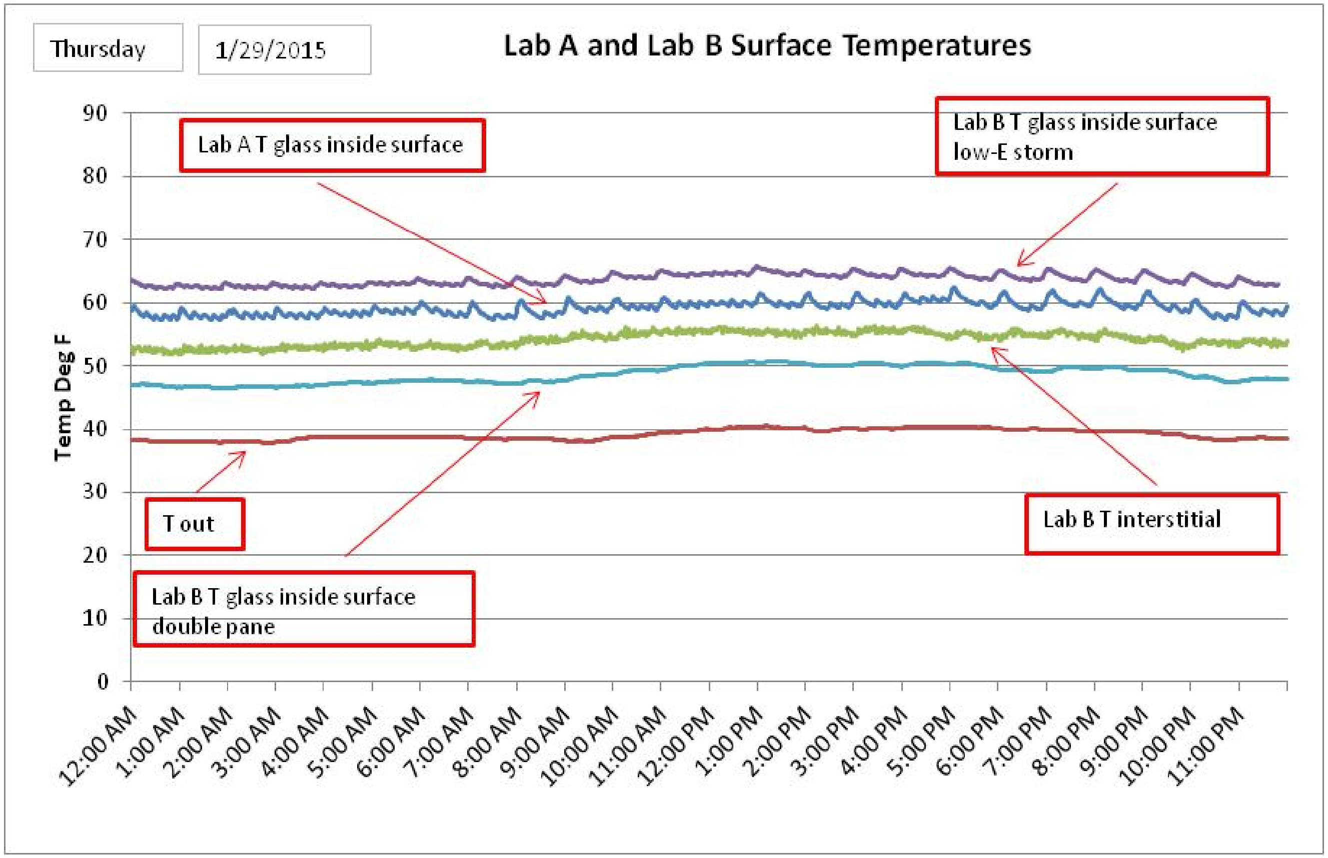
Temperature Profile – Interior Storm Windows

Interior glass and interstitial temperature comparison during the heating season

- Average Outdoor Air Temperature (OAT) = 40°F
- Experimental home (Lab B) is 4–6 ˚F warmer than the baseline home (Lab A)



HVAC Energy Savings

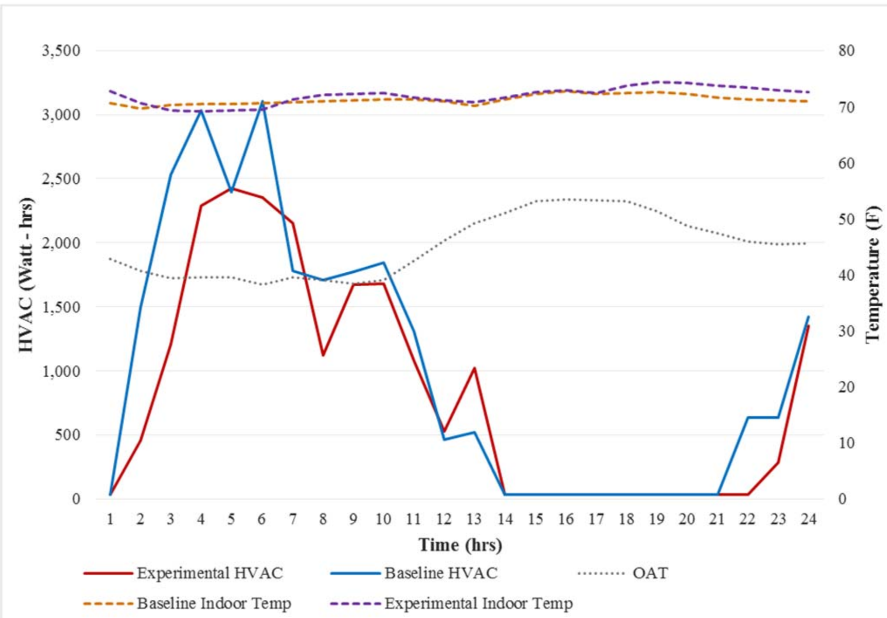
- Average savings from low-E storm windows of 8.1% annually (retrofitting 74% window area), compared to 12% for triple-pane primary windows.

Experimental Period	**Operating Scenario**	**Average Daily Energy Savings***	**Average Energy Savings (%)**
Summer Cooling Season	With Storm Windows in Lab Home B	1,186 ± 202 Wh	4.2 ± 0.7
Winter Heating Season	With Storm Windows in Lab Home B	3,405 ± 659 Wh	8.1 ± 1.9
EnergyPlus Modeled Results	With Storm Windows in Lab Home B	1,006 ± 62 kWh	7.8 ± 1.5
Estimated Annual R-5 Results[3]	*With R-5 Windows in Lab Home B*	*1,784 ± 189 kWh*	*12.2 ± 1.3*

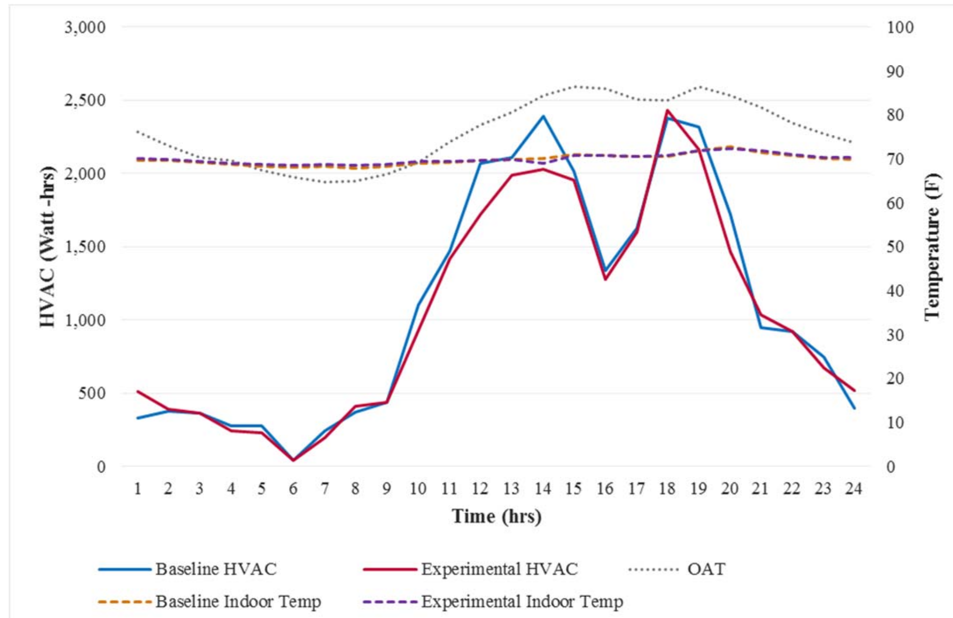
[3] Widder et al, 2012. *Side-by-Side Field Evaluation of Highly Insulating Windows in the PNNL Lab Homes*. PNNL-21678, Pacific Northwest National Laboratory, Richland, WA.
* Savings based on 74% of the total window area covered by interior storm windows

HVAC Energy Use

- Heating and cooling season energy savings



HVAC Energy Consumption on Cold, Sunny Winter Day



HVAC Energy Consumption on Hot, Sunny Summer Day

Insulating Cellular Shades Preliminary Evaluation

Three Measurement Scenarios

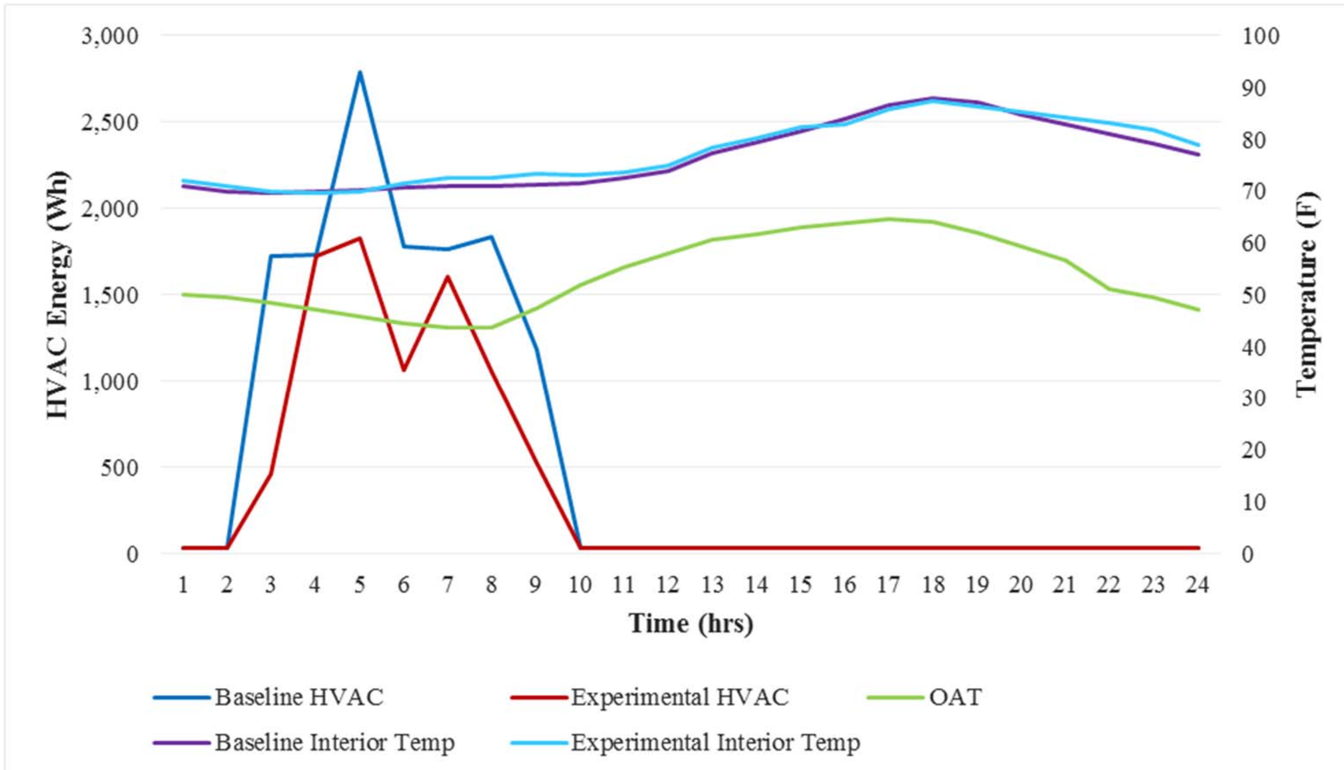
1. Optimum Operation
   - Operation schedule – HD Green Mode
   - Baseline/Control home - no shades
2. Cellular shades-standard vinyl horizontal blind comparison
   - Operation schedule - HD Green Mode
   - Baseline/Control home - standard vinyl horizontal blind
3. Static Operation
   - Window coverings closed
   - Baseline/Control home - vinyl horizontal blind

HVAC Energy Savings

- HVAC energy savings is based on the operational schedule and baseline technology.

Experimental Period	Operating Scenario	Number of experimental days	Baseline	Average Energy Savings (%)
Summer Cooling Season	Static Operation – no operational schedule implemented	14	Vinyl horizontal blinds	13.3 ± 2.8
Summer Cooling Season	Optimum Operational Comparison – HD Green Mode operational schedule	7	Vinyl horizontal blinds	10.4 ± 6.5
Winter Heating Season	Optimum Operational – HD Green Mode operational schedule	9	No window attachments	17.6 ± 8.1

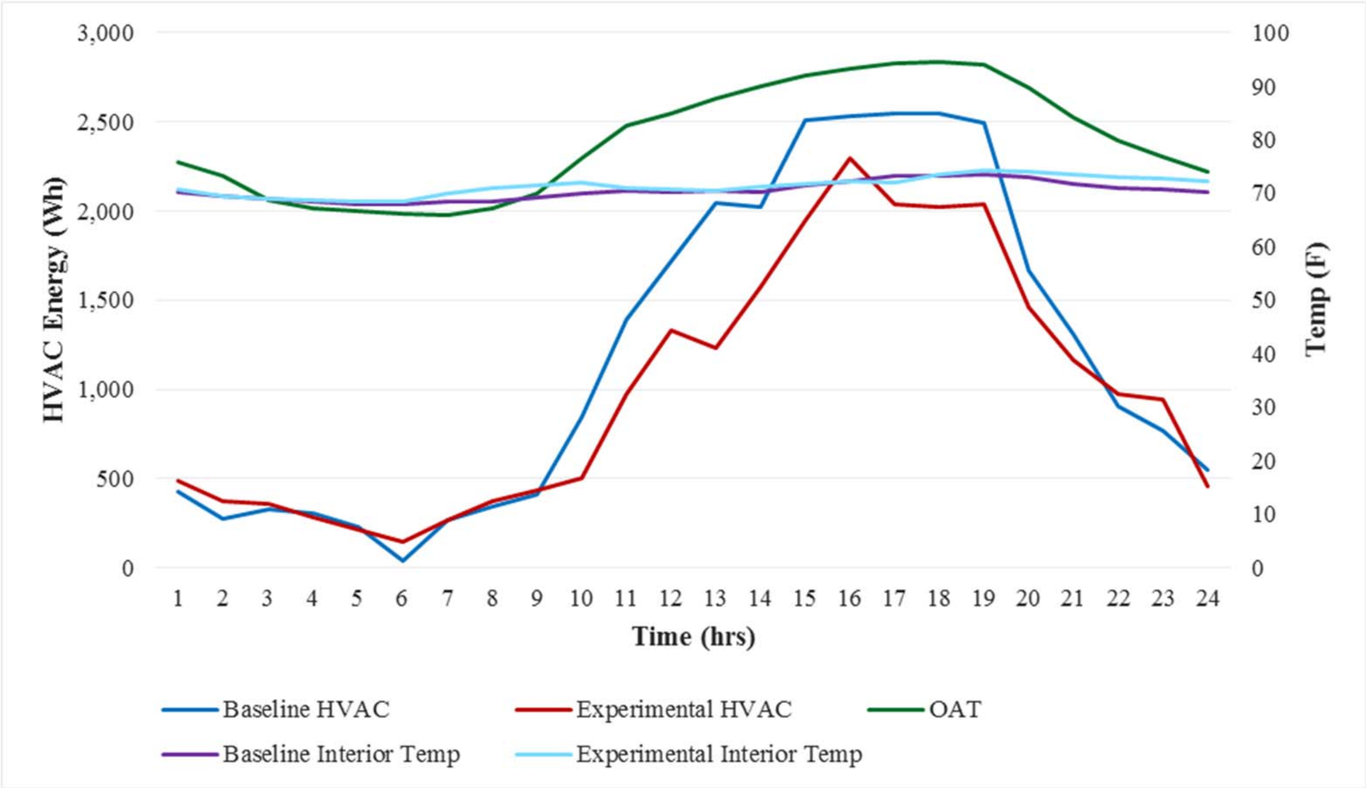
Insulating Cellular Shades: Preliminary Heating Season Data



- HVAC usage during the implementation of the HD Green Mode schedule.
- Comparison between Hunter Douglas Window Attachments in Experimental Home (red) and No Window Attachments in Baseline Home (blue)

Experiment	Number of Days	Savings/ Confidence (95%)
Heating Season – Optimum Operation	9	17.6 ± 8.1%

Insulating Cellular Shades: Preliminary Cooling Season Data



- Insulating value of the Hunter Douglas Cellular Shades (Red) compared to vinyl horizontal blinds (Blue)
- No operational schedule (Static)

Experiment	Number of Days	Savings/ Confidence (95%)
Cooling Season – Static Operation	14	13.3 ± 2.8%

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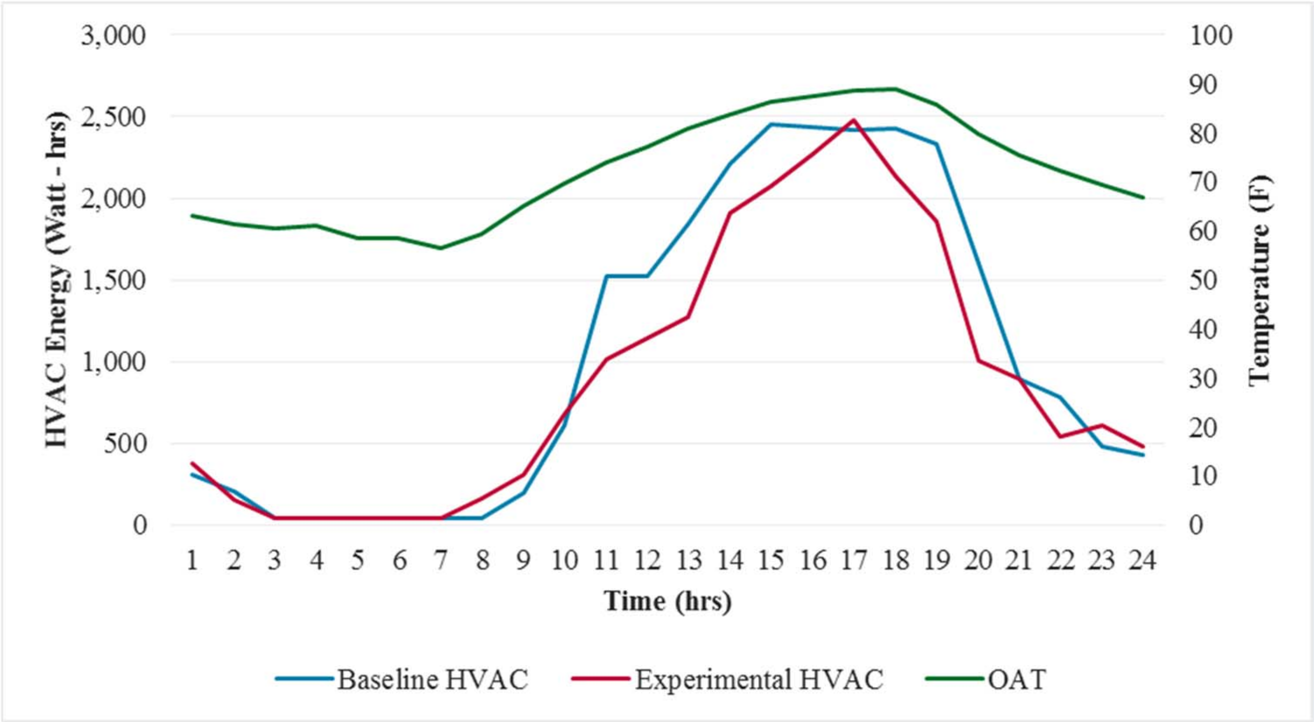
Insulating Cellular Shades: Preliminary Cooling Season Data



- HVAC Usage during the Implementation of the HD Green Mode operational schedule.
- Comparison between Hunter Douglas Cellular Shades and vinyl horizontal blinds

Experiment	Number of Days	Savings/ Confidence (95%)
Cooling Season – Optimum Operation Comparison	7	10.4 ± 6.5%

Remaining Research Questions

- Operation and Automation
  - Optimal operation? Likely operation? Value of automation?
  - Coverage Optimization?
- Optimizing Return on Investment
  - Minimizing costs while maximizing benefits
- Combinations of Attachments
- Assessing Durability and any Unintended Consequences and

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Time for Q&A

Field Implementation Success Stories

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Lab-Home Study and Results

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Window Attachment Efforts at PNNL

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