Integrated Whole-Building Energy Efficiency Retrofit Solution for Residences in Cold/Very Cold Climates

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Market and Implementation Collaborators (MIC) Advisory Board:

Challenge

Problem Definition:

- Whole-building "deep" efficiency retrofits targeting the aging U.S. residential building stock face challenges with **market fragmentation, project complexity and cost, disjointed workflows for design and implementation**, disruption for residents during installation, and barriers to acceptance of the final product's aesthetic appearance.

Examples of single-family attached residences in cold/very cold climates (James Geddes Housing Development, Syracuse Housing Authority)

Goals:

- Develop an ***integrated*** **"one-stop-shop" whole-building solution and protocol** that leverages insulated modular building envelopes and compatible HVAC systems**.**
- **Develop and demonstrate integrated prototypes** for a transformational whole-building retrofit solution that achieves 75% savings in energy used for thermal loads (HVAC and DHW).

Preliminary Results:

- Results to date show the energy savings potential of the whole-building retrofit approach is **78%** relative to the median thermal energy use intensity (EUI) for the single-family attached building type in cold/very cold climates.

Solution

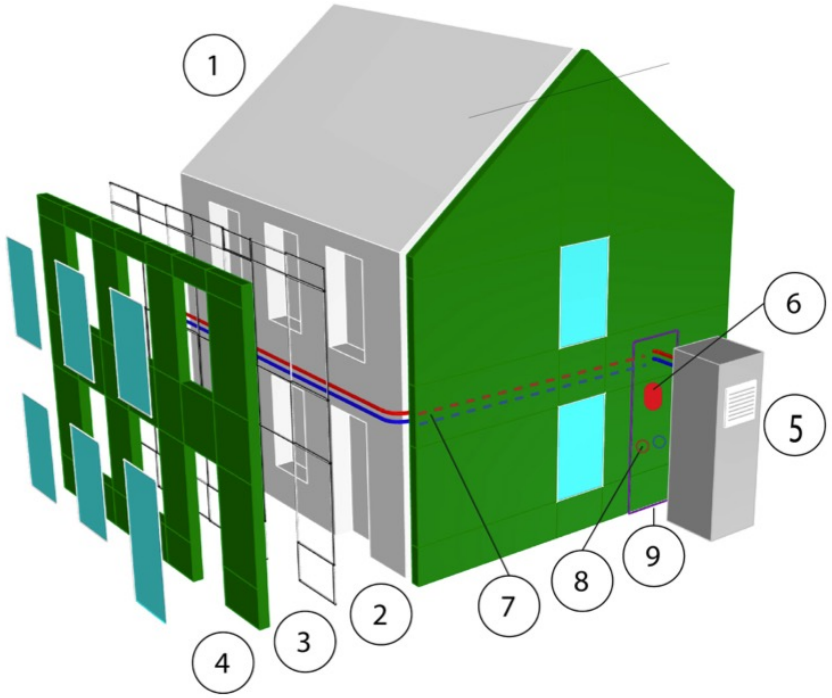
Project Objectives:

To develop and verify an affordable integrated whole-building deep-energy retrofit solution for residences in cold/very cold climates that includes:

1) **A highly-insulated R-30 modular exterior building envelope and attachment system** with integrated flashing solution for windows, doors, and penetrations for mechanical services with airtightness of ≤ 1.0 L/s/m^2 @50 Pa;

2) **An envelope-integrated HVAC system** that connects to a compatible modular mechanical pod with real-time performance monitoring to enhance indoor space conditioning and maintain < 800ppm of CO_2 for enhanced indoor air quality;

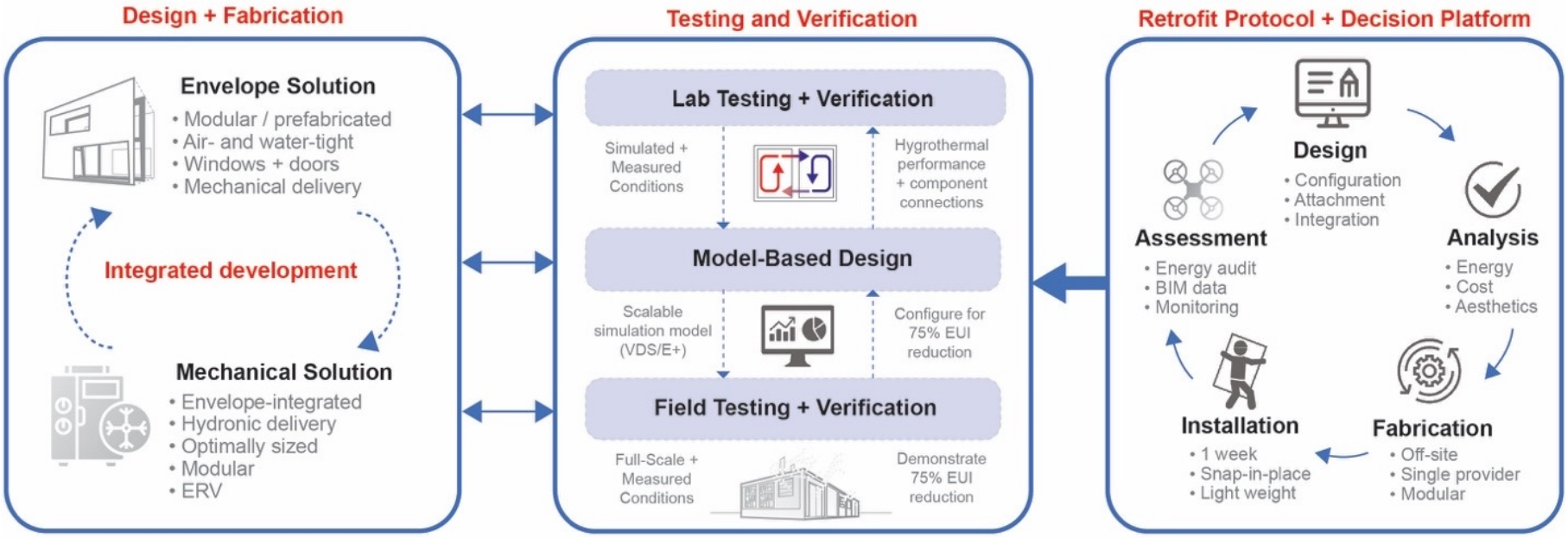
3) **Retrofit protocol and decision-making platform** including a digital component database and modular-based design and analysis tool for selecting and scaling the retrofit modules and optimizing the entire retrofit system for site-specific conditions.



1. Existing single-family attached residence
2. Structural mounting grid
3. Prefabricated insulating panel system
4. Screwless install doors and windows
5. High-efficiency mechanical pod
6. Smart monitoring system
7. Supply/return runs behind envelope panels
8. ERV penetration through existing building
9. Air- and water-tight seal

Objectives

Key Technical Components and Process:



Task 2.0

Design, development and fabrication of mid- and full-scale prototypes for integrated retrofit solution

Task 3.0

Testing and verification through laboratory chamber testing, model-based simulations, and field testing on actual building

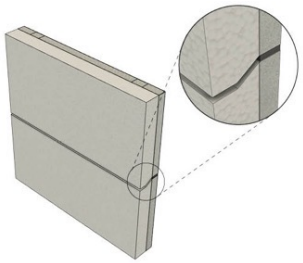
Task 4.0

Design workflow development and documentation for configuring retrofit components for off-site fabrication and fast installation

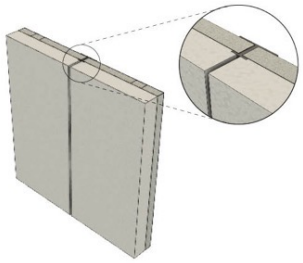
Key Envelope Components

Prototype testing and model-based evaluations at mid-scale and full-scale

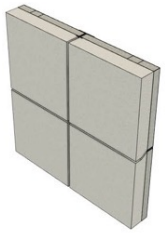
(1) Opaque structural panel



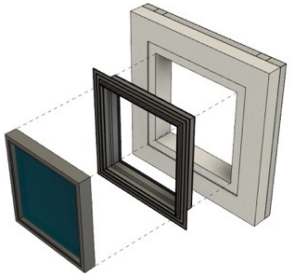
(2) Panel-to-panel horizontal seam and gasket detail



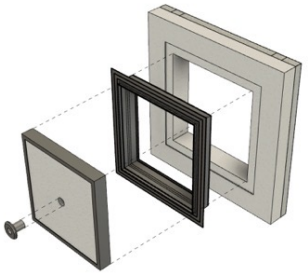
(3) Panel-to-panel vertical seam and back gasket detail



(4) Panel-to-panel vertical and horizontal seam



(5) Panel-to-window with integrated flashing system



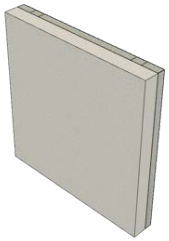
(6) Panel-to-HVAC penetration and integrated flashing system

Building Energy and Environmental Systems Laboratory (BEESL), Syracuse University

Building Envelope Systems Test (BEST) Laboratory, Syracuse University

Key Envelope Components

Design, development, and fabrication of envelope components



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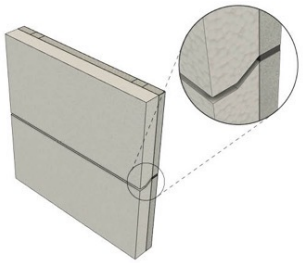

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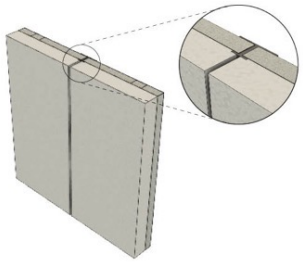

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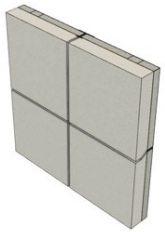

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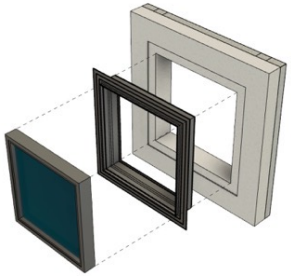

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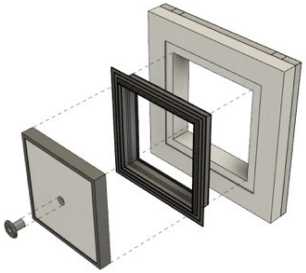


(6) Panel-to-HVAC penetration and integrated flashing system

Prototypes fabricated for mid-scale chamber testing at Syracuse University's Building Energy and Environmental Systems Laboratory (BEESL)

Key Envelope Components

Structural testing of envelope components

Fabrication of panel specimens by Cocoon Construct for structural testing in collaboration with Intertek and RDH Building Science

Top: 4A, 4B, 6A, 6B FIC Four-Point Loading Flexural Test Setup with 2" x 8"Wood Compression Plates.

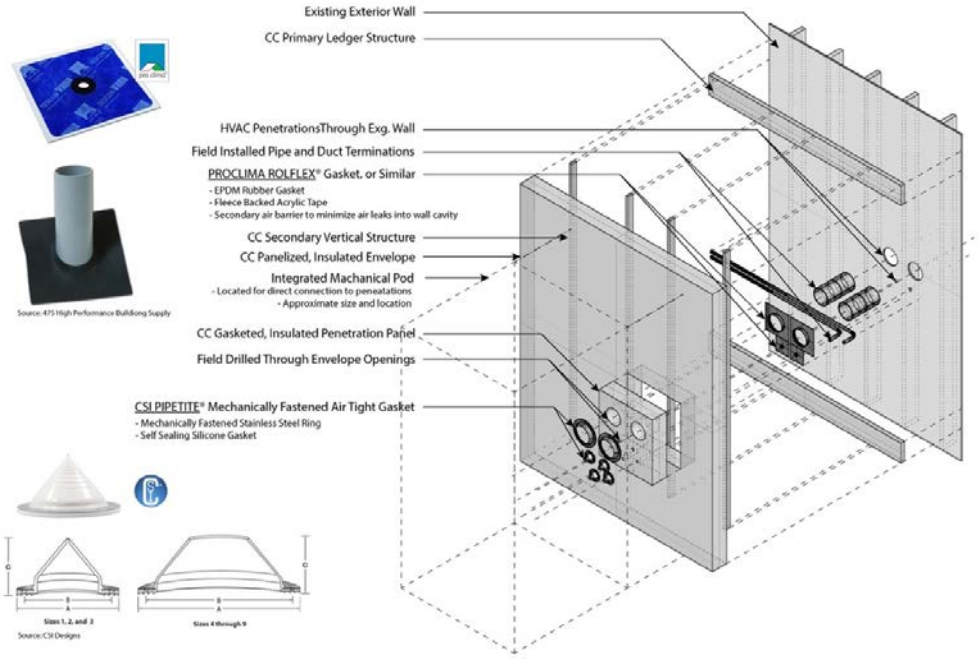
Bottom: 6C FIT Flexural Test Failure Mode; 2" x 8" Wood Plates Were Removed for Photo.

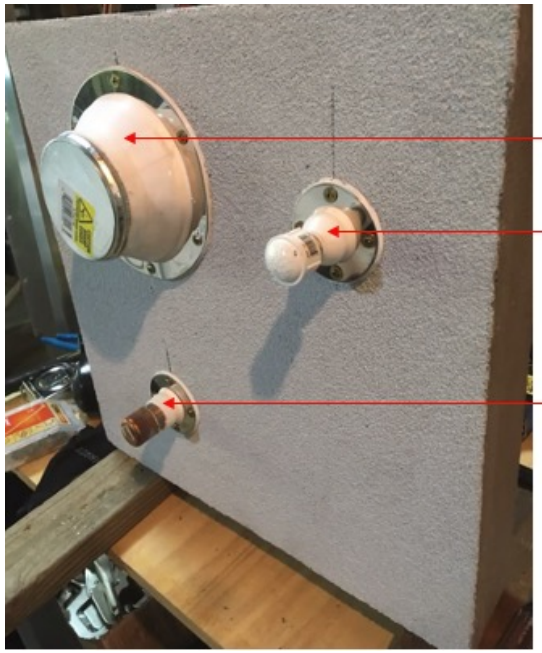
6A FIT Flexural Test Failure Mode Detail

6B FIC Flexural Test Failure Mode Detail

Mechanical Integration

Prototype testing and model-based evaluations at mid-scale and full-scale



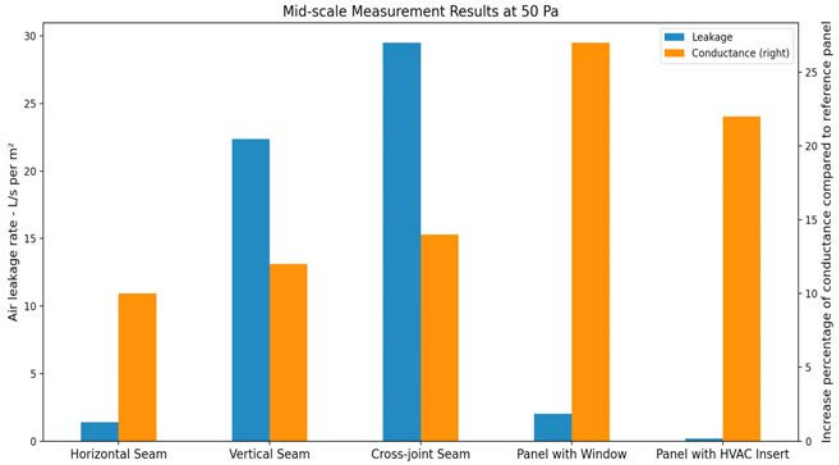


HVAC penetration panel for mid-scale prototype testing

Key Envelope Components

Mid-scale chamber testing for thermal resistance and airtightness

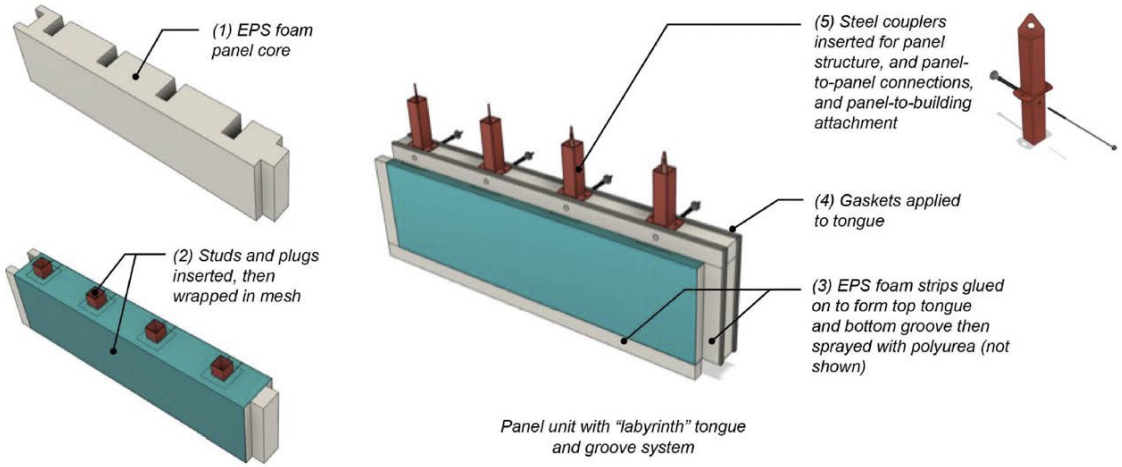
Prototypes installed in the BEESL testing chamber, Syracuse University



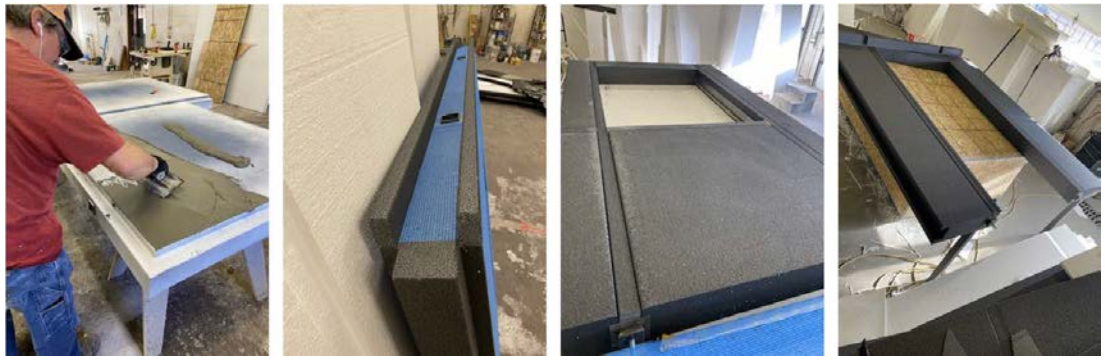
- Results of first designs showed increase in conductance and airtightness;
- Vertical seams and cross-joint seams showed highest leakage;
- Gasket material and profile required re-evaluation;
- A new strategy for improving performance of the joints was developed and will be tested on the BEST lab;

Key Envelope Components

Design, development, and fabrication of panel + attachment system



Panel unit with "labyrinth" tongue and groove system



Fabrication of structural insulated envelope panels

Full-scale prototype installation partial mock-up showing service cavity and adjustable attachment system.

Integrated Retrofit Solution

Prototype testing and model-based evaluations at full-scale

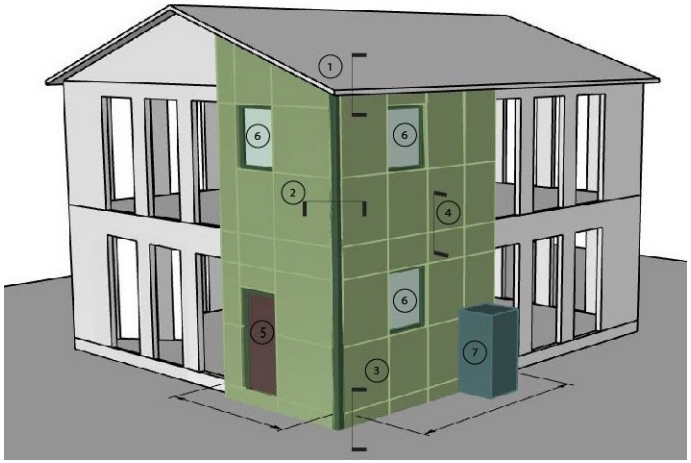


Diagram of BEST Lab with area originally designated for full-scale prototype testing, including panel types, attachment methods, windows, doors, and HVAC integration.

Objectives of full-scale prototype:

- Demonstrate integration of envelope retrofit panel system, integrated doors and windows, and mechanical pod and components.
- Test retrofit system thermal performance and air leakage at full scale in the field.
- Test installation method and sequencing with professional feedback.
- Identify protocol for code review and permitting processes associated with retrofit installation on actual building.

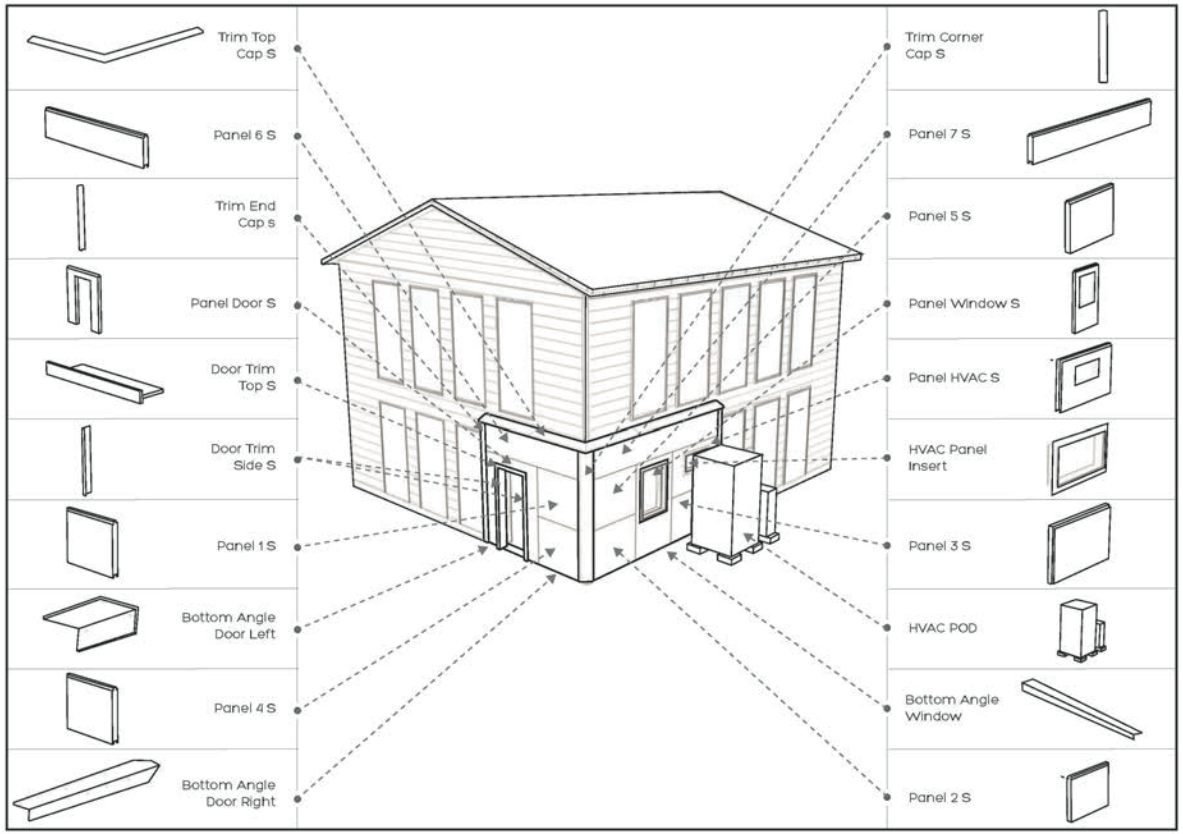
Integrated Retrofit Solution

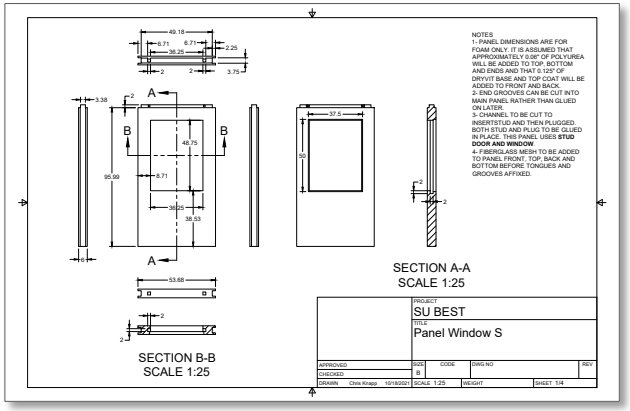
Prototype testing and model-based evaluations at full-scale

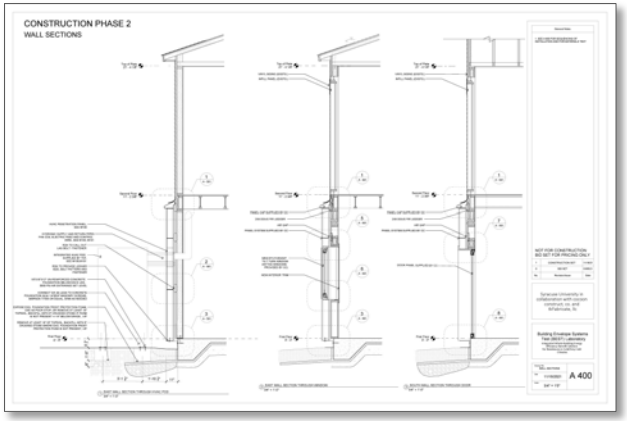
Sensor layout for interior zone of south-east test room for benchmark testing and measurements of full-scale installation

Integrated Retrofit Solution

Full-scale prototype design, technical detailing, documentation, fabrication

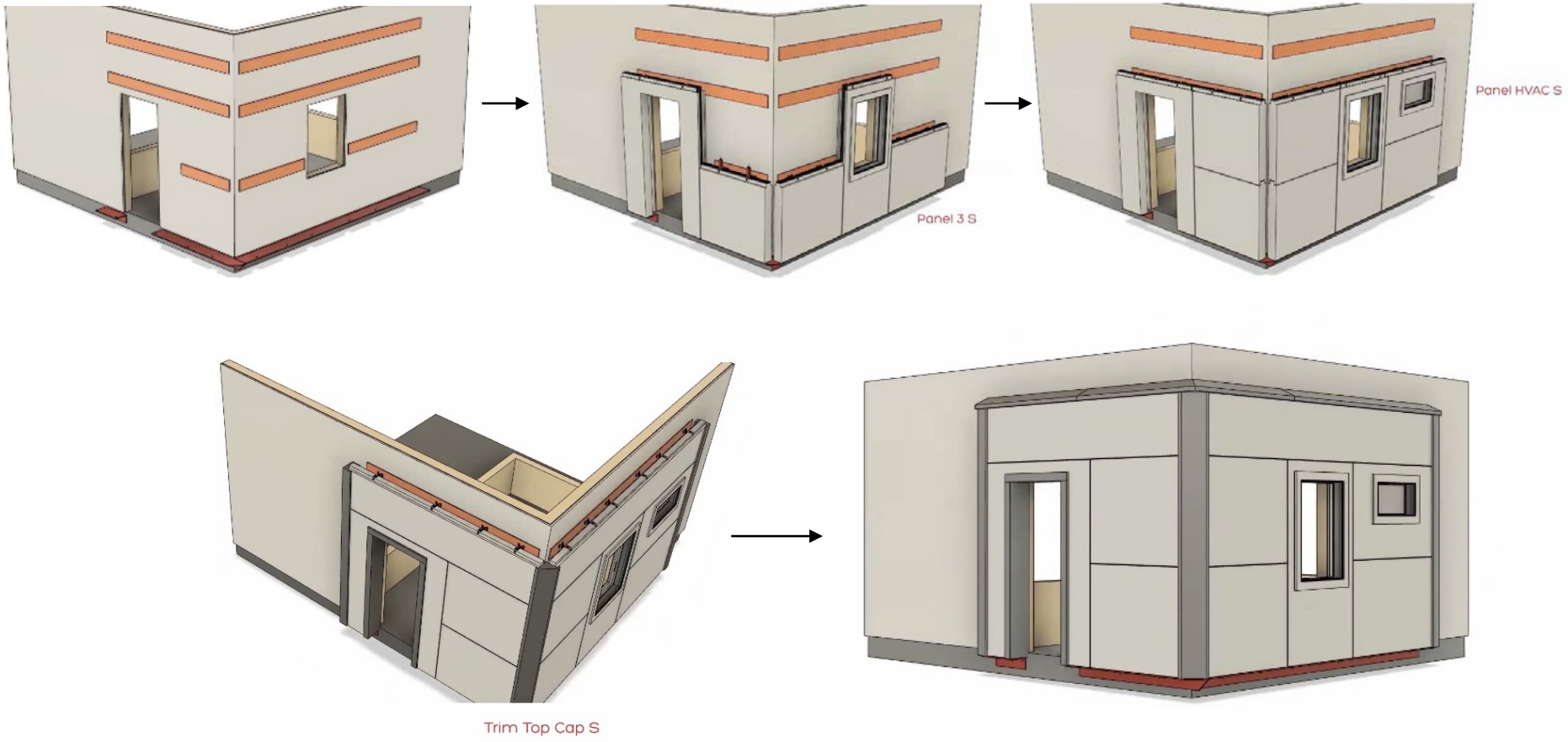






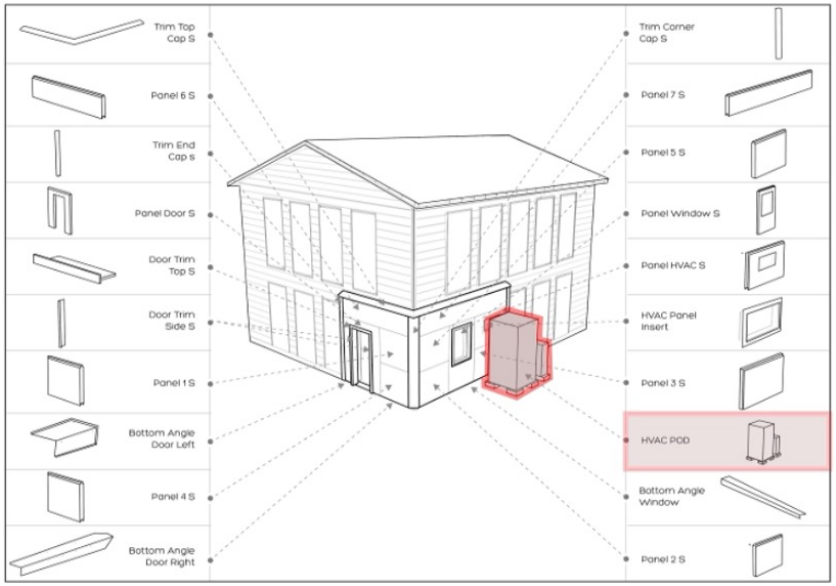
Integrated Retrofit Solution

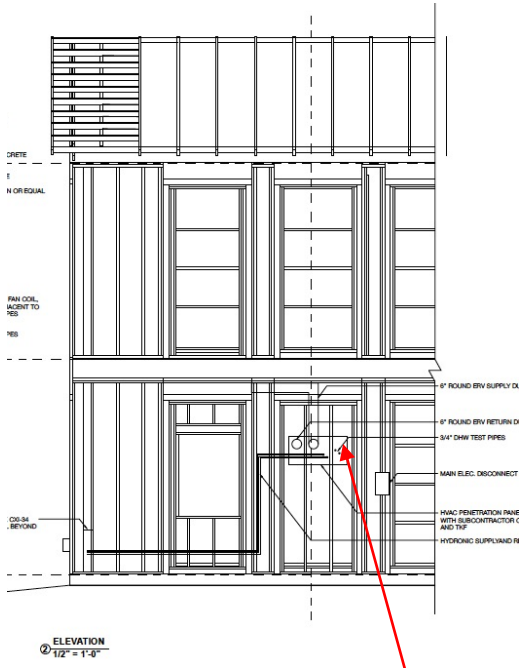
Full-scale prototype design, technical detailing, documentation, fabrication



Integrated Retrofit Solution

Full-scale prototype design, technical detailing, documentation, fabrication





HVAC panel insert

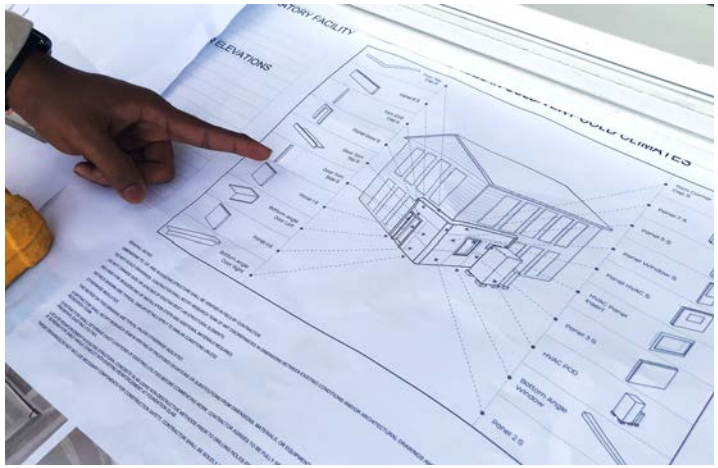
Integrated Retrofit Solution

Full-scale prototype test fit

Integrated Retrofit Solution

Full-scale prototype installation


Panel delivery




Panel fit test. Note: Wood ledgers designed for BEST facility test only; not intended for future implementation.


Panel fit test


Hydronic pipe runs

Integrated Retrofit Solution

Full-scale prototype installation

- Cost- and time-tracking based on: design → fabrication → delivery → installation (in progress)
- Installer feedback on-site and post-installation

Day 1 **-** Mobilize equipment, Demo vinyl siding + insulation at ledger locations, Install steel ledger + wood ledgers

Day 2 **-** Panels delivered to site, Unload + stage panels, Review attachment system, Begin panel fit test

Day 3 **-** Mechanical pipe installation, Pod delivered to site, Panel fit complete, Final Panel installation, Pod hook up

Energy Savings Potential

Predicted energy savings potential for single-family attached residences in cold/very cold climates

RETROFIT STRATEGIES	BASELINE[d]	PROJECT GOALS	SPECIFIC STRATEGIES	Thermal EUI (kBtu/ft²/Year) after Cumulative Retrofit Strategies	INCREMENTAL ANNUAL ENERGY SAVINGS (%)	SUBTOTAL (%)
Airtightness	2.2 ACH_{50}	1.05 ACH_{50}[a]	Pre-compressed foam tape gasket solution, envelope, integrated window, and door installation	31.92	5.27%	14%
Insulation	R-17[c]	R-30 (R-27 measured[b])	Insulated prefabricated panel solution, including panelized roof modules	28.85	9.13%	
Heating Equipment Efficiency	80 AFUE[c]	3.0 COP	Pod based heat pumps	17.34	34.15%	64%
Cooling Equipment Efficiency	9.1 EER[c]	23 EER	Pod based heat pumps	16.84	1.48%	
DHW Efficiency	0.56 EF[c]	2.43 EF	Pod based heat pumps	**7.43**	27.92%	
Expected Energy Saving	--	75% Energy Savings	--	--	--	**78%**
Indoor Air Quality		< 800ppm of CO_2	Pod based energy recovery ventilation with heat recovery efficiency of at least 80% and CO_2 enabled boost function			

[a] Based on the target airtightness level for the retrofitting system.
[b] Based on the mid-scale BEESL chamber test results for retrofitting panels.
[c] 2014 Building America House Simulation Protocols by NREL.
[d] Baseline conditions (thermal EUI is 33.7 kBtu/ftÇ/year) for the single-family attached building located at 150 Small Road, Syracuse, NY

Results indicate savings of **14% from the envelope system** and **64% from the integrated HVAC pod**, for a **projected total 78% energy savings** achieved from the retrofit approach relative to the median EUI for the single-family attached building type in cold/very cold climates.*

**Data for the full-scale prototype test forthcoming with results validated by January 10, 2022.*

Energy Savings Potential

Predicted energy savings potential for all applicable building types in cold/very cold climates

RETROFIT STRATEGIES		SINGLE-FAMILY ATTACHED			LOW-RISE MULTIFAMILY			SINGLE-FAMILY DETACHED		
		Before 1950	1950-1979	1980-1989	Before 1950	1950-1979	1980-1989	Before 1950	1950-1979	1980-1989
Baseline Thermal EUI (kBtu/ft²/year)		82.93	76.10	40.57	99.67	85.36	53.56	98.60	89.14	54.00
Number of Buildings for each Period*		427,748	585,545	376,170	579,350	509,969	97,977	7,373,282	10,166,239	2,092,709
Exterior envelope panel	Airtightness (1.0 L/s per m² at 50 Pascals)	26.99%	29.46%	23.24%	26.15%	30.44%	20.28%	26.01%	28.82%	18.37%
	Insulation (R-27 measured)	23.10%	26.10%	7.79%	16.11%	19.28%	5.87%	23.94%	26.93%	13.67%
Integrated HVAC Pod	Heating Equipment Efficiency (3 COP)	21.01%	16.09%	20.16%	25.02%	17.18%	22.91%	24.48%	19.96%	29.52%
	Cooling Equipment Efficiency (23 EER)	0.80%	0.48%	0.48%	1.81%	1.75%	2.73%	1.83%	1.18%	1.76%
	ERV (0.88 efficiency) **	3.35%	3.64%	6.80%	2.78%	3.17%	5.00%	2.50%	2.75%	4.51%
	DHW Efficiency (2.43 EF)	11.35%	12.36%	23.19%	12.59%	14.70%	23.42%	7.52%	8.32%	13.73%
Annual Thermal EUI Reduction (kBtu/ft²/year)		71.81	67.07	33.14	84.18	73.84	42.96	85.07	78.42	44.04
Annual Thermal Energy Savings (%)		**87%**	**88%**	**82%**	**84%**	**87%**	**80%**	**86%**	**88%**	**82%**
Annual Thermal Energy for each Period (TBtu/year) *		43.10	38.50	21.50	106.40	63.00	8.60	727.70	912.80	173.10
Annual Thermal Energy Savings for each Period (TBtu/year)		37	34	18	90	55	7	628	803	141
Total Number of Buildings		22,208,989								
Annual Thermal Energy Saving (TBtu/year)		1,812								

The energy savings potential of the whole-building retrofit approach developed in this Phase 1 project ranges from **82% to 88% relative to the EUI for individual buildings used as the baseline cases**, including a single-family attached building type, a low-rise multifamily type, and a single-family detached type.*

**Data for the full-scale prototype test forthcoming with results validated by January 10, 2022.*

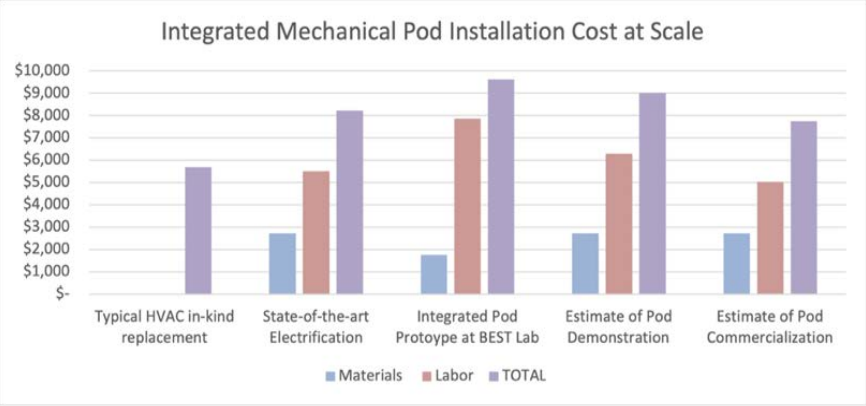
Cost Considerations

Preliminary cost of system components

- Panel prototypes fabricated for testing were $70/sf (labor and materials) – note: early-stage prototype
- Pod prototype fabricated for testing was $9500 (labor, materials, delivery to site)
- Further analysis of cost and labor tracking in this Phase 1 project will consider: design → fabrication → delivery → installation (in progress), as well as installer feedback

Considerations moving forward

- Further market data is needed to base value and pricing strategy to inform product development, and validate the manufacturing location and transportation strategy
- Costing out just the panels or pod is very small piece of the full pricing picture
- Cost reduction strategies must continue to use low-cost materials, lean manufacturing methods and just-in-time delivery, simplified coordination and assembly to reduce time on site.



Key Learnings

Performance requirements for *integrated* whole-building retrofit solution:
- Modular panel R-value and airtightness targets to reduce thermal EUI by 14%
- Pod heating/cooling/DHW efficiencies to reduce thermal EUI by additional 64%
- Panel structural performance targets to meet size and layout for range of applicable building types

Design requirements for *integrated* whole-building retrofit solution:
- Panel size and layout; kit-of-parts
- Panel gasket design for increased airtightness
- Attachment system design and cavity depth for adjustability and integrated mechanical pipe runs
- Pod equipment design optimized for modular envelope performance

Fabrication and installation requirements:
- Transportation and storage of retrofit panels and pod
- Sequencing of installation, coordination between integrated panel and pod components

Additional outcomes produced:
- Digital component database (in progress)
- Protocols for building structural and site assessment
- Methods for design documentation for fabrication and fast installation.
- Building owner considerations for: approvals, code compliance, maintenance and repair, owner and tenant engagement, aesthetics (from MIC workshops)