Three Rivers Builders

The Three Rivers House

2015 Race to Zero Student Design Competition

Carnegie Mellon University

ZERO
ENERGY READY HOME
U.S. DEPARTMENT OF ENERGY

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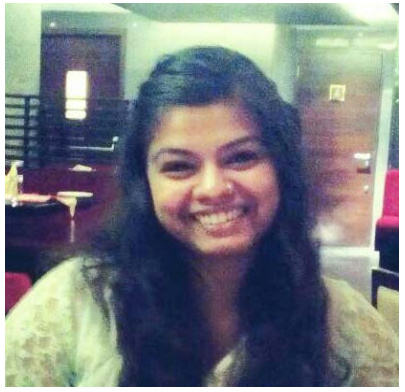
The Three Rivers Team

Timothy Spencer

Zoe Kaufman

Rohit Motwani

Swapnil Banzal



Prachi Gupta

Steve Lee

Design Goals

1. Net-Zero source energy
2. Affordable to the median consumer in Pittsburgh
3. Prioritize energy conservation over generation
4. Visitable by persons with disabilities
5. Water efficiency
6. Design a building system that can be adapted to meet net-zero anywhere in North America
7. Design a building system for which a weather-tight envelope can be erected by an experienced crew in one day
8. Design for unpredictable occupant behavior
9. Aesthetically appealing

Project Snapshot

Location: 1424 Fallowfield Ave, Pittsburgh, PA

IECC Climate Zone: 5A

Built up area: 1640 ft2

3 bed, 3 bath, 2 stories

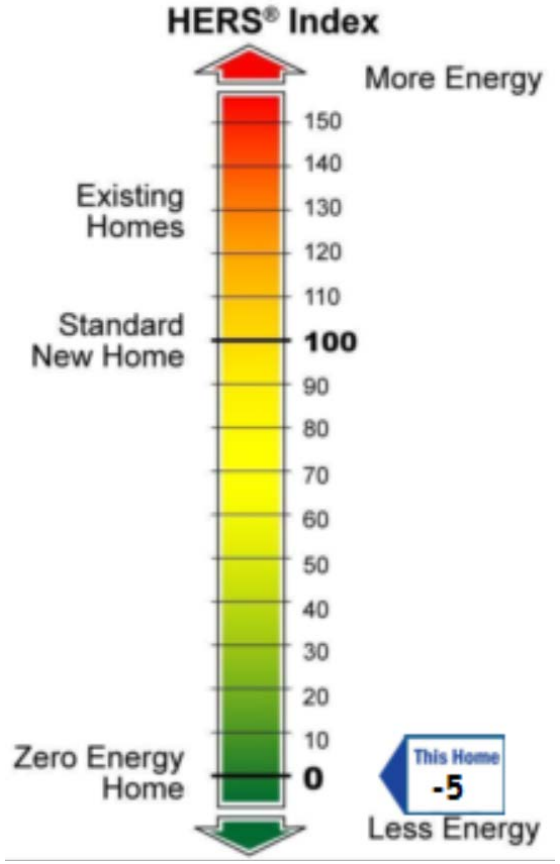
HERS Score: **35** without PV; **-5** with 7kW PV

Monthly energy bills: **$53** without PV; **-$1.50** with PV

Ground-Source Heat Pump: COP=5.1, EER=15.7

ERV effectiveness: 83% sensible, 77% total recovery

Instantaneous gas water heater: EF=0.95



HERS score with rooftop PV

Context & Site – Location

1424 Fallowfield Ave - a vacant lot on Mt. Lebanon, Pittsburgh, PA

- Southern exposure
- 60' x 115' lot
- Former site of foreclosed home

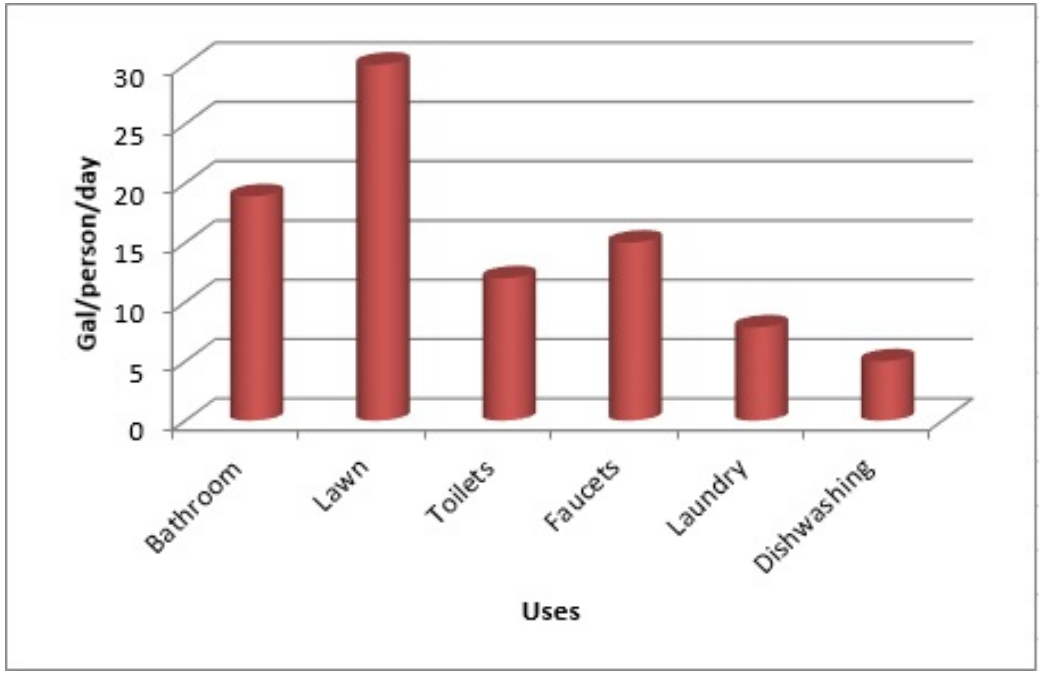
Neighborhood & Community

- Transportation
  - 0.2 mi to light rail station
  - 23 minutes to downtown Pittsburgh via light rail
  - <0.5 mi walk to Market District, elementary and high schools, and parks
- Visual integration
  - Urban infill
  - Modern, high-performance take on surrounding Pittsburgh architecture

(Image source: Google Maps)

Context & Site – Water

- Pittsburgh is a wet climate, but its combined storm/sewer system is undersized, causing pollution and wasting water and energy
- Impervious surfaces cause overflow of sewer system
- >30% of household water use in Pittsburgh goes to watering lawns
- Roof has catchment area of 1000 ft2
  - Use rainwater capture for landscaping
- 825-gallon storage tank placed at 2nd-story height to use gravity for irrigation



Context & Site – Climate

Heating-dominated

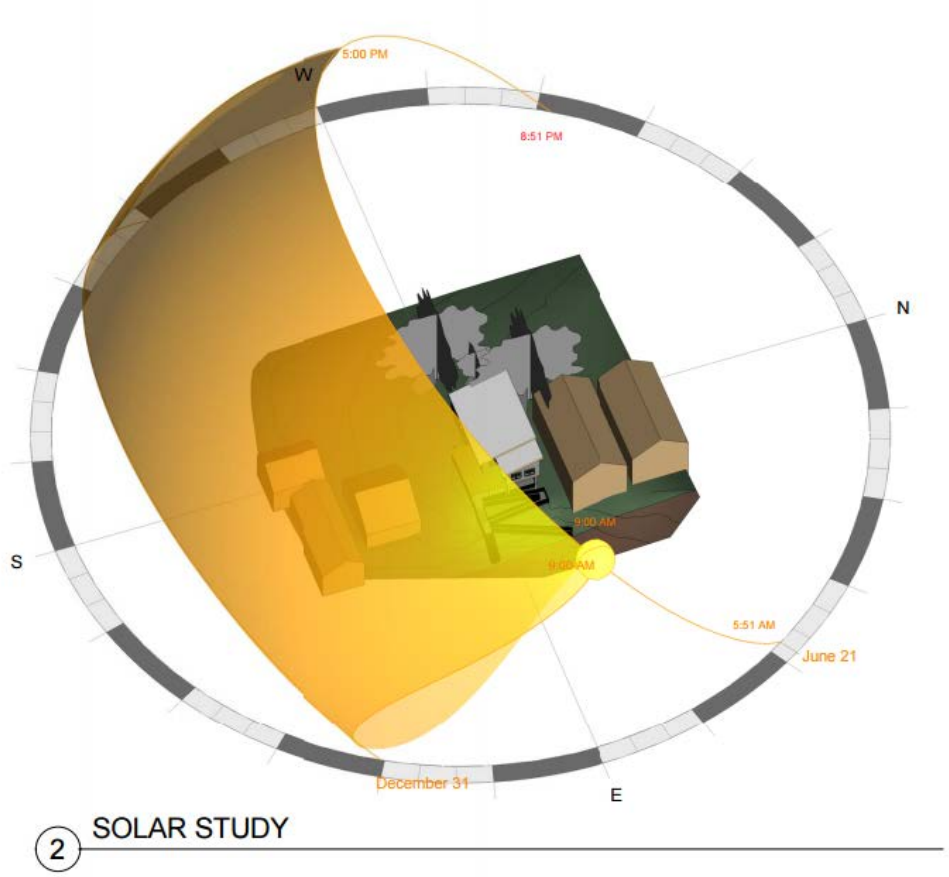
- HDD65: 5053
- CDD65: 654
- Capture internal gains
- Design for strategic solar gain

Overcast: only 2021 hours of sun and 59 clear days per year

- Design for efficiency first, then solar energy

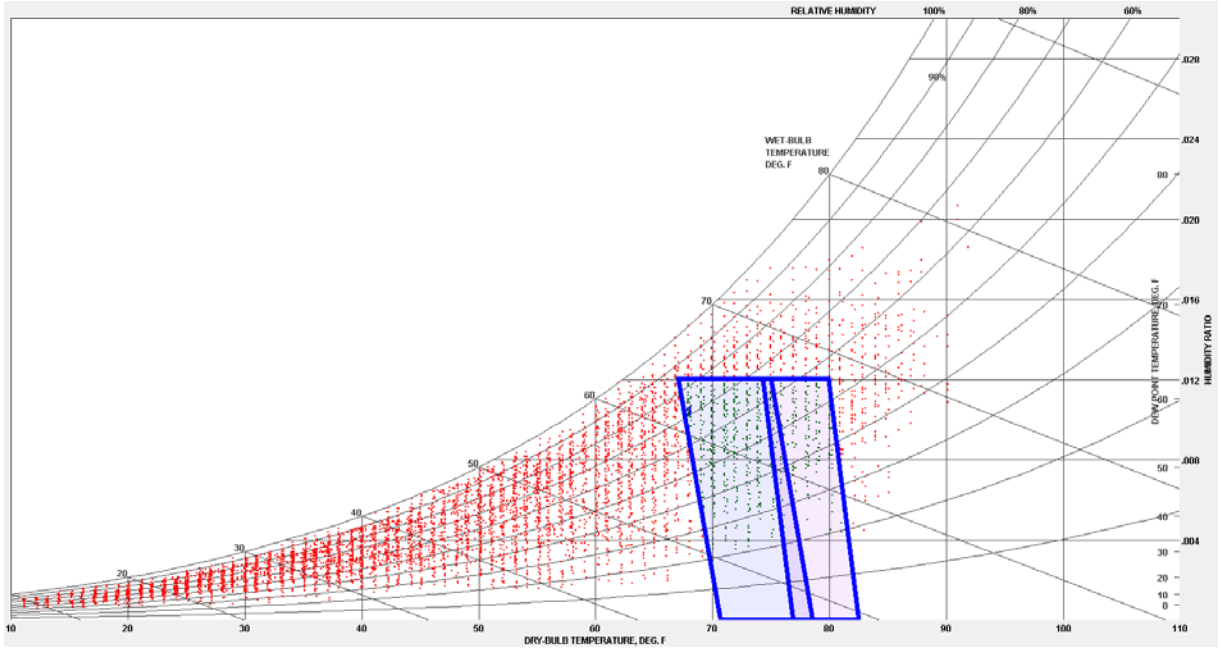
Humid summer, dry winter

- Hygrothermal design and analysis



Context & Site – Climate

- Build tight, insulate right
- Mechanical system sizing and efficiency
- Passive design for shading and solar gain



(Climate Consultant 6.0, 2015)

Strategy	Comfort Contribution (Percent of Year)
Normal Outside Conditions	10.1%
Insulation	23.9%
Sun Shading	7.3%
Passive Solar Gains (Low Mass)	7.9%
Conventional Heating	51.5%
Dehumidification	6.9%
Conventional Cooling	3.4%

Layout

Small footprint

- Use minimal energy
- Minimize construction costs, material use, and space conditioning
- Maintain a manageable building size and shape

Open layout

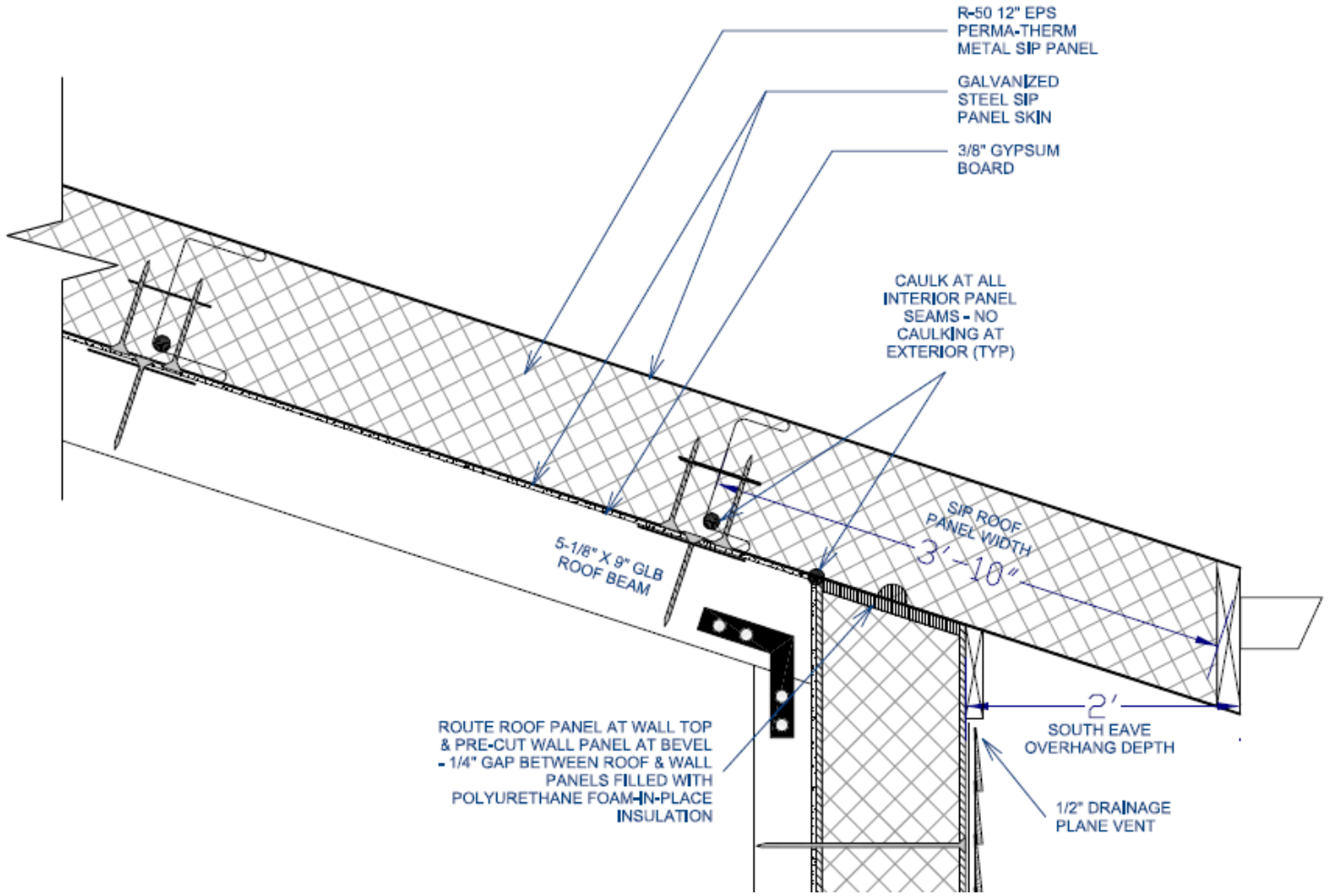
- Minimize circulation space
- Daylighting
- Multi-purpose spaces
- Effective air flow

Integrated spatial and MEP design

- Minimize plumbing pipe length
- Minimize ductwork

First floor

Second floor



Envelope Durability

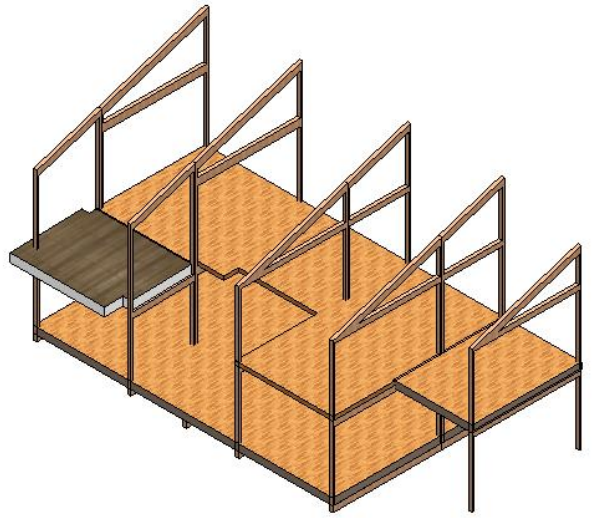
A Versatile Building System

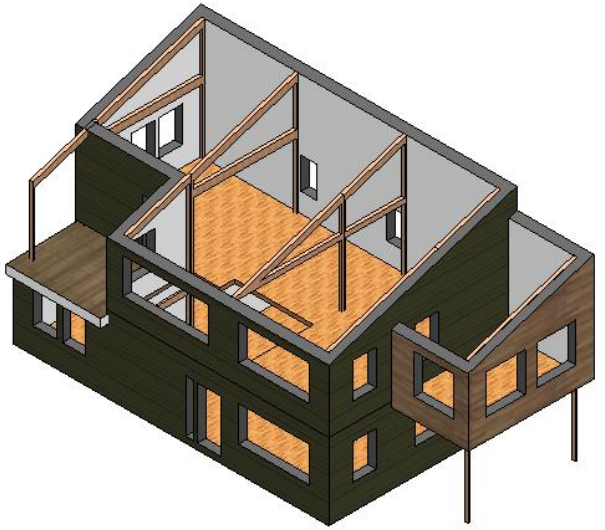
Envelope Goals

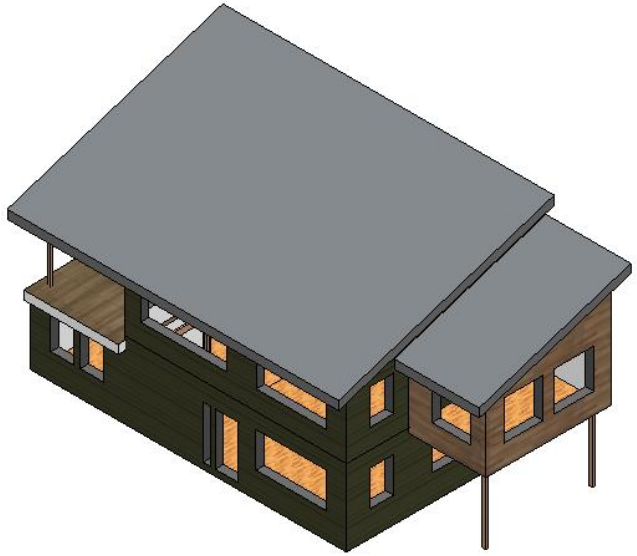
- Super-insulated and air sealed to extremely high levels
- Very low thermal bridging
- Easy to erect
- Durable and long lasting
- Termite resistant
- Moisture and mold resistant
- Can work in a variety of climate zones with minor modifications

A Versatile Structural System

- Prefabricated materials
- Speed of construction
- Adaptable to any US climate zone
- Minimal thermal bridging







Design for Prefabrication

- Reduced labor cost
- Quality Construction and Air Sealing
- Transportability - All elements are designed to fit on the back of a flatbed truck (<14' wide in PA)
- Cradle to cradle - EPS foam insulation is recyclable

GLB internal frame

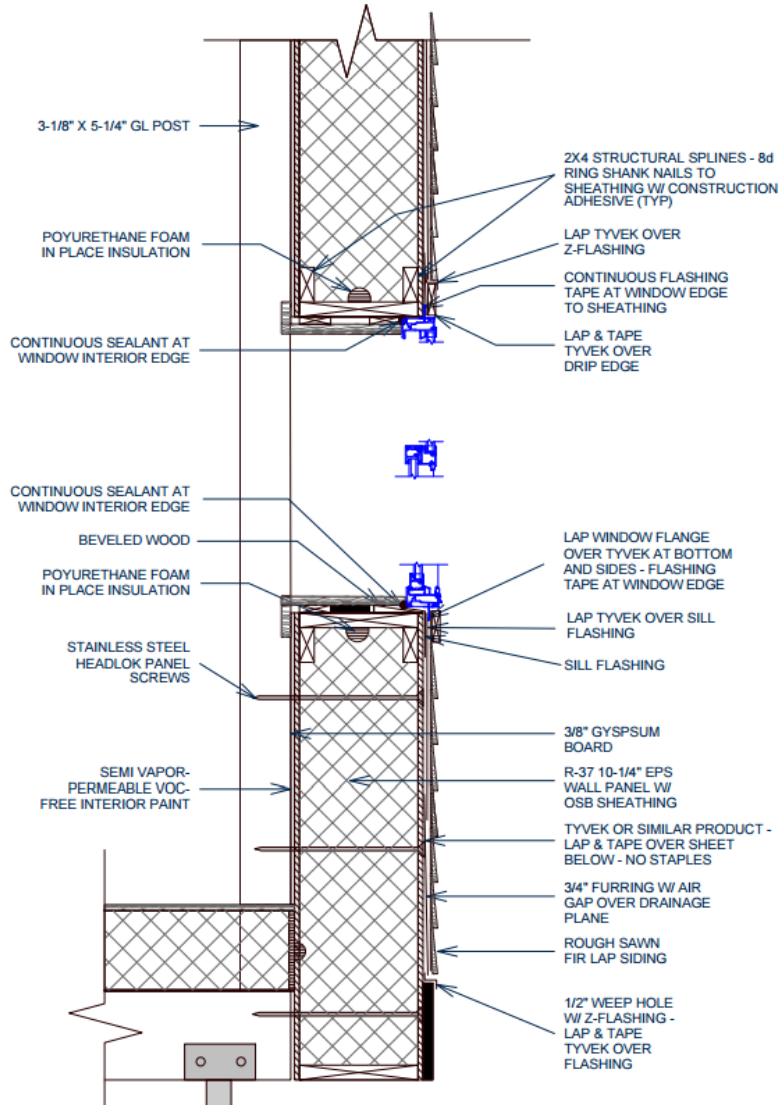
Murus SIP Walls

PermaTherm Steel SIP Floor & Roof

Cross Laminated Timber Internal Floor

SIP Walls

- Vented drainage plane beneath cladding
- Tyvek house-wrap water barrier
- Caulking and sealing applied to the inside of panel edges
- Walls attached to internal GLB frame
- Housewrap overlaps top of window

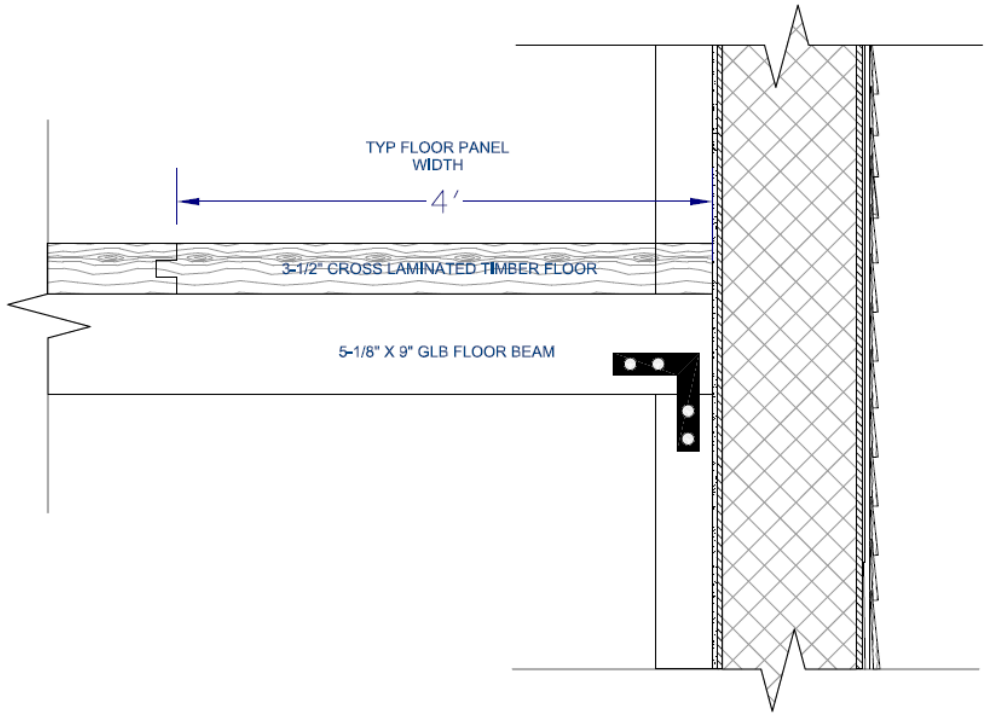


Typical Wall Construction

(Buildingscience.com, 2015)

CLT Panel Floors

- Eliminate Rim-joist Thermal Bridging
- Manufactured from wood harvested with Sustainable Forestry Practices
- Moisture management
- Aesthetics



TYPICAL CLT FLOOR CONSTRUCTION

SCALE: NTS

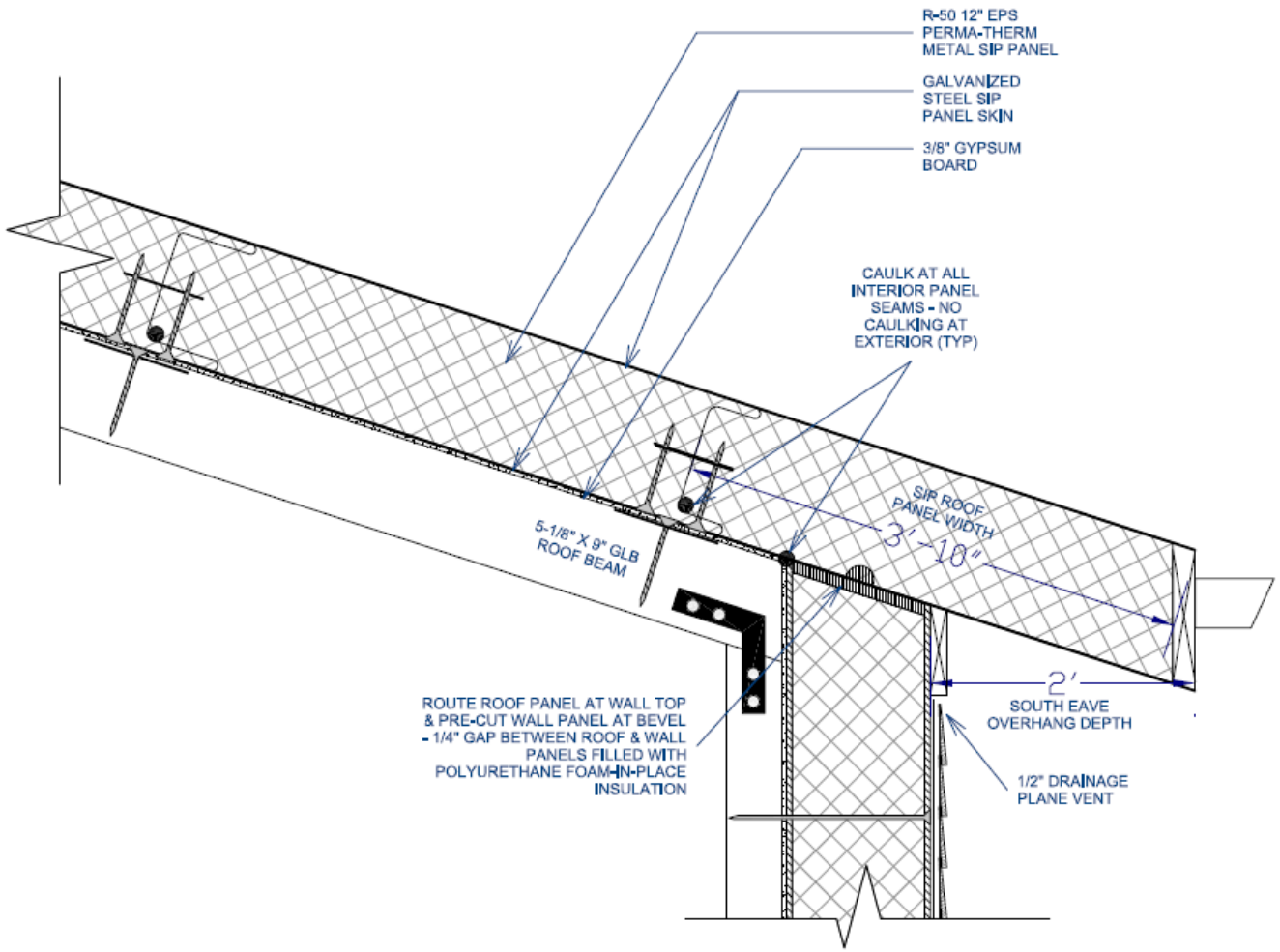
FSC®

Aesthetics of Sustainability

- CLT flooring creates an attractive, biophilic interior space
- Forest Stewardship Council wood is specified on construction documentation

Steel SIP Roof Panels

- Designed for refrigerated warehouses
- Internal spline eliminates thermal bridging from fasteners
- Galvanized - Durable to moisture
- Time saved - Needs no additional roofing surface

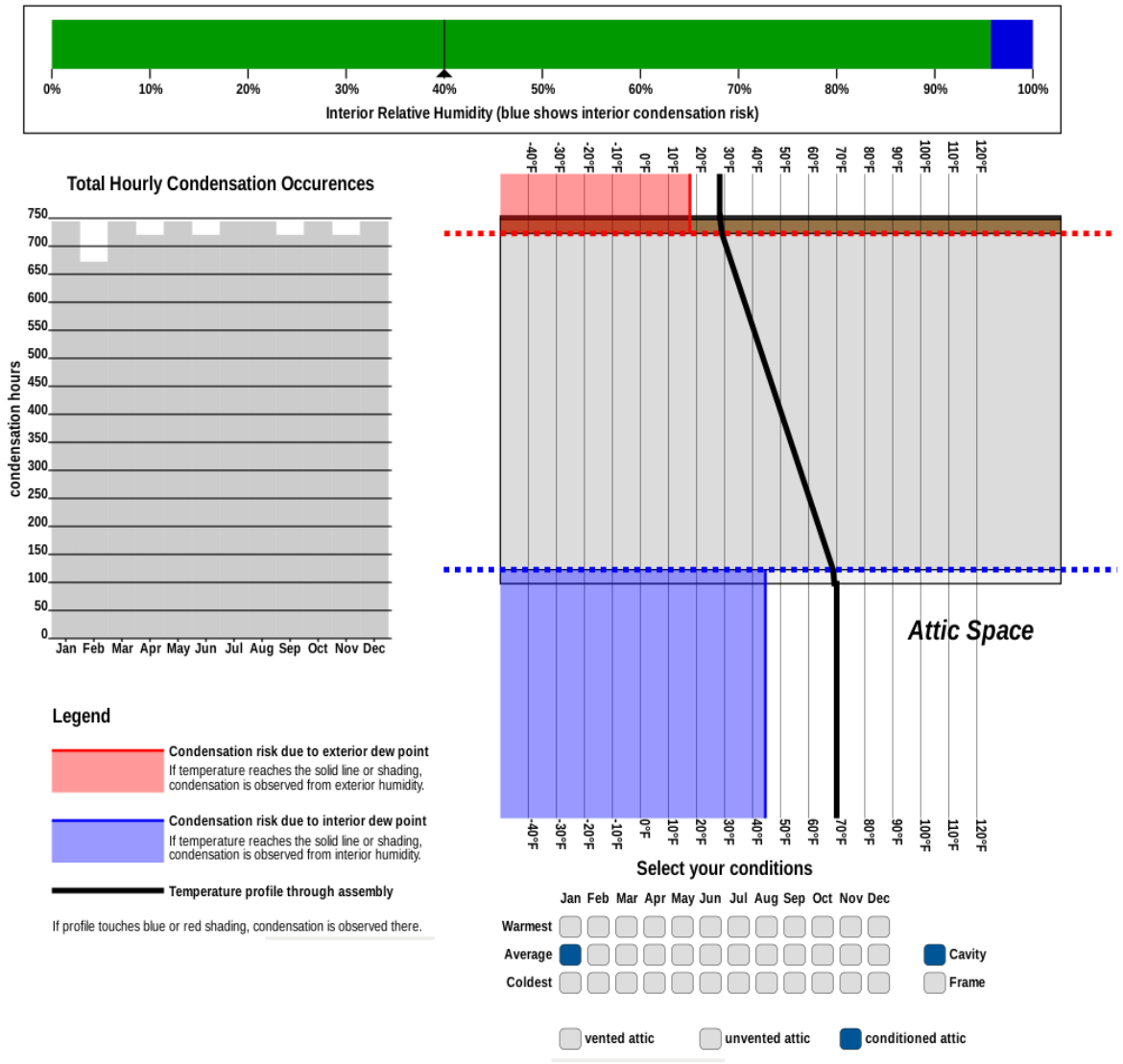


TYPICAL ROOF CONSTRUCTION

SCALE: NTS

Hygrothermal Analysis

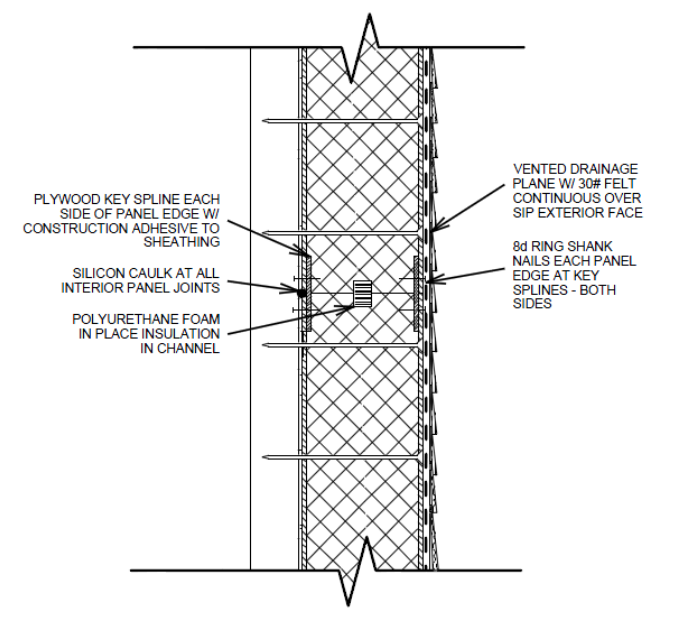
- Modelled by industry partner and building scientist Michael Sypolt on his custom designed software
- Software models condensation based on construction and TMY weather data
- Condensation occurs where the black line crosses into the red or blue fields
- Roof assembly shows no risk of condensation.



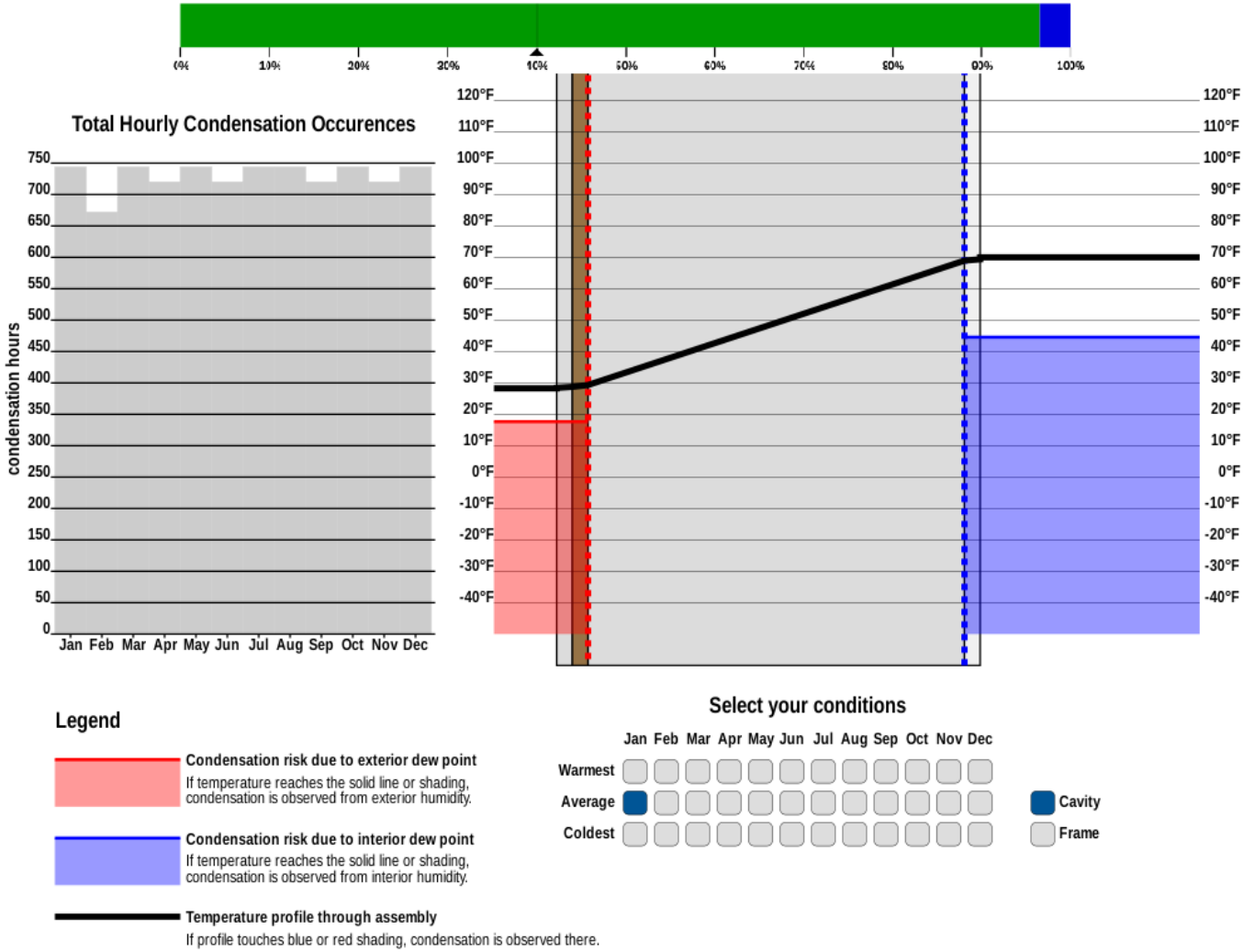
(Michael Sypolt, 2015)

Hygrothermal Analysis

- Wall assembly shows no risk of condensation



Typical SIP Wall Panel Joint



(Michael Sypolt, 2015)

Indoor Air Quality

(Image Credit: Jennifer Horton, 2015)

Air Quality in Pittsburgh

If you live in Allegheny County, the air you breathe may put your health at risk.

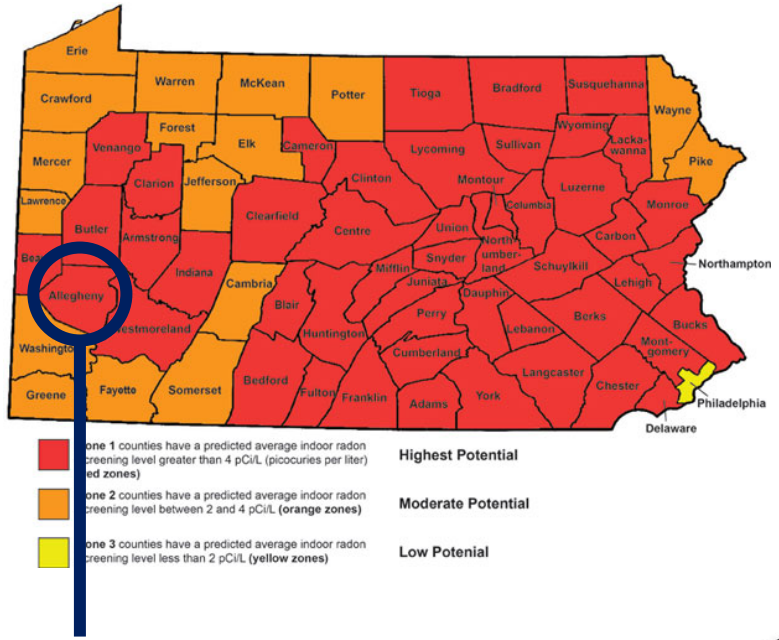
Ozone	Particle Pollution 24-hour	Particle Pollution Annual
F	F	Fail

You can make a difference in the air that you breathe.

(American Lung Association, 2015)

- Allegheny County ranks 6th in particle pollution in US
- Top 2% for cancer risk due to air pollution
- High risk of Radon: >4 pCi/L

PA Radon Map (EPA, 2015)



Pittsburgh, PA

Indoor Air Quality Strategies

Indoor air quality must be better than outdoor air quality

- Small particulate filtration
- Tight envelope
- Balanced Air

Moisture management for humid summers and dry winters

- SIPS
- CLT floor
- Dehumidifying cooling system

Air Quality through Ventilation

Balanced ventilation for less infiltration

- RenewAire GR90 ERV with MERV-13 filter
  - 40-110 cfm (45 cfm required according to ASHRAE Standard 62.2 calculation method)
  - Recovers some humidity in winter
  - CO2 vacancy sensor
- Bathroom - Panasonic WhiserGreen exhaust fan in ceiling
  - Multi-speed with time-delay control
- Kitchen - contaminants exhausted from range hood to outside
  - 36" range hood for 30" stove
  - Variable speeds up to 300 cfm
  - ERV make-up air built in
- MERV-11 filter for recirculated air to filter out indoor air pollutants

RenewAire GR90

Air Quality in a Tight House:

Avoid combustion gas sources

- Appliance selection
- Direct-vent gas water heater
- Electric range
- No attached garage to avoid car fumes

Whirlpool Gold 36”

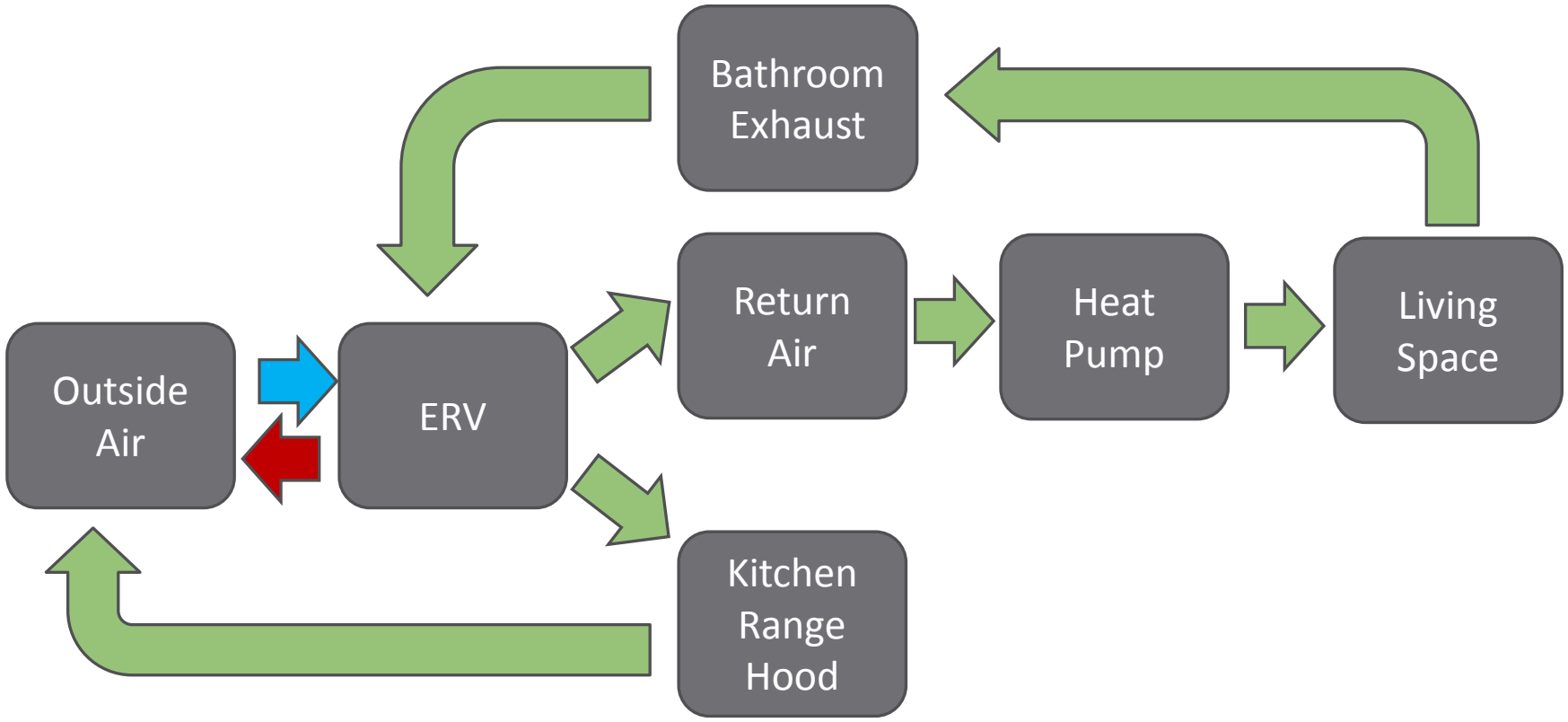
range hood

Reliance TS-240-GIH

water heater

Materials

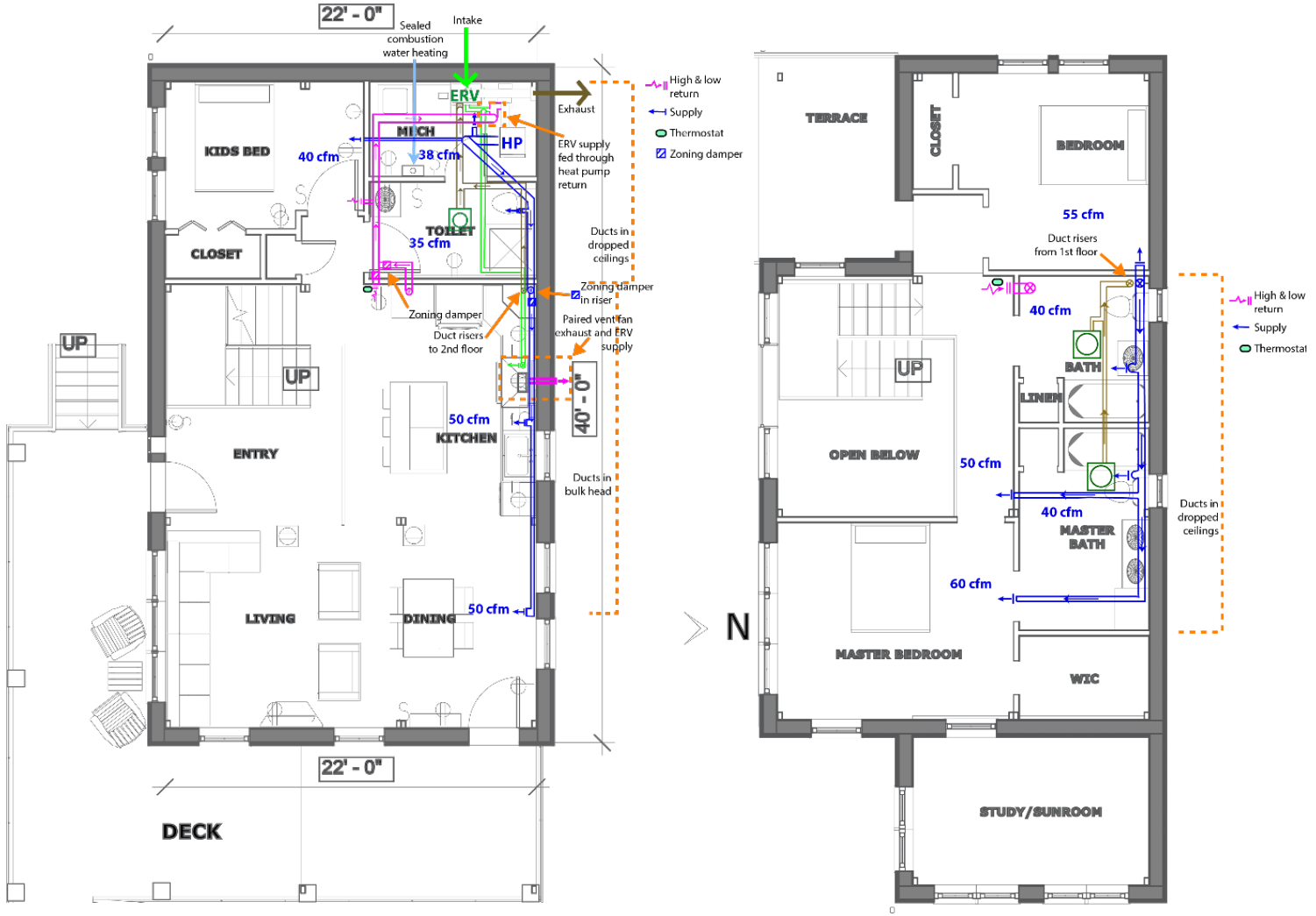
- Hard surfaces and non-VOC finishes
  - No off-gassing materials--hardwood and tile
  - Don't trap moisture, as per EPA's Indoor AirPLUS
- Less on-site construction means less construction debris in mechanical system



Space Conditioning

Simple Layout, Integrated Systems

- Designed for short ductwork
- Forced air to combine heating and cooling distribution and achieve faster response time
- Integrated ERV and heat pump



First Floor

Second Floor

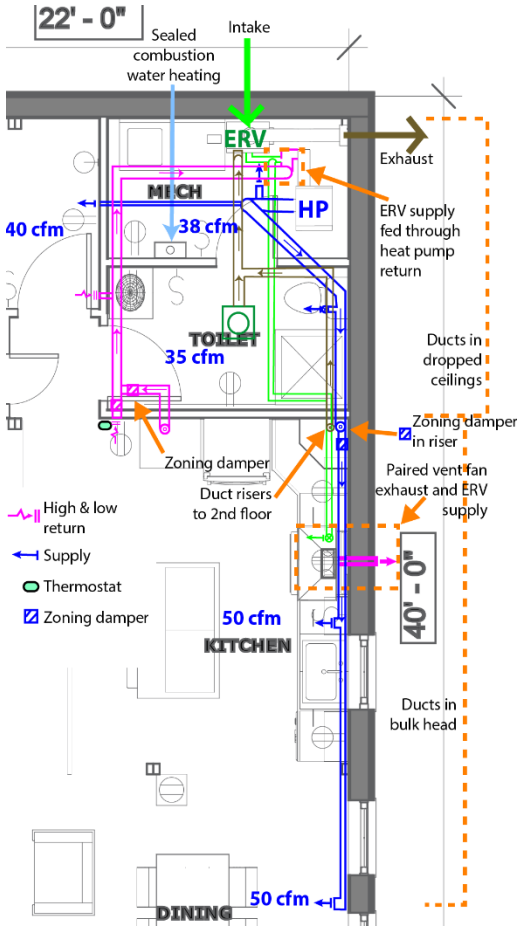
Mechanical plan

Geothermal Heat Pump

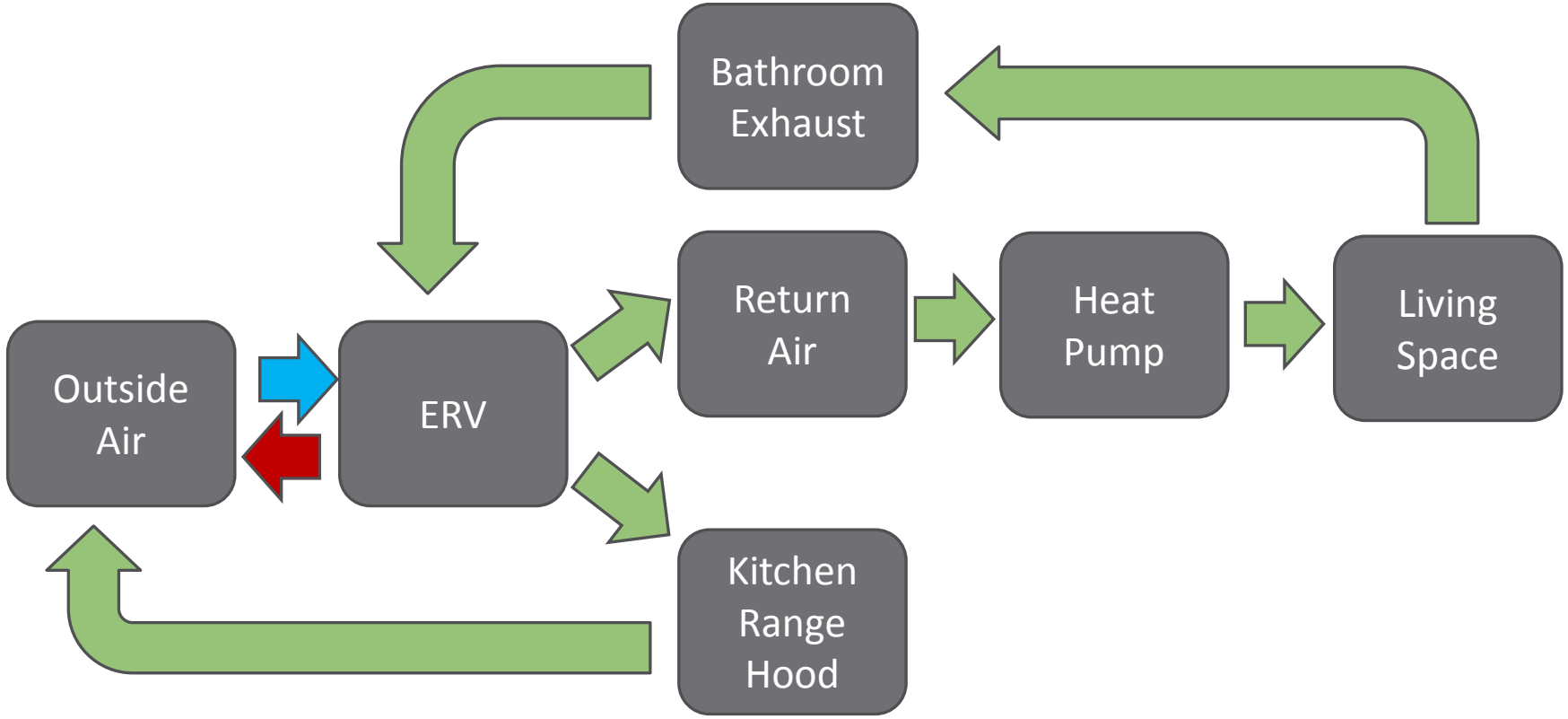
- 50F Pittsburgh ground temperature
- Closed-loop Water Furnace 5 Series 012
- Horizontal geothermal
  - Lower construction cost
- First-cost justified by savings in energy and maintenance
- COP of 5.1 more than makes up for source energy conversion
  - Twice as source energy effective as a 96% AFUE boiler
- Cooling capacity sized properly for comfort and dehumidification, avoiding sporadic operation

	Cooling capacity (Btuh)	EER	Heating capacity (Btuh)	COP	Pump GPM	Ventilation fan min. efficiency (cfm/watt)
Energy Star for Homes		12		3.5		1.2
IECC 2015						1.4
Proposed design	12,300	15.7	14,800	5.1	4	4

Airflow Path



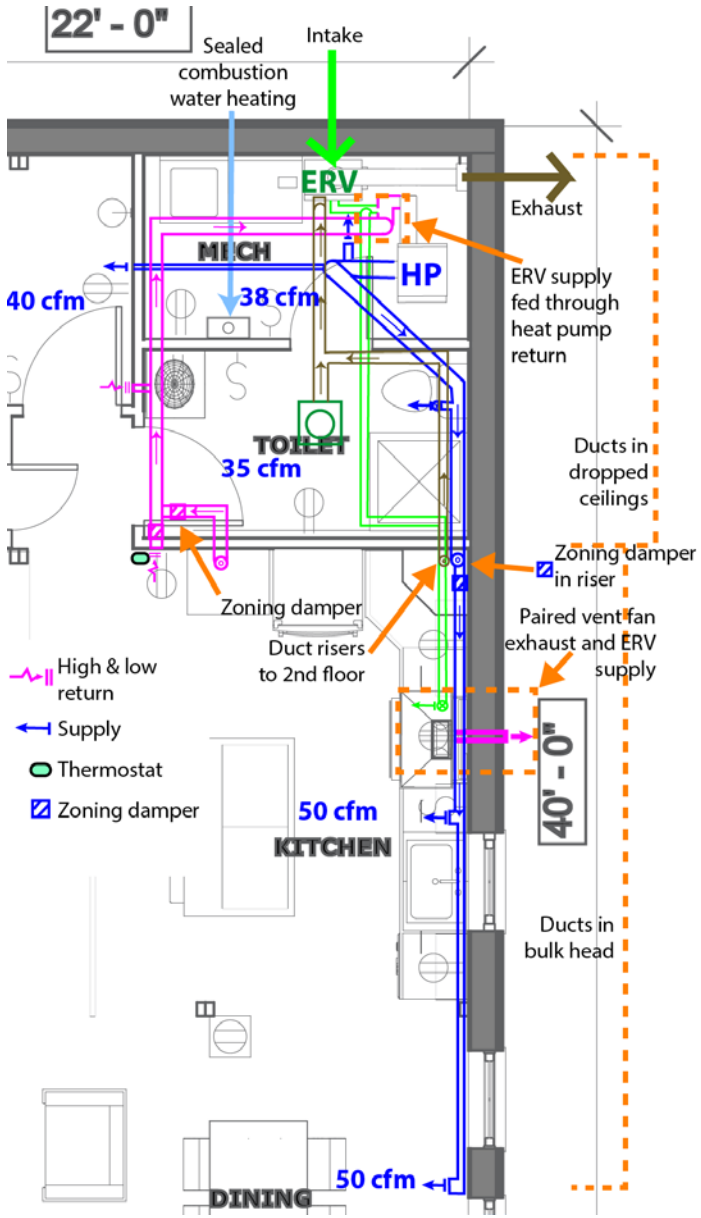
Mechanical plan, first floor



- No cold air directly enters living spaces
- No depressurization

Air Distribution

- Small ducts because of small loads
- Most of ducting spans 1 wall
- Return air located away from supply for proper mixing
- High and low returns for seasonal responsiveness
- All ducting inside thermal envelope



Mechanical plan, first floor

Controls and Zoning

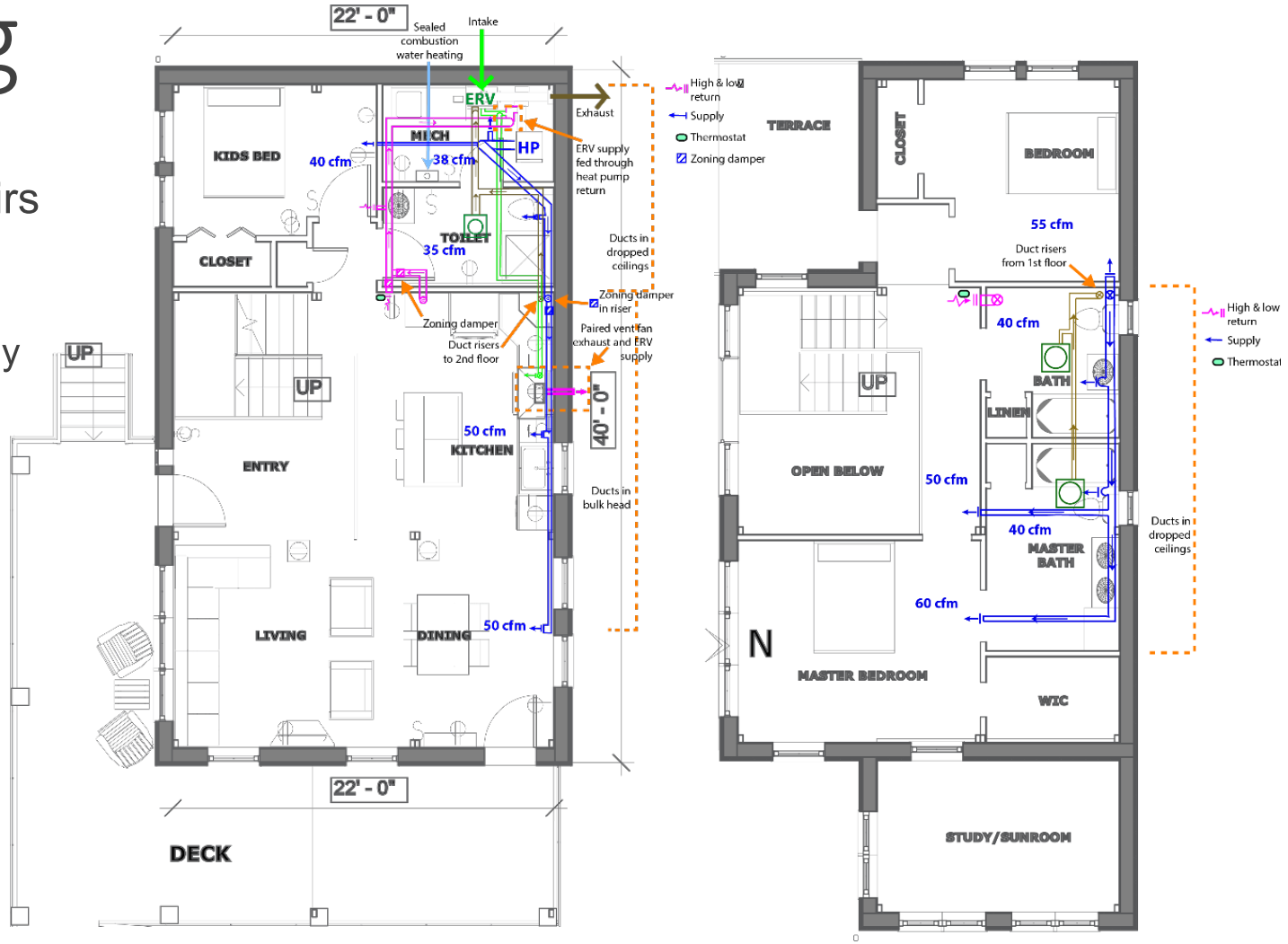
2 main thermal zones: upstairs and downstairs

- Remedies uncomfortable air stratification
- Uses less energy with the option to condition only one level

Wiser wireless thermostat

- Programmable, 4-event, 7-day schedule
- Easy operation and smart controls
- Accounts for imperfect occupant behavior

Sun room cantilever is designed as unconditioned space



Mechanical plan

Home Energy Management System (HEMS)

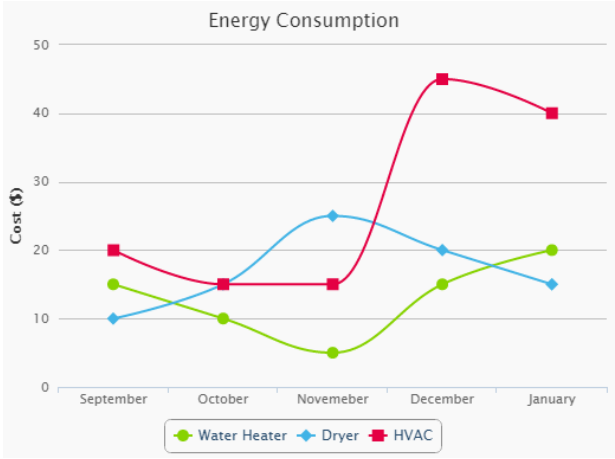
"You can't manage what you can't measure."

Occupant behavior is unpredictable

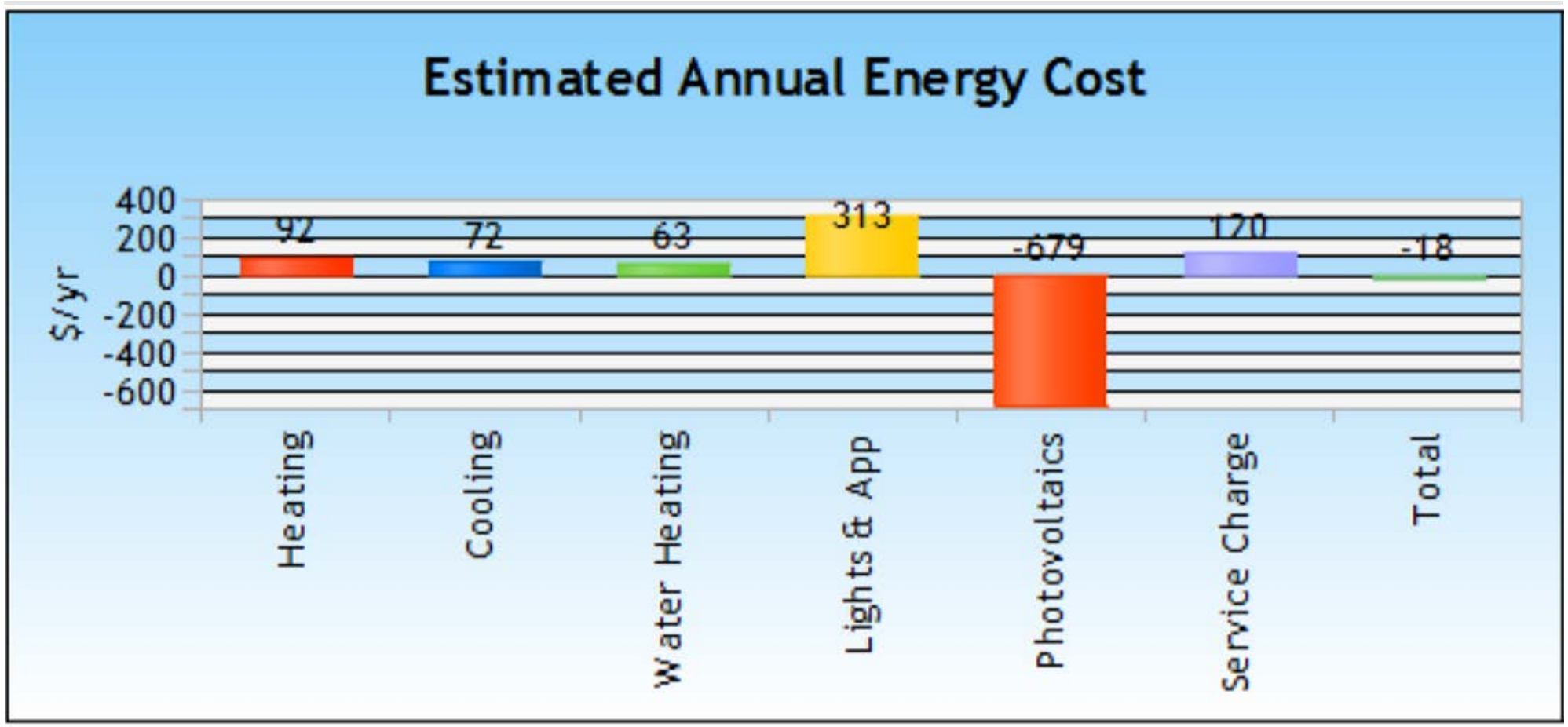
Energy use AND production should be transparent

Wiser Home Management system by Schneider Electric

- Remote energy management based on energy use and projected bills
  - Remote control of thermostat, lights, and other major appliances
- Real-time net metering
- Provides alerts to users
- Integration with thermostat and compatible with geothermal heat pump



Wiser user interfaces



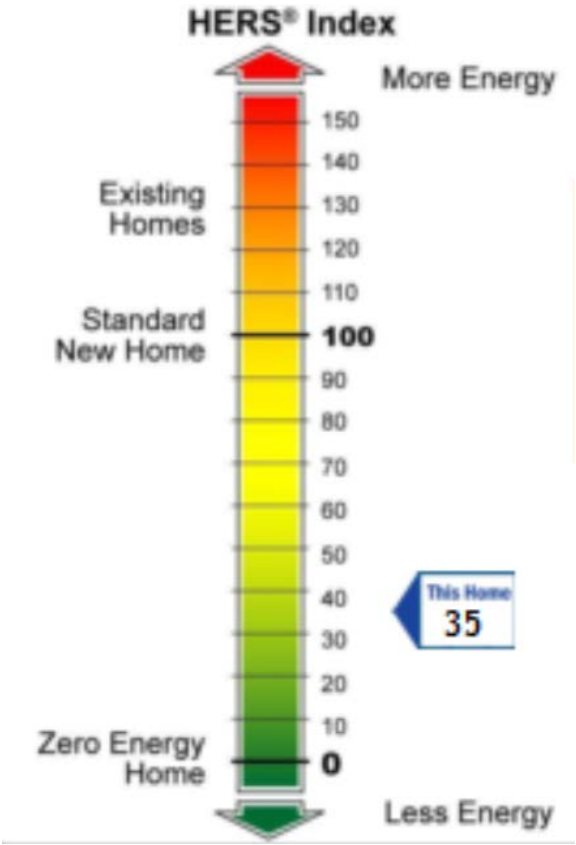
Energy Analysis

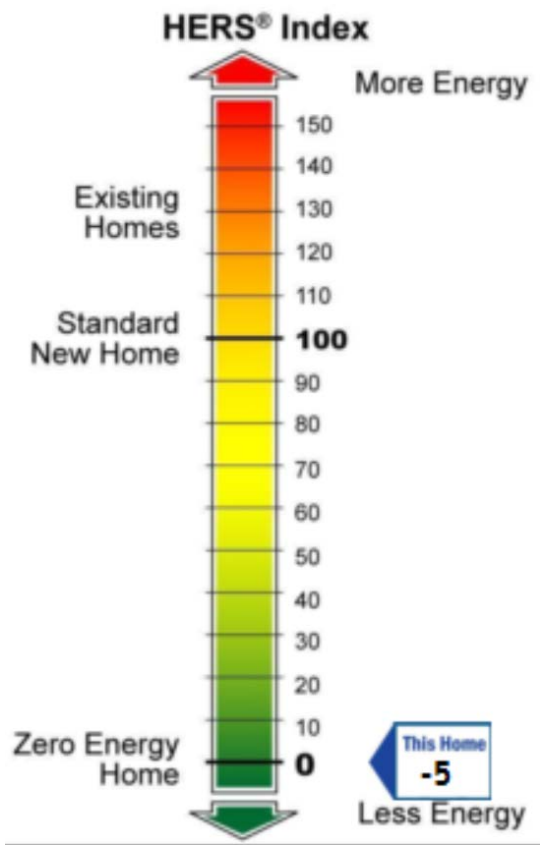
HERS Index Score

Without Energy Generation

A HERS score of 35 before rooftop PV panels are added indicates a high level of energy conservation

Estimated annual energy cost is $639 without PV





With Rooftop PV Panels

A HERS score of -5 shows the that the home reaches net zero

Estimated annual energy costs are net negative

- Orienting the house in the "worst case" orientation in REM/Rate yielded a HERS Score of 40 and increased peak cooling loads by 1300 BTU/hr, indicating well-thought-out orientation and envelope design

Renewable Energy Design

PV chosen over solar thermal

- Limited roof space--with recent PV price drop and maintenance requirements of solar thermal, space is best spent for PV
- More direct energy tracking and monitoring with PV
- Net metering laws in Pennsylvania

PV system sizing for source energy net zero

Pittsburgh													
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Average
Sun hours	1.7	2.5	3.5	4.6	5.5	6.1	5.9	5.2	4.2	3	1.8	1.4	
Days in month	31	28	31	30	31	30	31	31	30	31	30	31	
	52.7	70	108.5	138	170.5	183	182.9	161.2	126	93	54	43.4	**3.79**

- Monocrystalline panels for efficiency and optimizing space
- Low maintenance fixed roof-mounted system
- Little shading anticipated due to siting

Calculating array size needed for net-zero source energy

Equation: Energy use (kWh/yr) / 365 / (sun hours/day) / .75 derate factor

7.01

Calculating kWh/yr generated by system

Array size	6	7
kWh produced	6224.4	7261.8

Net Zero Balance Sheet

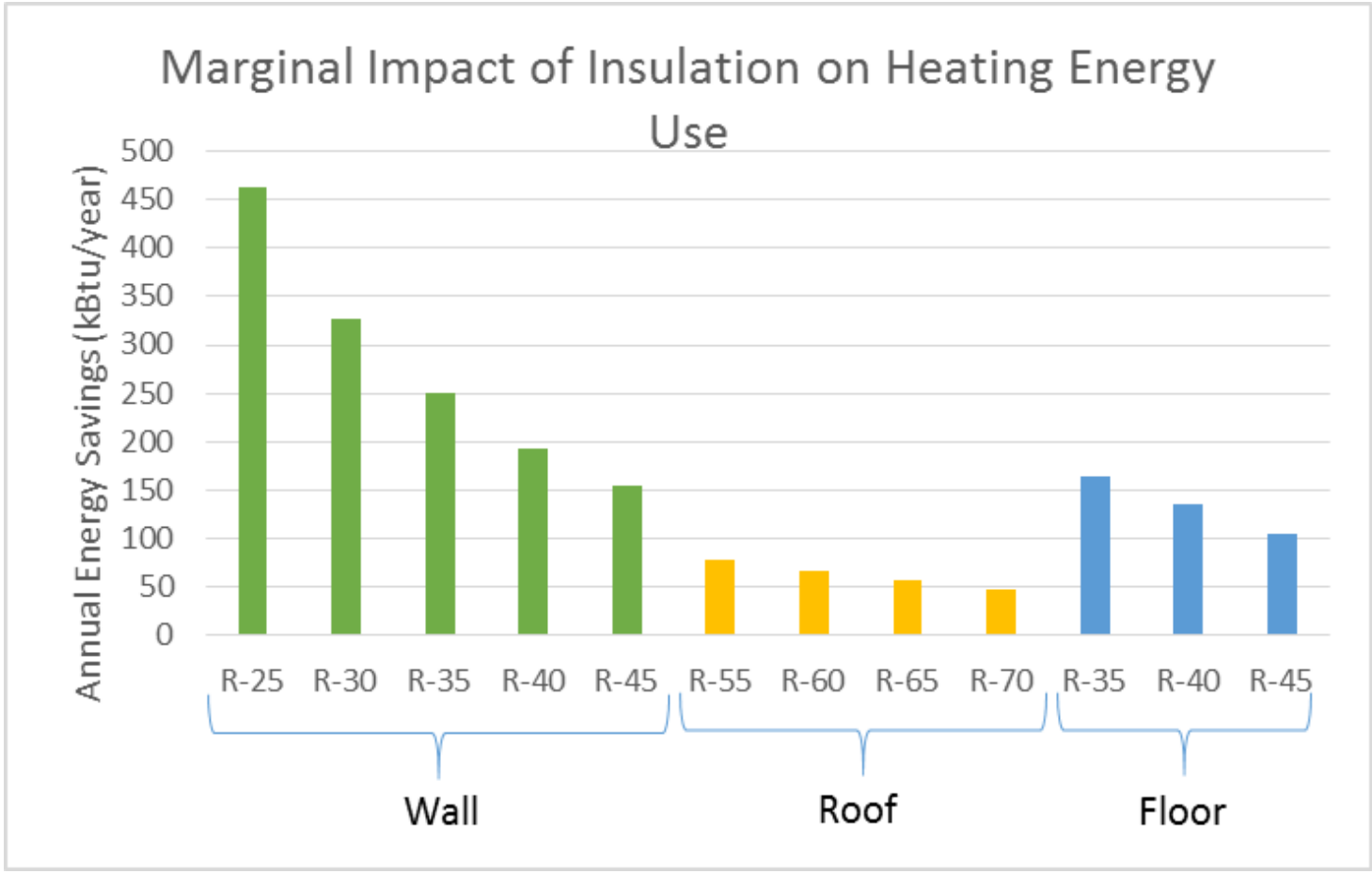
- Site energy EUI is 4.77 kBtu/ft2/year
- Source energy EUI: 0.19 kBtu/ft2/year
- CO2 Emissions: 0.08 lb/ft2/year

Annual Zero Energy Balance	Site Energy		Source Energy		Carbon Emissions (lb) (based on source energy)
Natural gas	**kBTUs**	**kWh**	**kBTUs**	**kWh**	
	11,600	3,399	12,180	3,569	5464
Electricity		**kWh**			
	21,000	6,153	65,940	19,320	29580
Total Energy Consumed/Emissions Generated	32600	**9,552**	78,120	**22,889**	35043
Renewable Energy	**kBTUs**	**kWh**	**kBTUs**	**kWh**	
Produced on site (7kW array)	24782	7,261	77,814	22,800	34906
Imported or derived from on-site processes		0			
Purchased		0			
Total Renewable Energy	24782	**7,261**	77,814	**22,800**	34906
Net Balance in kWh (Renewable Energy -Total Energy)		**-2,291**		**-90**	**-137**

Site EUI (kBTU/ft2/yr) [US Residential Avg EUI: 44 kBTU/ft2]	**19.88**	**Source EUI (kBTU/ft2/yr)**	**47.63**	**CO2 emissions EUI (Ramseur, 2014)**	**21.37**
Site EUI with renewables	**4.77**	**Source EUI with renewables**	**0.19**		**0.08**

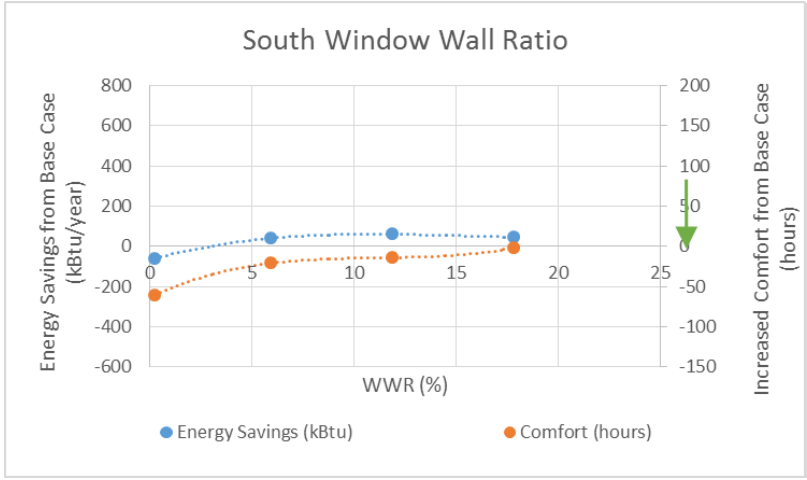
EnergyPLUS Modelling - Insulation

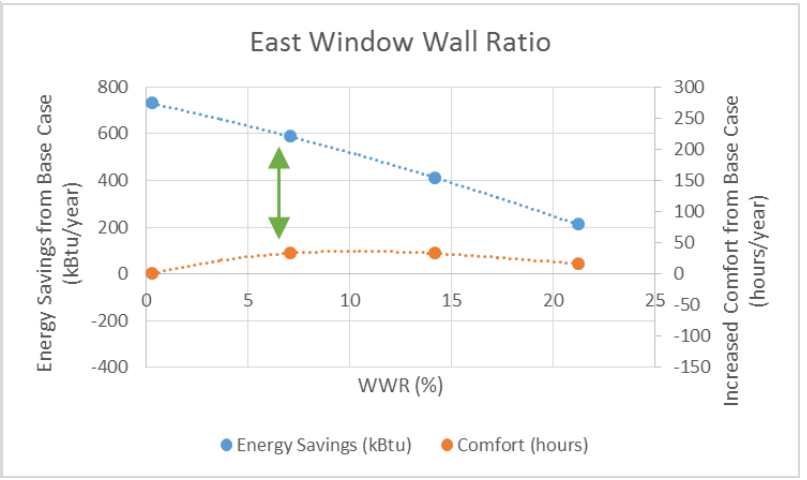
- Graph shows marginal changes in energy savings with each additional R-5 layer of EPS insulation
- Changes in energy use compared with IECC 2015 levels of insulation
- Finding the most valuable place to put insulation
- Create the best value for the high cost of super-insulation

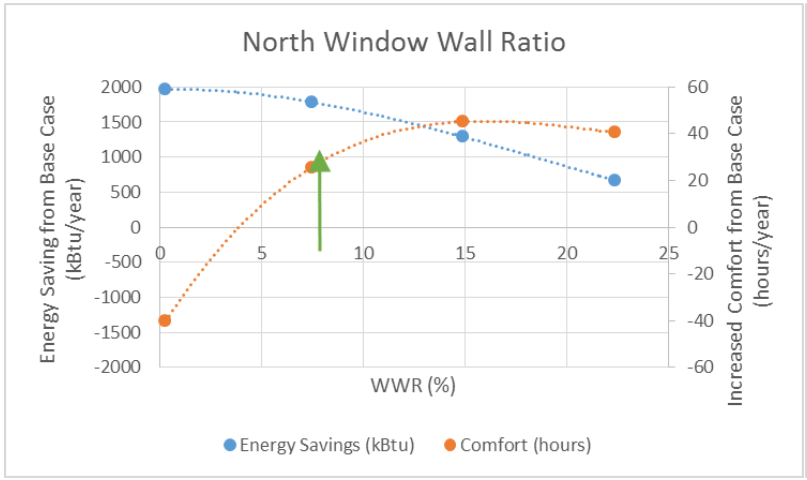


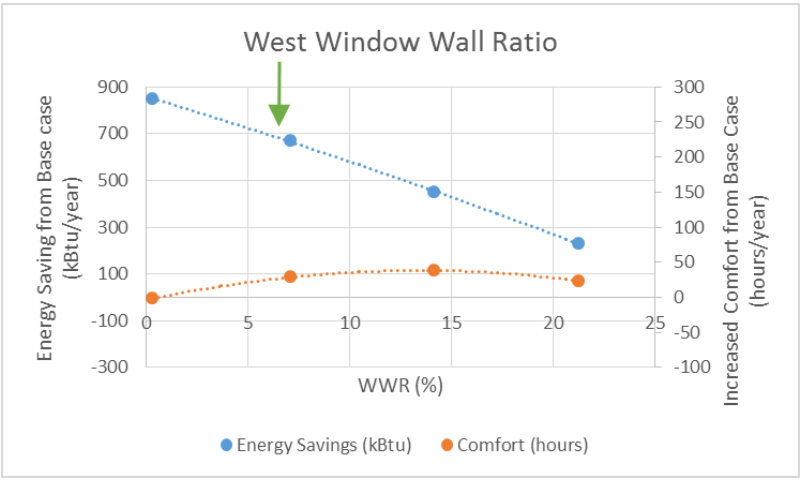
EnergyPLUS Modelling- Window/Wall Ratio

- Comparing changes in hours of comfort to changes in energy savings
- North WWR has strongest effect on energy use or comfort
- South WWR has little effect on energy use
- Higher WWR on east and west facades increase energy savings and reduce comfort



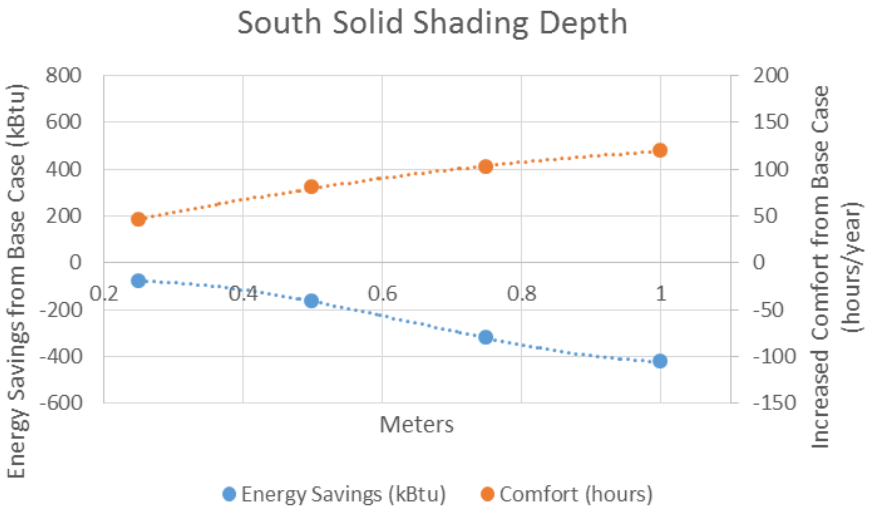


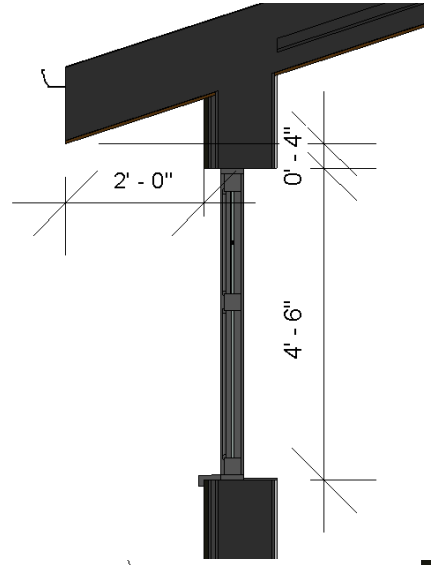


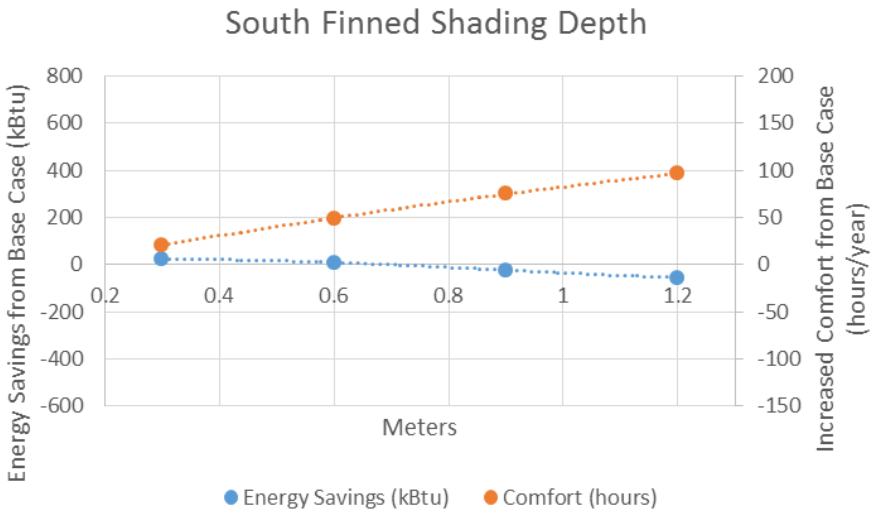


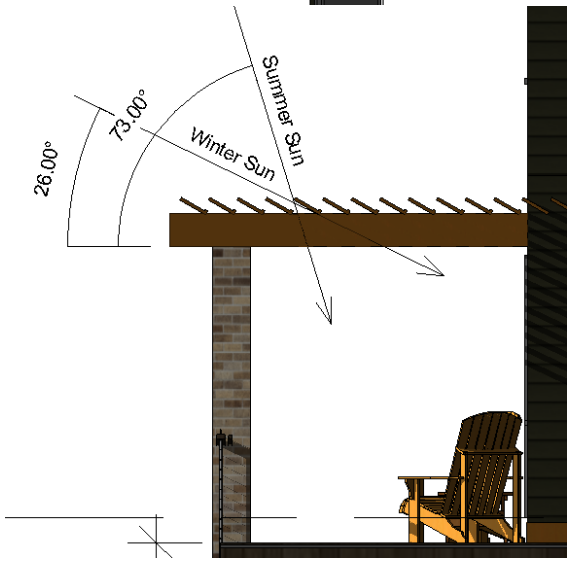
EnergyPLUS Modelling- External Shading

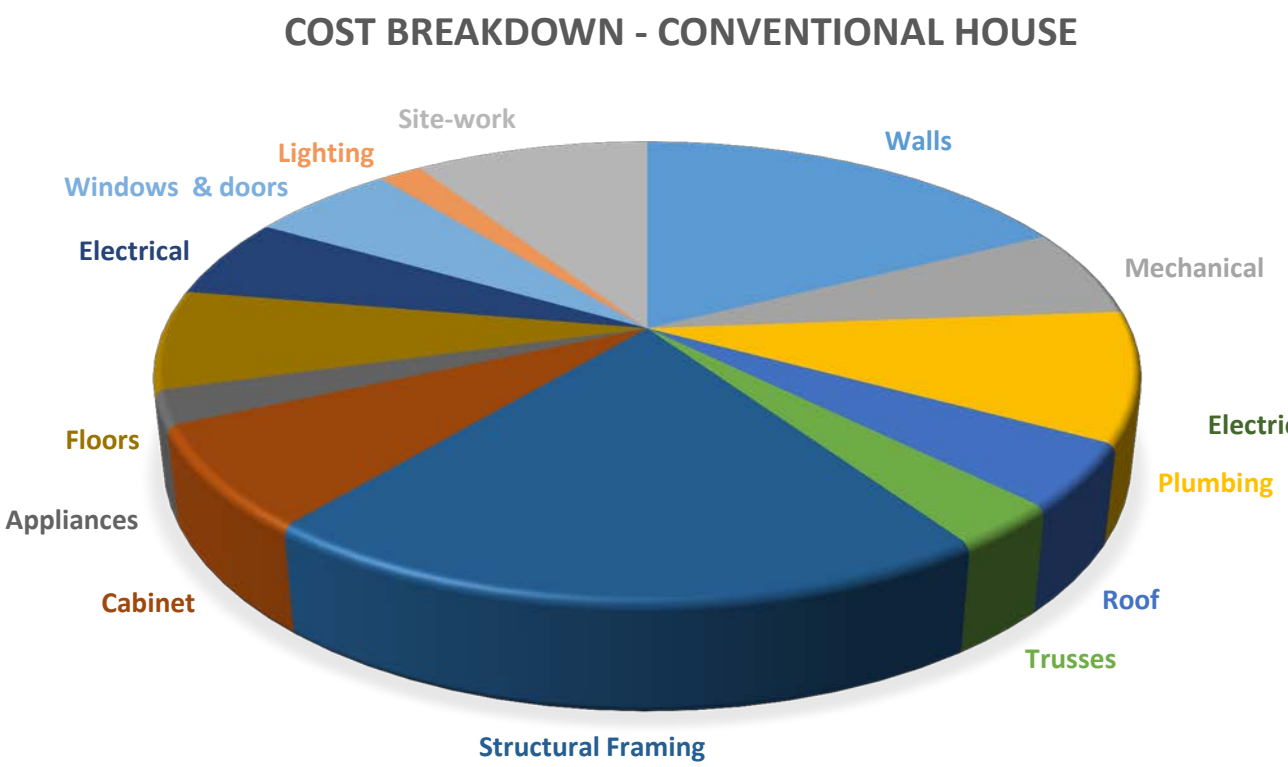
- Compared changes in hours of comfort to changes in energy savings
- Solid shading increases comfort but reduces energy savings
- Trellis shading increases comfort and has little effect on energy use
- Trellis fins are angled at 30 degrees to allow winter sun but deflect summer sun

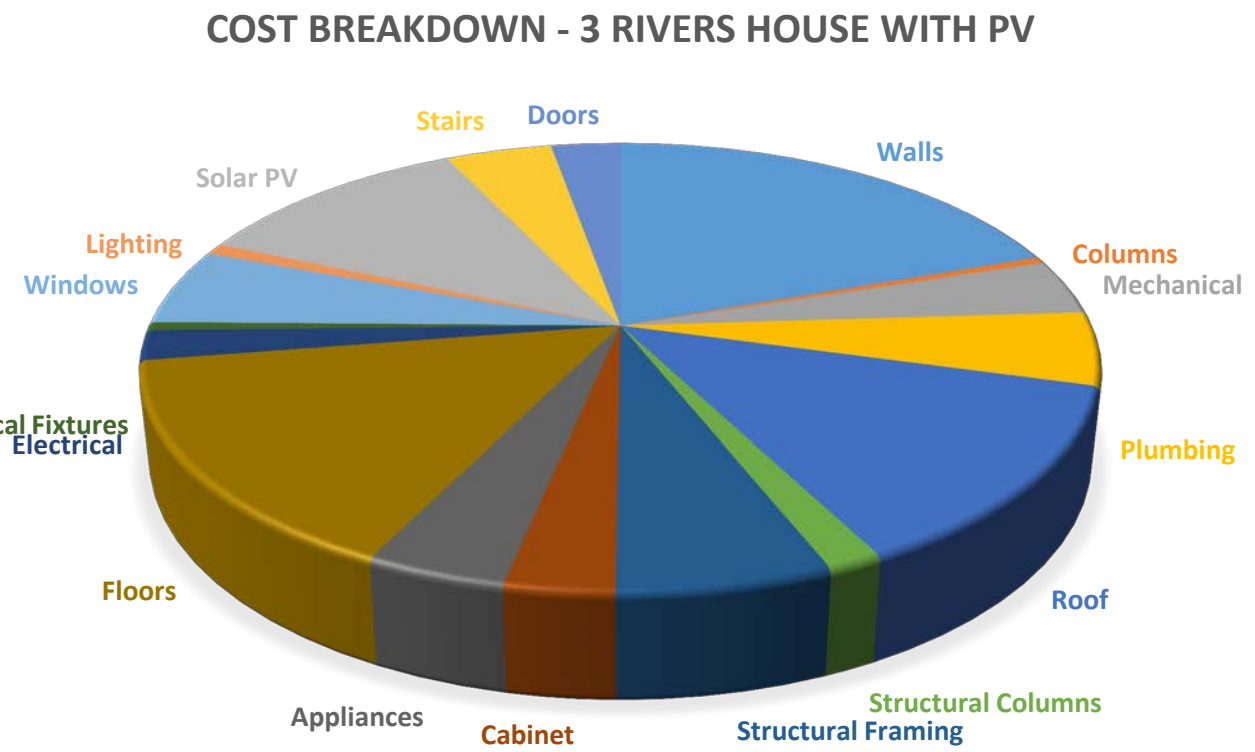












Financial Analysis

Assumptions

1. Costs are based on RSMeans and adjusted for Pittsburgh
2. Soft costs are based on a percentage value of total construction cost obtained from NAHB's national construction cost survey
3. 10% downpayment
4. 3% Interest rate

Affordability

- Affordable on a household income of $51,000 (2014 Median for Pittsburgh)
- Target Cost: $280,500
- Profit Margin: 6.8%

Pittsburgh median household income year 2014 [1]	$51,291	Source: Department of Numbers Pittsburgh Pennsylvania
Property taxes	$4,484	Assuming property value to be $200,000
Home insurance [2]	$700	Source: Henshaw
Estimating annual mortgage	$12,910	=28% of Median household income less property taxes and home insurance
Monthly mortgage	$1,076	Annual mortgage/12
Sales price based on monthly mortgage for a 30 year loan	$280,500	Interest rate is 3% and after taking into account a 10% down-payment a total loan principal of around $255,000

Cost Comparison

Payback Period of High Performance Features:

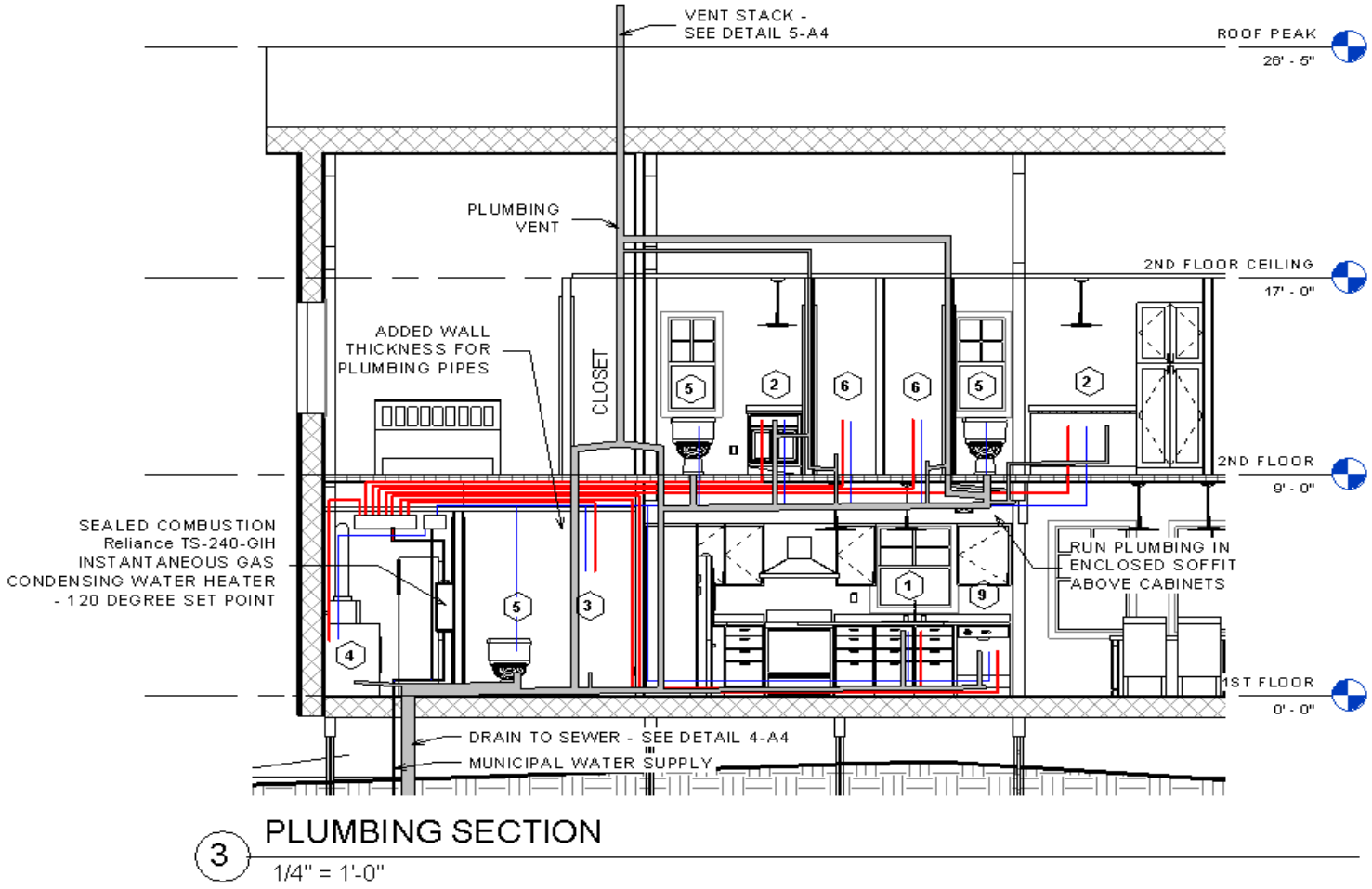
- With PV panels: 12.5 years
- Without PV panels: 24 years

Increased cost over average home:

- $16,200

High Performance Features			
Component	3 Rivers House	Conventional	Difference
Structural Framing	$ 19,466	$ 36,438	$ (16,972)
Walls	$ 39,045.32	$ 26,243	$ 12,802
Roof	$ 26,128	$ 7,932	$ 18,196
Appliances	$ 8,051.48	$ 4,189.00	$ 3,862
Windows and Doors	$ 15,300	$ 10,117	$ 5,183
HVAC	$ 7,963	$ 10,980	$ (3,017)
Plumbing	$ 1,796	$ 11,823	$ (10,027)
Flooring	$ 19,970	$ 12,378	$ 7,592
Lighting	$ 1,618.00	$ 3,008.00	$ (1,390)
Total	$ 139,337	$ 123,108	$ 16,229

		National Average Single Family house		3 Rivers House	
I.	Sale Price Breakdown	National Average	Share of Price	3 Rivers House	Share of Price
A.	Finished Lot Costs	$74,509	18.60%	$ 2,500.00	0.89%
B.	Total Construction costs	$246,453	61.70%	$ 229,764.81	81.91%
C.	Financing Costs	$5,479	1.40%	$ 3,927.00	1.40%
D.	Overhead and General expenses	$17,340	4.30%	$ 12,061.50	4.30%
E.	Marketing Cost	$4,260	1.10%	$ 3,085.50	1.10%
F.	Sales Commissions	$14,235	3.60%	$ 10,098.00	3.60%
G.	Profit	$37,255	9.30%	$ 19,063.19	6.80%
	Total Sales Price	$399,532	100%	$ 280,500.00	



Plumbing, Lighting & Appliances

Appliances

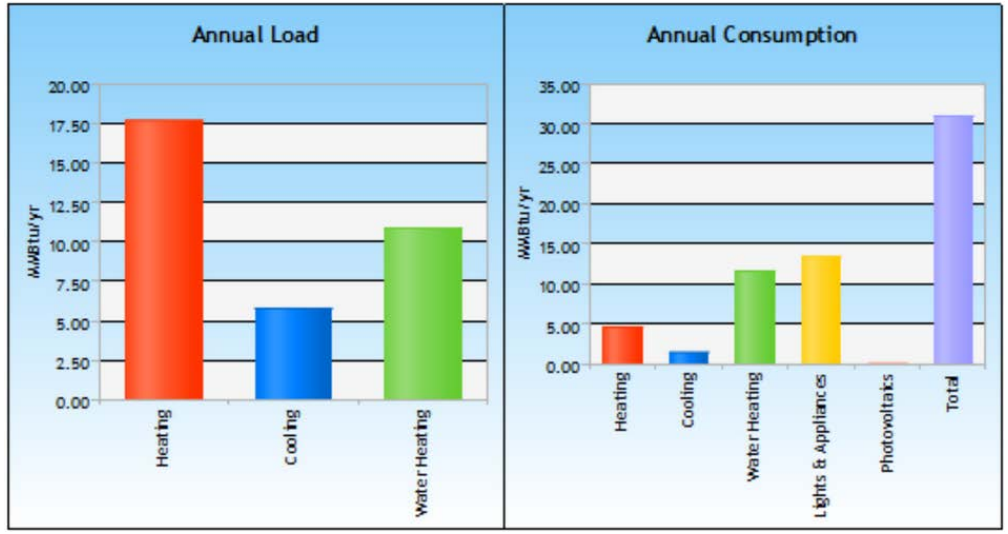
Lighting and appliances are largest end use, indicating efficient design and importance of managing occupant behavior

Highest performing Energy Star and Watersense appliances, wherever possible

Ventless dryer

- Envelope integrity with fewer penetrations
- Avoid combustion appliances
- Don't exhaust heat unnecessarily

Dishwasher with water heater reduces water heating loads by requiring DHW to be heated to 120°F instead of 140°F



Predicted annual load and energy consumption for Three Rivers House without PV

Lighting

100% LED lighting

- Longest-lasting and most efficient
- Reduce harmful chemicals

Daylighting and minimum required light levels supplemented with task lighting

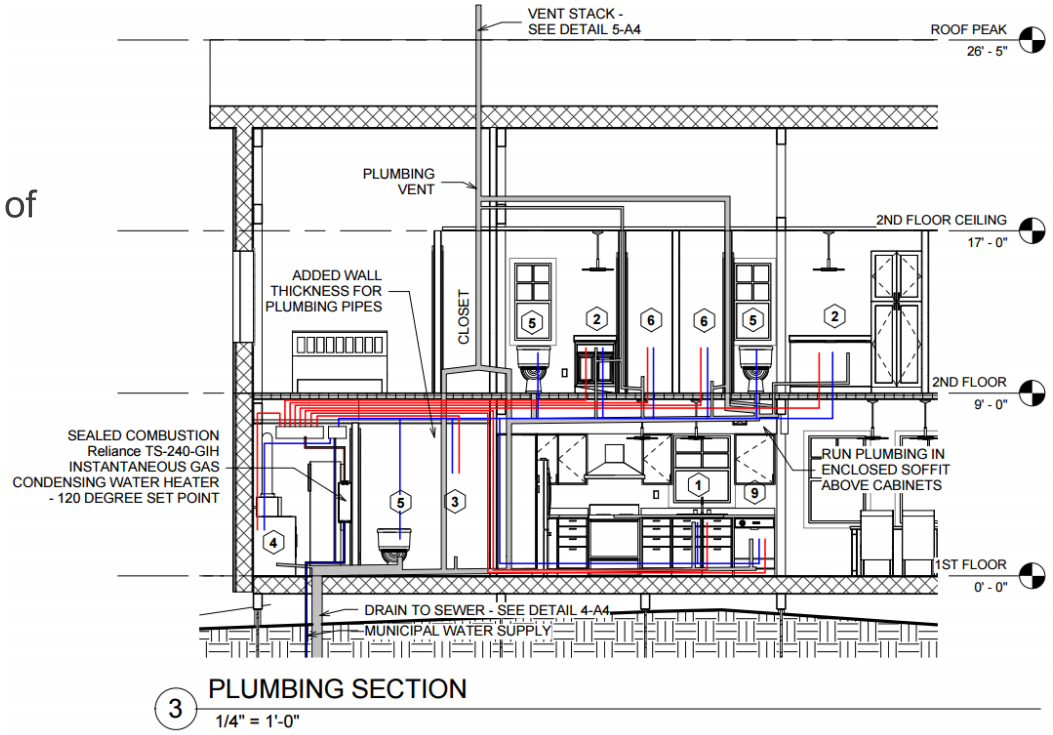
- Main living spaces planned and oriented to receive daylight when occupied

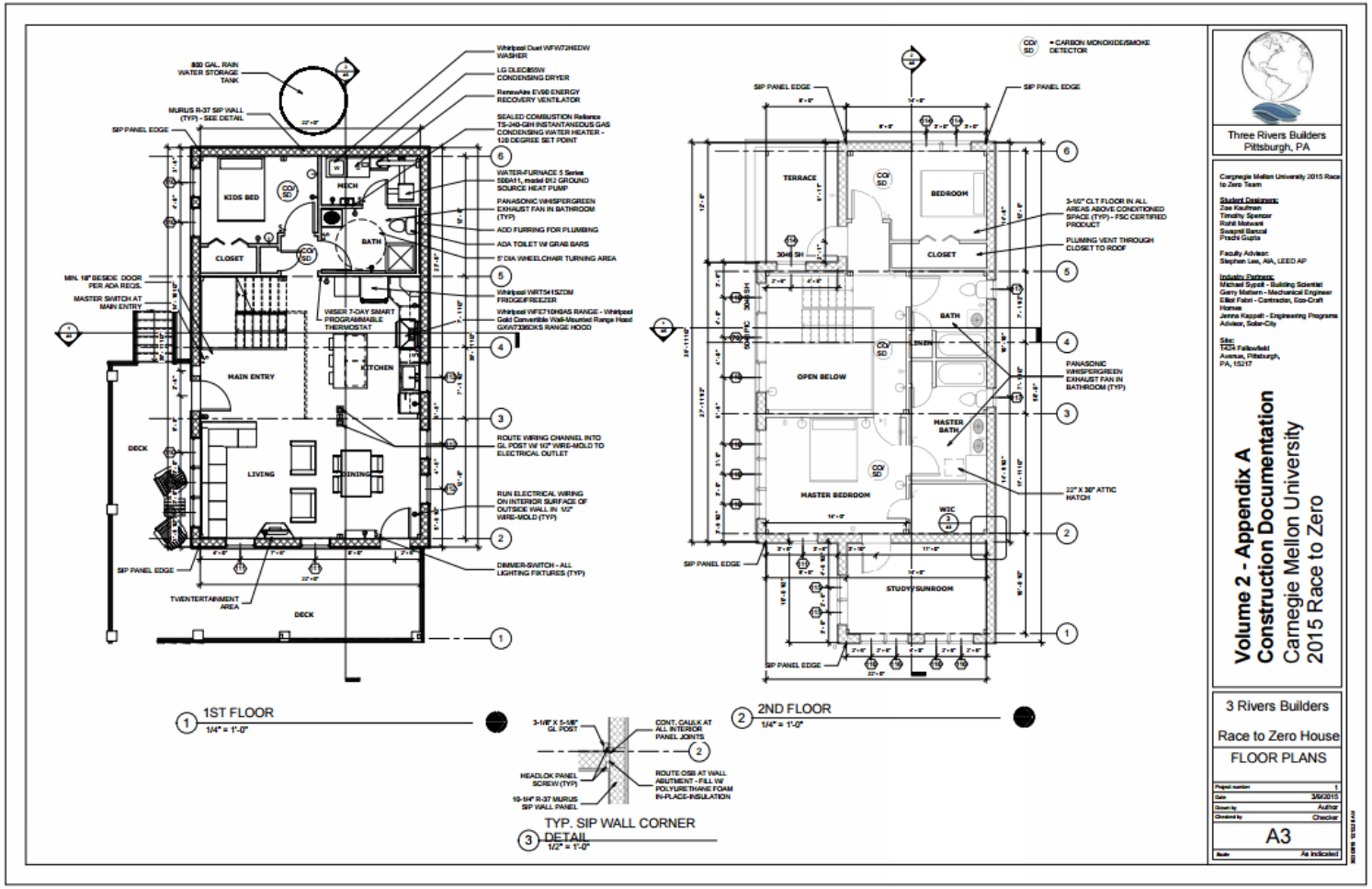
Leviton SureSlide dimmer switch

Lighting controls and dimmers address occupant behavior

Plumbing

- Reliance TS-240 instantaneous condensing direct-vent water heater with EF=0.95
  - No storage tank required--water heating only when required
- Bathrooms and kitchen located in the same area to minimize length of piping
  - Toe space under cabinets for plumbing
  - Ducts and piping in soffit above cabinets
- PEX tubing
  - Flexibility, fast and easy installation, noise reduction
- Home-run hot water system
  - Average wait time: 7 seconds (discounting the dishwasher)
  - Watersense appliances mean lower flow but slightly longer wait time
- Central vertical plumbing vent to reduce envelope penetrations

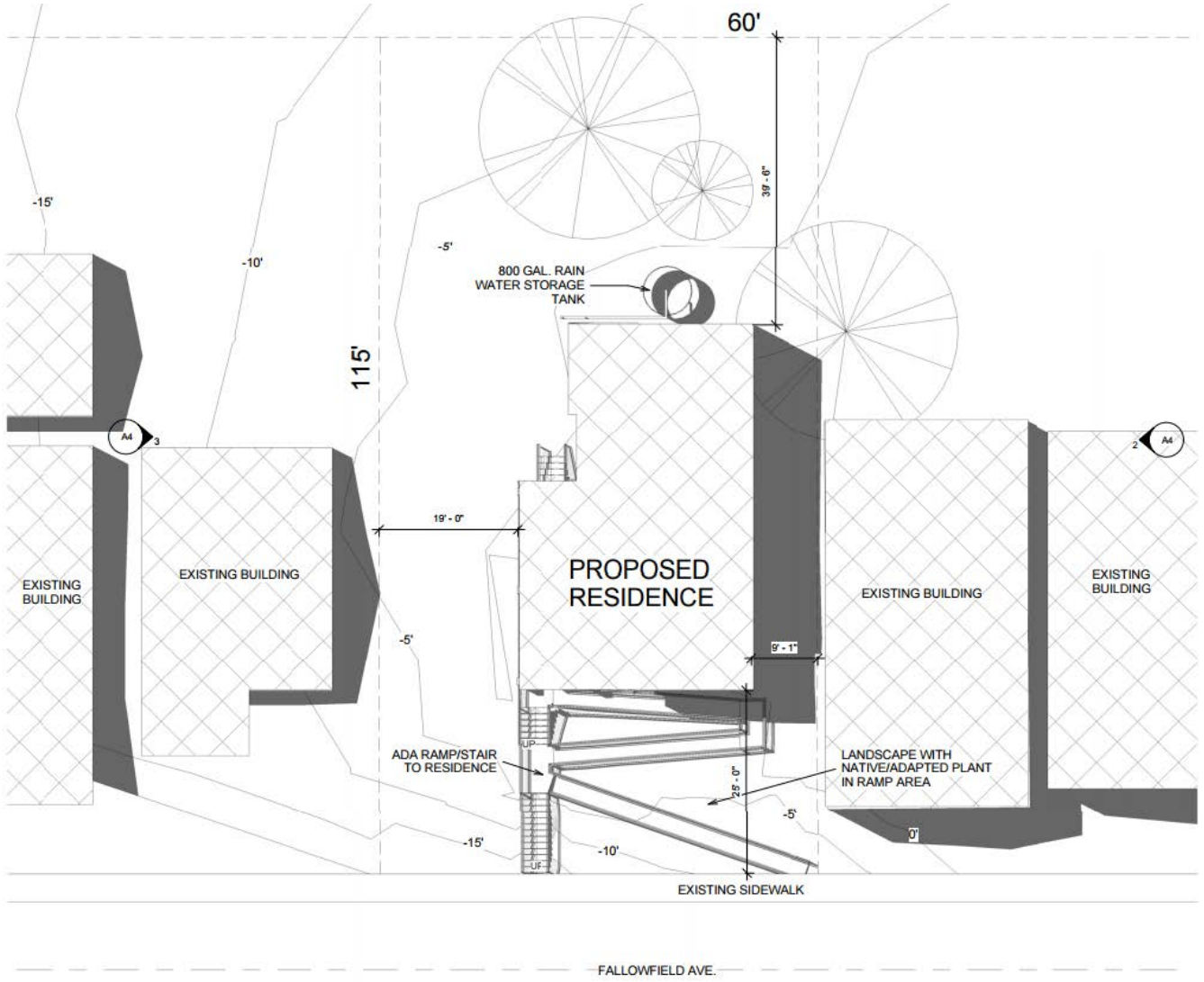




Construction Documentation

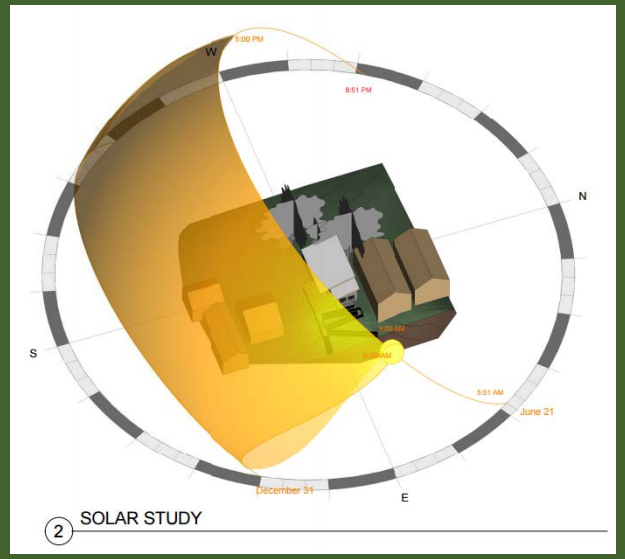
Site Plan

- Little shading from neighboring buildings
- Handicap accessible stair-ramp at entry to home
- Rainwater storage tank for site irrigation
- Located on a previously built infill lot
- 6900 ft^2 lot



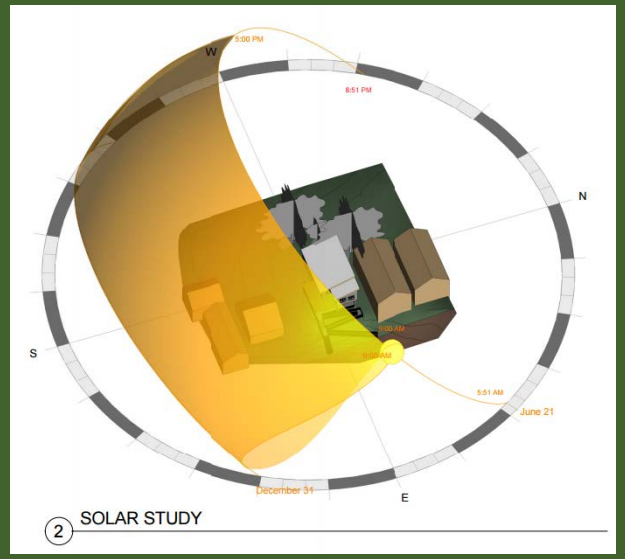
The Three Rivers House

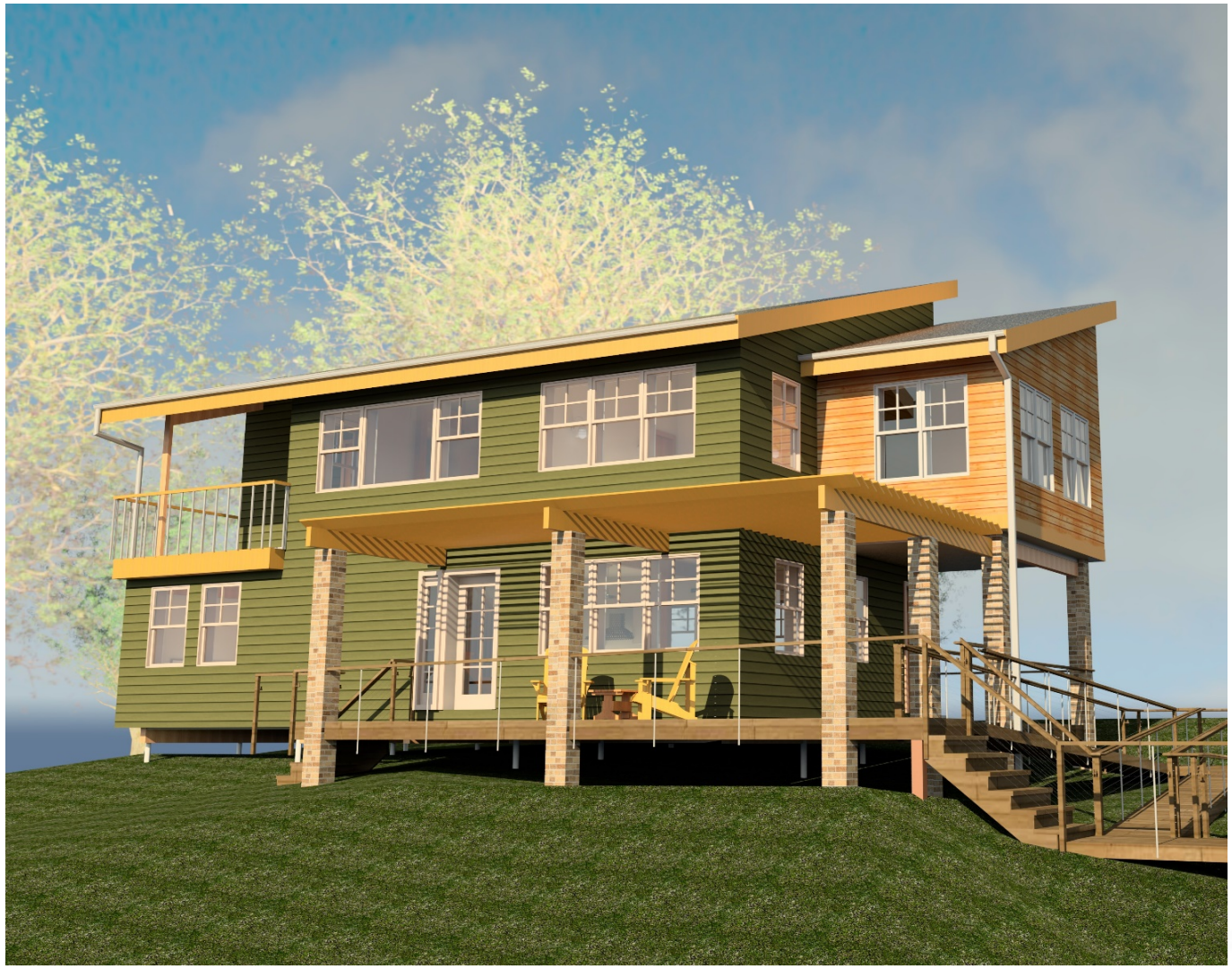
- Summer Solstice at noon
- Windows mostly shaded
- Shaded outdoor living spaces



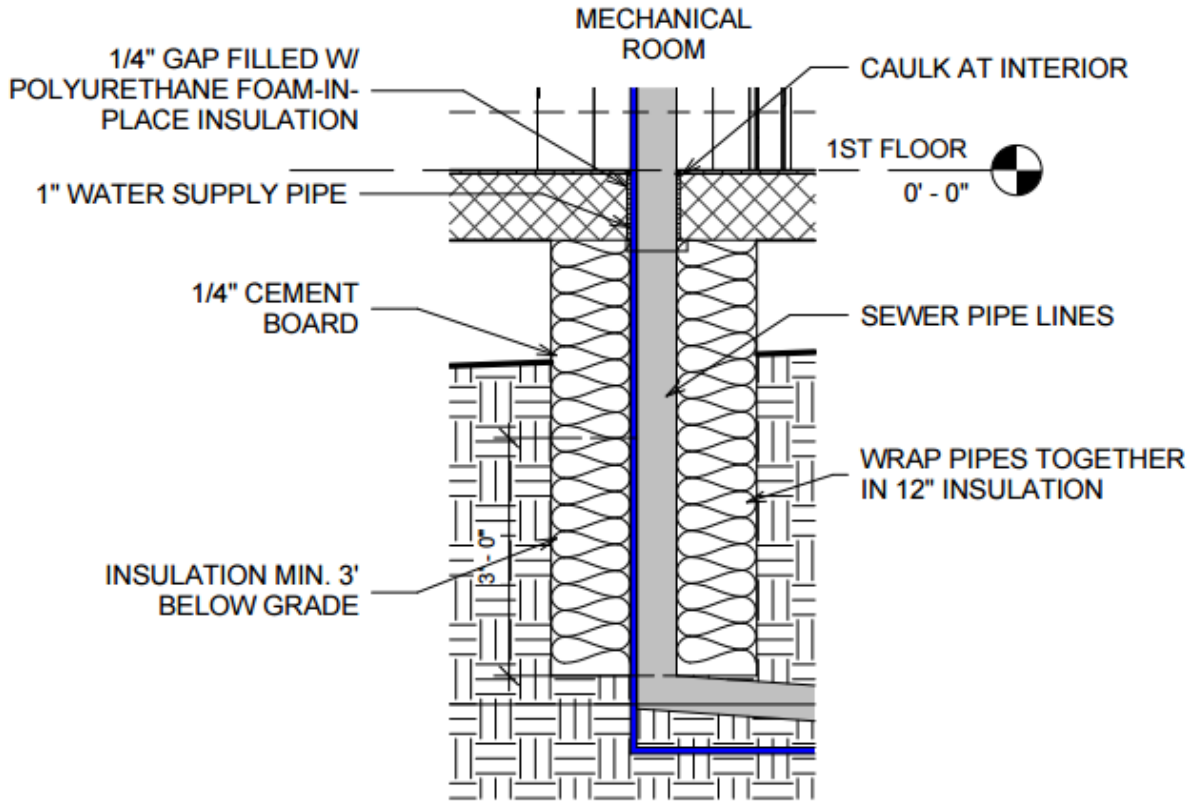
The Three Rivers House

- Winter Solstice at noon
- Sunlight penetration into living space





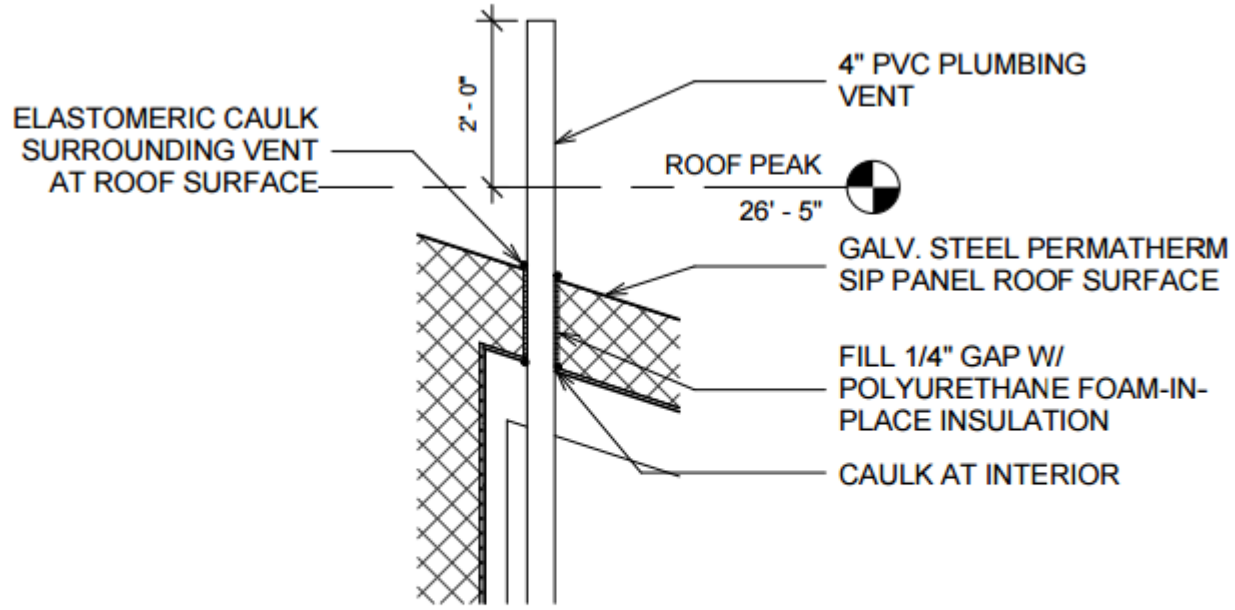
Utility Connection Air Sealing & Insulation



4 UTILITY CONNECTION

1/2" = 1'-0"

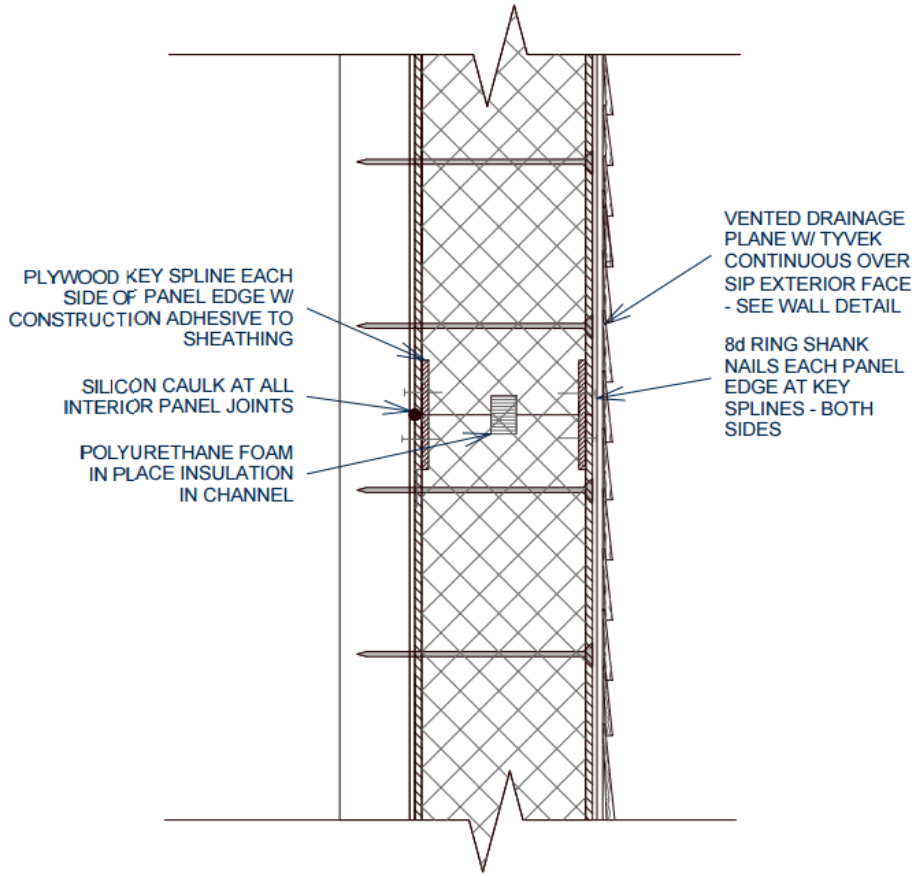
Plumbing Vent Air Sealing



5 PLUMBING VENT

1/2" = 1'-0"

SIP Wall Joint Detail



TYPICAL SIP WALL PANEL JOINT

Industry Partners

Industry Partners

Gerry Mattern

Consulting MEP engineer and Adjunct Professor, Carnegie Mellon University School of Architecture and Civil and Environmental Engineering

Ligonier, PA

Consulting for MEP design

Nina Baird

Zero Energy Housing advisor, Carnegie Mellon University

Pittsburgh, PA

REM/Rate and IAQ guidance

Jenna Kappelt

Engineering Programs Advisor, SolarCity

San Mateo, CA

Solar energy expertise

Elliot Fabri, Jr.

Pittsburgh Modular Home Builder

EcoCraft Homes

Pittsburgh, PA

Design and prefabrication consultation

Michael Sypolt

PHP/MySQL developer and Building Science specialist

TransitGuru Limited

Pittsburgh, PA

Hygrothermal analysis