Heating and Cooling Energy Modeling of 3D-Printed Concrete Construction of Residential Buildings

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Overview

- Major industry need: guidance on how to model performance of 3D-printed construction (3DPC) wall assemblies
- Scope:
  - Characterized a prototypical 3D-printed wall construction for use in whole-house energy modeling tools
  - Performed an analysis using the BEopt tool to estimate residential building energy implications of 3DPC compared to wood frame construction (WFC), and concrete masonry unit (CMU) wall constructions.
  - Annual energy and peak demand of a typical 3DPC wall construction was compared against WFC and CMU construction scenarios that meet the 2018 International Energy Conservation Code (IECC) in each of the eight IECC climate zones.

Motivations

1. Potential benefits of 3D-Printed Concrete (3DPC) construction:

- High thermal mass of 3DPC walls helps reduce indoor temperature swings driven by significant outdoor temperature variations during from day to night
- Building thermal performance resilience associated with 3DPC structures

2. Identification of best use/practices related to 3DPC construction:

- Most effective for both energy efficiency and thermal comfort in warmer climates[ǂ]

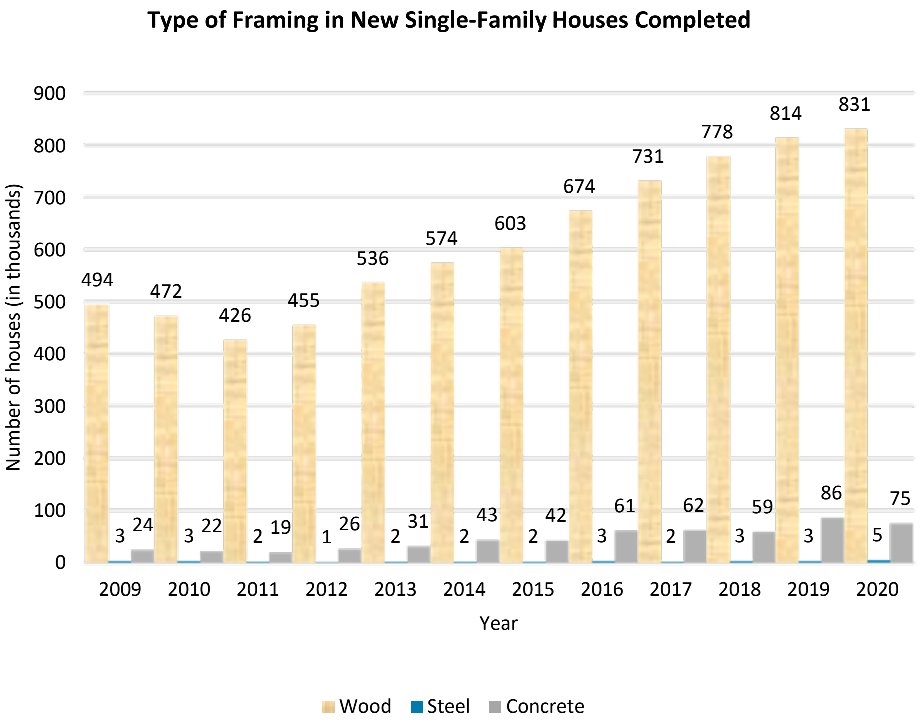
3. Outstanding challenges and opportunities

- Establishing an approach to energy modeling of 3DPC walls to include appropriate mass, insulation, and thermal bridging
- Limited data available on energy performance of houses built with 3DPC

References:
[ǂ] https://web.ornl.gov/sci/buildings/conf-archive/2001%20B8%20papers/080_Kosny.pdf, https://www.yourhome.gov.au/passive-design/thermal-mass

General Construction Types for New US Homes

- Wood/stick/timber frame (~ 90% *)
- Concrete (~ 10% *)
  - Concrete masonry units (CMU)
  - Autoclave aerated concrete (AAC)
  - Insulated concrete forms (ICF)
- Structural insulated panels (SIP) (<2%)
- Steel frame (<0.5% *)



* Reference: US Census Bureau (MCD): Cheryl Cornish, S., 2022. Characteristics of New Housing. [online] Census.gov. Available at: https://www.census.gov/construction/chars/ [Accessed 6 May 2022].

3D-Printed Concrete (3DPC) Construction – An Emerging Technology

CNBC — 3/22/21

REAL ESTATE

3D-printed housing developments suddenly take off – here's what they look like

PUBLISHED FRI, MAR 12 2021-3:36 PM EST | UPDATED MON, MAR 22 2021-11:53 AM EDT

Diana Olick

WORLD ECONOMIC FORUM — 11/9/21

Industry Agenda | SDG 13: Climate Action | SDG 09: Industry, Innovation and Infrastructure | Infrastructure

The world's "largest neighbourhood" of 3D-printed homes to be built in US

Home / Construction 3D Printing / 3 new AM houses being completed in the US by COBOD customers — 10/30/21

AM Industry | Architecture | Construction 3D Printing

3 new AM houses being completed in the US by COBOD customers

Changing America — 12/21/21

Shared Destiny. Shared Responsibility.

Resilience › Smart Cities

First 3D-printed, owner-occupied home in US to be unveiled

AP NEWS — 4/27/21

3D printing's new challenge: Solving the US housing shortage

By TERENCE CHEA April 27, 2021

TRANSFORM — CNN BUSINESS — 3/18/21

The first 3D-printed housing community in the US is being built in the California desert

By David Williams, CNN
Updated 7:38 AM ET, Thu March 18, 2021

INNOVATIVE DESIGN — 1/3/22

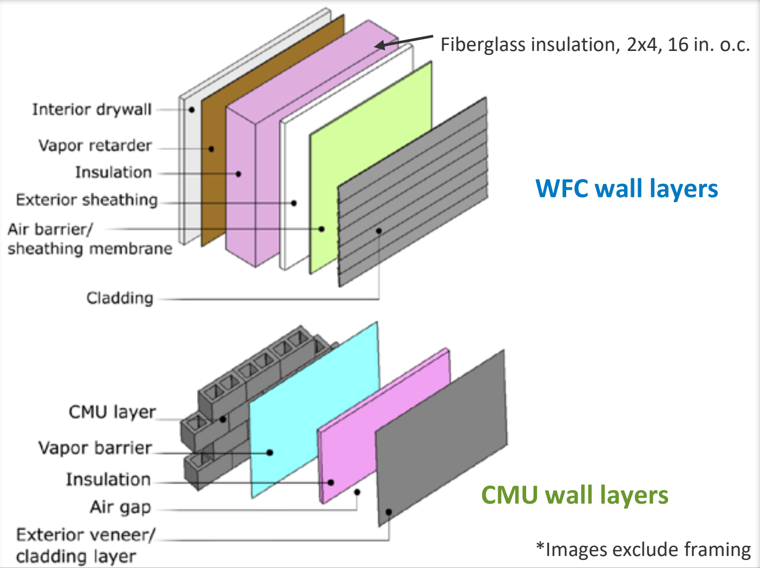
Habitat for Humanity Debuts First Completed Home Constructed Via 3D Printer

In Virginia, the new homeowners also receive a miniature 3D printer to build anything they'll want or need

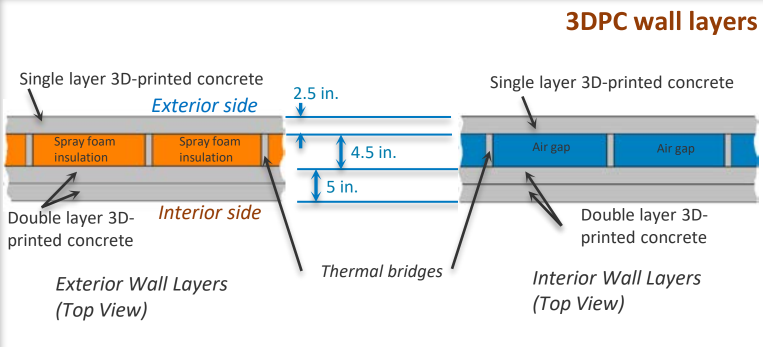
By Jessica Cherner
January 3, 2022

Modeling Approach

- References/baselines:
  - Typical wood frame construction (**WFC**)
  - Typical concrete masonry unit (**CMU**) construction



- Compared against:
  - High thermal mass walls: 3D printed concrete layers with exterior wall cavities filled with expanded polystyrene foam insulation (**3DPC**), identical interior wall cavities with air gap



Modeling Workflow

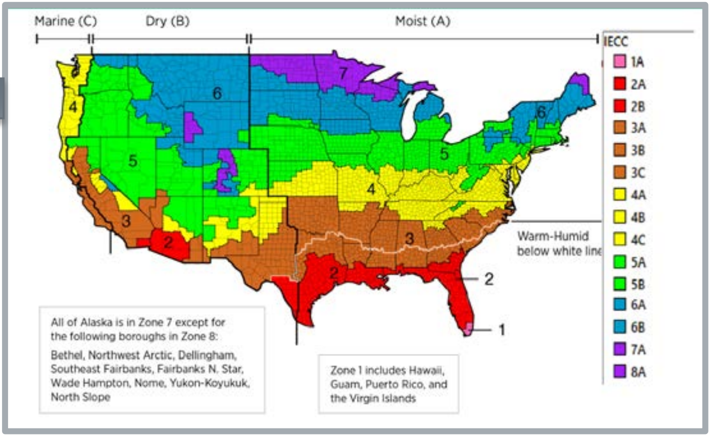


Image source: https://basc.pnnl.gov/images/iecc-climate-zone-map

Each of the 8 IECC Climate Zones

Residential Building Codes/Regulations (IECC 2018, 10 CFR §430.31)

Building Design-Specific Inputs

Location- Specific Inputs

Model Assumptions and Material Properties

BEopt Model

- Baseline 1 (WFC)
- Baseline 2 (CMU)
- 3DPC

Time Series Outputs (Peak Energy Demand)

Annual Average Outputs (Annual Energy Consumption)

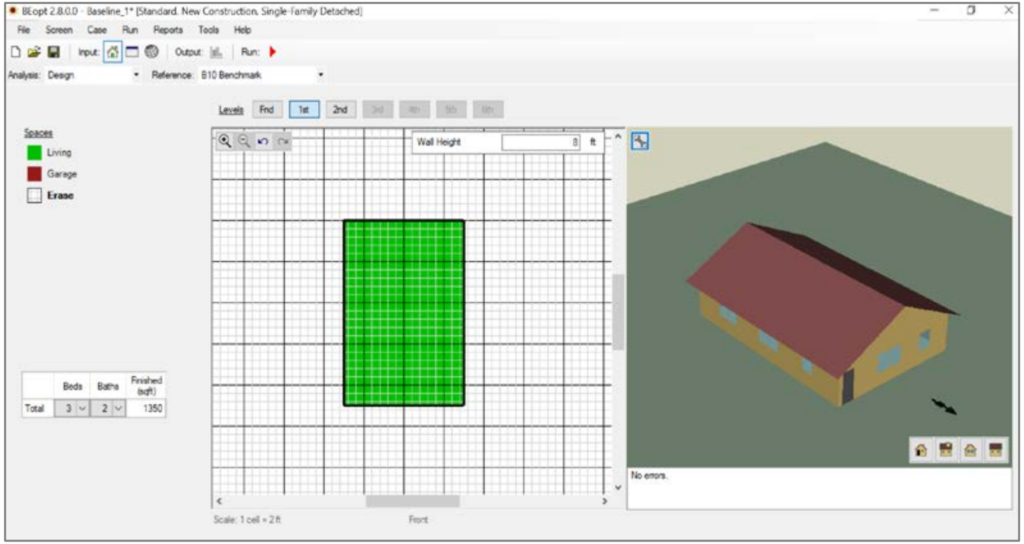
BEopt Modeling

Building characteristics

- 3 Beds, 2 Baths, 1350 ft^2
- One-story above grade level
- Slab-on-grade foundation
- Single orientation (N-S length)

Exterior wall types

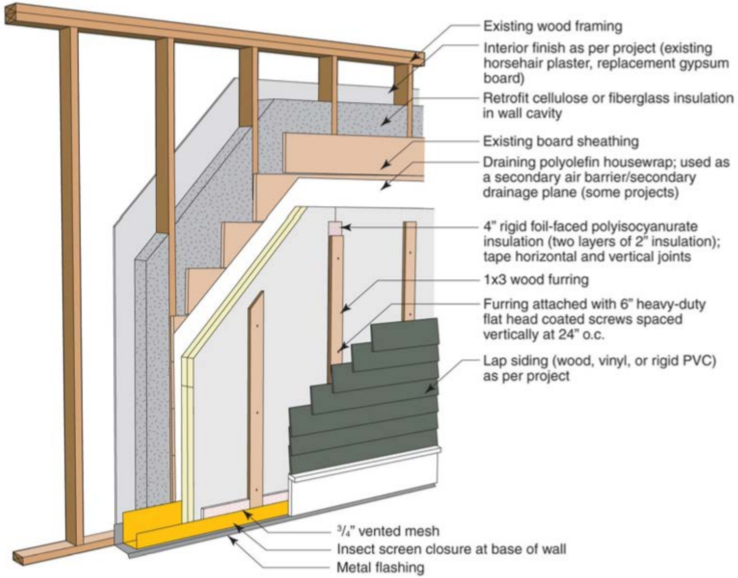
- WFC (Fiberglass insulation, 2x4, 16 in. o.c.)
- CMU (12 in. hollow, continuous rigid foamboard exterior side insulation)
- 3DPC (Double layer concrete with insulated core)



BEopt Graphical User Interface

Simplified Wall Modeling in BEopt

BEopt calculates assembly U-factors for each surface based on thermal properties of its layers



(Source: https://www.nrel.gov/docs/fy13osti/54643.pdf)

Wood Frame Construction (WFC)

Wall Layer Properties + Framing Factor → Assembly U-Factor

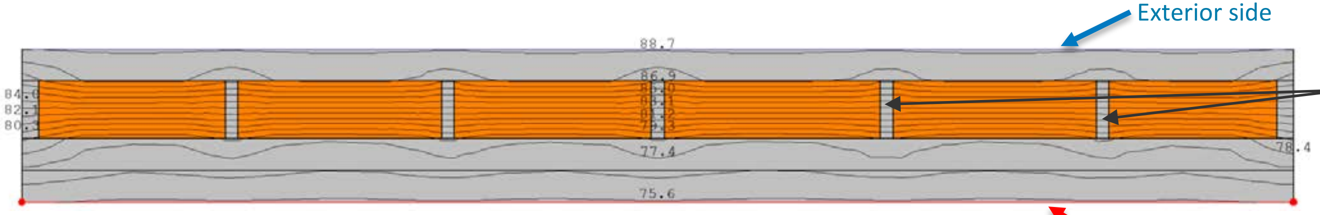
$$U_{parallel} = U_{cavity} * (1 - ff) + U_{wood} * ff$$

$$U_{assembly} = 1/(1/U_{parallel} + 1/U_{continuous})$$

Where,
ff: framing factor, fraction of the wall assembly composed of structural framing
$wood$: framing material (studs, windows, doors etc),
$cavity$: cavity insulation material,
$continuous$: drywall, sheathing, siding, & air barrier layers

(+ … similar for CMU and 3DPC for window and door frames)

3DPC Wall Assembly Model



Thermal bridging for the wall assembly, including around doors and windows accounted for with uniformly distributed thermal bridging in the *THERM* model

Top section view of a 100 in. long 3DPC wall segment

- *THERM 7.7* software used to perform 2-D finite element heat transfer analysis across 3DPC exterior wall segment to estimate the assembly U-factor
- Assumes a similar degree of thermal bridging as CMU wall construction (7.6% framing factor)
- Emissivity = 0.9 (*THERM* default based on ASHRAE Handbook)
- Summer Conditions:
  - Exterior Temperature = 89°F; Film Coefficient = 4.0 Btu/h-ft^2-F
  - Interior Temperature = 75°F (summer set point); Film Coefficient = 1.46 Btu/h-ft^2-F
- Winter Conditions:
  - Exterior Temperature = 0°F; Film Coefficient = 5.988 Btu/h-ft^2-F
  - Interior Temperature = 72°F (winter set point); Film Coefficient = 1.46 Btu/h-ft^2-F
- Calculated U-Factors:
  - Summer = 0.0485 Btu/h-ft^2-F; Winter = 0.0487 Btu/h-ft^2-F (Average = **0.0486 Btu/h-ft^2-F**)
- Calculated R-Values:
  - Summer = 20.63 h-ft^2-F/Btu; Winter = 20.54 h-ft^2-F/Btu (Average = **20.585 h-ft^2-F/Btu**)

Simulation Approach

Compute U-Factor of the 3DPC wall assembly based on material properties and a 7.6% framing factor (similar to a CMU wall)

Adjust thermal conductivity of plain wall in *BEopt* for the given geometry to match the U-Factor given by *THERM*

Modeling Assumptions

Assumptions applicable across all three designs (WFC, CMU, and 3DPC)

- Air leakage: 5 ACH50 for Climate Zone (CZ) 1 & 2, and 3 ACH50 for CZ 3 to 8
- Duct leakage: 4 CFM25 per 100 ft^2 (in vented attic space)
- Heating system: Central gas furnace - 80% AFUE
- Cooling system: Central air conditioner - SEER 14
- Heating setpoint: 72 °F, Cooling setpoint: 75 °F (IECC 2018 Table R405.5.2(1))

Assumptions specific to WFC construction

- Cavity insulation R-13 for CZ 1 & 2, R-20 for all other CZ
- Wall sheathing with OSB for CZ 1 through 5; R-5 XPS with OSB for CZ 6 to 8
- Exterior finish: Wood siding, light (R-1.4)
- Framing factor: 25%

Assumptions specific to CMU construction

- 12-inch hollow CMU
- Wall sheathing with R-4 XPS continuous exterior insulation for CZ 1; R-6 Polyiso for CZ 2; R-13 XPS for CZ 3 to 5; R-20 XPS for CZ 6, R-21 XPS for CZ 7 & 8
- Exterior finish: Fiber-Cement, light (R-0.2)
- Framing factor: 7.6%

Assumptions specific to 3DPC construction

- 5-inch interior concrete layer (two bead layers, 2.5 in. each), 4.5-in. gap (exterior walls have open cell spray foam insulation, interior walls have air in the gap), 2.5-in. exterior concrete layer
- Exterior finish: Fiber-Cement, light (R-0.2)
- Framing factor: 7.6%; assumes a similar degree of thermal bridging around structural members, doors and windows as CMU construction.

Table 1. Wall Assembly Modeled U-Factors (Btu/h·ft²·F)

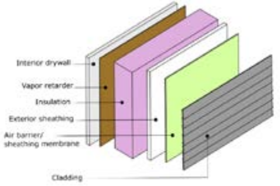
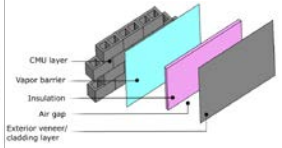
2018 IECC Climate Zone (CZ)	WFC	CMU	3DPC
	 	 	
1	0.087	0.108	0.053
2	0.087	0.100	0.053
3	0.059	0.058	0.053
4	0.059	0.058	0.053
5	0.059	0.058	0.053
6	0.044	0.041	0.053
7 and 8	0.044	0.040	0.053

Table 2. 3DPC Wall Properties

3DPC Layer Property	Concrete [a]	Open Cell Spray Foam Insulation [b]	Air (STP)
Density (lb/ft³)	95.01	0.50	0.0765 [c]
Thermal Conductivity (BTU.in/h-ft² -F)	1.39	0.242	0.015 [d]
Specific Heat (Btu/lb.ft)	0.174	0.345	287 [e]

References

a. Suntharalingam, T., Upasiri, I., Gatheeshgar, P., Poologanathan, K., Nagaratnam, B., Santos, P. and Rajanayagam, H., 2021. Energy Performance of 3D-Printed Concrete Walls: A Numerical Study. Buildings, 11(10), p.432.

b. https://australianmodernbuildingalliance.org.au/images/amba/resources/Physical_properties_of_polyurethane_insulation.pdf

c. https://www.grc.nasa.gov/www/k-12/BGP/airprop.html

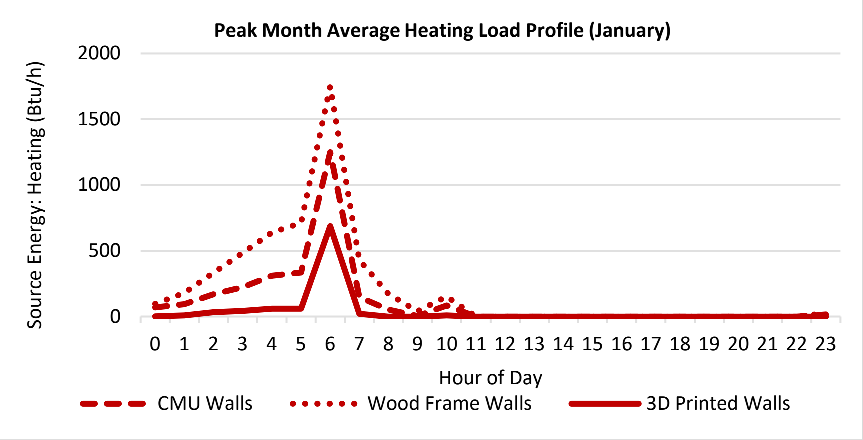
d. http://hyperphysics.phy-astr.gsu.edu/hbase/Tables/thrcn.html

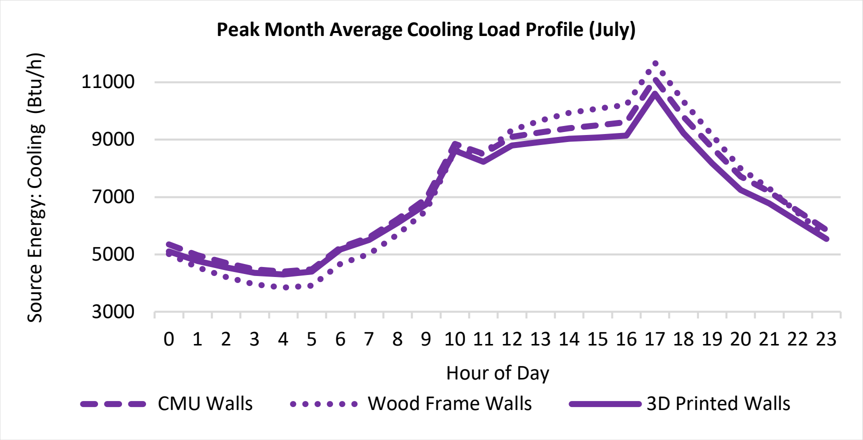
e. https://www.ohio.edu/mechanical/thermo/property_tables/air/air_Cp_Cv.html

Model Limitations

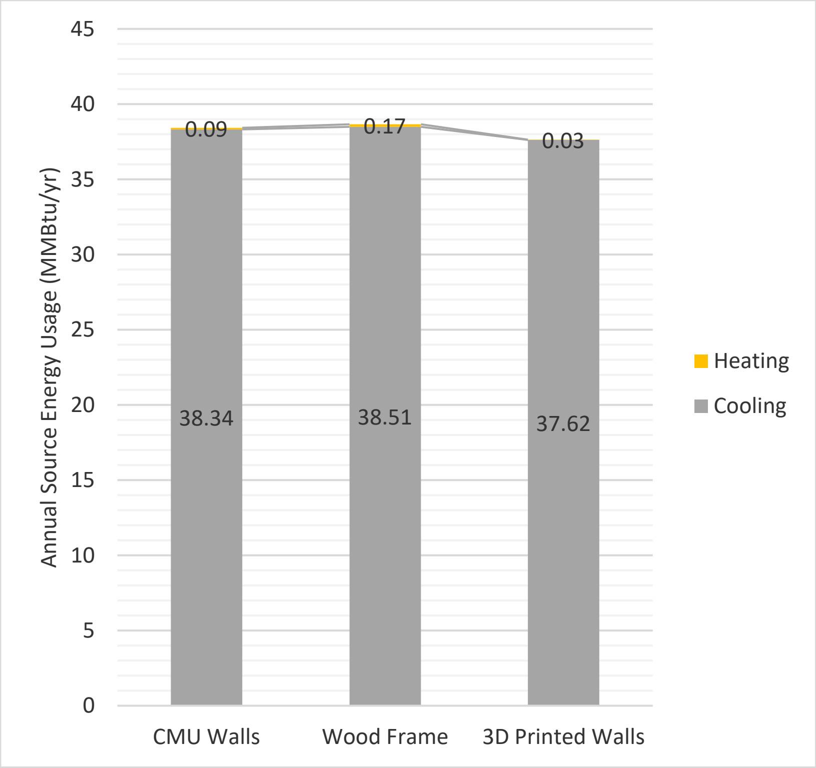
- Variations in heat transfer across different locations within the same wall are not accounted for. An overall heat transfer coefficient (U-factor) is considered across each wall with an associated framing factor.
- WFC and CMU walls follow prescriptive insulation values from IECC 2018, while 3DPC walls follow industry practices, so each wall differs in their assembly U-factor.
- Model calibration has not been performed with measured quantities and parameters

Annual and Hourly Energy Usage: Climate Zone 1

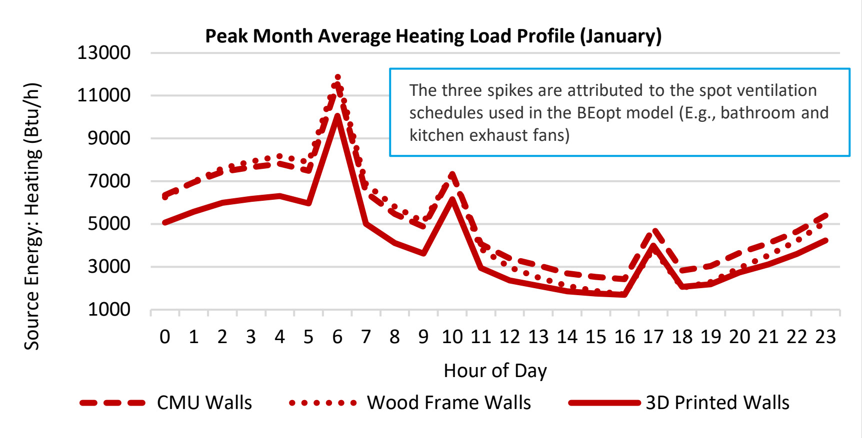


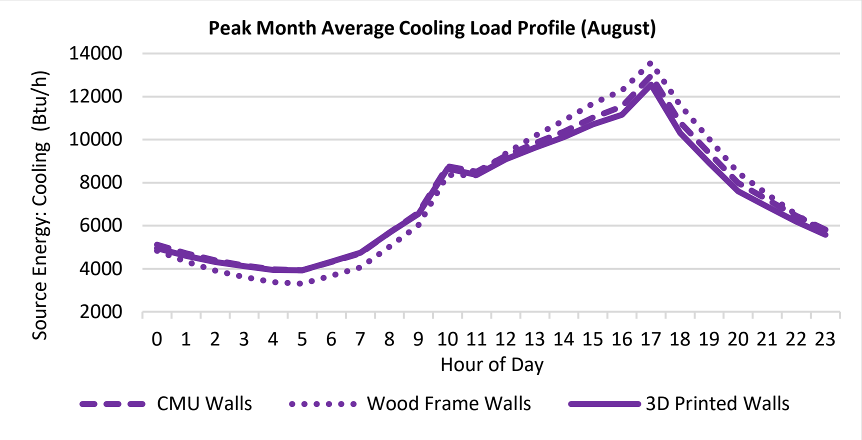


Reference City: Miami, FL

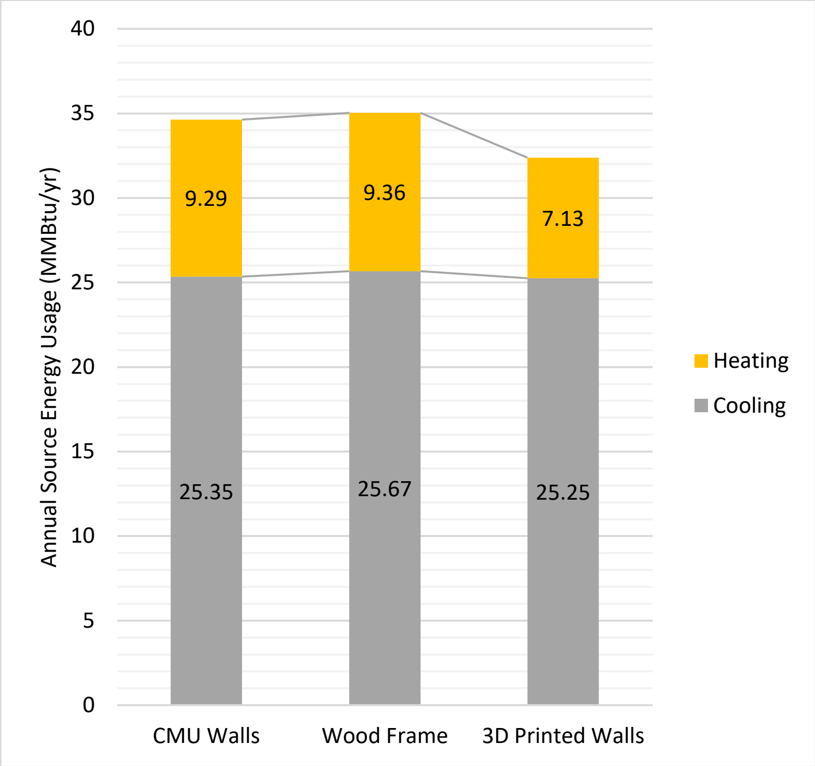


Annual and Hourly Energy Usage: Climate Zone 2

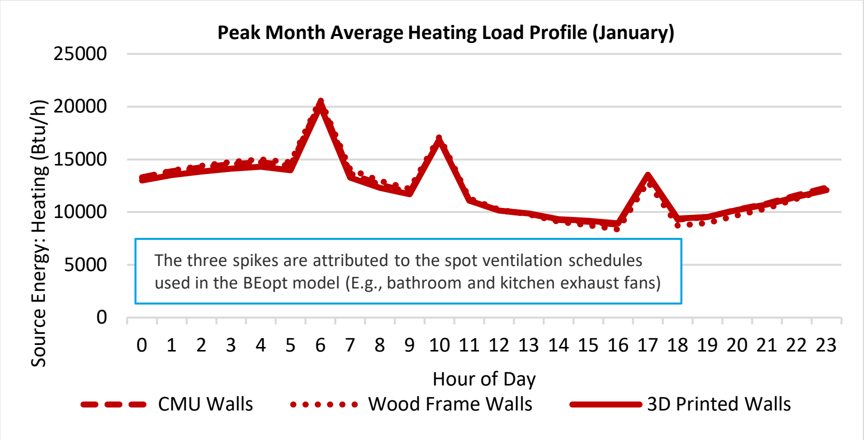


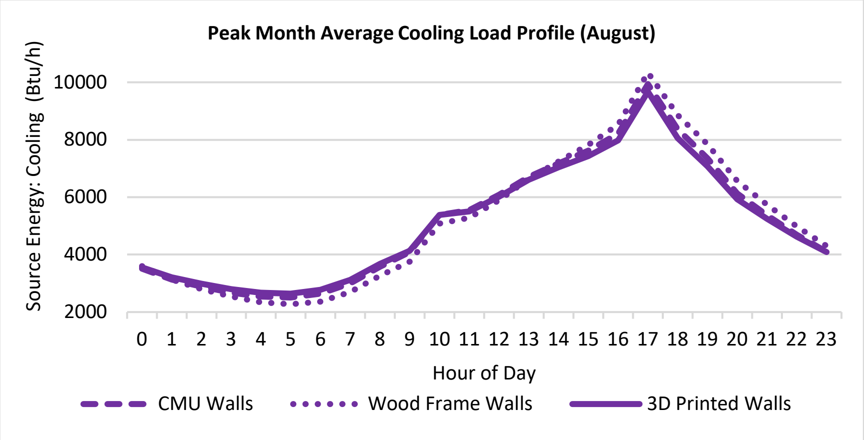


Reference City: Houston, TX

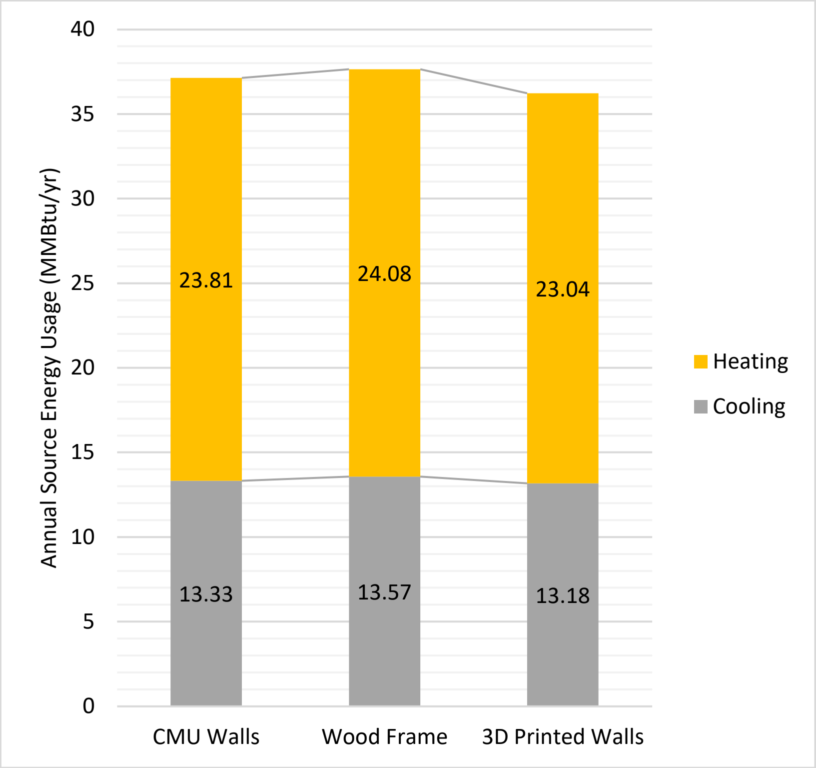


Annual and Hourly Energy Usage: Climate Zone 3

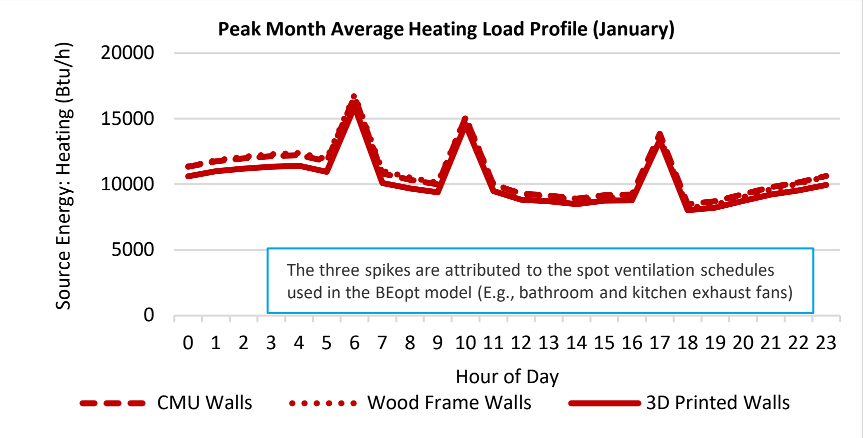


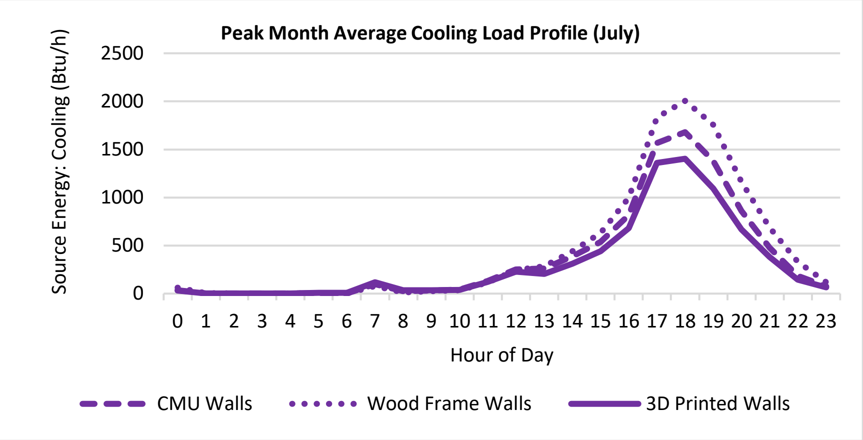


Reference City: Atlanta, GA

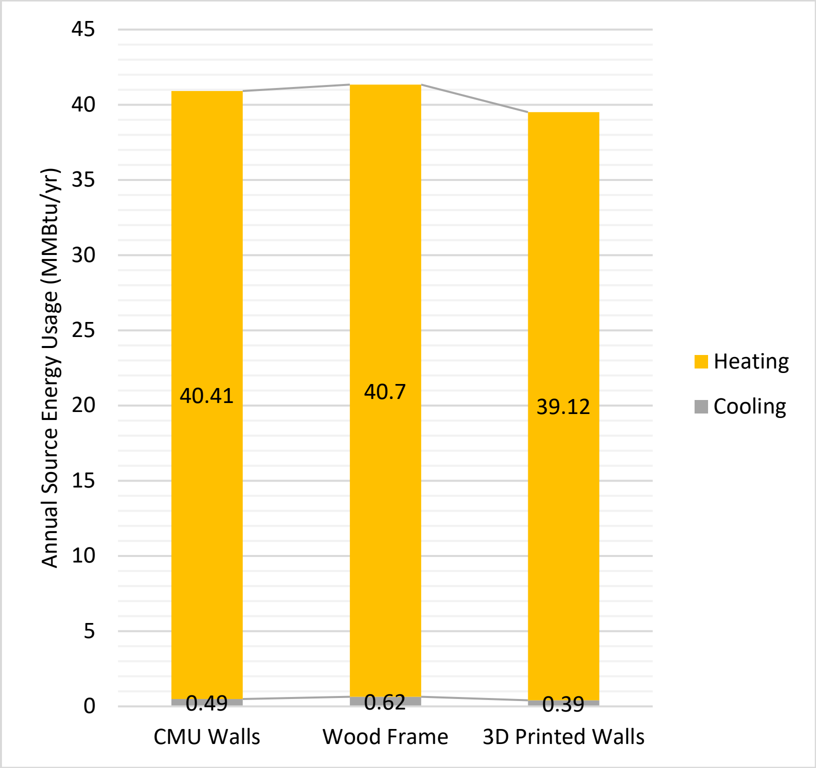


Annual and Hourly Energy Usage: Climate Zone 4

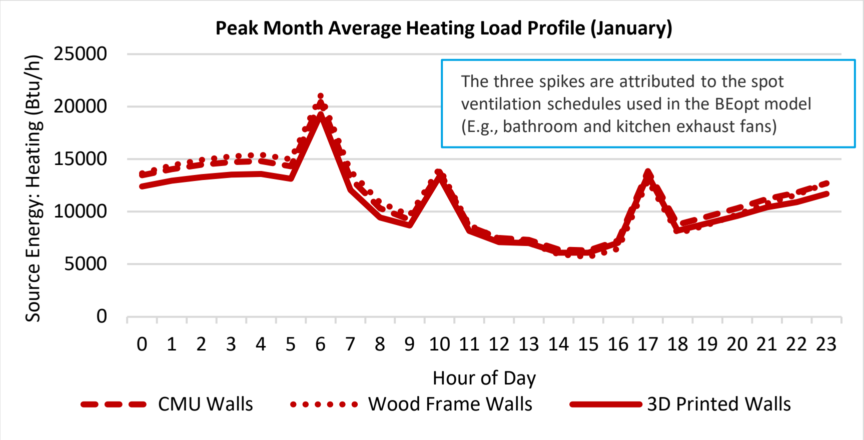


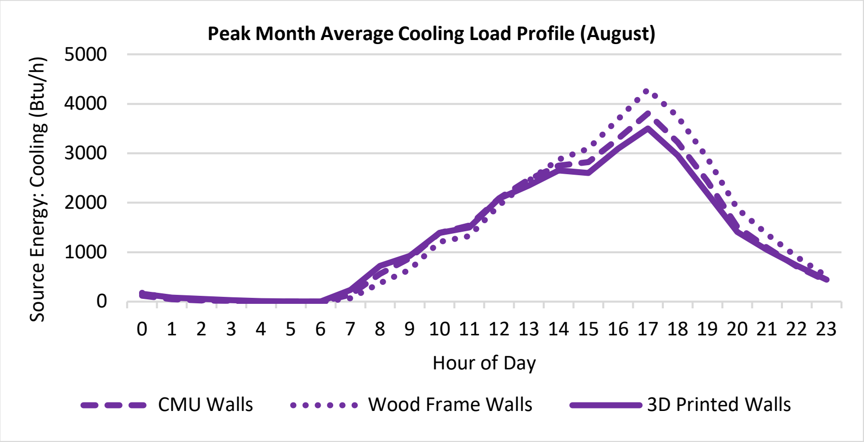


Reference City: Seattle, WA

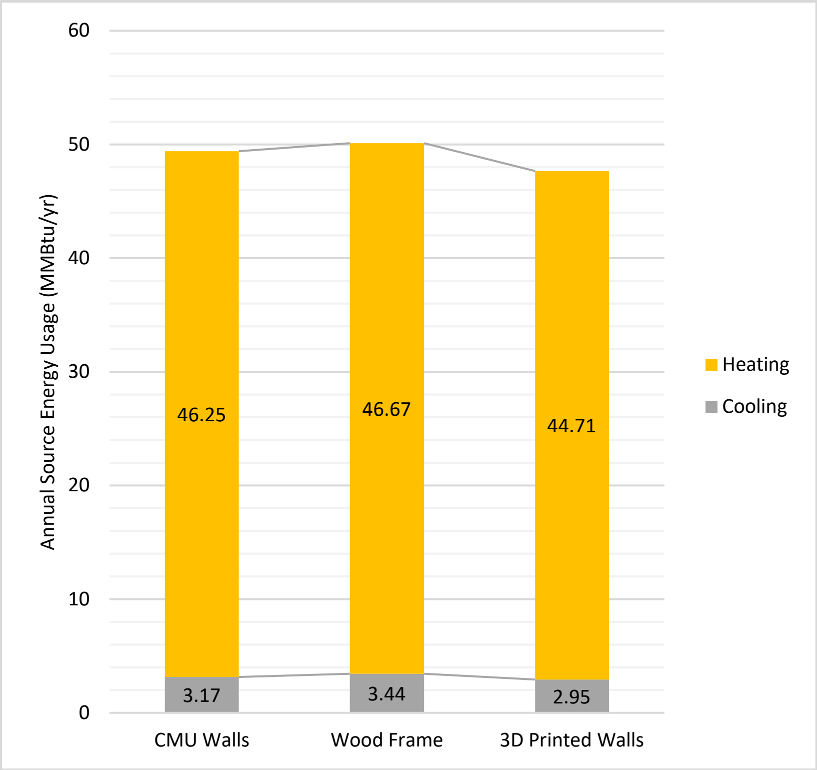


Annual and Hourly Energy Usage: Climate Zone 5

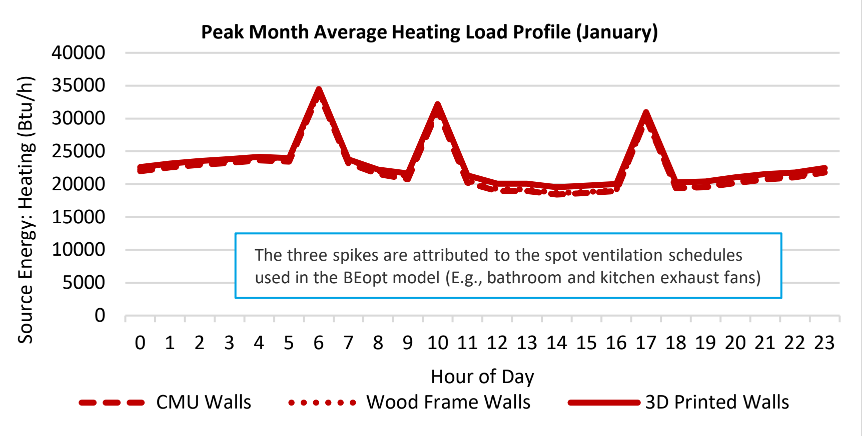


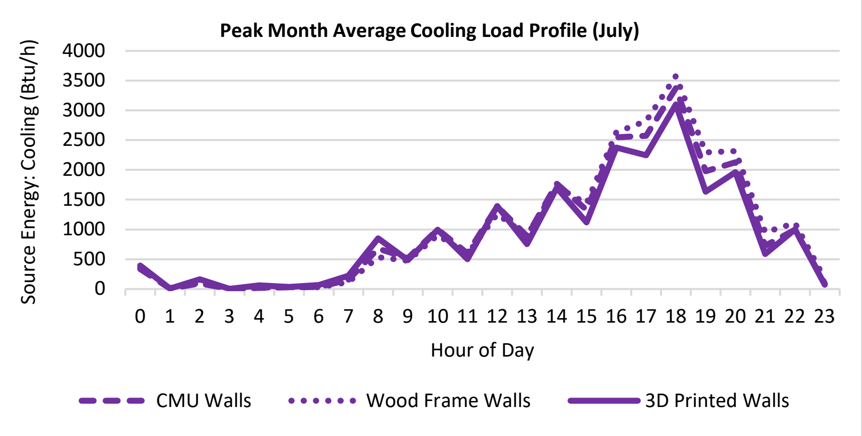


Reference City: Denver, CO

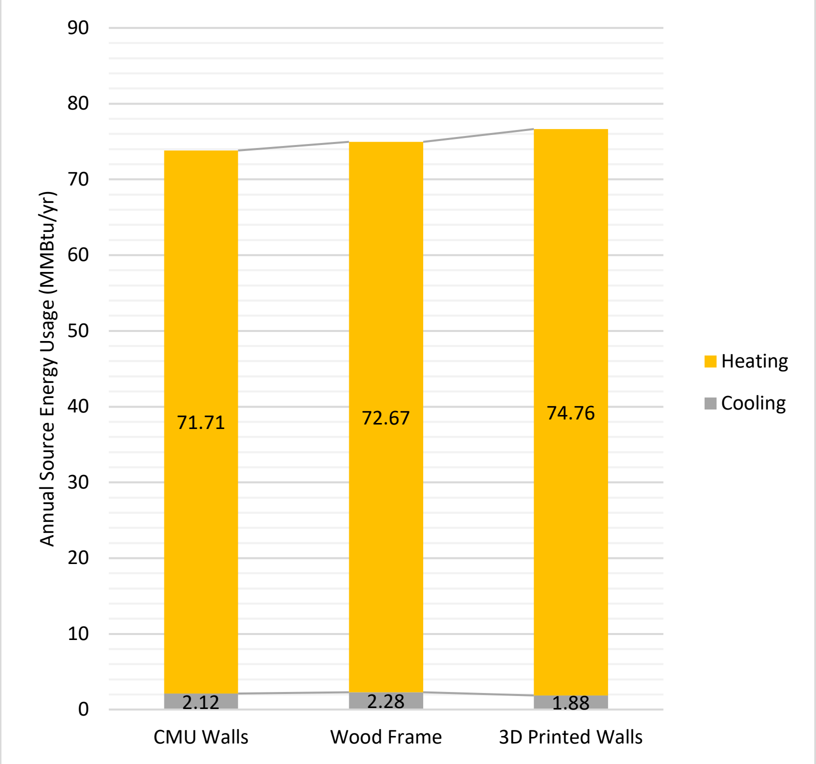


Annual and Hourly Energy Usage: Climate Zone 6

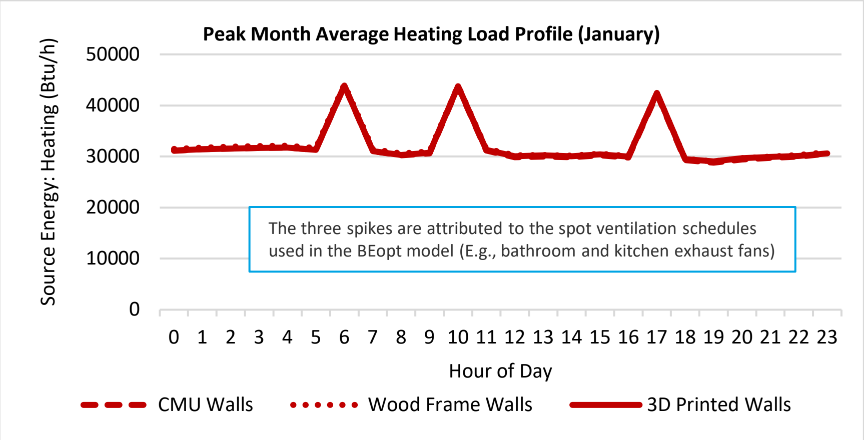


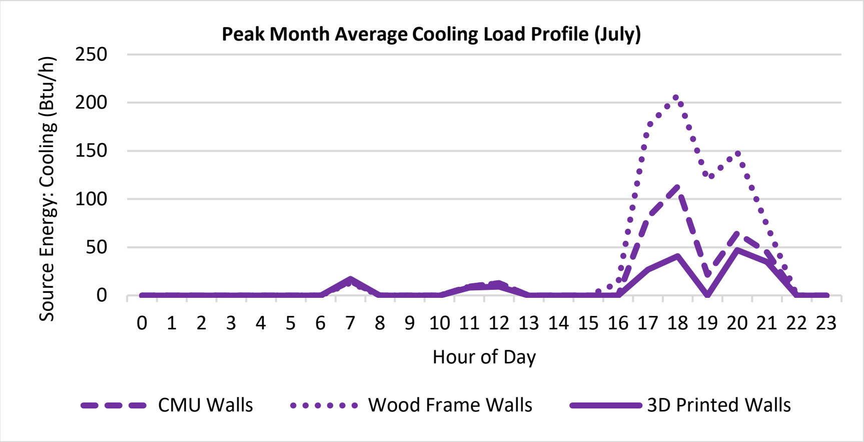


Reference City: Rochester, MN

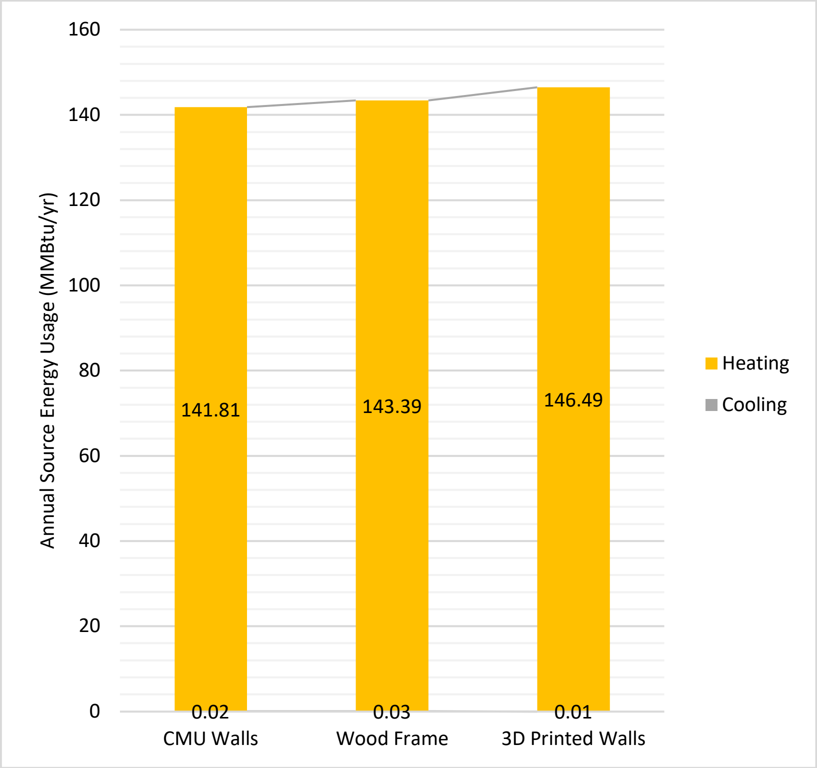


Annual and Hourly Energy Usage: Climate Zones 7 & 8





Reference City: Fairbanks, AK



Results Summary

Table 3. Heating and Cooling Demand (Peak Demand in Btu/h, Annual Usage in MMBtu)

Wall Construction	Load Type	CZ 1	CZ 2	CZ 3	CZ 4	CZ 5	CZ 6	CZ 7 and 8
CMU	Peak Heating	5878.29	23089	26320.6	24863.5	33474.9	44162.9	54727.2
	Peak Cooling	16411.8	19038.9	14806.1	7012.67	11779.9	8820.4	1529.69
	Annual Heating	0.09	9.29	23.81	40.41	46.25	71.71	141.81
	Annual Cooling	38.34	25.35	13.33	0.49	3.17	2.12	0.02
WFC	Peak Heating	7149.5	24128.8	26368.1	24902.4	33801.1	44480.1	55367
	Peak Cooling	17107.6	19275.5	15007.4	7662.03	12941	9191.83	2115.35
	Annual Heating	0.17	9.36	24.08	40.7	46.67	72.67	143.39
	Annual Cooling	38.51	25.67	13.57	0.62	3.44	2.28	0.03
3DPC	Peak Heating	4427.67	21095.1	26026.2	24574.7	32933.6	45352.9	56552.3
	Peak Cooling	15733.9	18528.1	14343.1	6435.26	10870.7	8504.5	905.71
	Annual Heating	0.03	7.13	23.04	39.12	44.71	74.76	146.49
	Annual Cooling	37.62	25.25	13.18	0.39	2.95	1.88	0.01

Table 4. 3DPC Peak Demand Savings, Btu/h (% Savings)

Load type	Compared to	CZ 1	CZ 2	CZ 3	CZ 4	CZ 5	CZ 6	CZ 7 and 8
Peak Heating	WFC	2721.8 (38.07)	3033.7 (12.57)	341.9 (1.30)	327.7 (1.32)	867.5 (2.57)	-872.8 (-1.96)	-1185.3 (-2.14)
	CMU	1450.6 (24.68)	1993.9 (8.64)	294.4 (1.12)	288.8 (1.16)	541.3 (1.62)	-1190.0 (-2.69)	-1825.1 (-3.33)
Peak Cooling	WFC	1373.7 (8.03)	747.4 (3.88)	664.3 (4.43)	1226.8 (16.01)	2070.3 (16.00)	687.3 (7.48)	1209.6 (57.18)
	CMU	677.9 (4.13)	510.8 (2.68)	463.0 (3.13)	577.4 (8.23)	909.2 (7.72)	315.9 (3.58)	624.0 (40.79)

Table 5. 3DPC Annual Usage Savings, MMBtu (% Savings)

Load type	Compared to	CZ 1	CZ 2	CZ 3	CZ 4	CZ 5	CZ 6	CZ 7 and 8
Annual Heating	WFC	0.14 (82.35)	2.23 (23.82)	1.04 (4.32)	1.58 (3.88)	1.96 (4.20)	-2.09 (-2.88)	-3.10 (-2.16)
	CMU	0.06 (66.67)	2.16 (23.25)	0.77 (3.23)	1.29 (3.19)	1.54 (3.33)	-3.05 (-4.25)	-4.68 (-3.30)
Annual Cooling	WFC	0.89 (2.31)	0.42 (1.64)	0.39 (2.87)	0.23 (37.10)	0.49 (14.24)	0.40 (17.54)	0.02 (66.67)
	CMU	0.72 (1.88)	0.10 (0.39)	0.15 (1.13)	0.10 (20.41)	0.22 (6.94)	0.24 (11.32)	0.01 (50.00)

Notes:

1. Color scales in the Tables 4 and 5 represent the numeric values of the energy savings (Btu) with darkest green representing the most positive energy savings and darkest red representing the least energy savings
2. Color scale in Table 4 is independent from that of Table 5
3. Peak refers to the highest load hour in the year for a given location

Conclusions

- **Peak demand** reduction associated with 3DPC is generally more pronounced than the annual heating/cooling usage reduction
- **Peak cooling** savings are greatest in CZ 5 (Denver), likely due to the increased thermal mass taking advantage of high diurnal temperature swings in the summer (nearly 50˚F swing on peak day).
- **Peak heating** savings are higher in warm climates (CZ 1 and CZ 2), as the lower relative U-factor of the 3DPC homes can insulate much better during the short periods of cold weather.
- **Heating peak demand and annual usage** associated with 3DPC are lower than WFC and CMU except in CZ 7 and CZ 8. Although the 3DPC wall assembly U-factor (0.053) falls within the IECC 2018 threshold for Mass Walls (0.057), the wall still has much lower performance than WFC and CMU walls which follow IECC 2018 prescriptive insulation levels.
- 3DPC shows promise in curtailing **peak cooling** demand, particularly in areas with large daily temperature swings. The demonstrated influence of temperature swings and 3DPC thermal mass on peak cooling demand indicates the potential for use in pre-cooling or other thermostat setpoint control strategies in a wider range of climates.

The 3DPC wall model is not tailored to CZ-specific needs, and therefore exceeds code-level insulation requirements in the warmest climates, while falling short of WFC and CMU insulation levels in cold climates. However, this aligns with current industry practices, and the insulation levels were therefore modeled to represent these practices. This provides a useful comparison of performance across climates but does not explicitly isolate benefits of the increased thermal mass in these homes.

Suggested Future Work

- Economic analysis including costs associated with construction and logistics
- Identification of optimal material properties (structural and insulation) for maximizing energy saving for each climate zone
- Analysis of effective air leakage reduction attributable to 3DPC construction technique
- Customizing insulation levels and techniques for 3DPC construction based on climate zone
- Assessment of the impact of 3DPC construction on Home Energy Rating System (HERS®) Index
- Analysis of non-energy metrics related to 3DPC construction (E.g., thermal comfort, carbon/embodied carbon)

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The End

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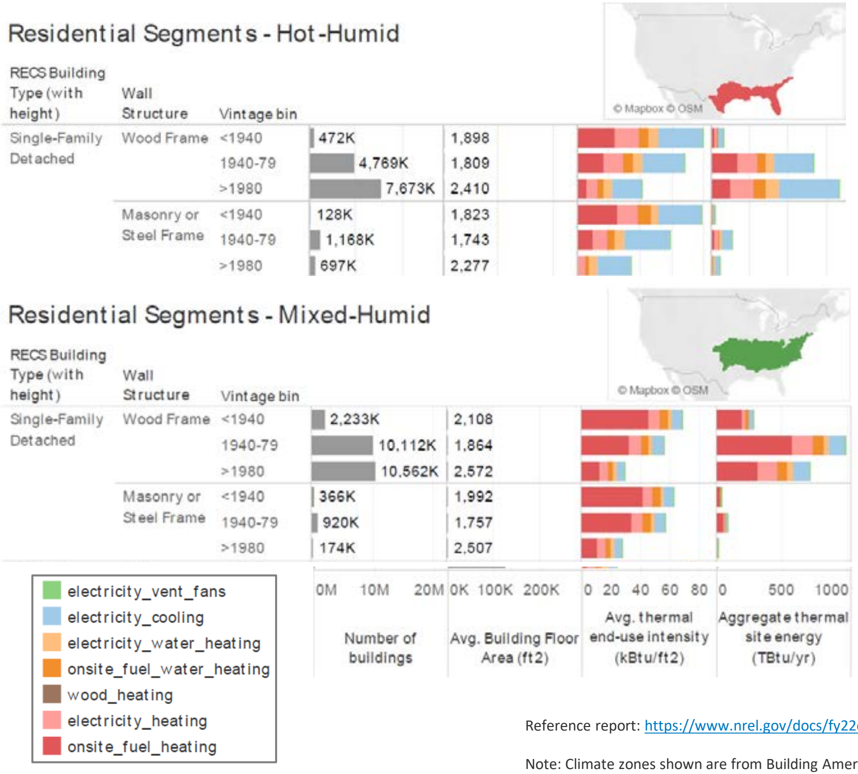
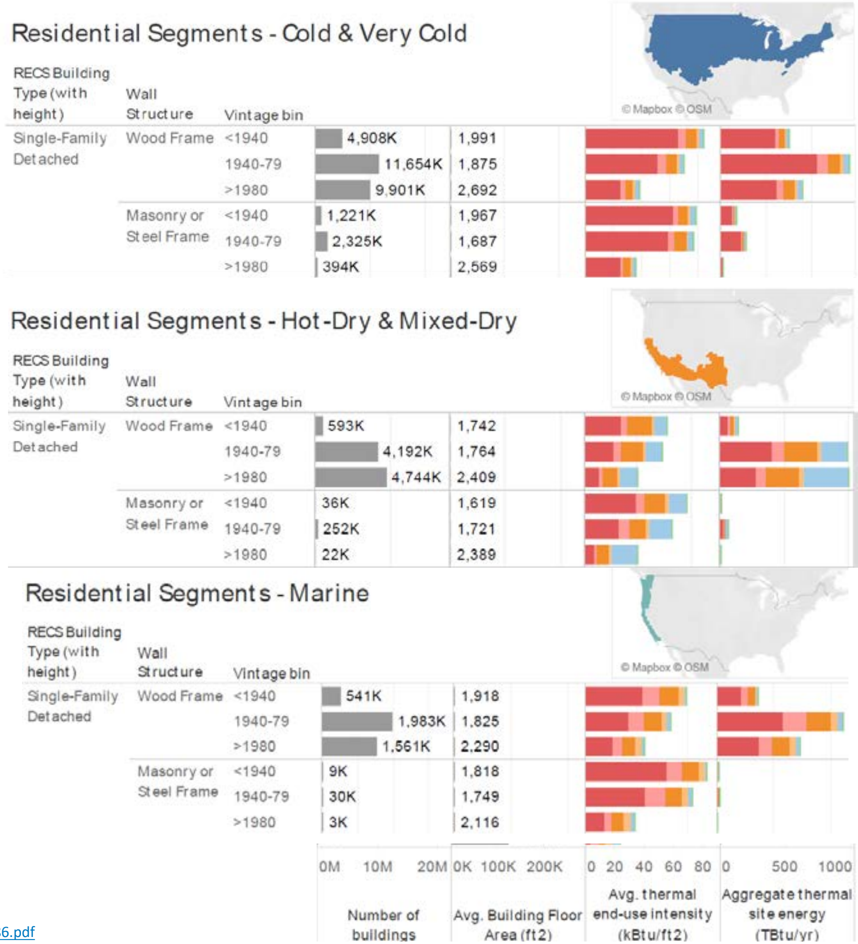
Supplemental: Residential Energy Use Patterns by Construction Type and Climate Zone





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Note: Climate zones shown are from Building America Program (https://www.energy.gov/eere/buildings/building-america-climate-specific-guidance)