Modular Multifamily Construction: A Field Study of Energy Code Compliance and Performance Through Offsite Prefabrication

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ABSTRACT

Prefabrication in a controlled, factory setting may improve the energy code compliance and energy performance of modular buildings compared to traditional sitebuilt buildings. A detailed literature reveiew, however, found little data supporting this premise. As a result, a USDOE-funded 'pilot' study was funded to compare the energy code compliance of 10 modular and 10 sitebuilt commercial multifamily buildings under construction in 4 climate zones. This study also compares the post-occupancy energy performance of an additional 25 modular multifamily buildings to a baseline of more than 120 sitebuilt multifamily buildings.

INTRODUCTION

The goal of this project is to determine if greater quality controls associated with offsite modular construction improves energy code compliance and energy performance. To date, the energy code compliance of 11 modular multifamily buildings are compared to a baseline of 9 sitebuilt multifamily buildings under construction in the metro areas of Los Angeles and San Francisco, CA (CZ 3B and 3C), Philadelphia, PA (CZ 4A) and Seattle, WA (CZ 4C). Similarly, the energy performance (kBtu/sf/yr) of 14 completed modular multifamily buildings were compared to a baseline of sitebuilt multifamily buildings in the same metro areas using 24-months of post-occupancy energy use data. Multifamily buildings were defined as apartments and similar R-2 occupancies (i.e., condominiums, dormitories and assisted living) at least 4 stories in height above grade. For mixed-use multifamily projects, data collection was limited to residential units and spaces directly associated with residential units (i.e., corridors, stairwells, lobbies, offices and other common spaces). Applicable commercial codes included the 2016 and 2019 California Title 24 Energy Code and the 2015 and 2018 International Energy Conservation Code (IECC) with state amendments.

At present, code compliance plan reviews have been completed on 20 projects. Factory and (or) construction site inspections have been completed on 17 (85%) of these projects. Preliminary results suggest that the performance of key energy measures in modular multifamily construction slightly exceeds the performance of key energy measures in sitebuilt construction, particularly in climate zones 3B and 3C. While no project used the prescriptive path for energy code compliance, most key energy measures for most buildings sampled met or exceeded the prescriptive energy code requirements for each code in each climate zone. While few differences were observed between the types of materials and equipment used in either modular or sitebuilt multifamily construction, the installation quality of envelope measures (e.g. insulation, air barrier, etc.) in modular multifamily construction appeared to be significantly better when compared to sitebuilt construction.

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Similarly, there appeared to be little difference in the post-occupancy energy performance of modular multifamily construction and sitebuilt construction among buildings of similar age and typology. Differences in site energy use intensity between modular (36.4 kBtu/sf/yr) and sitebuilt (35.0 kBtu/sf/yr) multifamily construction were on average <3.8%. However, ENERGY STAR™ scores for modular multifamily construction (87) were somewhat higher on average compared to sitebuilt multifamily construction (81), suggesting that when normalized for occupancy and other energy use factors, the energy performance of modular multifamily construction may slightly exceed the energy performance of sitebuilt construction. To date, energy performance benchmarking has been completed on 14 (of 25 planned) projects.

BACKGROUND

Stagnant productivity and ever-present workforce shortages are driving a renewed interest in prefabricated construction. Building components manufactured in a controlled factory setting can reduce project cost, time, site logistics, and waste while also improving quality, labor productivity and safety (Grosskopf, et. al., 2020). Off-site construction is the fabrication and assembly of building elements at a location other than the construction site and may consist of single and multitrade assemblies such as pipe racks, headwalls, and bathroom pods to complete volumetric building modules (Figure 1).

Figure 1 Prefabricated volumetric building modules being placed (Dec 2020).

For schedule or occupancy-driven projects having standardized, repetitive building units such as apartments and hotels, offsite prefabrication of building modules can proceed simultaneously with onsite construction, reducing time, project overhead and the impact of weather (Dodge, 2020). The Modular Building Institute (MBI) found that modular multifamily projects were completed 6-8 months faster on average than comparable sitebuilt projects, reducing costs and improving affordability (MBI, 2019). Offsite prefabrication can further reduce material use and waste generation 20-25%. Modular projects can not only reduce the number of workers onsite, but also reduce (or eliminate) many of the safety risks common on sitebuilt projects. In contrast to a transient workforce under the control of multiple trade contractors, offsite construction relies on a stable, permanent workforce under a central point of control. The repetitive nature of prefabrication in a controlled factory setting also allows fabricators to better utilize lower-skilled and older workers. As a ‘super-sub’ the modular manufacturer can consolidate the scope, mark-ups and contingencies of several subcontractors while providing a productive offsite work environment free of disruptions from other trades and unpredictable site conditions.

Although modular construction accounts for less than 5% of the U.S. commercial construction market, significant growth is being realized in California and in the Northeast where energy costs and housing affordability are forcing many residents to transition from single to multifamily housing. According to the Department of Housing and Urban Development (HUD), 24.6% of the U.S. population now lives in 32.6 million multifamily residences. As a result, the use of panelized and permanent modular construction (PMC) in multifamily is expected to increase from 16% of projects in 2017 to over 50% of projects by 2025 (Dodge, 2020).

METHODS

To determine if modular construction can improve energy performance compared to traditional sitebuilt construction, a methodology was developed to validate the energy code compliance of 11 modular and 9 sitebuilt commercial multifamily buildings under construction in the metro areas of Los Angeles and San Francisco, CA (CZ 3B and 3C), Philadelphia, PA (CZ 4A) and Seattle, WA (CZ 4C). This methodology consisted of 1) identification of priority energy measures, 2) development of data collection protocols, 3) selection and training of data collection team, 4) project recruitment, 5) data collection and 6) data analysis. Multifamily buildings were defined as apartments and similar R-2 occupancies (i.e., condominiums, dormitories and assisted living) at least 4 stories in height above grade. For mixed-use multifamily projects, data collection was limited to ~10% of residential units and spaces directly associated with residential units (i.e., corridors, stairwells, lobbies, offices and other common spaces). Applicable commercial codes included the California Title 24 Energy Code (2016 and 2019) and the International Energy Conservation Code (2015 and 2018) with state amendments.

Energy Measures

A total of 38 measures were selected for code compliance study based on their energy savings potential in commercial multifamily settings (Table 1). This process began with a PNNL developed inventory of energy code requirements applicable to various building types and climate zones of interest. These requirements were then grouped into energy measures that could be verified and evaluated for their impact on energy use. A sensitivity analysis was then performed using a prototype building simulation to estimate the energy cost impact of variation from code requirements for each measure. This allowed lost energy cost savings to be assigned to the range of conditions likely to be encountered in newly constructed buildings. Pre-inspection 'scouting' visits were conducted at several factory and project sites to ensure that the 38 measures selected for code compliance study were applicable to both modular and sitebuilt multifamily construction in climate zones 3B, 3C, 4A and 4C.

Table 1. Energy Measures

Category	Measure	
Envelope	Roof / flooring insulation	High reflectance ('cool') roofs
	Wall insulation	Window-to-wall ratio
	Window U-factor	Window SHGC
	Continuous air barrier	Entrance vestibules
HVAC – Cooling Equipment	Split AC efficiency	Split HP (cooling) efficiency
	PTAC/VTAC efficiency	PTHP/VTHP (cooling) efficiency
	Mini/multi-split (cooling) efficiency	
HVAC – Heating Equipment	Split HP (heating) efficiency	PTHP/VTHP (heating) efficiency
	Mini/multi-split (heating) efficiency	Gas furnace efficiency
	Central boiler (space heating) efficiency	
HVAC – Controls	Thermostat deadband	Thermostat setback
	Ventilation night fan control	Duct leakage
DHW – Equipment	Central boiler (DHW) efficiency	In-unit gas storage efficiency
	In-unit electric storage efficiency	In-unit tankless/instant efficiency
	Storage unit heat traps	Pipe insulation, recirculation
DHW - Controls	Central temperature maintenance	Central recirculation controls
Lighting Systems	Interior power allowance/LPD	Exterior power allowance/LPD
Lighting Controls	Manual control	Automatic time switch control
	Occupancy sensor control	Daylighting control
	Exterior lighting control	
Onsite Renewables	Solar PV/DHW	

Data Collection Protocols

Data collection for each project began with a review of construction documents followed by two (2) field inspections. Project drawings, specifications and energy code compliance reports were used to qualify each project for study inclusion, verify code, code year, code compliance path and, collect code compliance information on each of the envelope, HVAC, water heating and lighting measures identified for study (Table 1). Field inspections were then used to verify that installed materials and equipment were the same or equivalent to those specified in the construction documents. For modular multifamily projects, one inspection was conducted at the manufacturing site to verify envelope compliance and a second inspection was conducted at the construction site to verify HVAC, water heating and lighting compliance. For sitebuilt projects, both inspections were conducted at the construction site; the first prior to installation of finishes (e.g. 'dry-in' stage) and the second near the end of construction prior to occupancy (e.g. 'punchlist stage').

A data collection protocol was developed to provide step-by-step instructions on how to collect plan review, factory and site inspection data. Included within this protocol were instructions on minimum sample sizes for space types and use of project data collection forms. Data was collected from 10% of units in buildings up to 50 units (3 minimum). For buildings with more than 50 units, data was collected from 2% of additional units over 50 units. For building with more than 200 units, data was collected from 1% of additional units over 200. Data was also collected from 10% of common spaces, corridors and stairwells in each building (minimum 2 each). Electronic data collection forms were developed to record code compliance information for each measure during document review, factory inspection and site inspection (Table 2) and, to archive this information in a secure database. A photographic journal of products, labels, and observed conditions for each measure was prepared following each factory and site inspection to verify the code compliance information provided in the construction documents and in the data collection forms. Information identifying projects and project participants was redacted.

Table 2. Data Collection Form Information

Data Category	Data Collected	Document Review	Factory Inspection	Site Inspection
Building	Location, gross floor area, conditioned floor area, story height, dwelling units	✓		
Code	Climate zone, code, code year, compliance path	✓		
Roof	Assembly type, area, reflectance, insulation type, U-factor, install quality	✓	✓	
Wall	Assembly type, area, orientation, insulation type, U-factor, install quality	✓	✓	
Window	Assembly type, area, U-factor, SHGC, frame-pane type, WWR, orientation	✓	✓	
Air Barrier	Assembly type, air leakage rate	✓	✓	
HVAC	Equipment type, energy source, capacity, efficiency, unit count, duct location	✓	✓	✓
Controls	Thermostat type, deadband, setback, ventilation night fan control	✓		✓
DHW	Equipment type, energy source, capacity, efficiency, unit count, pipe ins.	✓	✓	✓
Controls	Temperature, recirculation control, heat trap	✓		✓
Lighting	Fixture type, fixture wattage, interior/exterior location, LPD	✓		✓
Controls	Manual, occupancy sensor, dimmer, daylight, photocell, time switch	✓		✓

Project Recruitment

To date, 11 modular and 9 sitebuilt commercial multifamily buildings have been recruited for code compliance study. A minimum of 2 modular and 2 sitebuilt buildings were recruited in each of 4 study climate zones (3B, 3C, 4A and 4C). Modular multifamily buildings were identified with the assistance of known multifamily modular manufacturers prior to construction (approximately 85% of commercial modular multifamily projects in study areas were fabricated by 6-8 manufacturers since 2010). Sitebuilt buildings were identified by multifamily internet search sites. Pre-inspection 'scouting' visits (e.g. 'walk ups') were conducted in each area to recruit sitebuilt projects appropriate for inclusion in the field study. For each building included in the field study, written approval was obtained by the project owner to provide construction documents and site access for data collection.

RESULTS

Energy Code Compliance

Data was first collected on general building characteristics to qualify projects for study inclusion and to ensure that the modular sample was comparable to the sitebuilt sample. As shown (Table 3) average building floor area, story height and number of residential units between samples are very similar. Of note, residential units in modular multifamily buildings were smaller on average with a greater composition of studio and one-bedroom units compared to sitebuilt buildings with a greater composition of two and three-bedroom units. Related, modular multifamily buildings were found to have a greater composition of affordable residential units compared to sitebuilt buildings with a greater composition of market-rate units.

Table 3. Building Characteristics

	Modular (n = 11)			**Sitebuilt** (n = 9)		
	Min	Max	Avg	Min	Max	Avg
Floor Area (GSF)	36,000	536,000	136,000	21,000	689,000	167,000
Story Height	4	7	6	4	9	6
Residential Units	40	410	127	14	363	111

Of 20 total code compliance projects, 13 are located in California. Six of these projects (3 modular and 3 sitebuilt) are located in the greater metro area of Los Angeles (CZ 3B). Seven projects (3 modular and 4 sitebuilt) are located in the San Francisco Bay area (CZ 3C). All projects were permitted under the 2016 or 2019 version of the California Title 24 Energy Code (Figure 2). Of the remaining projects, 5 (3 modular and 2 sitebuilt) are located in Philadelphia, PA and 2 (2 modular) are located within <10mi of Seattle, WA. Projects in Philadelphia were approved under the 2015 or 2018 version of the International Energy Conservation Code (IECC). Projects located outside of Seattle were approved under the 2018 IECC with Washington State Energy Code (WSEC) amendments. All projects for which code compliance path information was available, were approved by either performance path or envelope trade-off methods.

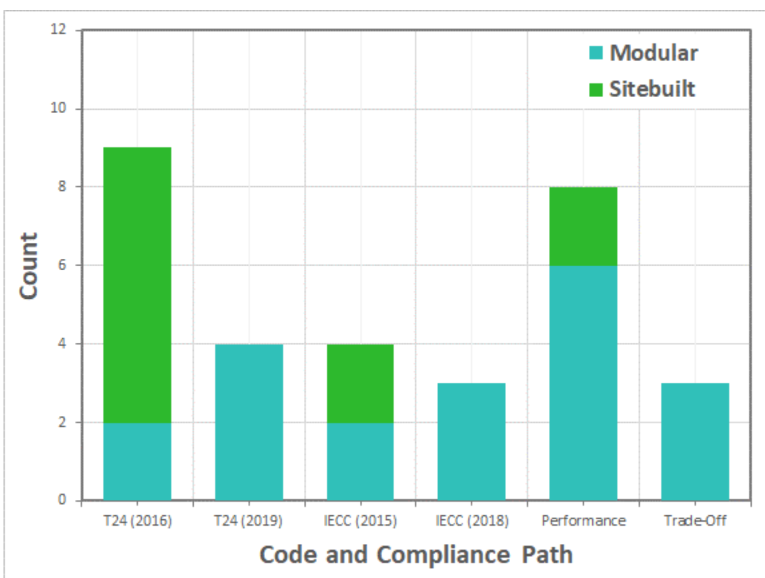

Figure 2 Modular and sitebuilt multifamily energy code and code compliance path.

Since all projects were approved by either performance path or trade-off methods, the prescriptive code compliance rates of individual measures were not used to compare the energy code compliance rates of modular multifamily buildings to sitebuilt buildings. For these projects, prototype energy use simulations will be performed to verify compliance. However, the average efficiency of key measures found in both modular and sitebuilt multifamily buildings were compared with respect to Title 24 energy code requirements in climate zone 3 and, IECC code requirements in climate zone 4 (Table 4).

Table 4. Average Efficiency of Key Energy Measures

	Climate Zone 3				**Climate Zone 4**			
	Modular	n	Sitebuilt	*n**	Modular	n	Sitebuilt	*n**
Roof (U)	0.027 ✓	6	0.030	13	0.027	5	0.026 ✓	3
Wall (U)	0.050 ✓	6	0.051	16	0.046 ✓	5	0.049	4
Window (U)	0.29	6	0.29	15	0.28 ✓	7	0.29	8
Window (SHGC)	0.22 ✓	6	0.23	15	0.29	6	0.29	8
Window-Wall Ratio	0.16 ✓	6	0.24	7	0.25	5	0.24 ✓	2
HVAC (SEER)	16.2 ✓	9	14.9	7	13.8	6	14.2 ✓	5
HVAC (HSPF)	9.7 ✓	8	9.1	7	10.7	6	11.7 ✓	2
DHW (UEF)	0.95 ✓	8	0.89	6	0.94 ✓	4	0.92	2
Lighting (W/sf)	0.28	6	0.23 ✓	6	0.32 ✓	5	0.47	1

* Includes partial data from 'scouting' visit projects described in methods section.

Preliminary results suggest that the average efficiency of key energy measures in modular multifamily construction slightly exceeds the average efficiency of key energy measures in sitebuilt multifamily construction, particularly in climate zone 3. While the prescriptive code compliance rates of individual measures were not used to compare the energy code compliance rate of modular multifamily buildings to sitebuilt buildings, most key measures for most buildings nevertheless met or were often better than the prescriptive energy code requirements for each climate zone. Exceptions include wall U-factor and window-to-wall-ratio (WWR) for a modular multifamily building in climate zone 4 using envelope trade-off and, HVAC SEER value for a sitebuilt building in climate zone 3 using performance path. Other exceptions include lighting power density for two modular projects in climate zone 3 using residential exclusions and (or) space type methods.

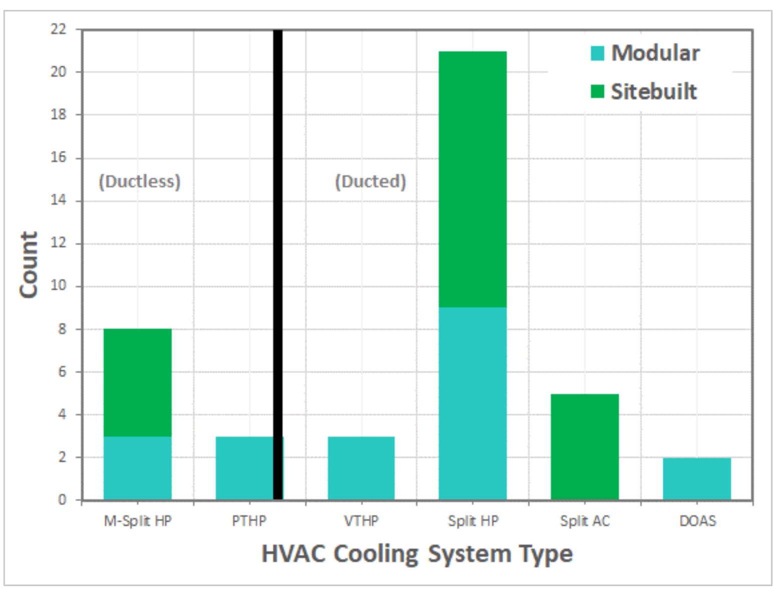

Figure 3 Modular and sitebuilt multifamily HVAC cooling system type.

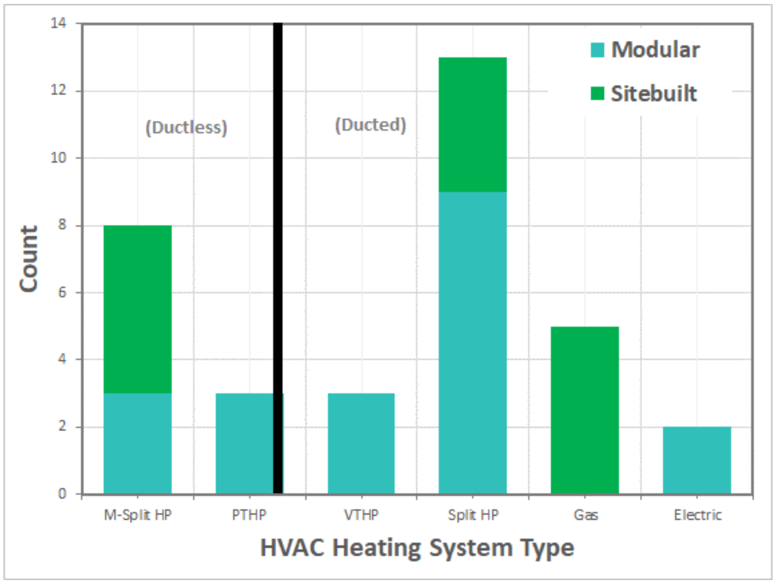

Figure 4 Modular and sitebuilt multifamily HVAC heating system type.

Since energy efficiency code requirements may vary by equipment type, energy source and size (capacity), data was collected on the primary HVAC and water heating equipment types observed in both modular and sitebuilt multifamily buildings (Figures 3-5). Packaged thru-wall systems were only observed in modular multifamily buildings. Split AC systems with gas heating were only observed in sitebuilt multifamily buildings. The most common HVAC system observed in both modular and sitebuilt multifamily buildings were split heat-pump systems followed by ductless mini-split and variable refrigerant flow (VRF) multi-split systems (≤30MBuh). The most common water heating system observed in both modular and sitebuilt multifamily buildings were central gas boiler systems (≥300MBtuh) and in-unit electric tank storage water heaters (<50gal).

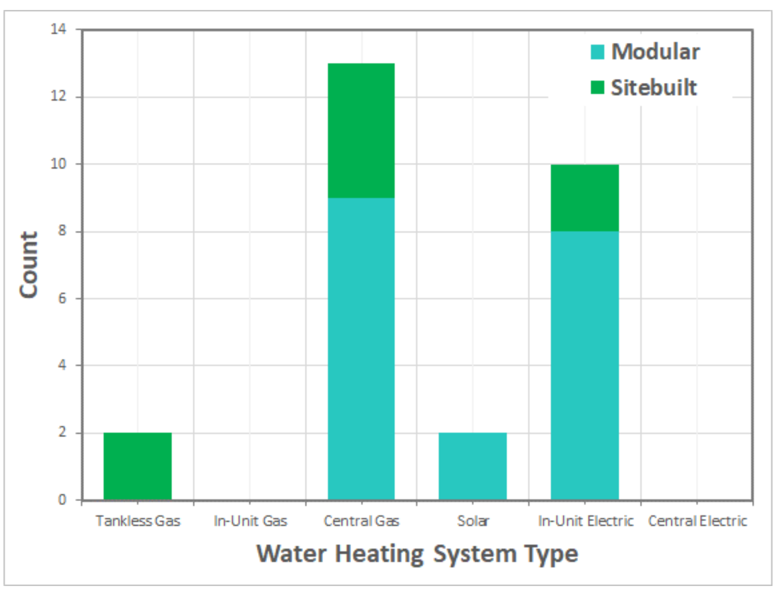

Figure 5 Modular and sitebuilt multifamily water heating system type.

Energy Performance

In addition to the energy code compliance study of 20 modular and sitebuilt multifamily buildings under construction, this study also compared the post-occupancy energy performance of an additional 14 (of 25 planned) modular multifamily buildings to a baseline of more than 120 sitebuilt multifamily buildings in the same 4 climate zones (Table 5). Beginning in 2015, energy benchmarking using the ENERGY STAR Portfolio Manager™ became required for commercial and multifamily buildings in Seattle, WA. By 2019, energy benchmarking was required for all commercial and multifamily buildings over 50,000sf in all study regions. Benchmarking data, including site energy-use intensity (kBtu/sf/yr), ENERGY STAR™ score (1-100), energy use by source, greenhouse gas emissions (GHGE) and other post-occupancy energy use data was obtained for each modular multifamily building in each climate zone. Site EUI and ENERGY STAR™ scores for each modular building were averaged for the years energy benchmarking data was available (e.g. data range). These values were then compared to benchmarking data over the same data range from a sample of sitebuilt multifamily buildings of similar size built in the same year and metro area (city, county, etc.) as the modular multifamily buildings.

Table 5. Energy Performance

	Modular						Sitebuilt			
	CZ	Year Built	Data Range	GSF	Avg Site EUI	Avg E-Star Score	No. of Bldgs	Avg GSF	Avg Site EUI	Avg E-Star Score
Mod 1	3B	2013	2017-20	69,111	45.2	58	10	68,658	37.2	74
Mod 2	3B	2017	2020	386,000	40.7	65	10	282,133	38.0	76
Mod 3	3C	2014	2019-20	500,000	30.9	95	10	253,521	38.4	78
Mod 4	3C	2019	2019-20	50,406	56.3	79	7	230,829	25.6	84
Mod 5	3C	2017	2019-20	107,521	51.7	87	10	195,892	29.9	87
Mod 6	3C	2017	2019-20	162,575	27.9	96	10	195,892	29.9	87
Mod 7	3C	2016	2019	66,813	57.1	93	10	122,263	30.6	86
Mod 8	3C	2017	2019-20	198,258	22.2	100	10	248,628	41.6	79
Mod 9	4A	2016	2018-20	65,864	33.4	78	10	189,307	44.1	62
Mod 10	4A	2012	2016-20	129,330	53.3	81	10	122,523	44.2	65
Mod 11	4A	2019	2020	218,277	15.0	100	7	138,605	32.9	81
Mod 12	4C	2014	2015-20	47,343	30.2	98	10	62,781	38.9	84
Mod 13	4C	2017	2019-20	41,132	24.2	-	5	42,903	31.4	92
Mod 14	4C	2018	2019-20	167,777	22.3	100	10	201,979	27.9	94
Average				157,125	36.4	87	129	167,494	35.0	81

Similar to the code compliance study, preliminary results suggest that the average post-occupancy energy performance of modular multifamily construction (36.4 kBtu/sf/yr) is slightly less than the average post-occupancy energy performance of sitebuilt multifamily construction (35.0 kBtu/sf/yr) among buildings of similar age and typology. However, ENERGY STAR™ scores for modular multifamily construction (87) are somewhat higher on average compared to sitebuilt multifamily construction (81), suggesting that when normalized for occupant density and other energy use factors, the energy performance of modular multifamily construction may actually exceed the energy performance of sitebuilt construction. In fact, the average floor area of modular multifamily buildings used in the compliance study (136,000sf) was 20% less than the average floor area of sitebuilt multifamily buildings (167,000sf). Yet, the average number of residential units in modular multifamily buildings used in the compliance study (127) was 15% greater than the average number of units in sitebuilt buildings. As a result, the occupant density for modular multifamily buildings may be up to 50% greater than the occupant density for sitebuilt multifamily buildings. Since permanent modular construction is regulated by the state in each sample area, the 14 projects recruited for participation in the energy performance study were identified through a permit search of modular multifamily dwelling units listed in the California HCD, Pensylvania DCED and Washington L&I databases.

CONCLUSION

Preliminary results suggest modular multifamily construction may improve building energy performance which may improve energy and housing affordability. While few differences were observed between the types of materials and equipment used in either modular or sitebuilt multifamily construction, the installation quality of envelope measures such as insulation and air barrier, appears higher for modular construction, and may result in a modest improvement in energy performance when compared to sitebuilt construction (Figure 6).

Figure 6 Modular (left) and sitebuilt (right) multifamily installed insulation quality.

Supporting this conclusion are air leakage test results completed following the initial submission of this paper. Blower door tests were conducted on 7 modular multifamily units and 11 site-built multifamily units. Results indicate that modular units had a higher air change rate (6.0) on average than site-built project units (4.7). Modular units however, were smaller (460sf) than site-built units (810sf). As a result, the envelope area of modular units was greater relative to unit floor area and volume. When normalized for this difference, the air leakage rate of modular unit envelopes (0.22 cfm/sf) was slightly better compared to the air leakage rate of site-built unit envelopes (0.23 cfm/sf).

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