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CAD-based Energy & Cost Models Prove Affordable Net Zero Energy Performance for WonderWindows + 24" On-center Framing

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Buildings and Transportation Science Division

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Mark Isaacs, CEO/Founder of GS Research LLC, can be reached at mark@wonderwindow.net. GS Research LLC holds the issued patent and patents pending for multi-pane windows established prior to this cooperative work with Oak Ridge National Labs.

EXECUTIVE SUMMARY

Windows are thermally the “weakest link” in the building envelope. Increasing the thermal resistance of windows can make buildings more energy efficient and reduce the cost of electricity needed for conditioning the building. The proper design and placement of framing can also help to reduce the thermal bridging that occurs near the window frame area. This study investigates the energy performance of multi-pane acrylic windows fitting 24" on-center framing.

Initial parametric analysis is done for a single zone accessory dwelling unit (ADU). Then, an energy model was developed for three types of wood-framed buildings: townhomes, stacked flats and hotels. A whole building energy simulation is performed for each of these building types in hot-humid Houston, mixed-humid New York, and cold-humid Minneapolis climates.

The results show up to a 39% reduction in heating, ventilation, and air-conditioning (HVAC) related electricity consumption for the cold climate compared to the Base case which has window and wall properties based on ASHRAE standard 90.1 2019. In the hot climate, a modest increase in electricity consumption was seen due to an increase in cooling electricity demand.

The ADU achieved Net Zero Energy performance in all 3 Climate Zones despite having the highest exterior surface area-to-floor area ratio: the ADU also had the highest PV kW to floor area ratio compared to the other multi-story building types. The townhomes, hotel and stacked flats respectively met 73, 52 and 57 % of electrical use in Houston, 71, 48 and 56 % in New York, and 63, 40 and 53 % in Minneapolis from energy produced by rooftop solar. If 400 W solar panels are used instead of 320 W panel used for energy simulation, it is estimated that in the townhomes, hotel and stacked flats rooftop solar can meet 91, 65 and 71 % of electrical use in Houston; 89, 60 and 70% in New York, and 79, 50 and 66 % in Minneapolis. A preliminary evaluation of cost shows that such superior performance can potentially be achieved at less first cost with this 24"on-center solution than conventional construction.

All the building types at the three locations used for simulation had net energy use intensity under 20 kBtu/sf/year with 320 W solar panel and under 17 kBtu/sf/year with 400 W solar panel. Further tailoring of building envelope R-values and window solar heat gain to particular Climate Zone locations for each building type shows promise in reducing the HVAC electricity use that comprises almost half of building energy use.

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1. INTRODUCTION

Buildings consume approximately 40% of total energy and more than 70% of the electricity generated in the United States (US EIA 2024). Windows generally have very low thermal resistance compared to opaque envelopes. A typical clear double-glazed has approximately R-2 thermal resistance at the center-of-glass which is lower near the edges of the glazing and frame (Hanam, Jaugelis, and Finch 2014).

GS Research LLC has developed multi-pane acrylic windows and daylight transoms that provide up to R-9 thermal resistance known as WonderWindows (WW). Integrating these windows with 24" on-center (oc) framing results in the elimination of thermal-bridging framing to improve the thermal resistance of the wall around the window.
The approach introduces the idea of the architectural bay, composed of one or more windows and the wall around it, as the 'Finite Element' of the building envelope: getting the bay 'right' from a thermal & solar standpoint suggests a path to realizing affordable Near and Net Zero Energy buildings (NZEB). NZEBs generate as much energy from on-site renewable energy as they consume on an annual basis. In this project, rooftop solar panels were added to the energy model of the buildings to evaluate the NZEB potential. The energy consumption of a building with WW is compared with a Base case whose wall insulation and window properties are based on ASHRAE standard 90.1 2019/ 2021 International Energy Conservation Code (IECC 2021)

2. TECHNOLOGY DESCRIPTION

WWs are multi-pane acrylic windows with ¾" dead airspaces as shown in Figure 1 and Figure 2. Various combinations of acrylic glazing, spacers, tapes, adhesives, and sealants were developed and tested to NFRC and AAMA 101 standards in past efforts by GS Research LLC (Isaacs, Bhandari, and Burger 2022) with ICC-ES Listings 1242 and 1243 now issued. The typical vision window provides an R-value of R6.7 with a solar heat gain coefficient (SHGC) of 0.57 and a visible transmittance (VT) of 62%.

Figure 1. R6.7 WonderWindow with 62% visible transmittance

Figure 2. Typical vision window: R6.7 at 22-1/2" x 48" (7.5 sf)

Setting the window in 24" on-center framing reduces the thermal-bridging of the wall around the window by safely eliminating headers, jack and cripple studs. The architectural bay formed by the window and the framing around it can be considered a "Finite Element" of the building envelope, with a one window example shown in Figure 3.

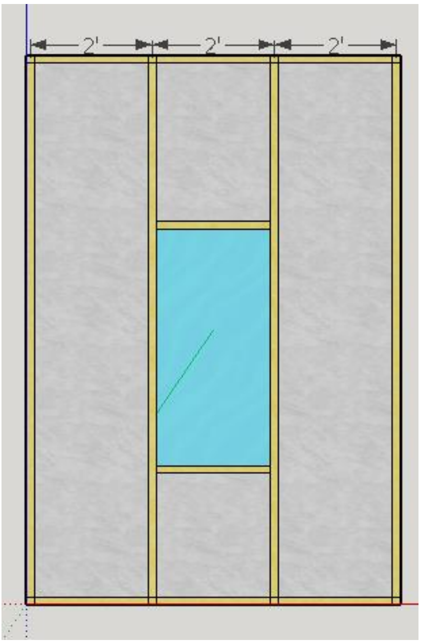

Figure 3. Window-integrated 24" on-center framing comprises the architectural bay of the window and the wall around it as a "Finite Element" of the building envelope.

Figure 4 & Figure 5 compare "Finite Elements" of WW-integrated 24" oc construction with conventional construction setting a PVC-frame window in a headered framed opening in a 2x4, 16" oc wall. The window-integrated 24" oc solution has 64% fewer pieces of lumber to buy, measure, cut, place, and nail than conventional 16" centered framing and comes with a 243% improvement in whole wall, effective thermal resistance.

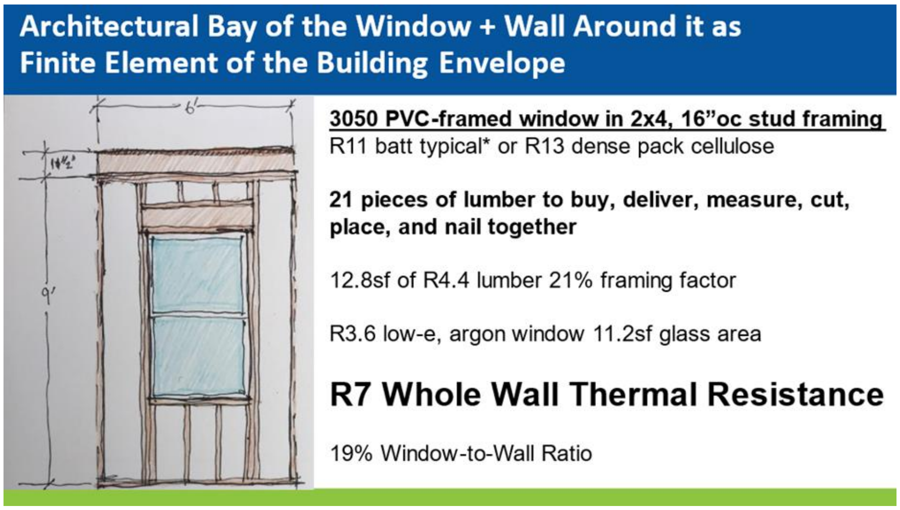

Figure 4. "Finite Element" of conventional 16" on-center construction

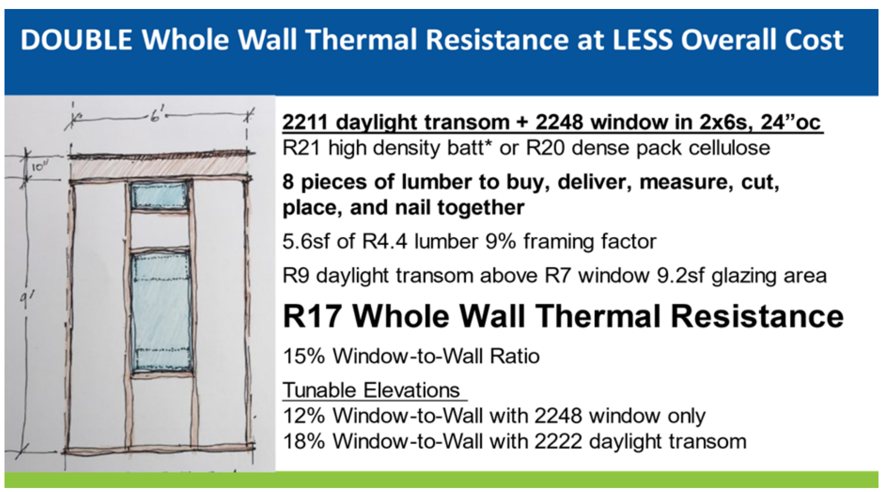

Figure 5. "Finite Element" of window-integrated 24" on-center framing solution

In a further improvement, 2" Extruded Polystyrene (XPS) R10 strips are added to the inside of the 2x4 studs and 2x10 rafters, both deepening the insulation cavity to allow more cellulose dense pack insulation and eliminating direct thermal bridging through framing to the exterior, as shown in Figure 6. 4" screws secure drywall through the foam to the framing.

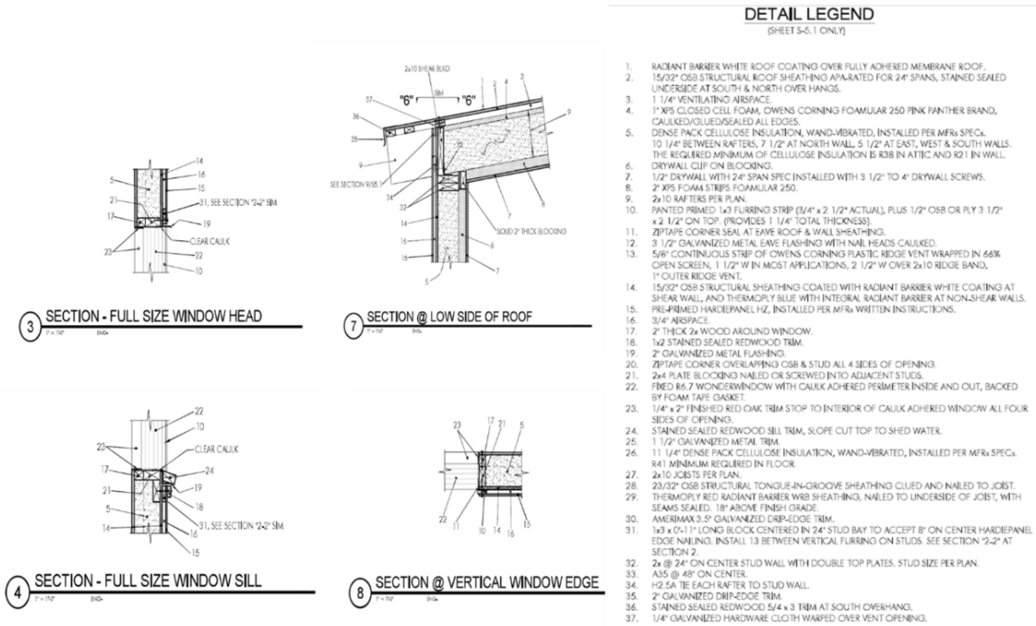

Figure 6. Head, sill, jamb and rafter details show how 2" XPS R10 foam strips add to cellulose insulation cavity depth and reduce thermal bridging of framing

R21 cellulose dense pack fits in the 5-1/2" cavity formed with 2" XPS over 2x4 studs. R28.5 fits in the 7-1/2" cavity formed with 2" XPS over 2x6 studs. R35 fits in the 9-1/4" cavity formed with 2" XPS over 2x8 studs in very cold climates. OSB sheathing with a radiant barrier facing the outside has ¾" furring strips applied 24" on-center to create a shaded, ventilated airspace between the added radiant barrier of the light-colored fiber-cement siding which acts as rain screen cladding. The thermal resistance of the combined radiant barrier assembly is currently being modeled in THERM in other work being performed by Berkeley Labs, but this assembly points the way to the effective R22 wall assumed in the energy models, with increasing R-values up to R36 as stud depth increases.

The 24" on-center "Finite Element" is the basis for architectural sketch designs for each of the building types purposely focused on compact forms with 'taut' unarticulated skins, addressing both affordability and the basic PassivHaus principle of reducing exterior surface area where practical. These schematic designs for each building type were modeled in Revit. An attempt to translate Revit computer-aided design (CAD) files for an accessory dwelling unit into "*gbxml*" format readable by EnergyPlus proved unsuccessful. Fixing Revit's translator and file conversion troubleshooting was beyond the scope of this work. Thus, the schematic designs were translated into building geometries using OpenStudio Python package which was finally exported as an EnergyPlus file. Section 3 discusses the energy modelling efforts conducted for the study, and results for HVAC related energy consumption for the buildings. Section 4 presents the result for net zero energy potential of the different building types and construction cost estimation and the conclusions based on the results are provided in Section 5.

3. ENERGY MODELING AND RESULTS

Whole building energy simulation was performed using a validated energy modeling tool EnergyPlus (U.S. Department of Energy 2024), for four different building types in three climate zones. The building types modeled for were:

- 1 story Accessory Dwelling Unit

- 3 story and 4 story townhomes
- 4 story hotel
- 3 story stacked flats

Each of these building types was modeled and simulated for Houston, New York City (NYC), and Minneapolis representing hot, mixed, and cold climate zones, respectively. The characteristics of these buildings including heating, ventilation, and air-conditioning (HVAC) systems are discussed in the following subsections.

3.1 ACCESSORY DWELLING UNIT (ADU)

The ADU represented a single-zone building with a floor area of 280 sf (Figure 7)with larger south-facing windows and a small north-facing daylighting window, and no east and west-facing windows. Views of the ADU based on the CAD model developed are presented in Figure 8 to Figure 10. The building with WonderWindows (WW) had the characteristics listed in Table 1. This unit was also used to analyze several variations in simulation parameters for their impact on building energy consumption. This included variations in wall insulation level, window-to-wall ratio, and window properties and shading which are listed in Table 2. The thermostat setpoint of 64 ºF for heating and 76 ºF for cooling was used for all the building types.

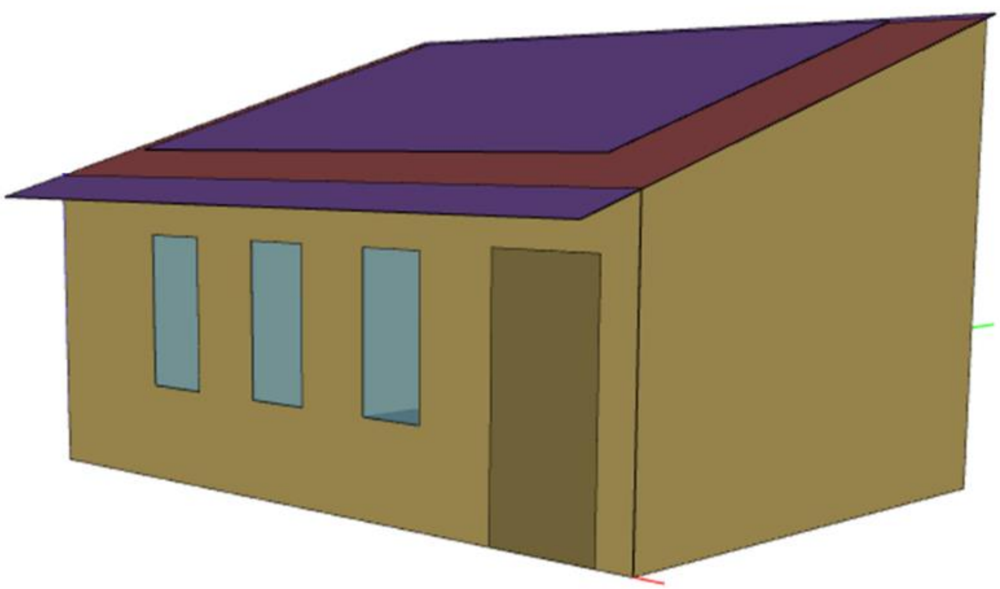

Figure 7. Energy model geometry of ADU showing south-facing window.

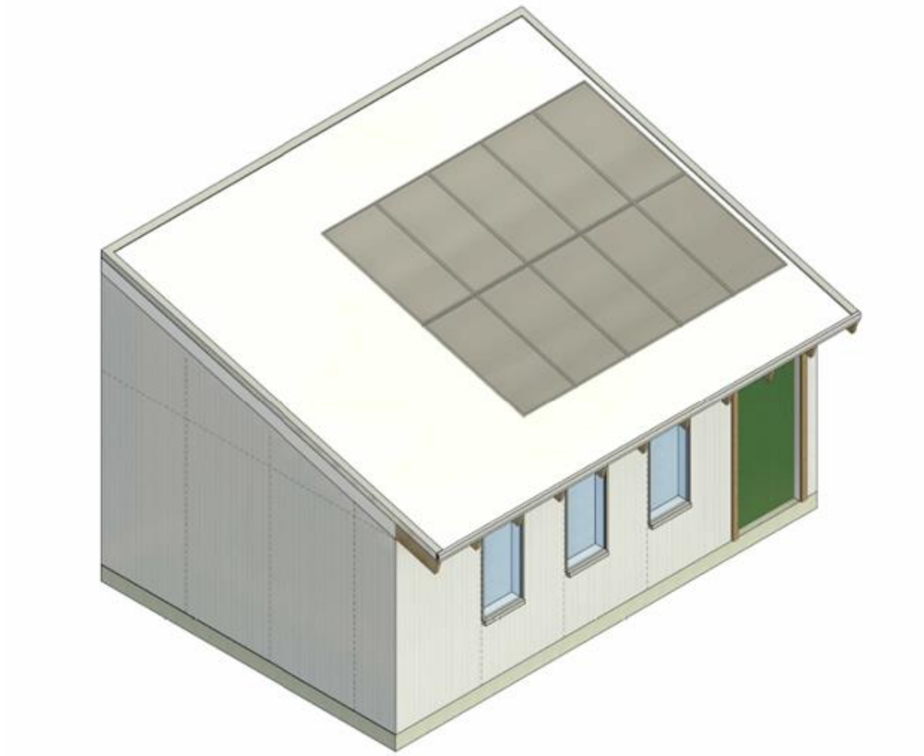

Figure 8. Revit CAD model: ADU viewed from Southwest

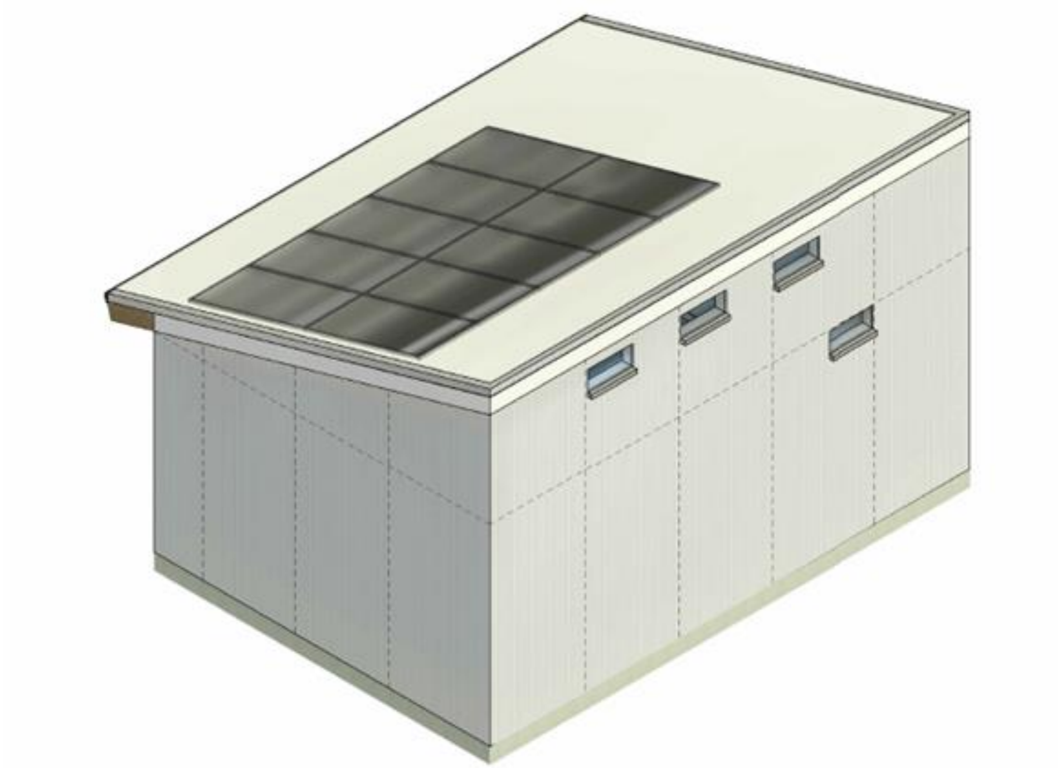

Figure 9. ADU viewed from Northwest

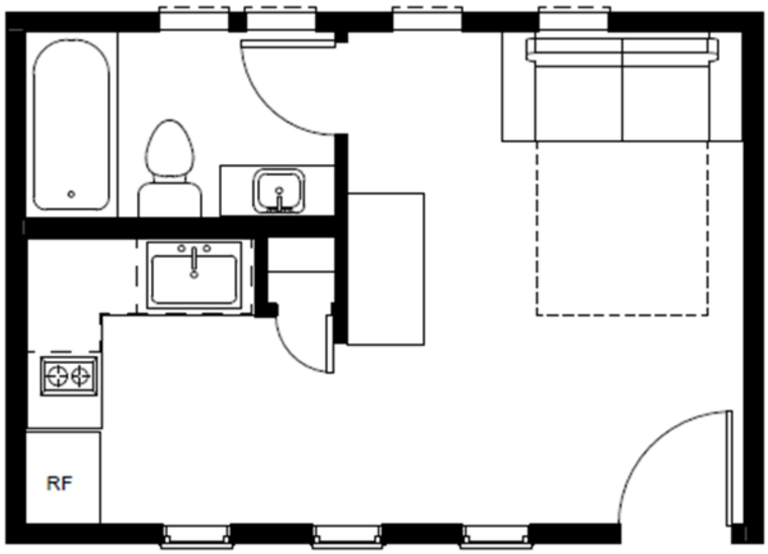

Figure 10. 14'x20' floor plan that shows kitchen, bath, and fold-out bed.

Table 1. Characteristics of ADU using WW.

Characteristic	**Value**
Floor Area	280 sf
Window area	22.3 sf south-facing 7.11 sf north-facing
Window Properties	U-value: 0.149/R-6.7 SHGC: 0.57 VT:62%
HVAC system (Heat pump)	Heating COP: 2.637/HSPF 9 Cooling COP: 4.31 / SEER 14.7
Thermostat setpoint	Heating setpoint: 64 ºF Cooling setpoint: 76 ºF
Building envelope insulation	Exterior wall: R15 Roof: R30 Floor: R43
PV capacity	Houston, New York: 1920 W Minneapolis: 2560 W
Internal loads	Cooktop, Microwave and Toaster 1500 W each (15 min each day)

Table 2. List of variations used for energy simulations.

Variation	**Description**
WW	WonderWindow and R15 wall without any variation
R25-Wall	Wall R-value increased to R25
R36-Wall	Wall R-value increased to R36
Shade	2' window overhang added for shading on South side
Window-North-R4.3	North facing windows changed to R4.3 and SHGC 0.65
Window-South-R4.3	South facing windows changed to R4.3 and SHGC 0.65
Window_30sf	Window area in the south changed to 30 sf
Window_60sf	Window area in the south changed to 60 sf
Window_73sf	Window area in the south changed to 73 sf

The ADU achieved net zero energy performance with 6 solar panels in Houston and New York, and 8 solar panels in Minneapolis (Figure 11). The "Total Electricity" in the figure is whole building electricity consumption from HVAC and non-HVAC end uses.

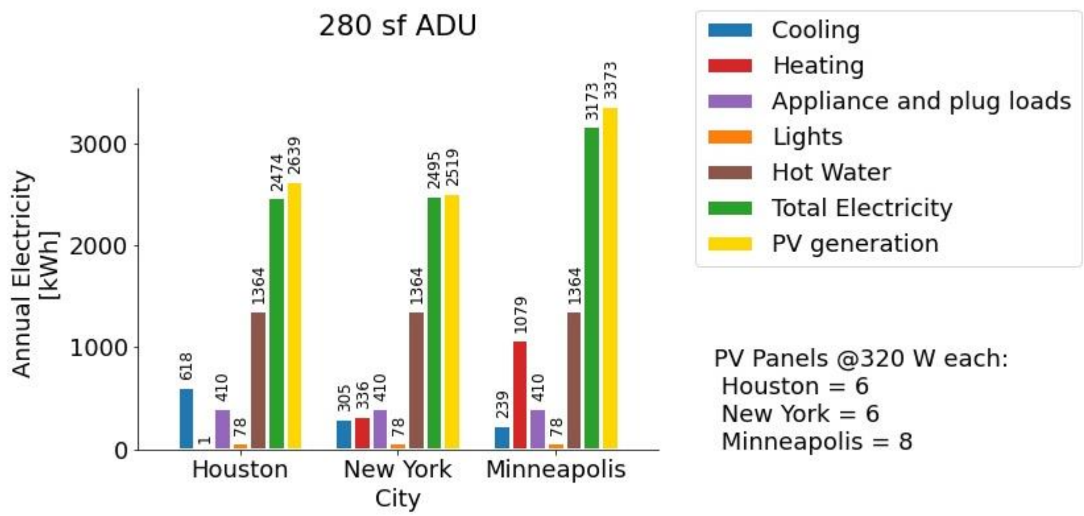

Figure 11. The ADU achieved Near or Net Zero Energy performance in all climate zones

The results for cooling and heating energy demands for the ADU with WW and the variations are provided in Figure 12 and Figure 13 respectively. The lowest cooling load in all 3 climate zones is achieved with horizontal window overhangs shading the south-facing windows. The highest cooling energy demand comes from an increase in window area in the south façade to 73 sf for all three locations. Other than increasing the window area to 60 sf and 73 sf the cooling energy demand is high for conventional construction which has lower R-values for wall sand windows.
The highest reduction in heating energy demand is attained by increasing the R-value of the wall. The window with a decreased R-value of R-4.3 and increased SHGC of 0.65 seems to reduce the heating energy demand. The heating load is also significantly reduced by increasing the south-facing window-to-wall ratio since it allows for solar heat gain while providing an insulation of R6.7 thermal resistance.

Overall HVAC-related electricity for these variations, which is the sum of cooling and heating consumption is shown in Figure 14. The lowest total HVAC load in Houston requires horizontal overhangs on south-facing windows. The lowest total load in NYC and Minneapolis are found by increasing wall insulation to R36 (which is of no apparent benefit in Houston). Increasing the south-facing window area reduces the HVAC electricity only in the cold climate of Minneapolis.

In both New York and Minneapolis, changing the window properties to a lower R-value of R-4.3 and higher SHGC of 0.65 reduces the HVAC-related electricity consumption. The increase of desirable winter sun in these locations is greater than the limited undesirable summer sun when shaded by horizontal overhangs.

Figure 12. Annual cooling-related electricity consumption for different variations.

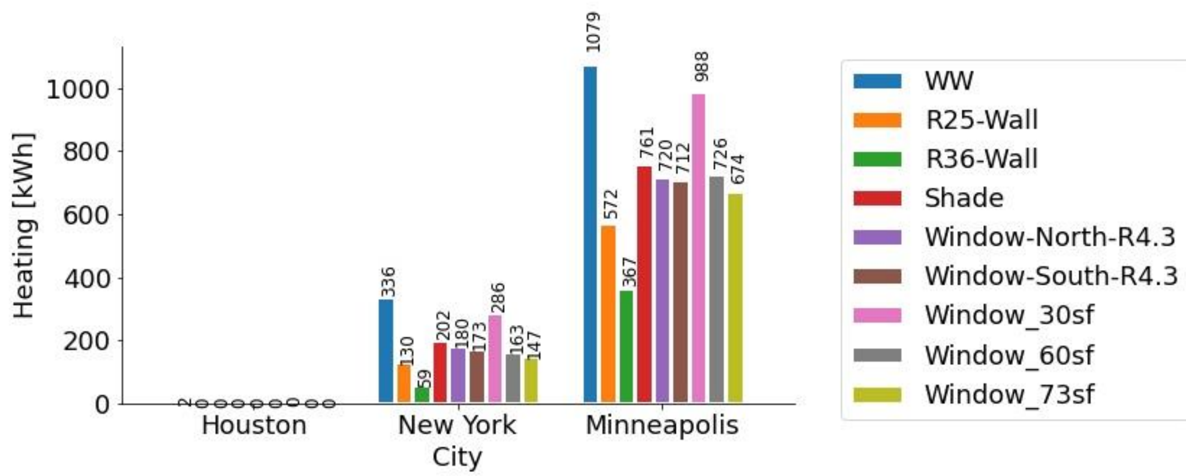

Figure 13. Annual heating-related electricity consumption for different variations.

Figure 14. Annual HVAC-related electricity consumption for different variations.

A Base case was modeled to represent conventional 2×4, 16" on-center construction, with properties listed in Table 3. The Base case for the ADU has the same floor area as the WW but has a window area different from the WW.   A typical conventional PVC-framed 3060 window has 14 sf of glass area compared to the 7.5 sf of a WW. Note that the listed R14 wall R-value is greater than the *effective* R7 calculated for the similar 'Finite Element' in Figure 4above which includes the impact of 14 sf of glass area .

The comparative energy consumption for the Base and WW in Figure 15 shows that WW has lower energy consumption compared to the Base for both cooling and heating in all three locations. The highest electricity savings was obtained in Minneapolis where WW has 437 kWh lower HVAC electricity consumption compared to Base. At New York and Houston, the electricity reduction was 238 kWh and 185 kWh for WW in comparison to Base.

Table 3. Characteristics of ADU with Base construction.

Variable	Value
Floor area	280 sf
Window area	South façade 45 sf North façade 18 sf
Window properties	U-value 0.5/R-value: R2 SHGC: 0.571 VLT: 62%
Envelope: R-value	Wall: R14 Roof: R30 Floor: R43

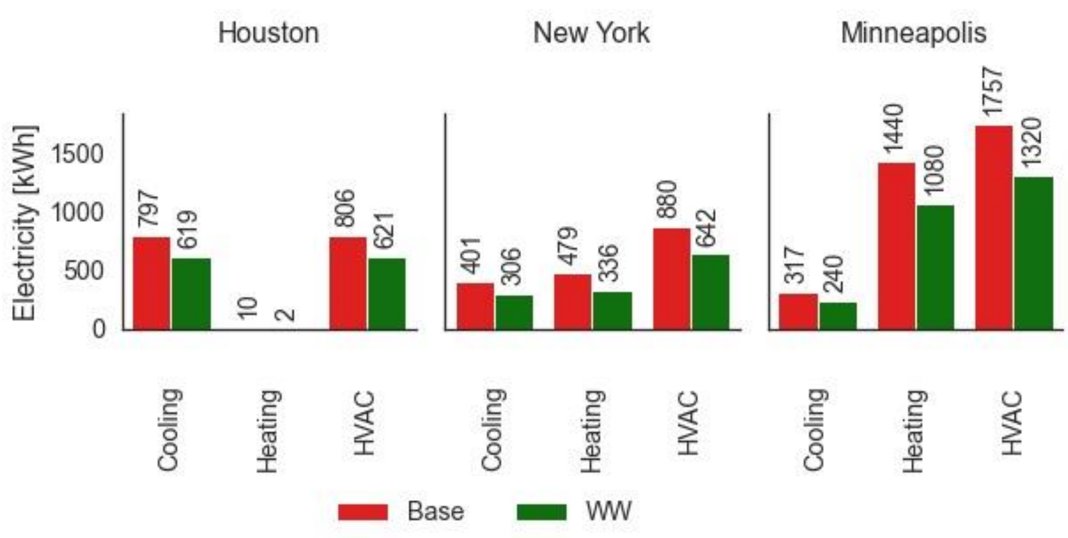

Figure 15. Annual electricity consumption for ADU: cooling, heating, and total HVAC (cooling + heating)

3.2 TOWNHOMES

The townhomes include six 3-story townhomes on the south side of the building and six 4-story townhomes on the north side of the building (Figure 16). Views of the townhomes based on the CAD model developed are presented in Figure 17Figure 8 to Figure 19. Each of the townhomes has a footprint

of 36' × 14' and has solar panels with a rated capacity of 6460 W on the rooftop of each unit. The properties of the buildings are listed in Table 4.

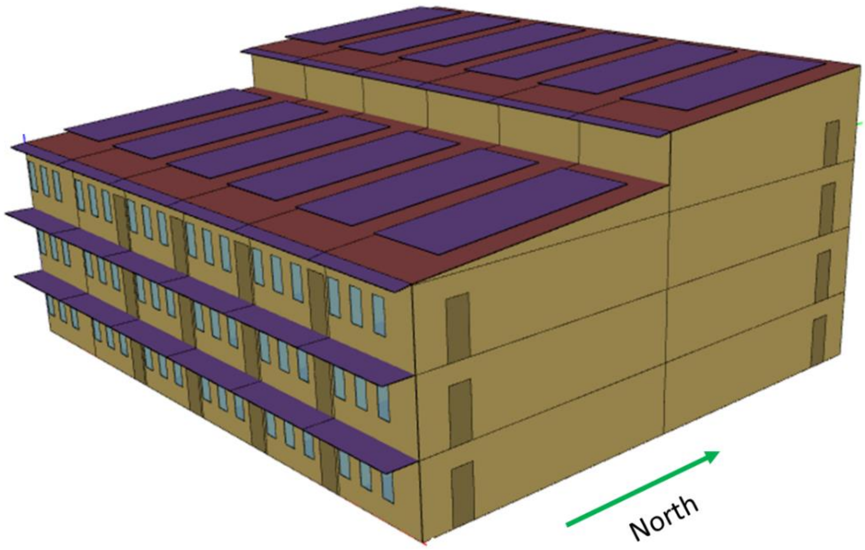

Figure 16. Energy model geometry of townhomes

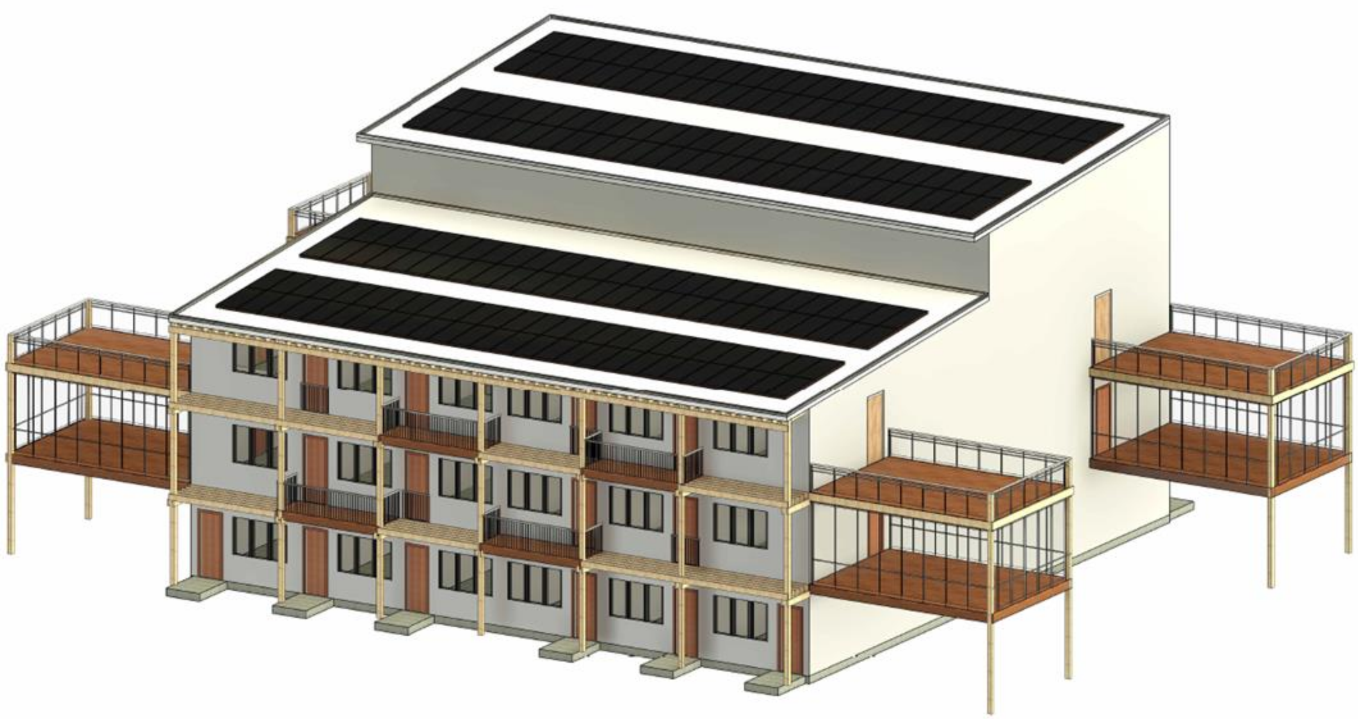

Figure 17. Architectural model viewed from the southeast, developed after the energy model, with a 4' roof overhang providing better seasonal solar control than the 2' overhang of the energy model. Six 2BR 3-story townhomes face South, with six 3BR 4-story townhomes facing North. The compact form minimizes exposed surface area overall through the sharing of party walls both side-to-side and back-to-back.

Figure 18. Architectural model viewed from the Northeast, with the fiber-cement panel exterior. Future iterative modeling of exterior vertical fins, or windows wrapped with exterior shading 'hoods' could document the reduction of summer solar heat gain in North windows in early morning and late afternoon/evening hours. Windowless east and west walls reduce summer heat gain and provide porches over covered parking between the buildings. The area devoted to solar panels could be increased if PV rooftops even with the roofline were added to these porches, narrowing the gap to Net Zero Energy performance, but at increased cost.

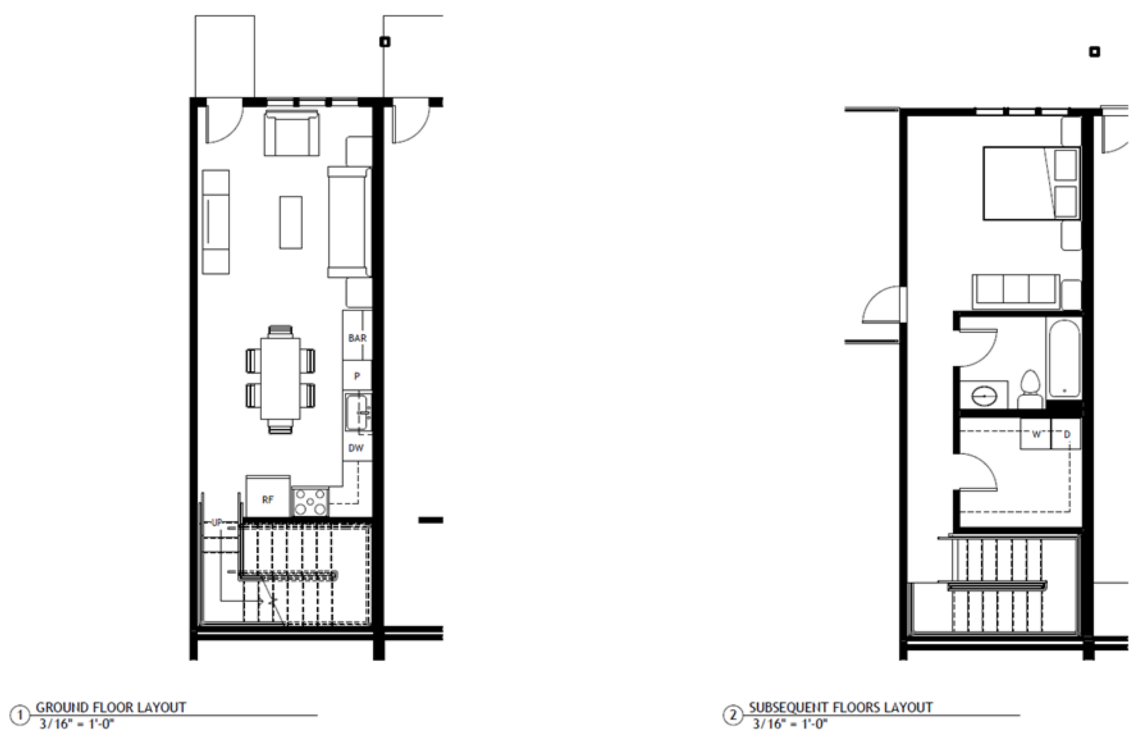

Figure 19. Typical townhome open floor plan with Great Room including Living, Kitchen and Dining. The typical upper floor plan at right puts living spaces in the daylit zone with bath, closet, and stairs playing supportive roles away from the daylit perimeter

Table 4. Characteristics of townhomes with WW and 24" oc framing

Variable	Value
Floor area	21170 sf
Window area	968 sf
Window-to-wall ratio	8.9 %
Window/Floor area	4.57 %
Window	U-value: 0.149/R6.7 SHGC: 0.57 62% VT
Opaque Envelope	Wall: R22 Roof: R47
HVAC system equivalent to a SEER2 23.9 mini-split heat pump	A unitary system supplying conditioning to each floor of the units Cooling COP: 6.7 Heating COP:3.5 Supplementary heater efficiency: 1
Electric equipment	Cooktop-3000 W (30 min per day) Microwave- 1000 W (30 min per day) Toaster- 1500 W (10 min per day) Oven- 3800 W (30 min per day) Refrigerator- 250 W (24 hours a day) Dishwasher- 1400 W (30 min for 3 days in a week) Clothes Washer/Dryer -2500 W (4 hours in a week)
Maximum occupancy	2 per 3 story townhomes 3 per 4 story townhomes
Water heater	50 gallon capacity heat pump water heater
Lights	0.2 W/sf
PV capacity	92 kW
Solar shading	2' roof overhangs for top floor 4' overhang for other floors representing balcony

The Base case for the townhomes has window properties and wall insulation per ASHRAE standard 90.1 2019, listed in Table 5. Except for the window and wall properties, all the other characteristics of the WW and Base case are the same. The wall thermal resistance in the table is only the resistance of wall section excluding the window.

Table 5. Wall and window properties for the Base case

Variable	Houston	New York	Minneapolis
Wall thermal resistance	R7.8	R7.8	R9.1
Window	U value: 0.487 / R2.05 SHGC: 0.245	U value: 0.382 / R2.62 SHGC: 0.353	U value: 0.360 / R2.78 SHGC: 0.37

A comparison is made for the electricity consumption of WW and the Base case for, cooling, heating, and total HVAC electricity consumption (Figure 20). The figure shows an increase in cooling-related consumption and a decrease in heating-related electricity consumption in all three climate zones. Overall, the total electricity use increased by 1.3 MWh in Houston, while it decreased by 9.5 MWh and 20.2 MWh in New York and Minneapolis respectively. The increase in cooling-related electricity is due to a higher SHGC of WW (0.57) compared with SHGC for the Base case, and higher insulation levels that keep internal heat gains from appliances inside as additions to cooling load, shown in Table 5. The reduction in heating electricity comes from higher thermal insulation of walls (R15) and windows (R6.7) for WW compared to Base. The difference in the electricity consumption in terms of percentage savings is provided in Figure 21. The figure shows 30% and 23.8% HVAC-related electricity consumption

reduction in Minneapolis and New York respectively. In Houston, the HVAC electricity increased by 3.6% compared with the Base case which suggests a need to tune exterior shading devices, between-the-pane grids, window tint, and/or interior shades and blinds for this climate. As is, WW's higher R-value and SHGC compared with the Base is more suitable for colder climates.

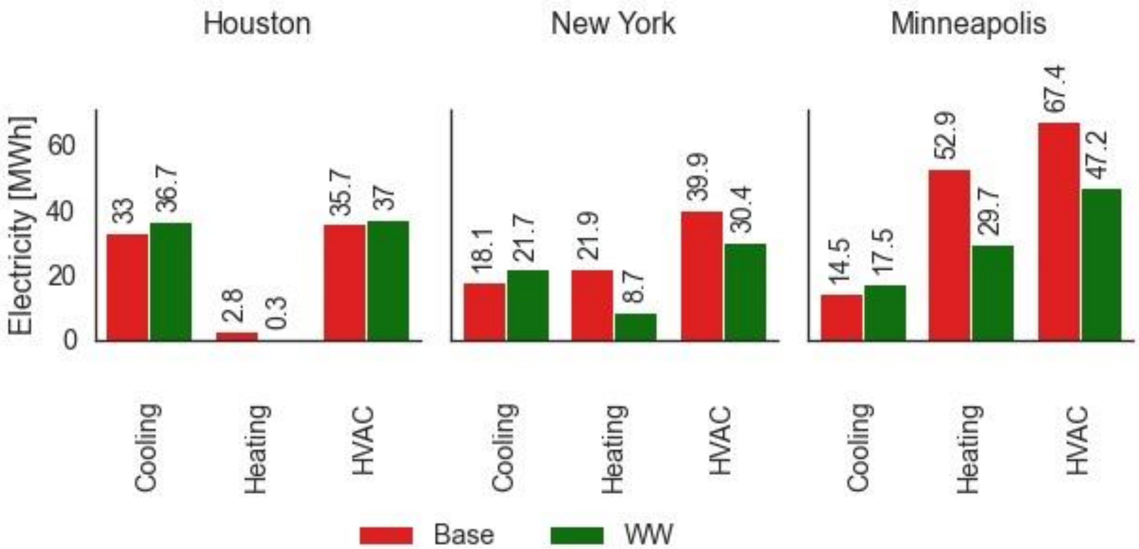

Figure 20. Annual electricity consumption for 3/4 story townhomes: cooling, heating, and total HVAC (cooling + heating)

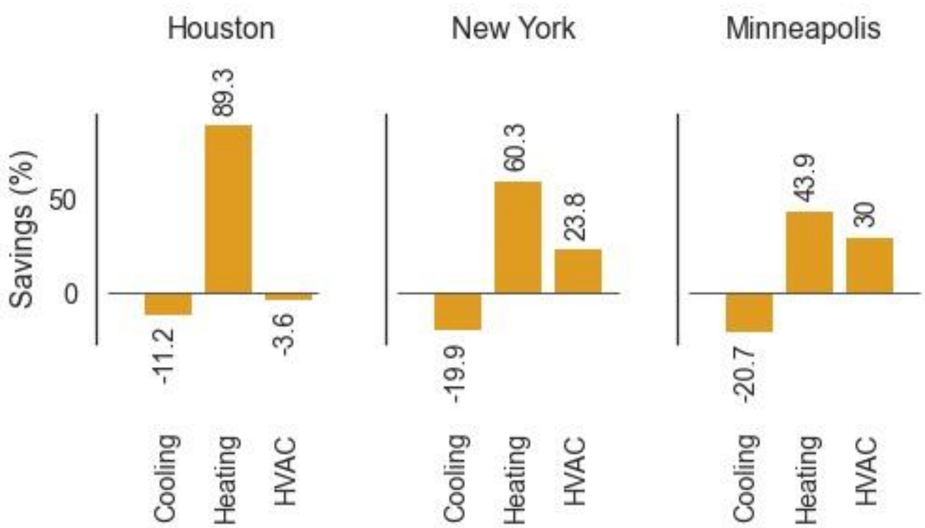

Figure 21. Energy savings (%) from the use of WW compared to Base for 3/4 story townhomes

3.3 HOTEL

The hotel building used for the simulation is a 4-story building with south and north-facing rooms. The geometry of the building is shown in Figure 22. Views of the hotel building based on the CAD model developed are presented in Figure 23 to Figure 25. The characteristics of the hotel building are shown in Table 6. The Base case has properties for walls and windows similar to the Base case of townhomes, listed in Table 5. Each room of the top floor of the hotel building had roof top solar unit with 20 solar panels each rated at 320 W.

Table 6. Characteristics of the hotel with WW and 24" oc framing

Variable	Value
Floor area	49286 sf
Window area	2915 sf
Window-to-wall ratio	13.1 %
Window area/Floor area	5.91 %
Window	U-value: 0.149/ R-value: R6.7 SHGC: 0.57 VT: 62%
Opaque Envelope	Wall: R22 Roof: R47
HVAC system equivalent to a SEER2 23.9 mini-split heat pump	A unitary system used to represent a heat pump system with supplementary electric heating. Cooling COP: 6.7 Heating COP:3.5 Supplementary heater efficiency: 1
Electric equipment	Coffeemaker-1000 W (10 min per day) Microwave-1000 W (5 min per day) Refrigerator-100 W (always on)
Maximum occupancy	2 per room
Water heater	50 gallon capacity heat pump water heater
Lights	0.2 W/sf
PV capacity	163 kW
Solar shading	4' overhang for all floors

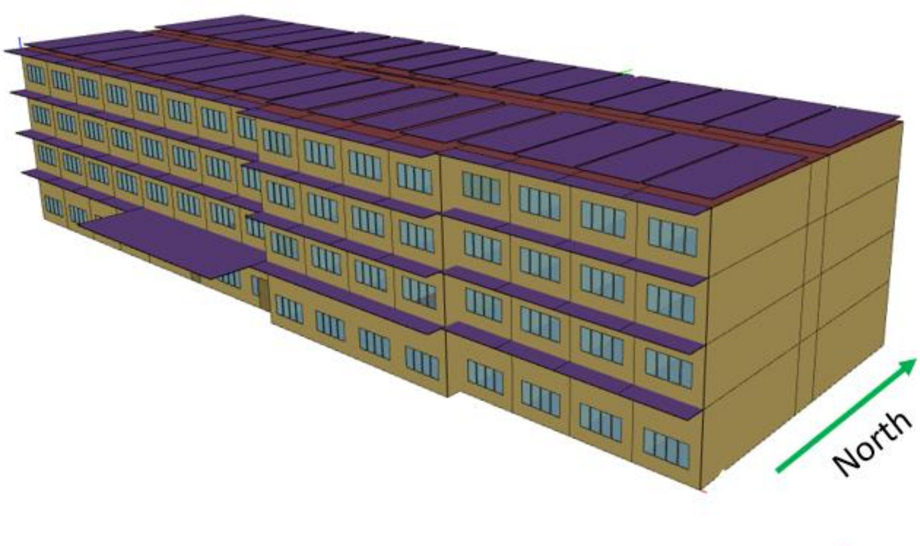

Figure 22. Energy model geometry of the hotel

Figure 23.Architectural model of the hotel viewed from the southeast with 4 windows with total area of 30sf per room. The daylighting and energy impact of 2-3 windows at 15-22.5 sf total area instead of 30 sf could be evaluated using iterative modeling.

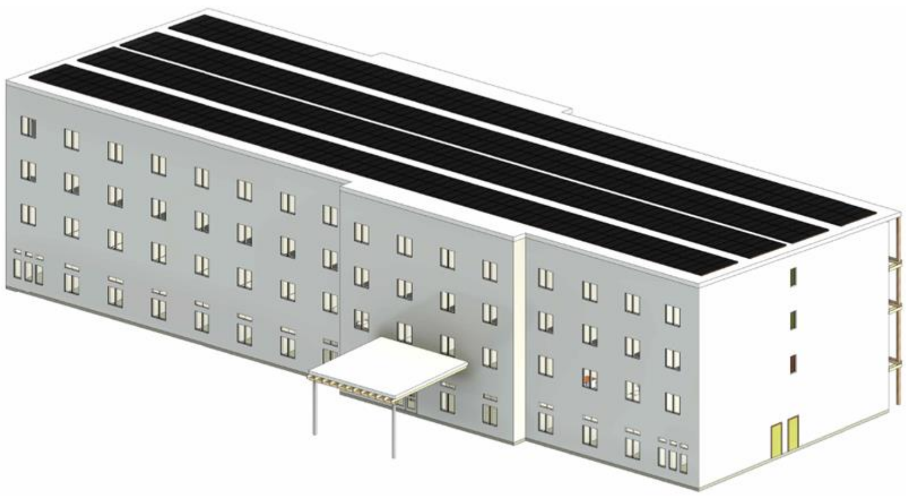

Figure 24. Architectural model of the hotel viewed from the northwest with 15sf in 2 windows per guest room.

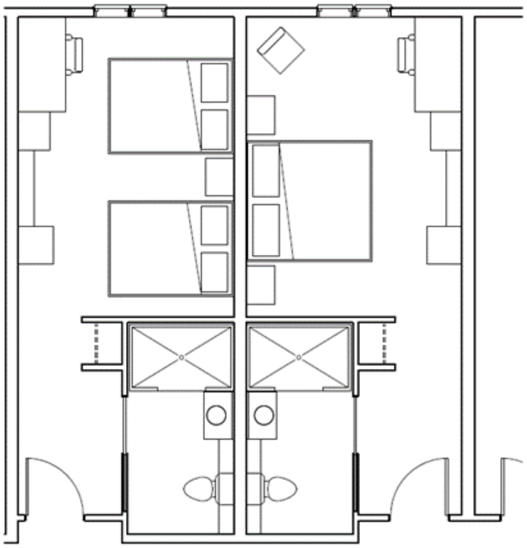

Figure 25. Typical guest room floor plans

The energy consumption for WW and Base for the hotel is shown in Figure 26 and the reduction in energy consumption from using WW and 24" oc framing wall is provided in Figure 27. It can be seen that in all the locations there is an increase in cooling energy consumption and a reduction in heating energy consumption from the use of WW as in the case of townhomes. The highest absolute electricity savings was seen in Minneapolis, which was 56.4 MWh, followed by New York which had a 28.3 MWh reduction in electricity consumption. Houston saw an increase in overall HVAC electricity by 3.2 MWh. In relative terms, there was a 3% increase in HVAC-related electricity consumption in Houston, which can be reduced by use by appropriate solar control using exterior shading devices. Minneapolis and New York saw a decrease in HVAC-related electricity consumption by 24.2% and 21.7% respectively.

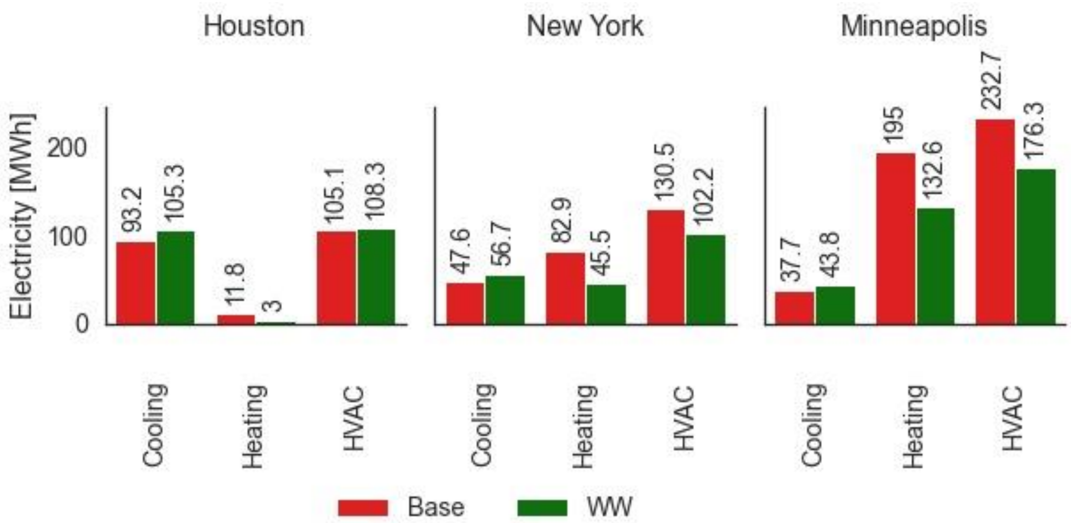

Figure 26. Annual electricity consumption for hotel: cooling, heating, and total HVAC (cooling + heating)

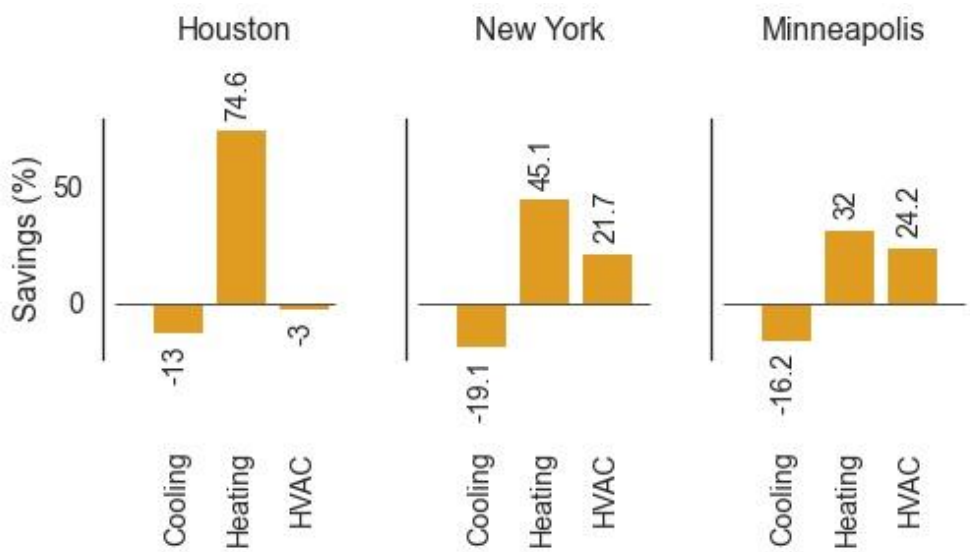

Figure 27. Energy savings (%) from the use of WW and 24" oc framing compared to Base for hotel

3.4 STACKED FLATS

The stacked flat buildings had a total of 12 units, each with a footprint of 24 ft × 36 ft. The south façade of the building had a 4 ft long overhang intended to provide shading to the windows, mainly during the summer season when the solar altitude is high. Each of the units has 42 rooftop solar photovoltaic panels installed. The solar panels had a rated power of 320 W each for electricity generation. The geometry of the stacked flats building is shown in Figure 28. Views of the stacked flats based on the CAD model developed are presented in Figure 29 to Figure 31. The characteristics of the stacked flats building are listed in

Table 7. The base case for stacked flats had window and wall properties similar to the townhomes and hotel. (Table 5). All the other characteristics of the Base case were the same as the WW.

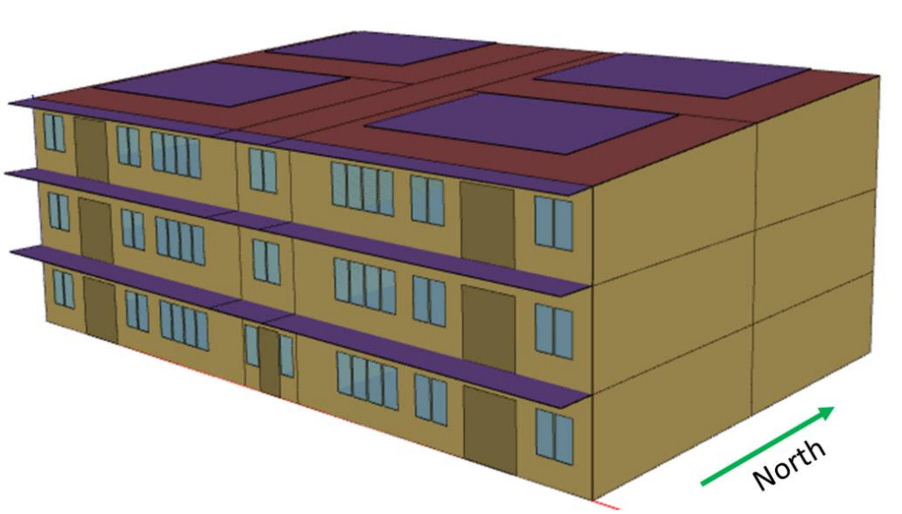

Figure 28. Energy model geometry of stacked flats

Figure 29. Stacked flats seen from the southeast. The IBC allows 3 story 12plexes with 1 stairwell when sprinkled. Like the townhomes, windowless east and west walls reduce summer solar gain, and provide access to porches covering parking between adjacent buildings.

Figure 30. Stacked flats seen from the northwest. Iterative design & energy modelling could optimize exterior shading of north-facing windows, perhaps as simply as adding a 9" wide painted fiber-cement panel at window head & jambs.

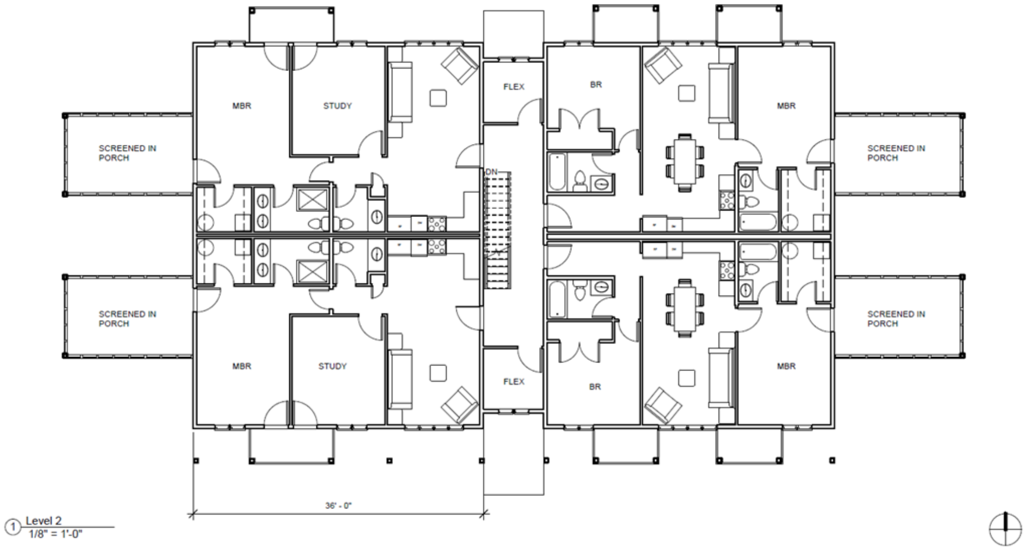

Figure 31. Four stacked flats per floor can use the 2 flex spaces available on 2nd & 3rd floors. Two unit types fit a 24'x36' footprint for affordable 864sf 2 BR/2 Ba & BR + study/1-1/2 Ba floor plan options. Larger variations of these units may have 4 to 6 bays instead of the 3 bays shown here per unit. Each bay at 12'x24' maximizes 24" on center structural framing efficiency.

Table 7. Characteristics of stacked flats with WW and 24" oc framing

Variable	**Value**
Floor area	11681 sf
Window area	803 sf
Window-to-wall ratio	11.14 %
Window area/ Floor area	6.87 %
Window	U-value: 0.149 SHGC: 0.57 VT: 62%
Opaque Envelope	Wall: R22 Roof: R47
HVAC system equivalent to SEER2 29.9 mini-split heat pump	Unitary system conditioning in each apartment Cooling COP: 6.7 Heating COP: 3.5 Supplementary heater efficiency: 1
Electric equipment	Cooktop-3000 W (30 min per day) Microwave- 1000 W (30 min per day) Toaster- 1500 W (10 min per day) Oven- 3800 W (30 min per day) Refrigerator- 250 W (24 hours a day) Dishwasher- 1400 W (30 min for 3 days in a week) Clothes Washer/Dryer -2500 W (4 hours in a week)
Hybrid water heater	50 gallon capacity heat pump water heater
Lights	0.2 W/sf
PV Capacity	53.76 kW
Solar shading (only on South façade)	3' roof overhangs for top floor 4' overhang for other floors representing balcony

The energy consumption for WW and the Base for the stacked flats is shown in Figure 32 and the reduction in energy consumption from using WW and 24" on-center framing wall is provided in Figure 33. Similar to townhomes and hotels, stacked flats with WW have higher cooling electricity consumption and lower heating electricity consumption compared to Base. Overall, HVAC electricity consumption was reduced for New York and Minneapolis by 4.2 MWh and 12.7 MWh respectively, while it increased for Houston by 1.5 MWh. The window-integrated 24" on-center solution reduced HVAC electrical consumption by 22.2% in NYC and 38.1% in Minneapolis.

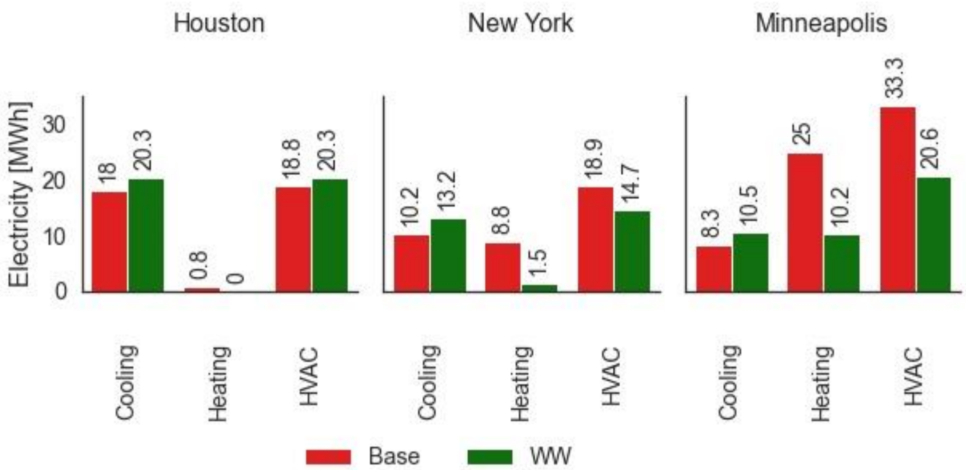

Figure 32. Annual electricity consumption for stacked flats: cooling, heating, and total HVAC (cooling + heating)

Figure 33. Energy savings (%) from the use of WW compared to Base for stacked flats

A monthly comparison of heating and cooling electricity consumption between WW and the Base case is shown in Figure 34 and Figure 35 respectively. For the heating electricity consumption it can be seen that WW has lower energy consumption than the Base in all the months and higher electricity savings is seen December through February. WW can potentially remove the need for heating in shoulder season months like March, April, and October. In the case of cooling electricity, the higher electricity consumption from WW does not occur in the peak summer months of June and July but during December through February in Houston. The overhang of the building shades the windows during the summer when the sun is at a high altitude. When the solar altitude lowers in shoulder seasons and further lowers in

the winter months, the high SHGC of WW allows in more direct sun. This solar heat gain is beneficial for passive heating in the mixed climate of New York and the cold climate of Minneapolis but is not useful in the hot climate of Houston which is cooling-dominated throughout the year. A surface coating or tint on one of the acrylic panes of WW or exterior shading devices can be used to reduce the unwanted solar heat gain in hot-humid locations.

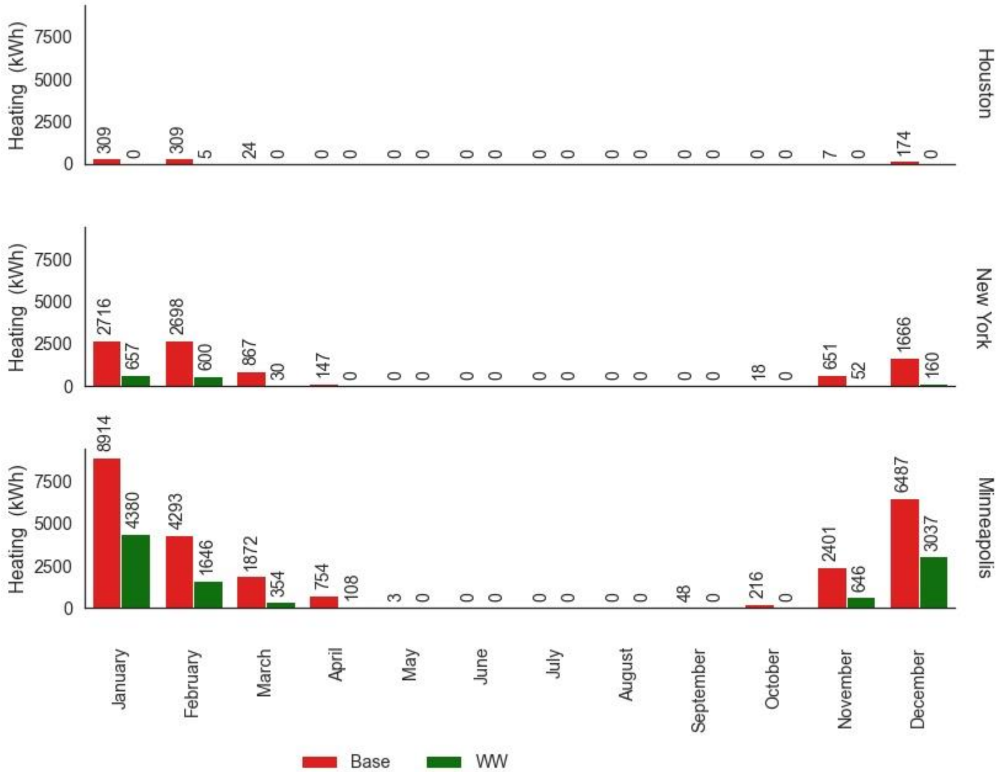

Figure 34. Monthly heating electricity consumption for the stacked flats

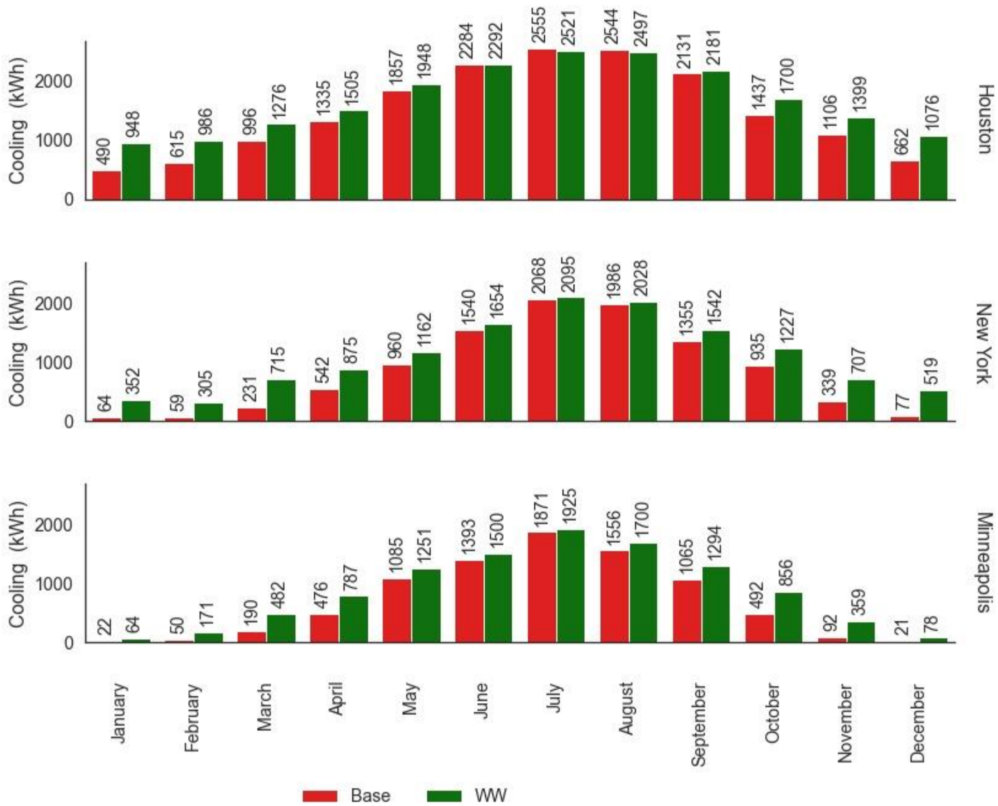

Figure 35. Monthly cooling energy consumption for the stacked flats

4. NET ZERO POTENTIAL AND COST CALCULATION

Electricity generation from PV panels, gross electricity consumption and net electricity consumption of the buildings is discussed in sub-section 4.1. Next, energy cost savings from the use of WW compared to the Base case is provided in sub-section 4.2. Sub-section 4.3 compares the construction cost of WW in 24" oc framing versus conventional 16" oc construction performed by GS Research LLC.

4.1 PV GENERATION AND ELECTRICITY CONSUMPTION

The EUI for each building type before PV generation (gross EUI) and after PV generation (net EUI) with number of PV panels, PV generation per unit floor area and percentage of gross EUI met by PV is provided in Table 8. For the ADU the maximum number of solar panels that could be installed was 12 but only 6 were needed in Houston and New York and 8 panels in Minneapolis for achieving Net Zero Energy performance. For the townhomes, hotel and stacked flats, the maximum number of 320 W solar panels that could be installed was 288, 512 and 168, respectively, installed on the rooftop of each building type. The installed PV kw capacity per unit floor area was lower in the other multi-story building types. The PV generation in Houston, New York and Minneapolis for townhomes was 73%, 71% and 63% of total electricity, for hotel was 52%, 48% and 40% of total electricity , and for stacked flats was 57%, 56% and 53% of total electricity.

Table 8. EUI and PV generation

City	Building	Gross EUI (kBtu/sf/yr)	No of PV panels	PV capacity per floor area (W/sf)	PV generation (kBtu/sf/yr)	Net EUI (kBtu/sf/yr)	Gross EUI met by PV (%)
Houston	ADU	30.1	6	6.86	32.2	-2.0	107
New York	ADU	30.4	6	6.86	30.7	-0.3	101
Minneapolis	ADU	38.7	8	9.14	41.1	-2.4	106
Houston	Townhomes	26.7	288	4.35	19.5	7.2	73
New York	Townhomes	25.7	288	4.35	18.2	7.5	71
Minneapolis	Townhomes	28.4	288	4.35	18.0	10.4	63
Houston	Hotel	28.8	512	3.32	15.0	13.9	52
New York	Hotel	28.4	512	3.32	13.7	14.7	48
Minneapolis	Hotel	33.5	512	3.32	13.5	20.0	40
Houston	Stacked flats	36.0	168	4.60	20.7	15.4	57
New York	Stacked flats	34.4	168	4.60	19.2	15.2	56
Minneapolis	Stacked flats	36.1	168	4.60	19.0	17.1	53

However, since this energy modelling was performed, 400 W solar panels have become widely available of similar size to the 320 W panels, offering an immediate 25% potential increase in electrical production. Table 9 provides the projected results in the scenario when 400 W solar panels were used instead of 320 W solar panel (which assumes the PV production would increase linearly under the same efficiency and incident solar radiation). This 25% boost would automatically yield PV generation in Houston, New York and Minneapolis for the townhomes to 91%, 89% and 79% of total electricity, for the hotel to 65%, 60% and 50% of total electricity, and for the stacked flats to 71%, 70% and 66% of total electricity, respectively. With 400 W solar panel, the net EUI for all the buildings in all 3 climate zones is under 17 kBtu/sf/year. The potential to reach Net Zero Energy performance will increase with further PV power generation improvements in the rated wattage of similarly sized solar panels.

Table 9. Projected EUI and PV generation based on 400 W solar panels

City	Building	Gross EUI (kBtu/sf/yr)	No of PV panels	PV capacity per floor area (W/sf)	PV generation (kBtu/sf/yr)	Net EUI (kBtu/sf/yr)	Gross EUI met by PV (%)
Houston	ADU	30.1	6	8.58	40.3	-10.2	134
New York	ADU	30.4	6	8.58	38.4	-8	126
Minneapolis	ADU	38.7	8	11.43	51.4	-12.7	133
Houston	Townhomes	26.7	288	5.44	24.4	2.3	91
New York	Townhomes	25.7	288	5.44	22.8	2.9	89
Minneapolis	Townhomes	28.4	288	5.44	22.5	5.9	79
Houston	Hotel	28.8	512	4.15	18.8	10.0	65
New York	Hotel	28.4	512	4.15	17.1	11.3	60
Minneapolis	Hotel	33.5	512	4.15	16.9	16.6	50
Houston	Stacked flats	36.0	168	5.75	25.9	10.1	71
New York	Stacked flats	34.4	168	5.75	24.0	10.4	70
Minneapolis	Stacked flats	36.1	168	5.75	23.8	12.3	66

4.2 ENERGY COST SAVINGS

The cost savings from HVAC electricity reduction discussed in Section 3 is shown in Table 10. Note, this does not include the cost analysis for the solar panels. The negative value for cost savings in the table indicates an increase in HVAC electricity-related costs.

Table 10. Cost savings from HVAC electricity reduction

Building	City	Annual HVAC savings (MWh)	Annual cost savings ($)	Total cost savings ($)	Total cost savings per floor area ($/sf)
Townhomes	Houston	-1.3	-132	-2642	-0.12
Townhomes	New York	9.5	1741	34827	1.65
Townhomes	Minneapolis	20.2	2432	48642	2.30
Hotel	Houston	-3.2	-325	-6502	-0.13
Hotel	New York	28.3	5187	103748	2.11
Hotel	Minneapolis	56.4	6791	135811	2.76
Stacked flats	Houston	-1.5	-152	-3048	-0.26
Stacked flats	New York	4.2	770	15397	1.32
Stacked flats	Minneapolis	12.7	1529	30582	2.62

The calculation of annual cost savings in Table 10 is done using electricity rates of 10.16 ¢/kWh, 18.33 ¢/kWh, and 12.04 ¢/kWh for Houston, New York, and Minneapolis using average electricity rates for their respective state in the year 2022 (US EIA 2024). The total cost savings are calculated assuming a 20-year period and the same energy/cost savings are obtained each year i.e. impact of the change in future weather or the cost of electricity is not considered to simplify the analysis. The area normalized cost savings for 20 years is in the range of $1.6-2.46/sf for New York and $2.56-3.06/sf for Minneapolis. In Houston, the cost penalty of 6 to 24 cents per square foot is significantly less than the savings obtained in New York and Minneapolis. This penalty could potentially be reduced or eliminated by fine tuning of the design and successive model iterations.

4.3 CONSTRUCTION COST

The cost of Net Zero Energy performance in new construction using the multi-pane WonderWindows in 24" on-center construction was evaluated in a couple of ways.

GS Research LLC presented the design for the 280sf ADU along with a $46,000 itemized budget and the results of its Net Zero energy performance (Table 8) for Houston, New York and Minneapolis at the NAHB HUD Housing Innovation Showcase in Washington, DC in June 2023. Detailed quantity take-offs of materials, equipment, appliances, ‘barebones’ furnishings, & sales tax were prepared from plans for the 280sf ADU, with the excel spreadsheet presented in its entirety in the APPENDIX A.

The $46,000, or $164/square foot cost, assumed do-it-yourself (DIY) labor with subcontracting out survey and construction staking, excavation, rock delivery, concrete, plumbing, HVAC, and electrical. Land, utility hook-ups, and permit fees above $500 were not included: all these items can add significant cost not covered here and are highly dependent upon location. Item numbers and unit prices of materials were quoted from lowes.com wherever possible: one’s local big box home store can supply most of what’s needed to achieve Net Zero Energy performance in wood frame buildings. A General Contractor

supplying all labor and material, subcontractors, general conditions, overhead & profit could put a 3-4x multiplier on the $46,000 budget, putting a turnkey new construction ADU in the range of $140,000-$200,000 plus land, utilities and higher permit fees.

GS Research's March 2024 entry for the Ivory Prize in Affordable Housing Innovation applied lessons learned about the cost and structural 'sweet spot' for Douglas Fir common in the West (compared to the Southern Yellow Pine found mostly in the South). Whereas SYP is adept at accommodating close to 16-foot spans for residential and light commercial loads, DF performs more cost effectively at 12-foot spans.

A 280sf ADU 20 feet long with 14' span lumber at 16" on-center typically must pay for 16-foot joists and rafters that are field cut. Conventional 2x4, 16" oc spacing builds in 30% more thermally bridging and radiating studs than 24" spacing. The headers, and jack and cripple studs of conventional window openings add to the thermal bridging and cost.

The excel spreadsheet prepared for the Ivory Prize itemized lowes.com costs for a 280sf ADU conventionally framed with 2x4s, at 16" centers essentially following 19th century framing practice versus a 288sf ADU 24' long with 12' spans and 21st century Window-Integrated Framing fitting windows between framing spaced 2 feet on-center.

Only the differences in quantities and cost between the 280sf conventional and 288sf Window-Integrated approach were itemized in the second spreadsheet in the Appendix.

The ADU designs were treated as 'finite elements' in themselves, stacked back-to-back into a 3 story 12plex. There was more than $10,000 in material cost difference between the conventional 16" and innovative 24" approach, which could yield close to $50,000 total first cost savings for the 24" framed solution over conventional construction, while delivering low EUI.

Adding 13.86 kw of solar panels to the available roof space at $2/Watt cost (net of the Federal renewable energy tax credit) yields almost **$20,000 in first cost savings for Near or Net Zero Energy performance.**

Careful optimization of structural, energy and cost aspects of the building envelope using WonderWindows in 24" centered framing holds the promise of net zero energy performance at less first cost than conventional 16" on-center construction. Scaling up these preliminary findings based solely on square footage for the other building types yields these potential savings targets for Near or Net Zero Energy performance using this approach (Table 11).

Table 11. Floor area based scaled up estimation of first cost savings target to achieve net zero energy performance

Building type	Floor area (sf)	First cost savings targets*
ADU 12plex	4,032	$19,800
Stacked flats 12plex	11,681	$57,400
Townhomes 12plex	21,170	$104,000
Hotel	49,286	$242,000

**to achieve net zero energy performance for window-integrated 24" oc framing over conventional 16" oc construction. These projected potential savings should be checked by up-to-date cost data for a specific project detailed in full.*

5. CONCLUSIONS

Whole building energy simulations were performed to evaluate the performance of WonderWindows combined with 24" oc framing. First, several variations were tested in a single zone ADU for which there was a reduction in HVAC electricity consumption when a window with higher SHGC was used in mixed and cold climates. In all 3 climate zones, increasing the window area led to higher HVAC-related electricity consumption for the ADU and a higher wall R-value significantly reduced electricity consumption.

The townhomes, hotel and stacked flat designs with WonderWindows increased cooling electricity consumption and decreased heating electricity consumption in all the climate zones. Total HVAC electricity was reduced for New York and Minneapolis compared to the Base case, while it increased for Houston. The results show up to a 39% reduction in HVAC-related electricity consumption for cold climates compared to the Base case which has window and wall properties based on ASHARE standard 90.1 2019. In the hot climate, a modest increase in electricity consumption was seen due to an increase in cooling electricity demand. Overall the cost savings of $1.6-2.46/sf for New York and $2.56-3.06/sf for Minneapolis from HVAC electricity reduction could be achieved over 20 years.

The ADU achieved Net Zero Energy performance in all 3 Climate Zones despite having the highest exterior surface area-to-floor area ratio: the ADU also had the highest PV kw capacity to floor area ratio among the building types . The townhomes, hotel and stacked flats respectively met 73, 52 and 57 % of electrical use in Houston, 71, 48 and 56 % in New York, and 63, 40 and 53 % in Minneapolis from energy produced by rooftop solar. If 400 W solar panels are used instead of 320 W panel used for energy simulation, it is estimated that in the townhomes, hotel and stacked flats rooftop solar can meet 91, 65 and 71 % of electrical use in Houston; 89, 60 and 70% in New York, and 79, 50 and 66 % in Minneapolis. All the building types at the three locations used for simulation had net energy use intensity under 20 kBtu/sf/year with 320 W solar panel and under 17 kBtu/sf/year with 400 W solar panel. A preliminary evaluation of cost shows that such superior performance can potentially be achieved at less first cost with this 24"on-center solution than conventional construction.

Further tuning of building envelope R-values, window size and SHGC, and solar control through exterior horizontal projections, vertical fins, between-the-pane grids, and/or window shading devices show promise in increasing the net zero energy potential in these modeled designs, but these detailed parametric analyses for each building type and climate zone are left for future study.

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APPENDIX A. COST OF CONSTRUCTION OF ADU

Table A1: WW 280sf ADU cost

	Qty	ITEM	UNIT PRICE ($)	TOTAL PRICE ($)	DIY
GENERAL CONDITIONS					
Survey				1,000	
Bldrs Risk & GL Insurance				1,000	
Permit				500	
Construction Plans				500	
SITEWORK					
Excavation/rough grade				1,500	
Rock base for slab	1	truckload of KYDOT #57 crushed limestone, or equal		500	
Rock for driveway/walks	2	truckload of KYDOT #57 crushed limestone, or equal	500	1,000	
Set grade, rake rock					**DIY**
Foundation drainage		4" slotted ABS corrugated pipe around 68' perimeter		300	
Ground tempered air vent		Screened 6" PVC pipe above ground, ABS corrugated below		400	
CONCRETE					
Slab		[5"/12"x14'x20']+[2'x(14+14+20+20)x.5']/27cf/cyx$200/cy	**200**	1,333	
Slab labor troweled finish		14x20x$3/sf	3	840	
Rebar, chairs & ties				100	
Anchor bolts/washers/nuts				100	
Mesh, poly,stakes				200	
Layout& formwork labor					**DIY**
CARPENTRY					
Slab formboards		reuse in roof framing			
Framing, W&D, & siding labor					**DIY**
Nails, screws, straps, adhsv				400	
roof sheathing 4x8 shts	10	Item#12214 19/32" osb	22	220	
wall sheathing 4x8 shts	24	Item#12214 19/32" osb	22	528	

floor sheathing 4x8 shts	2	Item#12218 23/32" osb T & G	25	50	
ziptape 3-3/4"x90' HD	4	Item#	35	140	
2x6x8 studs	7	Item#73600	5	35	
2x6x8 trtd plate	1	Item#2200361	8	8	
2x4x8 studs	24	Item#330564 SYP	2	53	
2x4x9 studs	6	Item#7013	5	30	
2x4x10 t&b plts & studs	10	Item#27172	5	50	
2x4x12 studs	17	Item#28349	9	155	
2x4x1 top & bottom plates	4	Item#29003	10	40	
2x4x10 treated plates	4	Item#2200359	8	32	
2x4x16 treated	2	Item#2296197	13	26	
2x10x8 loft joists + rafters	16	Item#77891	8	130	
2x10 x10' joists	11	Item#78045	11	125	
5/8"x6"x10' treated	8	Item# 312285 pre-stained/sealed at 2' overhang	10	80	
Frame pack					
Siding pack	24	shts. Hardiepanel HZ10 .312"x4'x8' fibercement panel	55	1,320	
Treated lath or 1x2x8	36	Item#489311 #1 SYP radius edge	3	108	
WINDOWS					
	3	2248 R7 with 1/2 grid	530	1,630	
	4	2211 R9	220	900	
DOORS					
	1	Item#4691 R8 pre-hung 3'x6'-8" f/g ext. panel RH door w/viewport/hdw		400	
	1	Item#785879 Painted pre-hung hollow core RH door		200	
	1	Item#442695 Screen door-stain with hdw		80	
ROOFING					
white roll roofing	4	Item#778381 100sf roll 3.3'x34'	120	480	
flashing, vent boot & trim				200	
microsphere roof coating		with long-handled brushes or rollers		**400**	
Roofing labor					**DIY**
PLUMBING					
W/D supply & drain				200	
condensate drain assy				100	
hot water		Item #919268 3.5gpm on-demand HW htr 220v 14.6kw		220	

kitchen sink + DW		Item #873618 33"x22" double bowl stainless sink + kit		150	
		Item #2743134 dual flush toilet + white cab kit		410	
		Online Set #GR_3842 tub/shower + kit		900	
Subcontractor labor				4,000	
ELECTRICAL					
Electrical layout					**DIY**
Bath fans	2	Item#553457 70cfm Energy Star fan,flex duct & lvrd vent	70	200	
200W service		Item#79498 outside service panel		220	
		Item#534784 inside service panel		210	
wire & circuit breakers				400	
temp pole + power				500	
ceiling fans and fixtures				300	
plugs & switches				400	
Subcontractor labor				1,800	
solar system	10	Mission 320W panels installed at $2/w after tax credit		**6,400**	
HVAC					
Heat pump		Item#5368704 Mr.Cool 9000 btuh SEER 21.5mini-split		1,100	
Subcontractor labor				1,800	
INSULATION					
cellulose dense-pack		vibrated, blown-in		**600**	
blower & vibrator rental				**400**	
Insulation labor					**DIY**
R10, 2" foam board	1.86	SKU#409926 HD, cut in 1-1/2" strips, glued to frmg	42	90	
R10, 2" foam board	2.83	SKU#409926 HD 16" at slab perimeter	42	140	
caulk adhesive				100	
muslin & cap nails				**120**	
DRYWALL					
1/2" rfd 4x8 shts	40	Item#341371	13	520	
1/2" purple shts	10	Item#121507	22	220	
mud & tape				100	
labor					**DIY**
TRIM					

labor					**DIY**
material				400	
accessories		2 towel bars at 24", TP holder		100	
PAINT					
Paint materials		interior & exterior paint, brushes, rollers, concrete stain sealer		600	
Paint labor					**DIY**
CABINETS & COUNTERTOPS					
Allowance		butcherblock counters			
		Item #5200811 48" butcherblock counter		120	
		Item #5200813 96" butcherblock counter		220	
		Item #5200812 72" butcherblock counter		190	
		Item #336276 30"x30" wall cabinet over RF		130	
		Item #336288 30" base cabinet with drawer		170	
		Item #336289 corner lazy susan base cabinet		230	
		Item #336302 36" sink base		160	
	4	Item #336275 24"Wx30" wall cabinets	110	440	
		Item #336281 36"x30" wall cabinet over sink		150	
Install					**DIY**
APPLIANCES					
	2	induction hotplates		200	
MW with fan/light		Item#520293 GE 100W SS		220	
toaster/oven		Item#3846375 1100w 4 slices		70	
RF		ModelWRT318FZDM 18.2cf ss		900	
stack WD		GE ModelGUD24ESSMWW		1,250	
DW		Frigidaire FFCD2413US 24" ss		400	
LANDSCAPING					
Allowance incl tools				800	
Landscaping labor					**DIY**
FURNISHINGS					
fold-out futon couch		Mikone multi-functional folding sofa bed		140	
Cascade camp chairs	4		80	320	

48" smart tv		Hisense 43" 1080p FHD LED Roku tv (43H4030F3)		200	
storage shelving units	3	Item#5022641 4'Wx6'Hx11"D	200	600	
5 walnut hooks	5	Item#4798687 4'Wx6'Hx11"D	70	350	
DIY wood ladder to loft	5	Item#19386 1" poplar dowel + 2@2x4x10	6	50	
TOTAL COST				**47,103**	

Table A2: WW Ivory Prize 280 sf conventional construction vs 288 sf window-integrated framing ADU

280sf conventional vs 288sf 21st century Only differences in cost noted 12 plex at 4 units x 3 floors slab on grade Meet or exceed 2015 IECC adopted 2022 Utah Material costs & Item #s are from Lowes Salt Lake City			
280sf 2x4,16"oc conventional			
DESCRIPTION	**QUANTITY**	**UNIT COST ($)**	**SUBTOTAL ($)**
FLOOR	**8**		
2x10x16 joists	16	26.65	426.40
2x10x10 bands	4	17.42	69.68
LUS210Z joist hangers	32	2.78	88.96
23/32x4x8 OSB subfloor	9	27.28	245.52
Pad	2.8	79.98	223.94
Laminate finish floor	280	2.49	697.20
FLOOR Subtotal			**1751.70**
ROOF	**4**		
2x8x16 rafters	11	18.98	208.78
2x8x10 ridge band & blocking	4	11.87	47.48
2x8x16 ceiling joists	11	18.98	208.78
2x8x10 band joists	4	11.87	47.48
19/32x4x8 OSB	10	21.00	210.00
30# roofing underlayment	1.4	32.98	45.81
asphalt shingles	9	44.36	399.64
R49 blown-in fiberglass	8	50.04	395.05
ROOF Subtotal			**1563.02**
WALLS	**12**		
2x4x104-5/8 studs 16"oc	54	6.98	376.92

2x4x8 gable end studs	6	4.26	25.56
2x4x10 plates	12	6.82	81.84
2x4x16 plates	8	11.15	89.20
2x6x10 dbld window headers	2	8.62	17.24
7/16x4x8 OSB	15	15.98	239.70
Tyvek	0.36	224.00	79.64
Hardiboard primed	69	15.62	1071.09
1x4 corner and window trim	44.5	19.52	868.64
1"x4x8 XPS cont's insulat'n brd.	15	32.28	484.20
R15 HD Batt	6	80.82	500.65
3060/3672 PVC frame windows	3	394.46	1183.38
WALLS Subtotal			**5018.07**
TOTAL for 12plex			**80482.48**
288sf 2x4,24"oc integrated construction			
FLOOR	**8**		
2x10x12 joists	13	20.92	271.96
2x10x12 bands	4	20.92	83.68
LUS28Z joist hangers	26	1.38	35.88
23/32x4x8 OSB subfloor LP350	9	41.00	369.00
Polyurethane finish 3 coat	1.5	65.98	100.77
R10 2" XPS strips all framing	3.2	45.68	145.61
FLOOR Subtotal			**1006.89**
ROOF	**4**		
2x10x16 rafters	13	26.65	346.45
2x10x12 ridge band & blocking	4	20.92	83.68
19/32x4x8 OSB	10	21.00	210.00
Grace ice and watershield	2.8	88.98	247.17
APOC 576 roof coating	0.9	356.04	323.67
2" R13 polyiso 4x8 cut to fit	9	30.86	270.03
.5" R2.9 polyiso 4x8 cut to fit	9	19.92	174.30
R33.4 cellulose densepack	37	13.48	499.26
ROOF Subtotal			**2154.55**
WALLS	**12**		
2x4x10 studs 24"oc	40	6.82	272.80
2x4x12 plates	10	8.22	82.20
2x4x16 plates	2	11.15	22.30

2x4x94-5/16 studs WW plates	3	3.27	9.81
Thermoply Blue 4x10 sheathing	12	38.00	456.00
.75x2.5" primed furring	33.3	7.78	259.33
4x8 Hardipanel primed	15	48.98	734.70
R21 cellulose 5.5"	26	13.48	350.80
2248 R7 WonderWindows	5	450.00	2250.00
WALLS Subtotal			**4437.95**
TOTAL for 12plex			**69928.75**
Material Savings Integrated v. Conventional			**10553.74**
x 4.5 for Labor & Subs, O&P, & General Conditions			**47491.81**
FIRST COST SAVINGS @ LESS than 15 KBTU/sf/year performance:			**$47,492**
Add solar panels to roof			
1344sf roof area at 32sf/panel with access = 42 solar panels			
42 solar panels @330W each@ $2/W net of tax credit			**$27,720**
FIRST COST SAVINGS WITH NEAR ZERO ENERGY PERFORMANCE BUILT IN:			**$19,772**
…and 8 MORE square feet in each of the 12 units: **almost 100sf MORE for almost $20,000 LESS COST!**			