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Simulation & Analysis of the Hydronic Shell Retrofit System as a Solution for Deep Energy Retrofits and Electrification of Large Multifamily Housing Communities in Cold Climate

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OAK RIDGE National Laboratory

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Buildings and Transportation Science

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SIMULATION & ANALYSIS OF THE HYDRONIC SHELL RETROFIT SYSTEM AS A SOLUTION FOR DEEP ENERGY RETROFITS AND ELECTRIFICATION OF LARGE MULTIFAMILY HOUSING COMMUNITIES IN COLD CLIMATE

Niraj Kunwar
Jyothis Anand
Piljae Im
David Goldstein*

*Hydronic Shell Technologies LLC

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OAK RIDGE NATIONAL LABORATORY
Oak Ridge, TN 37831
managed by
UT-BATTELLE LLC
for the
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ABSTRACT

Among 32 million multi-family buildings in the United States, approximately 42% have poor or no insulation. Envelope retrofits of these buildings will provide thermal resiliency and enable a pathway to electrification of space heating systems as a result of improved thermal performance. Hydronic Shell (HS) is a technology which combines an insulated retrofit panel with a heating, ventilation and air-conditioning (HVAC) thus enabling both envelope retrofit and space heating electrification. In this study, we used whole building energy simulation to evaluate energy impact of multi-family building retrofit with hydronic shell system. The simulation was performed for four locations of New York, Syracuse, Chicago and Boston. The results from the simulation showed more than 66% cooling energy reduction and more than 88% heating energy reduction from Hydronic Shell retrofit compared to Baseline building in all four locations. This reduction in energy consumption resulted in up to 219 MT reduction in annual CO2 emission. The cost reduction per floor area achieved from HVAC energy consumption reduction using Hydronic Shell retrofit was 0.66 to 0.99 $\$/ft^2$. The results also showed higher percentage of heating energy reduction comes from the envelope only retrofit and higher percentage of cooling energy reduction comes from the retrofit HVAC system for the four locations under study.

1. INTRODUCTION

According to the 2020 residential energy consumption survey, there are 32 million multi-family buildings in the United States, and approximately 42% of these have poor or no insulation (US EIA 2020). Electrification of buildings with heat pump is one of the key strategies to achieve the goal of 90% reduction of greenhouse gas emissions in buildings by 2050 (U.S. Department of Energy 2024a). Building electrification will also enable greater penetration of variable renewable energy sources. However, replacing the natural gas dominated heating system by electrical appliance will increase the electrical load in heating dominated climate. It is crucial to well-insulate the building envelope to mitigate the stress in the grid from electrification. The hydronic shell (HS) system discussed next can achieve dual objective of envelope retrofit with space heating system electrification.

HS is a complete heating, cooling, and ventilation solution that is integrated within an overclad façade retrofit system, forming a thermally active shell around the existing building that radiates heating and cooling through the existing façade and is supplemented by a proprietary fan coil component call the HydroBox. The retrofit envelope includes an R-25 wall layer with and triple pane window. The HS system also delivers fully conditioned ventilation air while removing exhaust air. All the heating, ventilation, and air conditioning (HVAC) distribution and components fit within a narrow air cavity formed between the new and existing façades. Minimal work is required within the building, making the installation non-disruptive to residents.

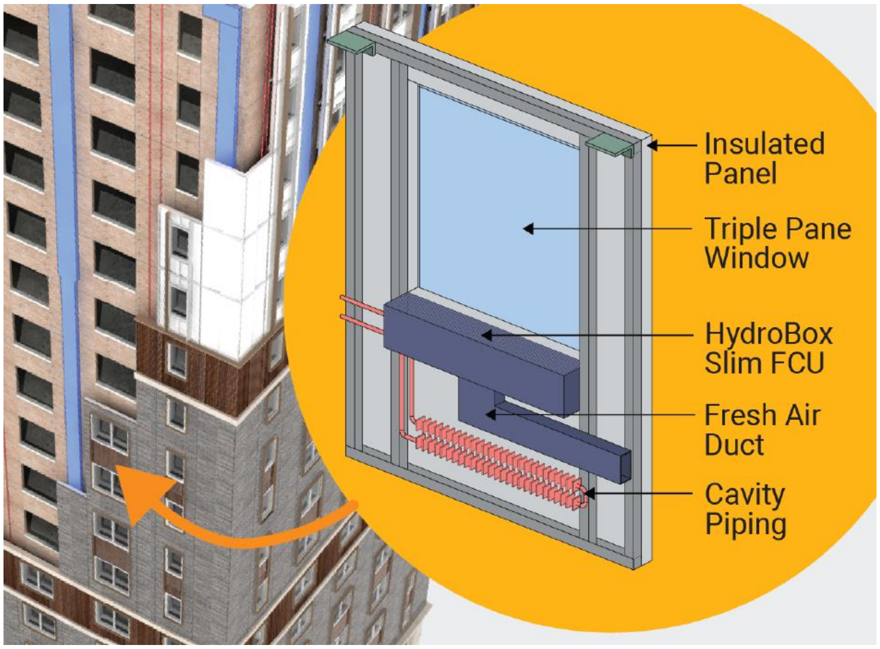

Figure 1. Hydronic Shell system which is a modular panel with HydroBox

Hot water, chilled water, and ventilation are supplied from central heat pumps and air handling equipment that can be located on the roof, in a mechanical room, or connected to a geothermal loop or district heating and cooling system. Hydronic distribution minimizes refrigerant quantities and associated health and environmental risks compared to refrigerant-based distribution systems. By radiating heat through the existing façade, the existing masonry becomes a massive thermal energy storage medium, providing a simple and low-cost solution for peak shaving and demand response while greatly improving passive survivability in the event of a power outage. The cavity convector/piping will be used as the primary source to heat/cool the space and the fan in the fan coil will be a secondary unit which is activated when the cavity convector cannot meet the space heating/cooling needs.

2. ENERGY MODELING

Whole building energy simulation is performed using EnergyPlus (U.S. Department of Energy 2024b) at four locations i.e. New York, Syracuse, Chicago and Boston. A high-rise prototype building model (Figure 2) was chosen for simulation to represent large masonry multifamily building after appropriate modifications. The characteristics of the high-rise prototype building model is listed in Table 1. The simulations were performed for three cases discussed in Sections 2.1 to 2.3.

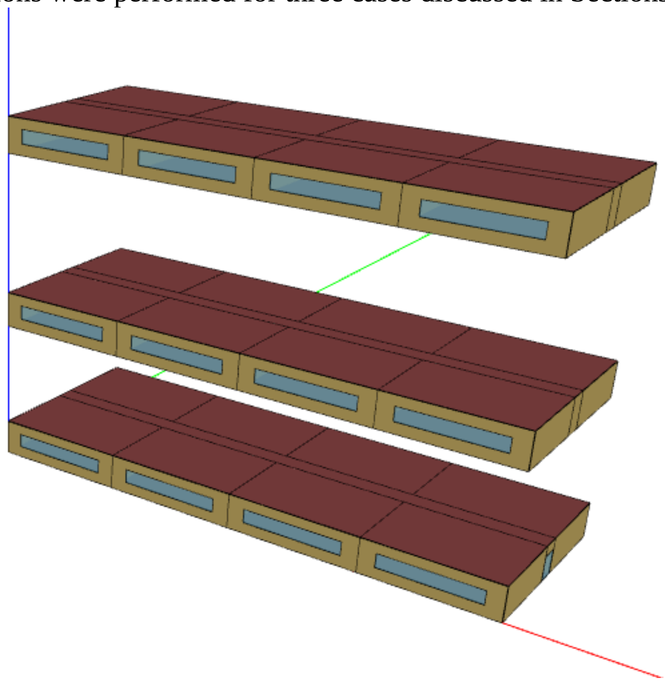

Figure 2. High-rise building model geometry (Note: The middle floor uses a multiplier of 8 to represent 8 floors)

Table 1. Characteristics of high-rise prototype building model

Characteristic	Value
Number of floors	10
Total conditioned floor area	75992 ft^2
Window to wall ratio	30%

2.1 BASELINE

The study used 2007 ASHRAE 90.1 prototype building model for High-rise apartment for developing baseline building model. The envelope of the high-rise building model was changed to represent Pre1980 apartment building. Therefore, the wall construction is changed to brick facing (outer layer) and concrete masonry unit with an effective U value of 0.33, the roof construction is changed to normal weight concrete wall with insulation (R6), and ground construction is kept same as the prototype building model. The windows are replaced with double pane with U value of 0.6 and solar heat gain coefficient of 0.6. The HVAC system of the prototype packaged terminal air conditioner (PTAC) with 3 cooling coil gross rated coefficient of performance (COP) and gas fired hot water type central boiler heating with coil efficiency of 80%. The cooling setpoint of model is fixed as 24℃ and that of heating setpoint is 21.1℃.

The annual average infiltration rate of the model is set to 1.15 air change per hour (ACH). Removed all windows on the east and west side of the model, except the entrance.

2.2 ENVELOPE UPGRADE

The Envelope Upgrade model is model where the building envelope of the Baseline is retrofitted with HS retrofit panel with R-25 thermal insulation. The existing window is also replaced with a triple-pane window with U-value of 0.15 Btu/(h.ft^2.ºF) and solar heat gain coefficient of 0.25. This model was developed so the energy savings that comes only from envelope retrofit, and the HS system could be differentiated. In this model, the as result of envelope retrofit, the air infiltration into the building was reduced from 1.15 ACH to 0.2 ACH.

2.3 HYDRONIC SHELL

Hydronic shell is modeled by replacing the HVAC system of the "Upgraded Envelope" model to mimic hydronic shell system i.e. convective coil in the cavity between the existing wall and retrofit façade layer and the fan coil unit with vent located at window-sill .

Figure 3. Vent in the window-sill from where the fan in the HydroBox blows conditioned air to space

The model for this system was created by modeling two systems in EnergyPlus 1) radiant system 2) unit ventilator.
Radiant system: For the radiant system "*ZoneHVAC:LowTemperatureRadiant:Constant*" flow object was utilized which could be used for both heating and cooling using hydronic pipe embedded in the wall construction. The hydronic pipe in this case was located in the air cavity between the existing masonry wall and the hydronic shell retrofit panel (with R-25 insulation).

Unit Ventilator: A unit ventilator was modeled to represent the Hydrobox fan coil unit using "*ZoneHVAC:UnitVentilator*" object. The until ventilator utilized hydronic coils for both heating and cooling along with fan for water-air heat exchange and also to supply air to the space.

Python EnergyPlus plugin was utilized the use these two systems to represent the HS system. First for sequence of equipment operation, the radiant system was used as the primary system and the unit ventilator was used as secondary system which was only used when the radiant system could not meet the space load. The inlet water flowrate and temperature to the unit ventilator was set to be same as outlet water flowrate and temperature of the radiant system. The flow rate and temperatures for cooling coils for radiant system and unit ventilator for a zone is shown in Figure 4. The graph is provided for 5 days in January and 5 days in July to depict how the system works during different weather conditions. The radiant system is the primary system and always operating whenever there is a cooling load in the space. The unit ventilator operates when additional cooling was needed and radiant system alone was not able to provide enough conditioning to the space. Figure 4 shows that after July 3, radiant system is in continuous operation i.e. flow rate is always at ~0.08 kg/s but the unit ventilator goes on/off during that period. The unit ventilator when in operation has same inlet temperature as outlet temperature form the radiant system.

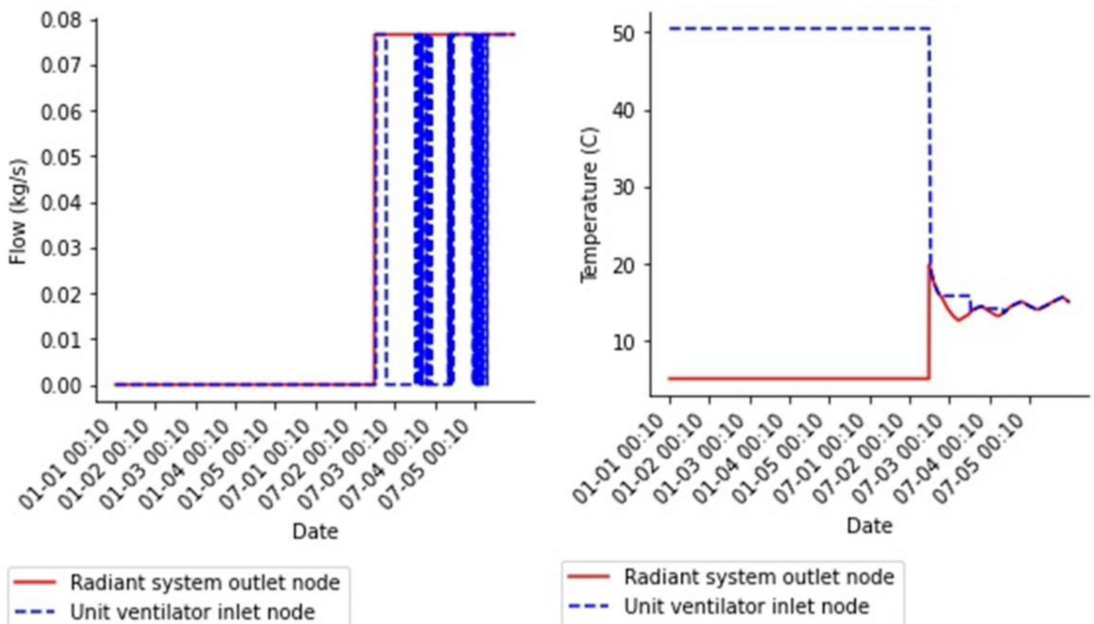

Figure 4. Water flow rate and temperature for cooling coils

The operation of radiant system and unit ventilator for heating is similar to cooling i.e. radiant system is used as primary system and unit ventilator is used to provide supplemental heating. The flowrate and temperature at the outlet of radiant system and the inlet of the unit ventilator is shown in Figure 5. Whenever, the unit ventilator is in operation it’s inlet node flow rate and temperature are same as the outlet node flow rate and temperature for the radiant system.

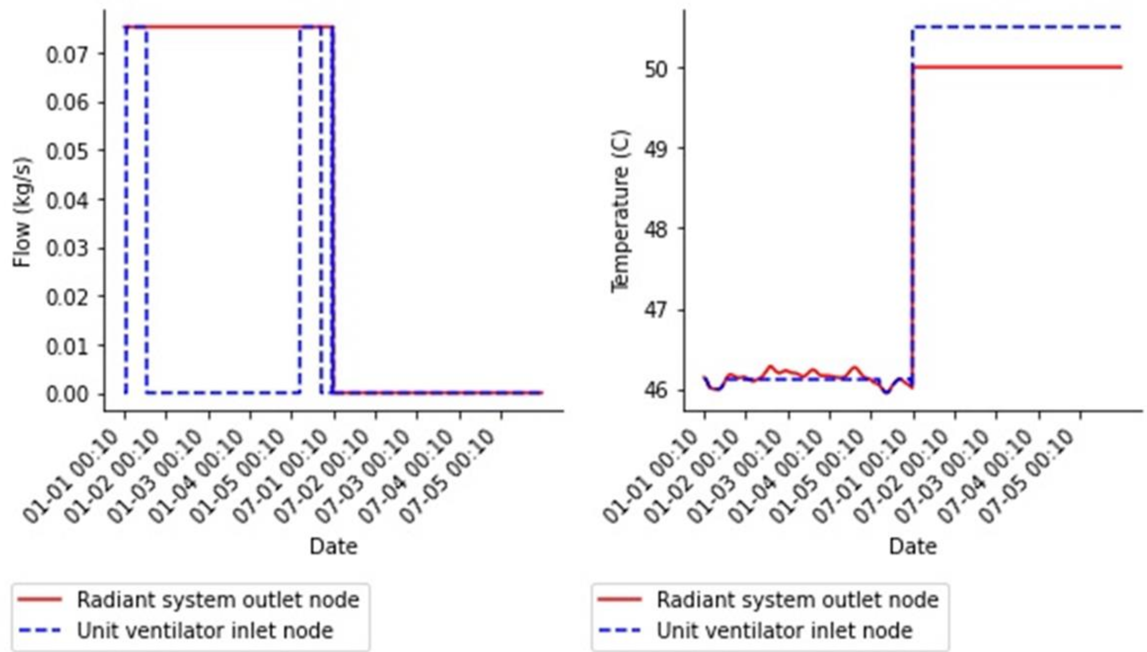

Figure 5. Water flow rate and temperature for heating coils

The fan of the unit ventilator was operating whenever unit ventilator was operating for either heating or cooling. During heating the fan air flow rate was 0.02 kg/s and during cooling the fan air flow rate was 0.08 kg/s (Figure 6). Using the system and operation described above the zone air temperature was maintained between 21 ºC and 24 ºC, as shown in Figure 7 for one of the zones.

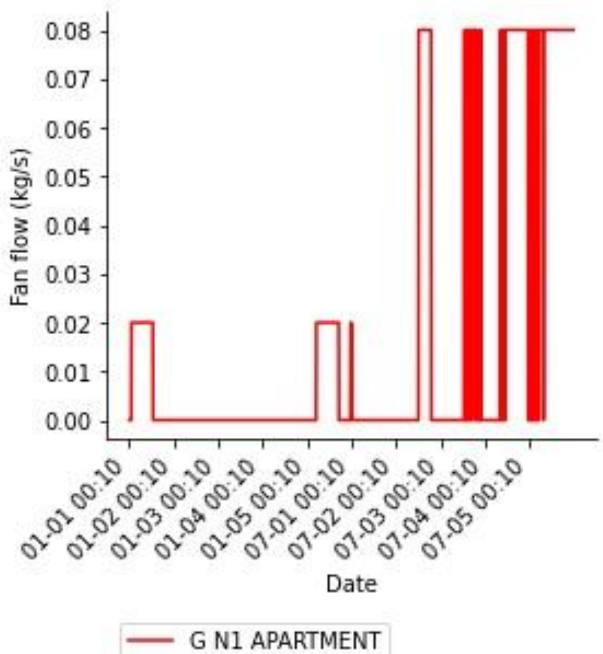

Figure 6. Fan air flow rate in unit ventilator

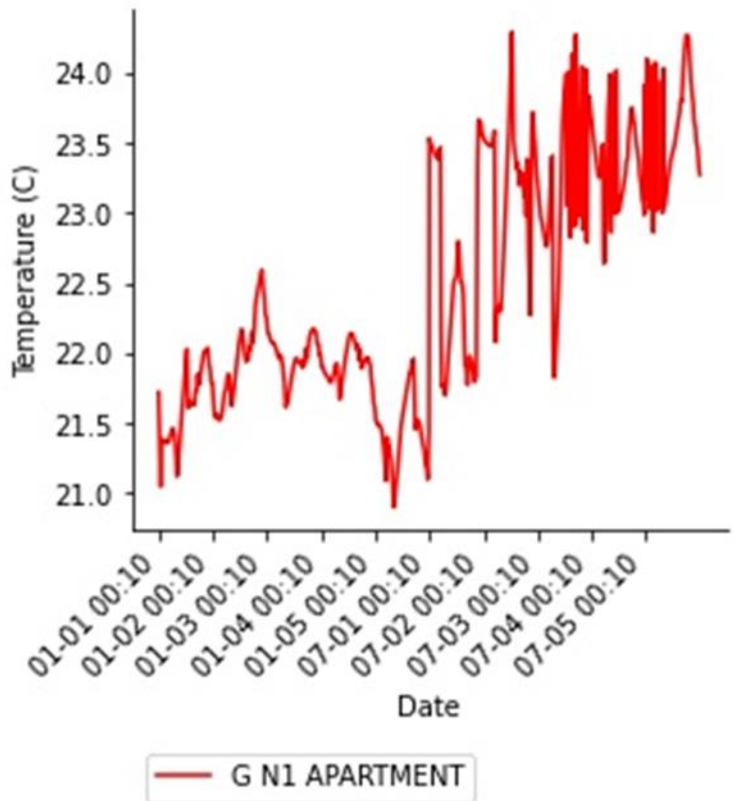

Figure 7. Zone air temperature

3. RESULTS

In this section, the energy consumption, carbon emission and cost analysis are done based on the whole building simulations performed for all four locations. All the results are based on HVAC related electricity or natural gas consumption.

3.1 HEATING AND COOLING ENERGY CONSUMPTION

The results for the site heating and cooling energy consumption is shown in Figure 8. One thing to note in this figure is that the heating for "Baseline" and "Envelope Upgrade" is using boiler which uses natural gas and fuel and "Hydronic Shell" uses electricity driven heat pump for providing both cooling and heating. Hence, a direct comparison of heating for Hydronic Shell case cannot be performed with other two cases. However, since Baseline and Envelope Upgrade both use same heating system it can be seen that significant energy reduction for heating is achieved from envelope retrofitting. The energy consumption in the range of 812-1159 MWh for baseline was reduced to 62-118 MWh after envelope retrofit i.e. resulting in at least 88% heating energy reduction in all four locations.
For cooling all three cases use electricity and Hydronic Shell has significantly lower energy consumption compared to other two cases. When comparing between the Baseline and the Envelope Upgrade, the cooling energy savings from envelope upgrade ranges from 4 to 20 %. The Hydronic Shell reduced the cooling energy from 66 to 75% which is significantly higher compared to only envelope upgrade. The corresponding energy use intensity (EUI) of the building model for all the cases in four locations is provided in Figure 9.

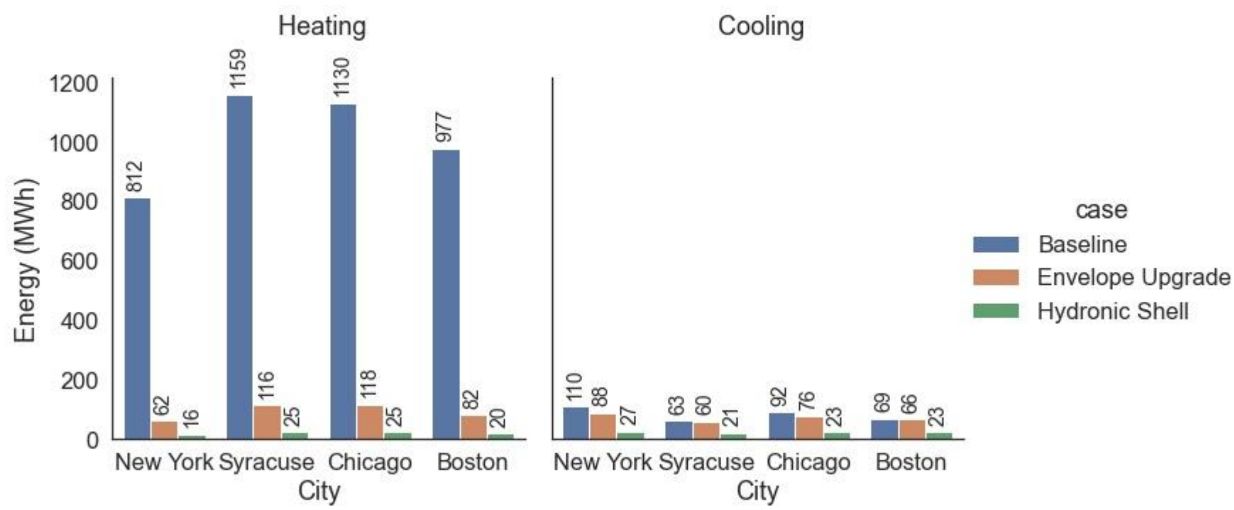

Figure 8. Heating and cooling energy consumption for three cases at four locations

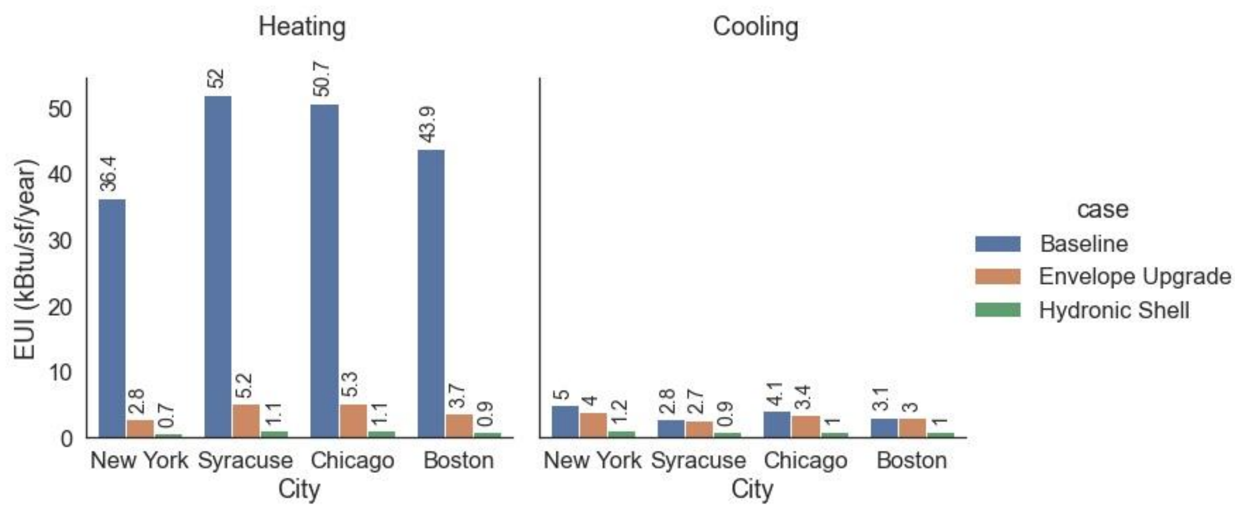

Figure 9. Heating and cooling EUI for three cases at four locations

3.2 PEAK DEMAND

The annual peak demand for total end use for the three cases at the four locations is shown in Figure 10. The peak demand is lowest for the Hydronic Shell which occurs during heating season, and for the Baseline and the Envelope Upgrade during cooling season (because for the latter two cases, the heating is provided using natural gas). Despite using electricity for both heating and cooling the peak demand for the Hydronic shell (101 kW to 106 kW) is approximately half of the peak demand for the Baseline (194 kW to 205 kW) for all locations.

Figure 10. Annual peak demand

3.3 CARBON EMISSION

The HVAC related CO_2 emission for the three cases at four climate locations is shown Figure 11. The CO_2 emission was calculated based on electricity and natural gas consumption for heating/cooling including the energy consumed by fans and pumps. For electricity the emission rate of 0.4173 kg CO_2 per kWh of electricity was used and for natural gas the emission rate of 53.07 kg/MMBtu of natural gas was used (US EPA 2024). The CO_2 emission was reduced by more than 75% just from the envelope upgrade compared to Baseline in all four locations (Figure 12). The use of Hydronic Shell system further reduced the CO_2 emission in the range of 87% to 89%. In absolute value, the maximum CO_2 emission reduction of 219 Metric Tons (MT) was seen for Chicago for Hydronic Shell compared with Baseline (Figure 11).

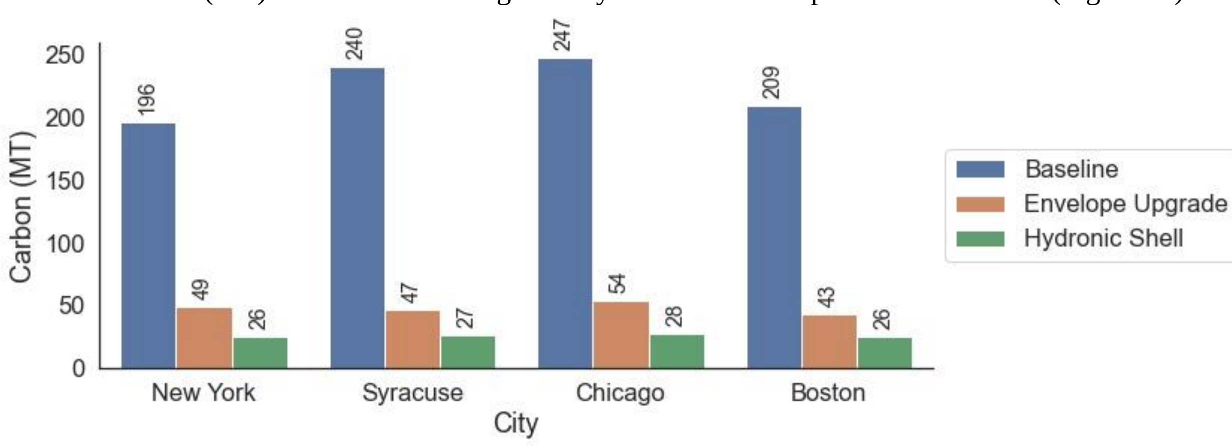

Figure 11. CO_2 emission for three cases at four locations

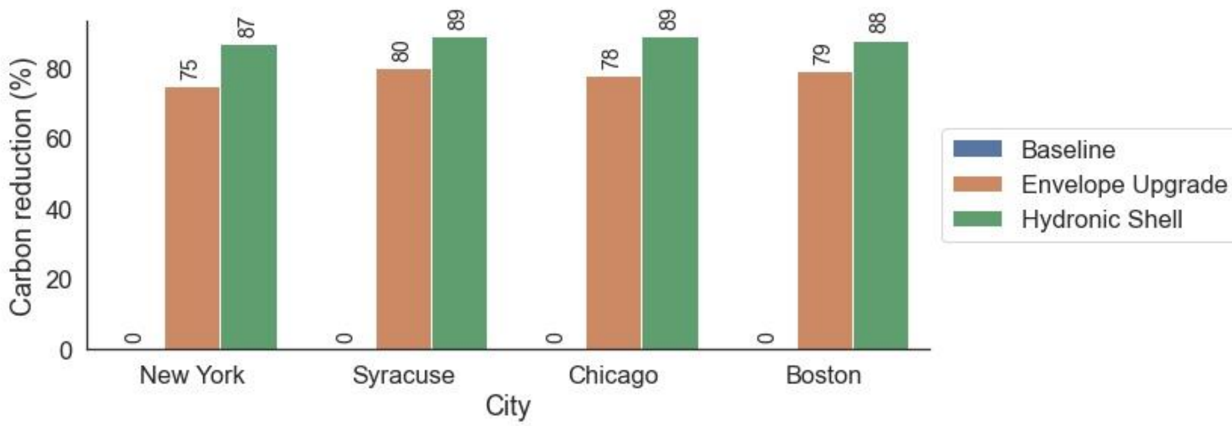

Figure 12. CO_2 emission reduction (%) relative to emission for Baseline

3.4 ENERGY COST REDUCTION

The energy cost reduction was calculated based on reduction in HVAC operation related electricity and natural gas consumption. For all the cases the electricity and natural gas consumption, and the rate of electricity and natural gas for each city shown in Table 2. These rates are annual average rate of electricity and natural gas for residential sector for 2023 (US EIA 2024). The total cost of HVAC related energy consumption (Figure 13) shows significant reduction from both Envelope Upgrade and Hydronic Shell compared to Baseline. The HVAC operation related cost is significantly lower for Hydronic Shell compared to Envelope Upgrade in all the locations. The cost savings per conditioned floor area is shown in Figure 14. The cost savings was in the range of 0.57 to 0.89 $\$/ft^2$ for Envelope Upgrade and 0.66 to 0.99 $\$/ft^2$ for Hydronic Shell compared to the Baseline.

Table 2. Rate of electricity and natural gas

Location	New York	Syracuse	Chicago	Boston
Electricity rate ($/kWh)	0.2225	0.2225	0.1582	0.294
Natural gas rate ($/1000 ft^3)	16.9	16.9	11.54	21.28

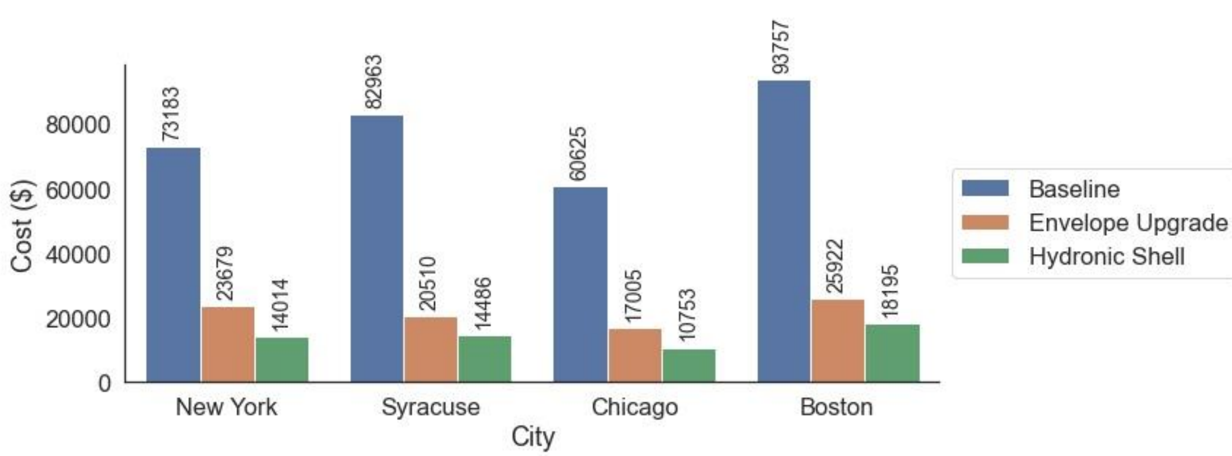

Figure 13. Total cost of HVAC related electricity and natural gas consumption

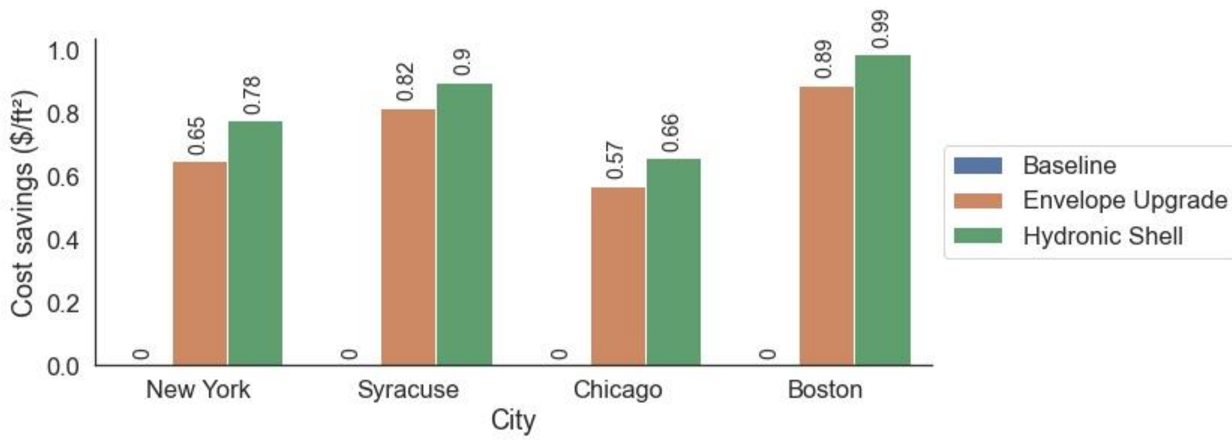

Figure 14. HVAC related cost savings per total conditioned area

4. CONCLUSIONS

Whole building energy simulation model was developed for a Hydronic Shell system which includes a HVAC distribution unit integrated with envelope retrofit. The simulation was run for Baseline case and one case only with Envelope Upgrade in addition to the Hydronic Shell system at four locations of New York, Syracuse, Chicago and Boston. EnergyPlus python plugin was used to mimic the operation of HydroBox unit by using a combination of radiant system and unit ventilator in EnergyPlus. The results from the simulation showed more than 66% cooling energy reduction and more than 88% heating energy reduction from Hydronic Shell retrofit compared to baseline building in all four locations. In addition, more than 50% peak electrical demand reduction from Hydronic Shell retrofit compared to the baseline. This reduction in energy consumption resulted in up to 219 MT reduction (i.e., 87 to 89% reductions) in annual CO_2 emission. The cost reduction per floor area achieved from HVAC energy consumption reduction using Hydronic Shell retrofit was 0.66 to 0.99 $\$/ft^2$. The results also showed higher percentage of heating energy reduction comes from the envelope only retrofit and higher percentage of cooling energy reduction comes from the retrofit HVAC system for the four locations.

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6. REFERENCES

U.S. Department of Energy. 2024a. "Decarbonizing the U.S. Economy by 2050: A National Blueprint for the Buildings Sector." https://www.energy.gov/eere/decarbonizing-us-economy-2050-national-blueprint-buildings-sector.

———. 2024b. "EnergyPlus V24.1." 2024. https://energyplus.net/.

US EIA. 2020. "Residential Energy Consumption Survey." 2020. https://www.eia.gov/consumption/residential/data/2020/index.php?view=microdata.

———. 2024. “Electricity Data Browser.” 2024. https://www.eia.gov/electricity/data/browser.
US EPA. 2024. “Greenhouse Gas Equivalencies Calculator.” 2024. https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator.