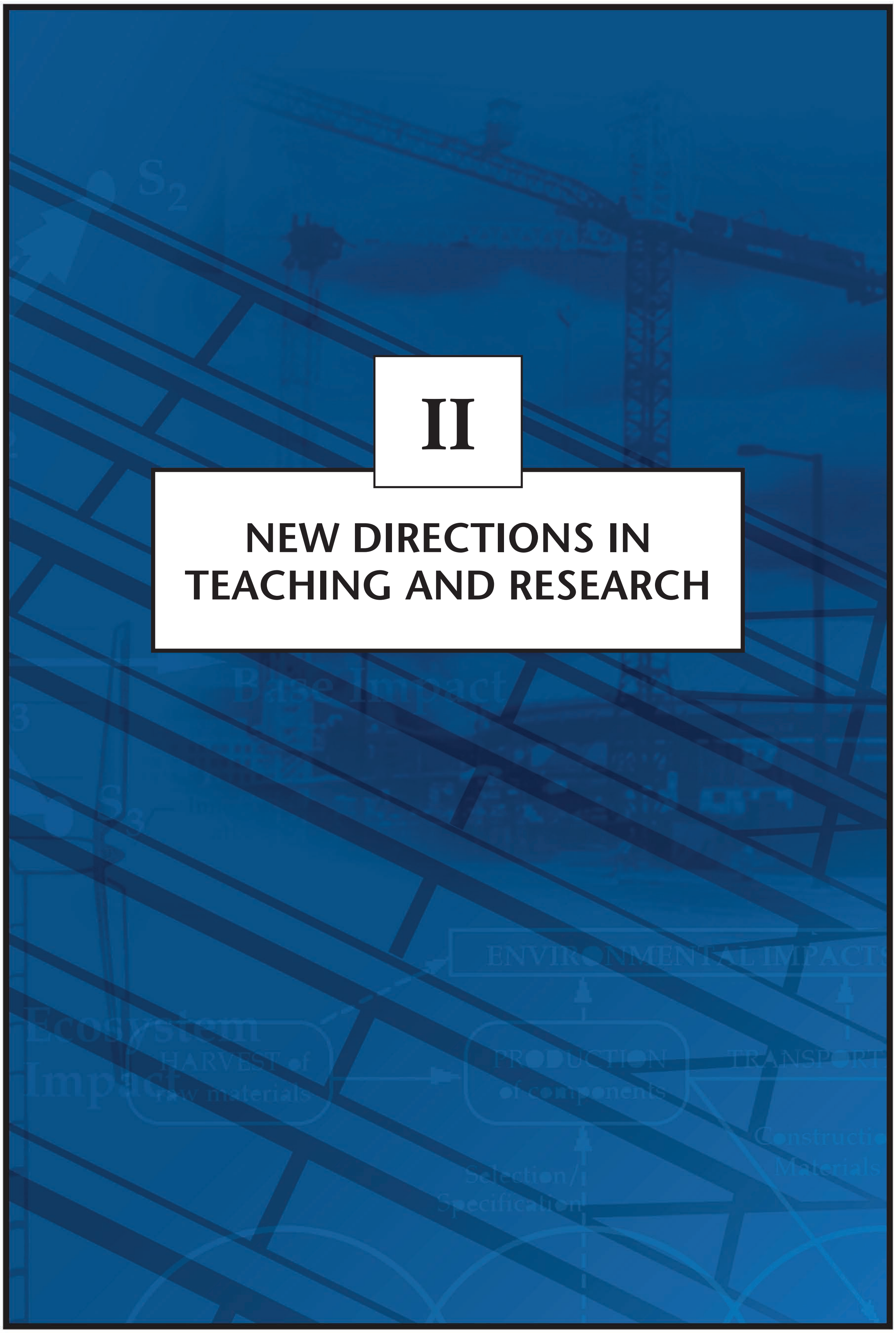

II

NEW DIRECTIONS IN TEACHING AND RESEARCH

PERFORMANCE EVALUATION OF SHIPPING CONTAINER POTENTIALS FOR NET-ZERO RESIDENTIAL BUILDINGS

Laura Battaglia[1] and Jeehwan Lee[2]

ABSTRACT

Recycled shipping containers have the potential to be successfully used as a net-zero ready home. This study aims to evaluate the outcomes of a high-performance shipping container single-family housing project located in Virginia Beach, Virginia. The project was awarded the Best Undergraduate Project in the Single-family division at the 2019 U.S. Department of Energy's Solar Decathlon Design Challenge.

The Hampton University Millennial Village Design Team designed a marketable net-zero ready container home for the ViBe Creative District in Virginia Beach, Virginia. Container Homes are not suitable for every homeowner, but they have a particular appeal to a generation of young and creative people across the country. For many municipalities in Virginia, where container housing is not readily accepted, the ViBe creative district has been having discussions with City code officials and local architects about the benefits. The Hampton University Millennial Village Design Team aimed to take advantage of the competition as an opportunity to explore a building construction method that is not widely seen in this part of the country. Testing design for net-zero readiness is a comprehensive way to understand how this type of construction performs from a building science standpoint. Collaboration with professional industry advisors helped the team to use research-based design methods to work on a unique project that the team believes will become a reality in the future.

For the performance assessment of a net-zero container house, several simulation tools were used to investigate the environmental impacts, daylight performance, envelope performance, Energy Use Intensity (EUI), Home Energy Rating System (HERS), and solar energy generation. As for energy standards and codes, the Virginia residential code (VRC) 2015, International Energy Conservation Code (IECC) 2015 and The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) 90.1-2013 for residential buildings were consulted to set each variable for the net-zero container house project. The Rem/Rate energy simulation software achieved the HERS index of 51 and 0 without and with the applications of roof photovoltaics, respectively.

KEYWORDS

shipping container, Net-zero house, Energy performance, Department of Energy's Solar Decathlon Design Challenge

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1. INTRODUCTION

The U.S. Department of Energy (DOE) Solar Decathlon is a collegiate competition, comprising 10 contests that challenges student teams to design and analyze highly efficient and innovative buildings powered by renewable energy, targeting energy performance, engineering, financial affordability, resilience, architecture, operation, market potential, indoor environmental quality, and innovation [1]. In 2019 the Hampton University Millennial Village Design Team's marketable net-zero ready container home for the ViBe Creative District in Virginia Beach was awarded for "Outstanding Undergraduate Achievement in the category of the single-family house project," creating a design for low-cost, zero-energy ready homes, built out of recycled shipping containers.

The Hampton University Millennial Village Design Team proposed a modular design, becoming an essential part of today's real estate portfolio because it can be more sustainable than traditional construction methods. The modularity of shipping containers makes it possible for each container to join together to form larger spaces. Depending on client demands, the modular container systems can be used for all types of spatial use such as living room, kitchen, bathroom, bedroom, and studio. In addition to that, it can be prefabricated with the insulation, doors, windows, water piping, electrical wiring, lights, kitchen, bathroom, heating and cooling equipment, furniture, and so forth to save time, labor, and energy. Modularity and prefabrication allow container design to be organized, consistent, and sequential through design, permitting, manufacturing, installing, and final buildout. Each of the five containers was intended to be built separately with most of the architectural components installed in the shop: walls (interior and exterior), wall and ceiling drywall, insulation, windows and doors, and electrical and plumbing lines. Modifications to the container structure are minimal [2–4].

2. BACKGROUND

2.1 Environmental Conditions

Virginia Beach (latitude/longitude: 36.9° North/76.2° West) is part of climate zone 4A located in a mixed-humid climate. This region receives more than 20-inch (50 cm) of annual precipitation, has approximately 5,400 heating degree days (65°F basis) or fewer, and where the average monthly outdoor temperature drops below 45°F (7°C) during the winter months. Climate data from the weather station in Norfolk international airport near Virginia Beach provides temperature range, radiation range, wind velocity range, sun shading chart, dry bulb temperature in a psychrometric chart. To achieve thermal comfort over the year in this climate zone, the Climate Consultant software recommends passive and active design strategies such as i) natural and fan-forced ventilation cooling (30%), ii) heating, and humidification if needed (26%), iii) internal heat gain (23%), iv) sun shading of windows (15%), and cooling and dehumidification if needed (13%) [5].

The City of Virginia Beach has actively taken steps to develop a healthy environment and a strong economy that contributes to the well-being of people in the community by adopting the STAR Community Rating System to evaluate local sustainability and resiliency. However, Virginia Beach is susceptible to hurricanes and flooding—second only to New Orleans for vulnerability to sea-level rise. The 2009 Virginia Beach Comprehensive Plan recognizes sea level rise as a primary concern for not only Virginia Beach but also for the entire Hampton Roads region. According to the Virginia Institute of Marine Sciences (VIMS), sea-level rise is expected to be 1.5 feet higher for the area over the next 20 to 50 years. Container housing offers a resilient solution to hurricane and sea-level rise threats that are ever-present in Virginia Beach. We will be elevating the containers two feet above grade and exploring connections that will be able to resist the 120 mph winds during a hurricane [6–7].

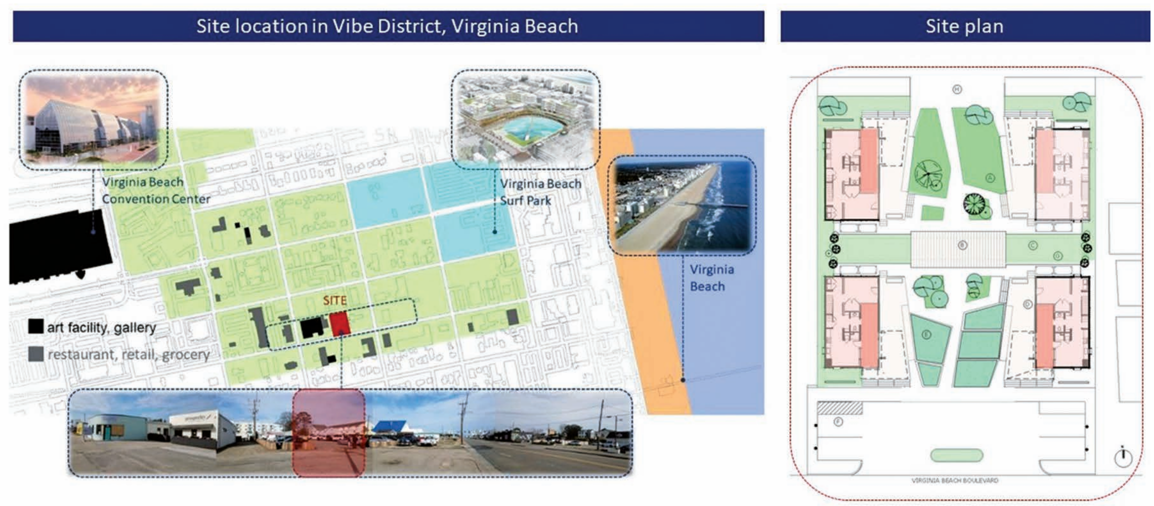
2.2 Site

In Virginia Beach, shipping containers abound in the Hampton Roads area, home to the nation's third-largest and busiest shipping port—the Port of Virginia. In 2018 alone, the four main facilities of the Port of Virginia, all located in Hampton Roads, moved a total of 1,612,760 container units. Although containers have been widely used on the west coast and in the southwest regions of the United States, they are a recyclable, modular, structurally sound, and a cost-effective solution to housing on the east coast [8].

The overall lot is along the main vehicular route—Virginia Beach Boulevard—and backs up to what will become a pedestrian thoroughfare. Located across from the acclaimed farm to table restaurant—Commune—and their sister bakery Prosperity, it has high visibility within the neighborhood. Currently, an abandoned lot, the vision is for four live/work container units, on individual 3,735 SF lots, to be located around a central gathering space and rain garden. The north and south end of the homes can be customized by murals to fit in with the aesthetic of the ViBe, and act as billboards to promote small business ventures that may be happening within the village.

The Millennial Village site is located along a future pedestrian corridor featured in the ViBe District Connectivity Plan as shown in Figure 1. The purpose of this plan is to provide a vision for critical pedestrian and bicycle connections between ViBe business and community destinations. The proposed street infrastructure improvements are needed to achieve the goals of the ViBe District by helping to attract and foster creative business, grow real estate values, stimulate commerce, and enhance the quality of life for citizens and visitors.

FIGURE 1. Site location (left) and site plan (right).



3. PERFORMANCE

3.1 Architectural Design

A preliminary design of the site was an effort in finding the right balance between engineering and architecture. The site strategy was decided after evaluating orientation options. This site initially allowed for an ideal southern exposure for building footprints that were oriented E-W (option A below). Each container unit was oriented along with North-to-South so that they could face a central gathering space that would allow for community interaction and vibrancy. Knowing that one container limits the width to less than 8′0″ we decided that three shipping containers on the main floor created the most efficient and comfortable use of space. We reduced the 2nd floor to two shipping containers to take advantage of passive ventilation through the east and west windows. Virginia Beach has a mild climate for much of the year, and the strategically placed windows and doors will allow the house to be passively ventilated as shown in Figure 2.

Simplicity is the key to all architectural design decisions. The second-floor bedroom layout is precisely the same as one another. They are large enough to include a king-size bed but to still feel comfortable. They are also large enough for two twin size beds to accommodate children or guests.

Establishing the proper adjacencies allows the house to function on both a private and public level without restricting the flow. The main door to the workspace maintains a separation when desired while keeping natural light extending into the kitchen through the clerestory windows in the wall that separates these two spaces. In both plans, the stacked mechanical/bathroom core exists as a compact unit as shown in Figure 3.

3.2 Building Envelope

One of the biggest challenges in using the unconventional construction method of shipping containers, especially in a mixed climate, was moisture control. To prevent any air and moisture infiltration into the exterior wall assembly, the team minimized the percentage of penetrations into the wall assembly, which is insulated to the interior of the existing container structure with closed-spray form insulation as shown in Figure 4. Penetrations around the windows were sealed using a galvanized steel "hood" at each opening that features a fully welded perimeter

FIGURE 2. Plan drawings (left) and a perspective view (right).

FIGURE 3. Plan Adjacencies.

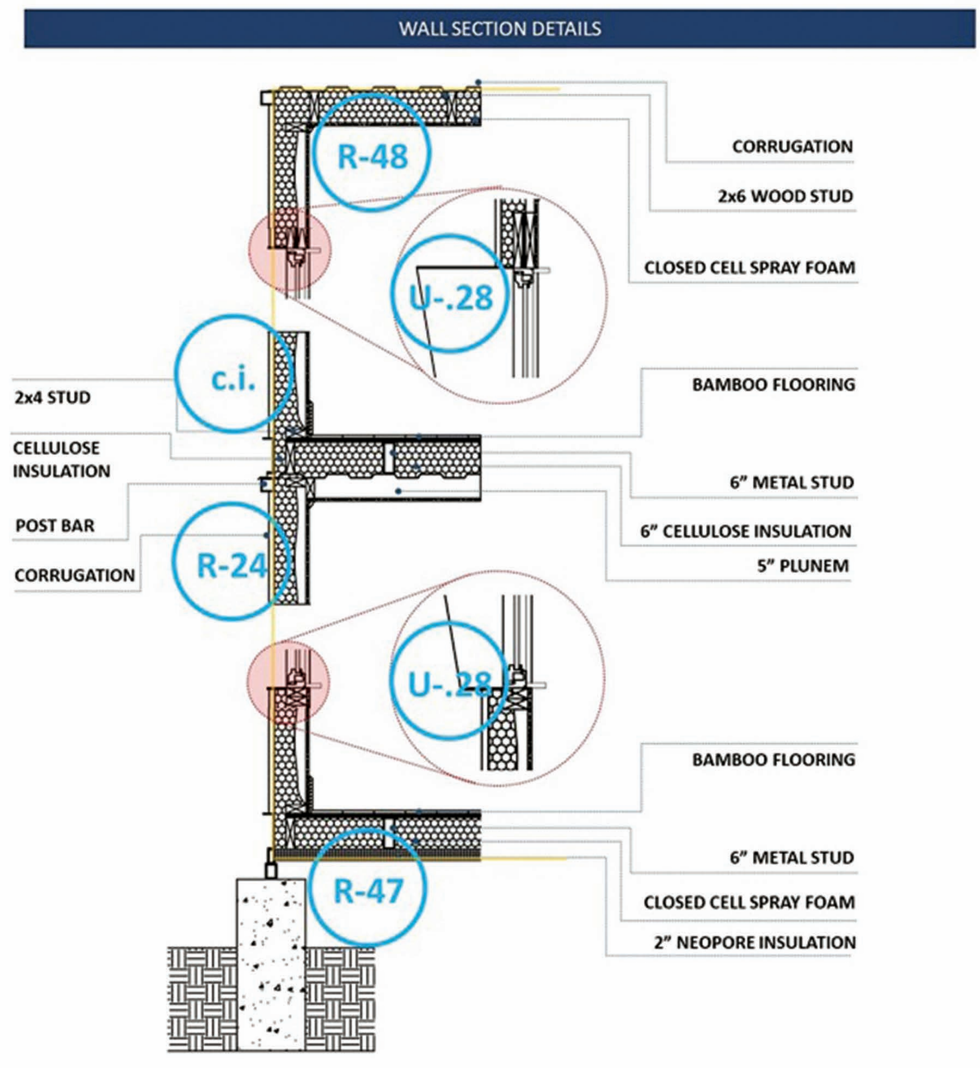
joint. The exterior was painted white to prevent additional heat transfer through the exterior wall assembly, and shade was provided on the roof from the P.V. solar array, the west side-2nd floor deck by the trellis, and the 1st floor by the canopy structure.

Moisture control: Shipping container building envelopes tend to be sealed with less unintentional ventilation. If the moist air is not exhausted properly, it can be trapped indoors, causing a cumulative increase in relative humidity over time in a sealed building. Holes and cracks in walls and crawl space by piping lines can allow entrance to more than just air. Water and moisture can also gain access to these areas through exposed cracks and holes if not sealed properly. Applied closed cell spray insulation to walls, roofs, and floors of a shipping container house is 100% moisture impermeable which eliminates drafts, heat loss, and moisture into indoor spaces.

Noise control: Cellulose Insulation consists of 65–75% recycled content and works to reduce noise, either by impeding the transmission of sound through an element of the structure or by absorption of sound at the surface. This cellulose soundproofing insulation is a sustainable alternative to traditional fiberglass and synthetic acoustical and thermal panels [9–10].

Thermal control: One of the most energy-consuming processes affecting shipping container energy usage is heat transfer through the building envelopes. Thermal bridging takes place when a section of a wall system has a higher conductivity than the surrounding material. Therefore, Indoor environmental quality control is one of the hardest parts of a shipping container house for dwelling satisfaction and comfort of building occupants. We decided on

FIGURE 4. Wall section drawing.

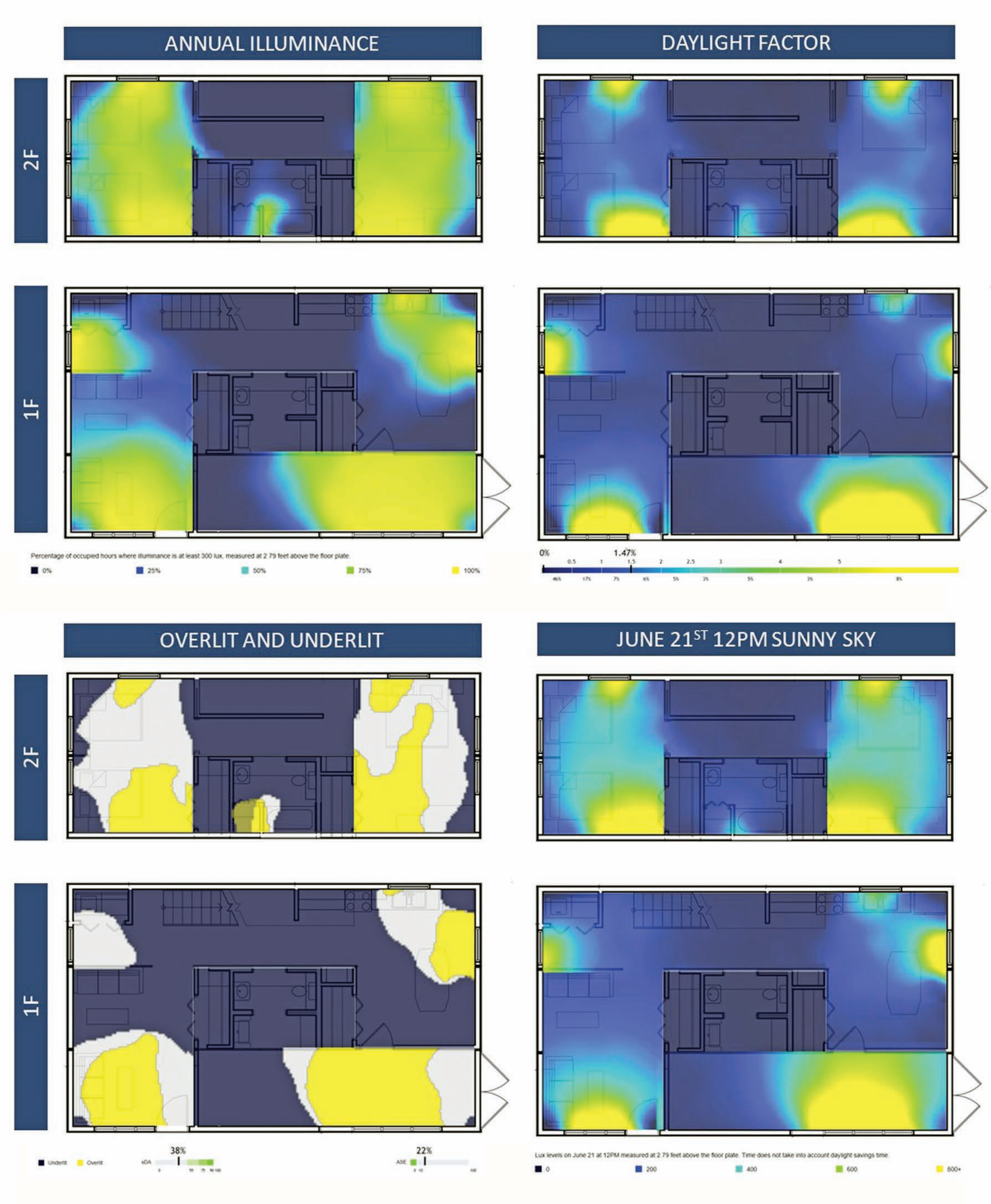


a continuous insulation layer with closed cell spray foam, enabling the building envelope to break heat transfer by unwanted air infiltration rate. The R values for roof, wall, and floor are higher than the requirements of the 2015 International Energy Conservation Code (IECC) for climate zone 4 [11].

3.3 Daylighting and Indoor Lighting

Sefaria software visualized daylighting performance, including annual illuminance levels, daylight factor (D.F.), and overlit and underlit as shown in Figure 5. The range of daylight factor for bedrooms, living room, kitchen, and the work area was between 2% and 3% that seem to have adequate daylight although electric lighting might be needed for some tasks [12]. However, potential visual discomfort was found near areas of windows and doors based on the simulation outcome of overlit and underlit. As a solution, window overhangs and adjustable shading devices on the deck area were applied facing South and East.

FIGURE 5. Daylight Performance.



In Table 1 and Figure 6, Dialux simulated the ambient indoor lighting distributions for visual comfort based on the Illumination Engineering Society of North America (IESNA) with Ligman's ceiling mounted LEDs for room areas and downlight LEDs for corridors. The annual illuminance of bedrooms, living room, kitchen, and work area was achieved by a recommended 300 lux during the entire year. The simulation outcomes show an average of 250 lux and 100 lux for room areas and corridors, respectively [12].

TABLE 1. Recommended Illumination Levels By IESNA and Dialux.

Room type	Light level (FC)	Light Level (Lux)	Power(W)
Bedroom	20–50 FC	200–500 lux	1F and 2F: 8W, 62.5 lm/W
Corridor	10–20 FC	100–200 lux	1F: 8W, 62.5 lm/W
Living room	20–30 FC	200–300 lux	1F: 14.5W, 137 lm/W
Kitchen	30–75 FC	300–750 lux	1F: 14.5W, 103 lm/W
Bathroom	20–50 FC	200–500 lux	1Fand 2F: 10W, 150 lm/W
Work area	330–50 FC	300–500 lux	1F: 16W, 156 lm/W

3.4 Energy Performance

According to the U.S. Energy Information Administration, residential electricity consumption consists generally of space cooling (17%), and heating (15%), water heating (14%), lighting (10%), and electric appliances (44%). Sefaira quantified building energy performance for the schematic phase of the design process. Iterative gauging window-to-wall ratios, orienting building façade, improving building envelope performance, and estimating proper mechanical systems not only showed design clues but also led to the advanced evaluation of building energy performance [13].

FIGURE 6. Indoor Lighting Simulation.

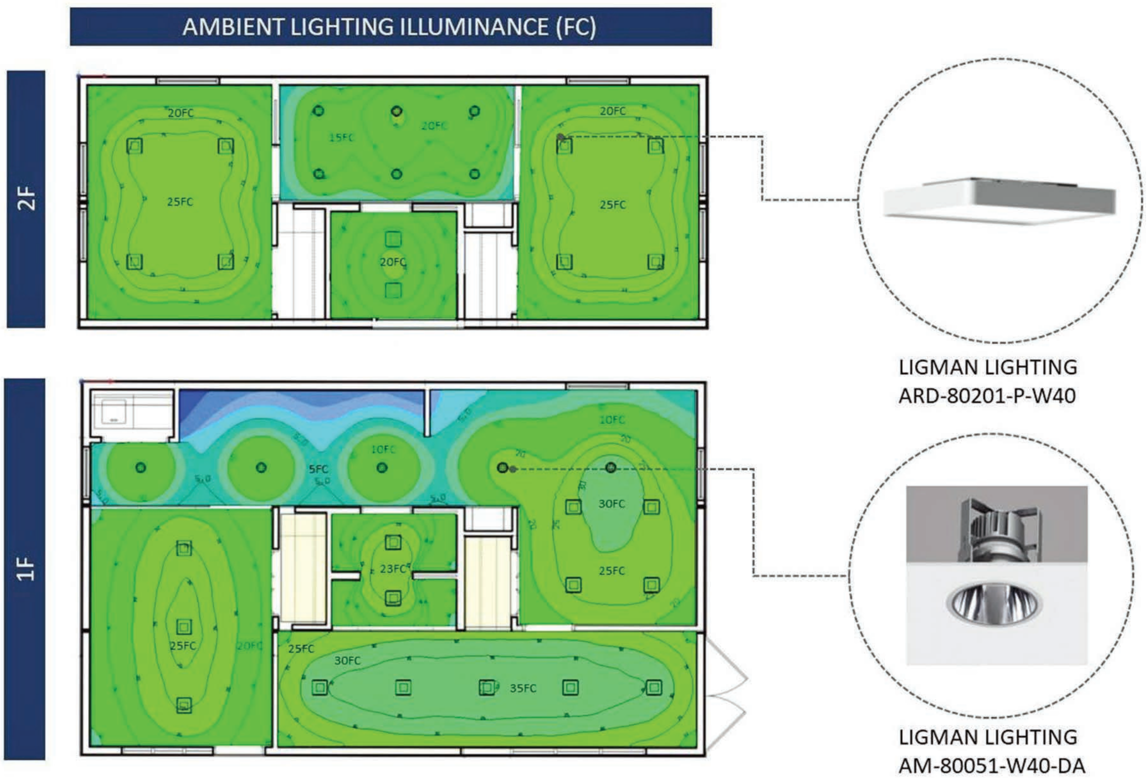
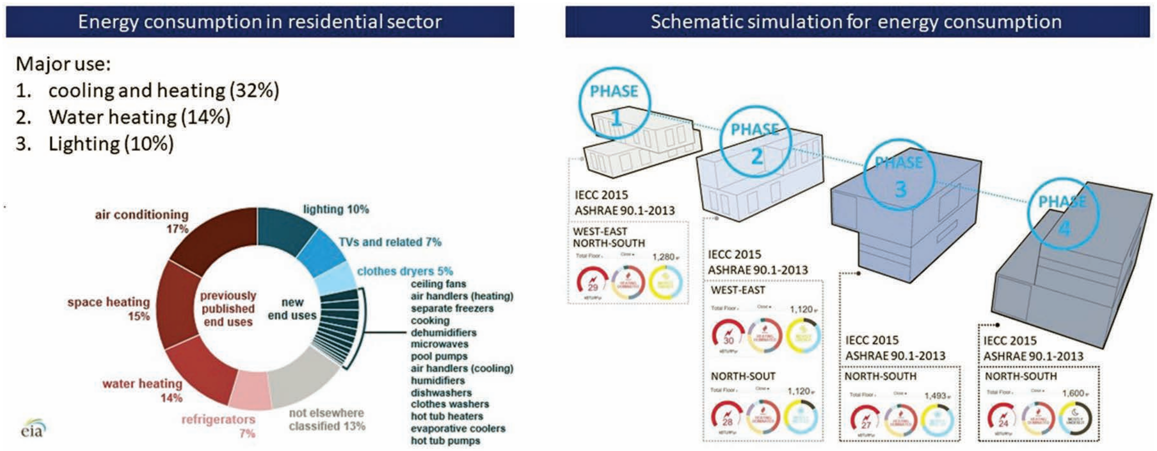


FIGURE 7. Energy Consumption (left) and Schematic Energy Simulation (right).



Sefaira provided opportunities to create real-time performance feedback using the EnergyPlus engine. Sefaira simulation showed the EUI of 24 kBTU/ft^2/yr (energy consumption), and PVWatts Calculator produced the electricity of 25 kBTU/ft^2/yr (energy generation) to make the net-zero shipping container live/work home. A series of energy simulation showed energy use intensity (EUI) ranging from 24 kBTU/ft^2/yr to 29 kBTU/ft^2/yr based on space volume, orientation, and wall R-values as shown in Figure 7 [14].

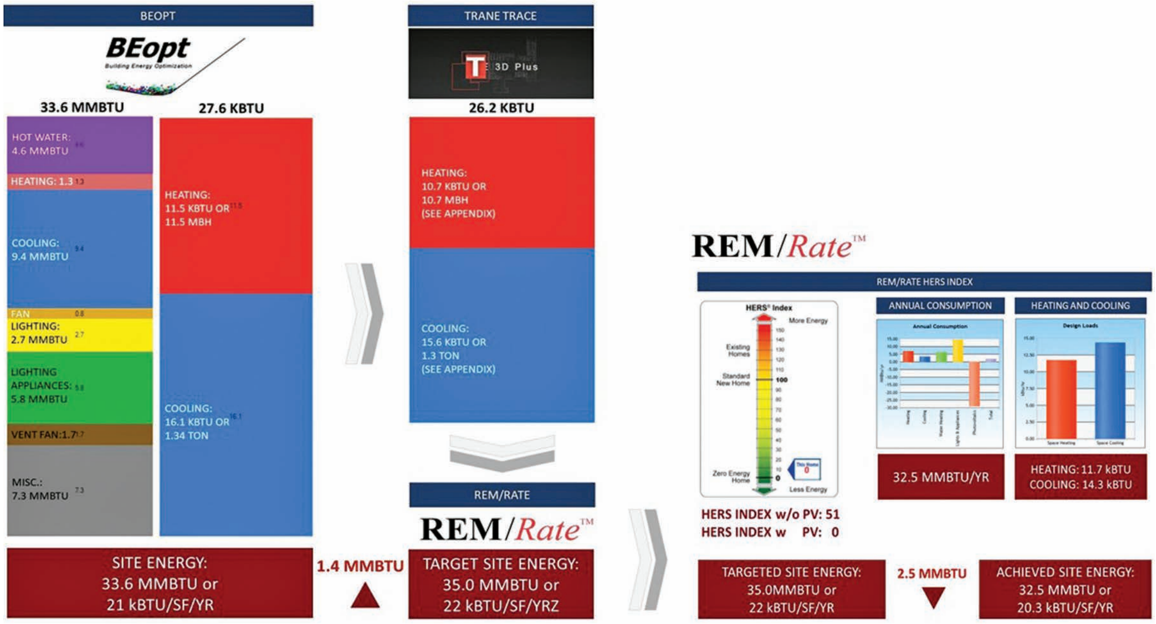
As supplemental energy modeling tools in Figure 3, BEopt™ (Building Energy Optimization Tool) and Trane TRACE 3D software were used to assess HVAC system performance, building design, and energy performance. The results from BEopt™ included 33.6 MMBtu (21 kBTU/ft^2/yr) as the total energy consumption and 27.6 kBtu for heating and cooling energy use. TRACE 3D Plus produced a total of 26.2 kBtu for heating and cooling energy use which is similar to the results from BEopt™ [15–16].

The Home Energy Rating System (HERS) Index is the industry standard for a home's energy efficiency. The lower the number means the more energy-efficient the home. The U.S. Department of Energy has determined that a typical resale home scores 130 on the HERS Index while a standard new home is awarded a rating of 100 [17]. For instance, a home with a HERS Index Score of 70 is 30% more energy-efficient than a standard new home and a home with a HERS Index Score of 130 is 30% less energy efficient than a standard new home. Based on energy simulation using Rem/Rate, the HERS index of 51 was achieved without photovoltaics and 0 with photovoltaics as shown in Table 2 and Figure 8.

3.5 Renewable Energy and Grid Integration Capabilities

In Figure 9, The team employed smart meters not only to operate with smart grids digitally but also to allow for automated and complex transfers of information between a user's home and energy provider. Smart meters deliver signals from energy providers that assist users in cutting energy costs. They also provide utility companies with information about electricity usage throughout their service areas. With the integration of advanced computing and communication technologies, smart meters are expected to enhance the efficiency and reliability of future power systems with renewable energy resources, as well as distribute intelligence and demand response.

FIGURE 8. Comparison of Heating and Cooling Energy By BEopt, Trance Trace, and Rem/Rate.



In Table 3 and Figure 10, eighteen solar panels (LG Neon) with efficiency between 18.6% and 19.5% were applied to the roof of this container house. The Inverter (Solaredge System) generates renewable energy between panels which results in a 2% greater yield. The communication from the optimizer to the inverter passes through the D.C. string wiring, so it is unaffected by mains harmonics along the communication lines. These harmonics are caused by electrical appliances such as dimmers, washing machines, and microwaves. Based on the amount of solar energy generation using PVWatts and SolarEdge, both solar energy estimators showed similar outcomes of about 9,600 kWh/year (32,700 kBtu/year) [18–19].

3.6 Mechanical and Plumbing Design

In Figure 11, the applied multistage heat pump is effective in running at different capacities to increase comfort levels and boost efficiency. A two-stage system (Trane XV20i) was used for better comfort and higher efficiency than a single-stage system. It also runs at lower speeds for longer periods of time, offering advanced temperature control, lower humidity,

TABLE 2. Comparison of Heating and Cooling Energy by Each Energy Simulation Tool.

Variable	BEopt	Trane Trace 3D	Rem/Rate
Heating energy (A)	11.5 kBTU	10.7 MBh	11.7 kBTU
Cooling energy (B)	16.1 kBTU	15.3 MBh	14.6 kBTU
Heating and Cooling (A)+(B)	27.6 kBTU	26.0 MBh	26.2 kBTU
Ventilating (CFM)	NA	773 CFM for cooling and heating each	N.A.

FIGURE 9. Smart Grid Integration to the Site

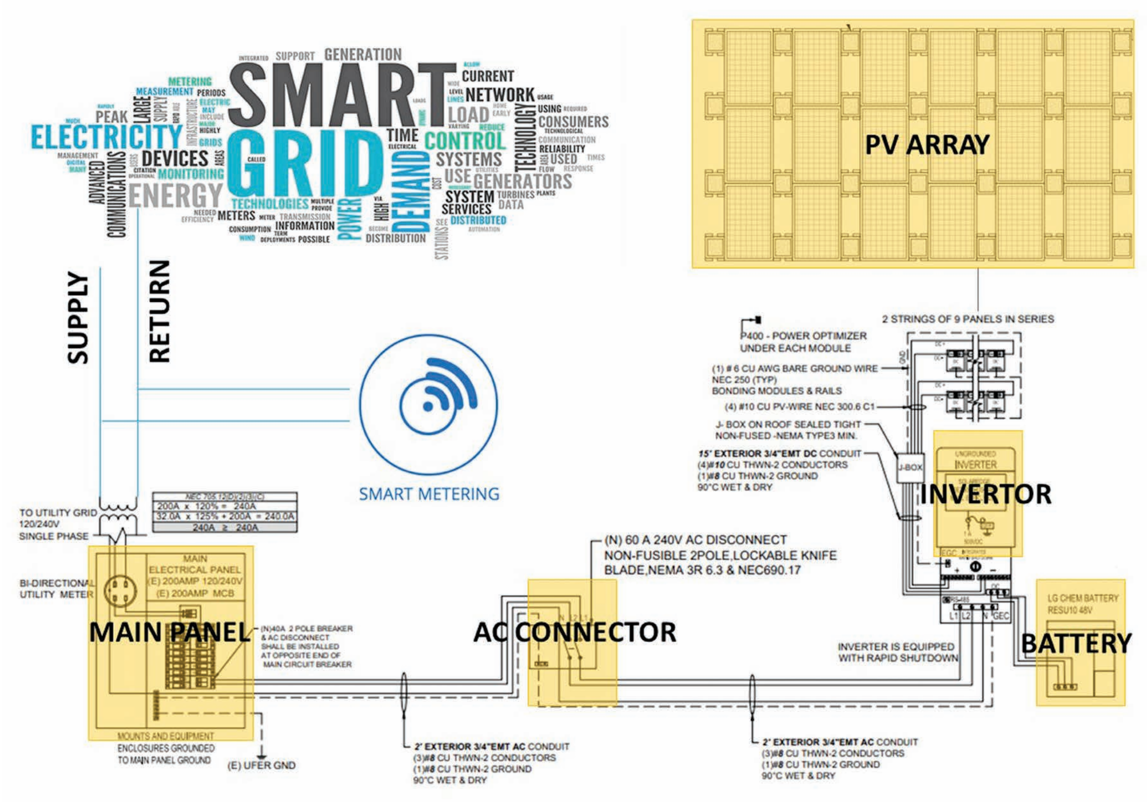


TABLE 3. Photovoltaic Specifications.

Item	Specification	Item	Specification
Total number of modules	18	Bay weight (lbs)	98
Module (W) / Dimension (inch)	365 / 67” × 40”	Module weight (lbs)	734
Total area (ft^2)	456	Ballast weight (lbs)	2496
Total kW in DC system (KW)	6.2	Average weight (lbs/ft^2)	6.40
Inverter (%)	98	Power optimizer (%)	99.5

FIGURE 10. PV Arrays (left) and Solar Energy Generation (right).

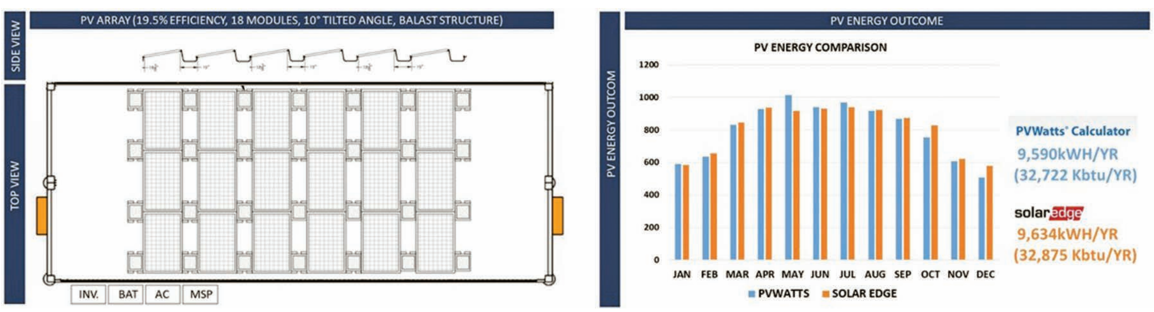
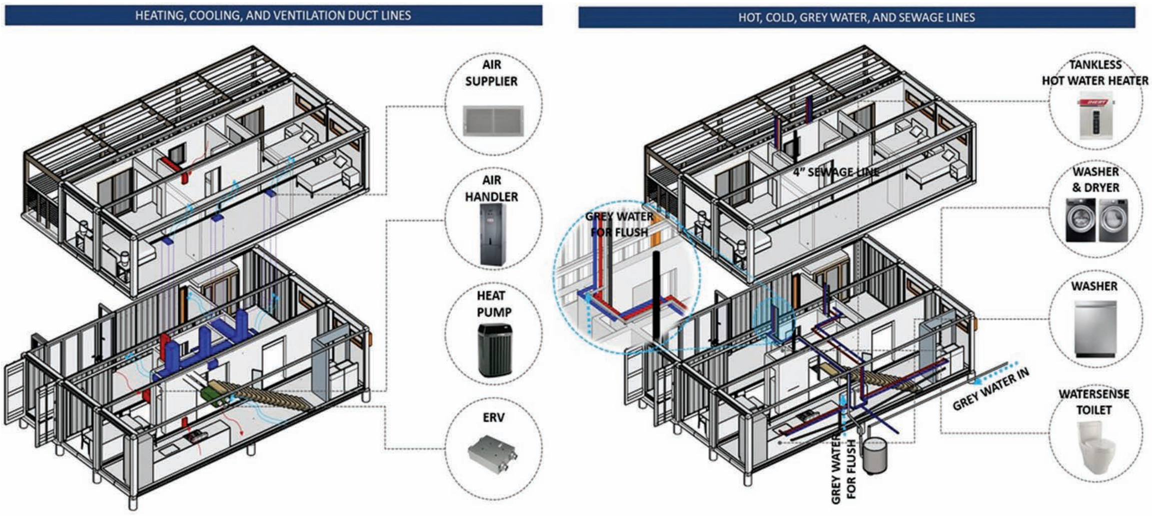


FIGURE 11. HVAC Units (left) and Water Pipe Lines (right).



reduced sound, enhanced filtration, and lowest cost per minute. The mechanical system with a SEER (Seasonal Energy Efficiency Ratio) of 19 and HSPF (Heating Seasonal Performance Factor) of 9.5 was designed to offer thermal comfort [20]. A fully insulated air handling unit (Hyperion™TAM7A0A24) and Nest Thermostat smart home system control indoor temperature, allowing owners to manage their home's heating and cooling remotely [21].

For heating, cooling, greywater, and sewage pipelines, there are several considerations for heat transfer, efficiency, noise, and safety. When the temperature difference between a pipe (and the pipe's contents) and the ambient air is significant, the heat loss and gain from the piping can be considerable. Adding a layer of insulation will minimize heat loss, gain cycle, and prevent wasting energy to make up for lost or gained energy. As a possible solution, adding a layer of insulation to piping and valve assemblies prevents the detrimental problems that can occur if water freezes within the pipes. Besides, structural noise has a sneaky way of traveling through pipework, so insulating piping and valves is a valid method to reduce noise. It acts as an acoustic decoupler by preventing noise transfer when pipes pass through a fixed structure such as a floor or wall and lower the noise of the materials moving through the systems.

Therefore, all pipes in wet walls with the closed-cell are insulated and capsulated based on the U.S. Department of Energy recommendation for insulating hot water pipes with a minimum R-value of 3 [22]. Used water and sewage lines are ½″ and 4″ in diameter, respectively with more than an R-value of 3. Tankless water heaters are designed to heat incoming water at a maximum output temperature based on simultaneous use and inlet water temperatures. IHeat Electric Tankless Water Heater Model S-16 has the capacity of heating 3.5 GPM which is equivalent to 2 showers (at 1.5 GPM each) and 1 sink (at 0.50 GPM each) running simultaneously or any combination equating to 3.5 GPM. S-16 can power a 3 to 4 bedroom 2-1/2 bathroom home, including a dishwasher and clothes washer [23].

4. CONCLUSION

The Hampton University Millennial Village Design Team designed a marketable net-zero ready container home for the ViBe Creative District in Virginia Beach. The Team proposed a modular design of the net-zero shipping container house. Through this project, the team has investigated the potentials of shipping containers for net-zero residential buildings as sustainable human habitats. Depending on client demands, the modular container systems can be used for all types of spatial use such as living room, kitchen, bathroom, bedroom, and studio.

At the schematic phase of building design and energy modeling, Sefaira simulation showed the EUI of 24 kBTU/ft^2/yr (energy consumption) depending on the number and orientations of shipping containers, window-to-wall ratios, and envelope materials applied to shipping containers. PVWatts Calculator produced the electricity of 25 kBTU/ft^2/yr (energy generation) to offset energy consumption and energy generation. A series of energy simulation showed energy use intensity (EUI) ranging from 24 kBTU/ft^2/yr to 29 kBTU/ft^2/yr based on space volume, orientation, and wall R-values.

BEopt™ (Building Energy Optimization Tool) and Trane TRACE 3D software were used to assess HVAC system performance, building design, and energy performance. The results from BEopt™ included 33.6 MMBtu (21 kBTU/ft^2/yr) as the total energy consumption and 27.6 kBtu for heating and cooling energy use. TRACE 3D Plus produced a total of 26.2 kBtu for heating and cooling which is similar to the results from BEopt™. The Rem/Rate energy simulation software achieved the HERS index of 51 and 0 without and with the applications of roof photovoltaics, respectively.

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