INTEGRATED ARCHITECTURAL AND ENGINEERING DESIGN STRATEGIES FOR A ZERO-ENERGY BUILDING:

Illinois Institute of Technology's Design Entry for the 2018 U.S. Department of Energy Race to Zero (Solar Decathlon Design Challenge)

Edoarda Corradi Dell'Acqua,[1] Jaime Marin,[2] Eric Wright[3]

ABSTRACT

This paper describes the design of InterTech, a zero-energy mixed-use student residence hall, developed in 2018 by an interdisciplinary team of Illinois Institute of Technology (Illinois Tech) students for the U.S. Department of Energy Solar Decathlon Design Challenge, formerly known as Race to Zero. The main focus is the team's integrated and iterative approach, which blended architectural design and engineering concepts and led to achieving the high-performance goal.

InterTech aims to provide an innovative housing solution to Illinois Institute of Technology's graduate students and their families. Located along State Street in between Illinois Tech's main campus and downtown Chicago, it offers a mix of living options providing both independence and access to the campus and to the city. In addition to the residential program, the project includes a small grocery/cafe connected to an outdoor public plaza, and an underground garage. Energy modeling was introduced in the early design stages. The potential of on-site renewable energy generation defined the project's target Energy Use Intensity (EUI) of 37 kBtu/sqft. Several passive and active strategies were implemented to reduce the building's total energy needs and meet the target EUI. The implementation of energy conservation measures led to a 25% reduction of the building's cooling load and a 33% reduction of the heating load. A design EUI of 28 kBtu/sqft was calculated, validating that this design met and exceeded the zero-energy goal.

KEYWORDS

zero-energy buildings, integrated design, high-performance buildings, renewable energy systems, energy analysis, mixed-use buildings, student housing

1.M.S., Lecturer, Department of Civil, Architectural and Environmental Engineering, Armour College of Engineering, Illinois Institute of Technology, Email: ecorradi@iit.edu.

2.CEM, ME Mechanical & Aerospace Engineering, Illinois Institute of Technology, Email: jmarin1@hawk.iit.edu.

3.LEED Green Associate, ME Architectural Engineering, Illinois Institute of Technology, Email: ewright7@hawk.iit.edu.

1. INTRODUCTION

1.1 Project background

Since 2016, eight teams from the Department of Civil, Architectural, and Environmental Engineering (CAEE) at Illinois Institute of Technology (Illinois Tech) have been finalists in the U.S. Department of Energy Solar Decathlon Design Challenge, formerly known as Race to Zero. The Solar Decathlon Design Challenge is an annual international student design competition that challenges participants to develop the project of a zero-energy building. This paper focuses on Illinois Institute of Technology's design entry for the 2018 Race to Zero competition. The project, titled InterTech, was presented at the National Renewable Energy Laboratory (NREL) in Golden, Colorado, on April 20–22, 2018, and it was awarded second place in the Small Multifamily Housing contest.

InterTech is a zero-energy solar-powered mixed-use residence hall providing off-campus housing to Illinois Institute of Technology's graduate students in Chicago. InterTech's design was developed as an academic project by an interdisciplinary team of Illinois Tech students in two graduate courses, "Net Zero Energy Home Design I & II," offered as a sequence in the fall and spring semesters by the CAEE Department. The design team consisted of eight students from the departments of Civil, Architectural, and Environmental Engineering (CAEE), Mechanical Engineering (MMAE), and from the College of Architecture (CoA). Team members included Narjes Abbasabadi, Brett Horin, Vitoon Jittasirinuwat, Ajay Kotur, Jaime Marin, Esther Rodriguez, Sergio Arias Solorzano, and Eric Wright. This paper describes the team's holistic and integrated approach to designing a zero-energy high-performance building.

1.2 Integrated principles of architectural and engineering design

InterTech features a well-balanced design that addresses architectural, spatial, and programmatic requirements while meeting the high-performance energy goal. The careful integration of architectural and engineering design concepts led to several instances in which the building's architecture facilitates and benefits from applying passive and active energy conservation and energy generation strategies. The design elements reflecting this integrated approach comprise a naturally ventilated atrium and garage area, the spatial organization of the units' layout and HVAC design, which optimizes access to natural light, and a roof-mounted PV system. Additional passive and active strategies incorporated in the project include a well-insulated and airtight building enclosure, high-efficiency equipment, appliances and fixtures, and a ground source heat pump.

The atrium is a central feature of the building's design; it acts as a connector between the North and South residential wings, which offer two different living options, traditional apartment units and dorm-style living. The purpose of the atrium space is two-fold: it contributes to decreasing the building's energy consumption by enhancing natural ventilation, and it responds to the social, programmatic requirements of a student housing project providing communal spaces for the residents.

Similarly, the design of a split-level on the ground floor was motivated by energy conservation requirements, and at the same time, it benefitted the building's architecture. Raising the South portion of the building four feet above the street level allowed the placement of openings to ventilate the underground garage area naturally. This design decision made it possible to have higher ceilings in the North portion of the building, which hosts a cafe/grocery store, thus enhancing the public space's architectural quality.

The layout of the residential floor plans further highlights the integrated design principles supporting the project. The residential units are arranged along the building's perimeter while the horizontal and vertical distribution and service areas are located in the center. This layout allows for the optimized use of natural light in the living areas. This spatial concept is reinforced and supported by the structural design and HVAC design, which follow the same organizational framework.

Finally, the overall building's shape and massing were influenced by the programmatic elements and energy considerations. The roof's tilt was determined to optimize the PV array and energy generation throughout the year.

1.3 The Design Process

The 2018 U.S. Department of Energy Race to Zero competition determined the project's primary goal of being a zero-energy building. Reaching the zero-energy target requires an iterative design process in which architectural decisions and their impact on the building's energy consumption are evaluated through energy models from the initial design stages. Early collaboration between the architecture and engineering team members was an integral part of InterTech's design development.

After defining the project's scope and analyzing the building site, the first step of InterTech's design process was establishing the potential for on-site energy generation through a roof-mounted photovoltaic system. The estimated amount of annual energy generated by the renewable system determined the building's target Energy Use Intensity (EUI). The following step of the design process involved implementing passive and active energy conservation design strategies that allowed to reduce the building's heating and cooling loads and the overall energy demand below the threshold defined by the target EUI.

2. ARCHITECTURE

2.1 Project Site and Constraints

InterTech aims to provide an innovative housing solution for Illinois Institute of Technology's graduate students and their families. Located just a few blocks North of Illinois Institute of Technology's main campus and providing a mix of living options, this project accommodates the needs of graduate students, who often split their time between work and education, offering both independence and access to the city and Illinois Tech's campus life.

With approximately 9,300 sqft, the rectangular building site is situated in Chicago's Near South Side on the corner of State Street to the East and 24th Street to the North. It faces a one-story building on the South Side, a park on the West, and a two-story brick building and the elevated train line to the East. The lot is close to different public transportation options, including the Chicago "L" and several bus lines. It has easy access to downtown Chicago, Illinois Institute of Technology's main campus and downtown campus, and cultural neighborhoods and destinations such as Chinatown and the Lakefront. A bike lane on State Street connects the site to Illinois Tech's campus and the Chicago Loop. In addition to being a very accessible neighborhood, Chicago's Near South Side has a diverse community with a majority of one-person households and a median age of 36.6,[4] making it an ideal living location for graduate students and young professionals.

4. https://www.cmap.illinois.gov/documents/10180/126764/Near+South+Side.pdf

FIGURE 1: Proposed Project Site and Location.

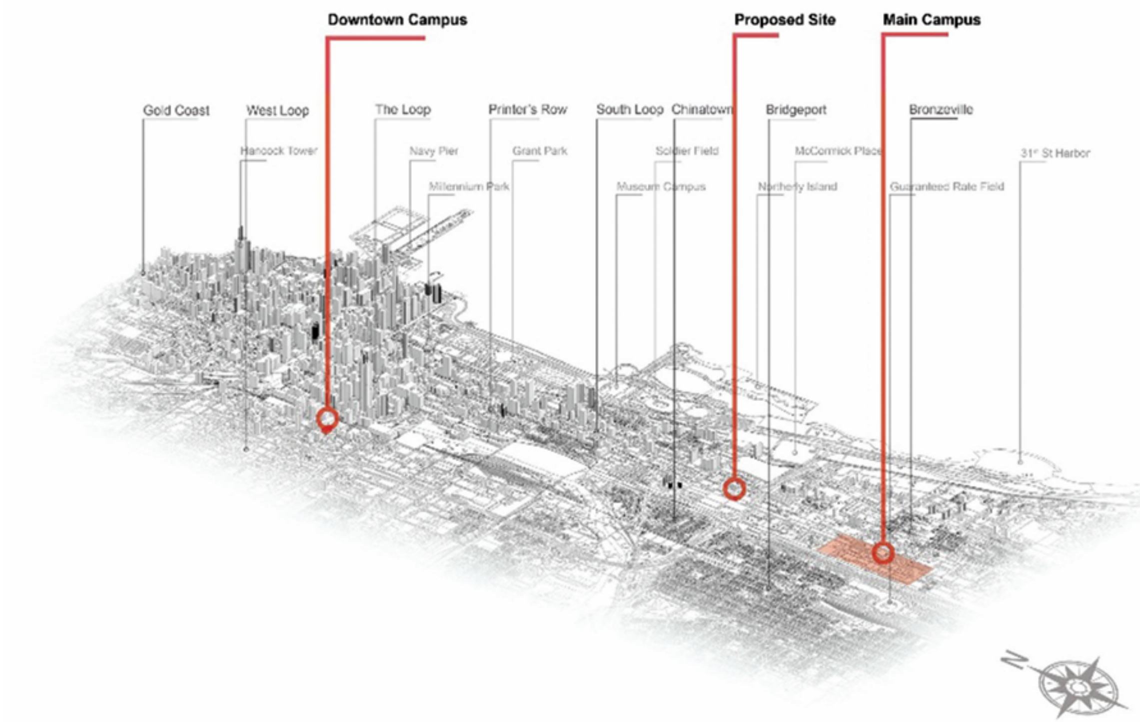
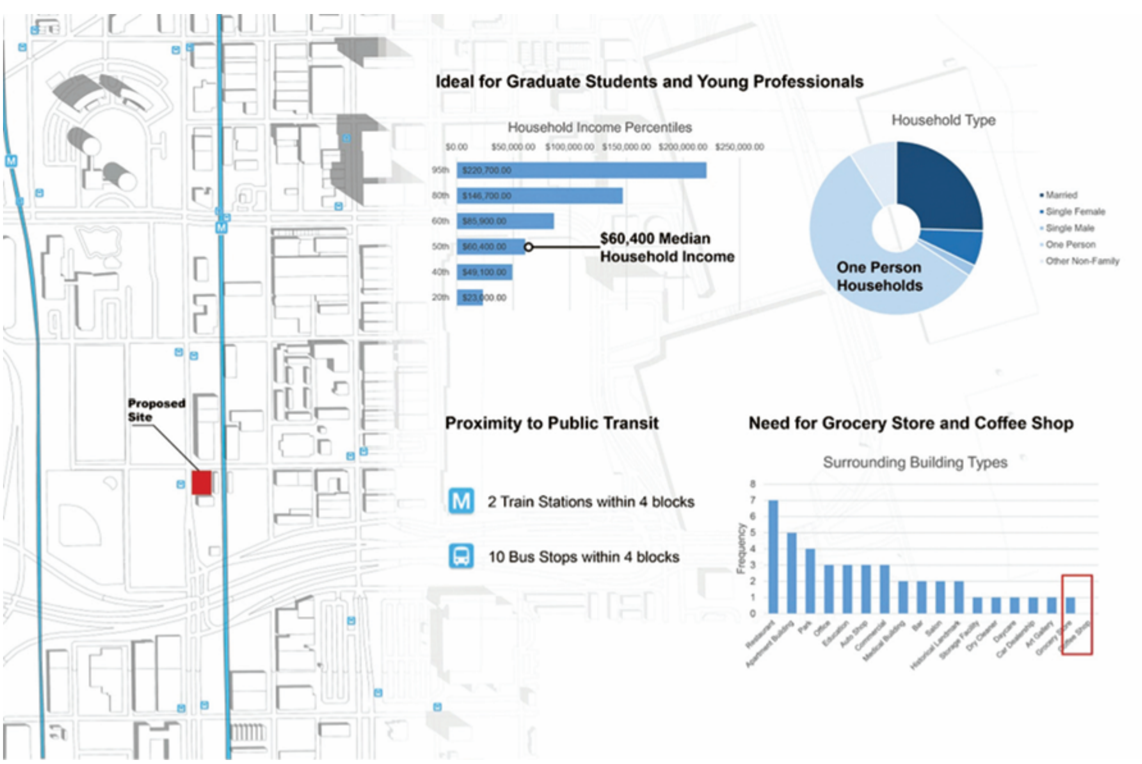


FIGURE 2: Project Site and Site Analysis.



The analysis of the surrounding urban context revealed the need for a grocery store and a coffee shop. This observation informed the decision to add a commercial activity to the residential program. A 1,500 sqft small grocery/cafe selling fresh produce was planned on the North end of the building. This space promotes a healthy lifestyle and serves the building's residents and the neighboring community. A plaza between the cafe/grocery store and the neighboring two-story brick building to the East provides a public outdoor space to the neighborhood. The design of this urban courtyard takes advantage of the 30' rear setback required by the Chicago Zoning Ordinance.

Located close to the elevated rail system and the Stevenson expressway, the site is impacted by high noise levels. For this reason, the building envelope was designed with great consideration for noise attenuation.

2.2 Architectural Design

InterTech features different living options for students, a small grocery and coffee space, an underground garage, and a public outdoor plaza. Its compact massing was informed by energy conservation considerations, zoning code requirements, and the building's scope and program. Located in a dense urban setting, the configuration and orientation of the rectangular 84'x111' urban site determined the building's orientation.

The building consists of two residential wings connected by an atrium. These two sections offer different living options and cater to the needs of graduate students and graduate student families, offering both independent living and shared multi-bedroom apartments. The North wing features two dorm-style units. Each unit is two-story high and includes six single bedroom spaces and a double-height communal living area and kitchen. The South wing offers traditional apartment units and provides a mix of studio, one-, two-, and three-bedroom apartments.

The space layout on the second and third floors with the housing units arranged along the building perimeter while core and circulation spaces are located in the center optimizes access to natural light. The HVAC system's design follows the same organizational structure:

FIGURE 3: Schematic Section.

FIGURE 4: First, Second and Third Floor Plan.

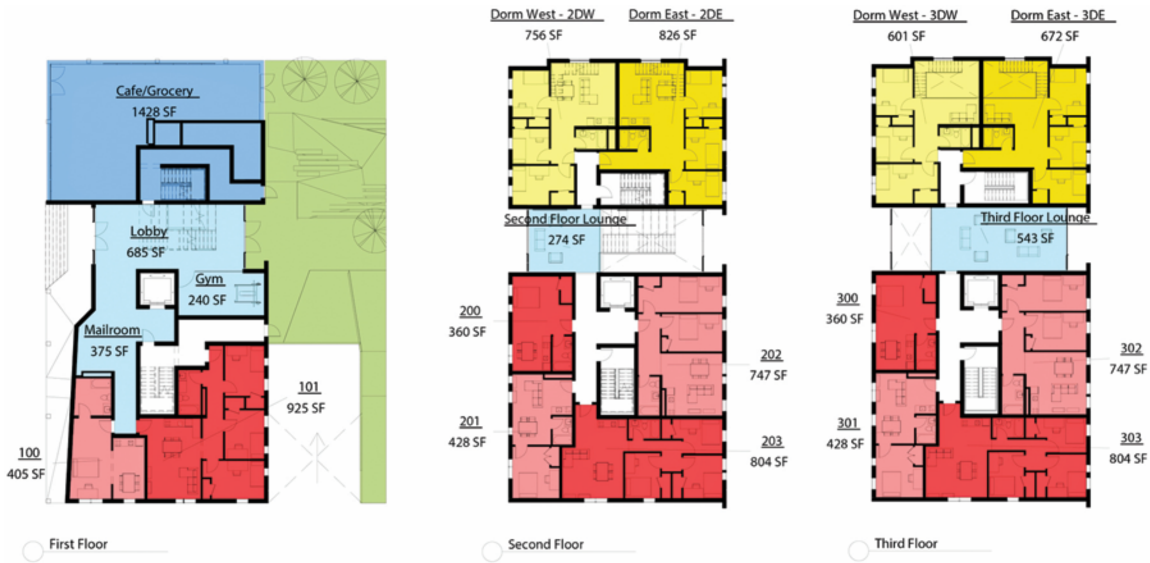


FIGURE 5: 3D Section of Dorm-Style Unit.

FIGURE 6: Dorm-Style Unit Interior Rendering.

the pipes run through the communal hallways that feature a dropped ceiling, while the living areas within the individual apartment units have taller ceilings to maximize the size of windows and access to daylight. On the ground level, the building's North section hosts a small grocery/cafe open to the community, while the South portion is reserved for the residents and features the student housing's main West and East entrances, two apartment units, and amenity spaces such as communal areas/lounges, a gym, and a mailroom.

The project aims to encourage social interaction and collaboration between residents and the surrounding community to enhance social life and support academic success. The three-story-high atrium space connecting the North and South residential wings is a central element of the building's architecture: it provides gathering spaces for the residents and creates a seamless connection between the building's main entrance on State Street and the outdoor plaza on the East. The atrium comprises two staggered double-height spaces—the lobby on the ground level and the second-floor lounge area—and a one-story high communal space on the third floor. A staircase featuring auditorium-style seating and facing the outdoor plaza connects the lobby to the second-floor lounge.

The public outdoor plaza provides additional opportunities for students to interact and socialize while relating to the neighborhood. With two public entrances, one facing the plaza

FIGURE 7: Atrium Space and Public Plaza.

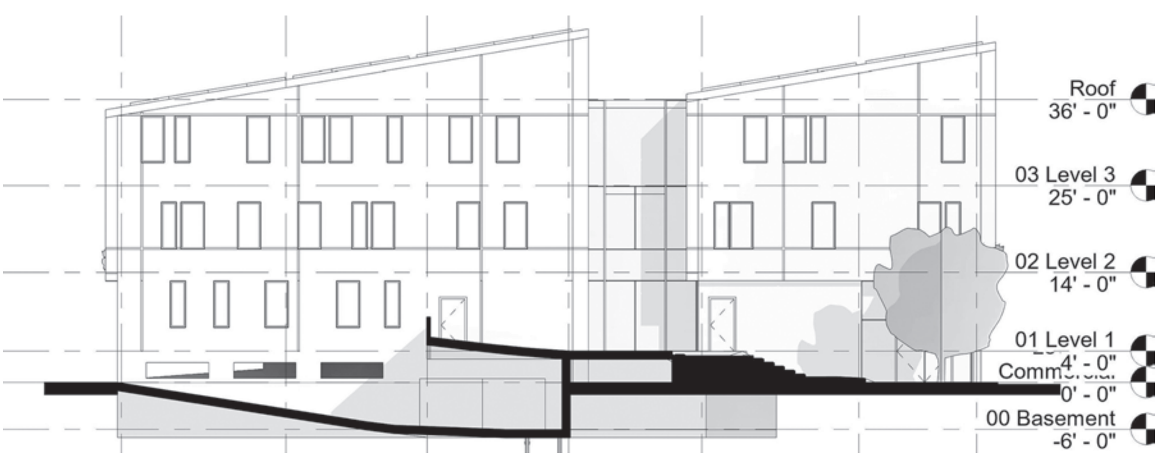
FIGURE 8: Street View of Plaza.

and one on State Street, the cafe/grocery store activates the North corner of the project site and engages the surrounding community.

The Chicago Zoning Ordinance also informed the design of an underground parking lot located under the South portion of the building. A provision of the Chicago Zoning Ordinance allows cutting the parking requirements in half if the garage space is below grade. Providing

FIGURE 9: Café/Grocery Store.

FIGURE 10: Section Through Parking Ramp and Public Plaza.



only half of the required parking spaces promoted a transit-oriented and sustainable lifestyle further supported by the site's proximity to several public transit options.

The biggest challenge presented by the underground parking space was providing sufficient ventilation to flush out the carbon monoxide emissions generated by the cars. Mechanical ventilation is energy-intensive and would have increased the building's energy demand. Thus, the decision to raise the South portion of the building four feet above the street level allowed placing openings along the South, East, and West perimeters of the underground parking space promoting natural ventilation. This design move prompted by energy-saving needs resulted in a split-level on the ground floor. From a programmatic and architectural standpoint, placing the parking space underground and the consequent difference in elevation between the South and North portions of the ground floor provided a series of advantages: It opened up space on the site for the outdoor plaza, it promoted sustainable living, and it resulted in four feet taller ceilings in the cafe/small grocery store.

Despite its off-campus location, InterTech is part of Illinois Institute of Technology. The building is a homage to the architecture of Illinois Institute of Technology's main campus: The windows of the cafe/grocery store were inspired by Ludwig Mies van der Rohe's most famous landmark on Illinois Tech's campus, Crown Hall; the design of the stairway in the outdoor public plaza is reminiscent of the staircase leading to the central dining area of the McCormick Tribune Campus Center (MTCC) designed by Rem Koolhaas of the Office of Metropolitan Archetecture OMA; finally, the InterTech's red color on the facade matches the color of the university logo.

3. ENGINEERING AND ENERGY DESIGN

InterTech's unique architectural characteristics required the development of a creative energy approach. The project features a mix of spaces with different energy consumption profiles and does not fit into a pure residential or commercial building category. This characteristic led to

FIGURE 11: Outdoor Plaza Staircase inspired by OMA's MTCC.

FIGURE 12: InterTech View from Sate Street.

a tailored energy design approach in which different energy conservation measures were analyzed and applied to the individual space profiles and thermal zones according to the desired systems' performance and occupants' comfort. All engineering design decisions were analyzed and evaluated using two energy models: a simulation of the photovoltaic generation system and a whole-building energy model, which accounted for all upgrades of InterTech's envelope and MEP systems' efficiency key parameters.

3.1 PV System Design

The first step of InterTech's energy analysis consisted of determining the maximum annual PV energy generation considering the project's geographic location, orientation, and unique size and configuration. This result determined the building's annual maximum energy consumption and defined the project's target EUI. The PV System sizing and simulation was performed using the *System Advisor Model* (*SAM*). SunPower® X22-360-C-AC modules were selected for the PV system due to the combination of their integrated microinverter technology, their high efficiency, reliability, and module-level DC to AC power conversion.

Once the architectural design and the MEP systems' selection were finalized, several iterations of the on-site generation model were run to determine the final configuration and size of the PV system array. As a result of this analysis, a roof area of approximately 5,800 sqft with 10 degrees tilt was determined. After considering rooftop usage factors, system losses, and efficiencies, the resulting PV system consisted of 272 roof-mounted modules. The ten degrees roof tilt was established to minimize auto-shading effects, thus maximizing the available area for the placement of PV modules. The system featured an array size of 97.92 kW DC and a maximum energy production output of 120,163 kWh. The target EUI, which was calculated to be 37 kBtu/sqft, was considered the most important result of this analysis. Providing the upper limit to InterTech's energy design, the target EUI influenced and informed all engineering design decisions.

3.2 Energy Conservation Strategies and Indoor Environmental Quality

In addition to meeting the zero-energy target, the building's occupants' health and comfort were a primary objective of InterTech's design. A series of passive and active strategies were implemented to reduce the building's heating and cooling loads and improve indoor environmental quality.

Optimal indoor environmental quality was achieved using zero-VOC materials, providing thermal comfort, adequate ventilation, and access to views and daylighting to all living areas. Energy conservation measures included the design of a compact building massing, a well-insulated and airtight building envelope, a naturally ventilated atrium space and underground garage, optimization of natural daylight, the use of high-efficiency equipment, LED light fixtures and ENERGY STAR rated appliances, control systems, outdoor air delivered through dedicated energy recovery ventilators, and a ground source heat pump with variable refrigerant flow units.

The building's efficient spatial layout facilitated the optimization of daylight. A spatial daylight autonomy (sDA) simulation was performed to analyze the amount of daylight in residential

FIGURE 13: Axon Showcasing Typical Finishes, Furniture, Appliances, and Fixtures.

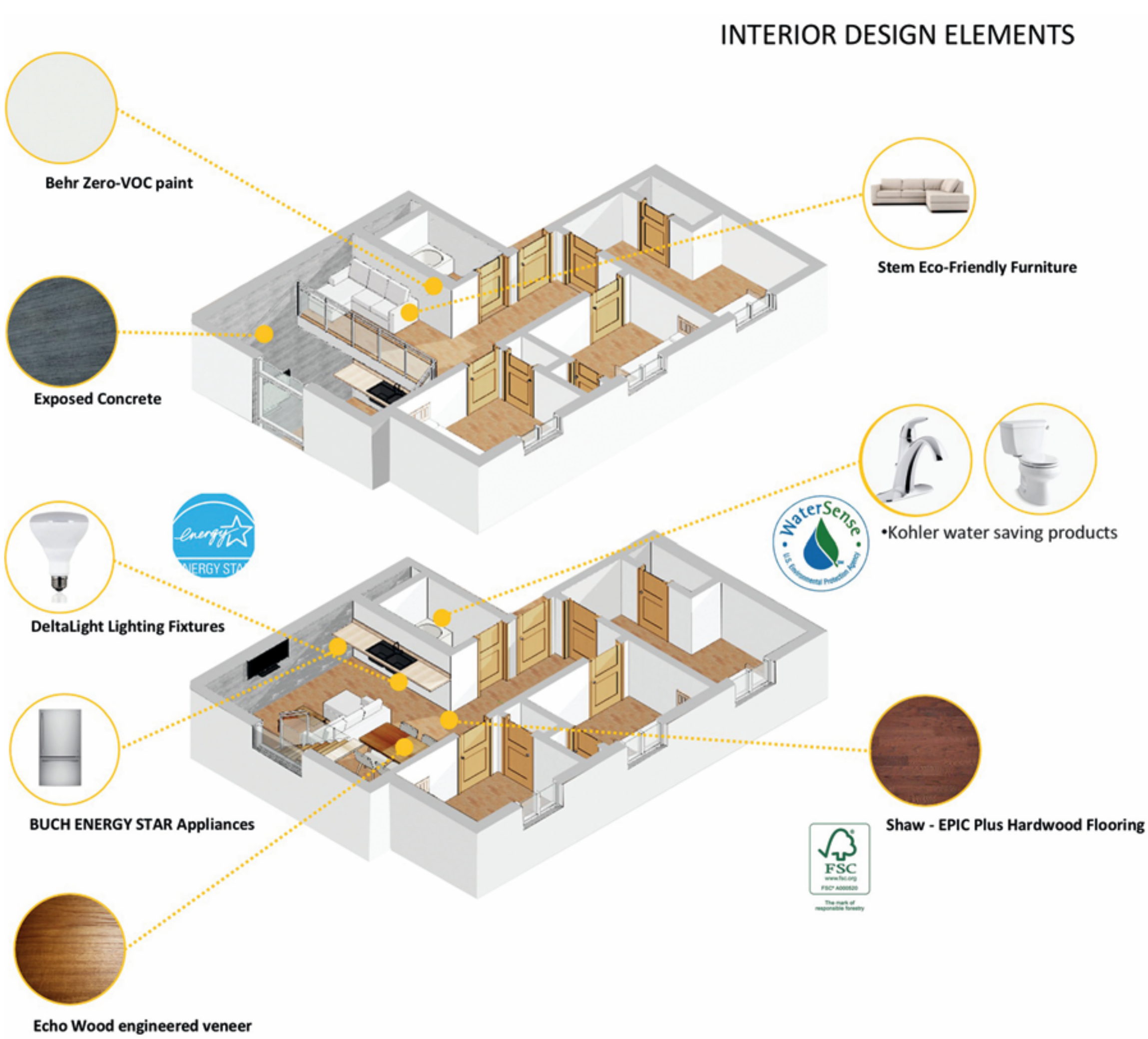


FIGURE 14: Spatial Daylight Autonomy Simulation. Spots in yellow comply with the daylight autonomy requirement of 300 lux for at least 50% of the year.

and communal areas. Figure 14 shows the percentage of floor area receiving a minimum of 300 lux for at least 50% of annual occupied hours. The simulation demonstrated that nearly all living spaces received sufficient daylighting for the majority of occupied hours.

The design of a high-performance envelope played a critical role in decreasing the building's heating and cooling loads, which led to reduced equipment sizing and hours of operation. The energy model was used to determine the external assembly's R-values required to meeting the target EUI, and a minimum R-value of 40 was calculated for the walls and the roof. The external wall assembly consisted of a 2" x 6" wood stud wall with 5 ½ inches of dense pack cellulose insulation in the wall cavity and 4 inches of graphite polystyrene rigid foam insulation. A continuous wood framed wall mounted outside the building's concrete structure had the objective of limiting thermal bridging. In addition to minimizing the effect of thermal bridges, the building envelope construction was specified to avoid water penetration, vapor infiltration, and air leakage. The project's design infiltration levels were compliant with the Passive House standard requirement of 0.05 CFM/ft^2 of the façade area tested at 50 Pa. These values were met through the use of continuous insulation and an air barrier. Furthermore, the continuous external wall construction provided improved acoustic insulation to the wall assembly thus mitigating the noise caused by the neighboring train and expressway.

Several iterations of daylighting simulations determined the window to wall area. Windows with a U value of 0.25 Btu/h*ft^{2}*°F and SGHC of 0.35 were specified, following the DOE's Climate Zone 5A Zero Energy Ready Home National Program Requirements.

The performance and durability of the wall assembly were evaluated performing a THERM and a WUFI analysis. The THERM analysis confirmed that the envelope would achieve the required minimum R-Value of 40. A hygrothermal analysis conducted using WUFI tested the moisture durability of the specified wall assembly. The results of an annual simulation showed that no surfaces developed 100% relative humidity throughout the year.

One of InterTech's strongest engineering design decisions to improve the building's energy efficiency was naturally ventilating the underground garage area. Openings to the parking garage were placed along the East, West, and South perimeters on the ground level. The design team performed a climate analysis paired with Computational Fluid Dynamics (CFD) simulations

FIGURE 15: Wall Assembly Detail.

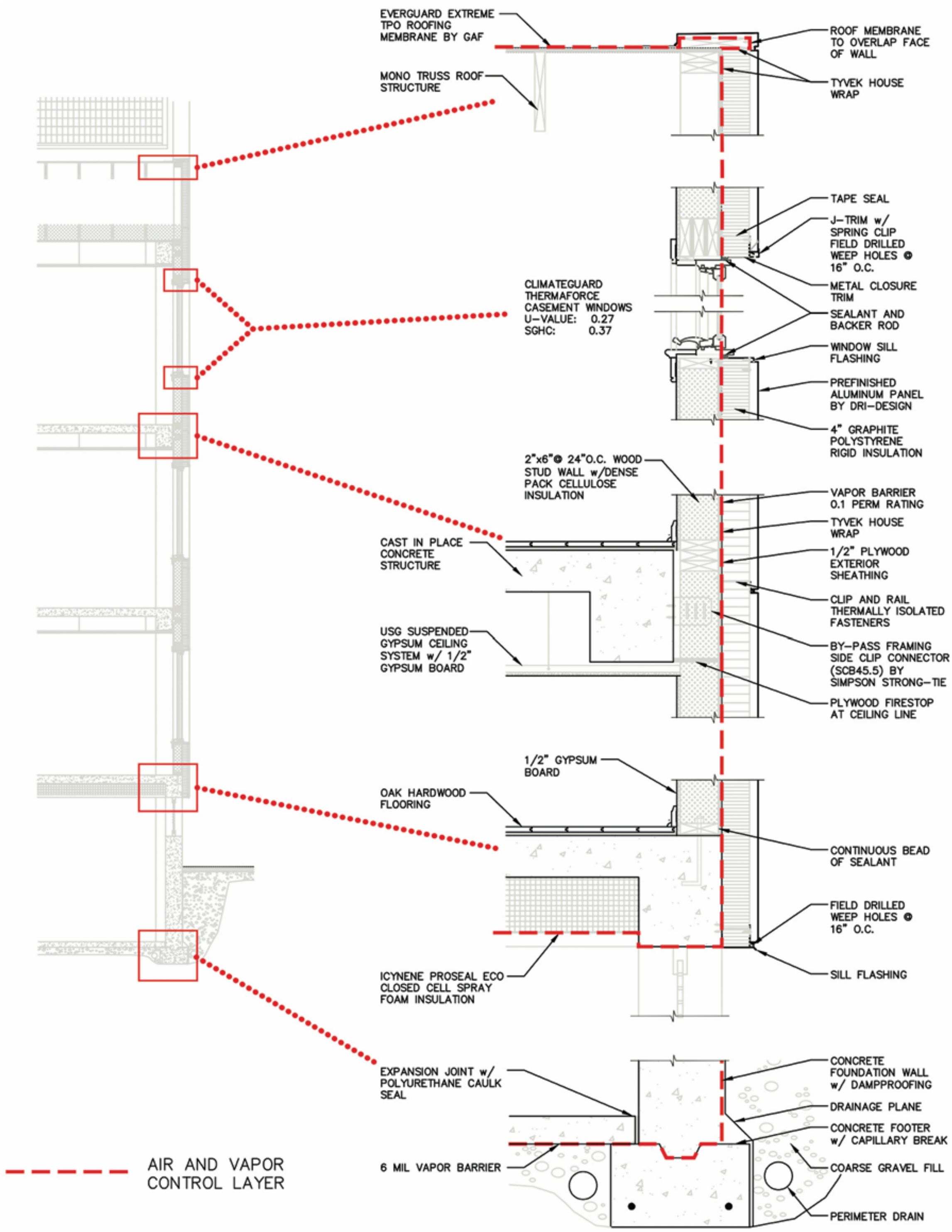
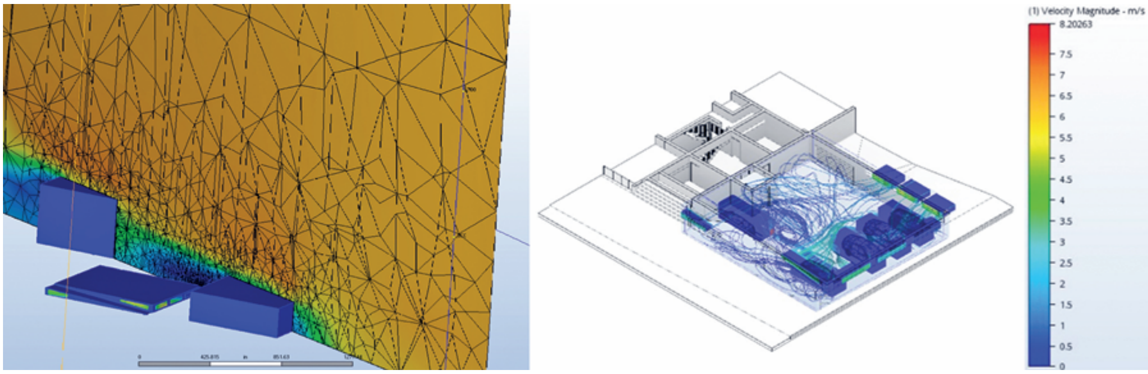


FIGURE 16: Interior & Exterior CFD Simulation detail.



to verify that the design would comply with the ventilation standards provided by ASHRAE 62.1-2016. These standards include a minimum exhaust rate of 0.75 cfm/ft^2 as specified in Table 6-4 in ASHRAE 62.1 and a maximum concentration of carbon monoxide of 9ppm every 8 hours as indicated in Table B-2.

A further analysis was conducted to demonstrate that the garage openings could adequately flush out carbon monoxide from idled cars through natural ventilation. The simulation was run for three wind scenarios, and particle traces were tested considering five cars idling in the underground 29,000 cubic foot garage area for five minutes. If every vehicle emits 1.187 g/min, five cars idling for five minutes in the underground garage will produce 31 ppm of CO. The analysis proved that, in the worst-case scenario, 90% of the CO would be flushed out in 30 minutes.

Figure 17 shows the residence time of air particles produced by the five cars. The table below shows the time needed for the CO emissions to flush out.

FIGURE 17: Residence time of particles origination from idling cars.

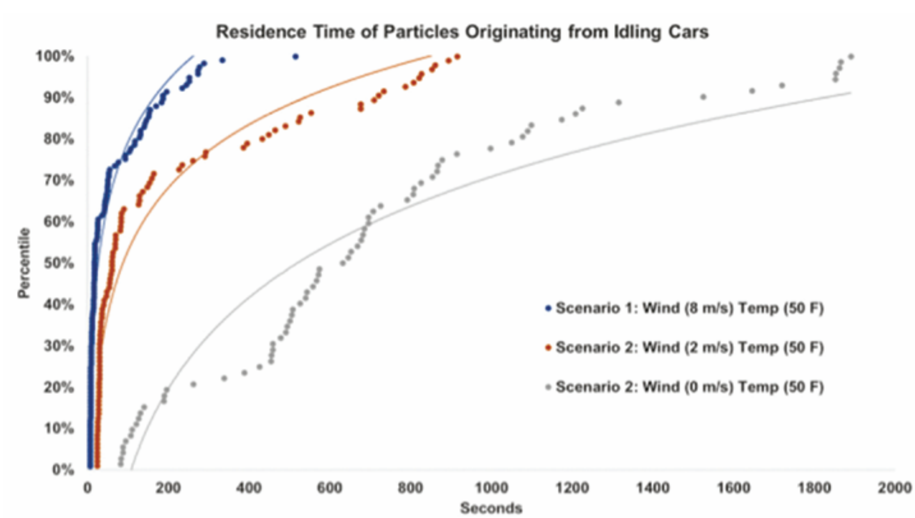


FIGURE 18: Residence Time of Carbon Monoxide with 5 cars Idling for 5 minutes.

Residence Time of Carbon Monoxide with 5 Cars Idling for 5 Minutes (resulting in 31 ppm of CO)		
	Time to below 8ppm (min)	Time for 90% of CO to be flushed out (min)
Scenario 1: Wind (8 m/s) Temp (50 F)	1.3	3.1
Scenario 2: Wind (2 m/s) Temp (50 F)	3.9	12.0
Scenario 2: Wind (0 m/s) Temp (50 F)	14.5	25.4

3.3 MEP Systems Design

The implementation of energy conservation strategies represented a turning point in InterTech's design development and in the achievement of the zero-energy goal. It resulted in a 25% reduction of the building's cooling load and a 33% reduction of the heating load.

When selecting InterTech's HVAC system, three different mechanical systems were evaluated before making a final decision. The alternate solutions included packaged rooftop units and air to water variable refrigerant units and were discarded because of space limitations, system efficiency, and cost.

FIGURE 19: Indoor VRF System.

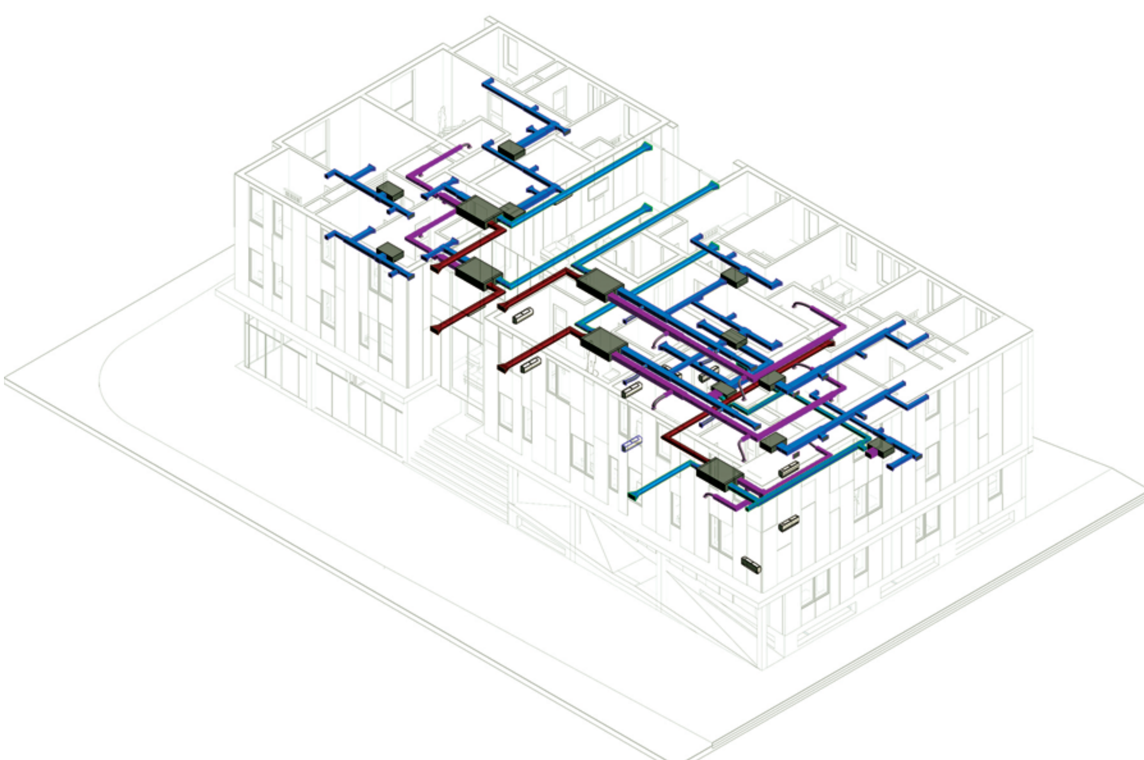
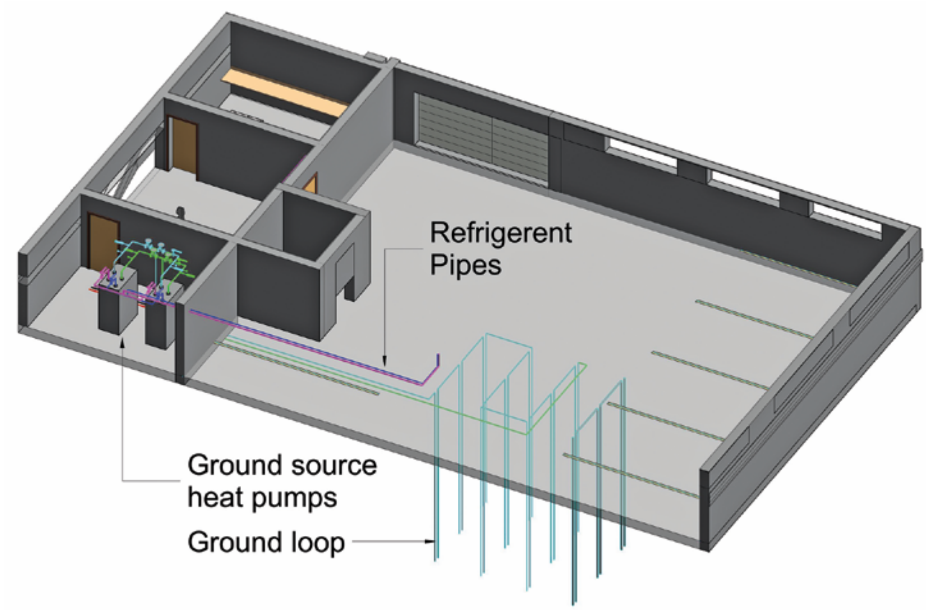


FIGURE 20: Mechanical Room Gshp Installation Detail.



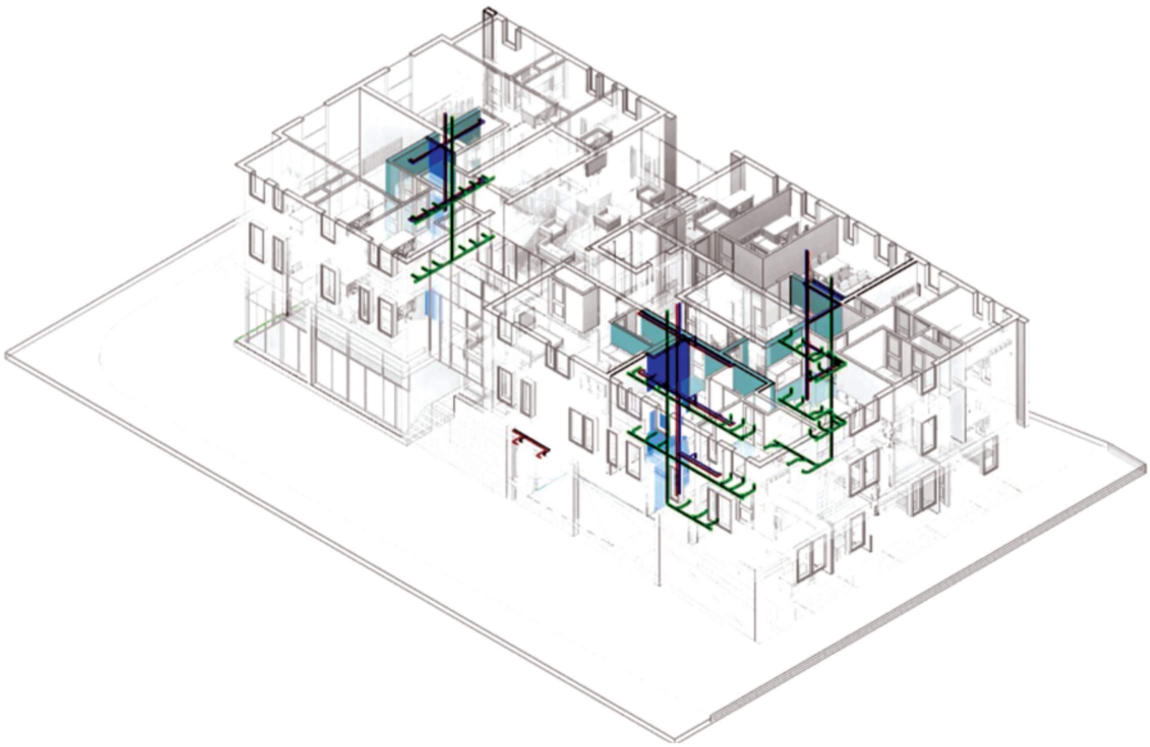
InterTech's HVAC design features a combined system consisting of two equally sized water to water ground source heat pumps (GSHP) with variable refrigerant flow (VRF) equipment to satisfy the building's heating and cooling needs. An indoor VRF unit connected to the central refrigeration circuit satisfies each apartment's zone load, while the outdoor air load is satisfied primarily by dedicated energy recovery (ERV) units. The ground loop used an ethylene glycol and water mixture with 30% ethylene glycol to comply with the most restrictive refrigerant international climate agreements. HFC-410A was the refrigerant specified for the secondary circuit. This refrigerant was selected for its no-ozone depletion potential and because it has no phase-out date. The ground source heat pump has an Energy Efficiency Ratio (EER) of 15, although current versions of this technology have higher-performing values.

According to the EPA Water Saving Requirements, low flow fixtures were specified in all residential units. The fixtures were grouped around three main risers, as shown in Figure 21.

The selection of low flow fixtures allowed conserving water and saving on water-heating energy. A desuperheater circuit rated with a coefficient of performance (COP) of 2 was paired to the water to water ground source heat pump. This device takes advantage of the geothermal system's waste heat to preheat domestic hot water, therefore reducing the energy needed to heat domestic hot water. Finally, water was supplied to each fixture through a Demand-Initiated Recirculation System. This system has the advantage of reducing the waiting time for hot water to reach the fixtures, which can result in energy, water, and cost-saving.

Regarding the building's electrical design, InterTech featured a Grid-Connected Renewable Energy System. In conjunction with a Net Metering agreement with the utility provider, this system would allow InterTech to use the grid as energy storage. During the summer months, when the photovoltaic system generates more electrical energy than needed, the excess energy can be redirected to the grid. On the other hand, during the Chicago winter months, when the energy generated by the renewable system cannot wholly offset the building's electrical energy

FIGURE 21: Main Risers.



consumption, the grid will provide the difference. In a zero-energy building, the annual balance between the amount of energy pulled from the grid and the amount returned to the grid should average zero. System elements specified in the project were lab certified to comply with UL 1741 and the National Electric Code (NEC) according to the testing protocols of IEEE 1547.

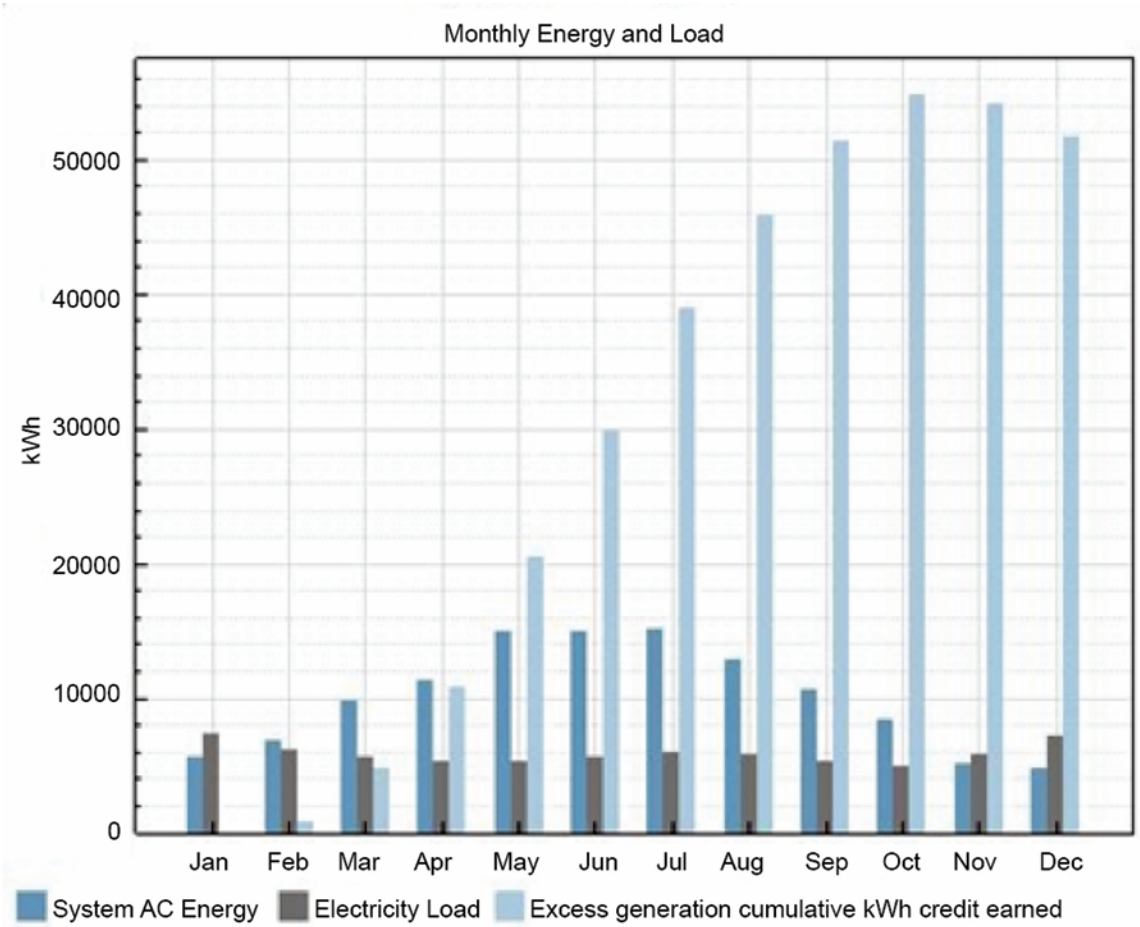
4. CONCLUSION

InterTech reached and exceeded the zero-energy objective using active and passive energy conservation strategies to reduce the building's energy demand and implementing an on-site renewable energy system that would meet the reduced needs. Its success lies in its iterative and integrated design approach, which explored the synergies existing between different building systems while catering to occupants' needs.

Innovative concepts are introduced at different stages of the design process, starting from the project's scope and program to the design of passive energy conservation strategies and efficient building systems. InterTech combined various programmatic elements within a compact design. It offered two different living options, an atrium providing communal spaces to the residents on each floor, a grocery store/cafe and an outdoor public plaza that engage the surrounding community, and an underground parking space. Passive strategies included a high-performance building envelope, natural ventilation in the atrium and underground garage space and optimized daylighting, while the mechanical design featured a water to water ground source heat pump with VRF paired with a desuperheater.

The project's most successful design elements resulted from moments of challenge and optimal collaboration. This approach determined many instances in which architectural

FIGURE 22: Monthly Energy and Load Net Metering Study.



and engineering design considerations influenced one another creating a balanced and integrated design.

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