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# Towards Net-Zero Energy Consumption with Near Net-Zero Initial Cost: A Case Study from Georgia, USA

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**Abstract:** This research presents a case study of a single-family home in Georgia, United States, that achieves near net-zero energy costs for the heating, ventilation, and air conditioning (HVAC) system with near-zero additional capital investment. Building information modeling (BIM), energy analysis, and practical common construction practices were integrated to trade-off between design and construction alternatives to achieve these results. An accelerated number of publications addressed net-zero energy buildings (NZEB). Much of this research addresses means and methods to make buildings produce as much energy as they consume (net-zero site or building energy) or make buildings produce energy and sell it to offset the buildings' energy bills (net-zero cost). However, NZEBs still constitute a small fraction of the building industry, which is mainly due to higher initial costs, significant deviations from common construction practices, or altering common building operations and comfort levels. In this research, a practical approach for achieving NZEB was tested and used in constructing a single-family home. BIM software that generates annual energy consumption with every design alternative was used during the design and construction phases of this home. The BIM model was also used to generate building materials quantities to estimate the initial construction cost. In this case study, the initial construction cost of the selected design was less than that of comparable homes in the same area. The post-occupancy evaluation showed that the annual energy consumption related to heating and cooling was 72% less than that of comparable homes in the same area. Energy consumption related to hot water consumption was 21% less, and energy consumption for lighting was reduced by 22%. In conclusion, general design guidelines and lessons learned are established to help the residential building industry adopt energy-efficient design and construction approaches to reduce energy consumption in homes without increasing the listed prices of homes.

***Keywords*:** net-zero energy, home, cost control

## 1. Introduction

Building energy consumption accounts for approximately 40% of the total energy consumption in some developed countries like the United States, with heating and cooling loads accounting for 30 to 40% of that consumption [1]. In the past 20 years, energy savings in residential buildings have been a major concern for users and regulatory agencies. Buildings account for 76% of the total electric use in the United States and are responsible for 40% of greenhouse gases [2]. Numerous initiatives around the world address reducing energy consumption in residential buildings for many


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reasons, including environmental, economic, health, and comfort.

Government and regulatory agencies usually establish minimum building performance standards that all buildings must achieve in terms of energy efficiency. Many residential builders base their standard practices around these minimum requirements and the common construction practices in their areas. Deviating from these common practices comes with many challenges, including the initial cost and return on investment. The common perception is that energy-efficient houses are much more expensive than the prevailing construction methods, which cannot guarantee a positive return on investment for sale or rental properties. The rapid advancement in building technology makes adapting energy-efficient construction methods using these new technologies difficult.

Many studies in different countries were conducted to determine the return on investment for residential house upgrades. As an example, a program funded by the New Zealand government was established to improve passive house energy performance to achieve better comfort levels. However, these initiatives did not result in a significant improvement in comfort and healthy indoor temperatures in houses with active heating systems that benefited from this program [3]. Another study was conducted in the United Kingdom on renovating existing buildings to achieve better energy efficiency. This study highlighted the cost increase and the technological and economic challenges that face these improvements [4]. Similar programs and initiatives exist in many other countries, including the Weatherization Initiative in the United States.

In a previous study, Taylor et al. [5] highlighted the economic challenges of implementing energy-efficient measures and developed a model for calculating the return on investment. According to this research, placing ducts in conditioned space, better envelope tightness, and thicker exterior wall insulating sheathing had the most significant return on investment for Zone 3 Climate in the United States, which is the climate zone for our case study house.

Several demonstration houses were also built for the houses to achieve net-zero energy or passive energy. Dan et al. [6] demonstrated how a passive house in a cold climate like Poland can achieve an 84% reduction in the heating load of the house. However, these measures increased the house cost by 27%, and the study did not include calculations for the return on investment or if these new construction details were commonly used in Poland [6].

It should be pointed out that most of these energy conservation measures did not address the holistic design and construction approach when applied to existing designs or to upgrading existing homes. Most of these studies also assumed that there would be an initial investment and cost increase associated with improving the energy efficiency of houses. Most of these studies do not address the interaction between the different energy-saving measures and how some measures might adversely affect other measures, nor do they address the practicality of acceptance of these changes by builders and investors.

The proposed energy conservation measures in our case study stem from the practical applications of these energy-saving measures, which start with the conceptual building design, building construction and detailing, applicable regulations, cost savings, and reducing the energy cost of the building.

## 2. Case study

The holistic design and construction approach was implemented in the design and construction of a house in Marietta, Georgia, United States. The house's conditioned area is 4,312 square feet (470 $m^2$).

### 2.1 *Design strategy*

The first floor consists of four semi-conditioned car garages, a conditioned entrance, a conditioned exercise room, and unconditioned storage (Figure 1). The second floor has open living, dining, and kitchen spaces (Figure 2). The third floor has bedrooms (Figure 3), and the fourth floor has guest bedrooms (Figure 4). The site was covered with large deciduous trees that provide shading during the summer and allow more solar radiation to reach the building during the winter (Figure 5). The building orientation is shown in Figure 6, and the weather data for the building location is shown in Figure 7.

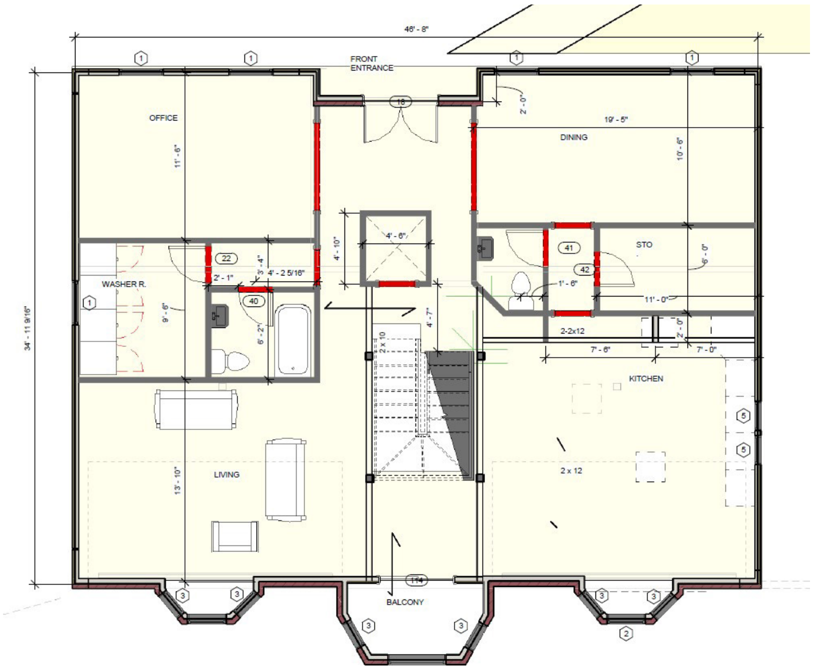


**Figure 1.** First-floor plan

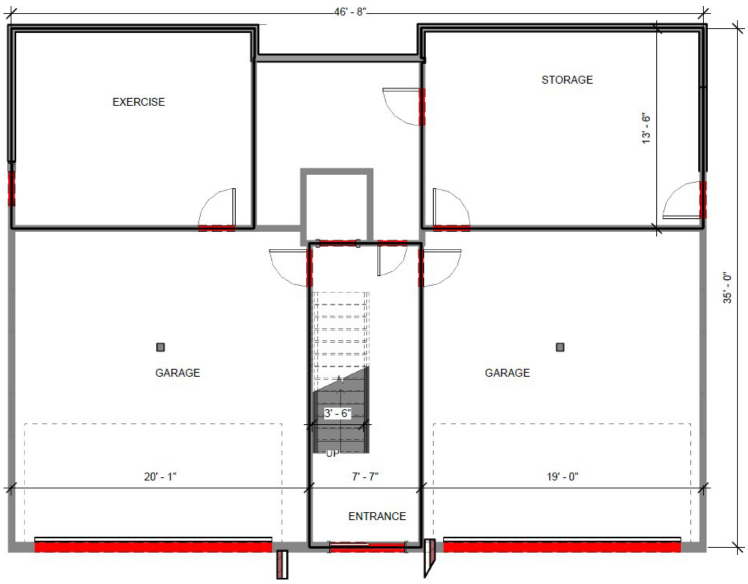


**Figure 2.** Second-floor plan

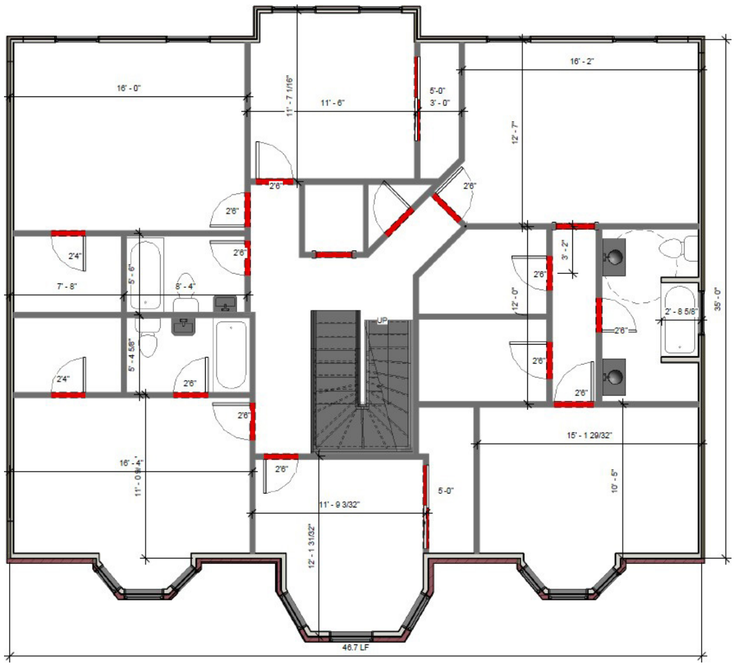

**Figure 3.** Third-floor plan

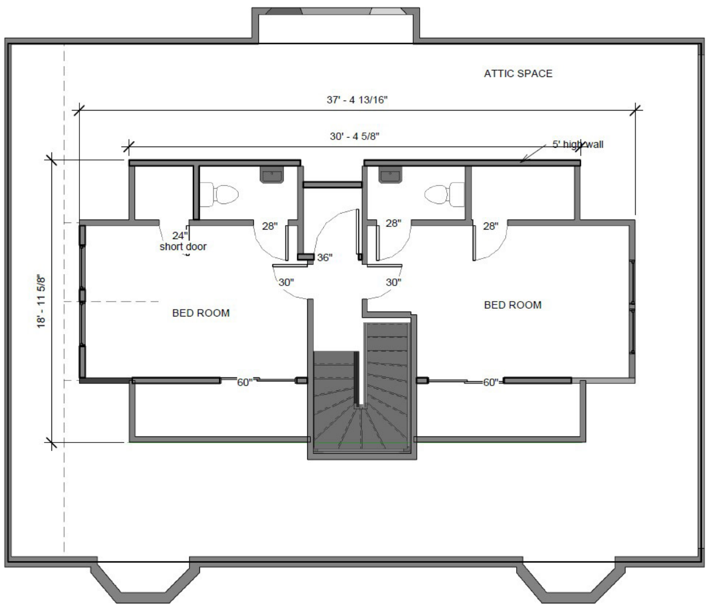


**Figure 4.** Fourth-floor plan

**Figure 5.** Outside picture of the house

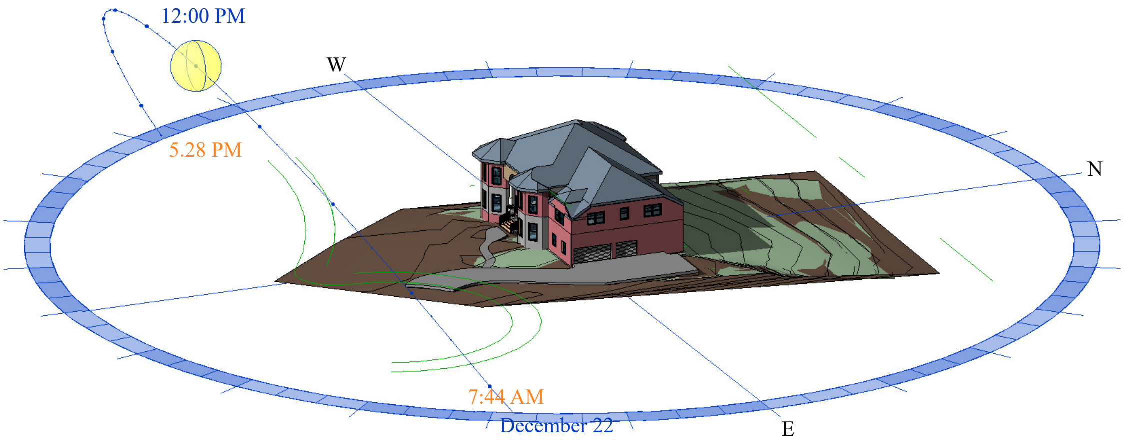


**Figure 6.** Sun path diagram of the building

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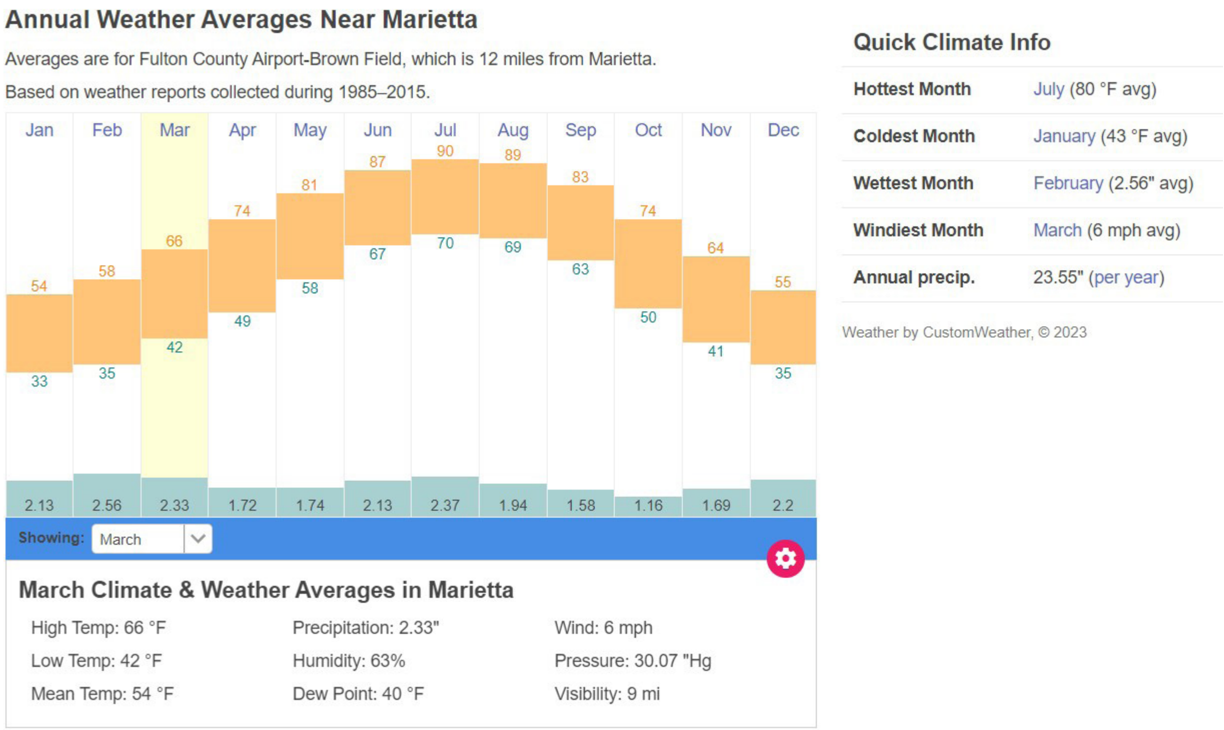


**Figure 7.** Weather data for Marietta, Georgia, United States [7]

The design strategy addressed energy savings during initial design and building formation, construction detailing, mechanical and electrical design, and comfort level. The following design and construction elements were considered in enhancing the base design.

## 2.2 *Heat loss form factor (HLFF)*

The HLFF is defined by the thermal envelope square area of the building divided by the floor area of the building. A typical single-story house has a HLFF of 4.0 [8]. A house with an HLFF of 3.0 is considered a good starting point for a passive house. Our case study house has a HLFF of 1.9, which is approximately 53% less than a typical single-family house. Assuming that we use the same floor and roof construction, this reduction in the HLFF can also be translated to an approximately 50% reduction in the building envelope structure. This reduction will significantly reduce heat gain and loss through the building envelope, and at the same time, it will significantly reduce the initial building cost.

## 2.3 *Wall construction*

A typical wall construction in single-family homes in Georgia consists of an exterior layer of vinyl siding or brick with a 2.0” air cavity, a moisture barrier, ½” wood sheathing, a 1 ½” × 3 ½” wood stud wall with R-13 batt insulation in between, and ½” gypsum board from inside. The total U value of this wall assembly is 0.089 Btu/h·ft²·F [9]. Instead of using this typical wall construction, we replaced the wood sheathing with ½” polyurethane insulation with reflective aluminum foil facing outside and R-15 batt insulation between the wood studs. Special attention was paid during the thermal installation to take maximum advantage of the insulation. The total U value of this wall assembly is 0.064 Btu/h·ft²·F [10]. To provide the required shear strength as required by code, the house’s corners should have at least 4’ 0” wide wood sheathing or provide metal bracing. The average U-factor for all exterior walls of the house was approximately 0.07 Btu/h·ft²·F which is approximately 27% better than the typical wall U factor. The cost of wood sheathing is approximately the same as that of insulation sheathing, and the installation of insulation sheathing is considered easier than that of wood sheathing because it is lighter and easier to cut. Using the insulation sheeting also satisfied the moisture barrier requirements; thus, vapor barriers were not needed, which resulted in extra savings. The cost of replacing R-13 with R-15 wall insulation was $0.15 per square foot of wall area. The cost of the moisture barrier offsets the extra cost of using R-15 in lieu of R-13 wall insulation. It should be pointed out that using continuous closed-cell rigid insulation will also reduce the possibility of moisture condensation inside the wall and move the dewpoint temperature outside the batt insulation.

## 2.4 *Roof insulation*

In a typical house, R-30 roof insulation is placed over the ceiling on the attic floor, and the attic space is usually vented. In Zone 3, attic temperatures in the summer are extremely high and can reach 140 °F. Knee walls in the attic will be insulated with R-13 batt insulation, as shown in Figure 8. In our design, the R-30 insulation was carried down along the rafters, which made the entire attic a semi-conditioned space. This eliminated the need for R-13 knee wall insulation. In a standard design, the heat transfer through the knee walls is significant since the air temperature in an unconditioned attic is extremely high. In addition, most ductwork and the AC unit for the third and fourth floors are placed in the attic space. Since the attic in our design is semi-conditioned, the air temperature in the attic is much lower, which significantly reduces heat loss from the ducts and AC system in the attic. The total cost increase related to insulation was approximately $0.5 per square foot, which is marginal. Although knee wall insulation is no longer needed, we decided to keep it as the cost savings are not significant.

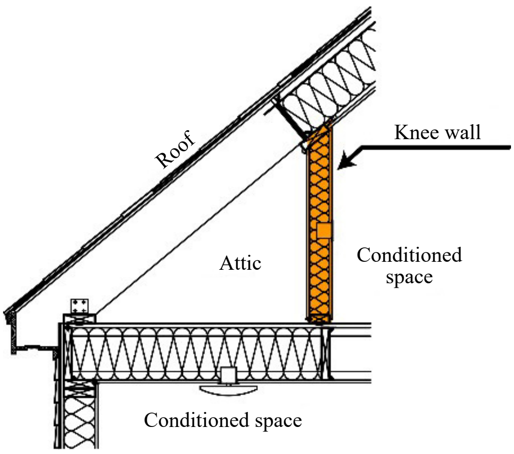


**Figure 8.** Typical roof insulation [11]

## 2.5 *Garage wall insulation*

Since most of the first floor's area is car garages, first-floor walls are not required to be insulated per code. However, these walls and the garage door were insulated in our case study to create a semi-conditioned space, so the indoor garage temperature will be relatively comfortable. This also helped in reducing the heat loss through the floor of the second floor over the garages. The garage ceiling was insulated with R-19 batt insulation which is equivalent to the minimum required by the code.

## 2.6 *Window selection*

In a typical house, single-hung or double-hung windows are usually used. A double-hung window has both movable window sashes. The advantage of double-hung windows is that they allow for more air ventilation compared to single-hung windows. However, single-hung windows are approximately 25 to 39% less expensive than double-hung windows, and they are more energy efficient because they are more airtight. We decided to use single-hung windows because natural ventilation is not considered in the house design, and they are hardly used in high-end houses similar to ours in a Zone 3 climate. Vinyl-framed single-hung windows were selected with a U factor of 0.29 and a solar heat gain coefficient (SHGC) of 0.28, which is better than the minimum performance required by the code. A south or north orientation is desirable for this climate zone. However, it was not possible to orient windows in these directions in this house due to site restrictions. Instead, most of the house windows were facing north or east. Large deciduous trees were maintained on the east side, which provide shading during the summer and allow for solar radiation during the winter. Window sizes and locations were carefully selected to provide adequate views and natural lighting without sacrificing total house energy efficiency.

### 2.7 *Air conditioning (AC) system selection*

In a typical house of this size, two split-system AC systems are usually used, with the compressors installed outside and the fan coil and furnaces installed inside or in the attic space. Most current systems have a seasonal energy efficiency factor (SEER) of 13, as required by code. We decided to use dual-stage SEER-16 units. One unit serves the entrance and the exercise room on the first floor as well as the second floor, and the second unit serves the third and fourth floors. These units are approximately 23% more energy efficient than single-stage SEER-13 units. A three-zone system for the upper floor was also installed so that the guest rooms were served by one zone, the master bedroom suite was served by a second room, and the children's bedrooms were served by a third zone. This zoning system provides maximum comfort, and at the same time, it allows the system to be set back in the guest bedrooms when they are not in use. Such zoning is not possible in a single-stage unit because closing some zones will restrict air circulation in the ducts, which might result in freezing the evaporation coil in the air handling unit. In a variable-speed dual-stage unit as used in the case study house, the compressors will run at half capacity during partial load, and the variable-speed fan in the air handling unit will be optimized to extract the maximum amount of moisture while providing the required cooling. Thus, the combination of dual-stage units with zoning dampers provided significant energy saving beyond the standard SEER-13 unit rating. The system also came with a 95%-efficiency gas furnace. This highly energy-efficient furnace was vented by Schedule 40 polyvinyl chloride (PVC) pipes. A standard furnace with less energy efficiency requires a double-wall steel vent pipe, which is much more expensive than PVC vent pipes.

The heating, ventilation, and air conditioning (HVAC) system is controlled by a dual-stage programable thermostat that activates the first stage at 50% capacity on partial load. This is specifically when some zones are not occupied or activated.

The SEER-16 unit is approximately 20% more expensive than the single-stage unit, which added approximately $3,000 to the total cost of the house. However, since the overall house construction is more energy efficient, the total AC system was reduced by 50%, resulting in a total savings of approximately $6,500. Thus, the net initial savings of the AC system were $3,500, and at the same time, we achieved much better HVAC system performance that is less noisy, provides better humidity level control, saves energy, and is also more durable than the standard system.

### 2.8 *Hot water heater*

A natural gas instant-on-demand water heater with 95% efficiency was used. This unit is vented with Schedule 40 PVC pipe in lieu of double-wall steel pipe, and it is power vented horizontally. Thus, the water heater was installed near the main demand points in the house and vented horizontally on the first floor. The extra cost of this efficient water heater was offset by the cost savings of using PVC venting instead of the double-layer steel vent pipe that had to run all the way up to the roof if a standard efficiency water heater was used. The standard natural gas water heater has 75% efficiency.

## 3. Building simulation

To examine the total energy savings of the house, a building simulation model was created using the EnergyPlus simulation engine in building information modeling (BIM) software (Revit). EnergyPlus is the Department of Energy's simulation tool for whole building energy performance that combines heat and mass transfer through the building envelope, provides hourly and annual energy consumption, and also provides peak cooling and heating loads [12]. The building simulation model was calibrated by comparing the monthly energy consumption during certain heating and cooling degree days with the actual natural gas and electric consumption. The model was also calibrated using the actual run time of the AC system during certain heating and cooling days. The zoning and the actual running time of the house were considered in the simulation. The whole house infiltration was assigned in the simulation model based on the blower door test results of the house.

The house was first simulated using EnergyPlus simulation software, which is interfaced with Revit modeling software. The base design included the prevailing standard of construction and the common practices in the region that comply with the state code and standards. The house was then simulated based on the actual construction as described before (Figure 9).

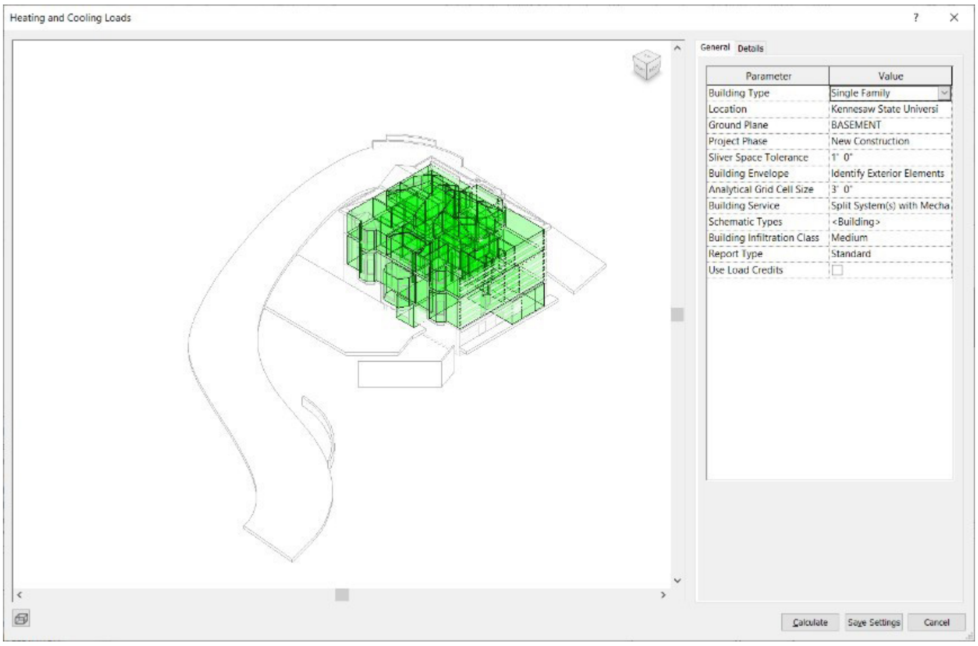


**Figure 9.** Building energy simulation of the house

## 4. Results

The simulation model calculated the peak heating and cooling loads. Figure 10 shows the base design, the revised design, and the heating and cooling loads.

The simulation results showed that the peak cooling load was reduced from 87,892 Btu/h to 45,976 Btu/h (52%). The peak latent cooling load was reduced from 10,210 Btu/h to 4,049 Btu/h (40%). The peak sensible cooling load was reduced from 77,862 Btu/h to 41,928 Btu/h (54%). The peak heating load was reduced from 60,340 Btu/h to 34,420 Btu/h (57%). The AC systems are sold based on their capacity (ton of cooling, which is 12,000 Btu). The installed system was reduced from 8 tons in the standard design to 4 tons in the actual design. The gas furnace was reduced from 80,000 Btu to 40,000 Btu based on the closest furnace system available on the market. This can be translated to a 35 to 40% cost reduction in the HVAC system, which can be translated to a 7% reduction in the total house construction cost.

The total house performance was simulated using the closest weather data to the house location. We used the average annual value of 140 million Btu needed for heating or cooling a house of the same size as the case study house. This number is based on the research conducted to estimate the energy consumption of housing in the United States [13]. The simulation results showed that the annual energy consumption was reduced to 39.2 million Btu, which can be translated to an approximate annual saving of $2,450. This saving can be translated to approximately $38,000 in home value.

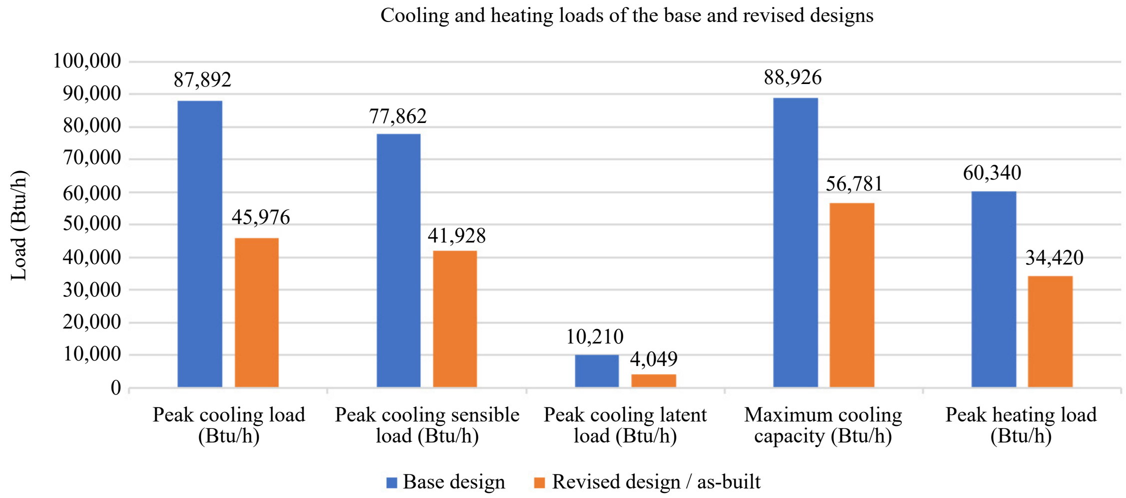


**Figure 10.** The house performance before design enhancement (base design) and the as-built performance

## 5. Conclusions

This research addresses how the energy efficiency of residential construction can be significantly improved without a significant increase in the initial cost. A holistic design and construction approach that used BIM tools to examine the contribution of cost-effective value engineering design alternatives to the energy efficiency of the building was observed. Much previous research addressed energy efficiency in residential buildings. However, this research did not address a holistic approach to selecting existing technology to reduce construction costs and at the same time improve its energy efficiency.

To maintain the initial construction cost in line with standard construction costs, the initial design of the building envelope must consider energy conservation. This case study addressed how energy conservation can be achieved without increasing the initial cost. However, it is limited to a specific design and climate zone. Energy simulation and cost-benefit analysis should be conducted for each design to determine the most energy-efficient and cost-effective design alternatives. General "rules of thumb" cannot be applied to a wide range of designs and climate zones to achieve significant energy savings without increasing the initial building cost. Energy conservation must also be considered during all design and construction phases, and cost-benefit analysis must be used when selecting the different building components and construction methods. With the advancement in computer simulation, more research is needed to create a holistic interactive energy analysis tool that is associated with data visualization for examining and suggesting energy-efficient and cost-effective design alternatives.

## Conflict of interest

There is no conflict of interest in this study.

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