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Giulia Marinello

Purdue University, United States of America, giulia.marinello3@gmail.com

Stephen L. Caskey

Purdue University, United States of America, stephen.l.caskey@gmail.com

Eric J. Bowler

Whirlpool Corporation, United States of America, eric.j.bowler@gmail.com

Eckhard A. Groll

Purdue University, United States of America, groll@purdue.edu

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Energy Simulation and Optimized Retrofit Practices Applied to a Real Dwelling

Giulia MARINELLO^{1*}, Stephen L. CASKEY¹,
Eric J. BOWLER², Eckhard A. GROLL¹

¹Purdue University, School of Mechanical Engineering, Ray W. Herrick Laboratories
West Lafayette, Indiana, USA
001 (847) 894-7594, gmarinel@purdue.edu
scaskey@purdue.edu, groll@purdue.edu

²Whirlpool Corporation, Saint Joseph, MI, USA
Eric_J_Bowler@whirlpool.com

*Corresponding Author

ABSTRACT

Sustainable construction practices have been increasingly applied in new residential construction for years. On the other hand, little has been done to retrofit the massive stock of already existent dwellings in the United States. Nowadays retrofitting practices represent a good monetary investment and reduce the carbon footprint of a building through reduction of energy consumption. The case of a real single family home is taken as an example to demonstrate the advantages of certain retrofitting practices. The analysis is done using software called Building Energy Optimization (BEOpt). Real energy consumption data are compared with the simulation model in order to check the accuracy of the model. As a second step, different retrofit solutions are analyzed in terms of energy savings and an annualized energy cost is used to identify the best solution. The analysis demonstrates that a 50% energy saving can be achieved with an initial investment of approximately \$30,000. Considering a period of 30 years, an annualized energy cost savings of 55 \$/year with respect to the pre-retrofit case is reached. This study is part of a research program called the ReNEWW (Retrofitted Net-zero Energy, Water and Waste) House. Considering that the final goal of the project is to be net-zero energy, additional calculations have been done to analyze the available renewable energy resources on-site. It is demonstrated that a 11.3 kW solar photovoltaic system coupled with a geothermal heat pump is able to achieve net-zero energy status.

1. INTRODUCTION

According to the US Department of Energy (DOE), residential housing units account for 22% of the total primary energy usage in the US (Buildings Energy Databook 2011). The average age of a single family home in the US is 34 years. These aging dwellings were built in a time when energy was cheap and carbon dioxide was not considered pollution. These dwellings do not have regard for many simple energy efficiency measures. The practice of retrofitting represents a huge source of energy savings. Although there are some general fundamental rules on how to retrofit a house, many different improvements can be applied and the optimum solution is normally based on the previous conditions of the house and on the climate zone where the house is located. In the past few years, many, increasingly sophisticated, software solutions able to provide an energy model of a residential building have been developed.

In this paper a typical 1920s vintage residential house located in West Lafayette, Indiana is taken as an example. The aim is to use an energy simulation engine to create a model, verify the model by matching the results with real time energy usage data before the retrofit and then use the model to predict the energy consumption post retrofit. The software used is BEOpt (Building Energy Optimization), developed by the National Renewable Energy Laboratory (NREL). The software is able to run optimization analyses and recommend the most cost-effective improvements that can be applied. This approach was utilized for the example home. The results of the energy simulation were

then compared with real data collected by the instrumentation system installed in the aforementioned house. The suggestions given by the energy simulation are used to inform actual retrofit actions, which will be implemented during the summer of 2014. Moreover, the energy simulation is able to predict the energy consumption of the house after the retrofit and give an important indication on sizing the solar energy system that will be installed on the roof of the house. The overall goal of the research program is to retrofit the residential building over the course of three years to create a net-zero energy, water and waste home. This study is part of the research program called the ReNEWW (Retrofitted Net-zero Energy, Water and Waste) House, a collaboration between Whirlpool Corporation and Purdue University.

2. BASELINE SCENARIO

2.1 Parameters chosen for the simulation

In order to validate the energy simulation, the first step is to simulate the example home before the retrofit by creating a 3D model and selecting the inputs (heat transfer resistance of the wall, type of windows, etc.) that match closely the real characteristics of the dwelling. The next step is to run the simulation and compare the results with real data on energy consumption collected at the house. An instrumentation system is currently installed in the dwelling and is able to monitor electricity, gas and water consumptions. The monitoring system was installed with the aim to collect real energy and water consumption data before and after the retrofit. An additional goal is to demonstrate that living in a net zero energy home does not require sacrifice on comfort or convenience. For this reason, temperature and relative humidity are also monitored in many rooms.

The energy simulation software chosen for this study is able to calculate the energy consumption of a house based on specific user inputs. Those inputs are related to the geometry of the home, the envelope characteristics, the HVAC system, and any other device that uses energy (lightings, appliances, etc.). The first step is to create a 3D model of the dwelling considered. Figure 1 shows the 3D model built in the simulation program of the test house.

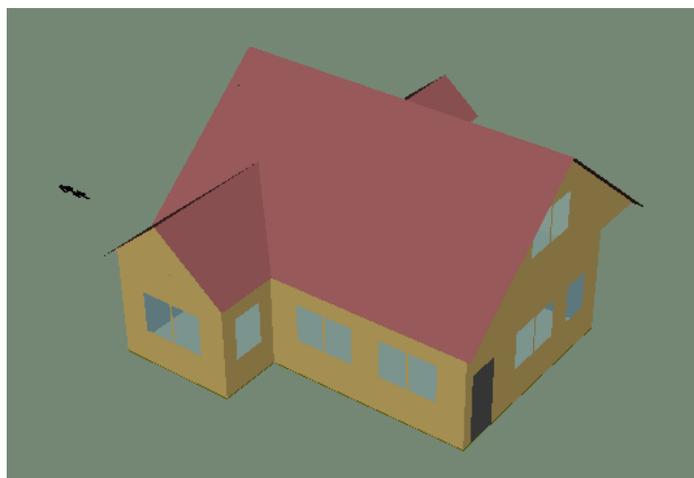


Figure 1: 3D model of test home in BEOpt

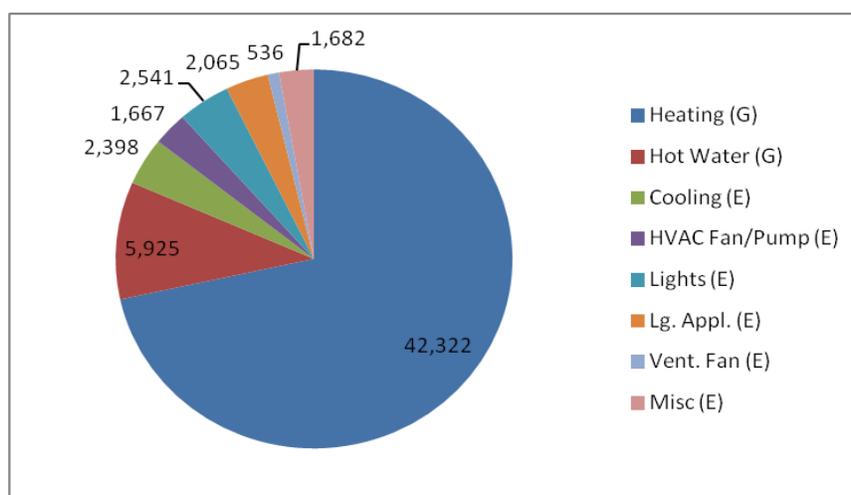
The factors affecting the energy consumption of a household can be divided in four main categories: the envelope, the HVAC (Heating, Ventilation and Air Conditioning) system, the end use devices (lightings, appliances, etc.) and human behavior. In the simulation program, it is possible to select inputs for the envelope, the HVAC system and the device characteristics (such as type of lights or energy class of the appliances) that represent the real condition of the existing home. The inputs can be chosen from a large library of predefined options present in the software. Human behavior (shower length, appliance usage, etc.) is more complex to describe and for that reason the software simulates human behavior from generally accepted assumptions. Those assumptions are based on several studies carried out by NREL to describe the average American family energy consumption. Therefore, human behavior is a parameter that cannot be adjusted.

Table 1 shows the main parameters chosen to simulate the current conditions of the test house.

Table 1: Software Baseline Scenario Inputs

Parameter	Input chosen
Location	Purdue University, West Lafayette, Indiana, USA
Square footage	266 m ²
N. of bedrooms	3
N. of bathrooms	2
Age	86 years
Heating set point	21°C
Cooling set point	24.4°C
Humidity set point	50%
Walls	Wood stud, uninsulated, 40.6 cm
Exterior finishing	Wood, medium/dark
Unfinished attic	Uninsulated, vented
Finished roof	Uninsulated
Roof material	Asphalt shingles, dark
Finished basement	Uninsulated
Carpet	60% of the floor area
Windows	Single-pane, clear, non-metal frame
Air leakage	10 ACH50
Refrigerator	Energy Factor (EF) =14.1, top freezer
Cooking range	Electric
Dishwasher	None
Clothes washer	Standard, MEF = 1.41 ft ³ /kWh-cycle
Clothes dryer	Electric
Lighting	20% fluorescent
Central air conditioner	SEER 10
Furnace	Gas, 80% AFUE
Water Heater	Gas standard (EF = 0.59, 151 liters)

Once the parameters were selected, the simulation was run to calculate the energy consumption of the household. The results of the simulation are visualized in Figure 2 showing the Baseline Case site annual energy consumption by end use.

**Figure 2:** Baseline Case Site Annual Energy Consumption by End Use in kWh

The modeled house is located in West Lafayette, Indiana, a cold climate zone. As expected the energy consumed due to the heating demand, over 70%, is much larger than the energy consumption related to all the other needs of

the house. In particular the yearly heating demand is 42,322 kWh, while the sum of all the remaining energy demands is 16,814 kWh. The high heating demand is attributed to lack of insulation and air sealing that characterizes homes of similar vintage and its location in a cold climate.

It is interesting to compare the percentage of energy consumption attributed to the different end uses of the test home with the average residential energy consumption as reported by the US Energy Information Administration (EIA). Recent data related to Indiana are not easily accessible, so the state of Illinois is taken for the comparison due to the similar geographical location and weather conditions. Figure 3 and Figure 4 show the percentage of energy consumption by end use of the test home and the one reported by the EIA for the state of Illinois respectively (RECS State Fact Sheet 2009).

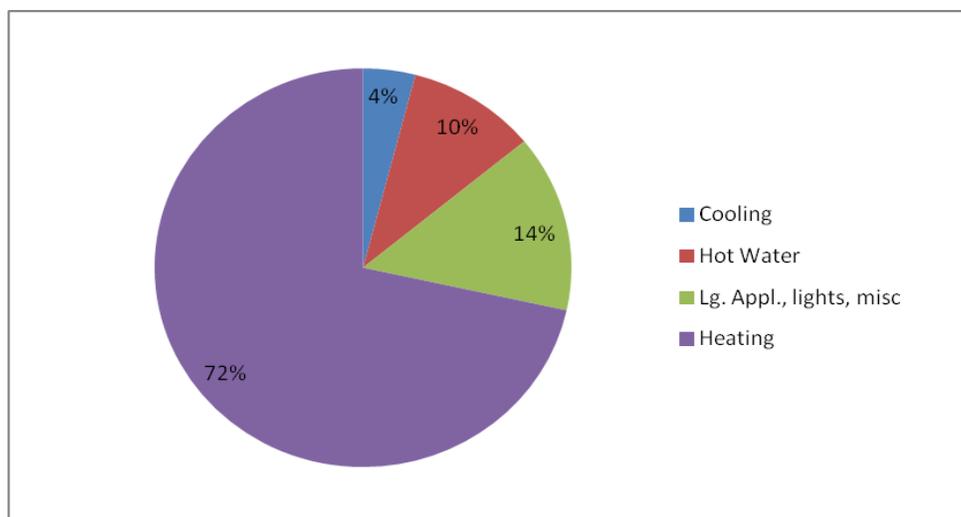


Figure 3: Test Home Baseline Site Energy Consumption by End Use

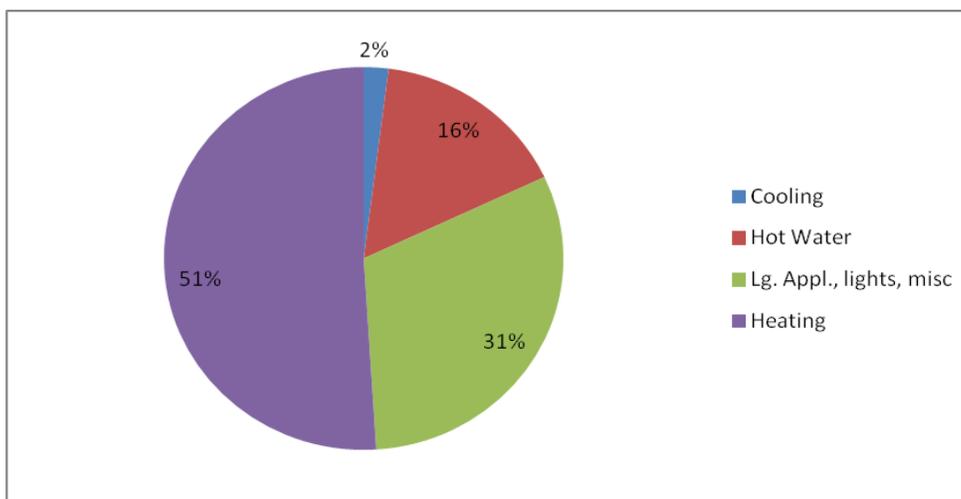


Figure 4: Illinois Residential Average Site Energy Consumption by End Use

The most noticeable difference between the two is the dissimilarity between the percentage of the consumption due to the heating in the two cases, 72% for the test house and 51% for the average residential home in Illinois. As highlighted before the test house is essentially uninsulated. Thanks to the analysis, it is possible to understand early on that the majority of the energy savings will come from the retrofit of the envelope.

2.2 Comparison between real and simulation data

The simulation reflects the condition of the existing house and for this reason can be used to confirm the accuracy of the model by comparing these results with real data. As previously mentioned, energy consumption is also

dependent on human behavior. The software follows the DOE Building America Simulation Protocol which reflects the average American family behavior (Hendron et al. 2010). In order to have an effective comparison the same schedule was replicated in the test house for a week and the electricity consumption of every single load (lights, appliances) was recorded. Full heating season data was used to compare the heating loads because the values are highly dependent on seasonal weather conditions. Unfortunately, there is no baseline measured data available regarding the cooling load as the instrumentation system was installed after the cooling season had ended.

Table 2 shows the comparison between the results of the simulation and the real data collected at the test house. The data presented are related to the site energy consumed in a year.

Table 2: Simulation versus Measured Site Energy Data

Load	Simulated (kWh)	Measured Data (kWh)	% difference
Heating	42,322	45,455	7.1%
HVAC fan	1667	1538	8.0%
Lights + miscellaneous	4223	4076	3.5%
Appliances	2065	1862	10.3%

The results show that, if inputs that best match the test house are given, the simulation engine is able to calculate the energy consumption of a household within 10% of the measured value.

3. RETROFIT SOLUTIONS OPTIMIZATION

The objective of the software optimization is to minimize the annualized energy related cost. The annualized energy related cost is calculated by annualizing the energy related cash flow over the analysis period, 30 years. With many combinations of different actions available to retrofit an existing building, the software identifies the retrofit solution package which produces the lowest annualized energy related cost while obtaining the maximum energy saving possible. The factors that affect the optimal retrofit solution of a single family home are weather conditions, product cost, local labor rates and energy and financing costs. It is important to identify where to invest money in order to have the highest energy savings possible. The previous analyses demonstrated that the envelope needs particular attention due to the high heating demand of the test house. Variations of the program inputs have been considered for all the characteristics related to the envelope, appliances and lighting. The HVAC system variation is not considered in this simulation. A simulation containing the new HVAC system that is already selected is shown in Section 4 in order to be able to isolate the impact of the envelope's improvements. The final goal of the project is to achieve a net-zero energy building, i.e. a building which is able to produce as much energy as it consumes with renewable energy resources on-site. For this reason, the HVAC system selected is a geothermal heat pump, due to its high efficiency use of electricity for heating and cooling.

When the software is used in optimization mode, different inputs for the same characteristic can be selected at the same time. For example a selection can consider multiple wall heat transfer resistances in the range between R-11 and R-19. Once the options are selected, the energy simulation engine is able to compare all the different combinations of options to generate a trade-off curve. The trade-off curve shows the energy savings and the annual energy cost related to any single combination of options chosen. With the trade-off curve, it is possible to identify the best solution both from energy savings and cost prospective. Figure 5 shows the trade-off curve obtained. Each point in the graph represents a different combination of building parameters and their associated investment and annual energy costs.

The point on the left side of the graph represents the baseline configuration. The annualized energy cost reported in this case is related solely to the yearly cost of the resources (natural gas and electricity) needed to cover the energy demand. For the retrofit solution the annualized energy related cost includes also the initial capital cost related to the retrofit solution annualized over a time period of 30 years. Most of the retrofit solutions result in an annualized energy related cost lower than the baseline solution including the capital and financing cost of the retrofit.

The curve created by the highlighted points (in black) represents the optimization front. The source energy savings that can be obtained are in the range between 45% and 55%, but the optimum solution (highest energy savings for

the lowest cost) it is obtained with annualized energy related costs equal to 2360 \$/year and a source energy savings of above 50%. The characteristics of the optimum solution are summarized and compared with the baseline one in Table 3 below. The parameters reported in Table 3 are the ones changed from the baseline simulation to the optimum solution.

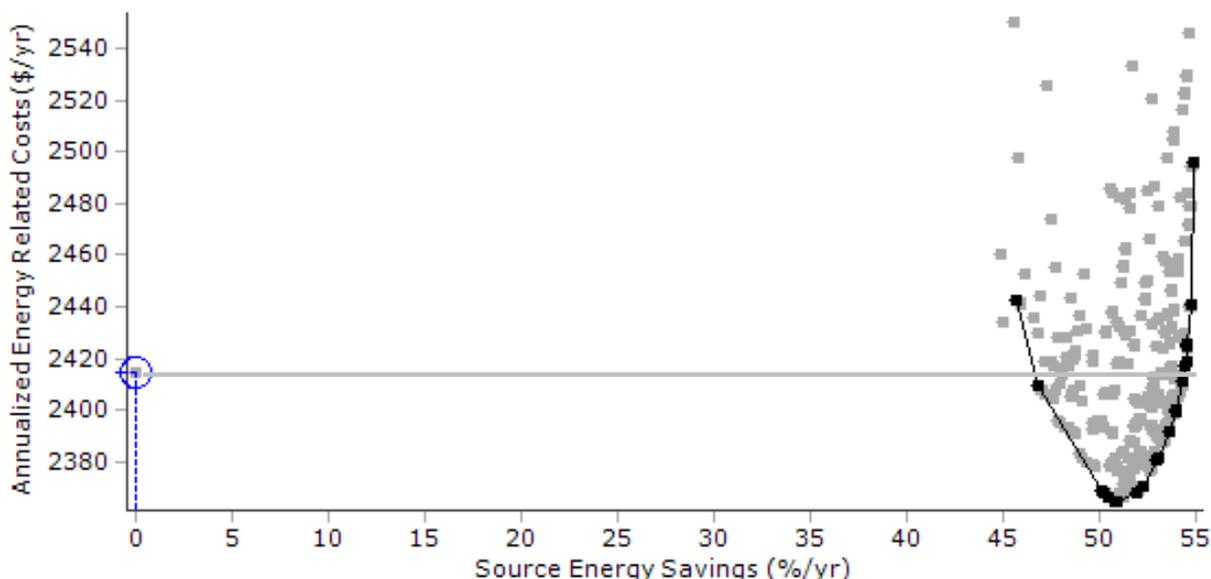


Figure 5: Cost/Energy Savings Optimization Curve

Table 3: Baseline vs. Optimum Parameters

Parameters	Baseline inputs	Optimum inputs
Walls	Wood stud, uninsulated, 40.6 cm	R-13 Fiberglass
Exterior Finishing	Wood, medium/dark	Wood, medium/dark
Wall Sheathing	none	R-5 XBS
Unfinished attic	Uninsulated, vented	R-25 Fiberglass, Vented
Roof material	Asphalt shingles, dark	Asphalt shingles, dark
Finished basement	Uninsulated	R-13 Fiberglass Batt
Windows	Single-pane, clear, non-metal frame	Triple-pane, High Gain, Low E, non-metal frame
Air leakage	10 ACH50	1ACH50
Refrigerator	EF=14.1, top freezer	EF=21.9, top freezer
Cooking Range	Electric	Electric, Induction
Clothes Washer	Standard	Energy Star
Lighting	20% Fluorescent	100% Fluorescent

The total capital cost of the optimum solution according to the assumptions considered by the simulation engine is \$32,037 allowing a cut to the energy consumption of the household in half (50% energy savings).

Figure 6 shows the modeled energy consumption of the test house before and after the retrofit in kWh. The total site energy consumption of the house decreased from 59,136 kWh/year to 24,855 kWh/year for a total energy saving of 34,281 kWh/year (58%). The largest reduction is in the heating demand, which dropped from 42,322 kWh/year to 24,855 kWh/year, a consequent energy savings of 30,356 kWh/year (71% reduction).

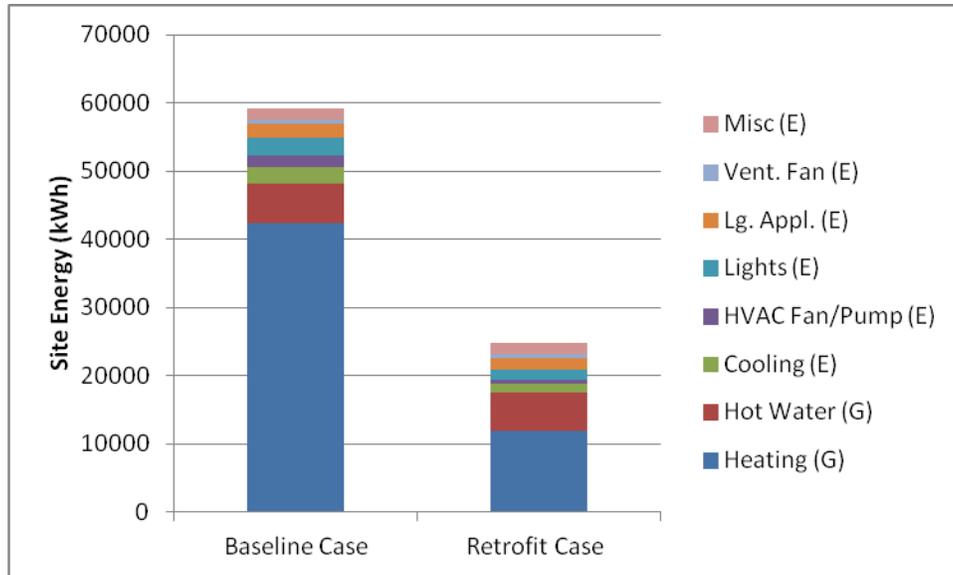


Figure 6: Site Energy Consumption of the Test House

4. PATH TO NET-ZERO ENERGY

In order to achieve the goal of a net-zero energy building it is necessary to produce energy on site and with renewable energy resources to satisfy the amount of energy consumed by the house over the course of the year. The main renewable energy system for the test house is a solar photovoltaic system that will be placed on the roof to generate electricity. Natural gas cannot be considered as it is not a renewable resource and it cannot be produced on site. Therefore, the heating and cooling system as well as the water heater (furnace and boiler, respectively) needs to be replaced with electrically driven systems. In this case, a geothermal heat pump was selected to meet the heating and cooling demands and a heat pump water heater for the hot water demand.

The same software was used to complete another simulation to evaluate the total energy consumption of the test house after the retrofit, including the presence of a geothermal heat pump. All of the other inputs were considered the same as in the optimum retrofit case scenario (Table 3 above). Figure 7 shows the results of this simulation.

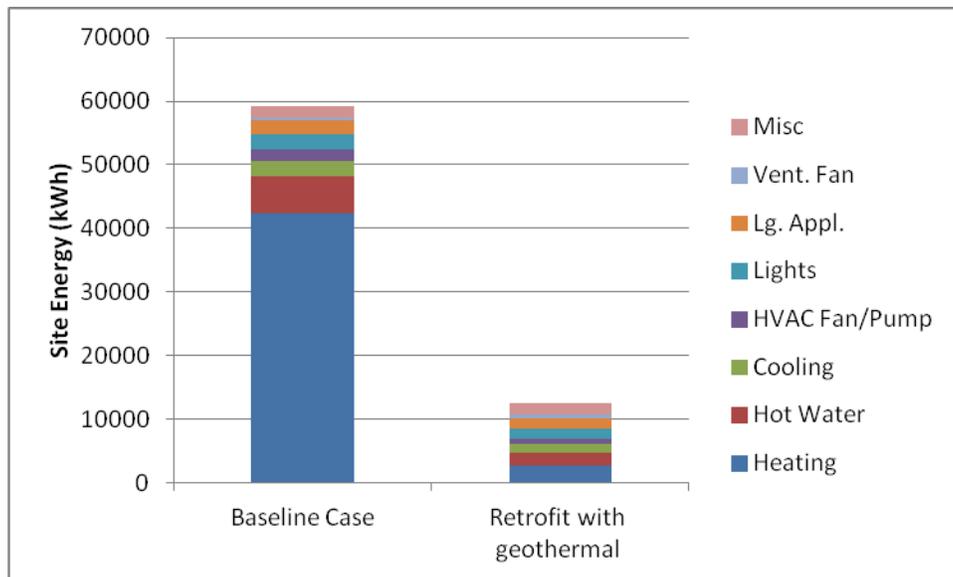


Figure 7: Predicted Annual Site Energy Use (kWh) of Optimum Retrofit with Geothermal Heat Pump

The total site energy usage of this scenario is lower than the one considered in the retrofit scenario without a geothermal system (12,424 kWh/year versus 24,855 kWh/year). The reason for the reduction of site energy is due to the high COP offered by a geothermal heat pump. The site energy consumed by the geothermal heat pump for a year to cover the heating and cooling demand is 4080 kWh. The sum of the natural gas energy (supplied to the furnace for heating) and the electricity (supplied to the air conditioner for cooling) consumed in the retrofit case is 13,387 kWh/year (see Figure 6). The use of a geothermal heat pump is able to bring a HVAC system energy saving of 9,307 kWh/year.

To conclude this analysis, it is necessary to evaluate the solar photovoltaic system. Because the sizing of the solar system is out of the scope of this paper, the analysis has been done simply with the use of the software available online PVWatt (Marion et al. 2000). The program considers the solar irradiance in West Lafayette and a roof pitch of 25° (test house roof pitch), but does not consider any shading. The solar system will be positioned partially on the South side roof and partially on the West side. The total site energy usage is 12,424 kWh/year and the only energy source utilized is electricity.

The simulation shows that with 1.33 kWp installed on the South side (corresponding to the total available space on the south side roof) and 10 kWp on the West side, it is possible to have a total electricity production equal to 12,313 kWh/year. From prior experience of the authors, the online software can under predict actual solar array production and it is believed that a 11.3 kWp system is more than enough to fulfill the net-zero energy requirement.

5. CONCLUSIONS

A single family home located in West Lafayette is taken as an example to investigate different possible retrofit solutions. The final goal of the project is to have the house considered to be net-zero energy. A simulation model of the dwelling was built with BEOpt. A comparison between real energy consumption data and the modeled consumption shows an overall difference of 5% between the two. Using the same baseline model, an optimization, with the objective to minimize annualized energy related costs, of all the possible retrofit solutions was run. The simulation demonstrates that a 50% energy savings can be reached with an investment of approximately \$30,000. According to the simulation, over a period of 30 years the annualized energy related cost is reduced by around 55 \$/year. The net-zero energy goal can be achieved for the test house by replacing the HVAC system with a geothermal heat pump, generating hot water with an air source heat pump and installing a 11.3 kWp solar photovoltaic system. Previous experience with the solar simulation program has shown that net-zero energy could be achieved with a system that is smaller than the modeled 11.3 kWp system.

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