A CRITICAL ANALYSIS OF THE PASSIVE HOUSE STANDARD FOR THE CLIMATES OF THE UNITED STATES

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ABSTRACT

This research demonstrates that when using current technologies and practices, the functional definition of a passive house as defined by Schneiders (Schneiders 2009) and later by Feist (Feist 2012) as a building that "can provide the necessary heating, cooling, and dehumidification through supply air ventilation" is not achievable in all U.S. climate zones. To make possible the widespread adoption of this low energy standard, the Passive House Standard itself needs to be adjusted and redefined for the United States. The study simulated a given sample building by testing building parameters such as the glazing percentage, solar heat gain coefficient, window U-Values, and R-Values for the walls, roof, and floor. For each of the 1000 TMY3 climate locations throughout the United States, 10,125 unique cases were simulated until every possible combination of the factors above were run. This process of optimization will demonstrate the sensitivity of certain passive house features to increases and decreases in energy use as well as the limits to what is achievable in passive house design and construction. To maintain precision between the climates, this research analyzed the simulated results for each passive house criteria against the data from within each climate set including temperature, radiation, dew point, and sky temperature. The analysis resulted in adjusted passive house criteria based on the characteristics of a specific climate data set's location.

INTRODUCTION

In the late 1980s and early 1990s, Dr. Wolfgang Feist and Professor Bo Adamson began research on the contemporary Passive House Standard. They advanced the work and research already completed in the United States and abroad. The first Passive House, Kranichstein, was constructed in October 1990 in Darmstadt, Germany (Feist). Following additional research and modifications, the Passivhaus Institute (PHI) was founded in 1996. In the late 1990s, the Passive House Planning Package (PHPP), an energy modeling tool, was developed and initially released. The PHPP has been continually refined with major updates released in 2001, 2004, 2007, Version 7 in 2012, and most recently, Version 8 in 2013.

Along with the development in energy modeling and the increasing understanding of building physics, came the development of certification criteria. Developing the defining criteria for certification also began the process of creating a marketable brand and product called Passivhaus. In 2007, the founder of the Passivhaus Institute, Dr. Wolfgang Feist, wrote that "A Passive House is a building in which thermal comfort [ISO 7730] can be ensured by only heating or cooling the supply air volume needed for sufficient air quality - without using additional circulating air" (Feist 2007). Therefore, supply air conditioning became the defining criteria for the Passivhaus Standard. By using the ventilation system for conditioning, there can be a significant savings in both economic, operating, and lifecycle costs due to mechanical efficiency, which drives passive house towards being the economic optimum building. These savings are achieved by investment in the building envelope, which is offset by savings from the reduction in

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size or even the elimination of the furnace or heating system. The envelope investment reduces the space conditioning loads of the passive house until they are small enough to be distributed by the mechanical ventilation system. Therefore, there is great importance placed on meeting the Heating Load, which is the amount of heating able to be provided by the flow rate of the supply air ventilation, and can be defined as:

$$P_H \leq 10 \text{ W/m}^2$$

The value of 10 W/m^2 for the Peak Heating Load calculation is based on the flow rate needed for ventilation, the specific heat capacity of the air, and the air temperature. In the central European climate fulfilling the peak heat load requirement led to an Annual Heating Demand of:

$$Q_H \leq 15 \text{ kWh/(m}^2\text{a)}$$

For controlling durability of the exterior envelope and limiting energy loss through infiltration, a requirement of building air tightness was added at:

$$n \leq .6 \text{ ACH}_{50}$$

In the central European climate the Annual Cooling Demand related well with the level of conditioning available using supply air conditioning. Therefore, the criteria for the Annual Space Cooling Demand was determined to be:

$$Q_K \leq 15 \text{ kWh/(m}^2\text{a)}$$

There is also a certification criterion that accounts for all of the energy used in the building. The term Primary Energy (PE) is often referred to as "source energy," which is the amount of power that must be produced at the power plant to provide energy for the entire building. On the other hand, site energy is the amount of energy the building actually consumes and uses locally. A PE factor of 2.7, the standard value used for passive houses, means that for every 1 unit of power consumed on site, 2.7 units of power must be produced by the power plant. The Primary Energy factor also acts as a sustainability requirement to cover "resource conservation, emission minimization, and climate protection" (Feist 2007). The Primary Energy criterion is:

$$W_p \leq 120 \text{ kWh/(m}^2\text{a)}$$

In summary, the criteria of the passive house standard are defined as:

Criteria	**I.P. Units**	**S.I. Units**
Annual Space Heat Demand:	4.75 kBTU/ft^{2}yr	(15 kWh/(m^{2}a))
or Peak Heat Load:	3.17 BTU/ft^{2}hr	(10 W/m^2)
Annual Cooling Demand:	4.75 kBTU/ft^{2}yr	(15 kWh/(m^{2}a))
Annual Primary (Source) Energy Demand:	38 kBTU/ft^{2}yr	(120 kWh/(m^{2}a))
Air Infiltration rate :	n $\leq$ .6 ACH50	(air changes per hour at 50 Pascals of pressure)

Figure 1 - Passive House Criteria

THE ANALYSIS

This study utilizes a full factorial experiment to quantitatively analyze the Passive House Standard for use in the United States. The results were determined through multiple building energy simulations using the Passive House Planning Package (PHPP) to analyze existing criteria for the certification of buildings as passive houses including the Annual Heating Demand, Peak Heating Load, Annual Cooling Demand, Peak Cooling Load, and Primary Energy Demand. The full factorial experiment was able to distill the inherent complexity of a building into variables that could be quantitatively studied through multiple iterations. The first step in creating the experiment was determining which of the building envelope components would be

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held constant and which would be part of the independent variables. The constants consisted of a simulated building and the corresponding additional inputs needed for the energy model. There were also independent variables, shown in Figure 2, which were varied as part of the full factorial experiment. In each climate location, one value of the independent variables was changed until every possible combination was simulated. The dependent variables, also shown in Figure 2, are the major certification criteria used to certify buildings to the Passive House Standard.

Independent Variables	Dependent Variables
Wall R-Value	Annual Heating Demand
Roof R-Value	Peak Heating Load
Slab R-Value	Annual Cooling Demand
Window R-Value	Peak Cooling Load
Window SHGC	Primary Energy Demand
Glazing Percentage	

Figure 2 - Independent and Dependent Variables

As previously mentioned, the simulation was a full factorial study that varied the values of the independent variables at set thresholds. This was repeated for each climate location. The independent variables chosen for the full factorial experiment were the factors that had the largest percentage impacts on the energy balance of the building. The variables were chosen because of their relationship to the performance of the building envelope and energy conservation through passive means. These variables were most influenced by the outdoor climate. Therefore, they were also the variables that were of the most interest when testing the applicability of the Passive House Standard for different climate zones. Because of this inherent complexity and the multitude of parts that comprise a building, the vast majority of the building's details were held constant. Most of these details have no effect on energy performance, but some of them do influence the energy performance values the study analyzed. However, most of these influences were minor, commonly standardized, or had typical values for most energy simulation purposes.

The independent variables were the wall R-Value, roof R-Value, slab R-Value, window R-Value, SHGC of the glazing, and Southern glazing percentage. A full factorial experiment consists of factors, shown above as the independent variables, and levels, or the possible values of those factors. Figure 3 shows the variables to be tested using small increments between the values. The six factors worked independently of one another and reached a high level of detail because the flexibility between the factors allowed them to discover the best case based on each specific climate. Within this experiment, every value was tested in every possible combination, with all of the variables working independently of one another, until all unique combinations were tested.

In a full factorial experiment, each factor is varied until every potential unique case has been simulated. This leads to large amounts of data because the number of combinations grows exponentially as a level or factor was added. To limit the number of combinations generated per simulation, the number of variables and their interactions were simplified. To do this, the R-Values for the wall and roof were linked so that they moved in tandem. The slab was left independent from the other insulation values. Because the floor or slab insulation can have large

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impacts both on heating and cooling and in varied climates, the best results may be achieved by having very high roof and wall insulation while having very low or nonexistent slab insulation.

Wall R-Value	Roof R-Value	Slab R-Value	Window R-Value	Glazing SHGC	South Glazing Percentage
20	40	0	3	.2	5
30	50	5	5	.3	15
40	60	10	7	.4	25
50	70	15	9	.5	35
60	80	20	11	.6	45
70	90	25			
80	100	30			
90	110	35			
100	120	40			

Figure 3 - Full Factorial Variables

There were five total factors, or variables, as the wall and roof have been combined to act as one variable. Therefore, two of the variables had nine levels and other three had five levels, this led to 10,125 unique cases. The cases were initially created using JMP Pro and simulated using the Passive House Planning Package (PHPP). The PHPP is a modeling tool developed by the Passivhaus Institut specifically for energy analysis of passive houses and is a static, or steady state, model, which means the simulation occurs for a set condition, such as a set temperature difference for the calculation of transmission losses. In this case, the boundary conditions vary by month and are summed to create annual results. The PHPP was chosen as the simulation engine because it allows many calculations to be run in quick succession and it is fully customizable and programmable through both Excel functions and Visual Basic coding. The engine behind the PHPP is Microsoft Excel and was originally developed using metric (SI) values. The version of the PHPP used in this study was a custom Imperial Units (IP) overlay. Programming both the IP overlay and the SI sheets, where the calculations occur, was critical to harnessing the true power of the program through customization. The process was automated through a data table and VBA Script and resulted in 10,125 unique combinations for over 1,000 TMY3 climate data locations in the United States.

Before the experiment could be run, the constants were input into the Passive House Planning Package. These consisted of building characteristics of the baseline building and the additional inputs needed for the PHPP. Many of these additional inputs were default PHPP values based on the building characteristics listed below:

- Single family residence
- Two story, slab on grade
- 1,600 square feet of treated floor area (~800 per floor)

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- Interior floor plan dimensions 23 ft. x 38 ft.
- Orientated with long sides facing North / South
- 9 ft. ceiling heights
- Roof truss with horizontal ceiling insulation

Using these characteristics led to specific entries in the PHPP and assumptions based on occupancy, usage patterns, and internal heat gains, as well as additional implied information about the building such as the level of thermal mass, the mechanical system, and other details that were not directly pertinent to the tested variables. Additional information regarding every simulation entry can be found in the thesis on which this research was based (Abendroth 2013).

RESULTS

The results were analyzed in a variety of ways. The first analysis was done without any adjustments or sorting performed on the data. In Figure 4, below, the Annual Heating Demand for each climate data location in Illinois has been plotted. The number of cases is shown from highest energy use to lowest energy use along the x-axis. The y-axis of all of the following graphs is either Heating/Cooling Demand (kBTU/ft^{2}yr) or Heating/Cooling Load (BTU/ft^{2}hr) depending on the figure's title. Each climate data set location is represented by a different color curve. The Heating Demand for all TMY3 locations in the state of Illinois is graphed in Figures 4 and 5. The Heating Load is shown in Figures 6 and 7. The Cooling demand is shown in Figures 8 and 9 and Cooling Load is graphed in Figures 10 and 11. All fifty states each had a similar graph for each certification criterion. Figures 4, 6, 8, and 10 show the limits of what is technically possible in a given location from, high to low. Figures 5, 7, 9, and 11 are a graphical cutoff from a statistical analysis program simulation and always show the best cases. The analysis program chooses the point that the new certification criteria should be based on of all of the variables, defaults, and assumptions utilized in the study.

If increasing the adoption of the Passive House Standard is one of the goals of attempting to set a recommendation for a new Passive House Standard set of criteria for the United States, then the value that is chosen must be achievable by more projects than the "perfect" project. Therefore, choosing the very best case as the new criteria for a certification standard that needs to be surpassed is not a viable option. If this were the case, many projects would be unable to obtain certification. If the site was not quite perfect, in terms of solar access, for instance, certification would be unobtainable for the building. Also, since the simulated building is rather compact, if the actual building attempting to be certified differed slightly from the simulated case, in shape, size, or treated floor area, then certification would again be unobtainable. If for some reason the most effective strategy could not be used, based on the figures above where it was shown that the strategies that worked, worked very well, the best case is again unobtainable.

When looking at the full curve of the Illinois simulations in Figures 4, 6, 8, and 10, the buildings that meet current certification criteria are near the right side of the graph in the higher case numbers. As stated in the previous paragraph, it does not make sense to create criteria at the far right edge of the figure. It also does not make sense to create target criteria on the left side of the graph. Such a target would be too easy to achieve and would ignore significant energy savings that would be relatively easy to realize. Therefore, the criteria should be somewhere between the far right and the far left, but pushed as far right as is reasonable and feasible so that the energy savings are maximized.

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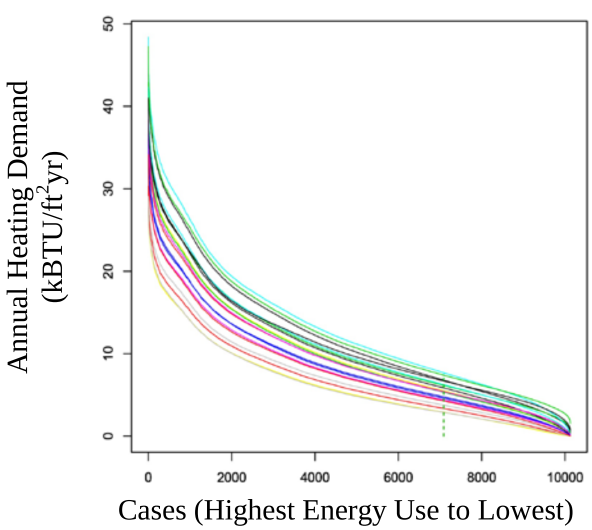
To determine the point at which the adjusted criteria should be set, a method was created that relied on the principle of marginal effectiveness between the cases. The marginal effectiveness increased at both the beginning and end of the full range of cases. Since finding the marginal effectiveness only in the area of good energy performance is of value, the cases of high energy use could be discarded. Using a statistical criterion, Bayesian Information Criterion (BIC), linear tangent lines could be tested by using logarithmic functions and an Analysis of Variance (ANOVA). The program 'r' was used to complete the analysis by comparing the tangent lines at each point. At each data point, the tangent was found and its fit was judged using the shape of the curves to each side of the point. The analysis cycled through the points until the best fit for both curves is found. This point happens to be the point where the slope begins to steepen and an increase in marginal effectiveness begins to occur. By finding this point, the standard criteria can be set in a way that maintains high standards for energy efficiency, yet still allows room for improvement or room to be more efficient than the standard demands. This room allows for design freedom and the possibility of creating an architecturally compelling building, along with freedom for the designer to use specific strategies customized for a given set of restraints.

The Annual Heating Demand for the state of Illinois using cases 8,000-10,125 is shown in Figure 5, below. In this figure, it is possible to determine the point where the marginal effectiveness begins to increase by using the two-slope method as described above. The vertical lines mark the points where the new criteria are plotted. The energy values that correspond to these lines were saved and utilized for further analysis. Note how the values chosen were pushed far to the right so that only the most efficient ten percent, or so, became the points and values chosen. At the same time, the most efficient cases are still able to surpass the certification criteria. In Illinois, the values for heat demand that were chosen would constitute a slight tightening when compared to the Passive House Standard's current criteria.

Figures 6, 8, and 10 show the full results and Figure 7, 9, and 11 show the best performing cases, cases 8000-10125, for the Heating Load, Annual Cooling Demand, and Cooling Load for Illinois respectively. Both of these graphs show the similar trend to the Annual Heating Demand.



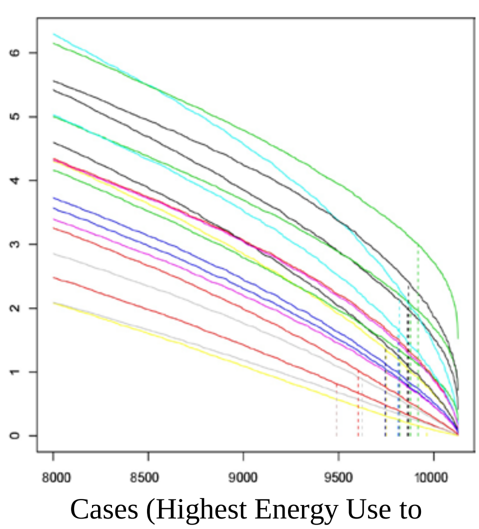


Figure 4 - IL - Heating Demand - Full

Figure 5 - IL - Heating Demand - Best Cases

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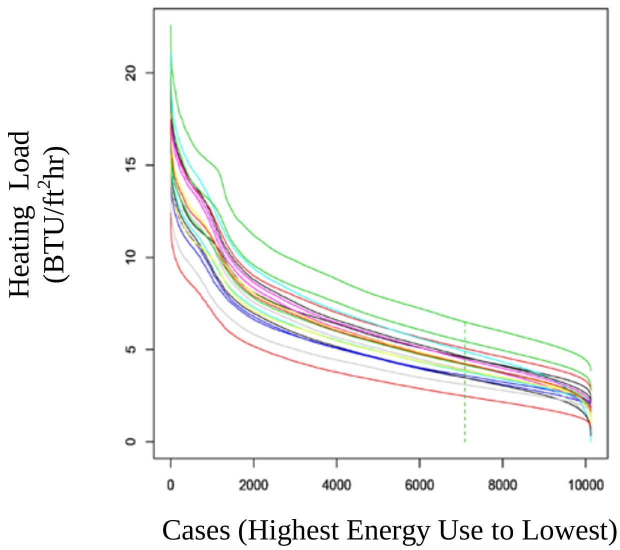


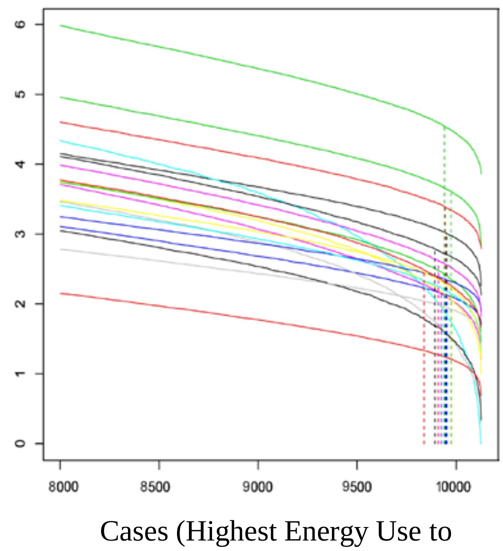
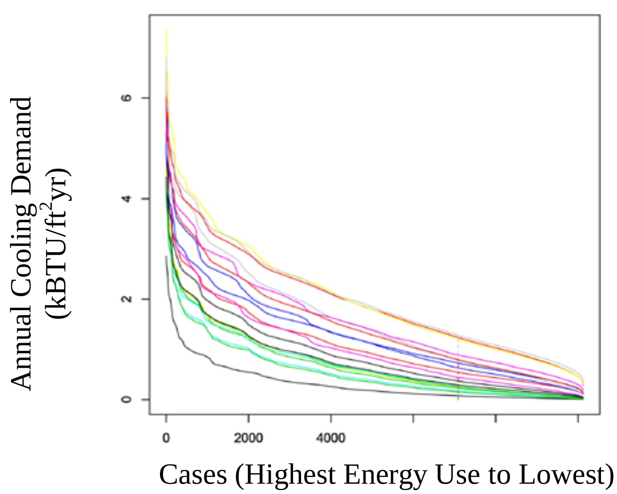


Figure 6 - IL - Heating Load - Full   Figure 7 - IL - Heating Load - Best Cases

The Heating Load results plotted in Figure 6 show the same trend as the Annual Heating Demand, but are enlightening due to their values. The current criteria for the Heating Load is 3.17 BTU/hr*ft^2. The loads for some locations in Illinois will meet that criterion, while the loads for others will not. Since all of the climate locations in Illinois can meet the Annual Heat Demand criteria, if the certification criteria between Demand and Load values were matched in a way that if you meet one heating criteria, you meet the other, much like the current Passive House Standard as it pertains to Central Europe, it would follow that every climate in Illinois should be able to meet the Heating Load as well. This proves that the assumption that a given Annual Heat Demand, 15 kWh/m^{2}yr (4.75 kBTU/ft^{2}yr) in central Europe, equates to a given Heating Load, 10 W/m^2 (3.17 BTU/hr*ft^2) in central Europe, is not accurate and that there are other factors that influence these two criteria at different rates.

The cooling cases for both demand and load are shown by the following figures.



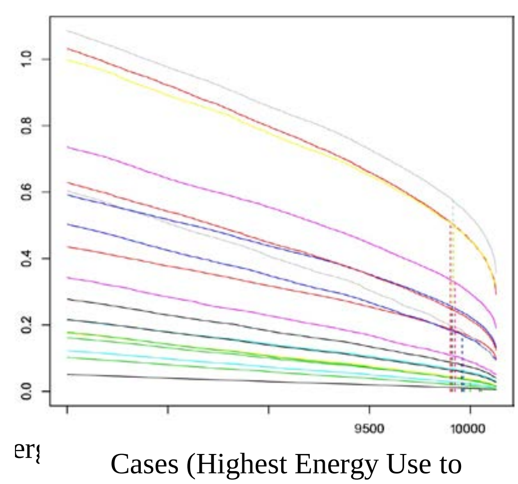


Figure 8 - IL - Cooling Demand - Full   Figure 9 - IL - Cooling Demand - Best Cases

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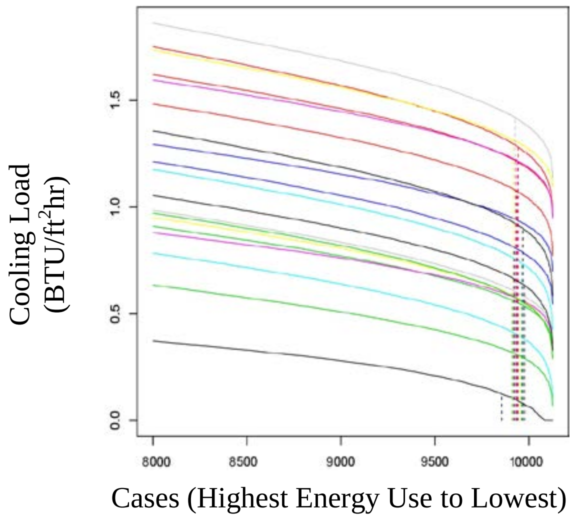

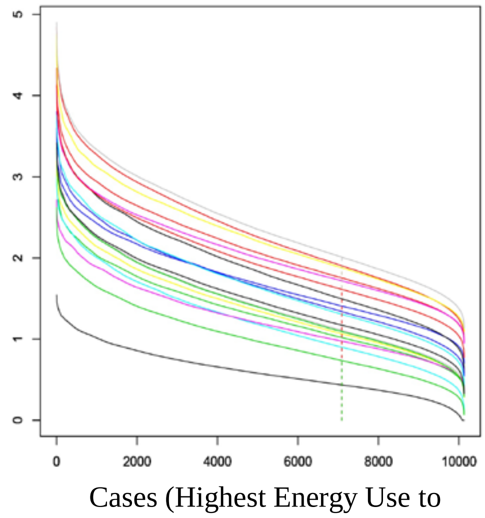

Figure 10 - IL - Cooling Load - Full   Figure 11 - IL - Cooling Load - Best Cases

Once the values for the Annual Heating Demand, Heating Load, Annual Cooling Demand, and Cooling Load were determined for every climate location, they were plotted against the characteristics of the climate location. The first graph, Figure 12, below, shows the relationship between the Annual Heating Demand and the average yearly temperature. Each of the plotted points represent the best fit case, found through the statistical analysis, for each climate data location. As expected, as the temperature decreases, the amount of heating energy needed increases. The trend is rather linear once the temperature is cold enough to create a heating demand. The cooling dominated and mixed climates are also plotted on the graph, which creates a significant grouping of cases that have a near zero Annual Heating Demand.

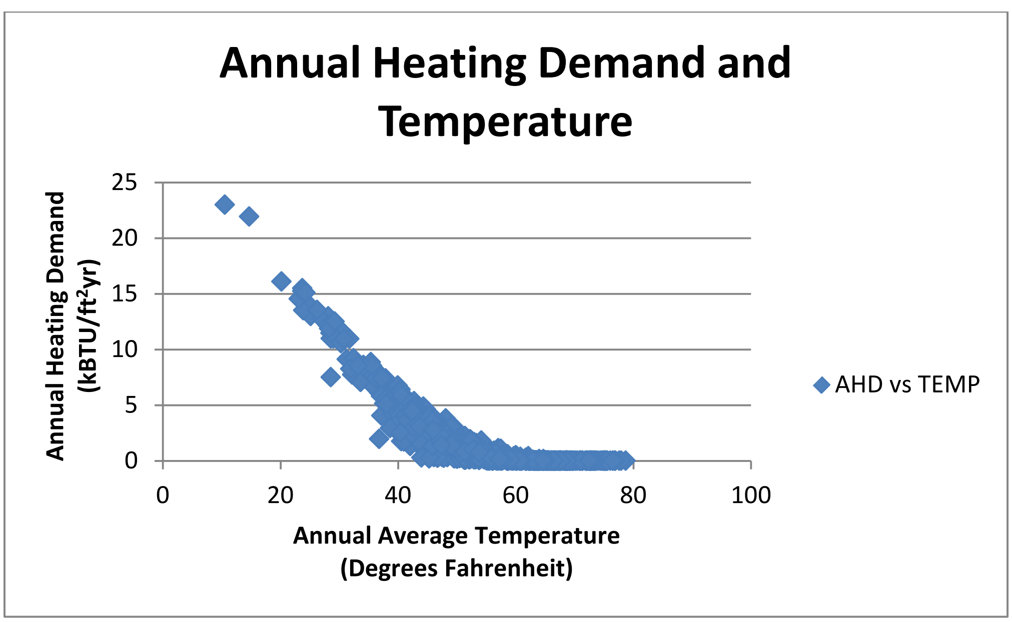

Figure 12 - Relationship between Annual Heating Demand and Temperature

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The relationship between the Annual Cooling Demand and temperature that is shown in Figure 13 is very similar to the relationship between Annual Heating Demand and average temperature except that as temperature increases, the Annual Cooling Demand also increases. Another difference is the rate at which the energy use increases with the temperature. The slope of that increase is visibly steeper than that of the Annual Heating Demand. The magnitude is also not nearly as great when compared to heating energy. Both of these characteristics can be partially attributed to the fact that the temperature difference for heating is very large compared to cooling. The larger temperature difference for heating equates to a larger heating energy use overall and the smaller temperature difference for cooling allows the increase in energy use to be stacked closer to vertical. In addition, the Annual Cooling Demand only measures sensible cooling. If latent energy were added into the equation, the cooling energy would be significantly higher and more in line with, or surpass, the heating energy depending on climate location.

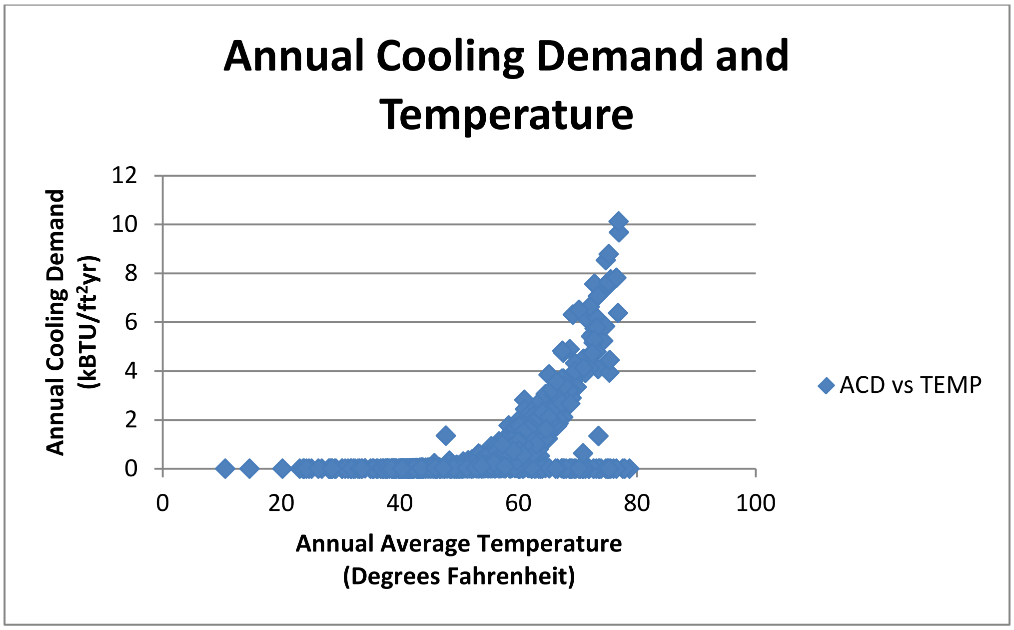

Figure 13- Relationship between Annual Cooling Demand and Temperature

Figure 14 shows the relationship between Heating Load and temperature. The temperature used in the analysis was the average of the two temperatures for the Heating Load calculation, which consists of a cold/sunny day and a warm/cloudy day. Since the temperature is no longer the annual average, the temperature is much colder than the annual average temperature used in the calculation of the relationship between temperature and the Annual Heating Demand. However, the same overall distribution and trends hold true for the Heating Load and temperature as for the Annual Heating Demand and temperature. There was one outlying case and a few specialized climates where the temperature was rather low, but the Heating Load was also very low and in some cases zero. With that in mind, the trend was very linear and there was a strong visual correlation.

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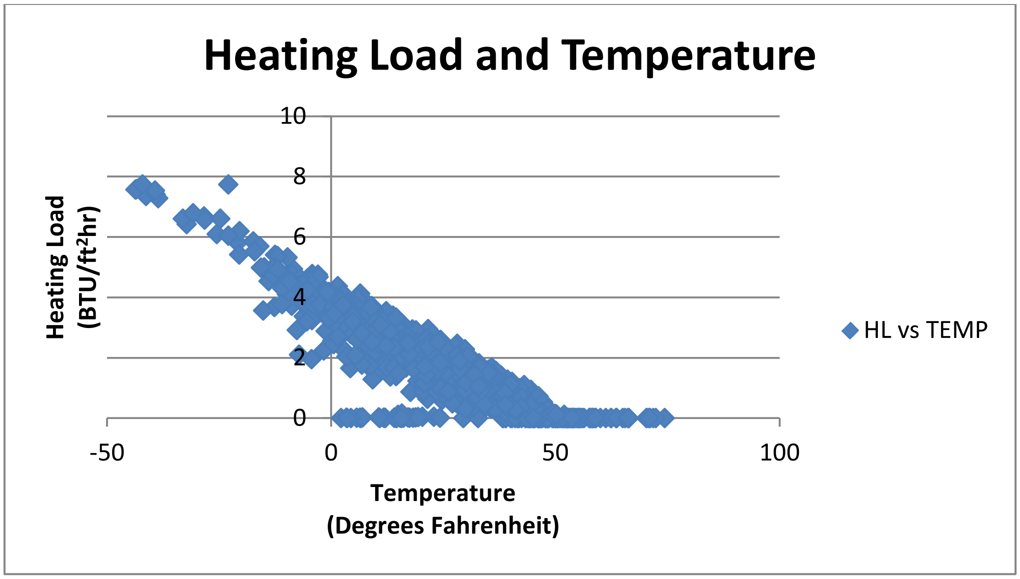

Figure 14 - Relationship between Heating Load and Temperature

The relationship between the Cooling Load and temperature as shown in Figure 15 also indicates a similar trend as seen between the previous graphs and analysis. As the temperature increases, the Cooling Load increases rapidly due to some of the causes mentioned earlier such as the small temperature differences between indoors and the exterior during the cooling season. Similar to the comparison between the Annual Heating Demand and Cooling Demand, the magnitude of the Cooling Load is not as great as that of the Heating Load.

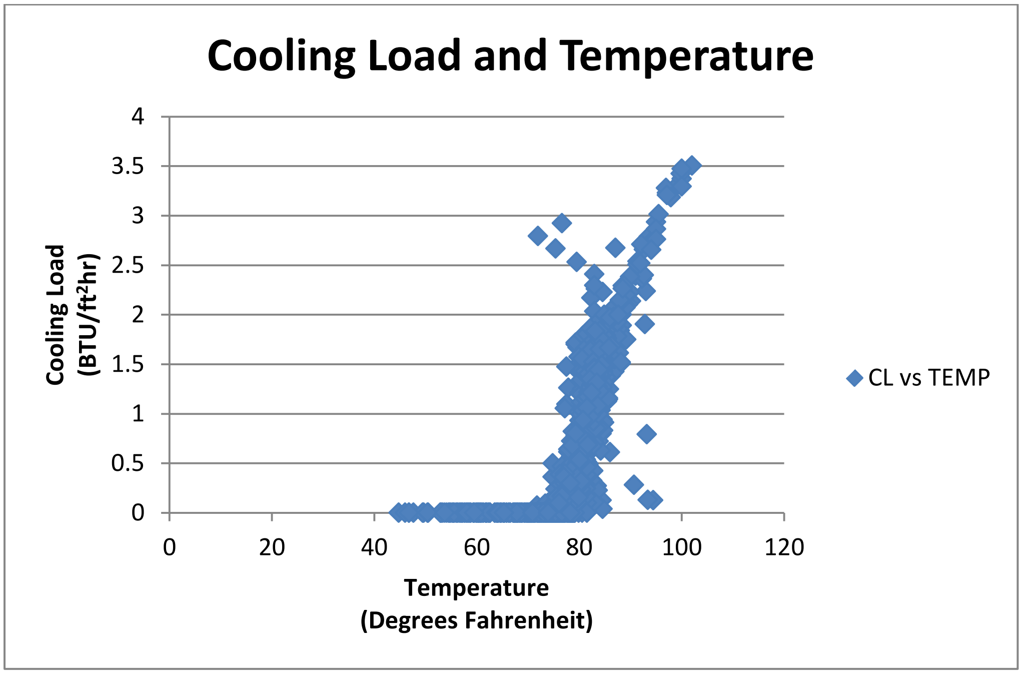

Figure 15- Relationship between Cooling Load and Temperature

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CONCLUSION

Figures 12-15, above, for the analysis between the various energy use graphs and temperature all show a strong correlation between the temperature and the energy use. In addition, all of the figures show trends that are to be expected, such as when the temperature decreases, heating will increase. The most interesting finding was that in the majority of climates, meeting the Passive House Standard is achievable. It was almost always possible to meet the Cooling Demand, due to the standard when the study was run counting only sensible energy. It is also possible to meet the standard in regards to Heating Demand and Heating Load, except for the most extreme climates, such as inland Alaska, where solar gain is limited, temperatures plummet, and the moderating effect of the ocean does not have an impact. Locations where there is a moderating water body, easily meet the standard and in many cases, those locations should have more stringent requirements. The other region where it is difficult to meet the standard is near the southernmost points in the United States, where internal heat gains become difficult to overcome because they cause a constant cooling load. The South in particular would have an even more difficult time meeting the standard if latent energy were accurately accounted for by the PHPP in this simulation.

While the R-values of the roof, wall, and slab were important in terms of energy use, after a certain point, those factors' ability to influence energy use is reduced. On the other hand, the window parameters, most significantly window R-Values and Solar Heat Gain Coefficients, have extremely large impacts regardless of climate. Whether the building in question is in a hot, moderate, or cold climate, the combination of window R-Value and SHGC were of utmost importance. Once technological advances allow windows with R-Values above ~R-15 to be commercially available at an economical price, meeting Passive House Standard would be achievable in all but the most extreme climates in the world.

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FIGURES

All figures have the same source:
Abendroth, Ryan. 2013. A Critical Analysis of the Passive House Standard for the Climate Zones of the United States. Master's Thesis. School of Architecture. University of Illinois at Champaign-Urbana

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