LOW ENERGY DWELLING IN COLD CONIFER-FORESTED MICROCLIMATES: A THERMAL EFFICIENCY CASE STUDY

Keith Bickford[1], and Frank Jacobus[2]

[1]The University of Idaho, Moscow, Idaho

[2]The University of Idaho, Moscow, Idaho

ABSTRACT: A proposed carbon neutral dwelling in a cold region, alpine-forested microclimate is analyzed using a building energy analysis program and is redesigned to improve energy efficiency. The Passive House standard is used as a design guideline and a Passive House certified dwelling is used as a case study for comparison. By increasing thermal performance parameters of the proposed dwelling, energy costs are reduced by 67%. Achieving carbon neutrality in terms of building operation is now attainable.

1.0 INTRODUCTION

With the initiation of the 2030 Challenge and the increasing threat of environmental instability due to CO_2 emissions, in large part as a byproduct of the building sector, it is imperative that engineers and architects work together to increase knowledge and awareness of design practices and principles that reduce building energy use and continue to advance technologies that aid in a reduction of the burning of fossil fuels.

This research analyzes thermal efficiency strategies for a low energy dwelling in a cold region alpine-forested microclimate through a case study comparison of energy reduction methods and their resultant effect on a building's energy use. Specific strategies for building envelope thermal efficiency and passive heating will be explored in an effort to minimize energy consumption associated with thermal comfort of the proposed structure.

1.1 HYPOTHESIS

Proven passive design strategies are not sufficient in predominately cold alpine-forested microclimates. Designing for passive solar heating in these climates can actually degrade the building's performance as a result of low solar insolation and high thermal losses through the window glazing. Therefore, buildings in cold climates must rely on extensive insulation and minimal sources of heat loss. Windows on southern walls must include movable insulation to cover apertures when there is no sunshine, while windows on non-southern walls must be minimized to avoid heat loss.

2.0 PROJECT BACKGROUND

In 2006, an interdisciplinary group of faculty and students from the University of Idaho began designing a carbon neutral campus at one of the university's field sites in McCall, Idaho. This campus houses the McCall Outdoor Science School (MOSS) and Environmental Learning Center. The goal is to redesign and rebuild the campus with the vision of the 2030 Challenge as a primary guide and motivation.

This research is a comparison between the first building designed for the McCall campus, a dwelling that will house up to 18 people, and the Waldsee BioHaus in Bemidji, Minnesota, the first passive house example in the United States. A preliminary study of the BioHaus and other passive house precedents indicates a reduction in energy use unlike any previous U.S. examples (Klingenberg, Kernagis, & James, 2008).

The two projects are analyzed for microclimate, site orientation, material selection, energy efficiency, and heating strategies. The BioHaus model's anticipated versus actual energy performance is a primary aspect of the inquiry. The BioHaus model and MOSS model are analyzed using energy modeling simulation software to establish benchmark performance levels and goals.

3.0 MOSS BUNKHOUSE CURRENT DESIGN

The MOSS bunkhouse is currently designed with straw bale walls and a SIP roof. The straw bale design was chosen for sustainability reasons. The straw is locally available and the building material is grown, not manufactured. This design has a wall R-value of R-30 and a roof R-value of R 45. The roof R-value could be increased by doubling the SIPs or by adding additional insulation within the ceiling space. Window area was maximized on the southern façade to maximize solar gain for winter heating. The windows on all other walls were optimized to reduce thermal loss while maintaining ample natural day lighting. A heat recovery ventilator (HRV) was intended, but not modeled due to software limitations. Space heating is accomplished by a biomass burner feeding a radiant floor heating system.

4.0 CASE STUDY SELECTION: WALDSEE BIOHAUS

The Waldsee BioHaus in Bemidji, Minnesota is the first certified Passive House in the United States. The BioHaus, designed by architect Stephan Tanner, was completed in 2006. The BioHaus is home to the German Language Village of the Concordia Language Villages, and serves as an educational and environmental learning center (Klingenberg, Kernagis, & James, 2008). The energy performance achievements of the Waldsee BioHaus and the similarity of climate between Bemidji, Minnesota and McCall, Idaho drove the decision to utilize the BioHaus as a benchmark for design consideration and for comparative analyses.

4.1 Waldsee BioHuas Building Envelope

The BioHaus measures 54' x 51' and has an interior floor space of nearly 5000 square feet. The BioHaus is constructed of highly insulated wall and roof panels, and a well insulated concrete slab to combat the extreme winters (Klingenberg, Kernagis, & James, 2008).

Below grade exterior walls are constructed of insulated concrete blocks and an exterior insulation and finish system (EIFS), and finished internally with gypsum board for a combined R-value of 55 (Klingenberg, Kernagis, & James, 2008).

First floor above grade exterior walls are constructed of 2" x 12" wood studs and water based Icynene spray foam insulation. The interior is finished with gypsum board and the exterior with Oriented Stand Board (OSB) and an 8" EIFS. The cumulative R-value is 70 (Klingenberg, Kernagis, & James, 2008).

Second story above grade exterior walls are constructed of 2" x 6" wood studs with water based Icynene spray foam insulation and exterior 2" Vacuum Insulated Panels (VIPs), which alone achieve an R-value of R-25.159 per inch. The interior is finished with gypsum board. This assembly has a combined R-value of 70 (Klingenberg, Kernagis, & James, 2008).

The lower roof over the apartment area is constructed of 12" TJIs insulated with water based Icynene spray foam insulation. This is then topped with a 2" VIP encapsulated between 2" rigid foam above and below for protection and to minimize thermal bridging. This assembly gives an R-value of 100 (Klingenberg, Kernagis, & James, 2008).

The upper roof assembly is constructed of 12" TJIs and 8" sleeper trusses with plywood sheathing on the exterior and gypsum board on the interior. 20" of water based Icynene spray foam insulation provides an R-value of 100 (Klingenberg, Kernagis, & James, 2008).

The 4" concrete slab is insulated with 14" of rigid foam for a system R-value of 55 (Klingenberg, Kernagis, & James, 2008).

4.2 Waldsee BioHaus Windows

Windows for the BioHaus are German sourced Müller Fensterbau Optiwin-brand 3 Passivhaus certified windows. These argon filled triple pane windows have wood frames and cork insulation and an R-value of 8. The ratio of glazing areas to above ground wall areas for south, north, west, and east walls is 48.9%, 16.5%, 26.4%, and 19.1% respectively. The south windows have operable external solar blinds to protect from undesirable summer heating (Klingenberg, Kernagis, & James, 2008).

4.3 Waldsee BioHaus Ventilation and Heating

To maintain high indoor air quality with minimal heat loss, the BioHaus receives fresh air year round through a 330' antimicrobial earth tube buried 8' to 9' below grade. The earth tube adds or removes heat from the incoming air by means of conduction to or from the roughly 55 degree Fahrenheit temperatures below ground. This pre conditioned air is further conditioned through a 85% efficient heat recovery ventilator manufactured by Lüfta. The combined system can warm cold winter -32 degree Fahrenheit air to 58 degree Fahrenheit before entering the building. This lessens the demand for a conventional heating system normally employed in this climate. Heating is provided through a ground source heat pump and passive-solar gain (Klingenberg, Kernagis, & James, 2008).

5.0 PASSIVE HOUSE, A HIGHER STANDARD

5.1 Passive House Background

A passive house refers to a well-insulated air-tight house with minimal thermal bridging, insulated glazing, and system energy recovery ventilation. The passive house became popular in the predominately cold Central European climate, where they could replace conventional heating systems with small electrical resistance heaters. These houses retained the heat from internal sources, such as people, lights and electrical appliances, as well as solar radiant heat through glazing. Heat recovery ventilators ensure high indoor air quality while recovering the heat otherwise lost through natural ventilation and exhaust fans. Early prototype homes in Germany could be heated with less than 0.9 watts/ft^2 of floor space. These figures represent a 90% reduction in energy consumption compared to a conventional home (Klingenberg, Kernagis, & James, 2008).

5.2 Passive House Standards

The Passive House standards were devised and perfected by Dr. Heist, a German Physicist and professor at the University of Innsbruck, Austria. Dr. Heist received research grants to develop the Passive House Planning Program (PHPP), a very thorough computer simulated energy analysis software. In 1996, Dr. Heist founded the Passivhaus Institute (PHI) in Darmstadt, Germany. The Passive House Standard is the strictest energy performance standard in Europe (Klingenberg, Kernagis, & James, 2008).

5.3 Passive House Certification

As of this writing, any Passive House certified building must use no more than 1.35 kWh/ft^2 (4.8 kBTU/ft^2) for heating and no more than 1.35 kWh/ft^2 (4.8 kBTU/ft^2) for cooling. Primary energy consumption for space conditioning, hot water, and electricity must not exceed 10.8 kWh/ft^2 (4.8 kBTU/ft^2). Passive House certification requires modeling with PHPP. After construction, they must pass a blower door test, and they must be monitored using installed devices. The blower door test must demonstrate an air-tightness of less than or equal to 0.6 Air Changes per Hour at 50 Pascals (0.6 ACH@ 50Pa) (Klingenberg, Kernagis, & James, 2008).

5.4 Passive House for Extreme Climates

Revised passive house standards are under consideration for northern Europe's harshest climates, such as Sweden and Denmark, where the strict energy performance requirements are deemed impractical (Nieminen, Holopainen, & Lylykangas, 2008).

5.5 Passive House in the United States

The Passive House standard found its way to the United States after architect Katrin Klingenberg visited Europe touring Passive Houses. Klingenberg designed the first Passive House in the United States. This house uses 1 kWh/ft^2/year for heating, although it was never officially certified(Klingenberg, Kernagis, & James, 2008). Klingenberg founded the nonprofit Ecological Construction Laboratory (e-co lab) in 2004. The Passive House Institute United States (PHIUS) was founded by Katrin Klingenberg and house builder Mike Kernagis in 2007.(Klingenberg, Kernagis, & James, 2008).

6.0 CLIMATE ANALYSIS

Building energy simulation programs rely on user input climate information to model building energy performance. Climate attributes considered are: dry bulb temperature, relative humidity, direct solar radiation, diffuse horizontal solar radiation, wind speed (not essential but preferable), wind direction (not essential but preferable), cloudiness, and rainfall (not essential but preferable) (Autodesk, 2008).

6.1 Climate File Selection

The US Department of Energy has climate files with the necessary attributes available for several locations in and around Idaho, but not for McCall Idaho. To select a suitable substitute for the modeling program, climates of other sites in and around Idaho were compared to the climate of McCall using climate charts from the National Climate Data Center (NCDC). The NCDC has information for most cities across the US including McCall. The charts and data for McCall were compared to charts and data for Idaho cities that have climate files available from the US Department of Energy. The climate of Soda Springs-Tigert AP most closely resembles the climate of McCall. The Soda Springs-Tigert climate file was utilized for all analyses of the MOSS model. (NCDC)

6.2 Solar Radiation

Passive design often relies on solar radiation for direct gain heating during heating months. Adjacent buildings and trees that obstruct the line of sight from the sun can reduce or eliminate the solar radiation that reaches the building. Building obstructions are easily identified and designers can and should plan accordingly. Predicting the amount of reduction of available solar radiation where trees are present can be challenging. Several research articles are available regarding the effects of tree shading in warm climates and at latitudes less than 40 degrees. An exhaustive search revealed no research conducted on the effects of tree shading in cold climates and at latitudes above 40 degrees.

The amount of solar radiation that reaches the building is dependent on tree canopy transmissivity. Tree canopy transmissivity is defined as the dimensionless ratio of solar radiation transmitted through the canopy to that incident upon it (Hardy, 2004). Canopy transmittance is a function of solar zenith angle and azimuth angle, canopy structure, tree height, and leaf area index (Hardy, 2004). Canopy transmittance (τ_c) is a measurement of incident solar radiation (Link, 2004).

Shading coefficients for ‘leaf-on’ trees range from 0.5 to 0.9 (Simpson, 1068). This translates to a 50% to 90% reduction in available solar energy for solar heating, or stated otherwise, only 10% to 50% of solar energy reaches the home.

To accurately model the thermal effects of a coniferous forest canopy, it is necessary to consider the angular and spectral distribution of the incoming solar radiation, and the effects of long wave thermal radiation given off by the trees (Link, 2004). The referenced literature measured solar and thermal radiation under canopies in boreal coniferous forests in Saskatchewan, Canada. This forest consists of mature boreal jack pines with a canopy height of 17 meters (56 feet). The angle of incoming solar radiation was 19.1°. The incoming solar radiation was measured between 6-10 February 1994. The results indicate incoming solar at 15% of above canopy radiation, and the long wave thermal radiation from the trees was non distinguishable. Seasonal variations in the canopy structure are relatively small in conifer canopies; therefore, canopy characteristics were assumed to remain constant over time (Link, 2004).

6.3 Field Measurements of solar radiation

Field measurements of solar radiation validate the findings of previous research were applicable in this scenario. Canopy transmittance measurements were taken at the McCall building site on October 13, 2008. Measurements were taken every thirty minutes between 9:00 am and 4:30 pm at the specific building site and at an unobstructed area adjacent to the building site. Sky conditions on this day were clear with exception of cloudy to partly cloudy skies between 10:00 am and 11:00 am. Measurements were taken using a Li-Cor PAR sensor. The Li-Cor PAR sensor measures irradiance in micromoles. The average canopy transmittance including the cloudy hours was 26.12%, while transmittance under clear skies (excluding the data points at 10:00 am and 11:00 am) was 24.25%. Light measurements were taken simultaneously with the solar radiation measurements. These measurements were taken using a Pasco LUX meter. The Pasco LUX meter measures irradiance in lux (lumens/square meter). The average ratio of lux at the building site (lx) to lux in an open area (lx*o*) throughout the measurement period was 19.17% (lx/ lx*o*).

The ponderosa pine trees at the MOSS model site are estimated to have a height in excess of 30 meters (100 feet). The additional height of the ponderosa pine canopy will further reduce incoming solar radiation.

6.4 Climate file modification for solar radiation

Once a suitable climate model for the MOSS model was identified, that climate model was modified to account for the reduced solar potential associated with decreased tree canopy transmissivity given a dense coniferous tree canopy.

Building energy analysis computer programs do not yet have the ability to account for this partial reduction in solar radiation potential caused by decreased canopy transmissivity. Therefore, the climate data used in the analysis program required modification to account for this reduction. The climate model contains two data fields of solar radiation data: direct solar radiation and diffuse solar radiation. This research assumes an equal reduction in both direct and indirect solar radiation. It stands to reason that, if diffuse solar radiation under the canopy was not reduced by approximately the same factor as direct solar radiation under the canopy, the LUX ratio would not be similar to the canopy transmittance ratio. The direct and diffuse solar radiation values in the historical climate data were reduced to 20% of measured data to account for reduced canopy transmittance. Energy Analysis was performed using the original and modified climate files for comparison.

7.0 MOSS REDESIGN: PASSIVE HOUSE

Initial modeling suggests that increasing the insulation value (R-value) of the MOSS building will yield the greatest savings in heating requirements and energy consumption. The straw bale and stucco wall construction was abandoned in favor of higher R-value 12" SIPs walls finished with exterior concrete siding and gypsum board on the interior. With an R-value of nearly 5 per inch, compared to the straw bale R-value of 1.36 per inch, the wall assemblies could be reduced from 22 inches to 14 inches while increasing R-value from R-30 to R-60. The roof R-value was also increased to R-100 by combining a 12" SIP panel with 10" blown in cellulose fiber insulation between rafters. The ceiling is finished in gypsum board for fire prevention. The original 4" concrete slab is maintained for its thermal mass value. The in-slab radiant floor heating is maintained, although now fired through a ground sources heat pump as in the case of the Waldsee BioHaus. An 85% HRV is also specified. The current HEED energy analysis modeling software is unable to account for the HRV energy savings at this time, although a new version may be available prior to the ARCC conference where the final findings of this research will be presented.

8.0 ENERGY PERFORMANCE MODELING

Models of the Waldsee BioHaus and The McCall Bunkhouse were created and analyzed using HEED (Home Energy Efficient Design) software.

Initial modeling results indicate a direct correlation between heating requirements and building thermal conductivity (U-value), where halving the U-value halved the heating energy consumption. As in any conductive circuit, energy consumption is in direct relationship to energy transfer through circuit components. In the case of buildings, the U-value is comprised of thermal transfer through the envelope and outside air exchange. To minimize heat loss and gain, the U-value must be minimized.

8.1 Modeling for reduced solar gain

The building models were analyzed using both unaltered climate data and the climate data altered to account for reduced solar radiation caused by reduced tree canopy transmissivity. These analyses predict an increase in energy costs associated with heating and lighting the building. The building is naturally cooled in the summer and the analysis does reflect higher internal temperatures in the summer due to the increased solar radiation associated with tree removal. This would be a factor to consider in warmer locations where internal temperatures exceed the comfort range. In the current location, external sun shades can be used to reduce summer heating.

8.2 MOSS Bunkhouse energy modeling

HEED modeling the current MOSS bunkhouse design suggests an annual heating requirement of 39.34 kBTU/sf with the unaltered climate file and 43.44 with the climate file altered for reduced solar gain. As stated earlier, current software limitations prevent modeling the energy savings associated with the HRV unit. The reduction of solar gain indicates a 10.4% increase in heating requirements.

8.3 Waldsee BioHaus Energy Modeling

HEED modeling of the Waldsee BioHaus in Bemidji Minnesota indicate an annual heating requirement of 12.76 kBTU/sf/yr. Energy modeling of the Waldsee BioHaus by the architect using the PassiveHaus Planning Package (PHPP) suggest an annual heating requirement of 4.35 kBTU/sf/yr (Klingenberg, Kernagis, & James, 2008). The difference is likely due to the HEED software's current inability to account for HRV.

8.4 Waldsee BioHaus in McCall Energy Modeling

HEED modeling of the Waldsee BioHaus using the McCall Idaho climate files indicate an annual heating requirement of 13.99 kBTU/sf/yr without considering tree canopy solar gain reduction, and 15.75 kBTU/sf/yr when using the climate file with 20% solar radiation. The reduction in solar radiation suggest a 12.6% increase in heating costs.

8.5 New Passive House Energy Modeling

HEED modeling of the newly designed Passive House dwelling in McCall suggest an annual heating requirement of 13.00 kBTU/sf/yr with the unmodified climate file and 18.69 with the climate file modified for reduced solar potential. This suggests a 66.96% reduction in heating costs if solar radiation is unlimited by trees and a 56.98% reduction if solar shading is considered. When comparing the new design without limited solar availability to the original design with solar limited solar radiation availability, the new design achieves a 68.99% reduction in heating energy.

9.0 MATERIAL CONSIDERATIONS

9.1 Structural Integrated Panel Systems

Structurally Integrated Panel Systems (SIPS) achieve exceptional overall R-values because they are constructed and installed without studs that cause thermal bridging in conventional wall systems. Since top and bottom plates are used and window cutouts are framed, thermal bridging in the wall assembly is not completely eliminated, but is significantly reduced.

9.2 Thermal Bridging

Thermal bridges are points in the building envelope where building elements with high thermal conductivity (such as studs) transmit heat through the building envelope. A code built wall with R19 insulation measures R22.43 through entire wall thickness and changes to R21.28 when 2x6" 16" OC studs are factored into the equation. A super insulated wall with R38 insulation (R41.43 through entire wall thickness) changes to R39.9 when factoring in 2x12" 24" OC studs. SIP walls can be constructed without studs, eliminating thermal bridging associated with conventional studs. Since top and bottom plates and window framing is still used with SIPS, not all thermal bridging is eliminated.

CONCLUSION

Reducing energy consumption in the built environment is critical in combating climate change, and is best achieved by increasing the thermal performance of the buildings. Proven strategies are readily available and should be employed wherever practical. Designing to Passive House energy performance standards by constructing a super insulated envelope with minimizing thermal bridging, and using a heat recovery ventilator greatly reduces energy use and carbon emissions associated with building operation, while at the same time, ensuring high indoor air quality. Building energy modeling with an accurate climate file that considers solar radiation potential at the microclimate level helped optimize critical passive design strategies such as glazing quantities and orientation. After thermal performance is optimized, other means of reducing energy consumption can be evaluated and implemented.

REFERENCES

Autodesk. (2008). Ecotect. Retrieved November 23, 2009, from welcome: http://ecotect.com/

Hardy. (2004). Solar radiation transmission through conifer canopies. Agricultural and Forest Meteorology , 126 (3-4), 257-270.

Klingenberg, K., Kernagis, M., & James, M. (2008). Homes for a Changing Climate. Larkspur, CA, USA: Low Carbon Productions.

Link, T. (2004). Old-Growth Seasonal Temperate Rain Forest Using the Simultaneous Heat and Water (SHAW) Model. Journal of Hydrometeorology [serial on the Internet] , 5 (3), 443-457.

NCDC. (n.d.). National Climate Data Center. (Joe, Editor) Retrieved November 13, 2009, from http://www.ncdc.noaa.gov/oa/mpp/

Nieminen, J., Holopainen, R., & Lylykangas, K. (2008). Passive House for a cold climate. Nordic Symposium on Building Physics. Copenhagen, Denmark: Div. of Building Technology / Department of Civil and Architectural Engineering / Royal Institute of Technology, Brinellvägen 34, SE-100 44, Stockholm, Sweden.

SIPA. (n.d.). Structural Integrated Panel Association. Retrieved February 18, 2010, from SIP Construction Details: http://www.sips.org/content/technical/index.cfm?pageId=20

US Department of Energy. Energy Plus Weather Data. Retrieved 2009 йил 23-11 from http://apps1.eere.energy.gov/buildings/energyplus/cfm/weather_data3.cfm/region=4_north_and_central_america_wmo_region_4/country=1_usa/cname=USA#ID