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Analysis of the passive design and solar collection techniques of the houses in the 2009 U.S. Department of Energy's Solar Decathlon competition

by

Timothy Robert Lentz

A thesis submitted to the graduate faculty

in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Major: Mechanical Engineering

Program of Study Committee:
Ron Nelson, Major Professor
Gregory Maxwell
Ulrike Passe

Iowa State University

Ames, Iowa

2010

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Nomenclature

A_c	Collector area
a_1	Collector heat loss coefficient
a_2	Collector heat loss coefficient
c_p	Specific heat
E	Energy
EA	Effective aperture
G_{ref}	Radiation on collector at standard test conditions
G_{sc}	Solar constant
I	Hourly irradiation on a horizontal plane
I_b	Hourly beam irradiation
I_d	Hourly diffuse irradiation
I_o	Hourly extraterrestrial radtiation
I_T	Hourly radiation on a tilted surface
$I_{mp,ref}$	Maximum power current at standard test conditions
k	Thermal conductivity
k_T	Clearness index
L	Heat load, heat loss
N	Number of points in sample
n	Day of the year
NOCT	Nominal operating cell temperature
P_{mp}	Power output at maximum power point
Q	Heat gain
R	Thermal resistance
R_e	Effective thermal resistance
R_{si}	Thermal resistance of inner surface
R_{so}	Thermal resistance of outer surface
R_b	Ratio of beam radiation on a plane to beam radiation on horizontal plane
R^2	Coefficient of determination
S	Absorbed radiation per unit area
SHGC	Solar heat gain coefficient
s_n	Sample standard deviation
T_a	Ambient temperature
T_c	Temperature of collector
T_{ref}	Temperature at standard test conditions
U	Heat loss coefficient
U_e	Effective heat loss coefficient
V	Volume
VHC	Volumetric heat capacity
$V_{mp,ref}$	Maximum power voltage at standard test conditions
WWR	Window-to-wall ratio
$\bar{x}$	Average of a sample
x_i	Observed data point
y_i	Observed data point
$\bar{y}$	Average of observed data

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$\hat{y}$	Value suggested by equation
β	Tilt angle, slope
γ	Azimuth angle
δ	Declination
η	Collector efficiency
η_{mp}	Efficiency at maximum power point
$\eta_{mp,ref}$	Collector efficiency at standard test conditions
η_0	Baseline efficiency
θ	Angle of incidence
θ_z	Zenith angle
μ_{Voc}	Temperature coefficient of open circuit voltage
$\mu_{\eta,mp}$	Temperature coefficient of efficiency at maximum power point
ρ	Density
ρ_g	Ground reflectance
τ	Transmittance
ϕ	Latitude
ω	Hour angle

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Introduction

The possibility of global warming is becoming an ever increasing threat in modern society. The primary cause of this warming is greenhouse gases generated through the combustion of fossil fuels. Combustion of fossil fuels is most common in energy production and usage. Over 2/3 of the energy consumption in the United States occurs in buildings and among those buildings, residential buildings account for 22% of total energy consumption. The total energy consumed by the U.S. residential sector in 2008 was 21,637 trillion Btu. Renewable energy consumption in residences totaled 599 trillion Btu while electrical sales were 4,706 trillion Btu, electrical losses accounted for 10,152 trillion Btu and direct fossil fuel use accounted for 6,179 trillion Btu. The average annual consumption per household in the United States is 95 million Btu. As Figure 1 shows, the majority of energy used in residences goes towards space heating and water heating. For both of these applications, the majority of energy comes from direct combustion of natural gas and the second most common source of energy is electricity from the grid [1].

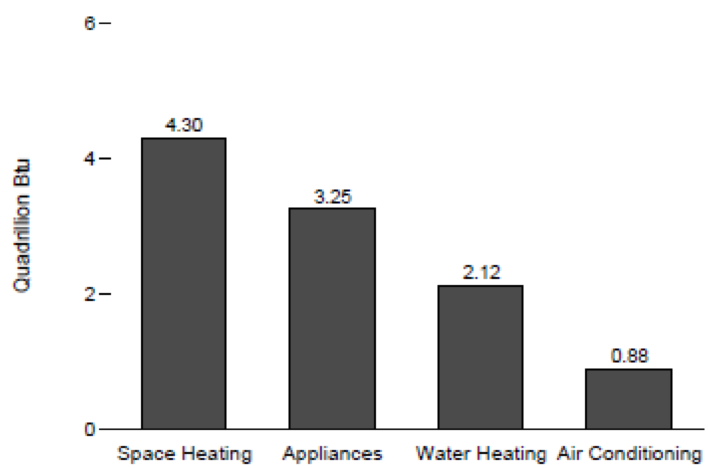

Figure 1 Household Consumption by End Use, 2005 [1]

In order to relieve the need for fossil fuel combustion, new construction must be environmentally responsible. New residences must reduce the amount of energy needed to operate and also focus on using energy from distributed sustainable sources. In order to promote these ideas and to develop new and effective design practices, the United States Department of Energy (DOE) has created the Solar Decathlon competition [2].

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The Solar Decathlon is an international competition that challenges 20 university teams to design and build an energy efficient, single-family home that is completely solar powered. The competition culminates at the end of two years of planning and building with a contest on the National Mall in Washington, DC. The teams transport their houses to the mall for several days of tours and both measured and subjective contests. There have been four Solar Decathlon competitions to date. This research will deal solely with the 2009 competition.

There are several passive solar design techniques that can be implemented into buildings. While in the design phase, these techniques can be tested using software packages that model heat transfer and energy usage in order to optimize the design. An alternative to such time consuming computer modeling is using rules of thumb. These quick calculations can be used to estimate proper sizing and placement of passive solar features. The goal of this thesis is to analyze the effectiveness of these rules of thumb by comparing how well the houses conformed to the rules with actual data collected during the Solar Decathlon competition. Additionally, active photovoltaic and thermal collection systems will be analyzed for each house.

Literature Review of Passive Solar Building Techniques

The literature review for passive solar building techniques will cover direct-gain, indirect-gain, shading, daylighting, thermal mass, thermal storage walls, insulation and windows methods of implementing passive solar building techniques. For this review, it is assumed that the buildings are in the northern hemisphere with most of the solar radiation coming from the south.

Direct-Gain

The direct-gain approach is used when a house has a large amount of south facing windows. These windows are placed deliberately to allow the sun to directly heat the living space [3]. When solar energy enters a window and strikes a surface, it is mostly converted to heat energy. The heated surfaces in turn heat the interior air. Direct-gain performance is increased if insulating devices such as blinds or curtains are used when the

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heat loss through the window would be greater than the solar radiation heat gain. The amount of heat gained from the sun is directly related to the amount of incident radiation transmitted through the glass [4]. Transmittance, τ, is the fraction of radiation that is transferred through a material. The total amount of solar gain for an hour can be calculated using the following equation

$$S = I_b R_b (\tau\alpha)_b + I_d (\tau\alpha)_d \left(\frac{1 + cos\beta}{2}\right) + \rho_g I (\tau\alpha)_g \left(\frac{1 - cos\beta}{2}\right)$$

which is the sum of terms for beam, diffuse and ground-reflected radiation. Each term is the product of solar insolation, the transmittance-absorptance product, and a view factor. This same equation can be used to calculate absorbed radiation for thermal storage walls, thermal collectors and PV systems [5].

While advanced calculations can be used to predict the necessary amount of windows for direct solar gains there is also a general rule of thumb. The total area of solar glazing (south facing windows) should be between 7% and 12% of the total floor space. The variation depends greatly upon the local climate and the amount of thermal mass available [6]. Thermal mass will be discussed more in depth later.

Indirect-Gain

The indirect-gain design strategy focuses on using the sun to heat an unconditioned space that is adjacent to the living space [3]. The advantage of the indirect-gain approach is that direct-gain spaces usually have large temperature swings and can even become uncomfortably warm in the winter. Indirect-gain decouples the heat collection from the actual living space for better temperature control [4]. Indirect-gain spaces are commonly referred to as sunspaces or greenhouses. There are two main forms of sunspaces: attached or enveloped. An enveloped sunspace is typically integrated into the architecture of the house and shares common walls with the living space on two or three sides. An attached sunspace typically shares only one common wall with the living space with the three remaining walls being exposed walls. See Figure 2 below for examples of both types of sunspace [3].

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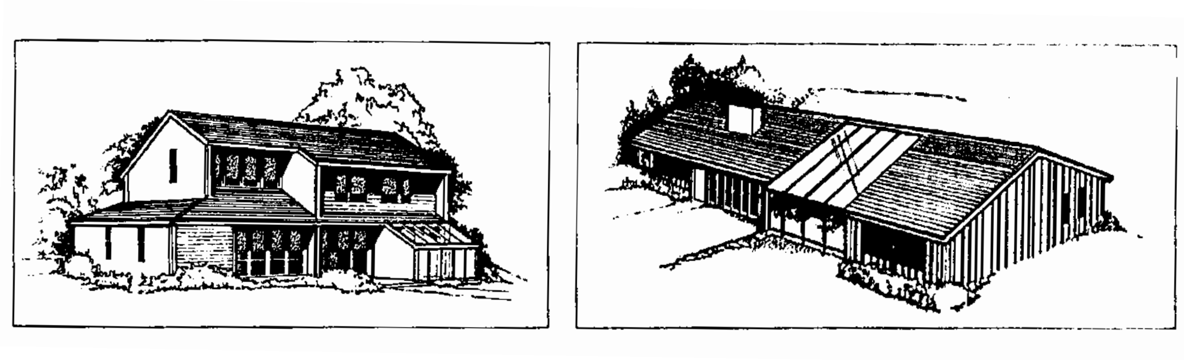

Figure 2 Examples of attached and enveloped sunspaces [6]

Generally the enveloped sunspace has better thermal performance because when it loses heat most of the loss is to the internal living spaces as opposed to the outdoors. As with the direct-gain approach, heat is gained through south facing windows in the sunspace. Windows can also be incorporated into the roof and walls of the sunspace to increase the solar collection area. However, the decreased thermal resistance of windows causes the extra glazing to decrease the performance of the space if not properly insulated. In northern climates it is recommended that double or even triple pane windows be used in a sunspace to increase performance [6]. With a properly sized sunspace, a house can achieve a solar heating fraction between 55% and 84% [4].

Shading

An important element of solar design for summer climates is reducing the amount of solar gains through windows and walls in the summer months. The most effective and affordable way to achieve this is through shading devices. Entire walls can have shading devices to reduce the outer surface temperature of the wall. Figure 3 shows four types of wall shading devices: a. vegetation. b. wooden or metal louvers. c. vegetation on a steel or hardwood mesh. d. a second skin with a low-emission layer on the inner surface and a heat-reflective outer surface.

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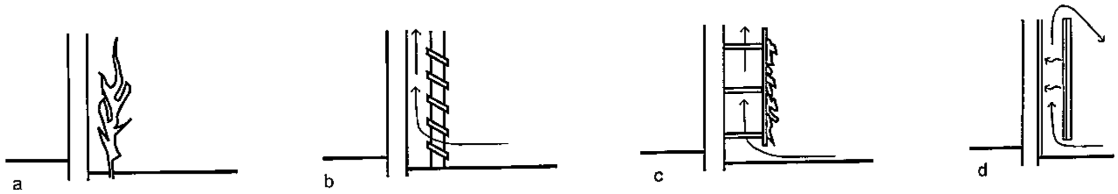

Figure 3 Examples of different types of wall shading [7]

More important than wall shading is window shading. Since windows are transparent they allow solar radiation into the living space. The primary goal of window shades is to completely block out any direct solar radiation on the window, reducing the possibility of heat gain. The orientation of shades depends on which face of the building they are on. Shades on the south and north faces of a building should be horizontal since the sun will generally have a high elevation when striking these surfaces. Shades on the east and west sides of a building should be vertically oriented since the sun will usually be at lower angles when striking these surfaces. Figure 4 shows proper shade designs based on orientation of the walls.

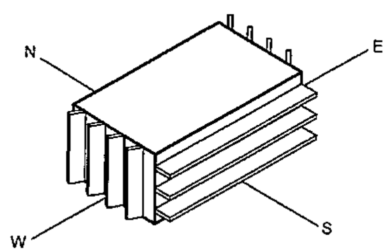

Figure 4 Vertical and horizontal shading devices (northern hemisphere) [7]

No matter what type of shading device is used, there are several goals that the design should accomplish:

- Shades should be on the outside of the opening
- Shades should be made of light and reflective materials to avoid absorption and re-radiation
- Materials should have low heat storage capacity for rapid cooling
- The design should prevent reflection onto any part of the building or openings
- Hot air should not be trapped against the building [7]

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Daylighting

One of the seemingly simplest ways to reduce electrical use is through daylighting. It makes sense that during the day, light can be provided by the sun rather than electrical light fixtures. Lighting, in fact, makes up a large portion of the electrical consumption in buildings. As shown in Figure 5 lighting is second only to heating in terms of energy use in U.S. buildings.

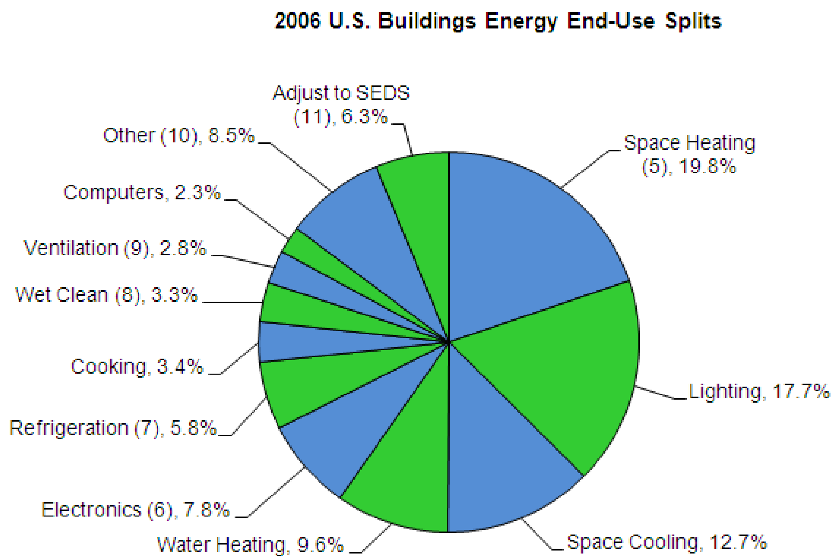

Figure 5 Energy by end-use in buildings [10]

While the concept of daylighting is simple, the actual design and implementation of daylighting is quite involved. There are many variables to take into account including but not limited to location, typical sky conditions, glazing materials, glazing location, room geometry, internal and external shading, glare and reflectance of internal surfaces. In order to take all of these factors into account, computer programs such as RADIANCE or PowerDOE are often used to predict the daylighting performance of a building during the design stages. A simpler method that is used during early design stages is rules of thumb. These are the criteria that will be used to analyze the Solar Decathlon houses.

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The first rule of thumb involves effective aperture, EA, which is used to determine the ideal amount of glazing. The effective aperture is the product of the window-to-wall ratio, WWR, and the visible transmittance, τ, of the windows.

The target value for effective aperture is 0.18. Any value above this target increases cooling loads more than it relieves lighting loads. This point is when daylighting saturation is achieved.

The second rule of thumb involves light penetration into the interior space. Light is considered to penetrate a space two-and-a-half times as far as the vertical height, h, of the window.

$$\text{Light penetration} = x = 2.5h$$

Ideally, light would penetrate the entire depth of a space so that all areas have access to daylight [8].

Thermal Mass

In both direct- and indirect-gain cases, it is important to store the incoming solar energy. Thermal mass is any material that stores energy from the sun. While all materials will absorb and store a certain amount of energy, some are better suited to the task than others. Generally, materials that are denser tend to store more energy than less dense materials. The measure of possible storage for thermal mass is the volumetric heat capacity (VHC). The VHC is determined by multiplying the density, ρ, by the specific heat, c_p, of the material. The VHC is a measure of how much heat is stored for a rise of 1°F for one cubic foot of material. A high VHC is desired for thermal mass. Another important property of thermal mass is the thermal conductivity, k, which is the measure of how quickly energy transfers linearly through a material for 1°F of temperature difference. The higher the conductivity of the thermal mass the faster the material will gain or lose

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heat. Table 1 shows the thermal properties of common construction materials used as thermal mass [9].

Table 1 Thermal Mass Properties [9]

Type of Material	Density ρ=lbs/ft^3	Specific Heat Cp=Btu/lb°F	Conductivity K=Btu-ft/ft^{2}hr°F	Volumetric Heat Capacity Btu/ft^3°F
Concrete	144	0.16	0.540	23.0
Concrete	140	0.20	1.000	28.0
Brick	123	0.20	0.400	25.0
Limestone Rock	103	0.22	0.540	23.0
Wood (Pine)	27	0.67	0.063	20.8
Adobe	106	0.24	0.300	25.0
Water	62	1.00	0.350	62.0

When sizing thermal mass for a direct-gain system, it is appropriate to take into account the amount of solar glazing. If the solar glazing is less than 7% of the total floor space, no additional thermal mass is needed because the "incidental" thermal mass of the building will account for the solar heat gain. If the solar glazing area is larger than 7% of the total floor area, additional thermal mass will be necessary. Depending on where the mass is located there are certain ratios for how much is necessary compared to glazing area.

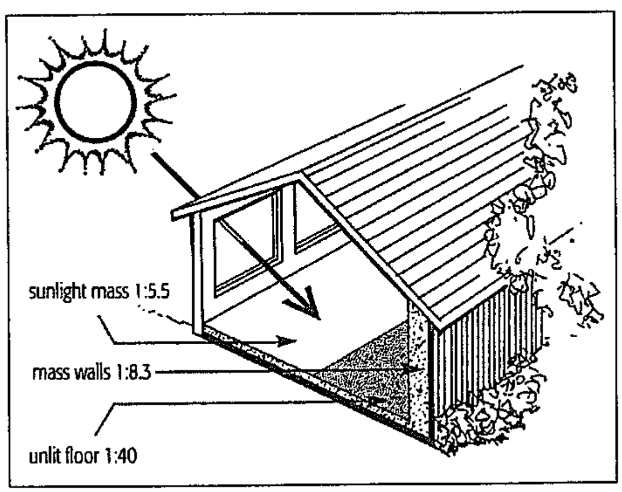

Figure 6 Glazing to thermal mass ratios [6]

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As seen in Figure 6, thermal mass that is placed in directly lit floor areas should be designed at a ratio of 1:5.5. This means that for every square-foot of solar glazing above the 7% limit there should be 5.5 ft^2 of sunlit thermal mass. For unlit floor areas the ratio is 1:40 and for unlit mass walls the ratio is 1:8.3 [6].

Thermal Storage Walls

A common application of thermal mass is in a thermal mass storage wall. These features are most commonly installed on the south side of a building. The most common type of thermal storage wall is a Trombe wall which utilizes a solid storage mass. The other common type of storage wall uses water as a storage mass. A thermal storage wall consists of five main components: external glazing, an air space, the storage wall, vents and a roof overhang. Figure 7 below is a diagram of a typical thermal storage wall.

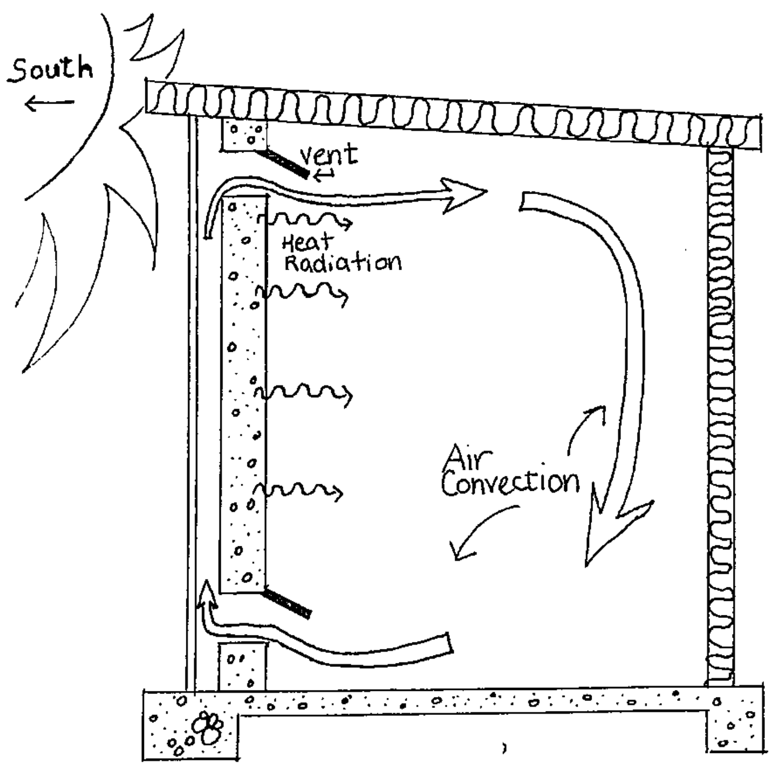

Figure 7 Vented thermal storage wall [9]

The glazing allows sunlight in while preventing the storage mass from contacting the external climate. Glazing selection is an important part of the design of thermal storage

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wall. Special selective coatings can be used to control the amount of heat lost to the surroundings. Double or triple pane windows also limit conduction losses through the glazing. The air space between the glazing and the mass wall is particularly important when used in conjunction with vents. The space needs to be large enough to allow proper ventilation. Vents at the top and bottom of the storage medium allow for a convective loop to be created, where the heated air from between the glazing and storage wall is vented into the living space while pulling colder air into the air space. The roof overhang must be sized so that the storage wall is mostly shaded in the summer to prevent unwanted heat gain. Conversely, the overhang should not shade the wall in the winter. This design can be achieved by taking advantage of the seasonal change in the elevation of the sun [9].

Insulation

A key to an efficient dwelling is insulation. Insulation helps maintain the interior climate at a desired temperature and either keeps heat in the building or keeps unwanted heat out depending on the season. Many solar designers recommend insulating walls to between R-22 and R-30 and ceilings to between R-40 and R-50. Increasing insulation beyond these points helps but there is a point where it stops being cost effective to continue increasing insulation. There is also an argument for superinsulating houses since certain types of insulation lose some of their R-value over time [6].

The R-value is a measure of the thermal resistance of a material. The U-value or heat loss coefficient is also a common insulating term, especially with windows, and is the inverse of the R-value (1/R). The resistance of a wall is determined by the paths that heat can take to transfer out of the wall. Similar to circuits, paths are either parallel or series. Walls are typically a combination of both parallel and series paths. The effective R-value, R_e, for a series path is:

$$R_e = R_{si} + R_{so} + \sum R_i X_i$$

Where R_{si} = inside surface resistance

R_{so} = outside surface resistance

R_i = R-value of the i^{th} material

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X_i = thickness of material i

The effective heat loss coefficient through j parallel paths is:

$$U_e = \frac{\sum U_j A_j}{\sum A_j}$$

Where A_j is the cross sectional area of the j^{th} material [4]. Table 2 and Table 3 show R-values for many common insulating and building materials.

Common insulation usually comes in batts, boards, loose fill or sprayed foam. The most common and cost effective form of insulation is fiberglass batt. Fiberglass can also be blown into ceiling cavities as loose fill. Cellulose fiber insulation, which is frequently made from old newspapers and other waste paper, is another loose fill option but can be sprayed into walls as well. Vermiculite and Perlite are two types of loose fill insulation that are made from expanded minerals. Vermiculite is no longer common for new construction since asbestos was commonly added as a fire retardant. The insulating values of all of these materials are highly dependent upon the material remaining dry. The vapor barrier on the exterior of the house typically keeps insulation dry and efficient [6].

Expanded cellular foam or cellular plastic is a type of insulation that actually acts as its own vapor barrier. These foams can come in open cell and closed cell forms. The closed cell form is more efficient and protects against water leakage better. These foams are sprayed into cavities in small layers as a combination of two chemicals. The ensuing reaction causes the foam to expand, sealing tightly to surfaces. Once hardened, this expanded foam also protects against air infiltration as well. Polystyrene boards are a premade version of the same product commonly used in retrofits. The boards come in varying thicknesses and can be cut to fit the needed geometry [11].

While insulating the walls and roof of a house are common practice, insulating other parts of the structure such as the exterior of a foundation or night insulation on windows is another way to increase efficiency. Also, unconventional insulating materials have been developed to meet special needs. Vacuum insulation panels are polymer cavities containing fumed silica or Perlite. A vacuum is pulled on the panels to remove the

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possibility of thermal conduction through trapped gas. An aluminum coating reduces permeability giving the panels an R-value of 23.6 [12]. Aerogel is another insulator used for special applications. It is a transparent material that is composed of super-dried silica-oxide. Aerogel has a thermal conductivity of 0.02W/mK. Due to its low thermal conductivity and high level of light transmission, aerogel has been used in the gaps between panes in windows and skylights to increase efficiency [13].

Table 2 Density and R-value of Insulation[4]

Insulation	Density		R-value	
	kg/m^3	lb/ft^3	°C-m^2/W-cm	°F-ft^2-hr/Btu-in.
Acoustic Tile	288	18.0	0.175	2.53
Cellulose Fill	40-48	2.5-3.0	0.257	3.70
Fiberglass Batt			0.218	3.15
Glass Foam	144	9.0	0.173	2.50
Insulation Board	288	18.0	0.182	2.63
Mineral Board			0.241	3.47
Mineral Wool Batt			0.231	3.33
Low Density Particleboard			0.128	1.85
Perlite (R-11)	80-128	5.0-8.0	0.187	2.70
Polystyrene Beads	16	1.0	0.248	3.57
Polystyrene Board (air)	29	1.8	0.277	4.00
Polystyrene Board (R-12)	35-56	2.2-3.5	0.347	5.00
Polyurethane (R-11)	25-40	1.5-2.5	0.433	6.25
Urea Formaldehyde Foam	11	0.7	0.289	4.17
Vermiculite	112-131	7.0-8.2	0.148	2.13

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Table 3 Density and R-value of Building Materials[4]

Insulation	Density		R-value	
	kg/m^3	lb/ft^3	°C-m^2/W-cm	°F-ft^2-hr/Btu-in.
Aluminum (1100 alloy)	2740	171	45×10^{-6}	6.5×10^{-4}
Brick (common)	1920	120	0.014	0.20
Brick (face)	2080	130	0.0076	0.11
Cement, Mortar, Plaster	1860	116	0.014	0.20
Concrete (heavy weight)	2240	140	0.0076	0.11
Concrete (medium weight)	1280	80	0.028	0.40
Concrete (light weight)	481	30	0.077	1.11
Gypsum, Plasterboard	801	50	0.062	0.90
Medium-Density Siding	641	40	0.106	1.53
Particleboard (high density)			0.0055	0.08
Particleboard (medium density)			0.0076	0.11
Particleboard (low density)			0.128	1.85
Steel (mild)	7830	489	2.2×10^{-4}	3.2×10^{-3}
Wood (hard)	721	45	0.63	0.91
Wood (soft)	513	32	0.087	1.25

Windows

Windows have already been discussed as a means for solar gain and daylighting but they must also be designed for efficient containment of energy. Compared to walls and ceilings, windows are typically the big energy losers of a building. There are several factors to take into account when determining the thermal efficiency of a window. The type of window is a big factor. Non-operable windows are the most efficient type because there are no moving sections and the whole window is built to be permanently sealed. Operable windows vary in their thermal performance due to the amount of moveable area that must be sealed. Awning, casement and hopper windows use compression seals and generally prevent infiltration better than sliders, single-hung and double-hung windows which feature sliding seals. Infiltration for windows is measured in cubic feet of air per minute per square foot of window surface (cfm/ft^2). It is recommended to use windows with an infiltration rate of less than 0.30 cfm/ft^2 for an efficient building.

Modern windows feature two or three panes of glass with air gaps in between the glass layers. The air gaps act as the principle insulating layers since air does not transmit heat as easily as glass. In higher end windows, the air gaps are filled with inert gases such

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as argon, krypton or even xenon which drastically increase the insulating value of the window. Adding inert gas instead of air adds almost one R unit in a double pane window.

The most promising recent advancement in efficient window construction is low-emissivity coating. Low-e glass as it is called is created by applying a thin coating of silver or tin oxide to a pane of glass. The coatings which are mostly transparent prevent the transmission of long wave radiation especially heat or infrared radiation. Up to 90% of long wave radiation can be reflected while allowing short wave radiation and visible light to pass through the coatings. Low-e coatings can increase thermal performance by 16% over a normal double pane window without coatings.

The framing materials for windows are also important factors in choosing efficient windows. The most common frame materials are wood, vinyl, metal, ABS plastic and fiberglass. Wood frames are the most common and are rather thermally efficient. The downside is that wood can be damaged by the elements so the exterior surfaces must be properly sealed and protected. Vinyl frames are comparable to wood from an energy standpoint but vinyl has a large coefficient of thermal expansion. This can cause seals to fail and leak when windows expand and contract due to temperature changes. ABS plastic frames have similar advantages and drawbacks to vinyl windows but are typically more weather resistant. Metal window frames are highly thermally conductive and are not recommended for use in an efficient building. Fiberglass frames offer a great balance between energy efficiency, weather resistance and reliability. The big drawback to fiberglass frames is that they tend to be more expensive than other frame options.

Wise placement of windows can also increase the efficiency of the house. If an operable window is needed for ventilation, it should be located such that the ventilation is maximized reducing the need for additional operable windows. Also, choosing windows with the proper solar heat gain coefficient (SHGC) for the region is important. It is recommended that for hot climates SHGC should be less than 0.4; between 0.4 and 0.55 for intermediate climates; greater than 0.55 for cold climates. Also, certain coatings could be chosen for each direction a window faces. East and north facing windows should have low-e coatings while west windows should have heat rejecting coatings to prevent excessive heat gain. Additionally, the north and east windows should account for no more

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than 4% of the floor space and the west windows should not account for more than 2% of floor space to limit thermal losses and unwanted gains. South facing windows can be either uncoated or use low-e coatings for solar heat gain [6].

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Literature Review of Solar Collector Technology

The literature review for solar collector technologies will cover photovoltaic collectors and thermal collectors.

Photovoltaic Collectors

Photovoltaic (PV) collectors are solar electric modules made up of a collection of semiconductor cells that create a flow of electrons. Most modules are made from single crystal or polycrystalline silicon cells that are doped with boron and phosphorus to facilitate electron movement [14]. Due to constant research and development, commercial silicon-based photovoltaic modules can reach efficiencies of up to 20% [15].

Recently, thin film photovoltaic modules have become available on the market. These modules use a very thin layer of amorphous silicon [14] or cadmium telluride [16]. Thin films can be applied to a flexible substrate for use in non-traditional applications or can be sandwiched between glass covers and made into a proper module. While thin films offer lower efficiency, between 5% and 13%, the smaller amount of material used makes them easier and cheaper to manufacture. The flexibility of thin films also suggests that they might be incorporated into building products such as shades or curtains.

Gallium arsenide photovoltaic cells have been developed that have greater efficiency and better temperature performance than silicon cells. This temperature performance suggests that these cells could be used in conjunction with concentrating lenses to increase electrical output. Single crystalline cells have been shown to reach efficiencies of 25% and thin film cells have reached 17% efficiency, far exceeding the capabilities of silicon. Since production of gallium arsenide cells is expensive, they are not common in residential photovoltaic modules [17].

Several types of advanced photovoltaic cells using chemical compounds are being explored. Copper sulfide cells offer the possibility of cheaper cells with better solar absorption but are hampered by lower efficiency. Copper indium selenide cells are another promising area of research. Specifically copper-indium-diselenide is the most promising since it is the semiconductor with the best solar absorption available. This results in a high current output but a very low open-circuit voltage. The answer to this problem has been

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alloying the material with gallium to increase the band gap which in turn increases open-circuit voltage [16].

Arrays are a collection of photovoltaic modules wired together. Usually strings of several modules in series are wired in parallel. Frequently a combiner box is used to combine the parallel strings into one set of wires which helps reduce clutter and makes running wires easier. Since photovoltaics produce direct current electricity an inverter is needed to supply alternating current loads. Inverters can be either standalone or grid-tied. In a standalone system, energy storage, usually in the form of a battery bank, is required. This type of system also requires charge controllers, takes up a lot of space and has an inherent maximum capacity for storage. A grid-tied system does not require much equipment besides the inverter since the electrical grid acts as an “infinite” storage source. Grid-tied inverters interact with the grid and typically disconnect themselves when there is a grid outage. While inconvenient for the homeowner, this is done for the safety of crews who may be working on the grid [14]. In the 2009 Solar Decathlon, only grid-tied systems were allowed.

Photovoltaic mounting structures can be either static or tracking. On most houses photovoltaic mounting structures are static and use the roof as an anchor. Static arrays need to be mounted at an angle that maximizes the year round production since the sun’s position changes throughout the year. Static arrays are frequently mounted close to or flush with the roof’s surface. This decreases air flow behind the modules, increasing temperature and decreasing efficiency. Arrays can also be mounted off the roof at a different angle to increase efficiency and increase cooling potential. Tracking mounting structures adjust their position frequently in an attempt to keep the array perpendicular to the sun, increasing output. Usually in a residential setting tracking arrays are mounted on a vertical pole as opposed to on the roof of the house. The drawback of tracking arrays is that they are generally more expensive than static arrays [14].

Thermal Collectors

In addition to using passive design strategies, heat can be collected from the sun through the use of active thermal collectors. These collectors typically come in two styles: flat plate or evacuated tube. Concentrating collectors are not typically used in building

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applications, so they will not be covered in this thesis. Flat plate collectors typically resemble photovoltaic modules. They have an outer glass window which covers an absorber plate. The absorber plate is where incident radiation is converted to heat. This heat is then transferred by conduction to a working fluid, typically a water-coolant mixture or air. In the case of air (Figure 8) there is typically an open cavity behind the absorber plate that allows the air to flow through. For a water based collector (Figure 9) a header pipe connects to several copper tubes which are attached to the absorber plate. In the case of both air and water-based collectors, large amounts of insulation are required to avoid heat loss to the surrounding environment [18].

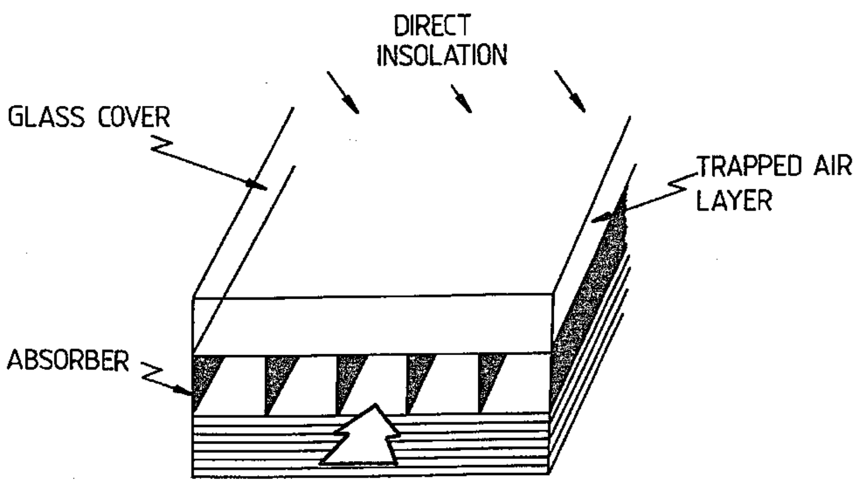

Figure 8 Flat Plate Collector - Air [18]

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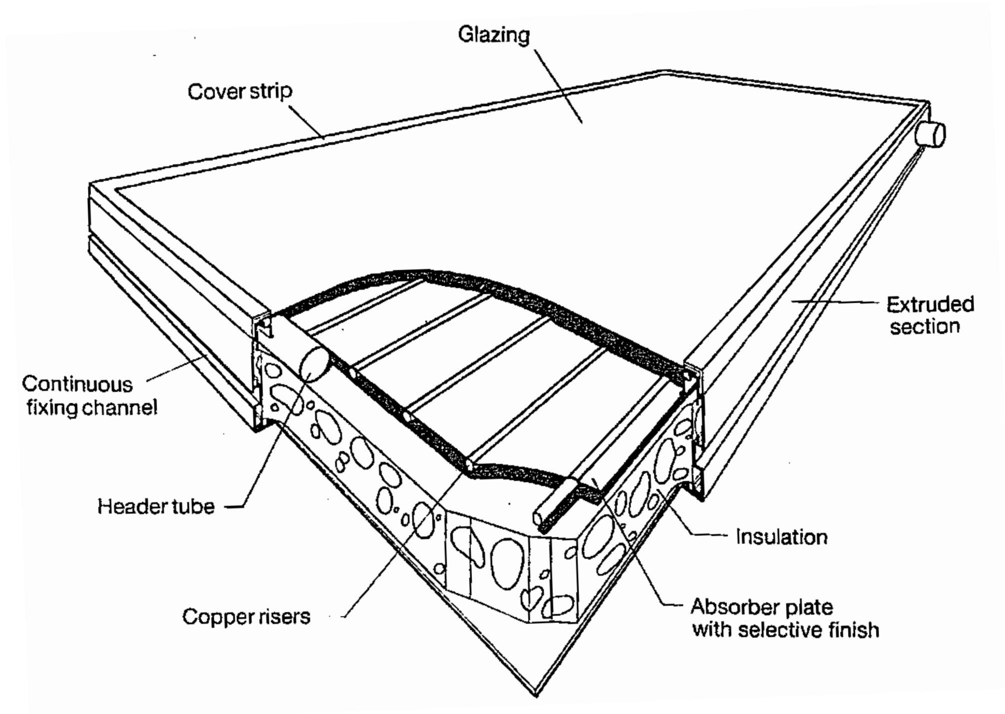

Figure 9 Flat Plate Collector - Water [18]

Evacuated tube collectors are nested glass tubes with a vacuum between the glass layers. The inner layer typically is coated with a selective coating that optimizes absorption of solar radiation and reduces infrared radiation to the surrounding environment. One variation of evacuated tubes circulates a working fluid through the inner glass tube. A second variation (Figure 10) uses a copper heat pipe containing a refrigerant to transfer heat from the collection area to a manifold where the working fluid absorbs the heat. This version has the benefit of a closed working fluid loop so if a single tube is broken it can be removed without draining the whole collector. Since there is no mass in a vacuum, the collector loses very little heat due to conduction and convection, increasing efficiency and maximum temperature [18].

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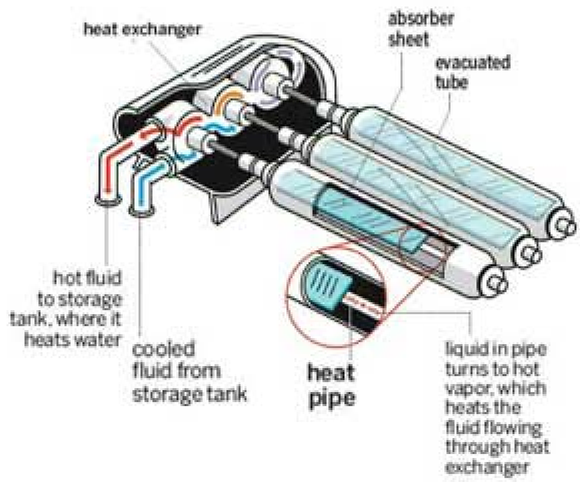

Figure 10 Evacuated Tube Diagram [19]

Since heat demand in a dwelling is minimal during the optimal thermal collection hours, collected heat must be stored somewhere. In an air-based collector, a packed bed can be used as thermal mass. This type of storage uses a pile of rocks and pebbles as the thermal mass to store energy. It can be tied into the ductwork of a forced air heating system or can be kept in contact with floors or walls for a more passive release. Packed beds are made with inexpensive materials and can be quite affordable as a space heating option. Water-based systems require an insulated storage tank to store heat. Since these systems frequently use an antifreeze mixture, a heat exchanger is required if the system is intended for domestic hot water heating. Usually a modified hot water heater can be used for water-based storage. Specialty solar heating tanks can be used as well but these are often expensive. As noted in Table 1, water has a much higher VHC than rock which enables water storage to take up less space than a packed bed. Stratification occurs in both packed bed and water storage so it is beneficial to draw heat from the top of the storage medium and add heat near the bottom [5].

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Methodology

The 2009 Solar Decathlon culminated with a competition in Washington, D.C. in which all twenty teams reconstructed their houses on the National Mall. This competition measured the houses in ten subjective and objective contests. The subjective contests (architecture, engineering, market viability, communications, lighting design) were judged by juries composed of industry professionals. The objective contests (comfort zone, hot water, net metering/energy balance, appliances, home entertainment) were directly measured. Some contests were task based such as hot water and appliances. Other contests such as comfort zone and net metering were directly measured throughout the course of the competition time. Each house was equipped with shielded temperature and humidity sensors to measure interior air characteristics. Bidirectional Wattnodes and current transformers were used in each house to determine the overall energy balance. Sensors were also placed in the center of the exterior competition site to measure exterior temperature, humidity and insolation on a horizontal surface. The competition assigned points based on how well a team met the criteria for each of the ten competitions. Specifically, full points were awarded in the comfort zone competition for maintaining an internal temperature between 72°F and 76°F and maintaining an internal relative humidity level between 40% and 55% during all scoring periods. Final rankings were released at the end of the competition.

Within this thesis the houses are analyzed based on the passive building techniques listed in the literature review. Quantitative values were calculated for the direct-gain rule of thumb comparing solar glazing as a percentage of floor space. For indirect-gain, the total area of solar glazing was calculated as was the thermal mass and volume of the sunspace. The sunspace volume was also compared to the interior volume of the living space. Daylighting values were calculated using the effective aperture rule of thumb. Thermal mass was analyzed both for total thermal storage and as a ratio to extra solar glazing area as shown in Figure 6. The building envelope for each house was analyzed and building average R-values for walls, windows, doors and roofs were calculated. The windows chosen for each house were analyzed for R-value and SHGC. North, east and west window areas were also analyzed as a percentage of the conditioned floor space.

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Shading was analyzed on a qualitative basis using the five design points listed at the end of the shading discussion in the literature review.

Full measurement data for all of the houses has been provided by the National Renewable Energy Laboratory (NREL). Temperature and humidity readings were recorded in 15 minute intervals for the entirety of the competition week. For each house the average temperature and humidity were calculated over the entire competition period and over the comfort zone scoring period only. Additionally, the sample standard deviation for temperature and humidity was calculated. Sample standard deviation, s_n, is calculated using the following formula

$$s_n = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - \bar{x})^2}$$

Where

N = size of the sample

$\bar{x}$ = average of sample

Standard deviation is a measure of how much variation from the average value exists in the data set. In the case of temperature and humidity measurements, standard deviation is also a measure of how well the house controls these parameters with smaller values meaning better control.

In order to see how passive design strategies affect the performance of the building several scatter plots were created. Linear regression was then used to fit a trendline to approximate the data points with the form y = mx + b. A coefficient of determination, R^2, was then calculated to determine how well each trendline fit the observed data. The coefficient of determination is calculated using the following equation

$$R^2 = 1 - \frac{\sum_i (y_i - \hat{y}_i)^2}{\sum_i (y_i - \bar{y})^2}$$

Where

y_i = observed data point

$\bar{y}$ = average of observed data

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$\hat{y}_i$ = modeled value

Values for R^2 range between 0 and 1. The closer R^2 is to 1 the more accurately the linear regression model fits the observed data, which would imply a direct linear relationship between the two data sets being compared.

The houses have also been evaluated based on their photovoltaic and thermal collection capabilities. The photovoltaic systems were analyzed using the site measured insolation data coupled with a simplified version of the one-diode method of predicting photovoltaic output. Thermal collectors were analyzed using the site measured insolation data and a simplified equation taking into account the efficiency of the collectors and the volume of thermal storage available.

In order to determine actual irradiance on the tilted surface of a collector, several corrections and equations need to be applied to the collected insolation data which is only applicable for a horizontal surface. First the hourly clearness index, k_T, must be determined using

$$k_T = \frac{I}{I_o}$$

Where

I = radiation on a horizontal surface (measured data)

I_o = extraterrestrial radiation

Extraterrestrial radiation can be found for an hour using the following formula

$$I_o = \frac{12 \times 3600}{\pi} G_{sc} \left(1 + 0.033 cos \frac{360n}{365}\right) \times \left[cos\phi \; cos\delta \; (sin\omega_2 - sin\omega_1) + \frac{\pi(\omega_2 - \omega_1)}{180} sin\phi \; sin\delta\right]$$

Where

G_{sc} = solar constant (1367 W/m^2)

n = day of the year

ϕ = latitude

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δ = declination

ω = hour angle

Hour angle is determined by the time of day relative to noon. The hour angle for noon is zero. The angle changes by 15° an hour with morning angles being negative and afternoon angles being positive. Declination changes based on the day of the year and can be determined using the following equation

$$\delta = 23.45 \, sin \left(360 \frac{284 + n}{365} \right)$$

Once k_T has been determined, the Orgill and Hollands correlation for ratio of diffuse radiation can be utilized to determine diffuse radiation. The correlation is characterized by the following equations

$$\frac{I_d}{I} = \begin{cases} 1.0 - 0.249 k_T & for\ 0 \le k_T \le 0.35 \\ 1.557 - 1.84 k_T & for\ 0.35 \le k_T \le 0.75 \\ 0.177 & for\ k_T > 0.75 \end{cases}$$

This correlation yields a value for diffuse radiation, I_d, which will be used in the final calculation for total radiation on a tilted surface. Since total radiation can be assumed to be composed only of beam and diffuse radiation, total beam radiation, I_b, can be found by subtracting I_d from I. Next is needed the ratio of beam radiation, R_b. The following equation can be used to calculate R_b

$$R_b = \frac{\cos \theta}{\cos \theta_z}$$

Where

θ = angle of incidence of beam radiation

θ_z = zenith angle, angle of incidence on a horizontal surface

These two angles can be calculated using the following two equations

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$$\cos\theta = \sin\delta\sin\phi\cos\beta - \sin\delta\cos\phi\sin\beta\cos\gamma + \cos\delta\cos\phi\cos\beta\cos\omega + \cos\delta\sin\phi\sin\beta\cos\gamma\cos\omega + \cos\delta\sin\beta\sin\gamma\sin\omega$$

$$\cos\theta_z = \cos\phi\cos\delta\cos\omega + \sin\phi\sin\delta$$

Where

γ = surface azimuth angle

β = angle of inclination of surface from the horizontal

Surface azimuth angle is the deviation from south of the line normal to the surface. The value is zero for a south facing surface with east facing surfaces being negative and west facing surfaces being positive. North facing surfaces are +/-180°. Finally, the amount of radiation incident on a sloped collector, H_T, can be determined using

$$I_T = I_b R_b + I_d\left(\frac{1+\cos\beta}{2}\right) + I\rho_g\left(\frac{1-\cos\beta}{2}\right)$$

Where

ρ_g = ground reflectance, assumed to be 0.3 for the National Mall

With radiation on the collector surface calculated, the output of a photovoltaic array was calculated using

$$P_{mp} = \eta_{mp} A_c I_T$$

Where

P_{mp} = output power at maximum power point

η_{mp} = collector efficiency at maximum power point

A_c = total collector area

Since insolation data was collected at 15 minute intervals, total energy output, E, can be calculated by multiplying P_{mp} for each interval by 0.25 hours.

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$$E = \sum (0.25h \times P_{mp})$$

Collector efficiency can be calculated using the following set of equations

$$\eta_{mp,ref} = \frac{I_{mp,ref} V_{mp,ref}}{A_c G_{ref}}$$

$$\eta_{mp} = \eta_{mp,ref} + \mu_{\eta,mp} (T_c - T_{ref})$$

Where

$\eta_{mp,ref}$ = collector efficiency at standard test conditions

$I_{mp,ref}$ = maximum power current at standard test conditions

$V_{mp,ref}$ = maximum power voltage at standard test conditions

G_{ref} = radiation on collector at standard test conditions (1000W/m^2)

$\mu_{\eta,mp}$ = temperature coefficient of efficiency at maximum power point

T_c = temperature of collector

T_{ref} = temperature at standard test conditions (25°C)

Values for $_{Imp,ref}$, $V_{mp,ref}$, G_{ref}, and T_{ref} can be found in manufacturer's data sheets for specific photovoltaic modules. Modules are typically tested at 25°C ambient temperature and 1000W/m^2 incident radiation. The temperature coefficient of efficiency can be calculated using the following equation

$$\mu_{\eta,mp} = \eta_{mp,ref} \left(\frac{\mu_{Voc}}{V_{mp,ref}} \right)$$

Where

μ_{Voc} = temperature coefficient of open circuit voltage

Collector temperature can be estimated using the following equation

$$T_c = T_a + \left(\frac{NOCT - T_{ref}}{G_{ref}} \right) I_T \times \left(\frac{3600s}{h} \right)$$

Where

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T_a = ambient temperature

NOCT = nominal operating cell temperature

Ambient temperature comes from the measured data provided by NREL while NOCT is a module specific parameter that is found on manufacturer's data sheets. In order to speed up the calculations and reduce human errors, a spreadsheet was created to compile all of the aforementioned equations.

The equations used for thermal collectors start with finding incident radiation on a tilted surface, I_T, as with photovoltaic collectors. Incident radiation is multiplied by collector aperture area, A_c, and efficiency, η, to find the total amount of energy collected, Q.

$$Q = I_T \eta A_c$$

Efficiency for thermal collectors is given by the equation

$$\eta = \eta_0 - a_1 \left(\frac{T_m - T_a}{I_T} \right) - a_2 I_T \left(\frac{T_m - T_a}{I_T} \right)^2$$

Where

T_m = average manifold temperature

η_0 = baseline efficiency

a_1 = heat loss coefficient

a_2 = heat loss coefficient

Thermal collectors are rated by the Solar Rating and Certification Corporation (SRCC). The baseline efficiency and heat loss coefficients are determined through SRCC testing and are available on their website. The average manifold temperature must be estimated for this calculation. Since these calculations are carried out in an iterative nature, the average manifold temperature was the new storage temperature from the previous iteration added to one half the difference of the new and old storage temperatures from the previous

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iteration. This estimation is probably below the actual manifold temperature, but it was chosen for simplicity.

A large factor on how much thermal energy can be collected is the temperature of the water entering the manifold. Determining this temperature requires calculating the temperature of the thermal storage water. The following equation is used in an iterative manner to determine storage tank temperature

$$T_{s,new} = T_{s,old} + \frac{Q - L}{V\rho c_p}\Delta t$$

Where

$T_{s,new}$ = the new storage tank temperature

$T_{s,old}$ = the storage tank temperature from the previous iteration

V = the volume of the storage tank

ρ = the density of the storage medium

c_p = specific heat of the storage medium

L = load or end-use of stored heat

Δt = time interval of each iteration

For the purposes of this calculation, the end-use of heat, L, had to be assumed. The choice was to set L at 153.5 W per 15 minute interval. This value was chosen based on the hot water competition requirement of providing 300 gallons of water at 110°F over the course of the week. Additionally, $T_{s,old}$ and T_m had to be estimated for the first iteration. These values were both set at 110°F since this is the target temperature for the hot water competition. The last equation also assumes that there is no stratification in the storage tank and the storage medium is fully mixed.

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Results

Calculated Values

Table 4 Direct-gain calculated results

Team	Solar glazing-floor space ratio	Extra Thermal Mass (Btu/°F)	Solar glazing unaccounted for (ft^2)
Cornell University	6.1%	0.0	0.0
Iowa State University	9.0%	342.6	10.5
Ohio State University	23.7%	1983.4	41.8
Penn State	43.7%	5463.4	132.2
Rice University	12.6%	0.0	28.3
Team Alberta	21.9%	557.5	30.2
Team Boston	33.1%	28.0	149.2
Team California	41.2%	62.7	185.1
Team Germany	24.2%	1507.8	0.0
Team Missouri	17.8%	0.0	69.1
Team Ontario/BC	44.0%	3331.8	193.3
Team Spain	20.9%	594.7	85.2
Universidad de Puerto Rico	16.9%	0.0	48.1
University of Arizona	32.2%	1657.6	93.8
University of Illinois	22.7%	0.0	79.4
University of Kentucky	16.9%	0.0	55.6
University of Louisiana	12.2%	0.0	30.3
University of Minnesota	28.2%	48.2	127.2
University of Wisconsin	27.6%	0.0	110.3
Virginia Tech	61.9%	5301.2	208.6

Direct-Gain

The calculated results for direct-gain solar glazing ratio, thermal mass and unaccounted for solar glazing are shown in Table 4. Unaccounted for solar glazing is the amount of glazing area that is not compensated for with incidental thermal mass or with additional dedicated thermal mass. As is shown in Table 5 only Cornell managed to design a house that stayed below the 7% solar glazing ratio. Additionally, Iowa State, Louisiana and Rice all managed to be close to the 7% to 12% range. These top four teams ranked 13, 11, 7, and 10 in the comfort zone competition. Virginia Tech, the team with most excessive amount of solar glazing placed 8th in the same competition. Based on the design rule of thumb, the majority of the houses in the competition were designed with excessive amounts of solar glazing.

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Table 5 Solar glazing in excess of design recommendation

Team	Solar glazing-floor space ratio	Percent above 7%	Rank
Cornell University	6.1%	-0.9%	1
Iowa State University	9.0%	2.0%	2
University of Louisiana	12.2%	5.2%	3
Rice University	12.6%	5.6%	4
University of Kentucky	16.9%	9.9%	5
Universidad de Puerto Rico	16.9%	9.9%	6
Team Missouri	17.8%	10.8%	7
Team Spain	20.9%	13.9%	8
Team Alberta	21.9%	14.9%	9
University of Illinois	22.7%	15.7%	10
Ohio State University	23.7%	16.7%	11
Team Germany	24.2%	17.2%	12
University of Wisconsin	27.6%	20.6%	13
University of Minnesota	28.2%	21.2%	14
University of Arizona	32.2%	25.2%	15
Team Boston	33.1%	26.1%	16
Team California	41.2%	34.2%	17
Penn State	43.7%	36.7%	18
Team Ontario/BC	44.0%	37.0%	19
Virginia Tech	61.9%	54.9%	20

Since thermal mass can help even out temperature swings and prevent overheating, it plays an important role in direct-gain passive solar heating. Table 6 orders the teams by the amount of thermal mass incorporated into the design of the house. The top seven teams had very deliberate uses of thermal mass while the remaining teams had thermal mass included in furnishings and counters. Of the top seven thermal mass designs, four used phase change materials (PCM) (Penn State, Ontario/BC, Germany, and Spain), two used water (Ohio State and Arizona), and one used concrete (Virginia Tech) as thermal mass. For Spain and Ontario/BC the total capacity for the PCM was given for a defined temperature range which allowed the storage capacity to be presented in Btu/°F units. The PCM used by Penn State and Germany did not have a defined temperature range and thus could not be calculated on a per degree basis. In order to make these calculations comparable to other forms of thermal mass, the total storage capacity was divided by 20°F.

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This temperature range was chosen based on the daily temperature swings measured in several of the houses.

Table 6 Thermal mass amounts

Team	Extra Thermal Mass (Btu/°F)	Rank
Penn State	5463.4	1
Virginia Tech	5301.2	2
Team Ontario/BC	3331.8	3
Ohio State University	1983.4	4
University of Arizona	1657.6	5
Team Germany	1507.8	6
Team Spain	594.7	7
Team Alberta	557.5	8
Iowa State University	342.6	9
Team California	62.7	10
University of Minnesota	48.2	11
Team Boston	28.0	12
Cornell University	0.0	13
Rice University	0.0	13
Team Missouri	0.0	13
Universidad de Puerto Rico	0.0	13
University of Illinois	0.0	13
University of Kentucky	0.0	13
University of Louisiana	0.0	13
University of Wisconsin	0.0	13

Coupling the data from Table 5 and Table 6 gives the results listed in Table 7. Factoring in thermal mass, the excessiveness of some team's solar glazing is reduced. Team Germany's house, which is ranked 12th in the amount of solar glazing, has enough thermal mass to compensate for all of the window area above the 7% threshold. This puts Germany alongside Cornell as the two teams that best designed their houses for direct-gain. Germany's design most likely had a greater effect on the performance of the house due to the greater thermal collection and storage capability. However, Cornell's design allows for less thermal loss through windows due to the reduced solar glazing area.

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Table 7 Amount of solar glazing not compensated for with thermal mass

Team	Solar glazing unaccounted for (ft^2)	Rank
Cornell University	0.0	1
Team Germany	0.0	1
Iowa State University	10.5	3
Rice University	28.3	4
Team Alberta	30.2	5
University of Louisiana	30.3	6
Ohio State University	41.8	7
Universidad de Puerto Rico	48.1	8
University of Kentucky	55.6	9
Team Missouri	69.1	10
University of Illinois	79.4	11
Team Spain	85.2	12
University of Arizona	93.8	13
University of Wisconsin	110.3	14
University of Minnesota	127.2	15
Penn State	132.2	16
Team Boston	149.2	17
Team California	185.1	18
Team Ontario/BC	193.3	19
Virginia Tech	208.6	20

Indirect-Gain

Only two teams designed houses with indirect-gain sunspaces: Iowa State and Spain. The calculated values for the solar gain ratio, thermal mass and volume ratios are shown in Table 8. Spain has a much larger solar gain ratio but no thermal mass and a smaller ratio of sunspace to living space. Theoretically this would mean that the air in the sunspace would get very hot but there would only be a short period of heat gain in the living space. Since the Iowa State house has thermal mass, more heat can be stored and released gradually into the living space.

Table 8 Indirect-Gain Calculated Values

Team	Solar glazing-sun space ratio	Thermal mass (Btu/°F)	Sunspace-living space ratio (ft^3/ft^3)
Iowa State University	114.7%	96.1	10.66%
Team Spain	432.4%	0.0	4.96%

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Daylighting

Calculated values for the effective aperture of each house are shown in Table 9. Team Alberta and Louisiana did the best job of designing for the 0.18 effective aperture value, differing by only 0.005 and 0.006 respectively. Most teams had an EA value higher than 0.18. This is most likely due to a high window-to-wall ratio than to a high visible transmittance value. As a result, these houses lose more energy through windows than is saved through daylighting.

Table 9 Ranked effective aperture calculation results

Team	EA	Difference from .18	Rank
Team Alberta	0.185	0.005	1
University of Louisiana	0.174	-0.006	2
University of Wisconsin	0.194	0.014	3
Universidad de Puerto Rico	0.166	-0.015	4
University of Minnesota	0.164	-0.016	5
Ohio State University	0.202	0.022	6
Rice University	0.148	-0.032	7
Cornell University	0.213	0.033	8
Iowa State University	0.119	-0.061	9
University of Illinois	0.110	-0.070	10
Team Spain	0.108	-0.072	11
Team Missouri	0.089	-0.091	12
University of Arizona	0.278	0.098	13
Team California	0.285	0.105	14
University of Kentucky	0.347	0.167	15
Team Germany	0.367	0.187	16
Team Boston	0.393	0.213	17
Penn State	0.488	0.308	18
Team Ontario/BC	1.357	1.177	19
Virginia Tech	1.462	1.282	20

Insulation

The R-values for walls alone, walls with windows and doors, roof alone and the entire envelope are shown in Table 10. The teams are ranked in order of most insulated house to least insulated. Designs that met or exceeded the recommended insulation values for each area are highlighted as well. Illinois had the most insulated house with the whole envelope R-value doubling that of the third most insulated house, Iowa State. The top two

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most insulated houses, Illinois and Germany also placed in the top two spots of the comfort zone competition although Germany won the competition with Illinois taking second. While the R-value is not a direct parallel to performance in the comfort zone competition, it surely has a strong effect on the outcome.

Some teams managed to design for the recommended R-values but still ended up with an extremely low whole envelope R-value. This is usually due to having too many windows and doors or having low quality windows and doors. Most notably, Team Boston had high R-values for walls and roof but a large amount of windows and doors with average R-values brought the whole envelope R-value down significantly. The same thing happened to Virginia Tech who designed a high R-value roof but ended up with the second worst envelope R-value. Lousiana also had good R-values in their walls but a large single-layer metal door brought the R-value of the whole building to about 1. An interesting observation is that most of the houses with higher insulation values were from northern climates while those with lower insulation values were from southern climates.

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Table 10 Insulation values for various house elements

Team	R-values (°F-ft^2-h/Btu)			
	Walls Only	Walls, windows, doors	Roof only	Whole envelope
University of Illinois	62.3	31.7	70.2	40.7
Team Germany	66.3	22.3	85.1	27.7
Iowa State University	33.2	15.6	38.9	20.4
University of Minnesota	52.2	10.2	70.1	15.6
Team Spain	28.0	12.4	28.2	15.4
Team Alberta	46.1	10.6	42.7	14.6
Team Missouri	26.7	10.6	41.4	14.0
Ohio State University	25.2	9.6	54.8	13.9
Team Ontario/BC	44.5	8.8	60.9	13.6
University of Wisconsin	28.1	11.7	44.4	11.7
Cornell University	21.7	9.2	35.1	11.6
Penn State	31.3	7.7	38.7	11.3
Team California	27.5	7.0	38.4	9.5
University of Kentucky	8.4	7.0	22.6	8.7
Rice University	19.1	6.2	25.5	8.0
Team Boston	31.9	5.1	53.9	8.0
University of Arizona	13.6	5.1	27.0	7.3
Universidad de Puerto Rico	6.9	3.5	18.5	5.1
Virginia Tech	16.0	2.9	48.5	4.4
University of Louisiana	27.3	0.8	10.3	1.1

Windows

Table 11 shows the weighted solar heat gain coefficient of southern windows, R-value, and glazing as a percent of conditioned floor space based on orientation. Designs that met or exceeded the recommended values for each area are highlighted as well. The table is sorted based on R-value of the windows. Several teams managed to create a design that either had the proper SHGC or a high R-value or windows in the proper proportions for energy efficiency but only Illinois managed do all of these things. This helps explain why Illinois has such a high envelope R-value in Table 10.

Several teams had extremely high percentages of windows, especially on the north wall. These high amounts of windows were probably designed with daylighting in mind. As Table 9 shows, many of the designs employed excessive amounts of windows for even daylighting standards. What is also notable, along with the large amounts of windows, is that the median window R-value is 3.7 to 3.75. While this is not a terrible R-value, it is

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also not outstanding. The expectation for an efficient housing design competition would be that the windows would be far better than those in an average house, especially since windows are typically the weak point in the building envelope.

Table 11 Window values

Team	Weighted SHGC	R-value	North %	East %	West %
Iowa State University	0.26	11.10	13.83%	2.02%	0.00%
Team Spain	0.21	10.53	12.37%	12.37%	33.17%
Team Germany	0.55	9.31	21.88%	14.83%	10.35%
University of Illinois	0.52	9.09	3.99%	0.67%	0.67%
Team Ontario/BC	0.44	8.00	6.07%	16.48%	21.97%
University of Kentucky	0.25	5.88	33.20%	8.30%	8.35%
Ohio State University	0.23	4.81	8.41%	16.46%	17.63%
University of Minnesota	0.24	4.76	9.57%	9.32%	1.41%
Team Alberta	0.39	4.27	9.90%	2.30%	3.30%
Penn State	0.70	3.75	11.44%	9.75%	3.81%
University of Wisconsin	0.19	3.70	21.52%	9.71%	24.04%
Team Missouri	0.27	3.49	14.46%	0.86%	2.80%
Cornell University	0.36	3.13	20.78%	13.68%	10.59%
University of Louisiana	0.23	2.94	19.48%	6.03%	6.03%
University of Arizona	0.40	2.86	42.06%	10.91%	8.44%
Team California	0.25	2.78	14.44%	15.87%	24.67%
Team Boston	0.29	2.63	30.83%	4.32%	0.00%
Virginia Tech	0.36	2.18	55.51%	0.00%	3.43%
Rice University	0.25	2.17	0.00%	16.90%	16.90%
Universidad de Puerto Rico	0.32	2.03	34.09%	1.22%	0.00%

Shading

It is very difficult to judge the houses based on shading because most of the houses use good shading techniques. The results of qualitative shading design analysis are listed in Table 12. All of the teams did well choosing materials with low heat storage. The shading design principle that most teams did not follow was keeping the shading device outside of the windows. This is actually one of the most important principles because with interior shading the solar radiation has already entered the building through the glazing. Most interior shading took the form of blinds or curtains.

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Table 12 Shading checklist

Team	Outside of glazing	Low absorptance	Low heat storage	Prevent reflection	No trapped air	Total
Team Alberta	x	x	x	x	x	5
Team Boston	x	x	x	x	x	5
Team California	x	x	x	x	x	5
Iowa State University	x	x	x	x	x	5
Penn State	x	x	x	x	x	5
Team Missouri	x	x	x	x	x	5
Ohio State University	x	x	x	x	x	5
University of Illinois	x	x	x	x	x	5
University of Arizona		x	x	x	x	4
Cornell University		x	x	x	x	4
Team Germany		x	x	x	x	4
Rice University	x	x	x		x	4
Team Ontario/BC	x		x	x	x	4
Universidad de Puerto Rico	x	x	x	x		4
University of Louisiana	x	x	x	x		4
University of Minnesota		x	x	x	x	4
University of Wisconsin	x	x	x		x	4
Virginia Tech	x	x	x	x		4
University of Kentucky			x	x	x	3
Team Spain	x		x			2

Temperature

The week of competition was comprised of several rainy and cloudy days interspersed with one or two sunny days. The average outdoor temperature for the competition was 60.2°F with a maximum temperature of 86.6°F and a minimum temperature of 45.1°F. With the average temperature being well below the comfort zone competition temperature range, the goal was to retain as much heat as possible in order to keep the internal temperature close to the 72°F to 76°F range. As Table 13 shows, few teams were able to maintain a high enough temperature over the course of the competition week. This is most likely due to public tours which frequently require leaving doors open for long periods of time. After removing the public tour hours from the calculation, eight teams have average temperatures within the required range.

Standard deviation of the temperature data set is also included in Table 13. Standard deviation allows for the determination of how well a house maintained a steady temperature. A small standard deviation indicates that the temperature remained fairly constant and did not differ much. A larger standard deviation indicates large temperature swings and poor temperature control. According to Table 13, the Illinois house had the best temperature control during the scored competition hours and was a close second over

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the whole week. Other houses exhibiting good temperature control were those of Ontario/BC, Ohio State and Germany.

Table 13 Average temperature and humidity

Team	Whole period				Competition hours only			
	Temperature		Humidity		Temperature		Humidity	
	Average	Stdev	Average	Stdev	Average	Stdev	Average	Stdev
Cornell	69.98	5.91	48.56	10.78	69.64	4.31	52.67	9.10
Iowa State University	69.34	4.22	49.10	8.08	70.19	3.12	51.60	6.83
Ohio State University	71.87	3.73	47.87	7.71	72.34	2.57	48.72	6.88
Penn State	71.85	4.24	51.58	9.49	73.92	3.06	53.93	7.97
Rice University	69.11	6.44	52.01	10.40	69.38	6.15	53.81	8.26
Team Alberta	73.03	4.69	47.32	8.80	73.46	3.38	49.40	7.38
Team Boston	70.67	4.92	51.53	7.53	72.29	4.29	54.50	7.20
Team California	69.87	6.09	48.66	9.49	70.45	6.49	50.05	9.87
Team Germany	74.37	3.44	44.36	7.17	74.14	2.81	46.93	6.47
Team Missouri	70.58	6.18	52.64	9.19	70.38	6.06	56.34	6.41
Team Ontario/BC	73.20	2.49	46.51	6.73	73.53	2.09	47.77	6.22
Team Spain	69.26	7.75	54.84	13.01	70.31	6.00	58.47	10.78
Universidad de Puerto Rico	68.61	6.74	50.91	8.85	70.13	6.41	52.01	7.59
University of Arizona	68.37	5.85	46.36	11.20	69.13	5.37	46.83	11.77
University of Illinois	74.24	2.65	48.39	8.66	74.43	1.43	51.79	5.29
University of Kentucky	70.38	5.83	52.40	10.76	71.38	5.04	55.56	8.98
University of Louisiana	70.97	5.44	45.40	7.66	71.40	4.68	45.45	5.14
University of Minnesota	71.10	4.22	51.28	8.45	71.80	3.33	53.22	6.68
University of Wisconsin	71.43	5.51	48.02	7.73	74.16	3.72	47.42	6.28
Virginia Tech	71.22	5.14	48.53	10.79	70.95	5.22	50.64	10.28

Temperatures measured by the competition organizers are graphed in Figure 11 below. The graph visualizes where peaks and valleys occurred for various teams. As should be expected, most of the peaks occurred during the public tour hours but carried over into the competition measurement periods. Many of the temperature peaks can also be visually correlated to outdoor temperature which is shown along with humidity in Figure 12. With this graph in mind, it should be no surprise that many teams had severe temperature peaks on the first Friday afternoon when the outdoor temperature peaked around 87°F.

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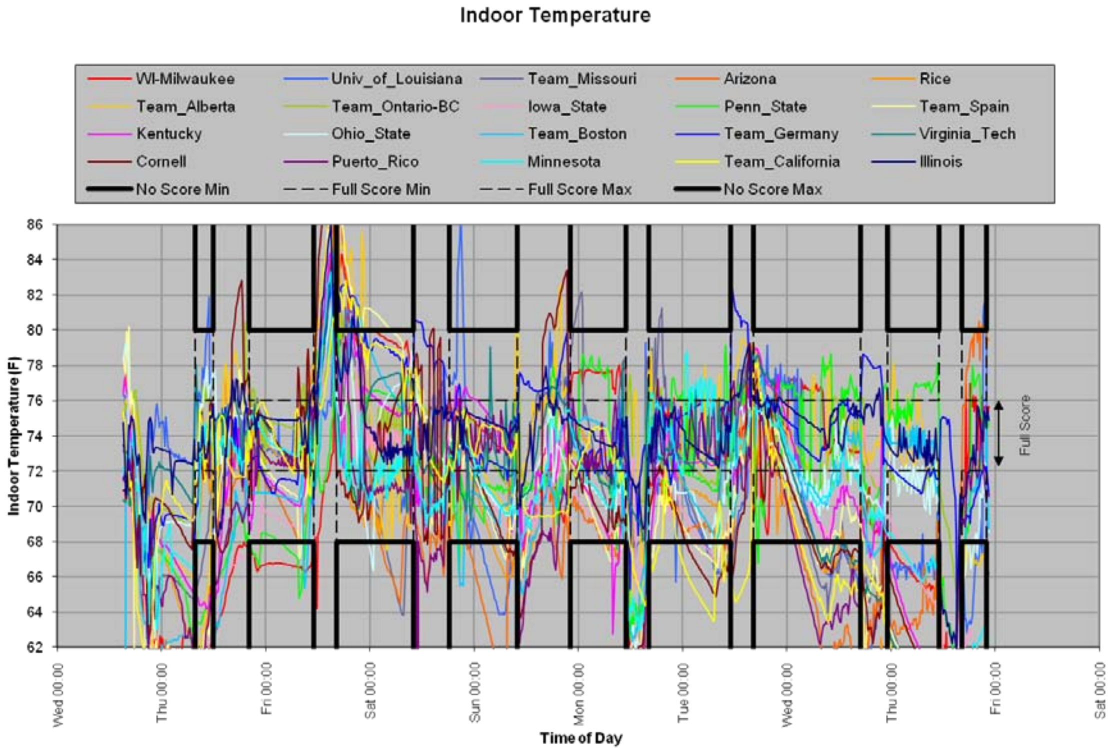

Figure 11 Measured indoor temperatures

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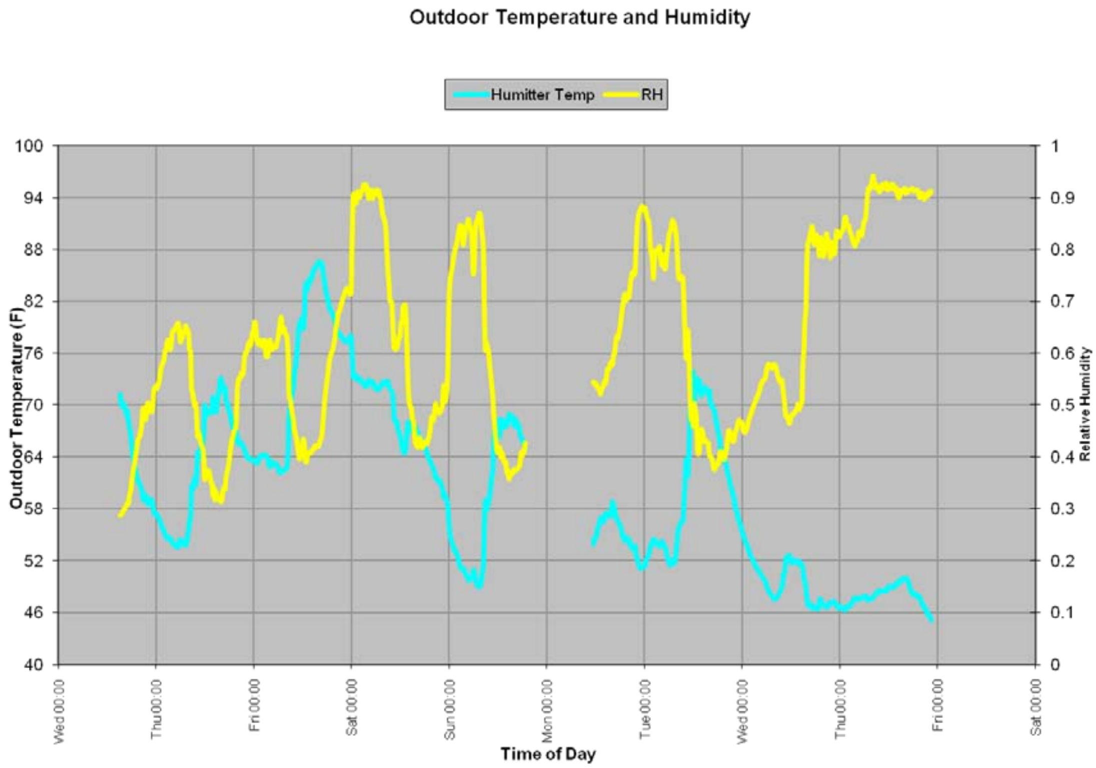

Figure 12 Measured outdoor temperature and humidity

Comparisons

For all plots and graphs showing blue diamonds and red squares, the blue diamonds represent data taken over the whole course of the competition while the red squares represent data collected only during the scored competition hours for comfort zone.

Solar Glazing

While direct gain through solar glazing is a primary source of passive solar heating, there is only a loose correlation between solar glazing area and average internal temperature of the houses. As shown in Figure 13, the R^2 value, or goodness of fit, is less than 0.1, indicating only a loose fit for the linear trendline. The trendline does indicate that increasing the amount of solar glazing results in a slightly increased average internal temperature.

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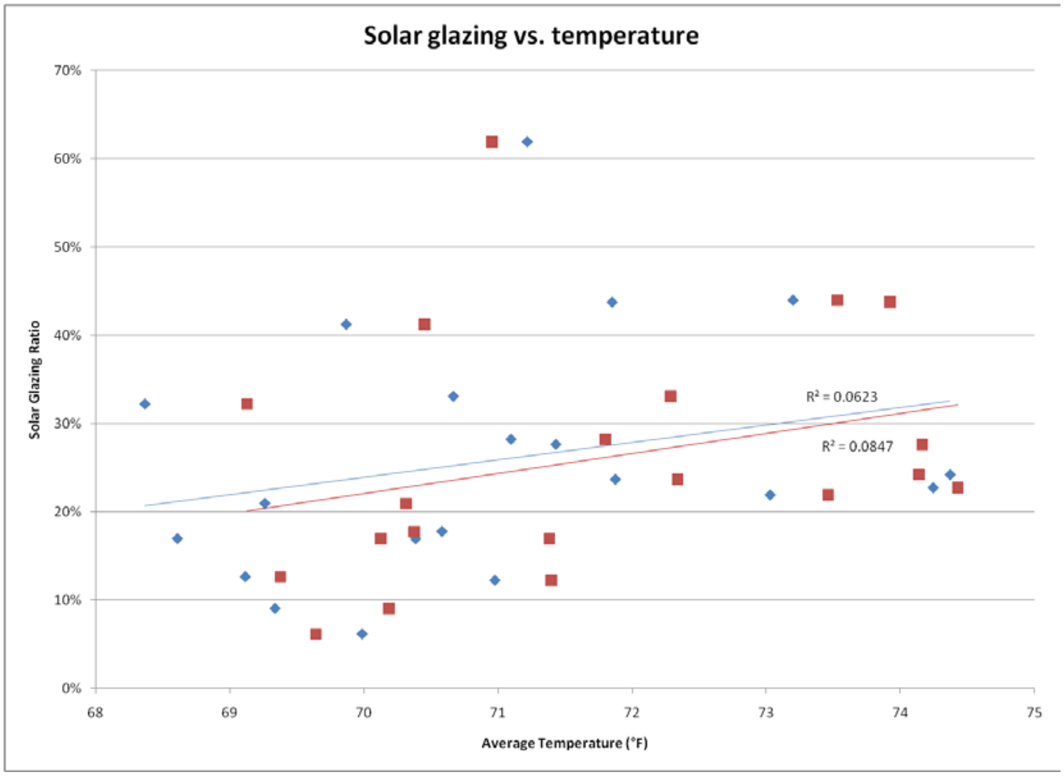

Figure 13 Solar glazing ratio vs. temperature

When viewing the effect of solar glazing on standard deviation of temperature, the correlation is even weaker. Figure 14 shows that there is almost no correlation during the competition hours and a weak correlation over the course of the whole week. The general trend shows that increasing solar glazing results in slightly smaller standard deviation values which means that there is slightly better temperature control.

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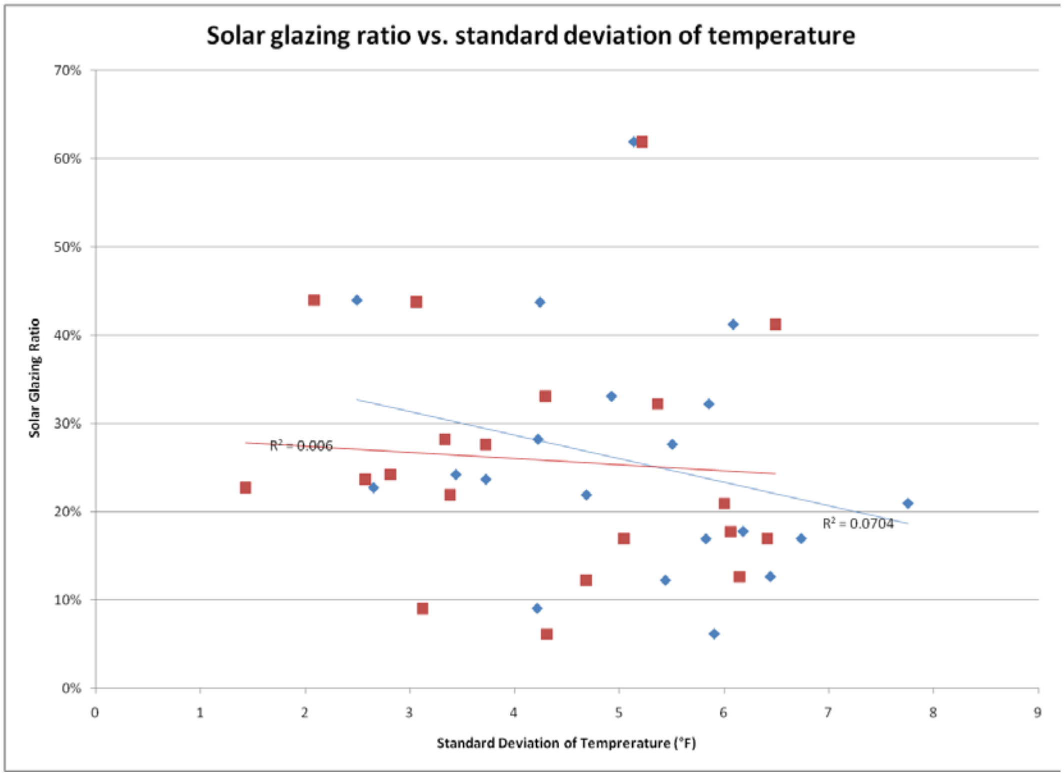

Figure 14 Solar glazing ratio vs. standard deviation of temperature

Figure 15 compares solar glazing to points earned in the comfort zone competition. Scores in this competition reflect the amount of time a house was able to stay within the desired temperature and humidity ranges. Again, there is only a very weak correlation between solar glazing and points earned. This could be partly due to the lack of significant hours of direct sunshine. The graph does show a slight tendency for houses with more solar glazing to earn more points in the competition.

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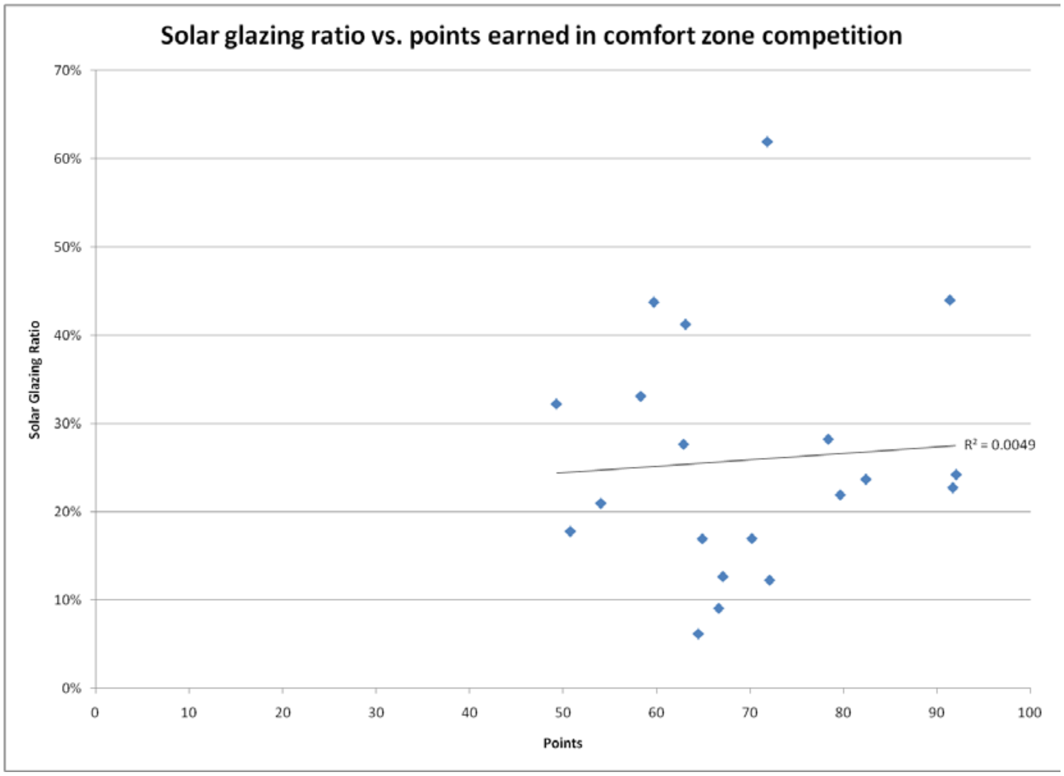

Figure 15 Solar glazing ratio vs. points scored in comfort zone competition

Thermal Mass

Amount of thermal mass is graphed versus average internal temperature in Figure 16 and Figure 17. Figure 16 shows all houses while Figure 17 shows only those houses with additional thermal mass. While both graphs show a weak correlation between thermal mass and internal temperature, the graph showing only houses with thermal mass has a somewhat better fit. Both graphs indicate that increasing thermal mass also increased average internal temperature. This is likely a direct result of the heat retention capabilities of thermal mass and that there was a general need for heating during the measured period.

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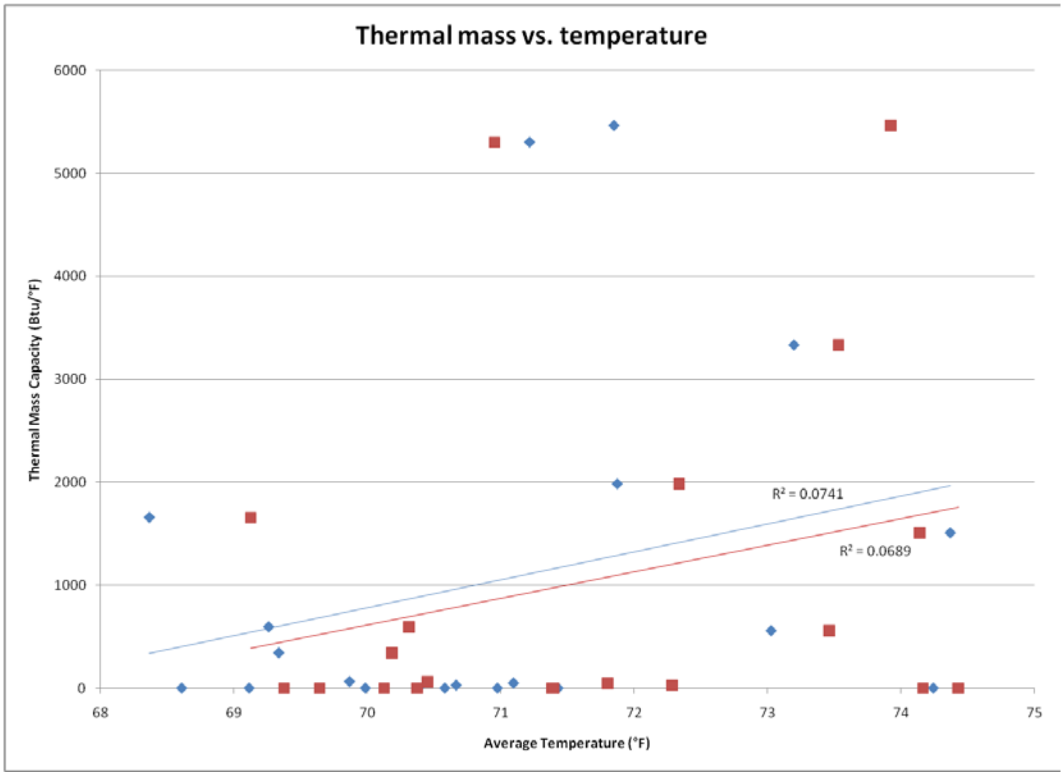

Figure 16 Thermal mass vs. temperature

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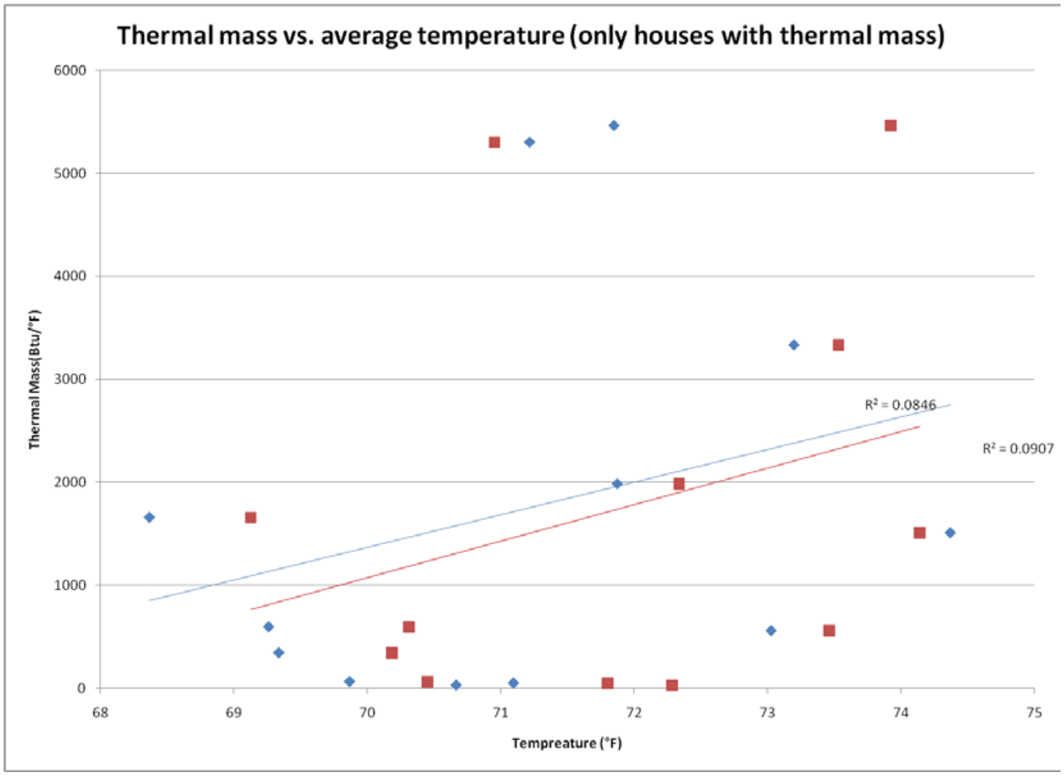

Figure 17 Thermal mass vs. temperature (houses with mass)

Thermal mass is graphed against standard deviation of temperature in Figure 18 and Figure 19 with Figure 19 only showing houses with thermal mass. A weak correlation exists in this comparison although with an R^2 value of 0.119 it is the strongest correlation seen thus far. The general trend shows that increasing thermal mass reduces standard deviation values. This is due to the ability of thermal mass to dampen temperature swings. Oddly enough, removing the houses without thermal mass (Figure 19) actually weakens the correlation. In this case, the trend does show a sharper trend of improving standard deviation with increasing thermal mass than was observed with all houses included.

There are two houses, Penn State and Virginia Tech, which have outlying data points in all of the thermal mass comparisons. This a direct result of the volume of thermal mass used. Virginia Tech utilized a concrete floor which allowed them to incorporate much more traditional thermal mass into the structure than other teams. Penn State used a high capacity phase change material incorporated into all walls and ceilings in their house. Other houses that utilized PCM either did not use a high storage capacity product or did not install the material in as much of the building.

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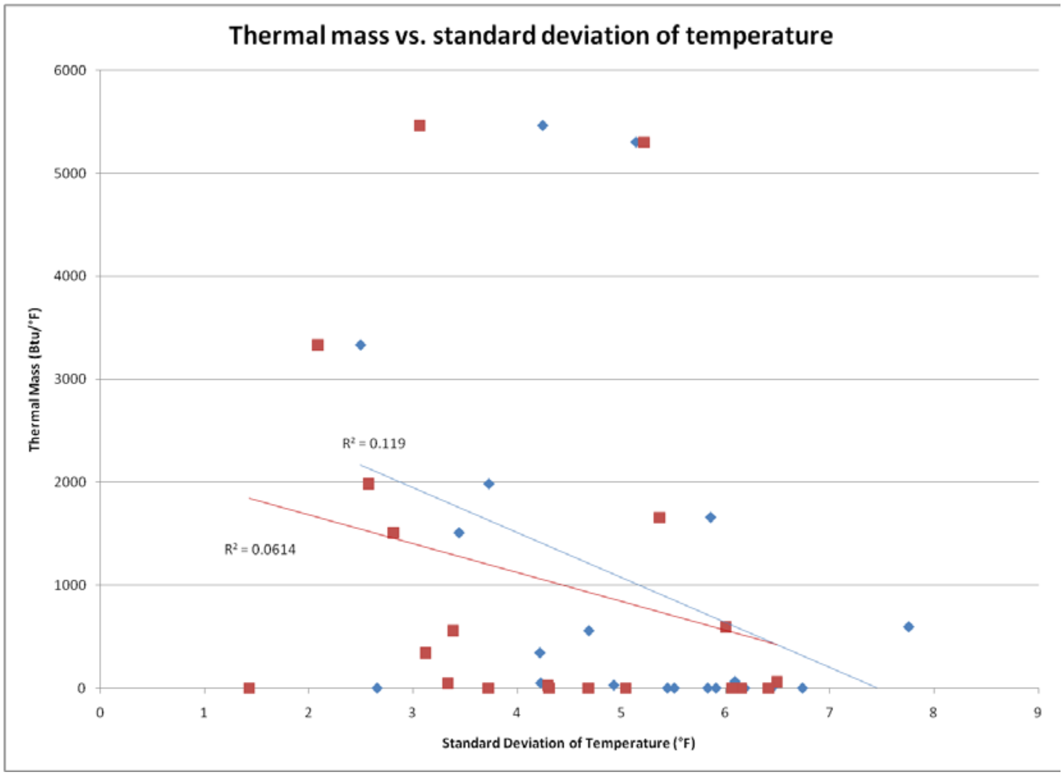

Figure 18 Thermal mass vs. standard deviation of temperature

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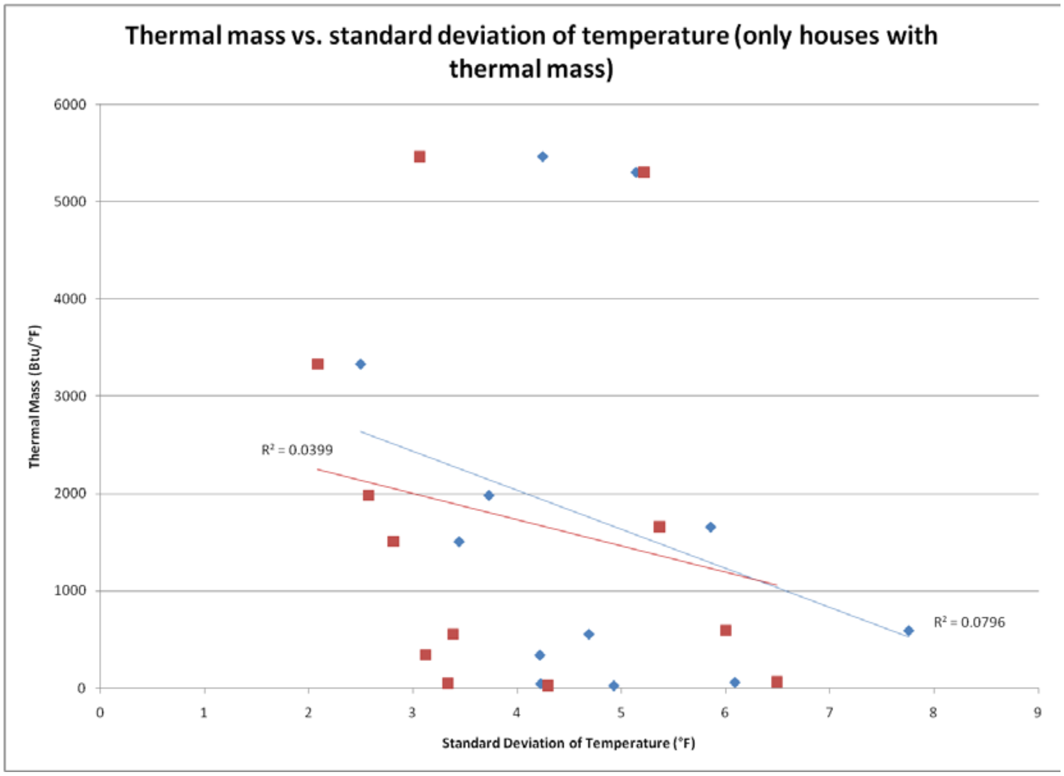

Figure 19 Thermal mass vs. standard deviation of temperature (houses with mass)

Unaccounted Solar Glazing

Unaccounted for solar glazing is solar glazing area that is not compensated for by appropriately sized and oriented thermal mass. Figure 20 is the plot of unaccounted solar glazing compared to average internal temperature. This graph should be comparable to Figure 13 which shows total solar glazing percentages. Most teams did not design their houses with enough thermal mass to compensate for excessive solar glazing area so the graphs should be quite similar. The trend is somewhat similar in both graphs with larger amounts of excessive solar glazing resulting in higher average temperatures. The difference between the two graphs is that there is less correlation between temperature and unaccounted for solar glazing.

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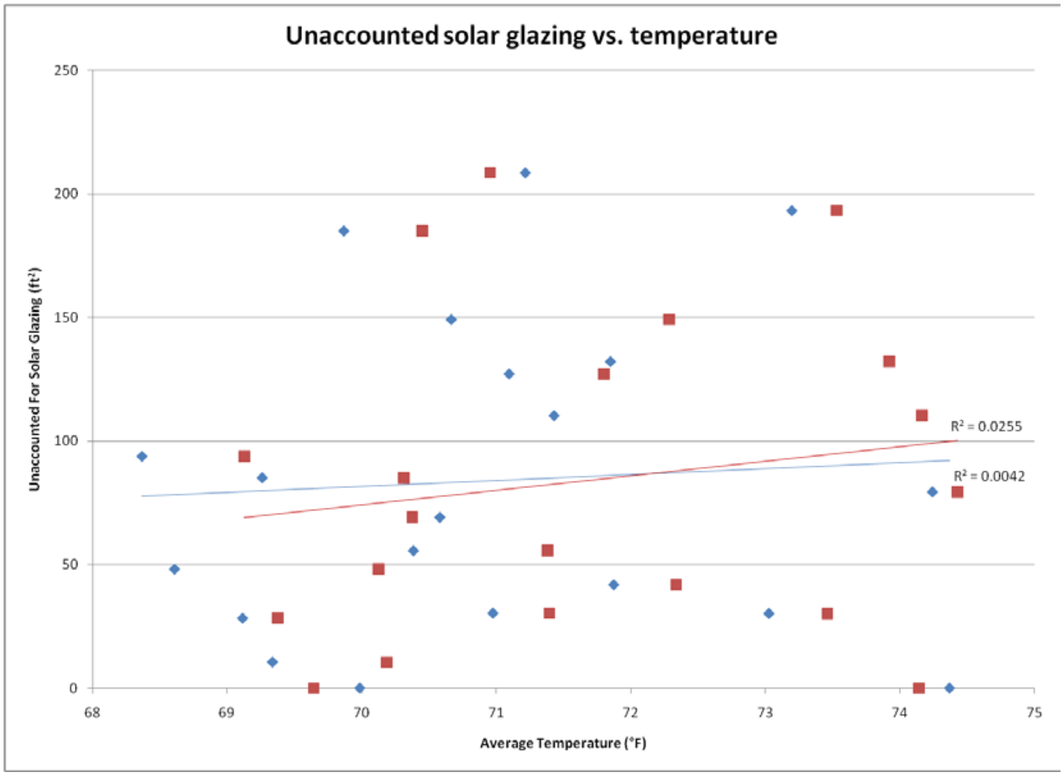

Figure 20 Unaccounted solar glazing vs. temperature

Figure 21 shows unaccounted solar glazing compared to standard deviation of temperature. In this graph there is a discrepancy between the trends of the whole time period and the competition time period. Typically, while the trendlines are not the same for the two time periods, they at least imply a similar correlation. This is not the case in Figure 21. According to the rule of thumb, greater amounts of unaccounted for solar glazing should result in a higher standard deviation and less temperature control. Only the trendline of the competition period supports this expectation. The R^2 value indicates that this correlation is very weak especially when compared to the correlation given by the trendline for the whole period. Even so, the correlation for the whole period is still a very weak one.

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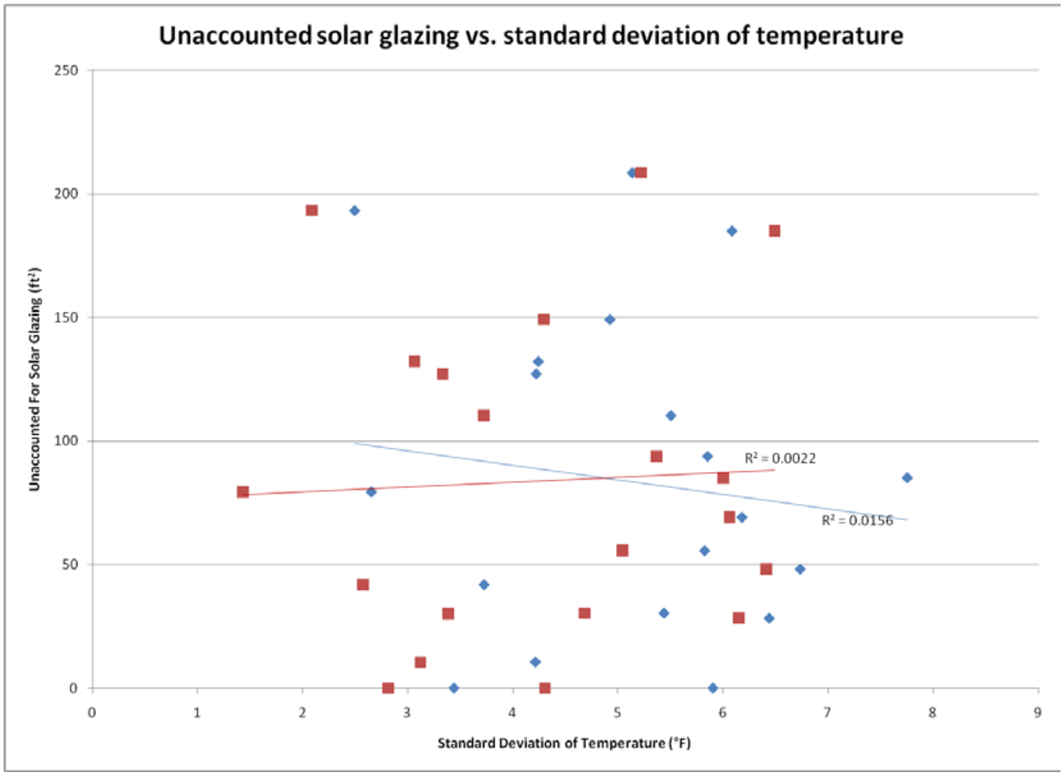

Figure 21 Unaccounted solar glazing vs. standard deviation of temperature

The comparison between unaccounted for solar glazing and points earned in the comfort zone competition is shown in Figure 22. A very weak correlation exists that implies that minimizing unaccounted for solar glazing resulted in a higher score in this area.

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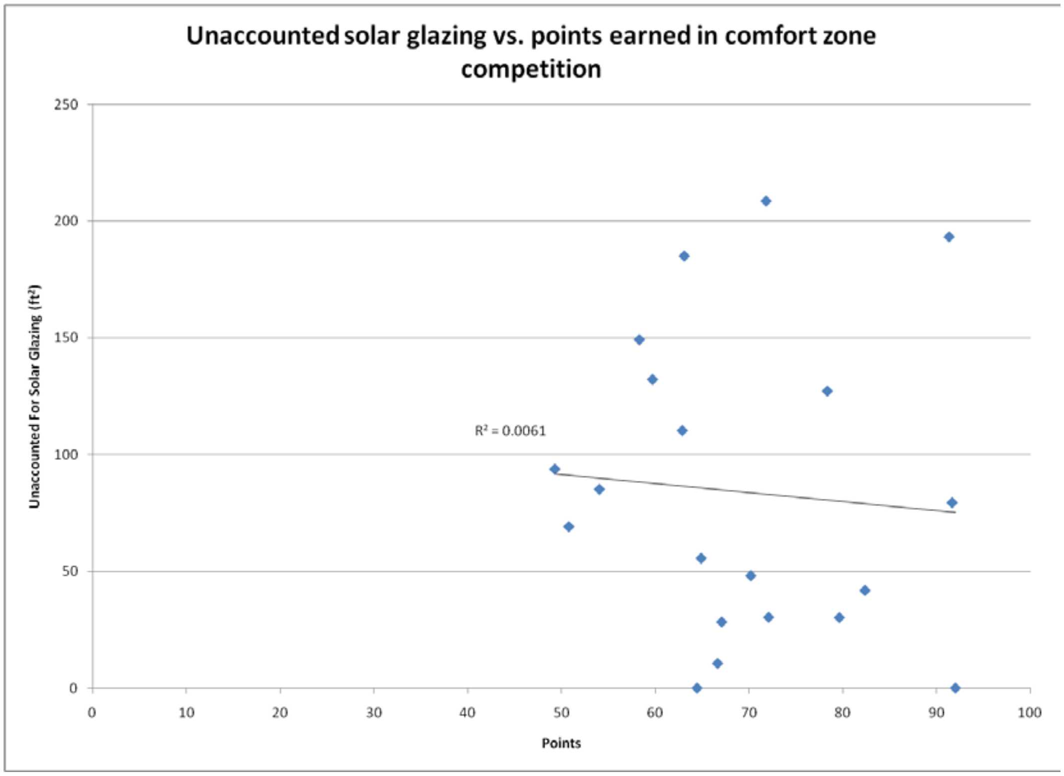

Figure 22 Unaccounted solar glazing vs. points earned in comfort zone competition

R-values

Thermal resistance for the whole envelope, walls alone, walls with windows and doors, roof alone and windows alone are graphed against average interior temperature in Figure 23, Figure 24, Figure 25, Figure 26 and Figure 27 respectively. In each case the argument for a highly insulated envelope is reinforced. On all of the graphs the fitted trendline indicates that increasing R-value results in higher average indoor temperatures. The correlation is also much stronger than in any other relation explored thus far with R^2 values ranging from 0.0877 to 0.6376 with most values being in the 0.2 to 0.5 range.

The elements which appear to be most directly tied to average temperature are roof and wall R-values. This would make sense since typically these two elements account for the majority of the area of a building's envelope. High insulating values in these two components often result in a high insulating value for the whole envelope. According to the slopes of the trendlines, increasing window R-value has the most significant effect on average temperature. This makes sense since windows are typically the weakest point in

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the insulation of a building. Even a small performance increase in this area results in a large increase in performance of the whole envelope.

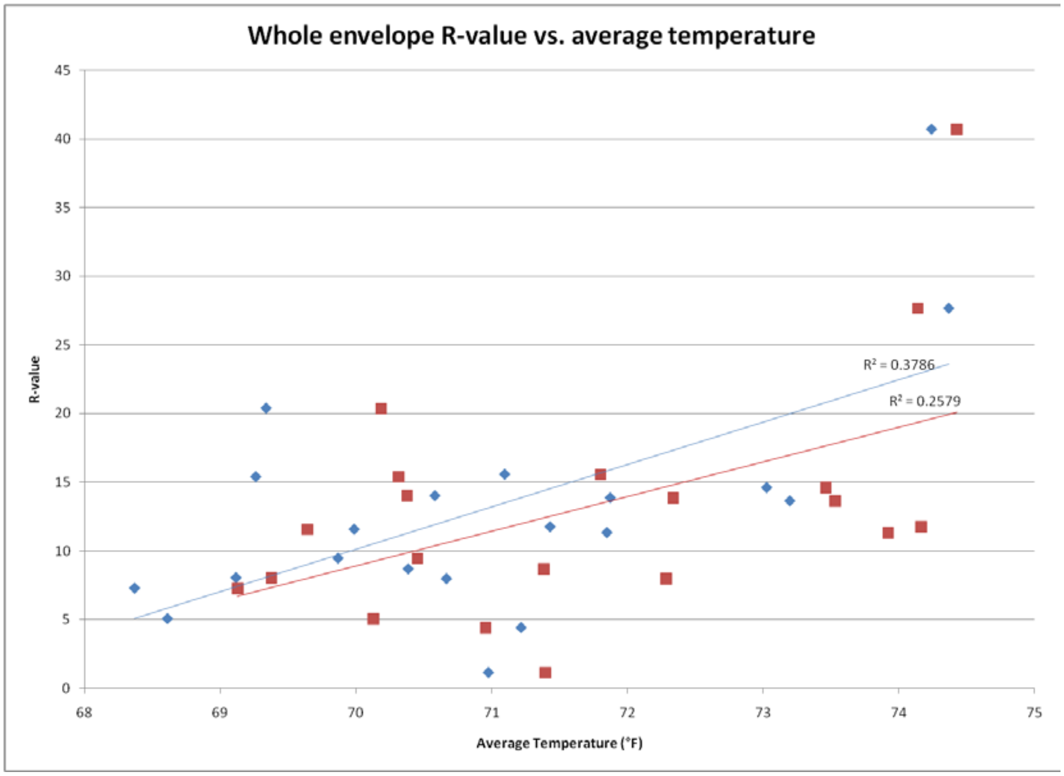

Figure 23 Whole envelope R-value vs. temperature

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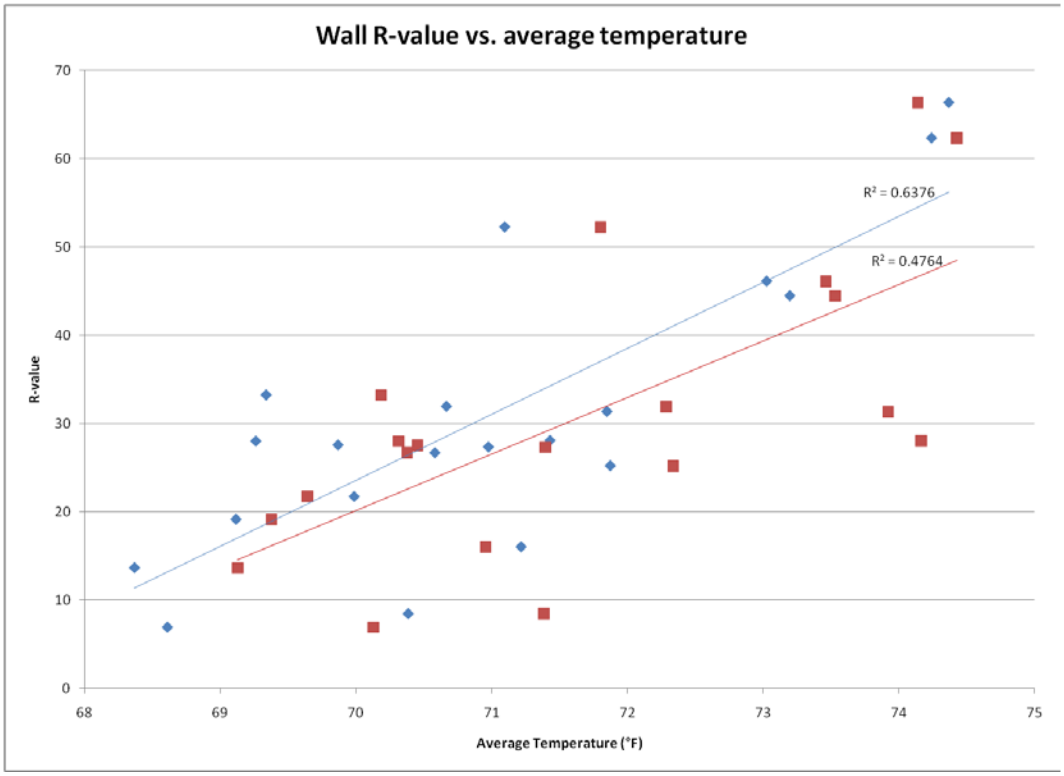

Figure 24 Wall R-value vs. temperature

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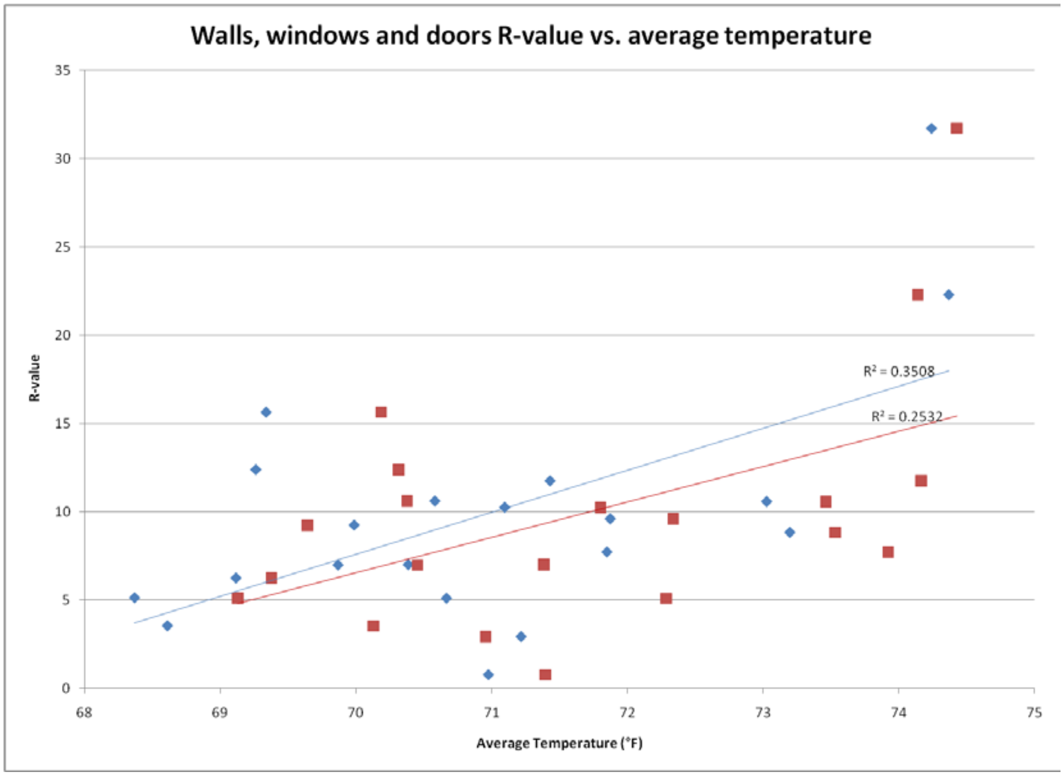

Figure 25 Walls, windows and doors combined R-value vs. temperature

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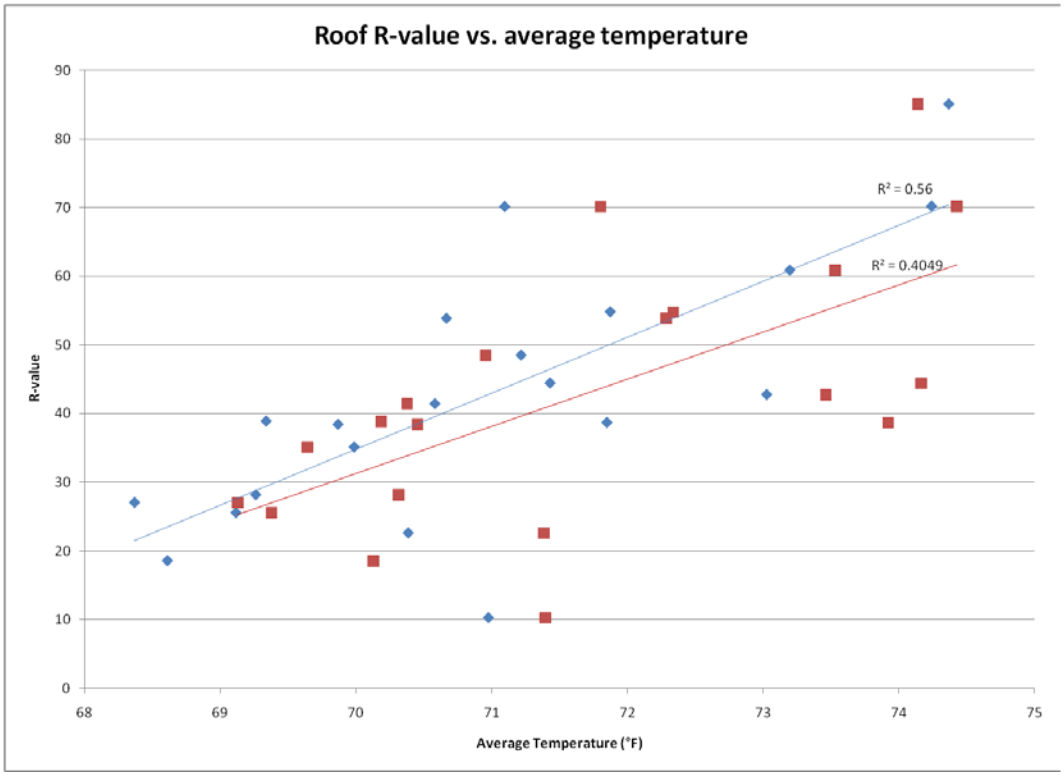

Figure 26 Roof R-value vs. average tempeature

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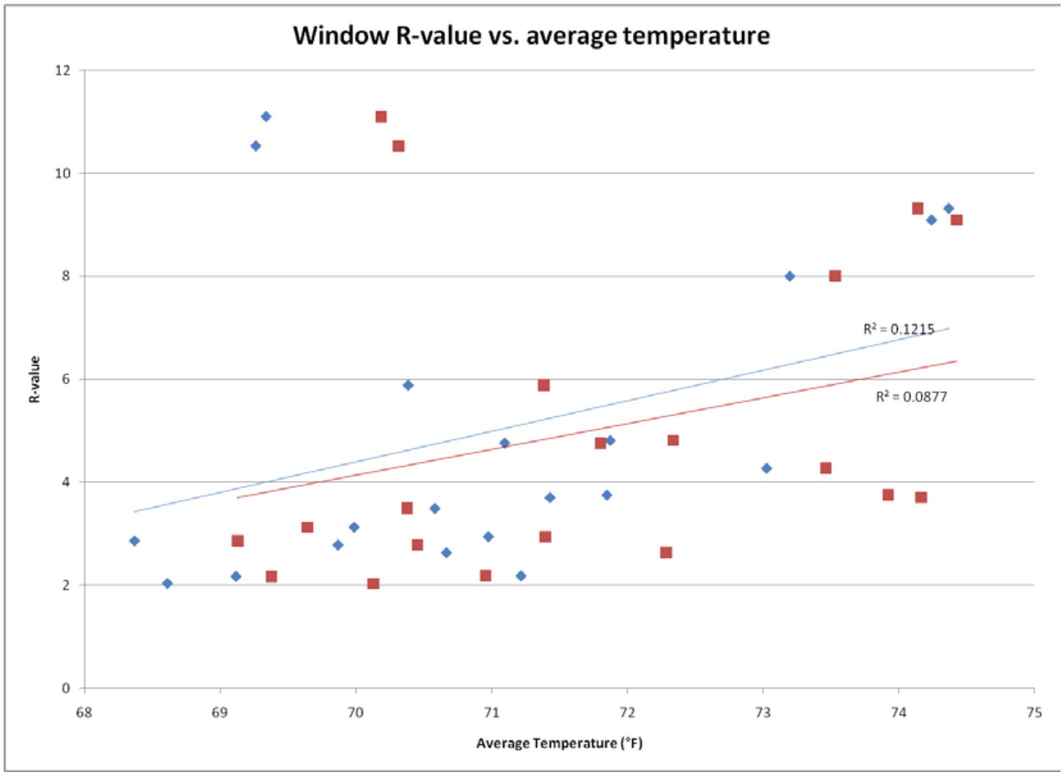

Figure 27 Window R-value vs. temperature

The same elements of the building envelope are graphed against standard deviation of temperature in Figure 28, Figure 29, Figure 30, Figure 31 and Figure 32. As with temperature, there is a somewhat strong correlation between increasing R-values and lower standard deviations. In other words, increasing R-values leads to better temperature control in the building. Goodness of fit is relatively high in these correlations with R^2 values ranging from 0.1491 to 0.5627.

Figure 33 shows the R-values of all three building elements (walls, windows, roof) and the whole envelope for comparison purposes. As with temperature, the steep slope of the window trendline indicates that a small increase in window R-value has a greater impact than a similar increase in either wall or roof R-value. This is again likely due to windows being the lowest R-value component of the envelope. Any improvement to the R-value of windows is proportionally larger than the same improvement would be for walls or roofs.

There are two points in Figure 27 that can be considered outliers. This is mostly due the fact that they exhibit low average temperatures despite high insulating values. The

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amount of solar glazing could play a role in the comparatively low temperatures. The two houses, Iowa State and Spain, had differing amounts of solar glazing. The Iowa State house had the second lowest amount of solar glazing which could account for that point's outlying position. Spain had the eighth lowest amount of solar glazing, which could still be the reason for the outlying nature of this point but seems less likely. The Spain house could have had a problem with its mechanical systems which could cause a low average temperature as well. This possibility is supported by the fact that Spain is an outlier in Figure 32 which indicates that the house had worse than expected temperature control. Oddly enough, these two houses are the only two that incorporated an indirect solar heating sunspace. Perhaps this design element is what caused these two houses to have uncharacteristically low average temperatures but this seems unlikely since the purpose of a sunspace is to contribute heat to the house.

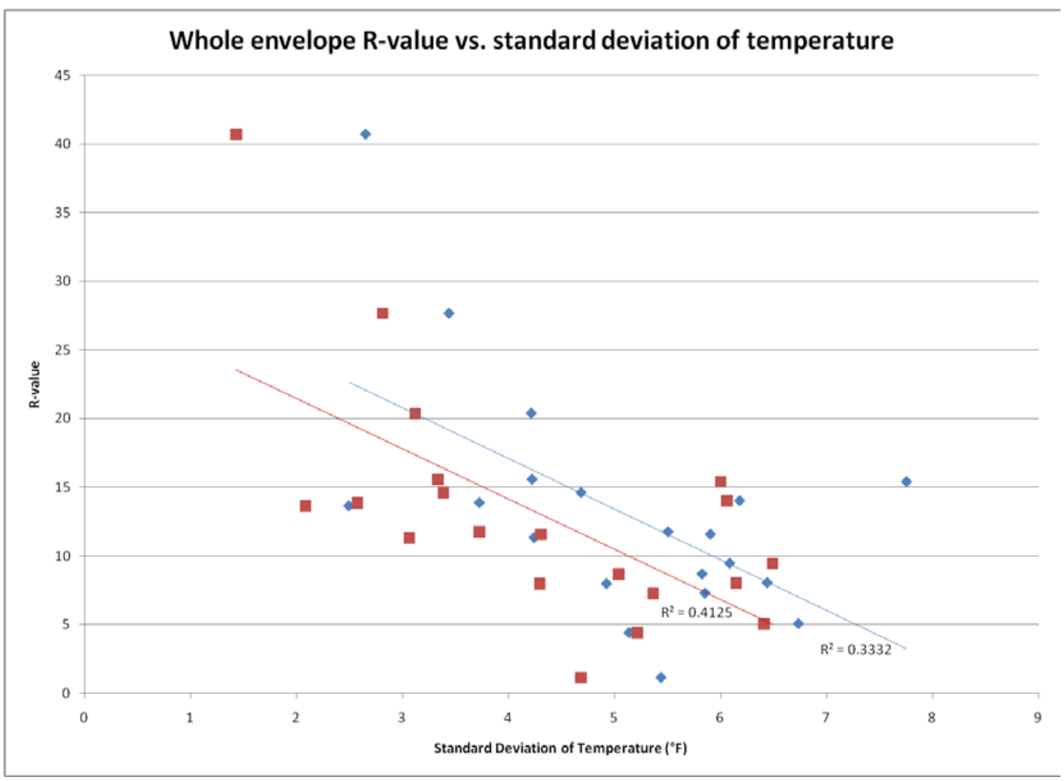

Figure 28 Whole envelope R-value vs. standard deviation of temperature

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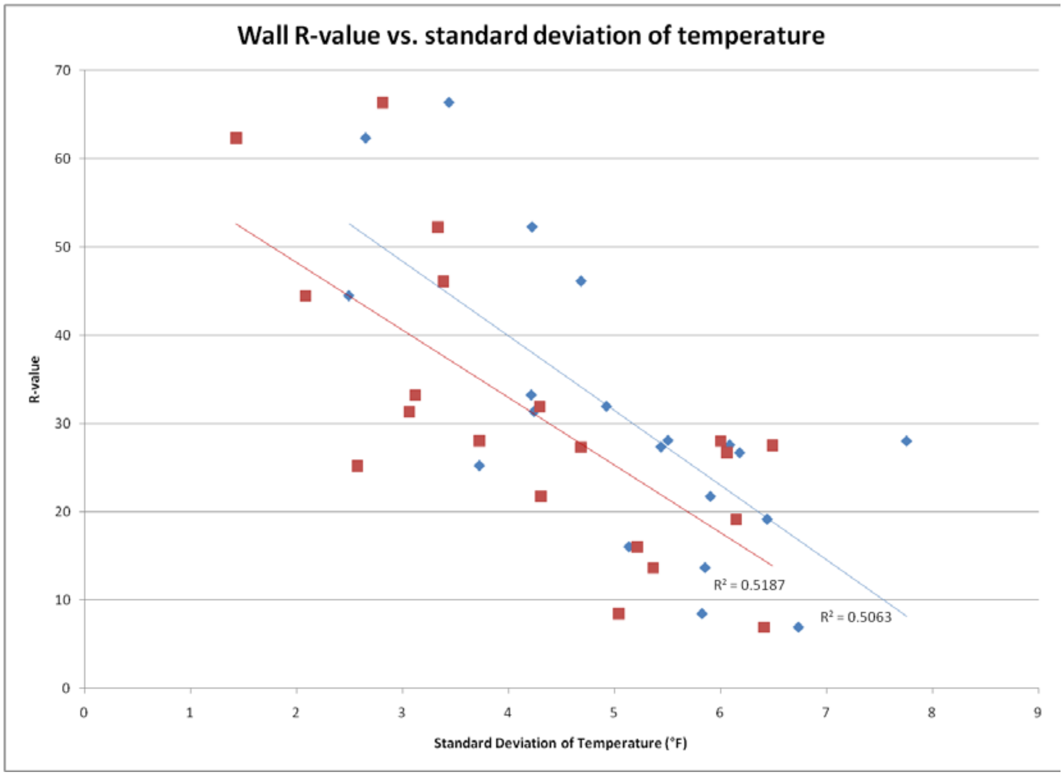

Figure 29 Wall R-value vs. standard deviation of temperature

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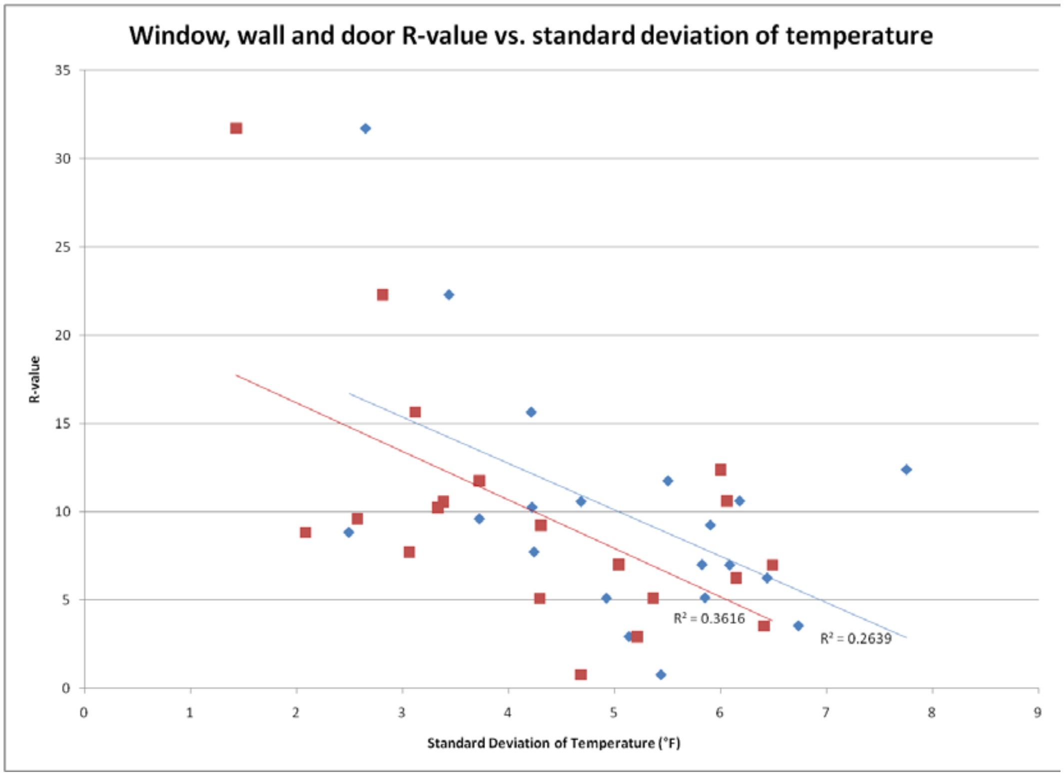

Figure 30 Windows, walss and doors combined R-value vs. standard deviation of temperature

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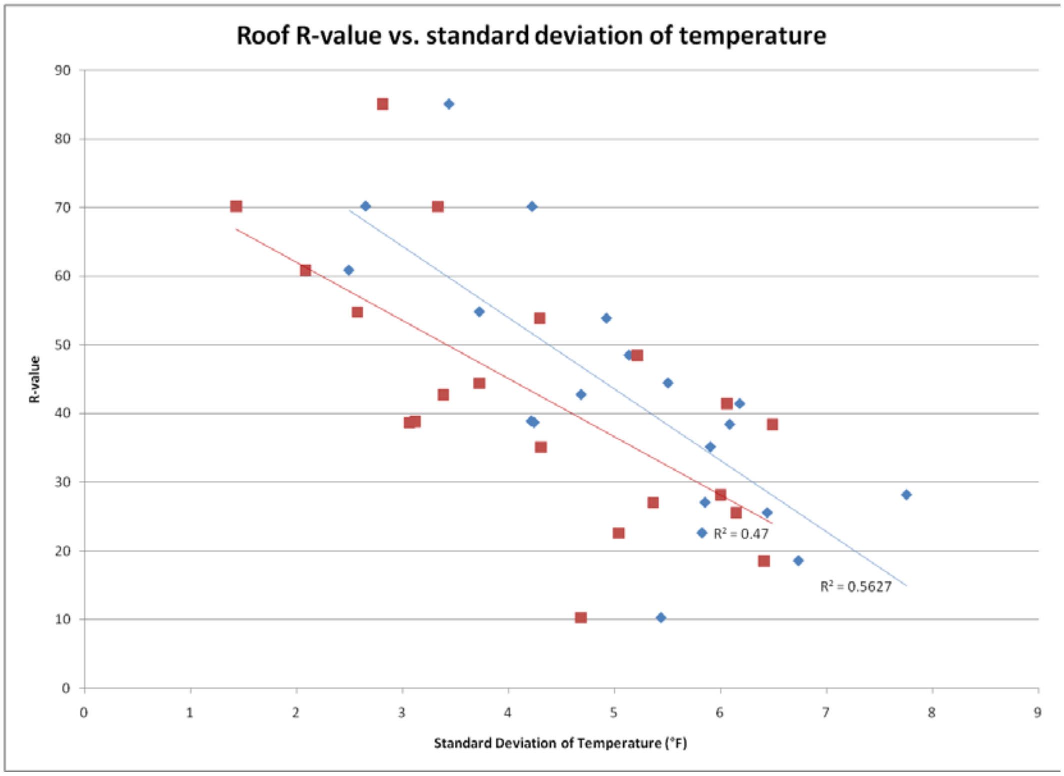

Figure 31 Roof R-value vs. standard deviation of temperature

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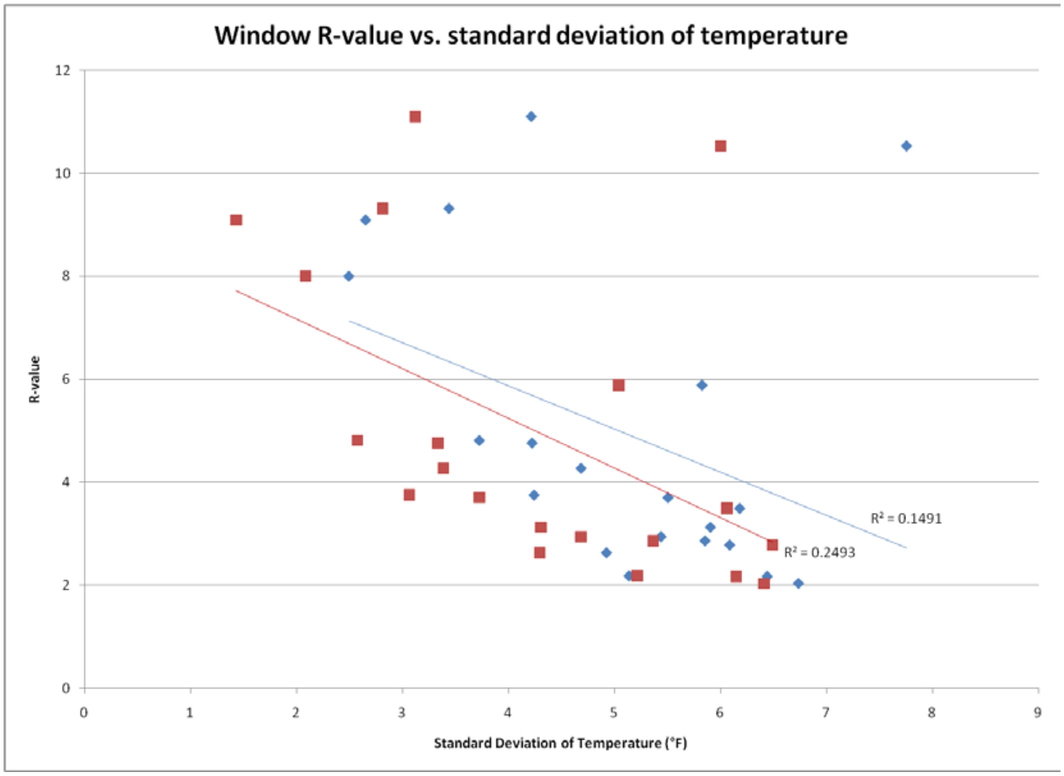

Figure 32 Window R-value vs. standard deviation of temperature

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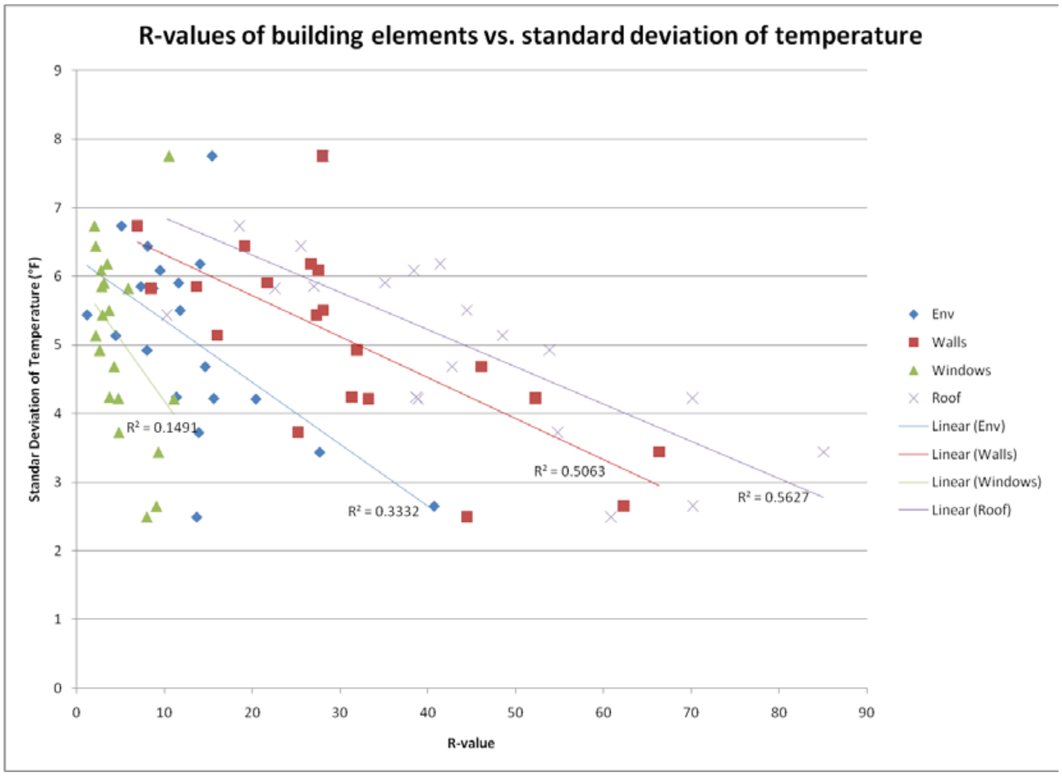

Figure 33 R-values of building elements vs. standard deviation of temperature

The R-values of building components are compared to points earned in the comfort zone competition in Figure 34, Figure 35, Figure 36, and Figure 37. Again the trendlines indicate that increasing R-value of all components results in a higher score in this competition, indicating a better performance. The wall R-value most directly correlated with the scores in the competition followed closely by roof R-value.

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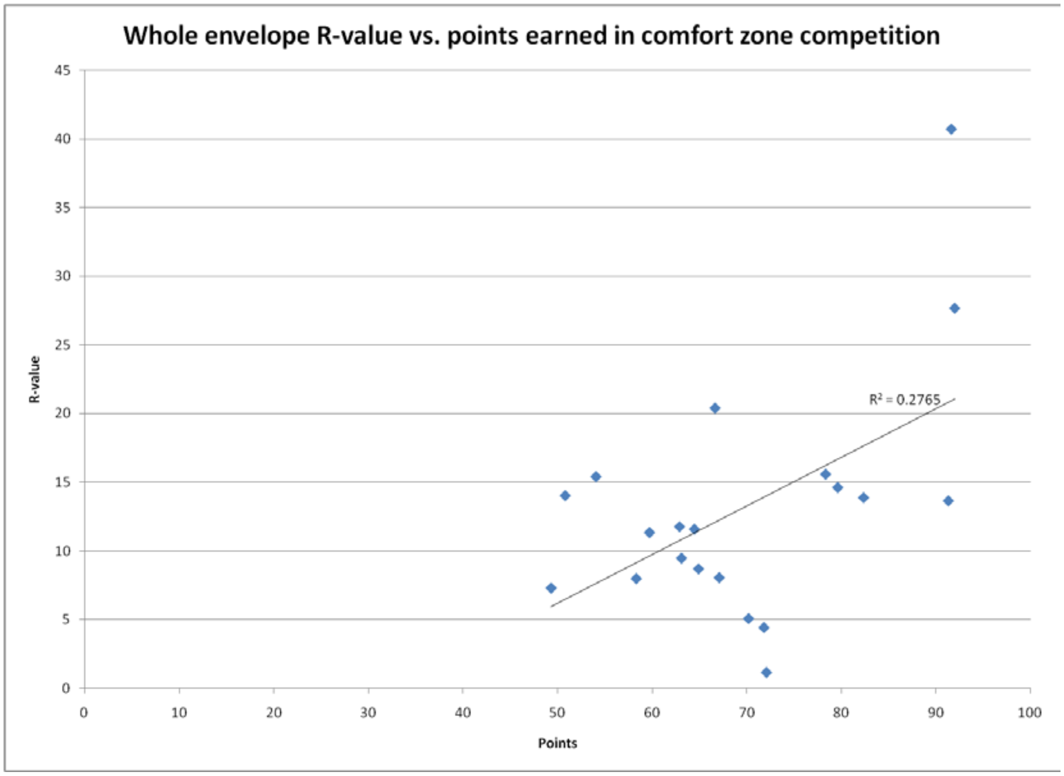

Figure 34 Whole envelope R-value vs. points earned in comfort zone competition

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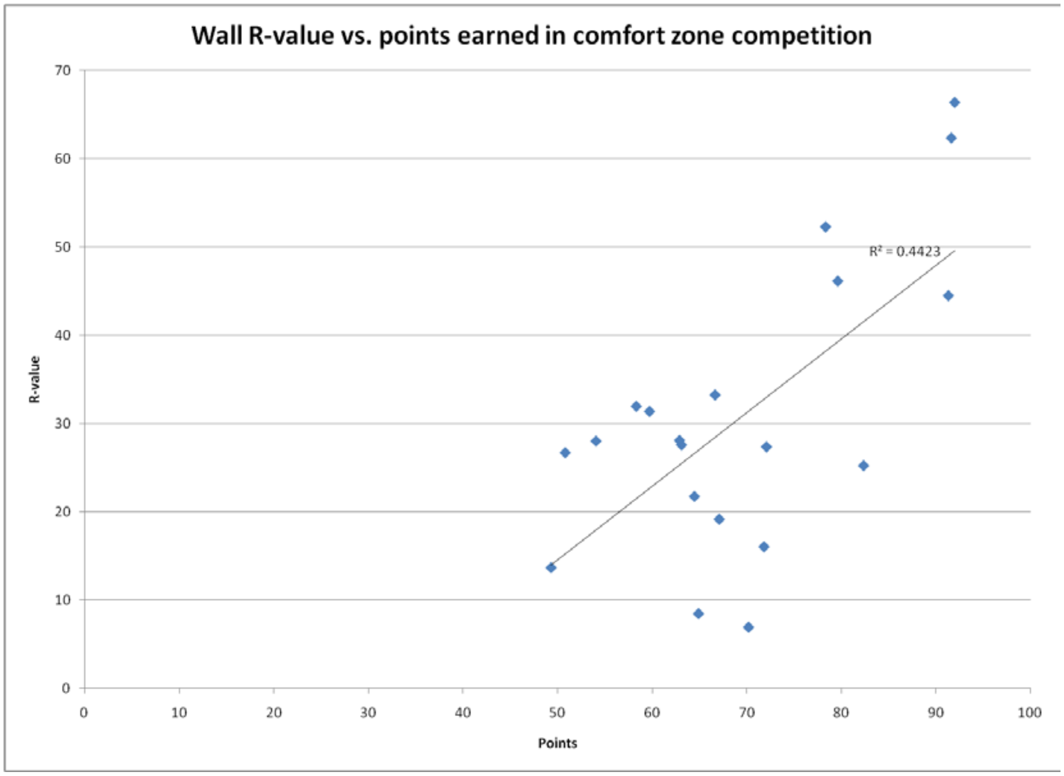

Figure 35 Wall R-value vs. points earned in comfort zone competition

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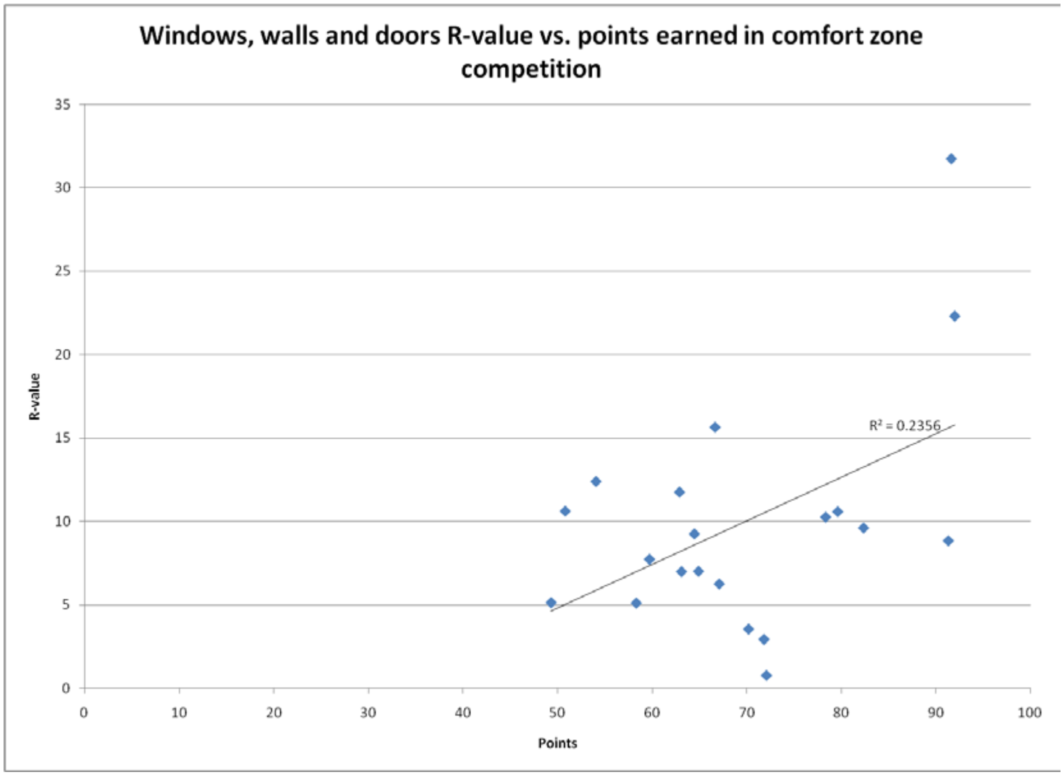

Figure 36 Windows, walls and doors combined R-value vs. points eaned in comfort zone competition

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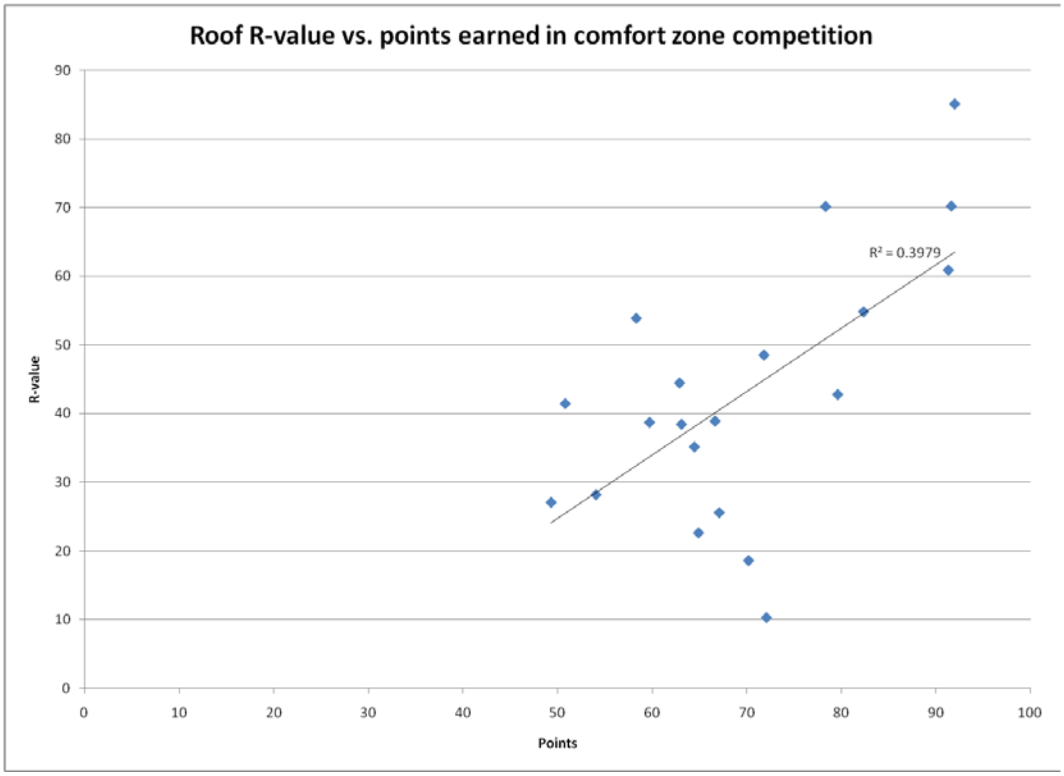

Figure 37 Roof R-value vs. points earned in comfort zone copetition

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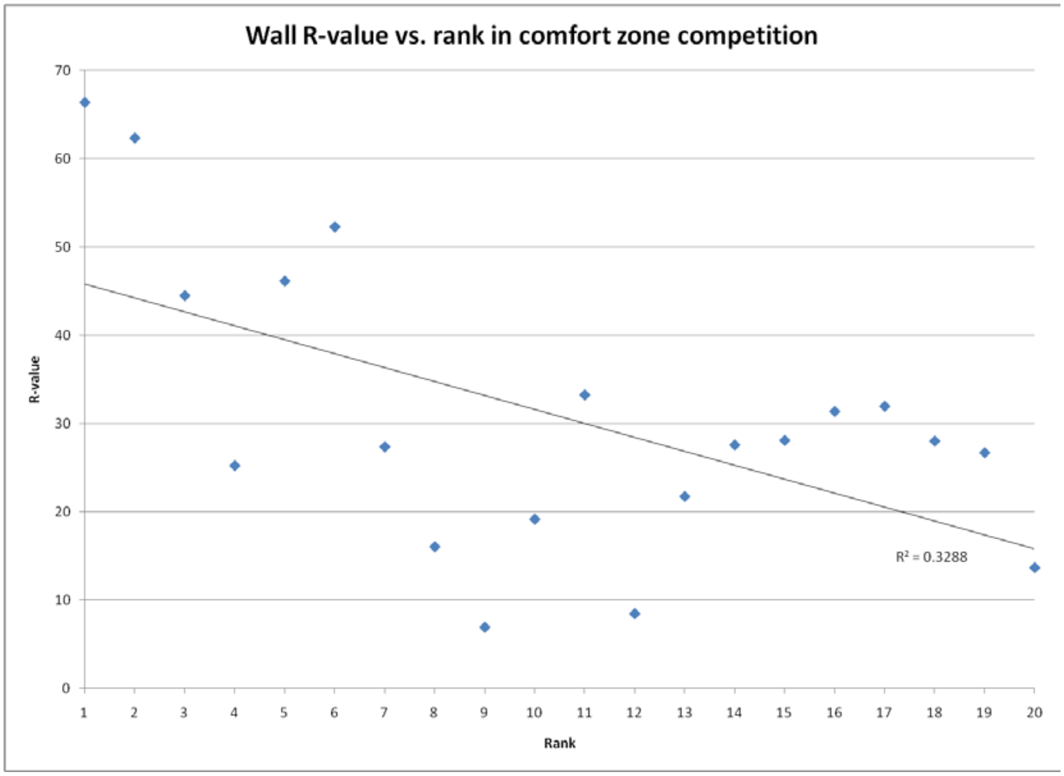

Figure 38 Wall R-value vs. rank in comfort zone competition

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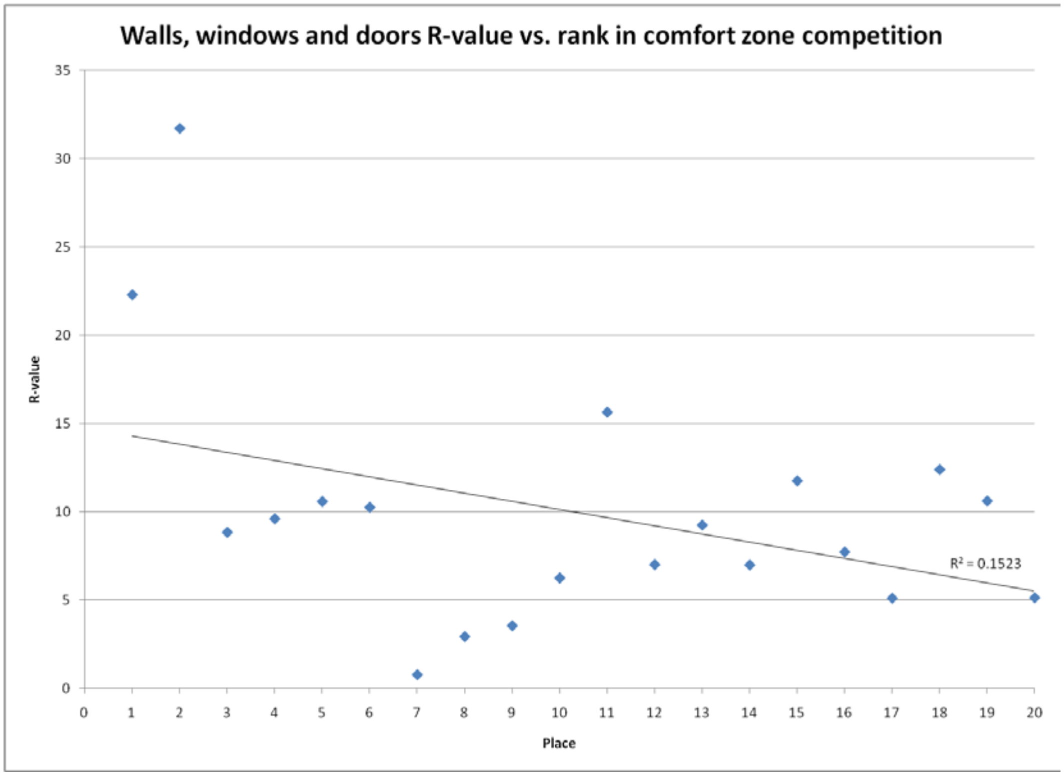

Figure 39 Walls, windows and doors combined R-value vs. rank in comfort zone competiton

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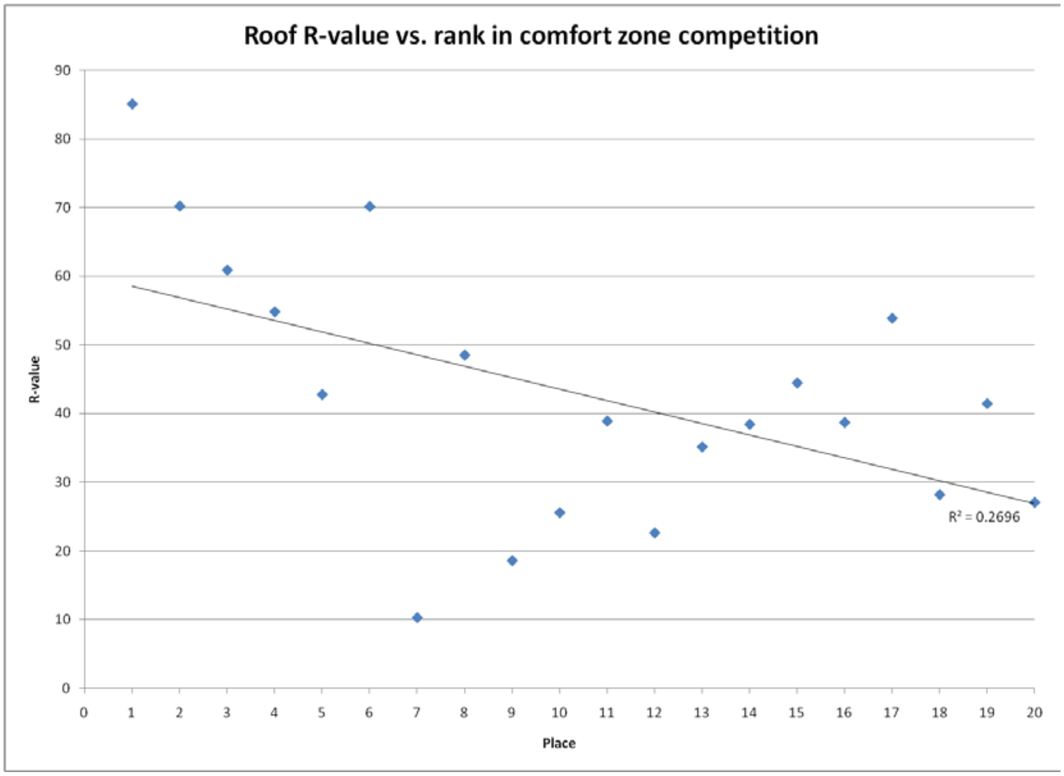

Figure 40 Roof R-value vs. rank in comfort zone competition

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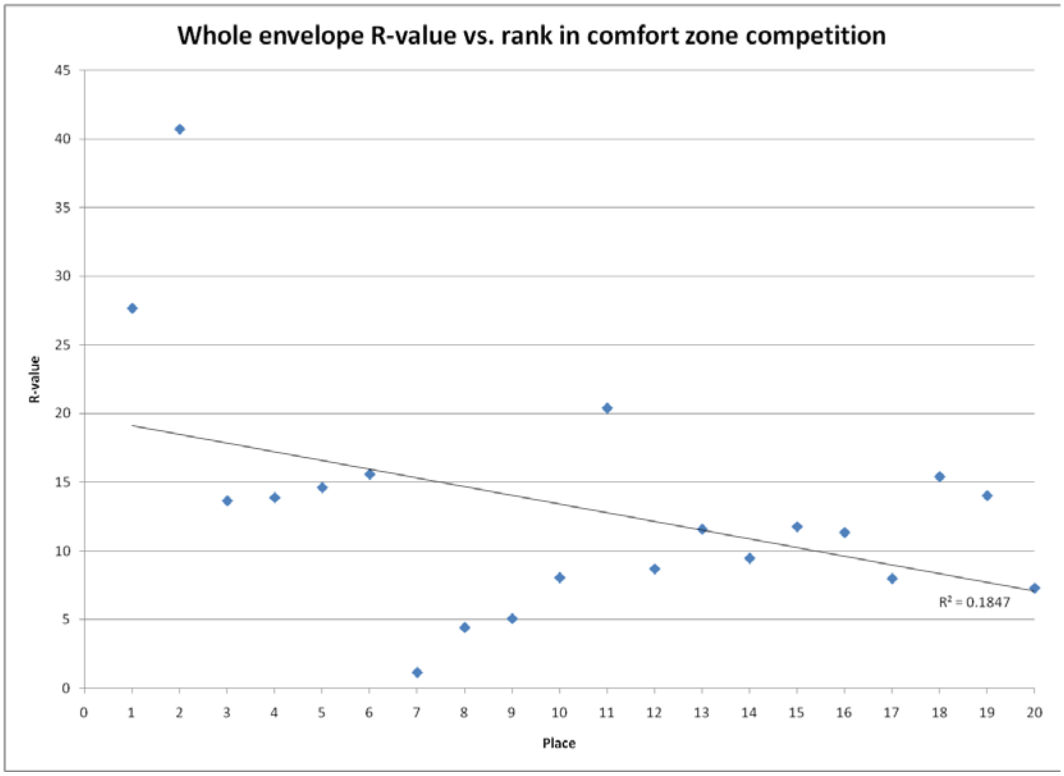

Figure 41 Whole envelope R-value vs. rank in comfort zone competition

Windows

Solar heat gain coefficient has been plotted against average internal temperature in Figure 42. The same values are plotted against standard deviation of temperature in Figure 43. The observed trend indicates that increasing SHGC increases the average temperature of the house. This is a good indication that direct solar heat gain is being utilized to contribute to the heating of the buildings. The correlation is moderately strong especially when compared to solar glazing area correlation in Figure 14. Increasing the solar heat gain coefficient also appears to increase thermal control resulting in a reduced standard deviation. Again this correlation has moderately strong fit.

One house, Penn State, is an outlier in both Figure 42 and Figure 43. The reason for its outlying position is the high solar heat gain coefficient of the specified glazing. It appears that the added heat gain was useful during the measurement periods since the house had one of the higher average temperatures and slightly better temperature control than many of the other houses.

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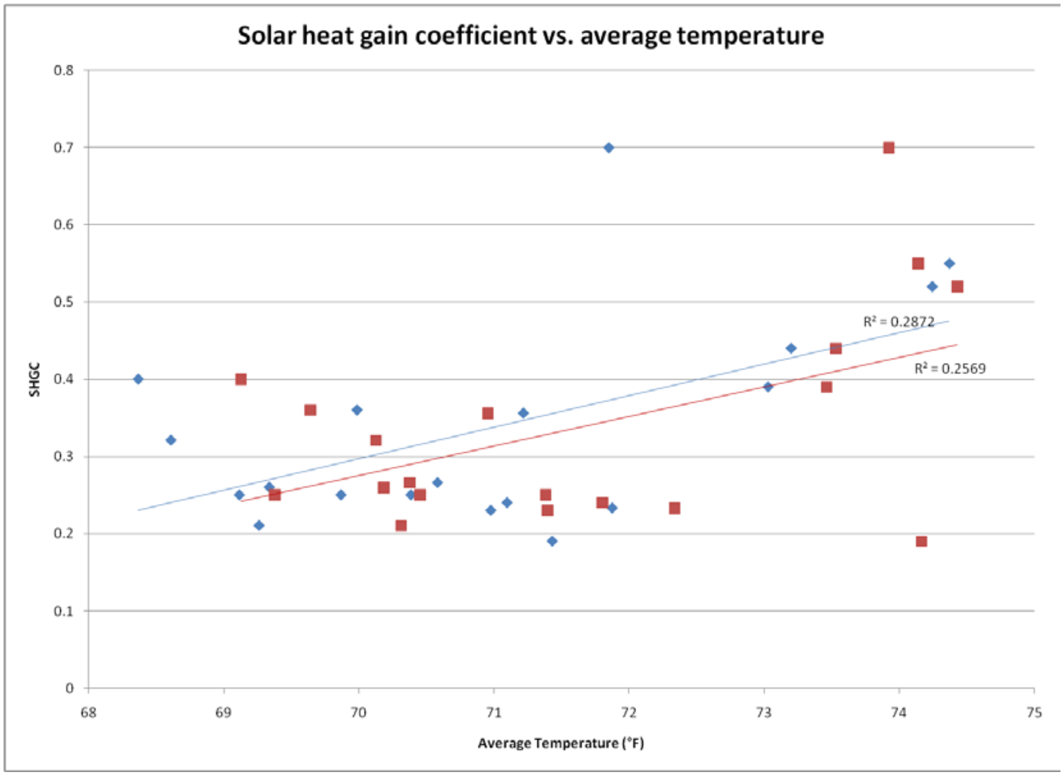

Figure 42 Solar heat gain coefficient vs. average temperature

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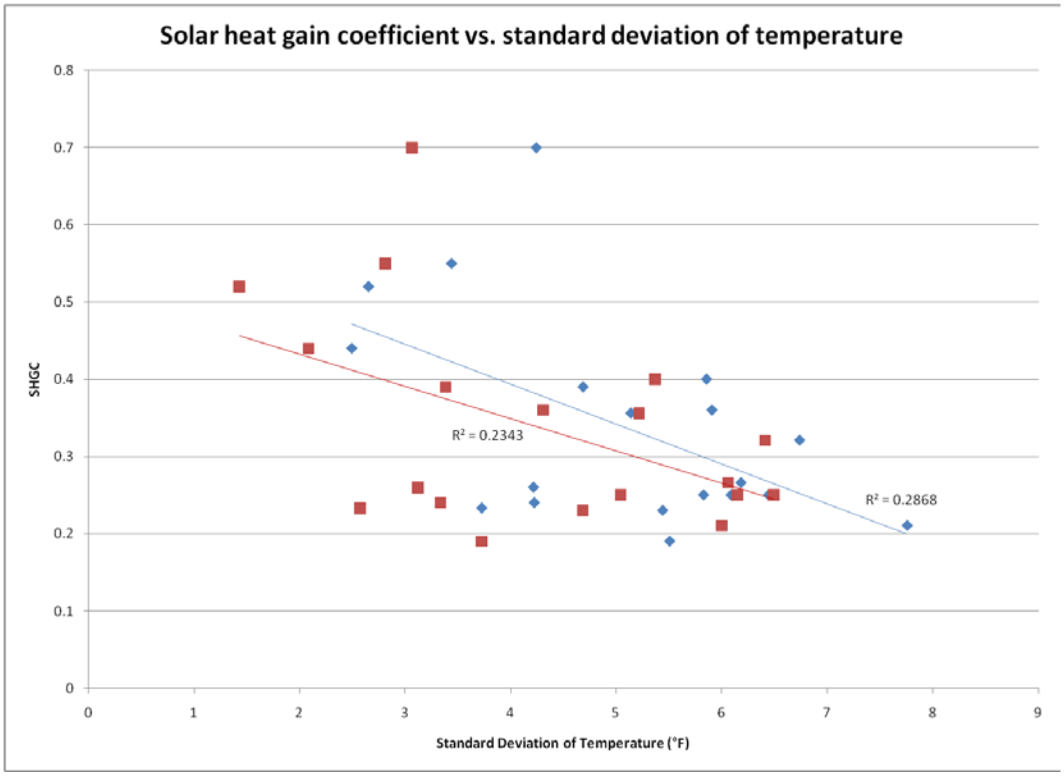

Figure 43 Solar heat gain coefficient vs. standard deviation of temperature

The ratio of windows to floor area based on orientation compared to temperature has been graphed in Figure 44, Figure 45 and Figure 46. The strongest correlation exists for northern windows and indicates that reducing northern window area results in higher average temperatures. This makes good sense since northern windows don't see much direct sunlight and thus serve only to lose heat. The trends for eastern and western windows indicate that there is very little effect on temperature from these orientations. It would appear that any heat lost through these windows is compensated for by the heat gained during times of direct sunlight. Of course these trendlines have extremely weak fits and therefore might not indicate anything.

The outlier on Figure 44 is Virginia Tech, a house that is mostly glazing on both the north and south sides. The expectation would be that since this house has the largest proportional north window area, it should also be losing the most heat through that façade and therefore have the lowest average temperature. The higher average temperature is likely due to a combination of the large amounts of solar glazing and thermal mass in this house. Good mechanical systems could also help maintain a high average temperature.

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These reasons are also the likely cause for Virginia Tech being an outlier in Figure 49 as well.

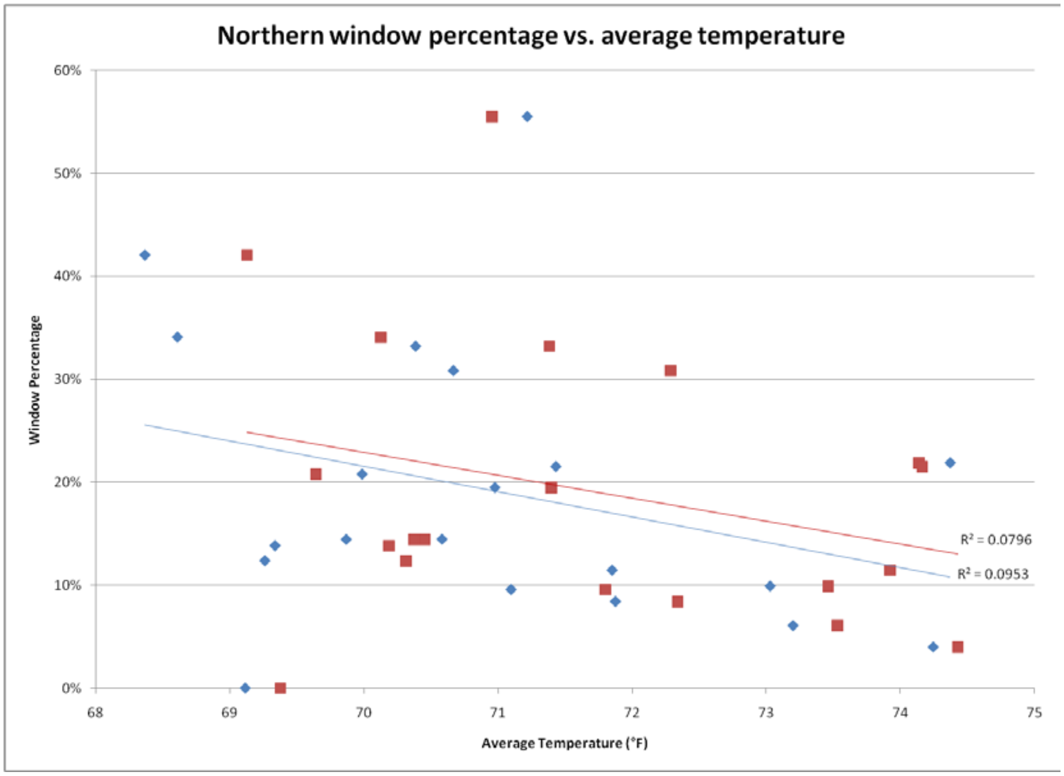

Figure 44 North window percentage vs. average temperature

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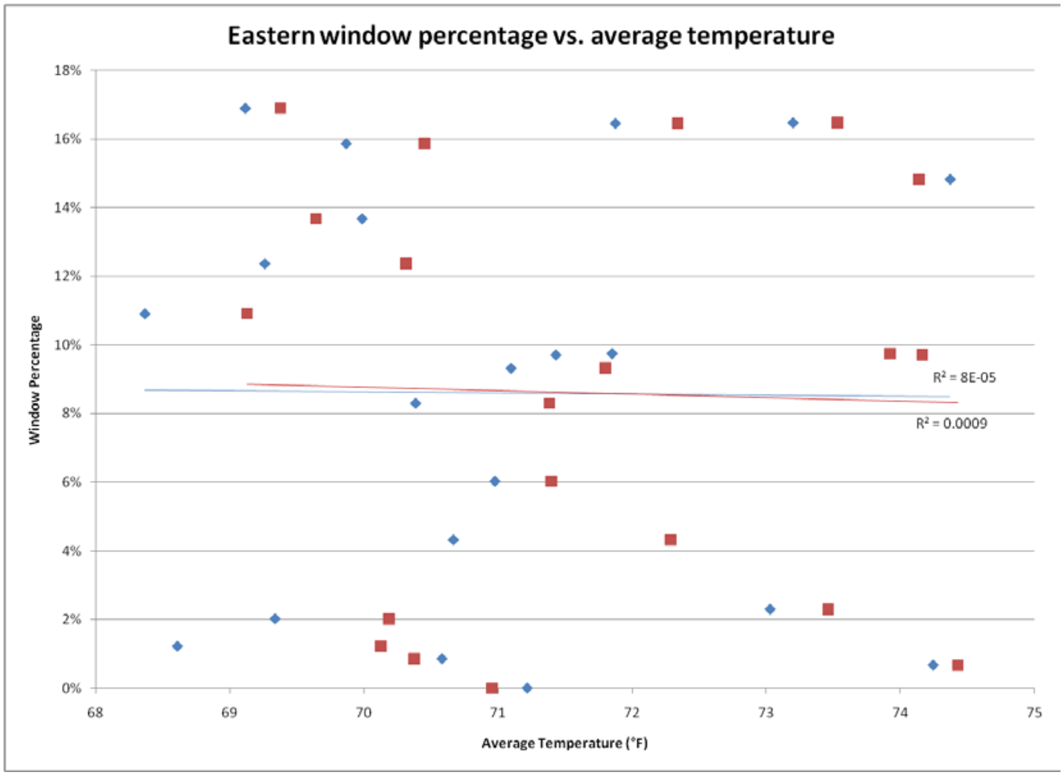

Figure 45 East window percentage vs. average temperature

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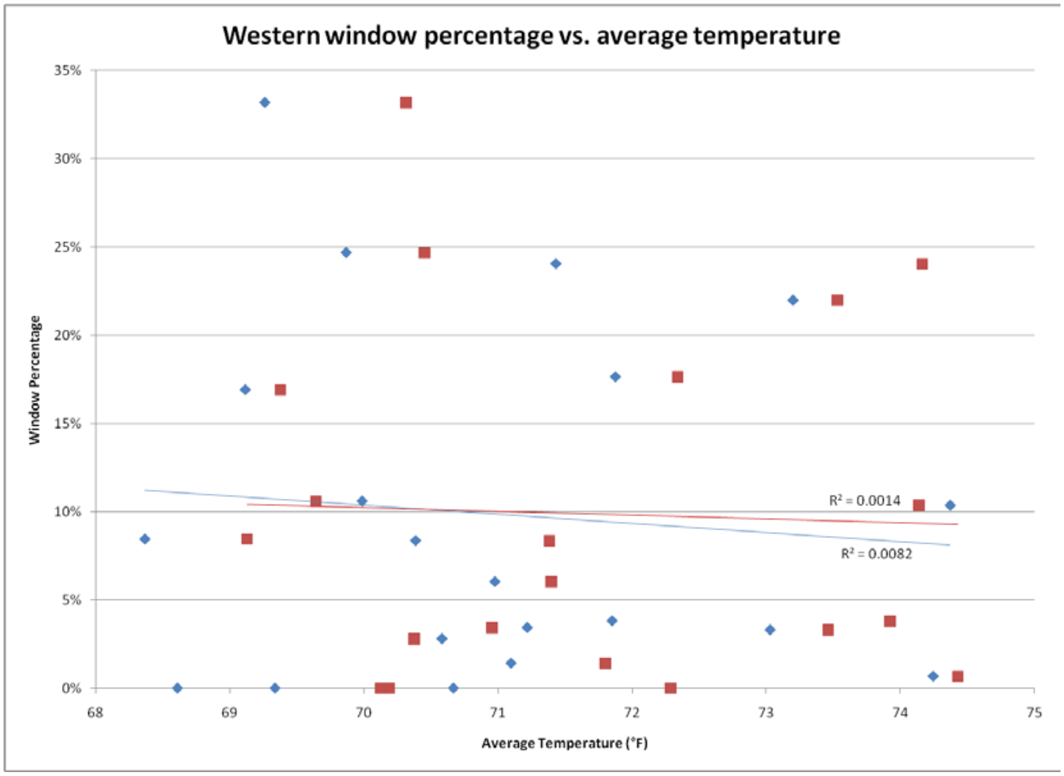

Figure 46 West window percentage vs. average temperature

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The effect of glazing percent on temperature control varied depending on the orientation of the glazing. As shown in Figure 47 north facing windows had the greatest effect on temperature control. The trend indicates that minimizing northern windows helps maintain steady temperatures. Again it appears that east facing windows have no effect on temperature control. With only a very loose fitting trendline, this observation could be in false. West facing glass has a similar effect on temperature control as north facing glass although the correlation is weaker. Similar correlations are seen when these non-solar glazing areas are compared to points earned in the comfort zone competition. As Figure 48 shows, in all cases, the correlation indicates that minimizing non-solar glazing increases points earned in this competition.

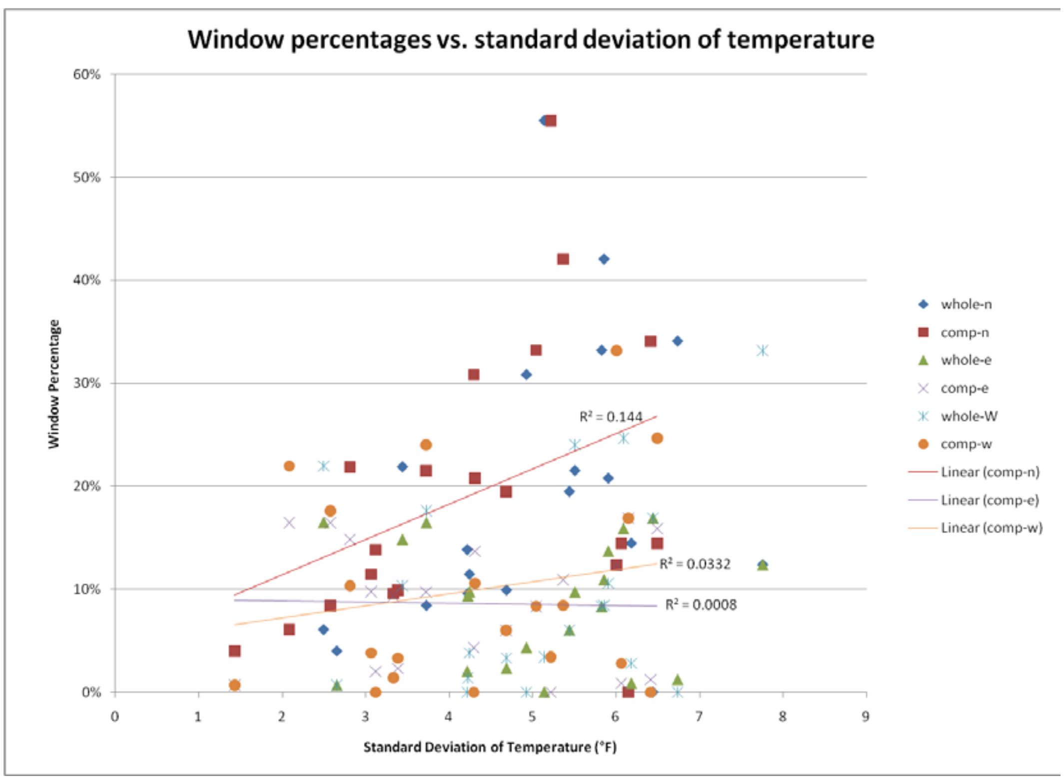

Figure 47 Window percentages vs. standard deviation of temperature

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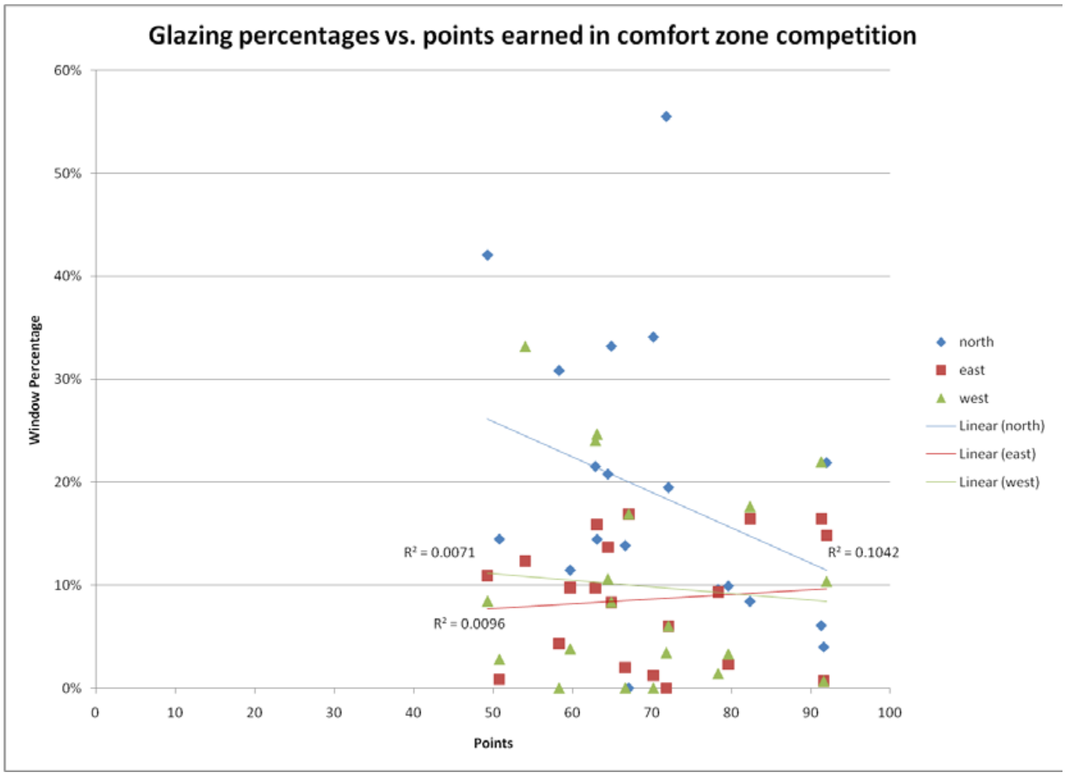

Figure 48 Glazing percent vs. points earned in comfort zone competition

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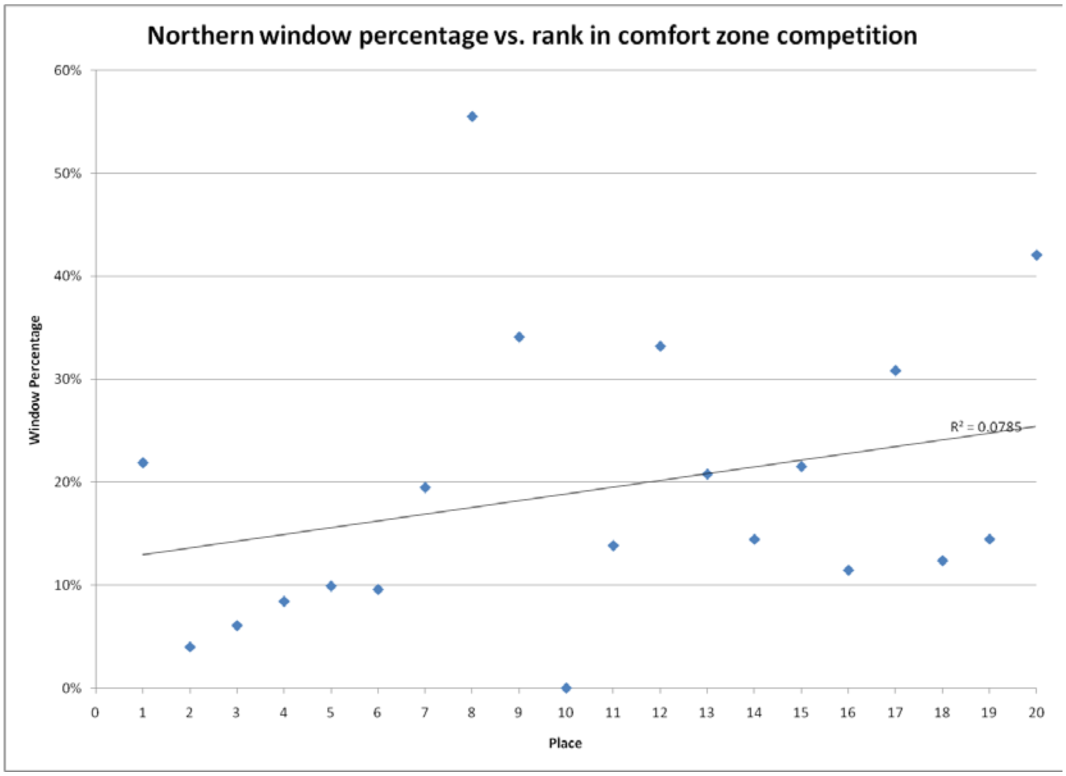

Figure 49 North window percent vs. rank in comfort zone competition

Daylighting

Since the only light measurements taken in the houses were task lighting at workstations, there is no data to judge the positive effects of daylighting design. The only relevant effect of daylighting that can be discussed is the impact on comfort zone results. Effective aperture is graphed against average temperature in Figure 50. The trendlines fit weakly but indicate that increasing effective aperture also increases internal temperature. This would make good sense since increased effective aperture means more light enters the building and transmission of light also means transmission of energy. The trend also implies that the effect of the direct gain portion of windows outweighs the effects of the heat losing windows on the north side resulting in net heat gains.

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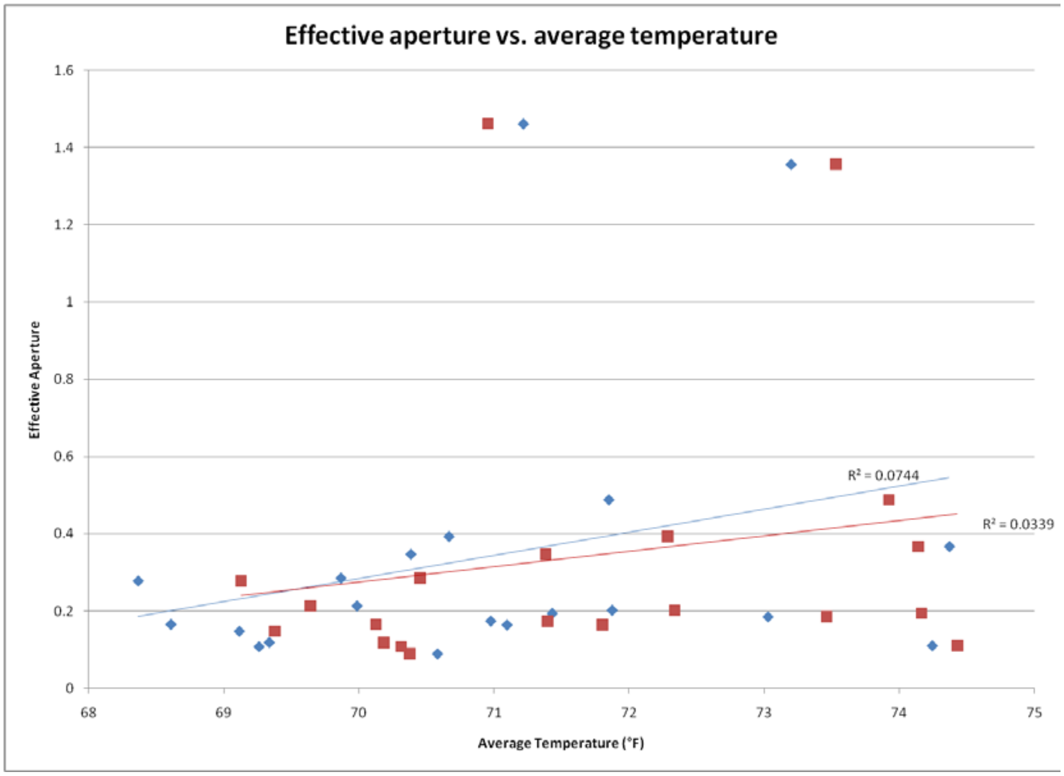

Figure 50 Effective aperture vs. average temperature

Effective aperture is also plotted compared to standard deviation and points earned in the comfort zone competition in Figure 51 and Figure 52 respectively. Increased effective aperture appears to result in tighter temperature control with smaller standard deviation. This increased temperature control is also the likely reason that Figure 52 shows more points being scored for teams with greater effective aperture.

There are two outliers that recur throughout Figures 48, 49 and 50. These two data points lie far outside the normal range that the rest of the houses fall in because the designs were very focused on using large amounts of glazing as an architectural feature. This caused both houses to have large window-to-wall ratios which in turn skewed the effective aperture calculations. It is important to note that both of these houses had very unique automated shading systems in place which shows that the designers were aware that they ran the risk of unwanted solar heating with so much glass.

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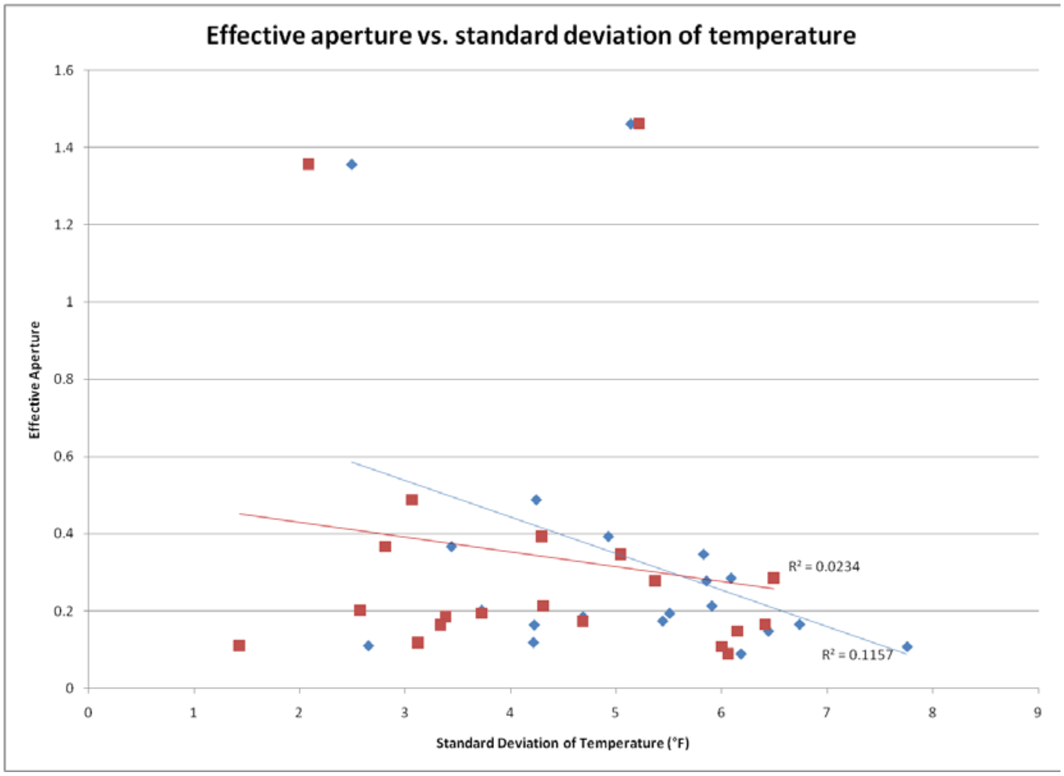

Figure 51 Effective aperture vs. standard deviation of temperature

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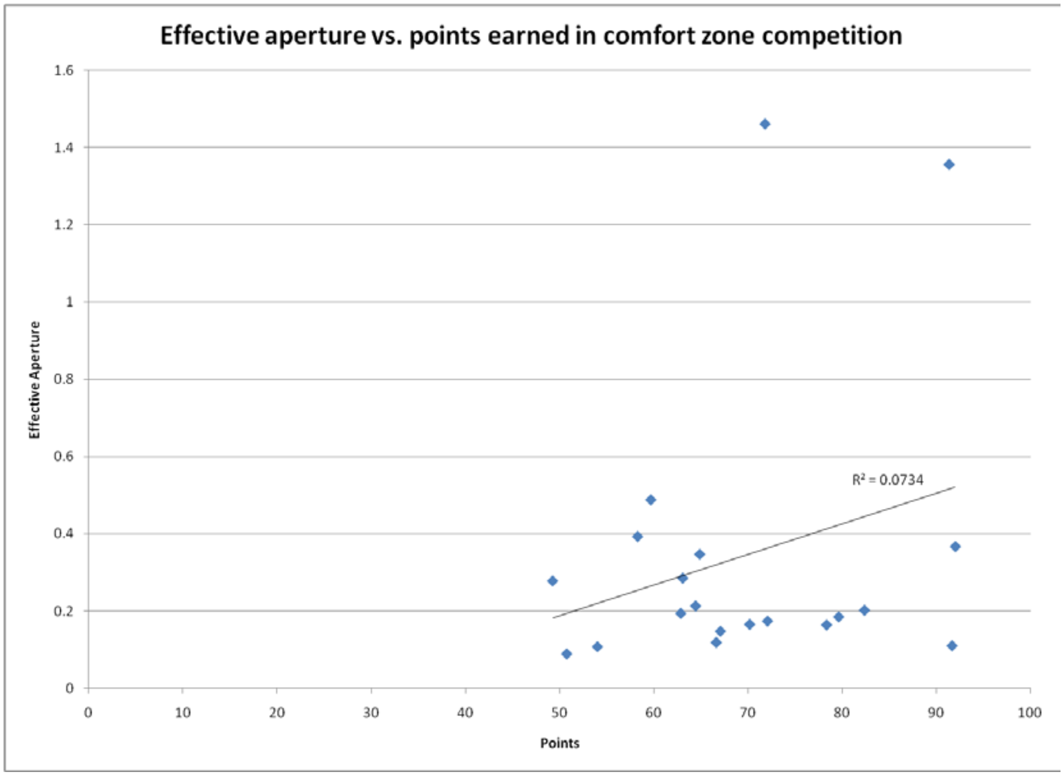

Figure 52 Effective aperture vs. points earned in comfort zone competition

Array

Photovoltaic array size is compared to placement in the energy balance competition in Figure 53. There is a moderately strong correlation between array size and placement with larger arrays placing higher. The largest array placed first in this competition but surprisingly the smallest array finished in the middle of the field at eleventh. The teams with arrays sized near the average size of 8.9kW tended to fall in the middle ranks between sixth and sixteenth place. The four largest arrays finished in the top five spots which agrees with the trend. The fifth and seventh largest arrays finished eighteenth and twentieth places respectively, defying the graphed trend.

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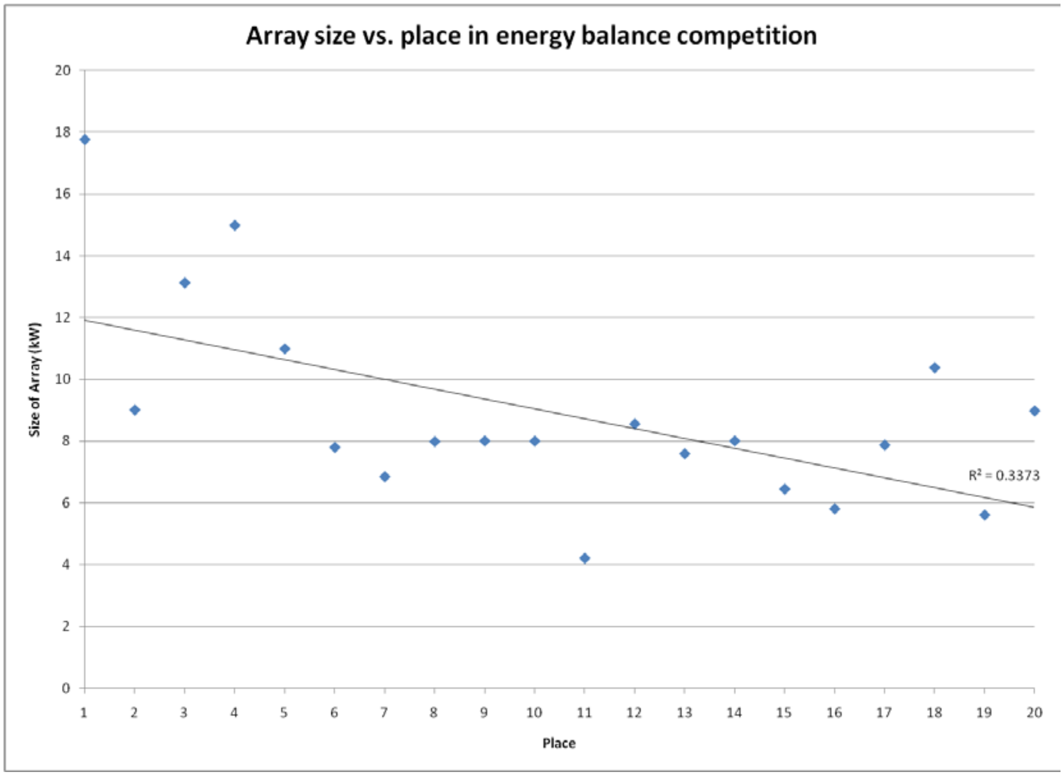

Figure 53 Array size vs. rank in energy balance competition

Photovoltaic Calculations

Cumulative energy output by the photovoltaic array is shown in Figure 54 as calculated from measured insolation and outdoor temperature data which are graphed in Figure 55 and Figure 12 respectively. From Figure 54 it can be guessed that Germany's house would produce the most energy in the competition followed by Kentucky and Ontario/BC. It might seem obvious that the house with the largest rated photovoltaic array would produce the most electricity but this is not always the case. Figure 56 shows predicted energy output compared to rated array size. As can be seen, the house with the second highest output has the fourth largest array while the house with the second largest array is predicted to produce the fifth most electricity. The trendline, which approximates a strong correlation, indicates that increasingly large arrays will produce more electricity. The location of data points in relation to the trendline gives an indication of whether or not the array is outperforming the average array. For example, the points lying above the trendline probably have a favorable array orientation or good temperature coefficients.

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The second largest rated array falls well below the trendline. This is most likely due to having north facing photovoltaics on the façade of the house.

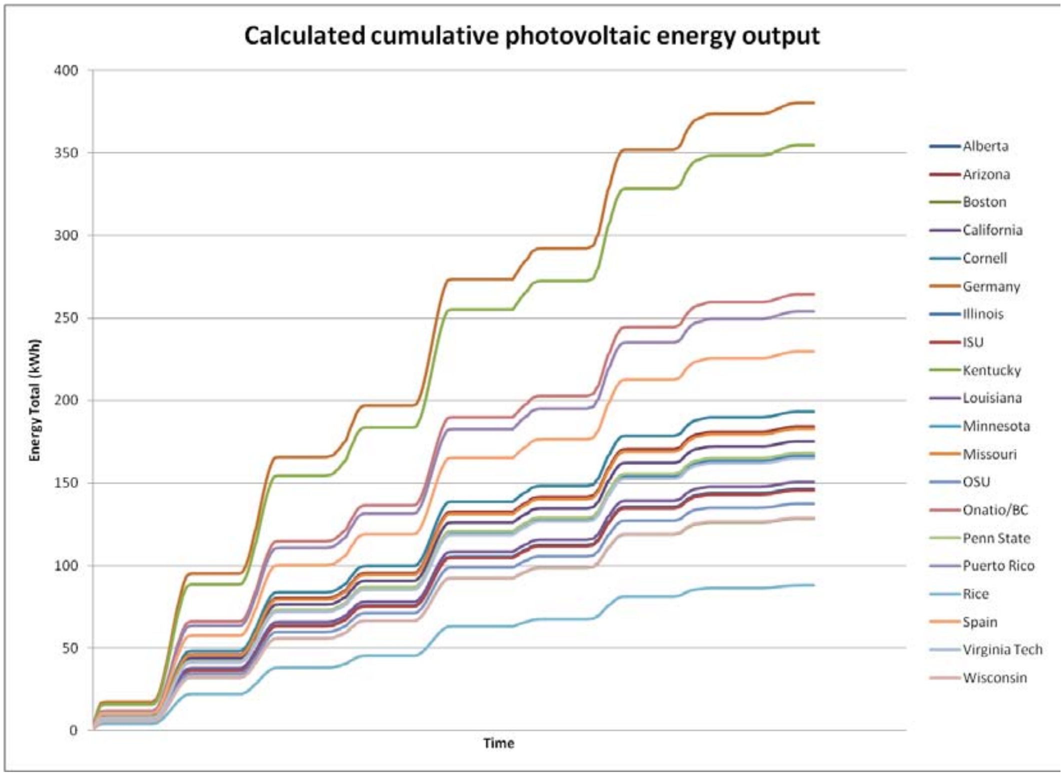

Figure 54 Calculated photovoltaic energy output

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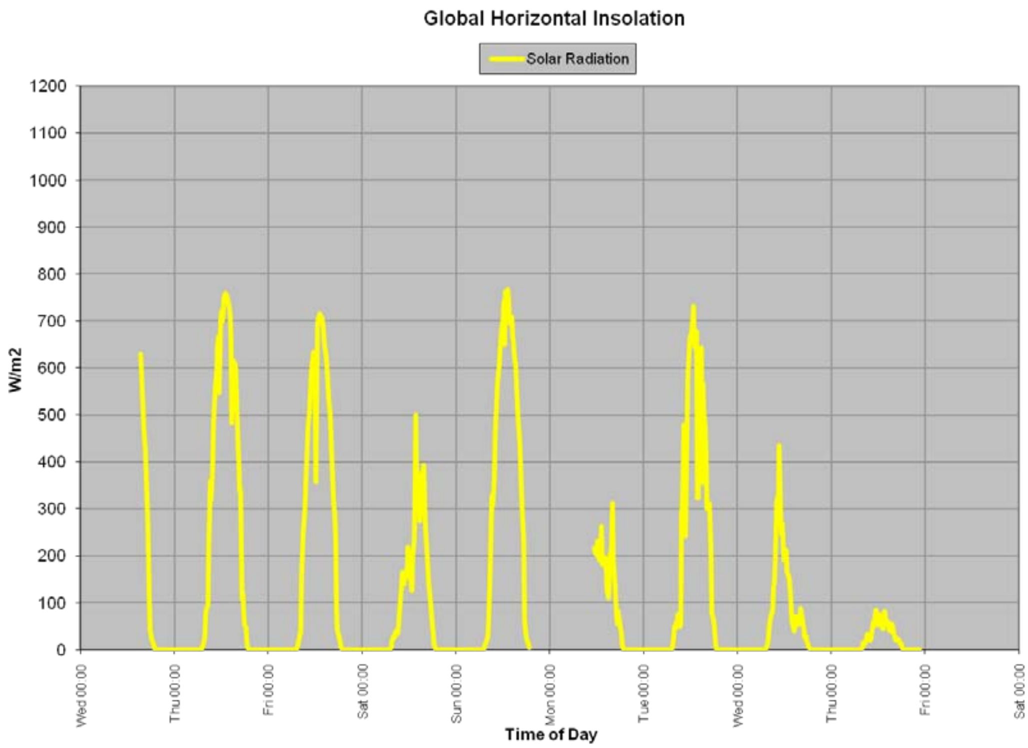

Figure 55 Measured insolation on a horizontal surface

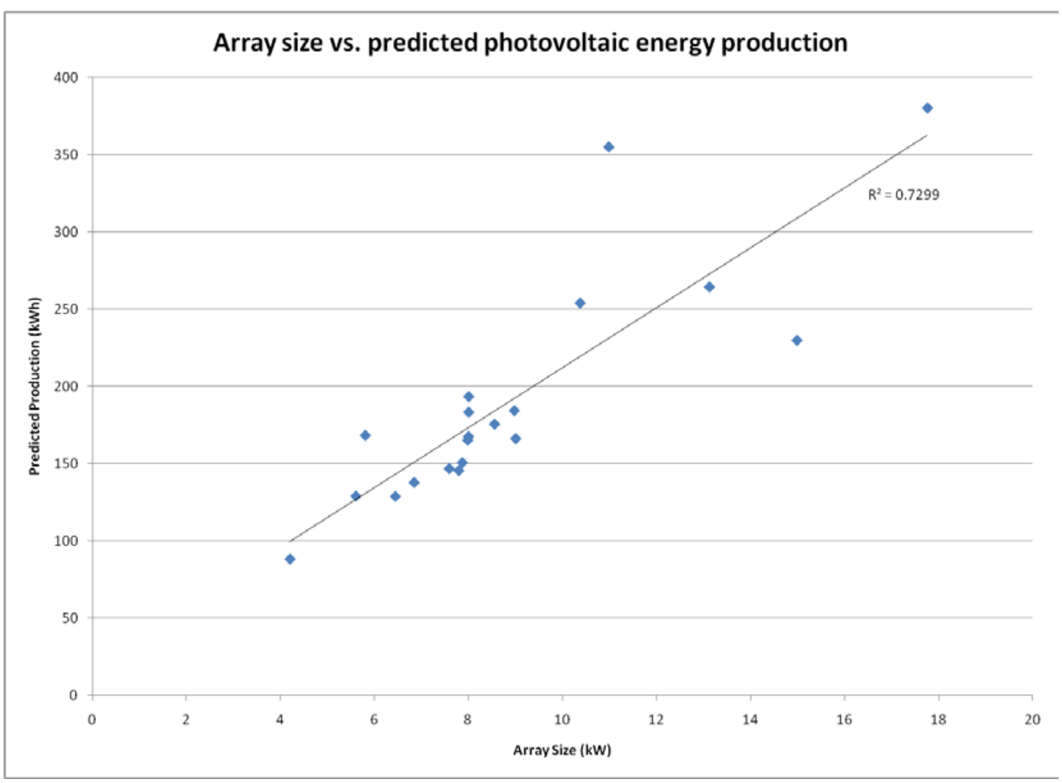

Figure 56 Array size vs. total calculated energy output from PV

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Predicted performance is plotted against the actual competition energy surplus in Figure 57. Assuming that all houses require about the same amount of energy to operate, the predicted performance should be a good indicator of the energy surplus. While this general trend does appear, the correlation is very weak. Part of the reason for this is human intervention. There are several data points clustered around 0kWh. Many of those data points should fall below the 0kWh mark but the reward for the competition enticed many teams to shut down their houses and opt out of other measured competitions in order to stay net positive. Additionally, it appears that some teams never utilized their photovoltaic array at all especially the two that fall below the -100kWh mark.

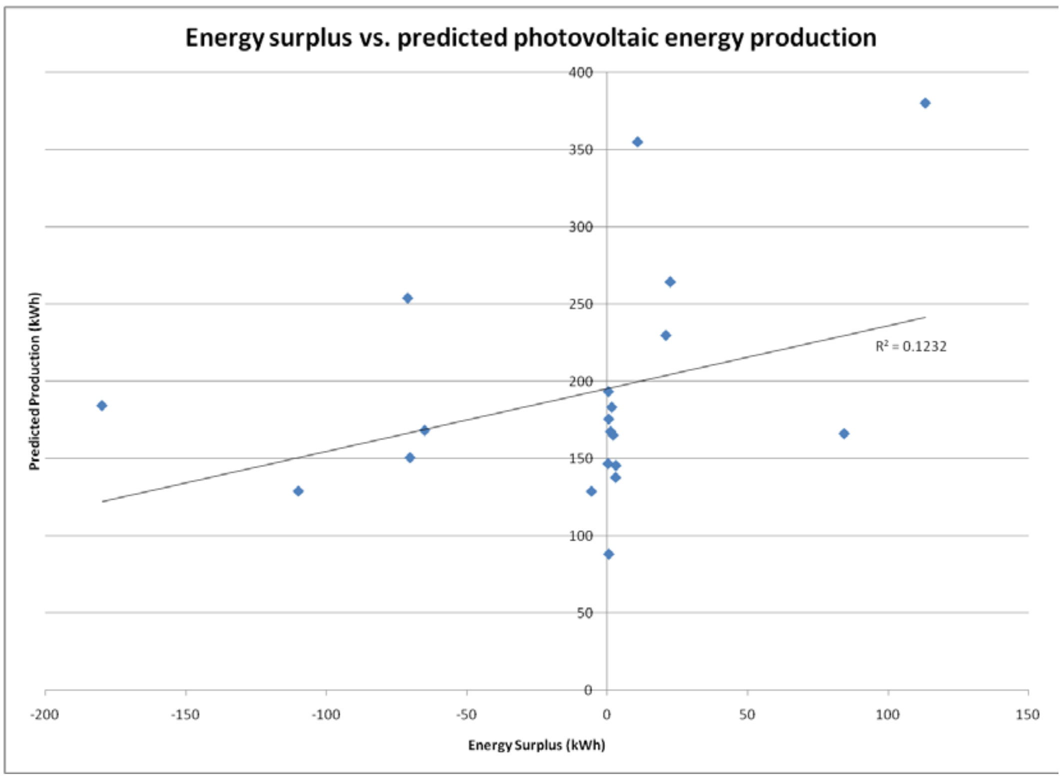

Figure 57 Energy surplus vs. total calculated photovoltaic energy output

When the predicted energy output is compared to place earned in the energy balance contest as shown in Figure 58, the correlation fits better. The trend indicates that predicted output correlates to a higher placement in the energy balance competition. This also verifies that the calculation method is valid. It can be inferred that data points that fall below the trendline on this graph correspond to more efficient houses while the points above the trendline correspond from less efficient houses. A good example of this

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inference is the point with a second place ranking. This house is Illinois', which features the most insulated envelope of all the houses. Conversely, the Puerto Rico house is above the trendline but ranked 18th in energy balance. Puerto Rico features a 10.37kW array and an R-5 envelope.

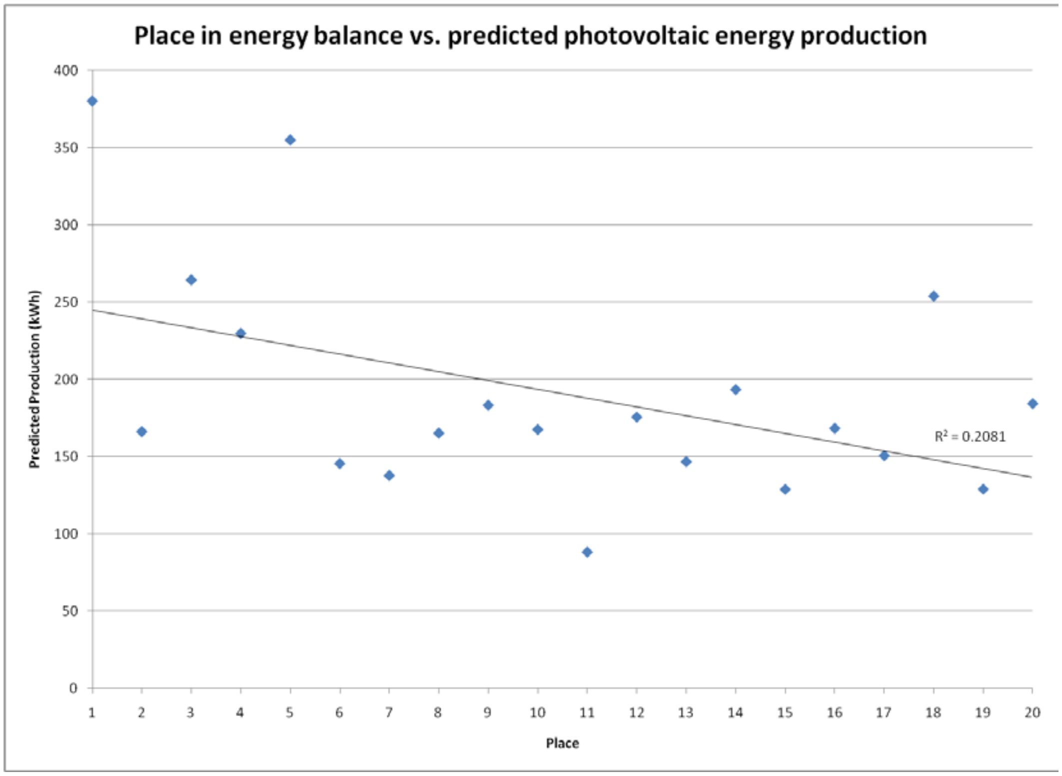

Figure 58 Place in energy balance competition vs. total calculated energy output from PV

Figure 59 gives an idea of how the actual electrical output and consumption looked for the competition week. Periods when the graph increases indicate that electrical output exceeded the demand of the house while decreases in the graph indicate times when electrical consumption outweighed production. As Figure 55 shows, there were only four days with significant peaks in available solar radiation. These four peaks can be seen in Figure 59 when the surplus increases sharply. Days without large amounts of sunshine are also visible as the surplus lines decrease over the course of a day. Figure 60 visualizes the differences in final energy balance.

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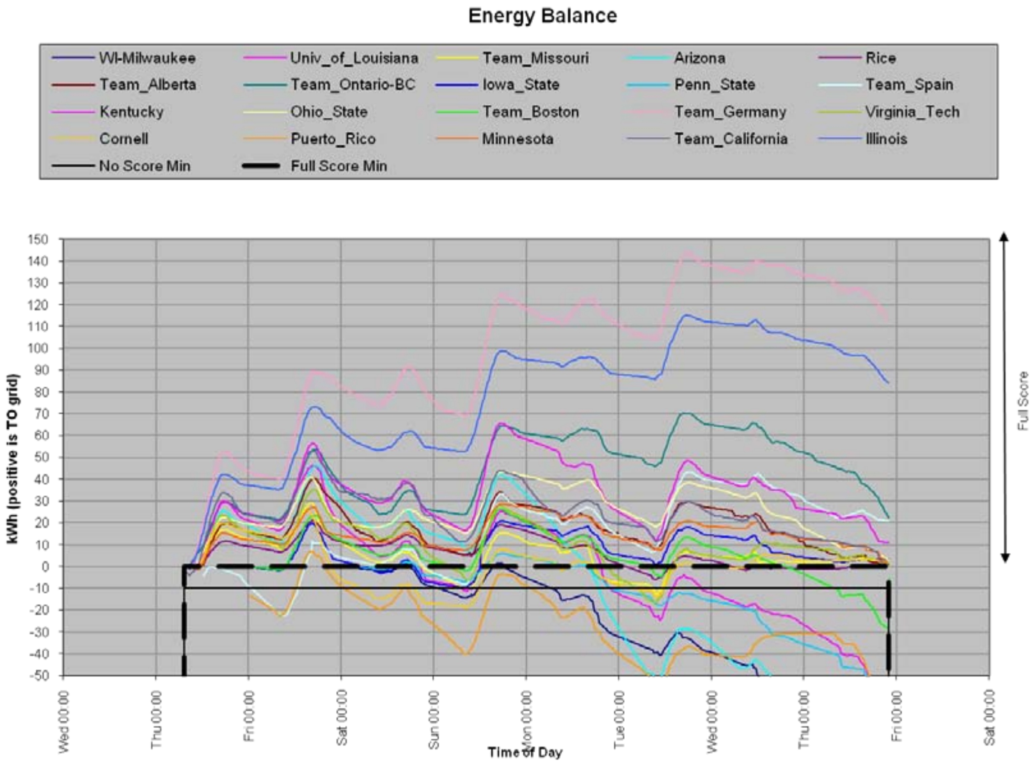

Figure 59 Measured energy surplus

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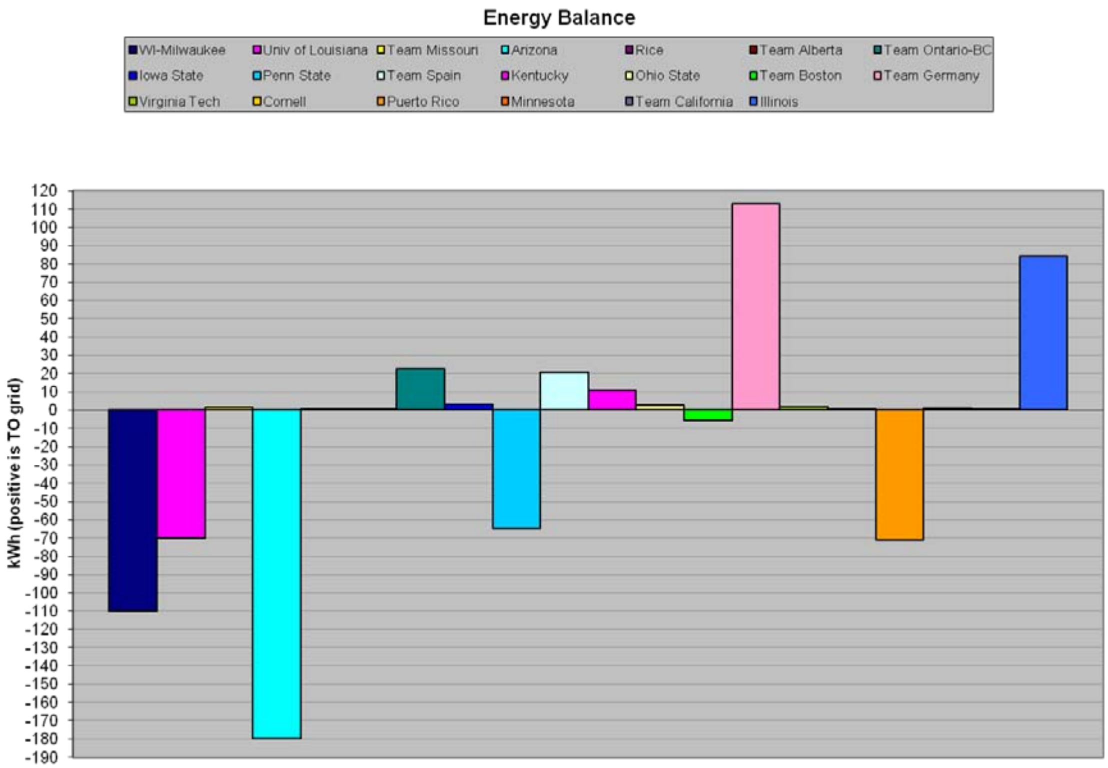

Figure 60 Final measured energy surplus

Thermal Collector Calculations

The results of the thermal collector calculations are listed in Table 14 sorted by predicted collected energy. The type of collector is also noted in this table. The majority of teams chose to use flat plate collectors as opposed to evacuated tubes despite the increased thermal losses associated with flat plate collectors. When comparing home climates with collector choice, the results are split. Evacuated tube collectors are better suited to northern climates due to reduced thermal losses but only about half of the houses from northern climates used them. Likewise, about half of the houses from southern climates used flat plate collectors. The one trend that is noticeable is that the five houses with the most thermal collection all used flat plate collectors. These houses also had the five largest aperture areas as well. It is likely that the aesthetic appeal of flat plate collectors allowed these teams to incorporate more collector area into their houses than teams choosing to use evacuated tube collectors.

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Table 14 Thermal collector calculation results

Team	Collected Energy (kWh)	Aperture Area (ft^2)	Type	Storage (gal)
Team California	119.12	161.46	Flat Plate	440
Team Alberta	77.10	142.17	Flat Plate	512
University of Minnesota	76.20	151.13	Flat Plate	211
Team Boston	74.59	123.78	Flat Plate	173
Team Ontario/BC	45.70	49.51	Evacuated Tube	150
Iowa State University	44.59	64.37	Evacuated Tube	200
University of Wisconsin	43.39	74.92	Flat Plate	80
Cornell	35.26	95.37	Evacuated Tube	120
Team Missouri	29.94	40.47	Evacuated Tube	119
Team Spain	29.49	229.92	Flat Plate	80
Penn State	29.25	59.42	Flat Plate	80
University of Arizona	29.00	22.28	Evacuated Tube	60
University of Kentucky	28.87	64.37	Evacuated Tube	120
University of Louisiana	28.06	38.73	Flat Plate	50
Rice University	25.11	32.18	Evacuated Tube	80
Universidad de Puerto Rico	22.63	20.24	Evacuated Tube	39
Ohio State University	19.72	32.18	Evacuated Tube	80

Several comparisons were used to analyze the thermal collector designs. Figure 61 plots predicted collected energy compared to aperture area. There is a moderate correlation between increasing aperture area and increasing thermal collection. Characteristics that affect the output of the collector other than aperture area can be judged from this graph as well. Data points falling above the trendline most likely have a better than average combination of efficiency and orientation. Points falling below the line have a worse than average combination of efficiency and orientation. The largest outlier on the underside of the trendline is Team Spain's house. The collectors used on this house were custom made unglazed collectors which are subject to large amounts of heat loss. Additionally, most of the collector area was placed on the northwestern side of the house and under the tilting roof which did not allow for much solar exposure.

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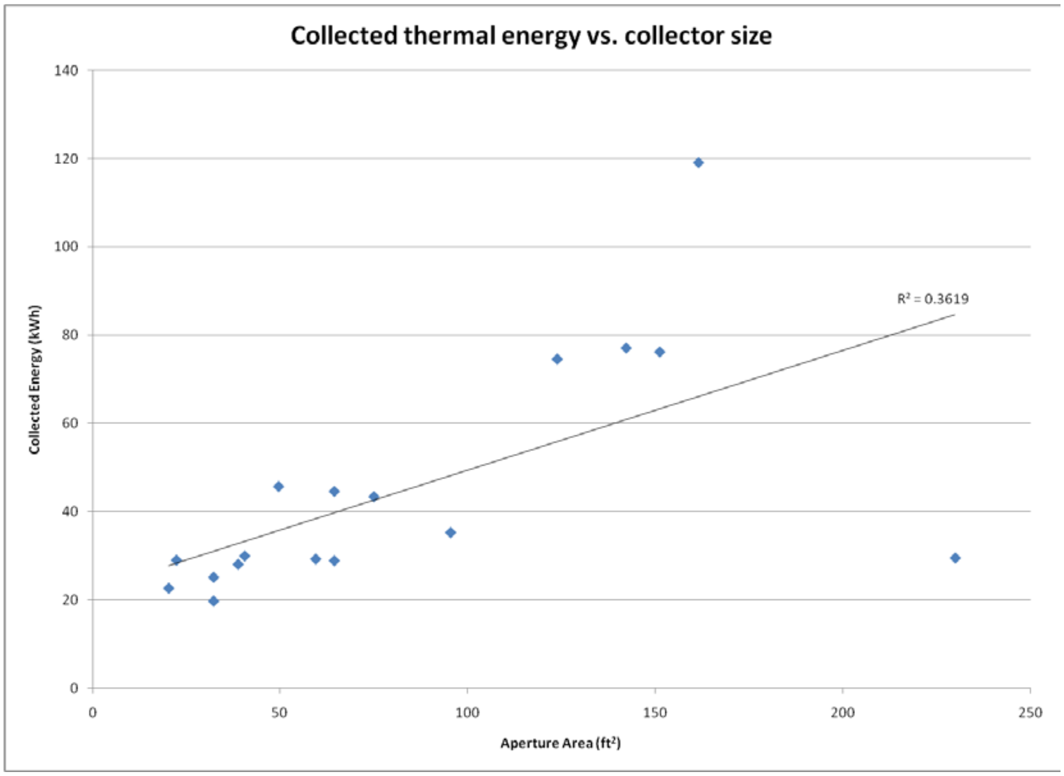

Figure 61 Thermal energy collection vs. collector size

Predicted collected thermal energy is also graphed compared to storage volume in Figure 62. There is a strong correlation between amount of thermal storage and collected energy. This is directly related to temperature increase. A larger storage volume will take more energy to raise the temperature, this keeps the average temperature at the manifold lower for longer which increases collector efficiency and allows more energy to be collected.

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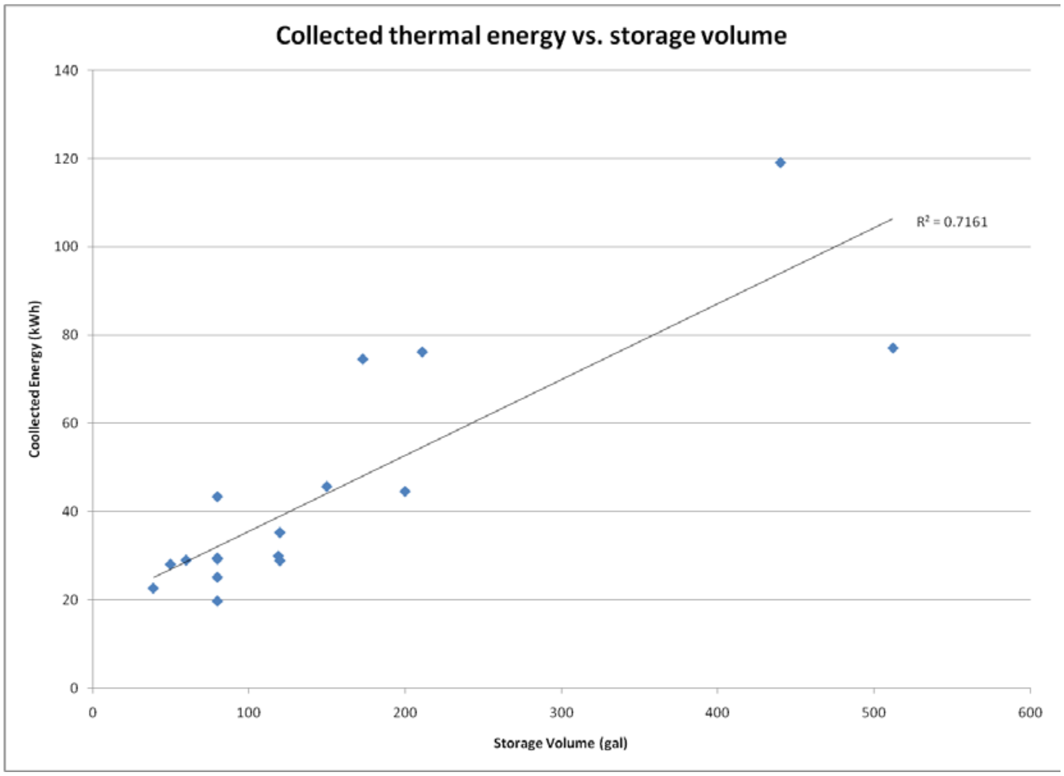

Figure 62 Thermal energy collected vs. thermal storage volume

Figure 63 compares collector size and storage volume. This graph does not imply anything about performance but it does give a view of how well teams designed their thermal systems. There is a general trend that teams with more collector area also had larger storage volumes. The relationship of data points to the trendline shows whether a system is storage heavy or collector heavy. As shown in Figure 62, it is better to be storage heavy than collector heavy. The one major outlier again is Spain who had a very large aperture area and a relatively small amount of thermal storage.

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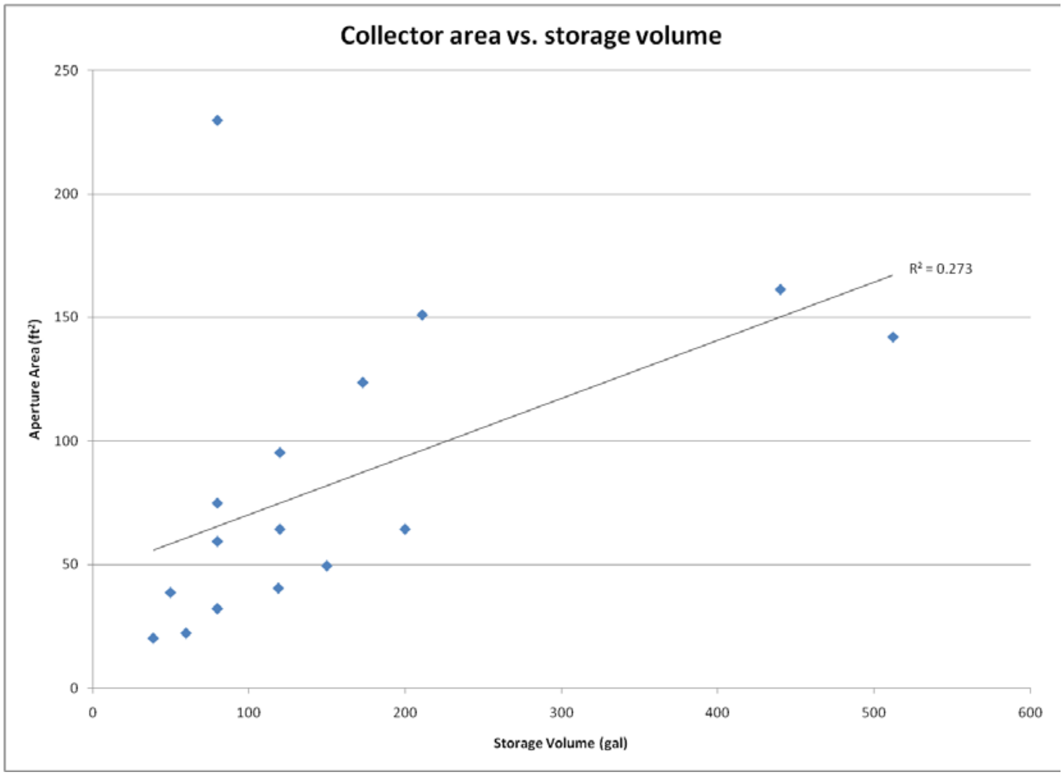

Figure 63 Thermal collector size vs. thermal storage volume

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Summary and Conclusions

Passive Solar Design Rules of Thumb

Direct-Gain

Direct-gain windows proved to be a useful design feature for many teams. The majority of teams added more solar glazing than was recommended by the rule of thumb but the correlations showed that the extra glazing was advantageous. The collected data suggests that the solar glazing limit suggested by the rule of thumb could be increased from 12% to 40%.

The addition of thermal mass played a strong role in temperature control and maintaining high temperatures. The rule of thumb governing amount of thermal mass relating to extra solar glazing could neither be supported nor rejected due to lack of data. Only two houses had enough thermal mass to compensate for all of the solar glazing. No strong correlation could be drawn between temperature control and fully accounted for solar glazing.

Daylighting

The rule of thumb governing daylighting was not supported by the collected data. The data suggested that increasing the effective aperture for daylighting beyond 0.18 also increased average temperature and improved temperature control. The rule of thumb is based on losing energy due to excessive window area which would result in lower average temperature and poor temperature control. It is likely that the trend visible in the daylighting graphs is due to the solar glazing which also caused a similar trend in the direct-gain graphs.

Windows

The rule of thumb governing solar heat gain coefficient was supported by the data. Houses with a SHGC between 0.4 and 0.55 typically had higher average temperatures. The rule of thumb for sizing north, east and west windows was partially supported by the data. The trends indicated that decreasing north windows helped maintain a higher indoor temperature but there were not enough data points that fell below the rule of thumb value to judge the effectiveness of the rule. The data points for east windows that fell below the

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rule of thumb value suggested that following the rule resulted in a cooler indoor temperature which is not the goal for this rule. For west windows the goal is to keep out unwanted heat gain and the data supports this. Data points falling below the 2% rule of thumb value were typically at a lower temperature. The trends also suggested that decreasing window areas on all sides helps improve temperature control.

Insulation

The data clearly shows a strong correlation between increasing R-values in all parts of the envelope and increased internal temperature and improved temperature control. The rule of thumb specifying a minimum of R-22 for walls and R-40 for roofs is also supported strongly by the data. Increasing R-values beyond these points leads to improved temperature control and higher average temperatures.

Best and Worst House Designs - Passive Solar Rules of Thumb

It is quite difficult to choose the best designs out of all twenty houses. All teams have been assigned a letter grade for how well each one met each of the rules of thumb. Table 15 lists the grades each house earned. Each house was given a grade point average based on the grades in each category. A is worth 4 points; B is 3 points and so on.

Table 15 Graded rule of thumb results

Team	Direct Gain	Extra Glazing	Thermal Mass	Insulation	EA	SHGC	R-win	N	E	W	GPA
Cornell	A	A	F	D	B	B	D	F	D	F	1.7
Iowa State University	A	A	C	B	C	C	A	D	A	A	3.0
Ohio State University	D	B	B	B	A	D	C	C	F	F	2.1
Penn State	F	F	A	C	F	C	D	C	C	B	1.6
Rice University	B	A	F	F	B	D	F	A	F	F	1.5
Team Alberta	C	B	C	B	A	B	C	C	A	B	2.8
Team Boston	F	F	D	C	F	C	F	F	B	A	1.2
Team California	F	F	D	D	D	D	F	D	D	F	0.6
Team Germany	D	A	B	A	F	A	A	F	D	F	2.1
Team Missouri	C	C	F	B	D	C	D	D	A	B	1.9
Team Ontario/BC	F	F	A	B	F	A	A	B	F	F	1.8
Team Spain	C	C	C	C	C	D	A	D	D	F	1.7
Universidad de Puerto Rico	B	B	F	F	A	B	F	F	A	A	2.1
University of Arizona	F	D	B	F	D	A	F	F	C	F	1.1
University of Illinois	D	C	F	A	C	A	A	A	A	A	2.9
University of Kentucky	B	B	F	F	F	D	B	F	C	F	1.2
University of Louisiana	B	B	F	D	A	D	F	F	B	D	1.6
University of Minnesota	F	F	D	B	A	D	C	C	C	A	1.9
University of Wisconsin	F	F	D	B	A	F	D	F	C	F	1.1
Virginia Tech	F	F	A	D	F	B	F	F	A	B	1.5

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Each rule of thumb was judged based on the numerical result of the rule of thumb calculation listed in the literature review of passive solar techniques. The only one that differs is the insulation category. In this category each house receives up to four points: one for having R22 or greater walls, one for having an R40 or higher roof, one point for a whole envelope R-value between 10 and 20 and two points for having a whole envelope R-value greater than 20. The ranges for each grade are listed for each category in Table 16 below.

Table 16 Grading criteria for rules of thumb

Grade	Direct Gain	Extra Glazing	Thermal Mass	Insulation	EA	SHGC	R-win	N	E	W
A	< 12	0 - 30	> 2000	4	0 - .03	.4 - .55	> 7	0 - 4	0 - 4	0 - 2
B	12 - 17	30 - 60	1000-2000	3	.03 - .06	.3 - .4 or .55 - .65	5 - 7	4 - 8	4 - 8	2 - 4
C	17 -22	60 - 90	100-1000	2	.06 - .09	.26 - .3 or .65 - .7	4 - 5	8 - 12	8 - 12	4 - 6
D	22 -27	90 - 120	0-100	1	.09 - .12	.2 - .25	3 - 4	12 - 16	12 - 16	6 - 8
F	> 27	> 120	0	0	> .12	.1 - .2	2 - 3	> 16	> 16	> 8

The three houses that most consistently followed the passive solar design rules of thumb were Team Alberta, University of Illinois and Iowa State University. Below is an explanation of how each team met the design criteria.

<u>Team Alberta</u>

This house had a somewhat large amount of solar glazing, the 11th most with a 21.9% solar glazing ratio. This was compensated for with large amounts of thermal mass integrated into the wall finishes of most of the interior. The use of Rundle stone on sunlit and shaded walls gave the thermal mass a good orientation to compensate for the large amount of solar glazing. This resulted in only 30.2ft^2 of unaccounted for solar glazing, the 5th lowest amount. The solar glazing also had a solar heat gain coefficient of 0.39 which is close to the 0.4 – 0.55 target range. Although for the climate this house will normally inhabit, the SHGC should be closer to 0.55 or above.

The Alberta house was the best ranked in daylighting. The effective aperture of the house was 0.185, only differing from the target value of 0.18 by 0.005. This is indicative of a good balance of windows to wall area. Proper daylighting design will let this house save energy on lights while not losing too much thermal energy through excessive window areas. In terms of oriented window-to-floor percentages, this house had 9.90% north

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facing, 2.30% east facing, and 3.30% west facing glass. While the north and west percentages were above the targets of 4% and 2% respectively, they were both significantly less than the majority of the other houses. Along with good amounts of windows, the Alberta house also had excellent shading to prevent unwanted solar heat gain. The shading system consists of motorized blinds that sit on the outside of the window and are deployed by a building control system. These blinds meet all five criteria for effective shading of windows.

The envelope of this house was very good as well. Although the whole envelope R-value was only 14.6, it was still the 6th highest value of all the houses. This was due largely to good wall and roof R-values that met the rule of thumb criteria. The walls were R-46.1 and the roof was R-42.7, exceeding the respective R-22 and R-40 rule of thumb minimum values.

University of Illinois

The University of Illinois house was designed with the goal of being Passive House certified. This design approach is evident in the house's impressive envelope. With a whole envelope R-value of 40.7, this house was by far the best insulated. The high envelope R-value is due largely to R-63.2 walls and an R-70.2 roof which both exceed rule of thumb design criteria. High R-value windows also helped super insulate this house, drastically reducing the need for heating and cooling systems.

The direct gain windows were too large by the rule of thumb criteria with a ratio of 22.7% and no additional thermal mass. This was beneficial during the competition week due to low outdoor temperatures. The team also used windows with a 0.52 solar heat gain coefficient which falls in the recommended range. It could cause some problems in the summer months, especially with such a highly insulated envelope. Aside from the direct gain windows, Illinois' window design was the best of all teams. They were the only team to design the north, east and west windows to the rule of thumb criteria. The house only has a 0.67% window to floor ratio for both the east and west walls and keeps the north wall windows below 4%. All of these measures help reduce heat loss during the winter. The Illinois house also employs shading which meets all five of the design criteria.

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This house had an effective aperture of 0.11 which allowed for some daylighting but not the maximum allowed by the rule of thumb. Again, with minimal window area, the house can retain heat well but at the expense of reduced daylighting capabilities. With such reduced non-solar glazing, the majority of lighting is gained through the solar glazing on the south façade. The massive amount of insulation most likely saves a greater amount of energy than is saved by replacing electrical lighting with daylighting, especially if energy efficient fixtures are used.

Iowa State University

The Iowa State house had a reasonable amount of solar glazing with a 9% ratio. This falls within the 7% to 12% range making this house one of only two to stay below 12% and the only house to actually fall in the desired range for solar glazing. The house incorporated a moderate amount of thermal mass with poured concrete counters in the kitchen, bathroom and bedroom. The horizontal orientation of the mass meant that it functioned as unlit floor which does not account for very much solar glazing. Only 10.5ft^2 of solar glazing was left unaccounted for, the third lowest amount of all houses.

This house had the third best overall envelope R-value with 20.4. Although the team only designed the R-33.2 walls to be above the rule of thumb value, they came close with the R-38.9 roof. What really helped create a highly insulated envelope were the house's windows and doors. The windows had the highest R-value of any at the competition with an R-11.1 insulating value due to the krypton gas fill, selective films, and triple panes. The house also boasted some impressive insulating doors. The prototype doors take advantage of high R-value vacuum insulation panels. With the combination of efficient doors and windows, the design team was able to drastically reduce the impact of the traditional weak spots in the building's envelope.

Daylighting fell a little short in this house. With an effective aperture of 0.119, there is only slightly more emphasis on daylighting in this house than in the Illinois house. As with the Illinois house, the increased wall area and reduced window area helps retain heat but creates a need for additional electric lighting. Window percentages on the east and west sides were both below the rule of thumb threshold at 2.02% and 0% respectively.

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Only the north windows were too large with a 13.83% ratio. The house also had appropriately designed shading with a combination of indoor curtains and adjustable outdoor aluminum louvers.

This house was one of only two to incorporate a sunspace for indirect solar heating. The sunspace is roughly 10% of the volume of the living space and has a solar glazing ratio of 114.7%. Additionally, the sunspace acts as an airlock for entering the house which minimizes the amount of air that escapes.

The three houses that ranked the worst in terms of following the passive solar design rules of thumb are Arizona, California and Virginia Tech. Listed below are some of the reasons why these houses failed to meet the design criteria.

University of Arizona

This house scored badly in the direct solar gain category due to the large amount of windows on the southern façade. Nearly the entire wall was composed of windows which could cause large amounts of unwanted solar gain. The house does have an interesting application of thermal mass in an attempt to compensate for the large solar gains. The window integrated water wall incorporates the fifth most thermal mass of all the houses. It wasn't enough though, leaving 93.8ft^2 of solar glazing unaccounted for.

The daylighting design of the house created a large possibility for energy loss. With an effective aperture of 0.278, the house had far too many windows, although the need for electric lighting is minimized during the day. Windows were excessive on every wall especially the north which had a 42.06% ratio, the second largest of any house. East and west windows were too large as well with ratios of 10.91% and 8.44% respectively. Along with large window areas, the insulating value of the windows was R-2.86. The house did have shading that met four out of the five design criteria. The shades were window integrated, motorized blinds. Additionally, the south windows were sloped to avoid direct exposure to the sun in the summer months.

The envelope of the house had the fourth lowest insulating value with R-7.3. This is mostly due to the large amount of windows and the use of steel in the structure of the

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house which created a thermal bridge through the majority of the roof and walls. This resulted in R-values of 13.6 and 27.0 for walls and roof respectively.

Team California

The California house featured excessive amounts of solar glazing with a ratio of 41.2%. This is the fourth highest ratio amongst the twenty houses. Only a small amount of thermal mass was incorporated into counters, leaving 185.1ft^2 of solar glazing unaccounted for. The house featured the third largest amount of unaccounted for solar glazing after Virginia Tech and Ontario/BC, two houses that were largely composed of windows.

The large amount of solar glazing helped contribute to an effective aperture value of 0.285, the seventh largest value in the category. While this is good for daylighting, it is bad for thermal efficiency. The glazing ratios were high for all the walls with values of 14.44%, 15.87% and 24.67% for north, east and west windows respectively. East windows were the fourth highest ratio and west windows were the second highest ratio overall. Both of these lead to heat loss and unwanted heat gain. The windows used had an R-value of 2.78 and a solar heat gain coefficient of 0.25 which are both rather low values. The house did feature good shading that met all five design criteria. Large wooden doors were installed that can slide over the large glass entrance doors to block out sunlight.

The overall envelope R-value was only the thirteenth best overall with a value of 9.5. The house featured good walls with an R-value of 27.5 which is above the R-22 recommended minimum. The roof R-value was good too but at R-38.4, it was still below the recommended value of R-40. The large amount of low R-value windows and doors is what caused the envelope R-value to drop to such a low level.

Virginia Tech

The Virginia Tech house featured the largest solar glazing ratio of all the houses with 61.9%. The house does incorporate the second largest amount of thermal mass in the concrete floor. Unfortunately, the large amount of sunlit thermal mass cannot compensate

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for the amount of windows, leaving 208.6ft^2 of unaccounted for solar glazing. This value is also the largest amount of unaccounted for solar glazing.

With the north and south façades almost completely composed of windows, the house had an effective aperture of 1.462. This value is the highest effective aperture calculated making the house the best for daylighting and the worst for thermal control. Window percentage on the east was within the rule of thumb range with a 0% glazing ratio but the north and west walls had ratios of 55.51% and 3.43% respectively. The north wall glazing ratio was the highest of all the houses. The windows had the third lowest R-value at 2.18. The shading system was a major feature of this house and met four out of five design criteria. Large computer controlled metal doors slid over the north and south facades on tracks.

The envelope had the second lowest R-value of all the houses with 4.4. The roof had a high R-value of 48.5 but the walls were below the rule of thumb values at 16.0. The low R-value windows which dominate the envelope of this building are what caused such a low overall R-value.

Best and Worst Houses - Energy Collection

In terms of projected photovoltaic and thermal collection, the top three teams are Germany, Kentucky and Ontario/BC for photovoltaic conversion and California, Alberta and Minnesota for thermal collection. When the values for photovoltaic conversion and thermal collection are combined, the teams that are projected to collect the most energy are Kentucky, Germany and Ontario/BC in order. Comparing design approaches for these six houses, there is one outstanding characteristic. Five out of six of these houses used the façade as well as the roof as an active solar collection area. In some cases it meant covering every available surface in photovoltaic modules and in other cases it meant incorporating flat plate thermal collectors into various facades to increase collector area. In either case, there is evidence for a desire to make solar collection both functional and attractive. These six houses are evidence that it can be done well, thus fulfilling one of the goals of the Solar Decathlon: finding a design approach that integrates solar collection into buildings.

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Table 17 Energy collection results

Team	Array Size (kW)	Predicted Collection PV (kWh)	Thermal (kWh)	Total (kWh)	Energy Balance Results Surplus (kWh)	Place
University of Kentucky	11.0	355.07	28.87	383.94	10.81	5
Team Germany	17.8	380.28	0.00	380.28	113.18	1
Team Ontario/BC	13.1	264.39	45.70	310.09	22.44	3
Team California	8.6	175.47	119.12	294.59	0.54	12
Universidad de Puerto Rico	10.4	253.93	22.63	276.56	-70.99	18
Team Spain	15.0	229.80	29.49	259.28	20.86	4
University of Minnesota	8.0	167.47	76.20	243.68	1.20	10
Cornell	8.0	193.32	35.26	228.59	0.42	14
Team Alberta	7.6	146.62	77.10	223.72	0.30	13
University of Arizona	9.0	184.23	29.00	213.23	-179.78	20
Team Missouri	8.0	183.19	29.94	213.13	1.61	9
Team Boston	6.4	128.70	74.59	203.29	-5.60	15
Penn State	5.8	168.21	29.25	197.45	-64.94	16
Iowa State University	7.8	145.40	44.59	189.99	3.09	6
University of Louisiana	7.9	150.52	28.06	178.58	-70.15	17
University of Wisconsin	5.6	128.85	43.39	172.25	-109.88	19
University of Illinois	9.0	166.12	0.00	166.12	84.29	2
Virginia Tech	8.0	165.14	0.00	165.14	2.12	8
Ohio State University	6.8	137.66	19.72	157.38	3.00	7
Rice University	4.2	88.06	25.11	113.17	0.57	11

Conclusions

While many teams failed to design houses that met the rules of thumb, there was some visible evidence that following these rules increases the performance of the houses. Several of the rules of thumb recommended staying below certain limits. Many of the graphical comparisons showed trends that contradicted the limits set by the rules of thumb. Most notably of these rules would be the direct-gain limit of 7% to 12% solar glazing and the maximum limit of 0.18 for effective aperture. Other rules of thumb were supported by graphed data. The most strongly supported relationship was between increased R-values and improved temperature control and average temperature.

Unfortunately, the nature of the Solar Decathlon does not put an emphasis on passive solar design in the objective contests. The comfort zone competition is more a measure of how well the HVAC system works in a house than how well the house is designed. Additionally, the energy balance competition draws the emphasis away from passive solar design and places it on purchasing excessively large photovoltaic arrays. This essentially facilitates the status quo and removes the incentive to make the buildings

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themselves greener. While the architecture and engineering subjective contests allow for credit to be given to passive solar features, there remains no way to effectively measure the performance impact of these design features within the context of the competition.

As a means of predicting future performance, the design rules of thumb are minimally effective. Table 18 shows how each house ranked using the prediction methods for photovoltaic electricity production, thermal collection and passive solar rules of thumb. The actual placements in energy balance and comfort zone from the competition are also listed. The passive rankings are a good way to get a rough idea of where a house would place in the comfort zone competition but rarely does it predict the place exactly. Only two houses have the same rule of thumb placement and comfort zone rank. Likewise only two houses had the same predicted photovoltaic rank and energy balance rank.

Table 18 Predicted rankings and actual results

	Predicted			Actual Results		
Team	PV	Thermal	Passive	Surplus (kWh)	Energy Balance	Comfort Zone
University of Kentucky	2	13	16	10.81	5	12
Team Germany	1	18	4	113.18	1	1
Team Ontario/BC	3	5	9	22.44	3	3
Team California	9	1	20	0.54	12	14
Universidad de Puerto Rico	4	16	4	-70.99	18	9
Team Spain	5	10	10	20.86	4	18
University of Minnesota	11	3	7	1.20	10	6
Cornell	6	8	10	0.42	14	13
Team Alberta	15	2	3	0.30	13	5
University of Arizona	7	12	18	-179.78	20	20
Team Missouri	8	9	7	1.61	9	19
Team Boston	19	4	16	-5.60	15	17
Penn State	10	11	12	-64.94	16	16
Iowa State University	16	6	1	3.09	6	11
University of Louisiana	14	14	12	-70.15	17	7
University of Wisconsin	18	7	18	-109.88	19	15
University of Illinois	12	18	2	84.29	2	2
Virginia Tech	13	18	14	2.12	8	8
Ohio State University	17	17	4	3.00	7	4
Rice University	20	15	14	0.57	11	10

Based on the average of the three prediction columns, the best performing houses were predicted to be Ontario/BC, Alberta, and Minnesota. The three lowest performing predictions are Rice, Virginia Tech and Wisconsin. The average of the two actual results columns shows that the three best performing houses are Germany, Illinois and Ontario/BC. The four worst performing houses were Arizona, Wisconsin, Boston and

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Penn State (tie). In the case of both best performing and worst performing, the predictions were only able to get one out of three correct.

Based on these comparisons, rules of thumb for passive solar house design are best used for rough estimations. Anything requiring more accuracy should utilize a computer model.

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