DEVELOPING THE NEXT GENERATION OF PASSIVE SOLAR FOR A COLD CLIMATE - ARCHELIO

By

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ABSTRACT

Solar energy has been harnessed by man for thousands of years. The ancient Greeks and Chinese used reflectors to start fires for cooking.[1] Since the beginning of recorded time, people have oriented their buildings to take advantage of the predictable movement of the sun across the sky. The vast quantity of energy that the Earth receives from the sun in one hour, is roughly equal to the amount of energy human civilization uses every year.[2] The goal of this thesis is to develop a new method of solar heating that will bring the sun to the building, rather than passively waiting for the sun to enter the building. The energy captured will then be stored in a controllable thermal mass for later use.

By case studying existing solar thermal energy plants, lens science, existing thermal mass technologies, and looking at the way nature has evolved its system of gathering energy, a new method of heating could be developed. The system would use technology from both active and passive solar technologies. Active sensors attached to large parabolic mirrors would seek out the sun, and focus the sunlight on a Fresnel lens. The lens would then direct a concentrated beam of light into a passive thermal

1 Cleveland, Cutler J. *Concise Encyclopedia of History of Energy*. 1st ed. San Diego, Calif.: Elsevier, 2009. Web.

2 Hough, Tom P. *Solar Energy: New Research*. New York, Nova Publishers, 2006.

storage unit. In theory, this storage mass could operate at very high temperatures, depending on the material and the location. The thermal mass would also have to be thermally separated from the environment, ensuring there are no combustibility or safety issues. The building could access this energy, either via a liquid transfer system, or more simply through an air transfer system. When the system has calculated that the thermal storage requirements for the building have been satisfied, the mirrors could be focused on photovoltaic panels to satisfy the electrical requirements for the building.

A system such as this will take another step towards mimicking the way nature draws energy from the sun, while actually using the site to provide energy rather than the typical practice of piping energy in to the building from other places. Instead of passive solar technology that relies on fixed geometry, this system would actively find the sunlight, and deliver it to the building. This form of heating would be truly green, natural and plentiful. By reducing the heating requirement of buildings, it is possible that the energy usage could be drastically reduced.

By focussing on initially absorbing the sun’s energy as heat, by eliminating the losses incurred by energy conversion, and by maximizing the quantity of energy absorbed with use of heliostat arrays, and a thermal mass, it will even be possible to span the sunless hours in a cold climate. The limit is only the size of the thermal mass, the losses of energy surrounding the mass, and the size of the collectors.

ACKNOWLEDGMENTS

I would like to thank the many people who have helped through this research. I would like to express my gratitude to my supervisors, Professor Janice Means and Professor Daniel Faoro who had the difficult job of guiding me through this research from afar. I can't thank you enough for taking the time to lead me through this work. Furthermore, I would like to thank Alex Temporale and ATA Architects for the patience they have shown through the last few years. Thank you to Fred Driedger, who without your guidance and inspiration this project would have never came to be. Special thanks to Joyce Coffin, for your helpful insight and encouragement. I would also like to thank my wife Andrea Driedger for her support over the past few years.

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CHAPTER 1 - INTRODUCTION - SOLAR ENERGY & COLD CLIMATES

Solar energy has been harnessed by man for thousands of years. Since the beginning of recorded time, people have oriented their buildings to take advantage of the predictable movement of the sun across the sky. In cold climates, solar energy harvesting has always been viewed as a supplement to a typical dwelling heating system. Because of the long hours of darkness, and the cold temperatures associated with cold climates, it is very difficult to maintain a comfortable temperature for humans using solar heating alone.

The aim of this research is to develop a new method of solar energy collection that will provide all the required heating energy for a typical dwelling, in a cold climate. With more efficient use of using the sun's energy, it may be possible to greatly reduce humanity's energy consumption, from sources other than the sun.

This project focuses on space heating, rather than space cooling. A cold climate can be defined as an area where the calculated heating design temperature is more than -7°C (19°F) below freezing for up to 2.5% of the hours in January.[3] Our building and clothing technologies have made it possible to survive at these extremes. They are literally life support, when the ambient temperatures fall outside of the limits of our bodies' thermal regulation systems. Doing heavy muscular work, the human body can

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3 Hutcheon, N. B., and G. O. Handegord. *Building Science for a Cold Climate*. SI metric ed. Ottawa: Institute for Research in Construction, 1995. Web.

survive in temperatures as low as -5°C (23°F), with little clothing. At rest, anything below 27 °C (80°F), engages the human body's self-heating systems, such as shivering, to avoid hypothermia.[4]

The human body's regulation of heat depends on the radiative heat gain from the environment, air moisture, air velocity and air temperature. Also critical is the thermal insulation of our clothing and the amount of work we are doing. If the temperature is too high, the body reacts by sweating. The evaporation of moisture reduces the body's temperature. When the temperature is too cold, shivering is induced, which can generate up to 500 W of additional heat to maintain body temperature.

The human body is typically at 37.0°C (98.6°F). The thermo neutral temperature for the human body is 27.0°C (81°F). Heat is constantly being generated by our internal cellular processes. To be comfortable, the human body must be in a constant state of energy loss.[5] Thermal comfort typically exists when a body's heat loss equals the heat gain. Therefore, the heating systems of our buildings are a major factor in maintaining that equilibrium and are vital to our survival in areas with a cold climate.

CHAPTER 2 - ENERGY USAGE THROUGHOUT THE WORLD

Our networks of energy supply and distribution are also important elements in the survival equation. Based on the data provided by the World Bank, Canada and the United States are among the

4 ACIA - Arctic Climate Impact Assessment (7 November 2005). Arctic Climate Impact Assessment - Scientific Report. Cambridge University Press.

5 Human Health - Arctic Climate Impact Assessment - www.acia.uaf.edu/PDFs/ACIA_Science.../ACIA_Ch15_Final.pdf

highest users of energy per capita throughout the world. As seen in Figure 1, countries that are subject to harsh climatic conditions seem to also use more energy to counteract the conditions. It is interesting to note that based on the data, Iceland ranks near the top of the highest energy users, possibly because of the climate, but also the availability of inexpensive geothermal energy. The Middle East countries of Qatar and Kuwait are also near the top, partially due to the harsh conditions, but also due to the availability of lower cost energy sources. Looking at the data, there is an obvious link between the availability of energy, the economic cost of the energy, and the per capita usage of energy in a country. Because of simple supply and demand, as energy supply becomes plentiful, the cost for energy drops, thus increasing the usage by the local population. As the population of the earth increases, the demand for energy will also increase. Costs are expected to increase unless alternate energy sources are found.

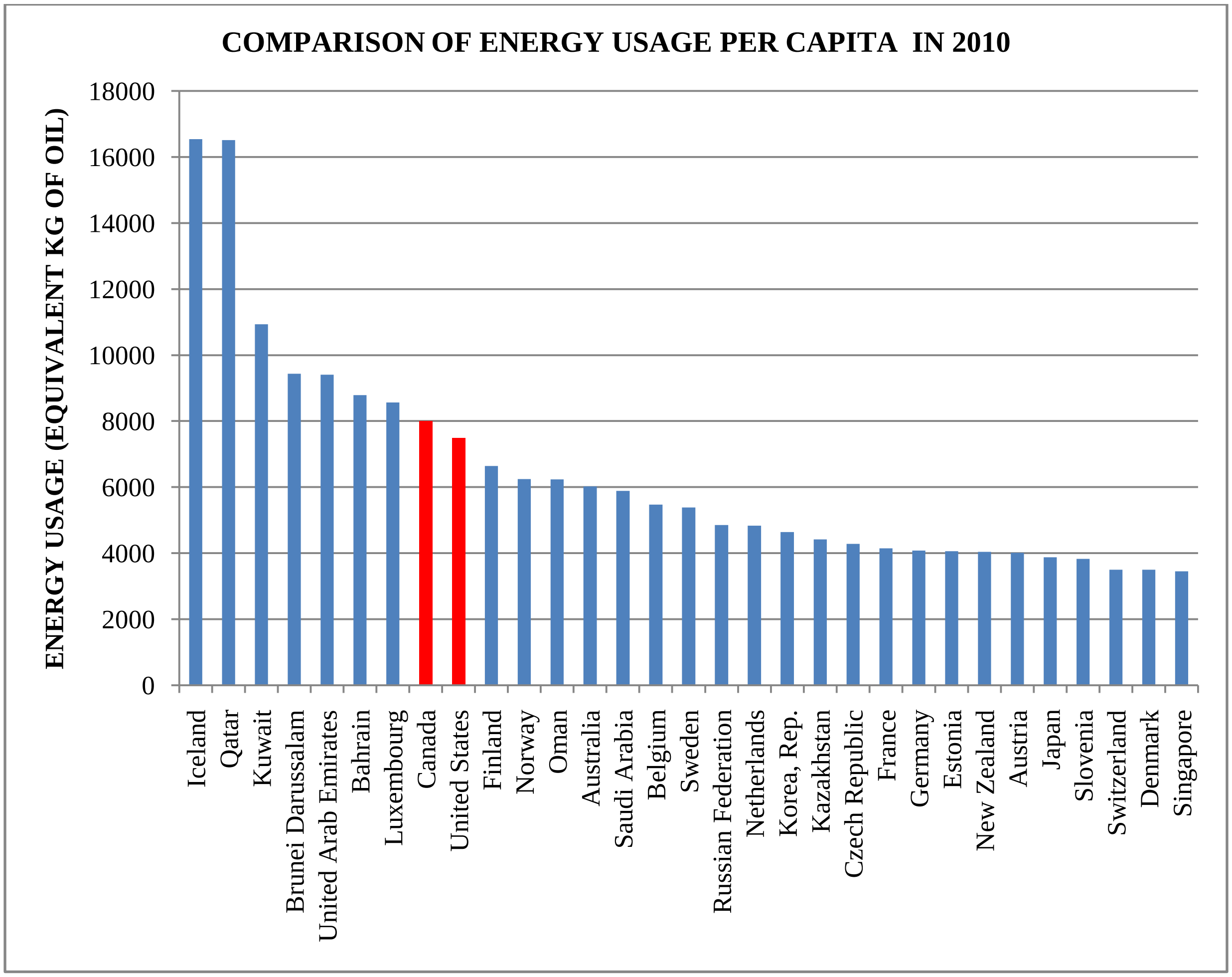

Figure 1 - 2010 DATA - WORLD BANK - http://data.worldbank.org/indicator/EG.USE.PCAP.KG.OE - Graph by Mark Driedger

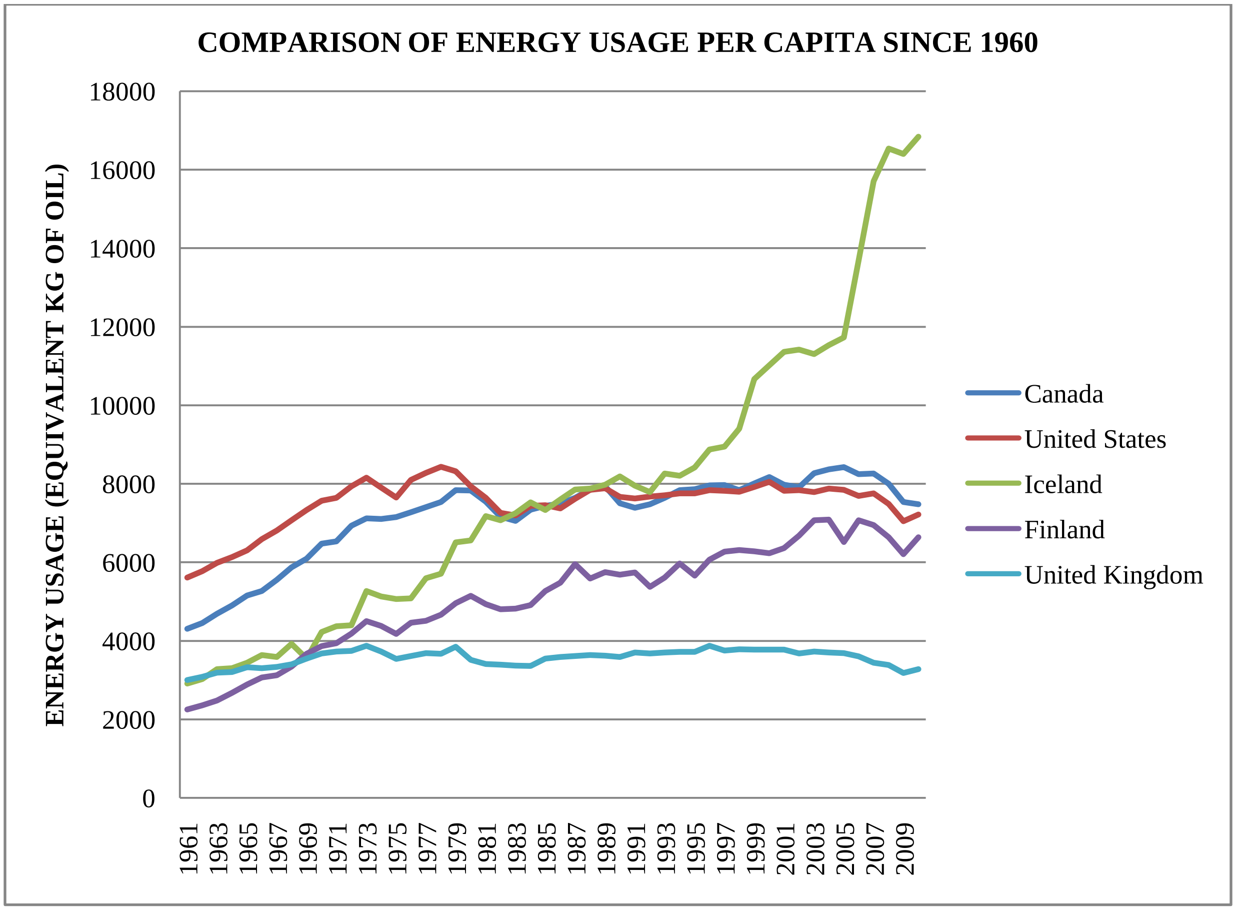

Figure 2 - 2010 DATA - WORLD BANK - http://data.worldbank.org/indicator/EG.USE.PCAP.KG.OE - Graph by Mark Driedger

Looking at the data, since 1960, we can see the effect of various energy policies and crisis played out through time. Although the entire trend of energy usage is an upward one, recent changes may suggest that either the conservation movement, or the increased cost of energy may be levelling off consumption in Canada and the US.

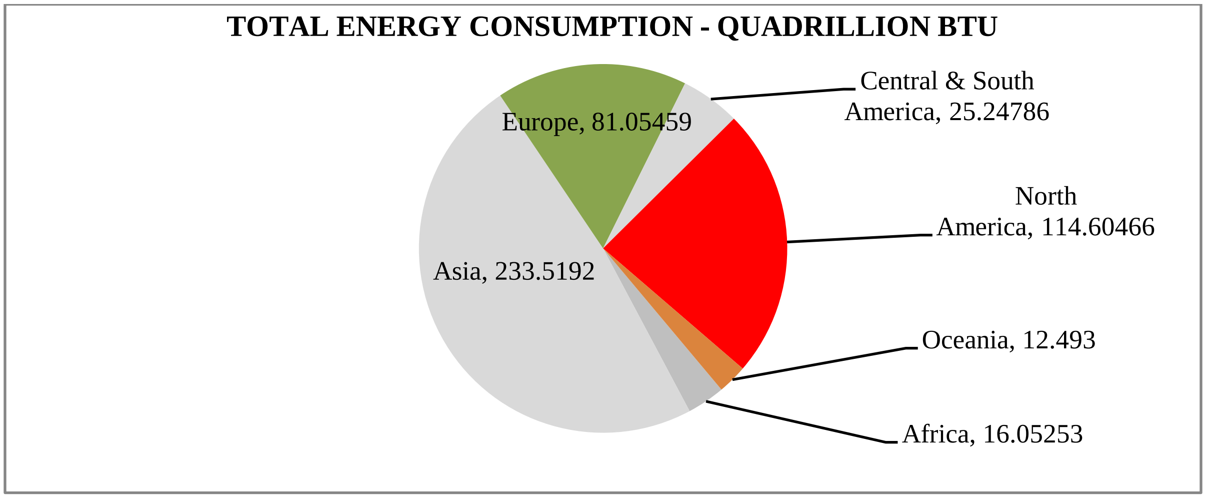

Figure 3 - Energy Information - U.S. Energy Information Administration - 2011 Data - http://www.eia.gov/ - Graph by Mark Driedger

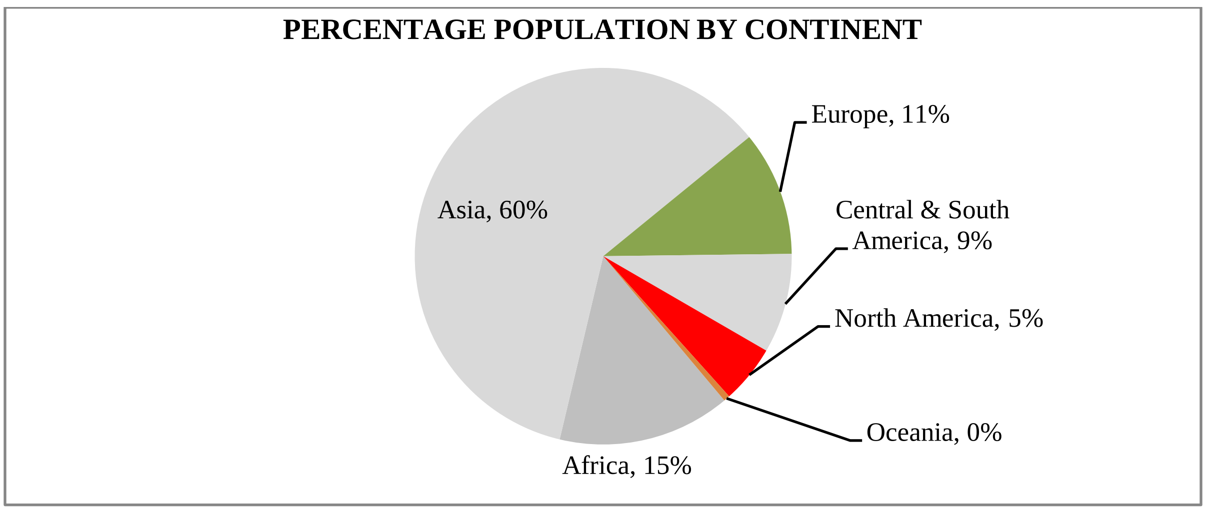

Figure 4 - Population Information - United Nations Statistics - 2010 Data - Graph by Mark Driedger

Even if our thirst for additional energy is slowing in North America, the data still suggests that there is a significant imbalance in energy usage in the world. Although North America contains approximately 5% of the World's population, it uses 25% of the available energy. Even though much of

Europe is similarly industrialized, its percentage use of world energy is much more closely aligned with its percentage of world population. As resources are pushed to the limit in the future, North America must not only slow its thirst for new energy but also decrease its overall use of traditional energy sources.

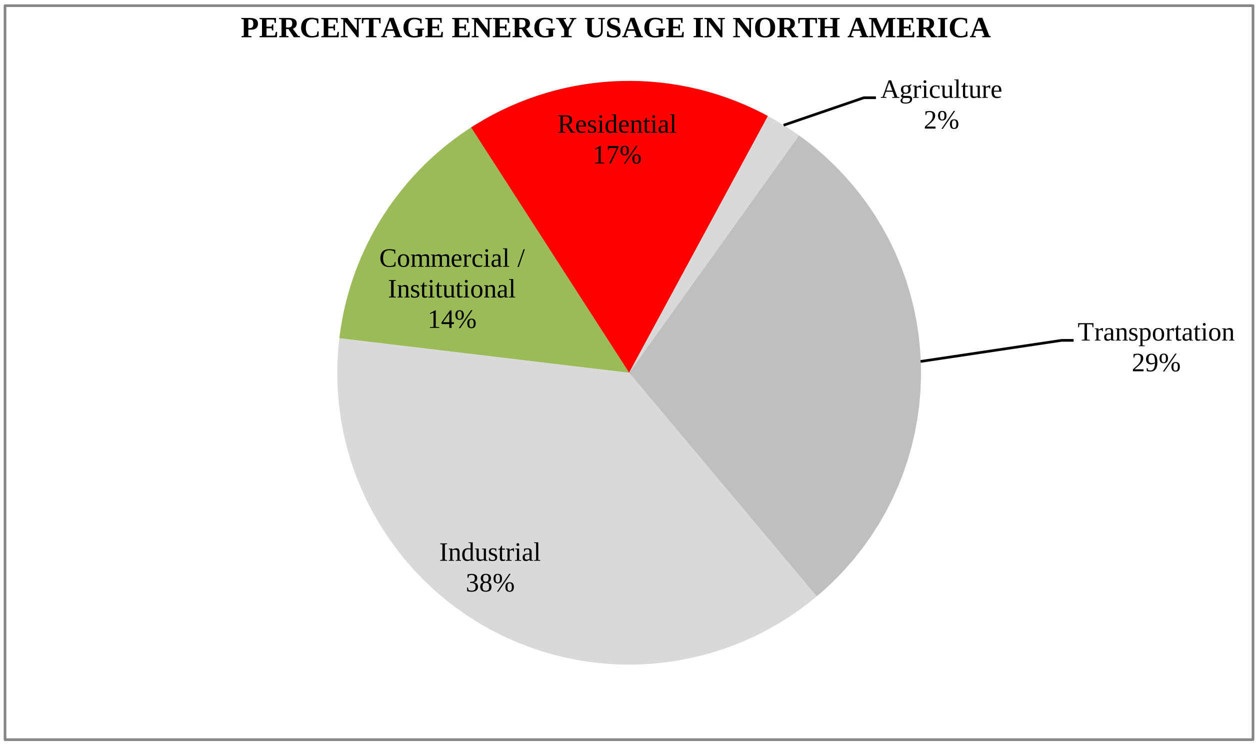

Figure 5 - Energy Information - U.S. Energy Information Administration - 2011 Data - http://www.eia.gov/ - Graph by Mark Driedger

So how can we reduce consumption in North America? In North America, approximately 31% of energy is presently being used by built form. North American architects therefore can play a significant role in this energy reduction in the construction of new buildings, and the renovation and retrofit of existing buildings.

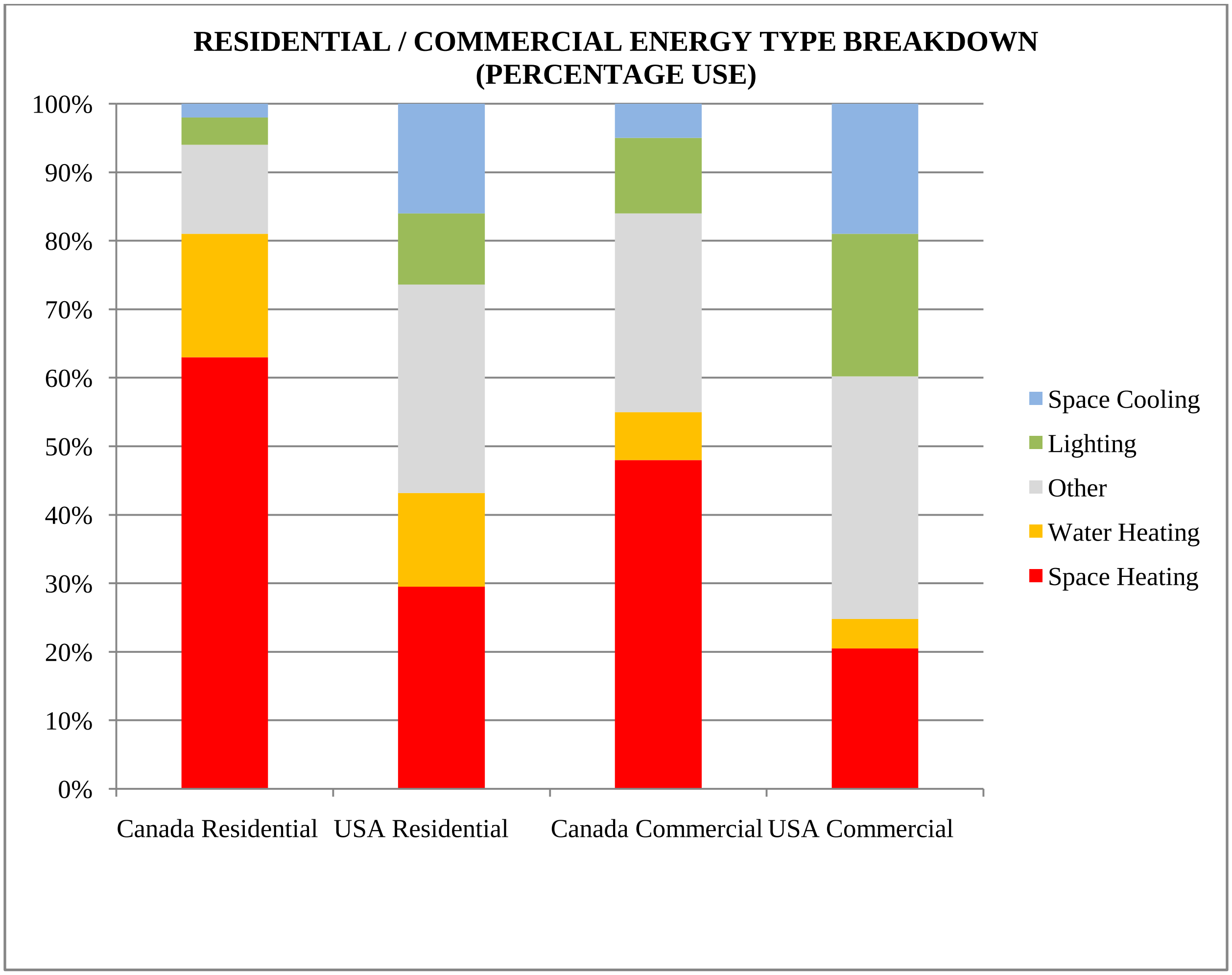

Figure 6 - Energy Information - National Resources Canada
http://oee.nrcan.gc.ca/publications/statistics/trends09/chapter3.cfm?attr=0

Residential & Commercial Energy Usage in America - http://buildingsdatabook.eren.doe.gov/TableView.aspx?table=2.1.5 - Graph by Mark Driedger

Of the 31% of the energy used by buildings, space heating is the largest energy requirement in both Canada and the US. The variances between the two countries may be attributed to the climate variations. Focusing on reducing space heating for a building can have a far reaching effect on the overall energy usage of the continent of North America. Sustainable design, with the focus on space heating reduction must be at the core of this new strategy.

CHAPTER 3 - SUSTAINABLE DESIGN

Humans have extracted fuel and expelled carbon dioxide at an increasing level over the past 300 years of industrial revolution. The CO^2, a relic of molecules assembled by organics from a different time, is being released into our atmosphere through our combustion processes. It is important to understand that the carbon itself is not new to this world; it is just presently being unnaturally concentrated into our atmosphere. The bonds within the fuels we use were originally formed by a combination of life and solar energy. The oil that we burn every day is simply a stored battery of energy from the sun, captured from many seasons ago. The unnatural concentration of the by-products of this energy is what is damaging to the present day environment. The carrying capacity of the carbon in our atmosphere has limits. Our actions have created that imbalance and will continue to do so until we change our practice. To reduce the unnatural concentrations of carbon, humans must to move towards a more "real-time" method of energy harvesting. Rather than leaning on the sun's energy stored in fossil fuels many years ago, man must focus on capturing and storing the excess energy from the sun today, to use tomorrow.

UPSETTING THE NATURAL BALANCE

Easter Island is an example of how humans can quickly overthrow the balance of the ecosystem by using up energy and resources unwisely. The people of Easter Island taxed the natural environment to the point where nature could not compensate or evolve to the unnatural stimuli being placed on it. Easter

Island, a small, isolated island in the South Pacific, was originally heavily vegetated, and was home to many different species of animals. Because of the lack of a reef around the island, early human inhabitants were forced to focus on the island's animals and engage in farming for sustenance, rather than the typical diet of fish.[6] As the population flourished on the island, the natural resources were harvested at an unsustainable rate . The ultimate over extension of land use resulted in the extinction of forests, the erosion of farming land, and the loss of animals for food. The society was ultimately crushed by over consumption. Today, man is continually pushing the delicate balance of the earth's environment through over consumption.

SUSTAINABLE ARCHITECTURE

The term "Sustainable Architecture" is an oxymoron. The act of building itself is automatically destructive to the environment, and often a selfish human endeavour. The EPA has noted that up to 40 percent of all waste in landfills comes from construction.[7] As per figure 5, approximately 31% of all energy produced is used by buildings. A typical building is parasitic to the environment, and provides no benefit to its surroundings, other than for the use of humans. A building operates in an ecological deficit with its surroundings. Energy and materials must be transported to the site, at the expense of other areas of the world, to keep humans comfortable.

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6 Diamond, Jared M. *Collapse: How Societies Choose to Fail Or Succeed*. New York: Penguin, 2011. Web.

7 Chambers, Neil B. *Urban Green: Architecture for the Future.* Palgrave Macmillan, 2011.

A building that operates in a sustainable manner, lives in a symbiotic state with its surroundings. This is similar to the bacteria that feeds in our digestive system, but in doing so is essential to our health, or the bee which feeds from the flowers, but inadvertently pollinates. A sustainable building must only take what is needed from its environment but in doing so give back some equal benefit. A building that is truly sustainable in this manner, is difficult to find, but should be our ultimate goal.

While the architectural industry may be preaching sustainability, the majority of what is being constructed is often not performing that way. Programs such as LEED are a good step forward for sustainability, but they do not focus enough on the energy side of the equation. The goal of any sustainable architect should be to reduce the energy required to run the building, while using materials that have the least detrimental effect on the environment. When looking at LEED NC 2.2, only 16 points out of 69 possible points are attributed to saving energy within the building.[8] These include EA1 Optimize Energy Performance, EA2 On-Site Renewable Energy, EA3 Enhanced Commissioning, EA5 Measurement & Verification and EA6 Green Power. Based on this, one can theoretically be able to achieve LEED Platinum, the highest possible LEED certification level on a building, with little regard to energy usage.

8 LEED-NC for New Construction: Reference Guide, Version 2.2. U.S. Green Building Council. 2005.

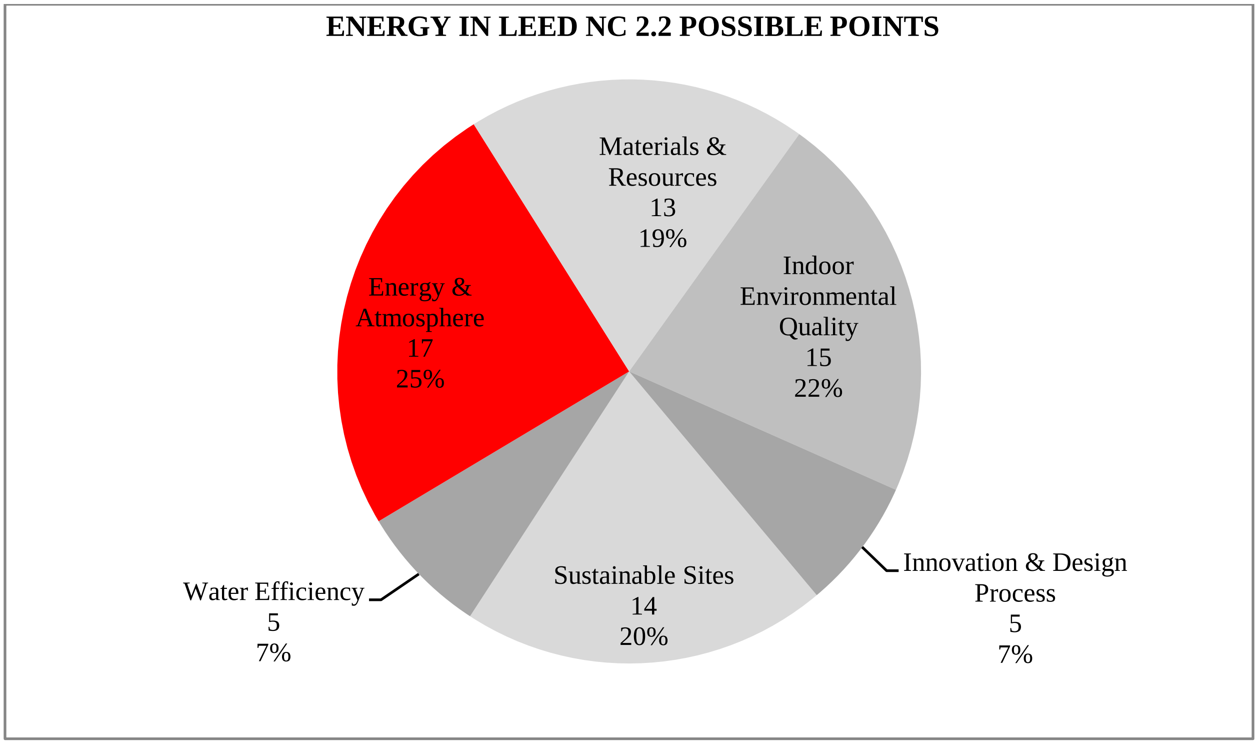


Figure 7 - LEED NC 2.2 - Graph by Mark Driedger

Another issue with LEED is the lack of a feedback mechanism that allows the building to be monitored throughout its life cycle. Without actually monitoring and publishing operational data, it is impossible to understand whether a building is operating as it was marketed to operate. LEED buildings could actually be using more energy than their counterparts, and still be marketed to the public as being green. Building operations must be continuously monitored to ensure the mechanical components are operating as planned. Building rating systems will continue to evolve to be more operational-based as time goes on. Operational systems such as ASHRAE Building Energy Quotient (BEQ) should be used over static, design based performance rating systems[9].

ENERGY & ENVELOPE

The performance of the exterior envelope becomes even more important in a consumer environment with little regard for total energy usage. In the suburbs, the average dwelling is increasing in size, as the availability of land gets smaller. The larger buildings create more exposed exterior walls, and take more energy to condition the spaces, putting further pressure on our infrastructure. Even though people continue to complain about gas prices, they continue to buy larger cars and houses. As countries around the world join the consumer lifestyle, and the world's population expand, the cost for energy will only get more expensive as fossil fuels decline in abundance. When it comes to energy and sustainable construction, the envelope can play a major part in reducing the operating costs of a building.

SUSTAINABLE MATERIALS

The LEED rating system is contradictory when it comes to material selection on a building. On one hand, LEED insists that a material is to be durable and last for a long time while exposed to the elements. Yet, a material such as plastic, will end up spending eternity in the landfill. The other side of the coin is that LEED also requires materials to be natural. Natural materials do not perform well, when

9 Means, Janice K. and Filza H. Walters. *Do High Performance-Labeled Buildings Really Perform at the Promised Levels?*, CLIMA2010 Congress CD

exposed to the elements, and tend to naturally biodegrade. In order to protect these materials, we cover them in "durable" materials to ensure they last. Both LEED strategies can get the building points in the LEED process. Instead, consideration should also be given to whether the materials can be recycled. Our fashion conscious society is constantly changing the finishes on the inside and outside of our buildings, and used building materials typically go straight to the landfill.

THE EARTH AT THE MACRO LEVEL

When searching for our definition of green, as Architects, we also have to understand the Earth system from a macro level. According to the 2nd Law of Thermodynamics no closed cycle system is truly sustainable. The planet Earth viewed by itself is not a closed system. Life on earth is entirely based on the constant energy inputs from the sun. Only by recognizing this input, and harnessing and constructing a system that uses and reuses this energy over a set period of time, are we truly building a sustainable product.

SUSTAINABLE BUILDING CASE STUDY

The City of London, England is a forward thinking municipality that monitors the energy usage of both its new buildings, and its existing building portfolio. The result is a database of energy usage that allows researchers to compare the performance of buildings, and market their performance.

Figure 8 - City of London City Hall - Photo by Mark Driedger

One of the buildings that are being monitored is London City Hall, by Norman Foster. The building, completed in 2002, has been described as being a "sustainable, virtually non-polluting public building."[10] The shape of the building was designed to maximize shading, and minimize the effects of the sun on the building. The glass facade tips towards the sun, creating shaded surfaces for the office space within it.

10 http://www.fosterandpartners.com/projects/city-hall/

Figure 9 - London City Hall - Photo by Mark Driedger

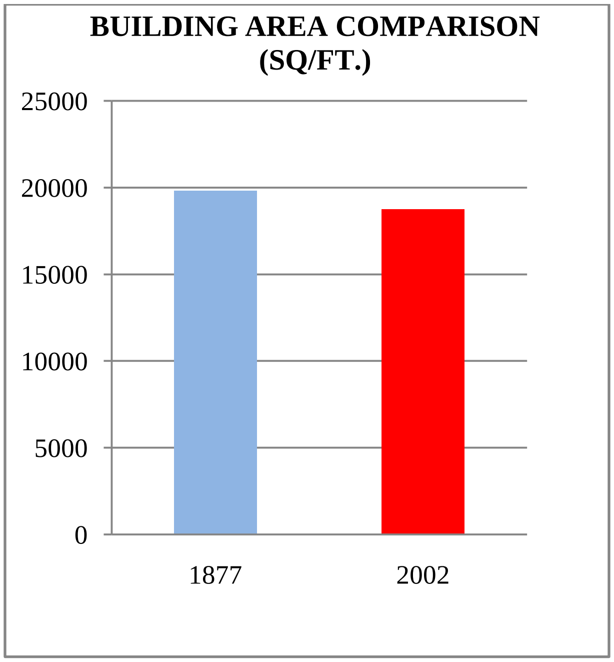
London City Hall, when compared to other City buildings, was given a D rating by the United Kingdom based Centre for Sustainable Energy.[11] The data compared the energy use, emissions, floor space and efficiency ratings for all public UK buildings. In fact, the building performs very similarly to Manchester City Council, a building constructed in 1877, and of a similar use and size. The building can clearly not be defined as sustainable, if it uses the same energy as a building constructed a century before.

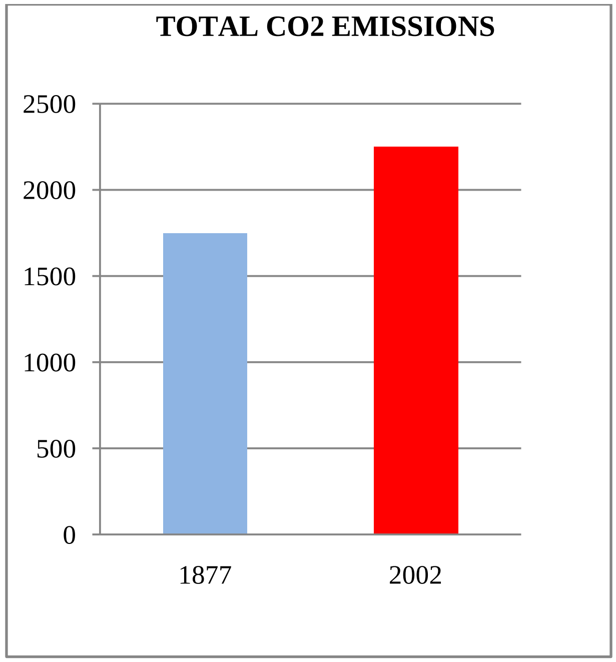
11 http://www.cse.org.uk/resources/open-data/display-energy-certificate-data

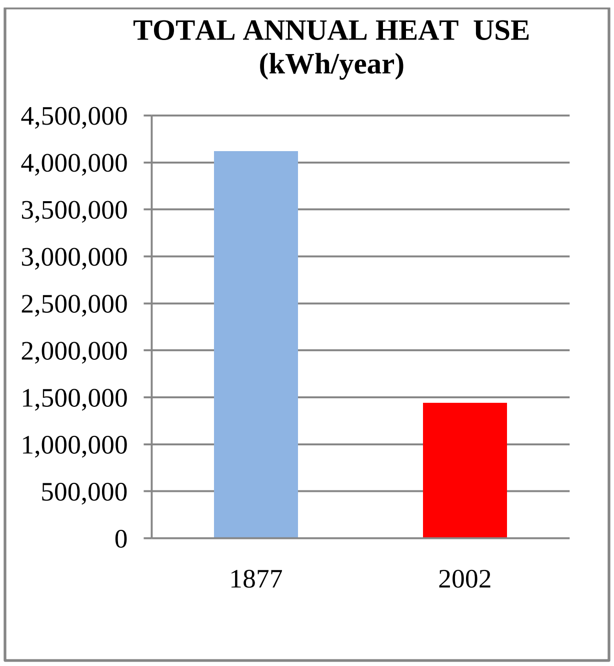
Figure 10 - Manchester City Hall[12]

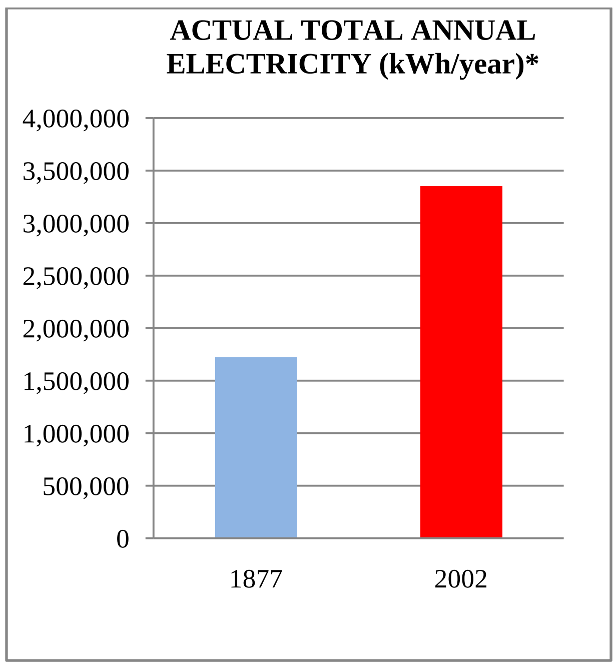
From the energy data, according to the Centre for Sustainable Energy, the modern building actually has a larger carbon footprint, than the 100 year old building. The electricity usage appears to be almost double the older building's electricity use. This may be because of the additional pumps and equipment required to run the geothermal system. Another reason could be the natural cooling thermal mass effect of the masonry walls in Manchester City Hall.

12 www.wikipedia.com


BUILDING AREA COMPARISON (SQ/FT.)
25000
20000
15000
10000
5000
0
1877
2002


TOTAL CO2 EMISSIONS
2500
2000
1500
1000
500
0
1877
2002


TOTAL ANNUAL HEAT USE (kWh/year)
4,500,000
4,000,000
3,500,000
3,000,000
2,500,000
2,000,000
1,500,000
1,000,000
500,000
0
1877
2002


ACTUAL TOTAL ANNUAL ELECTRICITY (kWh/year)*
4,000,000
3,500,000
3,000,000
2,500,000
2,000,000
1,500,000
1,000,000
500,000
0
1877
2002

Another significant difference in energy use is the amount of glazing on the modern building. Although the increased glazing does allow more natural light to filter into the building, glazing cannot compete with the thermal resistance values of typical wall assemblies when it comes to conductive heat loss. Recognizing instead that powered lighting in a building takes much less energy than heating a building, it is more important to limit glazing and increase wall cladding percentage to conserve energy. ASHRAE 90.1 which limits window to wall ratios is starting to be adopted by building codes around the world.

CHAPTER 4 - GLAZING PEFORMANCE & SUSTAINABLE DESIGN

Glazing and its structure or frame is from a thermal standpoint, the weakest point of a wall assembly. The U value, or thermal conductance of a window is typically much lighter than a standard wall assembly. Windows can also be a problem area within an envelope causing air and water leakage, thermal gain from the sun, and condensation. They are also vitally important to our buildings by providing natural light and ventilation[13.] With a window assembly, recent advances in glazing technology has actually reached a point where the frame of the assembly is the weakest point of the assembly in terms of thermal transfer.

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13 Hutcheon, N. B., and G. O. Handegord. *Building Science for a Cold Climate*. SI metric ed. Ottawa: Institute for Research in Construction, 1995. Web.

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ILF12001, Aug. 7, 2012

325 Casement as per EN ISO 10077-2 and EN673

Glazing	U-Factor Total Window (W/m^2-K)	U frame (head,jamb,sill) (W/m^2-K)	Ψ (W/m-K)	U centre of Glass (W/m^2-K)	SHGC centre of glass	Frame Height (head,jab,sill) (mm)
272-arg-Cl-arg-180, se	0.97	1.23	0.024	0.716	0.372	70.8
180-arg-Cl-arg-180, se	0.99	1.23	0.024	0.742	0.560	70.8

Notes:
1. U-value simulations performed according to EN 673 and EN ISO 10077-2 using Therm 6 and BFRC EN 673 calculation spreadsheet
2. SHGC simulation used Window 6.3
3. Cl is clear glass
4. arg is 90% argon, 13mm air gap
5. 272 is Cardinal's 272 low-e, 3 mm
5. 180 is Cardinal's 180 low-e, 3 mm
6. se is Edgetech's Super Spacer (E-class)
7. The size was 600mm x 1500mm as per standard North American ratings
8. See report ILF11001w-d for product information

Figure 11 - Window performance analysis[14]

As seen in the example above, in modern window designs, the U value of the frame loses energy at a higher rate than the glazing portion. Windows are typically the weakest point in a building

14 Enermodal Engineering

assembly.[15] In today's architectural landscape, clients and many architects seem to neglect the energy equation and choose large expanses of glass in their buildings. A snapshot of any major city in the world will show designers using curtain wall (glazing) as their primary assembly, putting the focus on views and aesthetics over energy considerations.

Figure 12 - City of London - Photo by Mark Driedger

15 Hutcheon, N. B., and G. O. Handegord. *Building Science for a Cold Climate*. SI metric ed. Ottawa: Institute for Research in Construction, 1995. Web.

USING COMPUTATION FLUID DYNAMICS TO ANALYZE WINDOW PERFORMANCE

Computational fluid dynamics allows designers to recreate real world physics in a virtual system. Designers are now able to simulate the complex performance of their assemblies, without complex laboratory testing. Computer processing speed has evolved to a point where these complex, three-dimensional calculations can be completed on a home personal computer. Autodesk CFD is a program that integrates directly into Autodesk Revit, allowing architects to simply pull their Building Information Models (BIM) straight into the program, to analyze three-dimensional flow.

USING CFD TO MODEL A WINDOW ASSEMBLY IN WINDY CONDITIONS

When the U-value of a window system is tested, the performance test is typically done in still air conditions. However, it is important to understand how wind affects windows. Using Autodesk CFD, a window system was modeled under different velocities of wind, to measure the effect on the assembly.

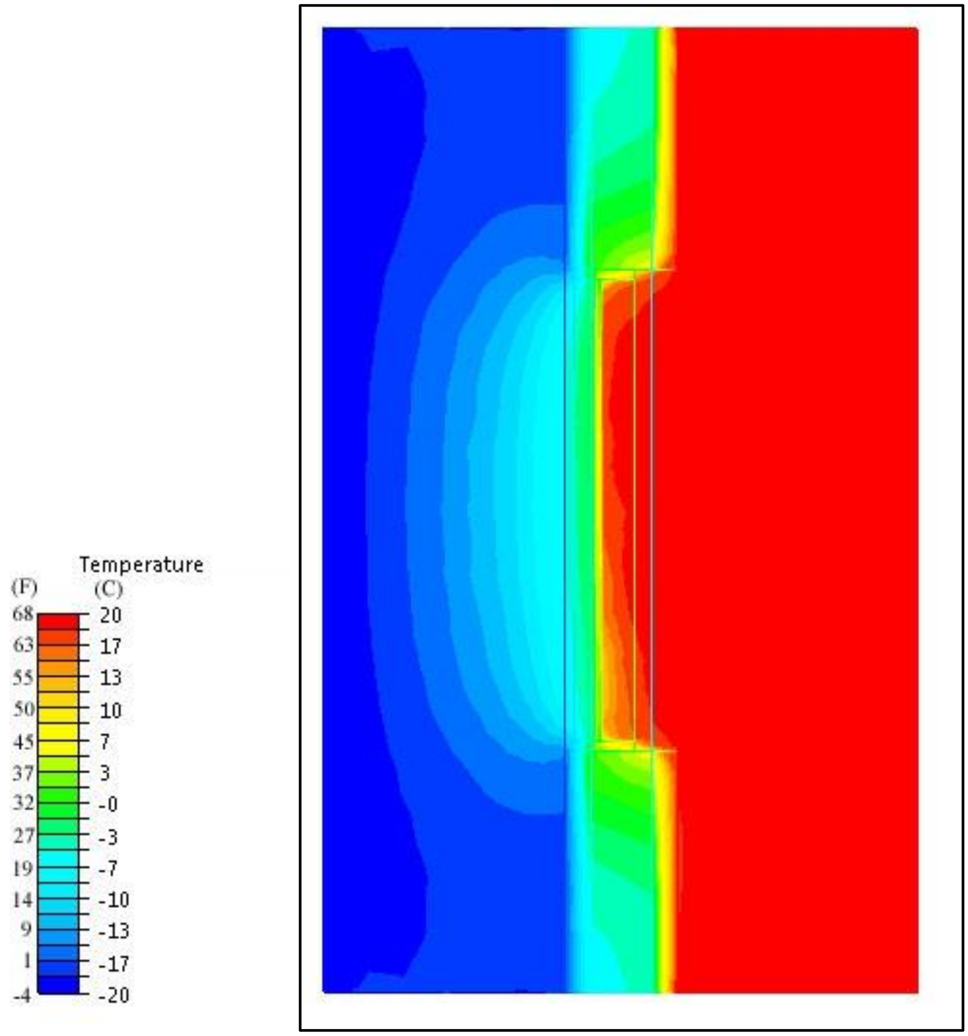

Figure 13 - A CFD Model of a window system in calm conditions

Figure 13 shows a window assembly in a calm winter scenario. The wall modelled is an insulated concrete form system (ICF) and the window modelled is the Inline Fiberglass window system shown in Figure 11. The interior of the assembly is at 20°C (68°F) and is shown in red, and the exterior temperature is -20°C (-4°F). The CFD model shows how a window effectively drops the insulating properties of the ICF wall by reducing the temperature of the wall immediately around the window's connection to the wall. This can be seen as demonstrated by the green areas around the window opening. The cyan "plume" of heated air can be seen on the exterior just outside the window opening. This "plume" is actually a vital portion of the insulating properties of the window system. The heated column of exterior air, although producing a heat loss for the building, increases the temperature of the interior pane of glass to a temperature of around 10°C (50°F), reducing surface heat transfer from the interior. A stable surface film is important to any thermal resistor that has a low resistance value, such as a window system or any assembly with little insulation.[16]

Figure 14 shows the same window system under a 10 m/s (22 mph) wind. The wind is directed perpendicular to the face of the glazing. The interior of the assembly is at 20°C (68°F) and is shown in red. The exterior temperature is -20°C (-4°F). In windy conditions, the protective plume of air on the exterior is eliminated, thus removing a large portion of the insulating factor of the window. The result is a reduction of the interior window temperature to approximately 2°C (36°F). The reduced surface temperature of the window increases the surface heat transfer with the interior causing a downward draft towards the interior of the building, which can be seen in the model.

16 Hutcheon, N. B., and G. O. Handegord. *Building Science for a Cold Climate*. SI metric ed. Ottawa: Institute for Research in Construction, 1995. Web.

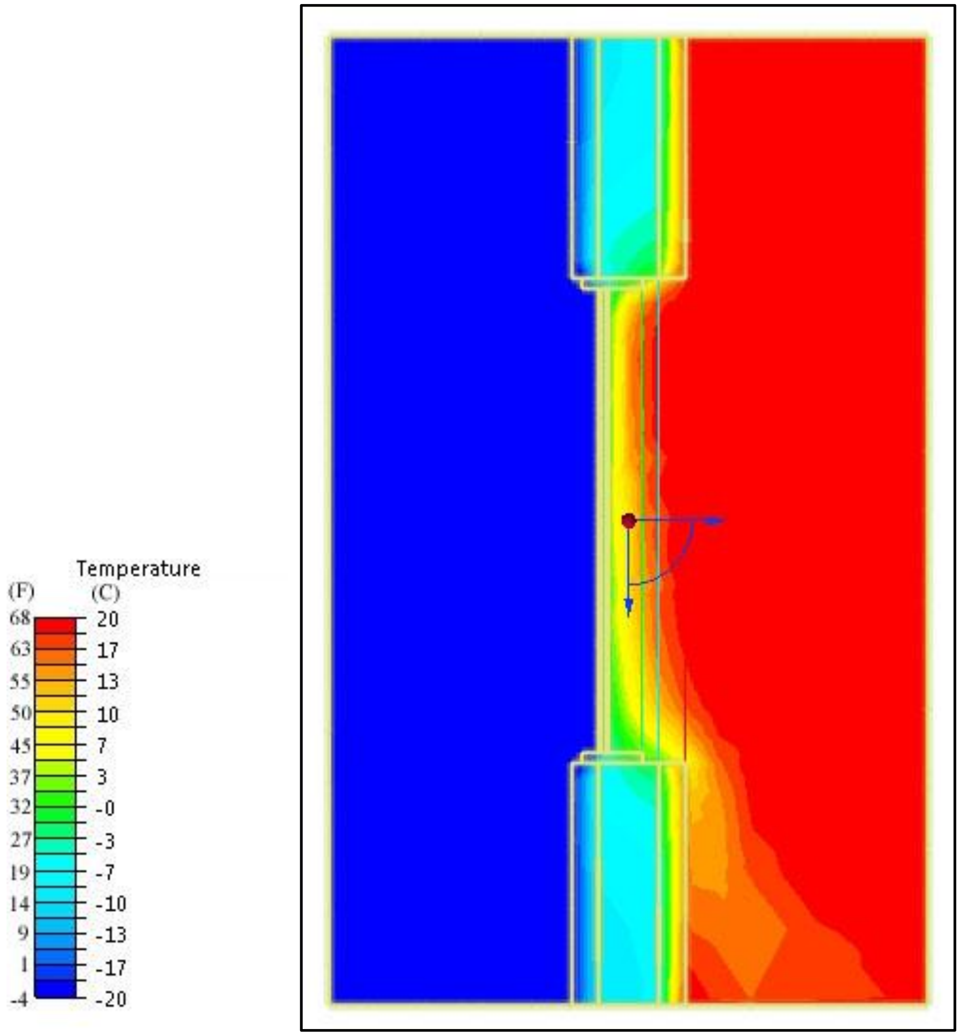

Figure 14 - A CFD Model of a window system in windy conditions

AT WHAT VELOCITY IS THE EXTERIOR SURFACE FILM REDUCED?

Using Autodesk CFD and Microsoft Excel, different velocities of wind were tested to determine its effect on the temperatures of the exterior wall, exterior window, interior wall, and interior window.

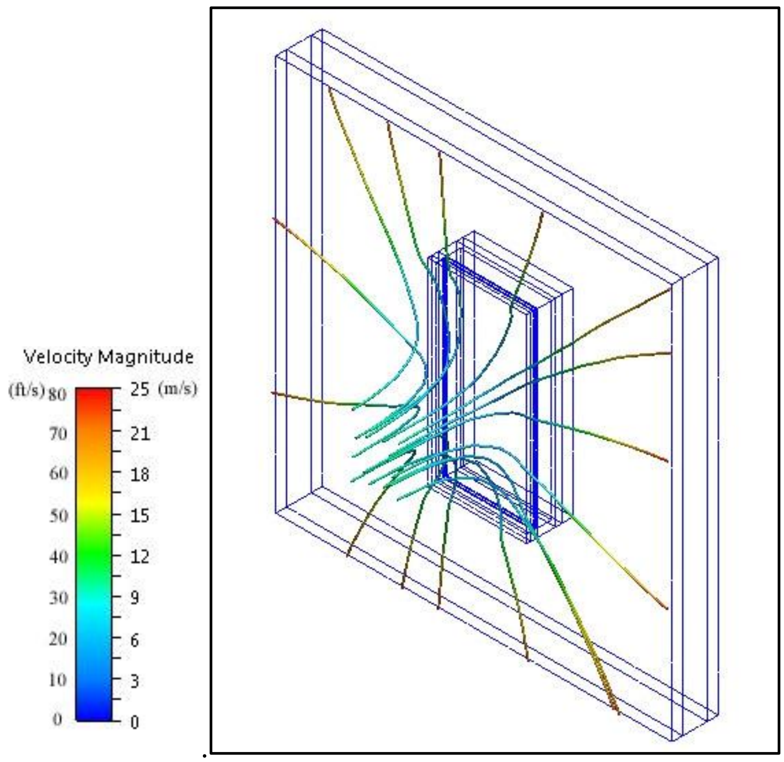

Figure 15 - A CFD Model of different velocities of wind on a wall assembly

As we can see by Figure 16, the temperature of the interior face of glass immediately drops as the exterior wind velocity is increased. The temperature eventually levels off, showing a reverse exponential relationship between wind velocity and temperature. The wall temperature change is not as pronounced, indicating that wind has a very small effect on well insulated walls. However, the pressures associated with higher winds would have an effect if the quality of the construction was not good. Improperly sealed window and wall assemblies would have increased air leakage in high wind situations.

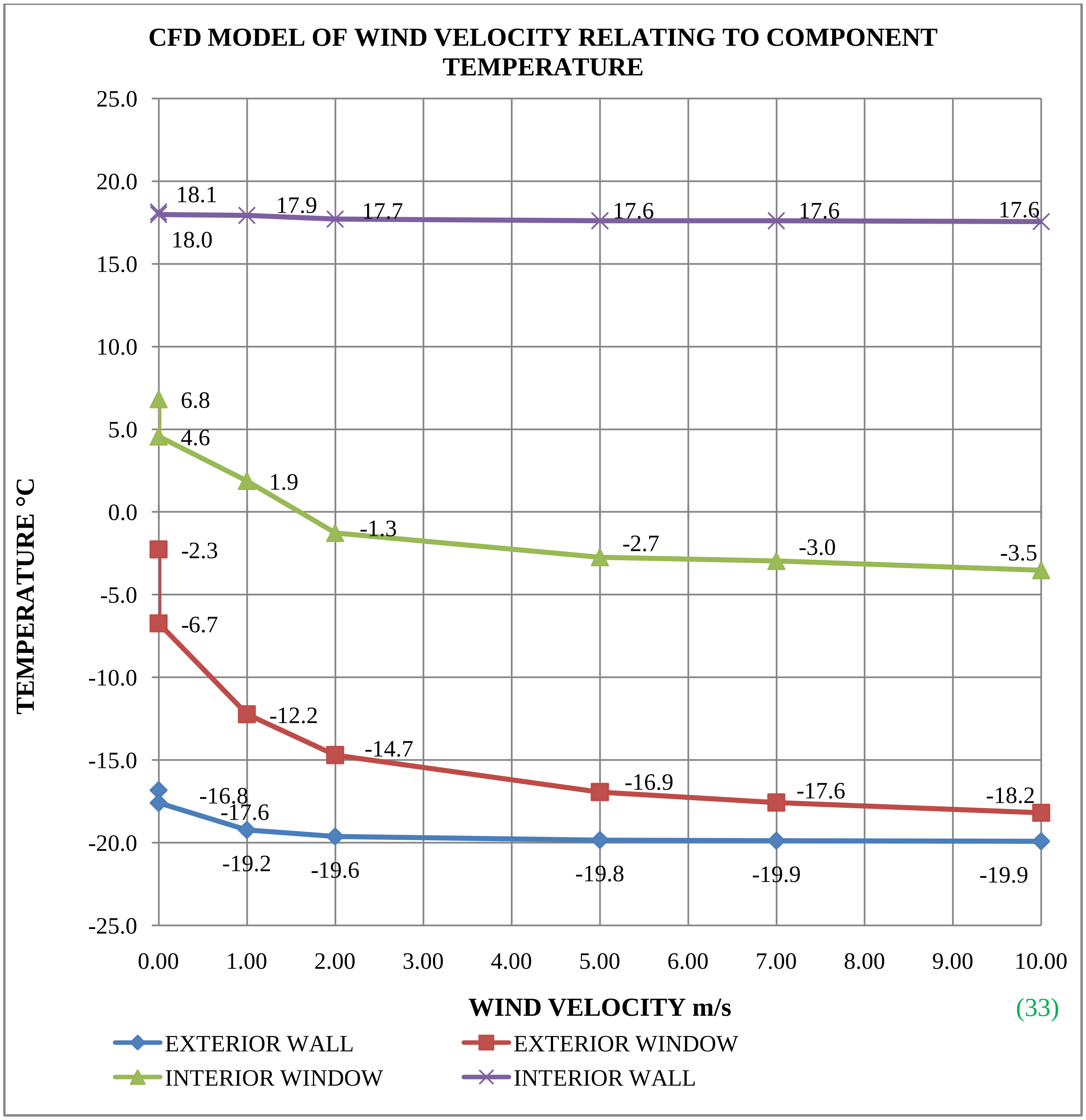

Figure 16 - Metric - Wind velocity related to component temperature - Graph by Mark Driedger

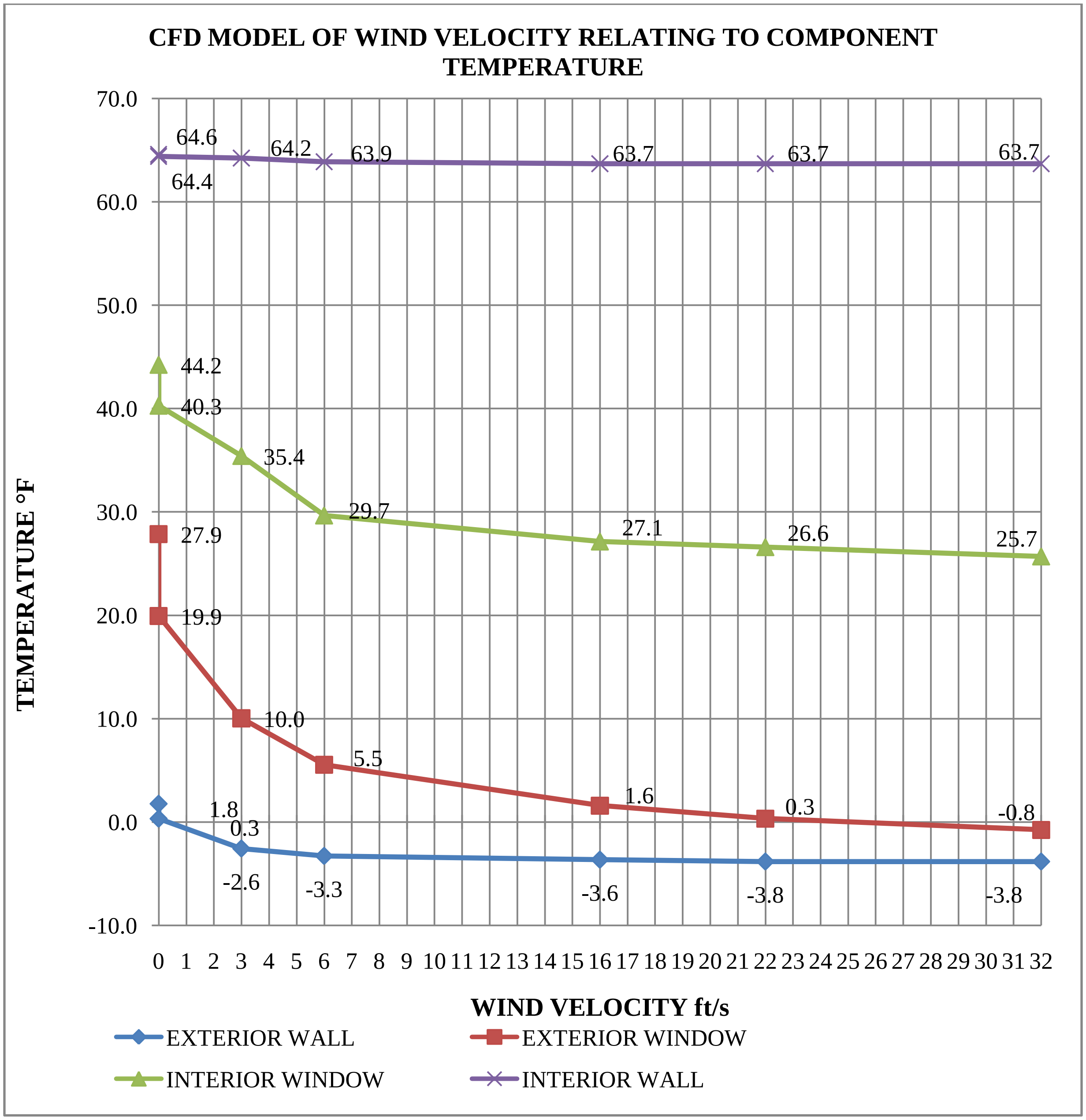

Figure 17 - Imperial - Wind velocity related to component temperature - Graph by Mark Driedger

We can therefore surmise from Figure 16 that the insulating effect of the exterior air film is very important to the performance of a window. It is very rare to have a windless day, so the performance of windows is actually much less than advertised much of the year. (Under a 2 m/s (4.5 mph) breeze on a -20°C (-4°F) day, the interior face of a window will drop to -2.7°C (27.1°F) , as opposed to the +6.8°C (44.2°F) degrees when it is not windy outside.)

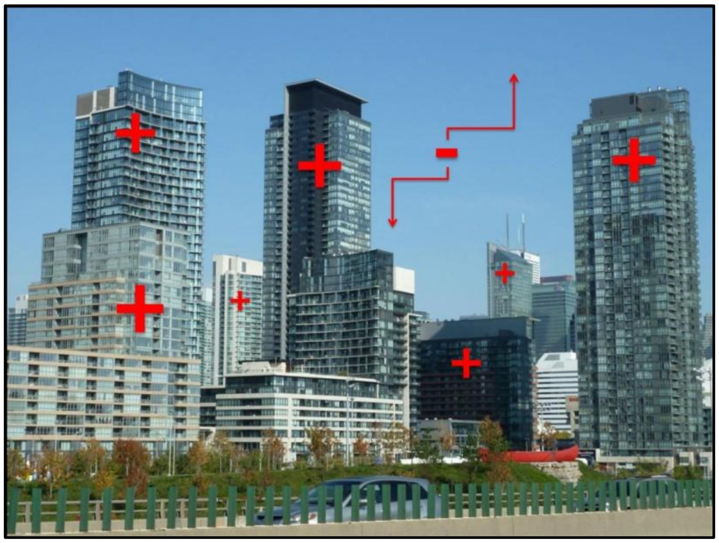

Figure 18 - Downtown Toronto

In a cold climate, the overuse of glazing is a rather short-sighted strategy. Present energy prices may support the practice, however, future energy prices may not. Either the energy performance of glazing needs to improve or less expensive energy supplies must be found for current designs to continue without prohibitive operating expense. Reducing the amount of glazing is one possible solution, but efficient harnessing of the sun to reduce our reliance on fossil fuels may be another strategy that would still allow us to maintain the ratio of windows to wall, we see today on our buildings.

CHAPTER 5 - THE HARNESSING OF SOLAR ENERGY

Solar energy is a product of the collision and fusion of hydrogen particles deep within the sun. The resulting electromagnetic radiation travels at light speed through the inner solar system, continuously spreading out and eventually arriving at the Earth in a wide variety of wavelengths. The entire trip lasts approximately 8 minutes.

As you move away from the sun, the radiant energy per unit area is reduced. At the edge of the earth's atmosphere, the sun's energy equals around 1,361 watts/ m^2. This intensity is defined as the "Solar Constant", though it does vary depending on the 11 year sun cycle and other solar activity.[17] Not all of this energy strikes the Earth, since 35% of it is reflected back into space.[18]

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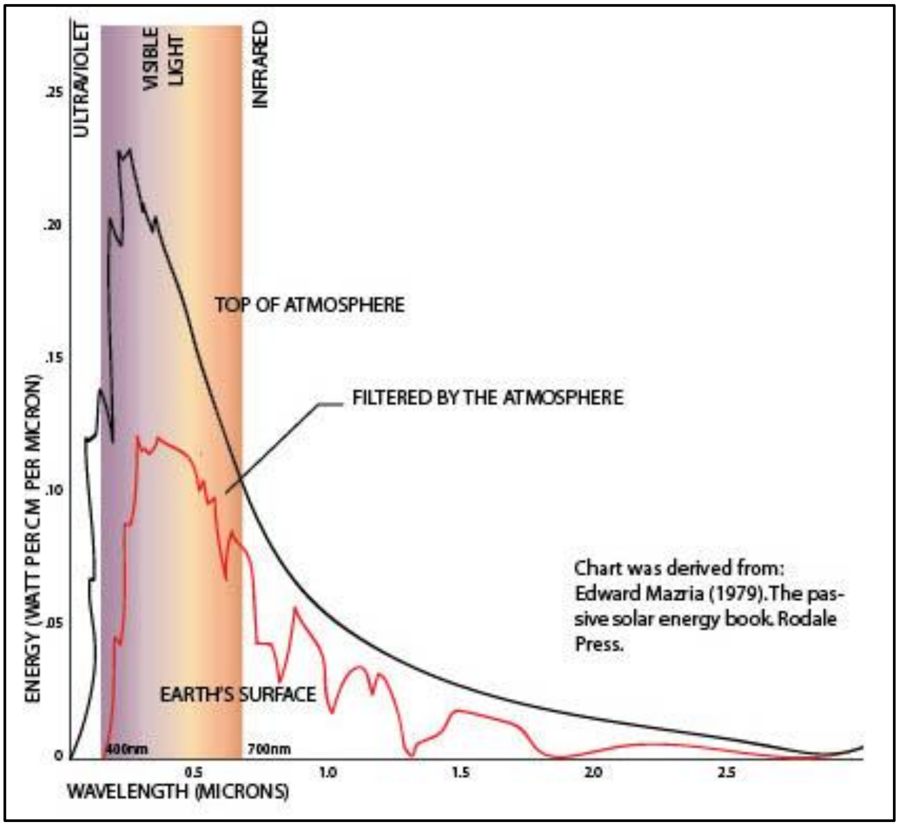
17 Qiang Fu, University of Washington, Seattle, Elsevier Science Ltd. http://curry.eas.gatech.edu/Courses/6140/ency/Chapter3/Ency_Atmos/Radiation_Solar.pdf

18 Mazria, Edward. *The Passive Solar Energy Book.* New York, Rodale Press, 1979



[19]

Figure 19 - Wavelengths of energy arriving on Earth - Graph by Mark Driedger

19 Mazria, Edward. *The Passive Solar Energy Book.* New York, Rodale Press, 1979

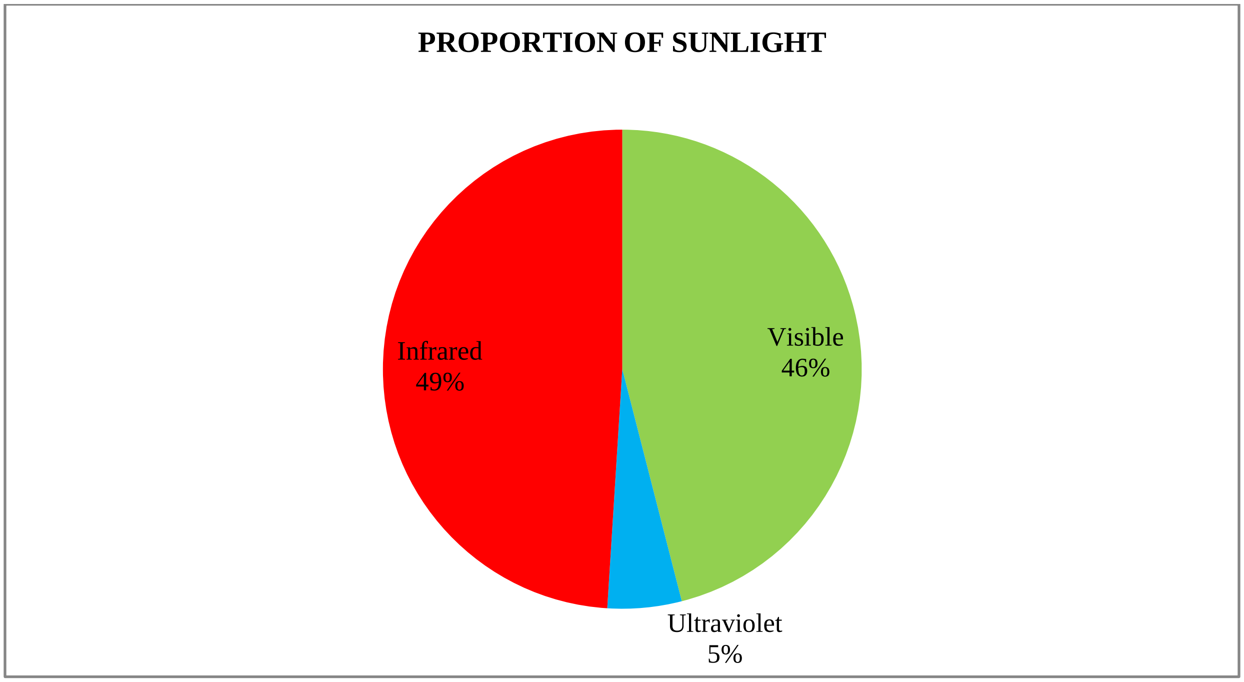


Figure 20 - Proportion of Sunlight[20]- Graph by Mark Driedger

The visible light proportion of the spectrum, is a significant portion of the total radiation reaching the Earth. However, as shown in the above diagram, it does not represent all of the energy. At sea level, with the sun at it's most powerful position in relation to the Earth, there are approximately 445 watts m^2 (41 watts per ft^2) of visible light, 527 watts per m^2 (49 watts per ft^2) of infrared light and 32 watts per m^2 (3 watts per ft^2) of ultraviolet radiation.

Other factors also affect how much solar energy is available at any one time. They are:

20 Mazria, Edward. *The Passive Solar Energy Book.* New York, Rodale Press, 1979

- location on the planet
- time of day
- time of year
- weather

The amount of solar energy that hits the Earth in a particular location, can also vary year to year. The graph below shows the variations in sun intensity at Pearson Airport, in Toronto, Ontario over a 5 year period.

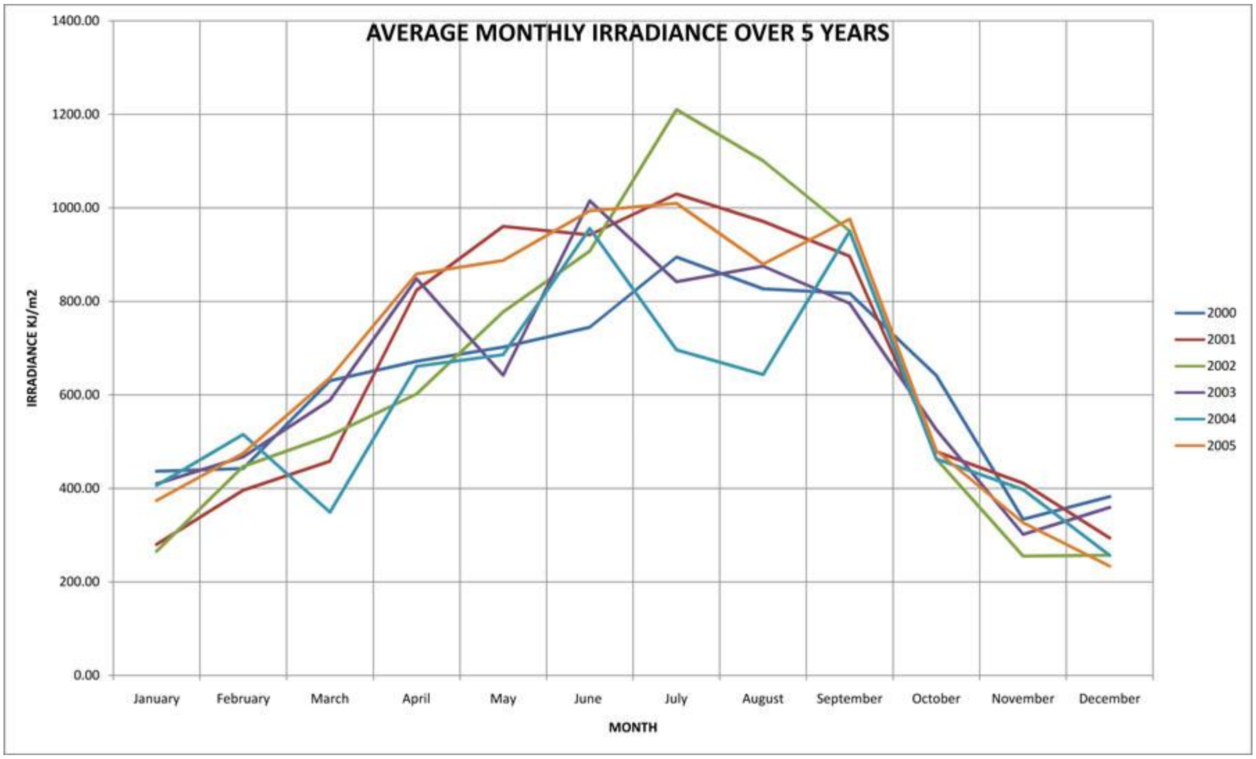


Figure 21 - Monthly Irradiance Variation - Pearson Airport 2000 - 2005 [21]- Graph by Mark Driedger

CONCENTRATING THE SUN'S RAYS

The sun's solar rays, when modified by optics can be concentrated. Concentrations up to a theoretical limit of 47,000 times can be achieved through new technology tracking arrays, and non-

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21 http://climate.weatheroffice.gc.ca/prods_servs/index_e.html

imaging optics.[22] The ultimate concentration of a beam of light is only limited to imperfections in the manufacturing processes and the heat losses of the designs. [23] At maximum concentration the beam of light will reach 5,500 ^{o}C (9,932 ^{o}F), which is the temperature of the surface of the sun.[24]

The amount of energy that is absorbed by the Earth each day, is also a larger number. The energy hitting the Earth in one hour, if captured, could power human civilization for one year.[25] The challenge is storing that energy. Battery technology is not yet advanced to the point where it can be efficiently used to store the quantity of energy available from the sun.[26] An alternate storage method must be found.

22 Laseau, Paul; James Tice. *Frank Lloyd Wright: Between Principles and Form*. John Wiley & Sons, 1991

23 Johansson, Thomas B., and Laurie Burnham. *Renewable Energy: Sources for Fuels and Electricity*. Washington, D.C.: Island Press, 1993. Web.

24 Deutsche Gesellschaft für Sonnenenergie. *Planning and Installing Solar Thermal Systems*. London ; Sterling, VA: James & James/Earthscan, 2005. Web.

25 Horn, Miriam; Fred Krupp. Earth*: The Sequel: The Race to Reinvent Energy and Stop Global Warming*. W. W. Norton, 2009

TRANSFORMING AND TRANSFERING ENERGY

The first law of thermodynamics states that energy cannot be created or destroyed, although it can be transformed from one form to another. When energy is transformed, there are always losses - usually in the form of heat, which is very difficult to capture. Transformation involves waste. Keeping energy in its original state, and thus limiting the losses due to transformation, is one of the best strategies to leverage the laws of thermodynamics in your favour. This strategy is also true when harvesting the sun.

Losses are also incurred when transferring energy from the transformation or collection point to the end user. Up to 10% of the power produced is lost through the transmission process.[27] Transferring energy from one point to another, must be kept at a minimum if a solar project is to be feasible.

PHOTOSYNTHESIS

The evolution of the leaf along with the process of photosynthesis brought about the concept of gathering sunlight on a mass scale. The leaf, in a sense, is a solar concentrator. By increasing the number of leaves, the plant can harness more energy from the sun.

All green plants use the process of photosynthesis to store chemical energy produced by exposure to the sun and to the atmosphere. The efficiency of the photosynthetic process has typically been calculated on the photosynthetically active region of the solar spectrum, which is 400 - 700 nm.[28] The

27 Rom, William N. *Environmental Policy and Public Health*. 1st ed. 14 Vol. San Francisco: Jossey-Bass, 2012. Web.

28 Blankenship, Robert E. *Molecular Mechanisms of Photosynthesis*, John Wiley & Sons, 2008

radiation outside of this spectrum is not included in efficiency calculations. In ideal conditions, taking the entire active solar spectrum into account, the maximum efficiency of green plant photosynthesis is 13%.[29] If only the photosynthetic spectrum is analyzed, the photosynthetic reaction is only as high as 5% in perfect conditions.[30] The leaf serves as an example of a system that is highly successful using a rather inefficient transformation process by compensating by having a very large area where energy can be collected. We too can benefit by mimicking that strategy.

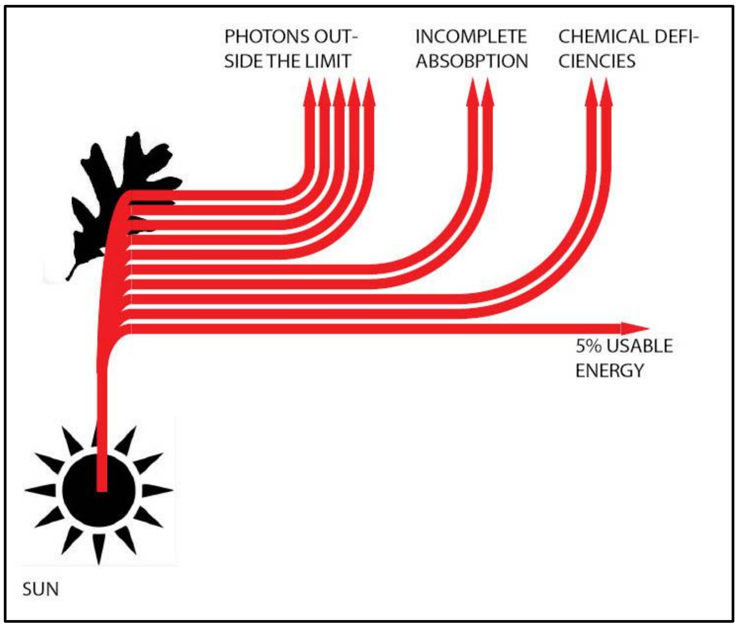

Figure 22 - Photosynthesis is less than 5% efficient [31]- Graphic by Mark Driedger

29 Bolton, James R. and David O. Hall. *The Maximum Efficiency of Photosynthesis,* Pergamon Press plc, 1991

30 Hall, David O.; Krishna Rao. *Photosynthesis.* Cambridge University Press, 1999

31 Graber, Peter; Giulio Milazzo, *Bioenergetics*, Springer, Basel, 1997.

PHOTOVOLTAICS

Solar cells have been steadily increasing in efficiency over the past 30 years. Experimental cells have been developed by Semprius that convert approximately 30% of the incoming energy into electricity. The average solar cell converts around 15% of the energy to electricity.[32] Photovoltaic technologies typically are subject to mechanical losses in the performance of the cell. Losses can be attributed to not transforming certain wavelengths of light, and instead reflecting them or absorbing them as heat. Heat is also a significant factor in the performance of the cell.. The lower the temperature, typically, the better performing the system is. Electrical resistance in the array is another area of loss. It should be noted that photovoltaic cells have an advantage of being able to produce energy even during cloudy days, by accessing diffuse light.

32 http://www.semprius.com/products/performance.html

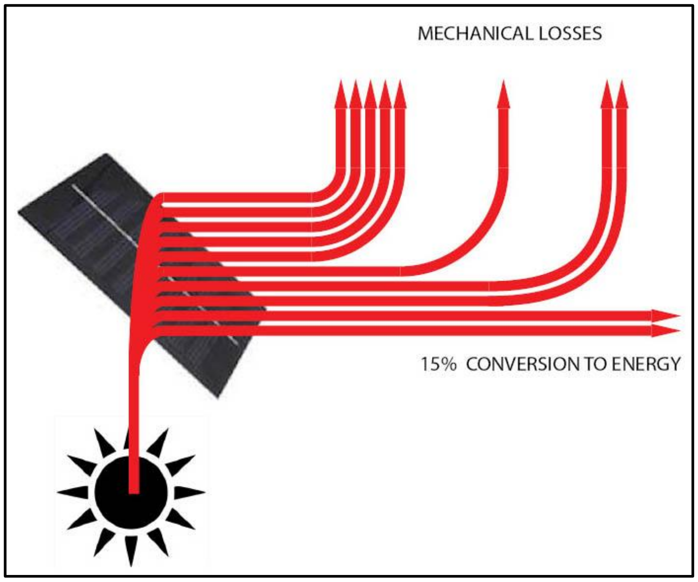

Figure 23 - Photovoltaic Cells [33]- Graphic by Mark Driedger

SOLAR THERMAL

Solar thermal plants also undergo the same mechanical losses. Solar thermal plants use reflectors to concentrate the sun's energy to heat an effluent that will turn a generator with the heat produced. These systems can only work during the day, and in direct sunlight, unless a heat storage medium is applied. In that case, the systems can continue to work a few hours after sunset.[34] At lower temperatures,

33 http://www.semprius.com/products/performance.html

34 Solar Thermal Power Plants, prepared for the EUREC-Agency - http://www.solarpaces.org/Library/docs/EUREC-Position_Paper_STPP.pdf

the systems can achieve efficiencies up to 40%. Using multistage heaters, high temperatures, and liquid salt effluent the efficiencies can push 50%.

In cloudy conditions, heat storage can be used to extend the energy capacity of the system. In the future, this may include graphite because of its compatibility with salt solutions.[35]

There are several designs that are presently being used:

- Parabolic Trough Designs - Trough systems use linear parabolic mirrors to concentrate uniformly on a single plane. The effluent used is piped centrally down the reflector unit, gradually heating it as it continues down the line. The average annual efficiency is calculated at 14%, with a peak efficiency of 21.5%.
- Central Receiver Systems - These systems use heliostats to track the sun by two axes following the sun throughout the day and the year. This is the most efficient way to concentrate the sun's rays and creates a very high temperature system. Because of the high temperatures, there are a variety of effluents that can be used to turn a generator.
- Dish Systems and Stirling Engines - Parabolic dish systems use reflectors to focus solar rays on a receiver. The system itself is also mounted on two axes controllers in order for the sun to be tracked year round. The receiver is based on a Stirling engine generator unit in which water is heated to steam to turn a generator.

35 High-Temperature Liquid Fluoride-Salt Closed-Brayton-Cylce Solar Power Towers - http://www.ornl.gov/sci/scale/pubs/SOL-05-1048_1.pdf

As we can see from Figure 24, the mechanical losses on a solar thermal application are relatively low compared to other energy systems. Looking further into the equation, the mechanical losses are a result of the transfer of the energy into electricity.

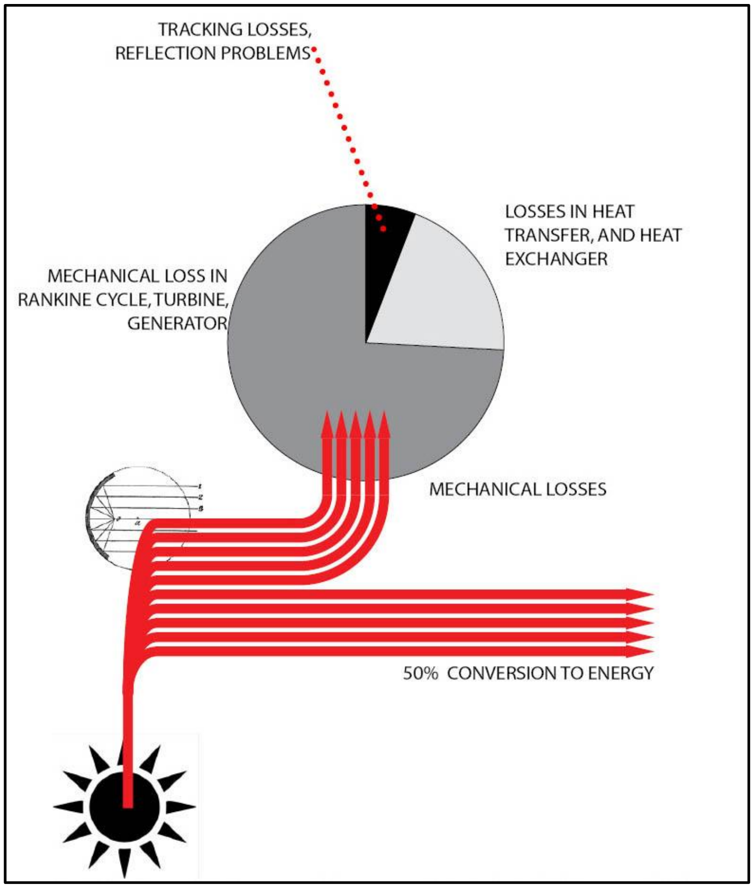

Figure 24 - Solar Thermal Plants [36]- Graphic by Mark Driedger

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36 Green Rhino Energy - http://www.greenrhinoenergy.com/solar/technologies/cst_energy_yield.php

OTHER WAYS TO CAPTURE SOLAR ENERGY

Theoretically, the most efficient way to harvest energy from the sun is through the construction of a black body. A true black body is an object that absorbs the entire incident radiation landing upon it. For the purposes of this study, we will refer to the constructed absorber as an "absorber", acknowledging that it is not a true black body. Light enters the absorber through a very small hole. The light strikes the far end of the enclosure where it is partially absorbed by a perfectly blackened panel. The reflected beam continues until it hits another portion of the enclosure, where it again is absorbed. This continues until all of the radiation is absorbed by the enclosure. Because the opening is very small, exiting rays are limited. The enclosure itself is super insulated, limiting energy loss.[37] Because humans are limited at making the entrance hole very small, a perfected blackbody has never been created by man.

Simple materials can also be used to capture the sun's rays. Graphite has a very high emissivity of 0.95 and is a good example of a material that approaches being a black body. Carbon black paint is also a good example as it has an albedo near 0. Both materials absorb most of the light hitting it and heat up quickly as a result. Flat black paint has an absorptivity of 0.96 and an emissivity of 0.87. The lower the emissivity, the better the material will be of containing the energy.[38] Selective surfaces typically used

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37 Siegel, Robert; John R. Howell. *Thermal Radiation Heat Transfer.* Taylor & Francis, 2002

38 Steven Winter Associates, Inc. *The Passive Solar Design and Construction Handbook*. John Wiley & Sons. 1997

in solar thermal applications are designed to absorb high amounts of energy from incoming rays, but also have a low emissivity values, reducing the amount of energy that is lost through radiation.

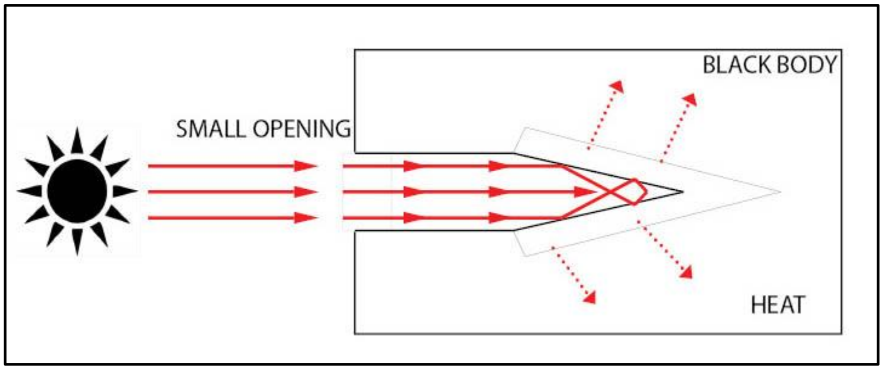

Figure 25 - The Absorber Set-up

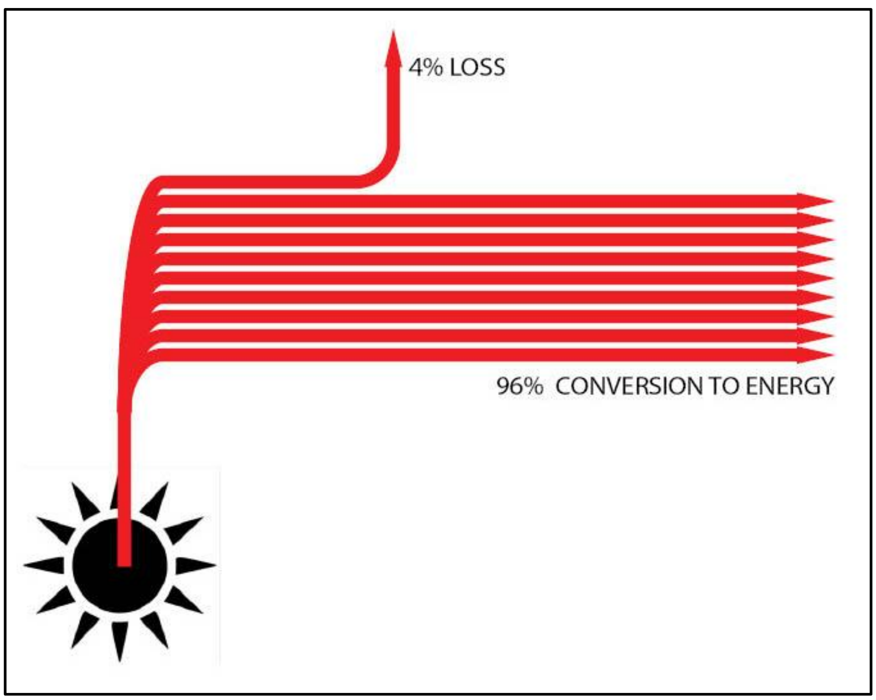

Figure 26 - Flat Black Latex Paint - Graphic by Mark Driedger

CHAPTER 6 - PASSIVE SOLAR DESIGN

Passive solar homes use glazing and thermal mass to absorb the sun's rays to assist with space heating. In the Northern hemispheres, the glazing is placed on the South facade to take advantage of the winter sun. Overhangs typically block the summer sun, and eliminate any overheating effects of the sun. The thermal mass absorbs the sun, and radiates the energy back out when the ambient temperature cools.

SIMPLIFIED PASSIVE SOLAR ENERGY EQUATION

In cold climates, passive solar will not work well, unless properly designed. Using the sample window from Inline Fiberglass shown in Figure 11, we can see that the 180-arg-CI-arg-180-se window has a U-Factor Total Window value of 0.99 W/m^2K (0.17 Btu/hr-sq ft-°F). This indicates that for a $1m^2$ ($10.76\ ft^2$) window system, for each degree difference between inside and outside, the system loses 0.99 W. On a cold January day at Pearson airport, in Toronto the temperature difference between the outside and the inside could be 40°C (104°F) . This would imply that the window would lose 40W a second on a calm winter day.

To calculate the gains from the sun, we can use weather data from Pearson Airport. Sunlight arrives on the site with varying intensity, slowly building up to noon, and tapering off through the day.

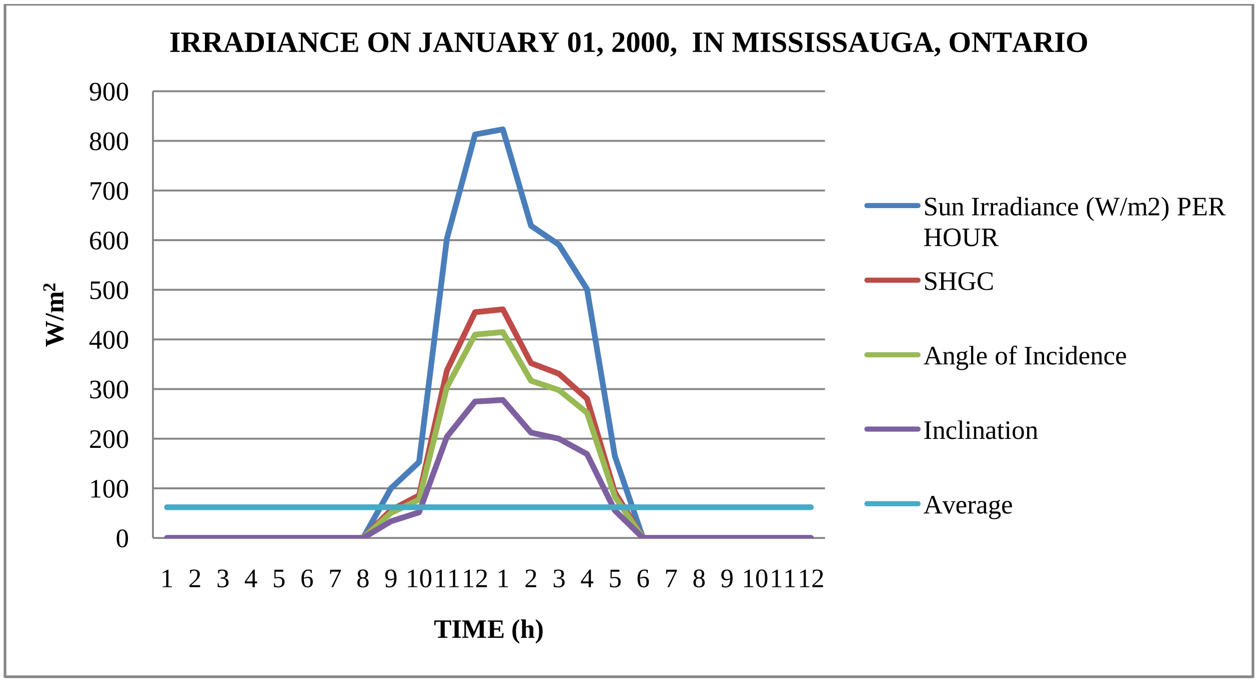

Figure 27 - Metric - Accessible Irradiance for Passive Solar - Graph by Mark Driedger

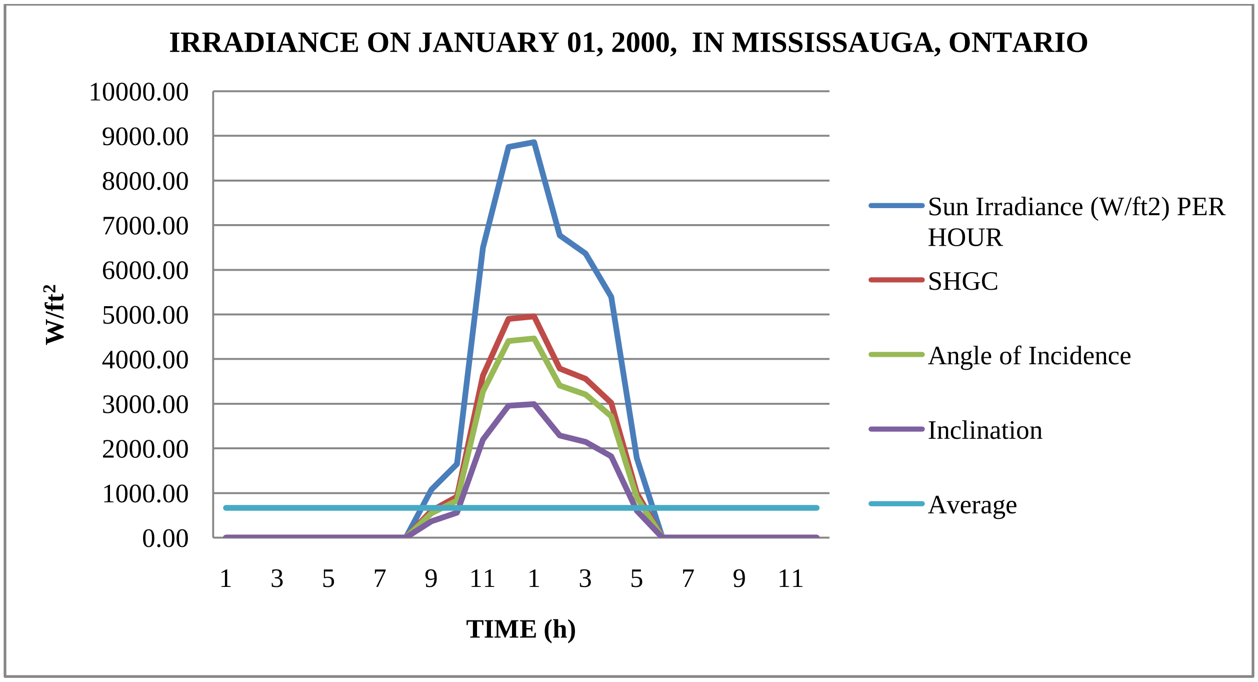

Figure 28 - Imperial - Accessible Irradiance for Passive Solar - Graph by Mark Driedger

The data shows the available Watts per m^2 on January 01, 2000. Because the sunlight has to travel through the window to the interior of the building, the efficiency losses of this process must be included.

- Solar Heat Gain Coefficient (SHGC) will reduce the energy as it passes through the window. In this case, the SHGC is 0.560 or 56% of the light is allowed through.
- Angle of Inclination due to Sun Angle - The sun at Pearson Airport at this time of the year is at 22.74 degrees from the horizon at its highest point at solar noon. Because windows become more reflective as the angle of incidence is increased, 90% is allowed through, at this particular time.

Because the sun angle changes throughout the day, this loss factor would continuously change during the day.

- Angle of Inclination due to window size - Because the effective opening of the window is smaller than 1 m^2 relative to the incoming rays, 67% of the rays are allowed through.

Therefore, if you were to average the wattage/m^2 over the 24 hour interval for a window, you would have 62 Watts/m^2 (6 watts/ft^2) gained on a sunny day with only 40 Watts/m^2 (4 watts per ft^2) lost. This simplified equation shows a 24 Watt/m^2 (2 watts per ft^2) gain every hour, and that gain could be used to assist in the heating of the building. The problem with this calculation is that it assumes a perfect day at noon.. There are many other factors that would affect the performance. Additional losses could be:

- Cloudy days - There are in fact only 2.8 hours of sun, on average, every day, in January, in Toronto.[39] This reality introduces significant error into the above calculation - in fact it eliminates any potential gain from the window.
- Building air leakage - No building is completely air tight. Energy is continually lost through air leakage in the connections of the window to the building structure.
- Conductive losses - No building can completely stop the conductive losses through the envelope insulation.

39 http://www.livingin-canada.com/climate-toronto.html

- A lower performing window - The window used in the above calculations is a relatively high performing window with a U value of 0.99 W/m^2K (0.17 Btu/hr-sq ft-°F). Typical windows can have much higher U values.
- Wind - As stated in previous sections and by ASHRAE, wind will reduce the efficiency of a window.[40]
- Energy Storage - Energy storage must be used to capture and slowly release the sun's energy within the building, in the sunless hours.
- Changing Angle of Incidence - The losses due to reflection would continuously change throughout the day, as the sun changes position.

Although passive solar may be suited for other areas of the planet, there just isn't enough sunlight in a cold climate such as Toronto to make typical passive solar technology worthwhile, simply using windows. Although there are some solar gain, this is lost quickly through the long winter nights. Without night time movable insulation, windows are a net loss for a building. Therefore in a cold climate, adding windows for the sake of increased natural day lighting is not a good strategy if you are trying to save energy.

HOW CAN WE REDUCE LOSSES ASSOCIATED WITH WINDOWS?

Window technology has drastically improved over the last 100 years. Single pane windows have been replaced by multi-plane assemblies with inert gasses, low emissivity coatings, films and thermal

40 ASHRAE Handbook. American Society of Heating, Refrigerating and Air-conditioning Engineers, Incorporated. 2013.

breaks. Although windows have improved, their thermal insulative performance still pales compared to wall assemblies.

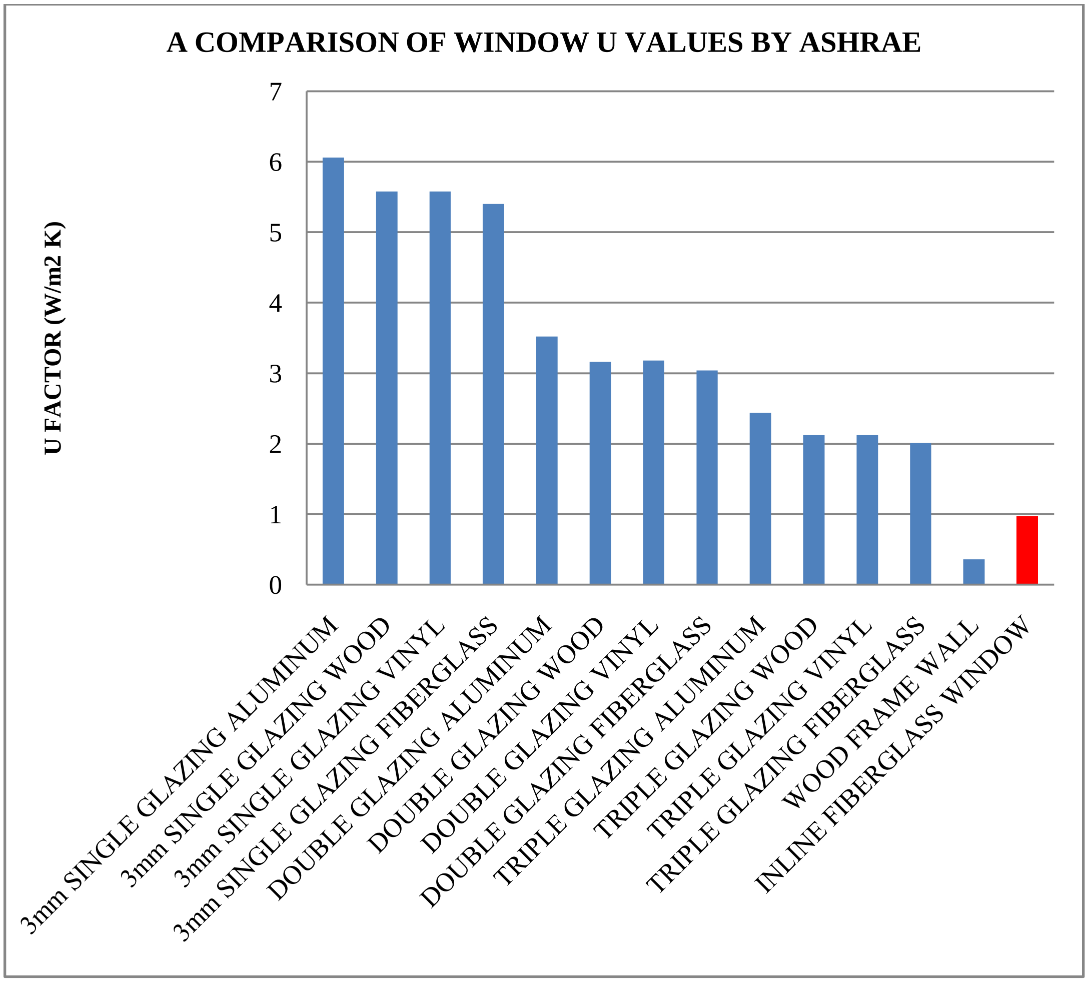

Figure 29 - Metric - A comparison of glazing types [41]- Graph by Mark Driedger

41 ASHRAE Handbook. American Society of Heating, Refrigerating and Air-conditioning Engineers, Incorporated. 2013.

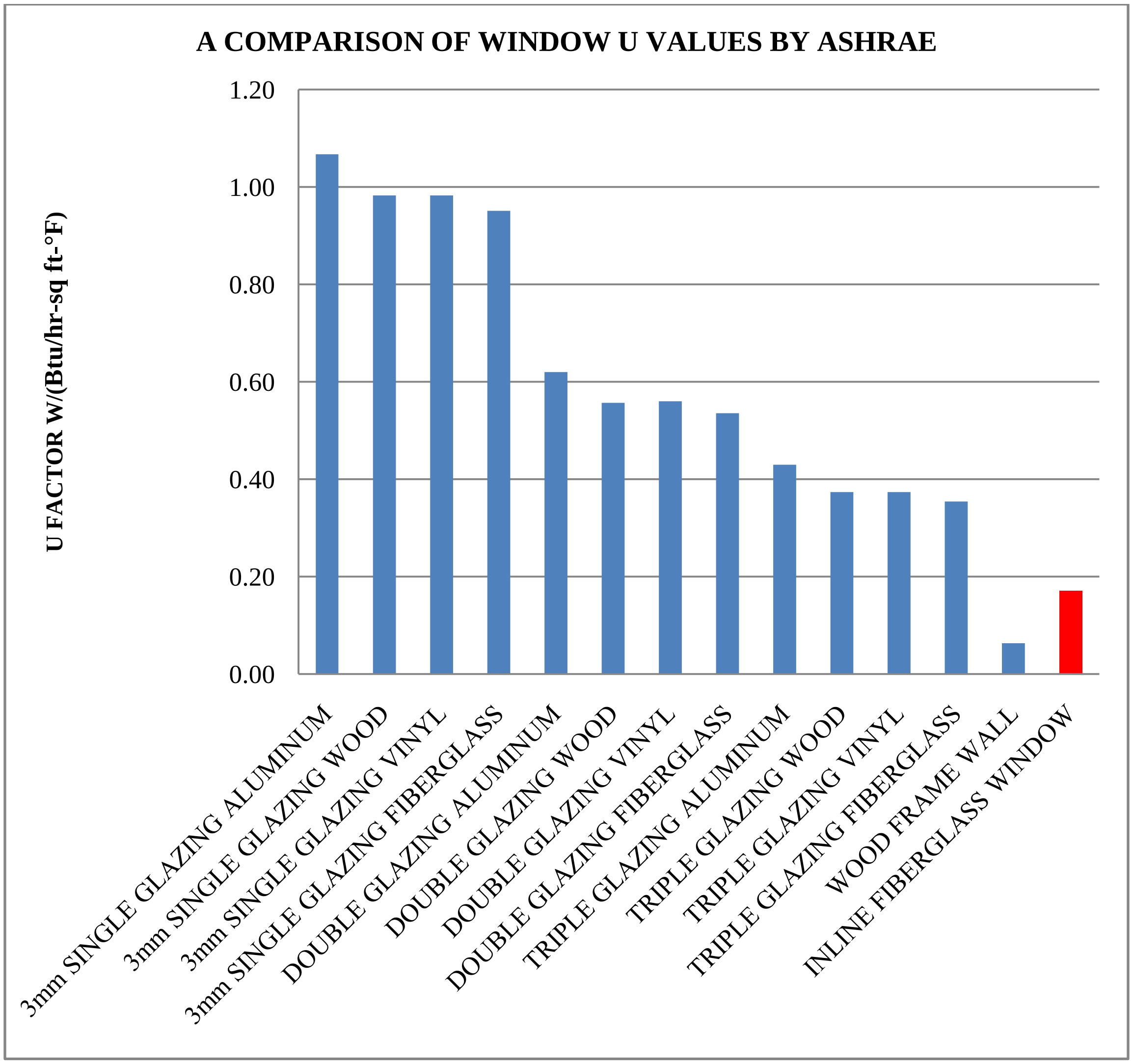

Figure 30 - Imperial - A comparison of glazing types [42]- Graph by Mark Driedger

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42 ASHRAE Handbook. American Society of Heating, Refrigerating and Air-conditioning Engineers, Incorporated. 2013.

Other methods need to be used to reduce the thermal losses of windows, or the window to wall ratio of glazing needs to be reduced significantly.

OTHER METHODS OF REDUCING THERMAL LOSSES IN WINDOWS - STUDY 1

The author constructed an insulated box with glazing on one side and an internal thermal mass was assembled. This structure was then exposed to radiant heat and its internal temperature were monitored.

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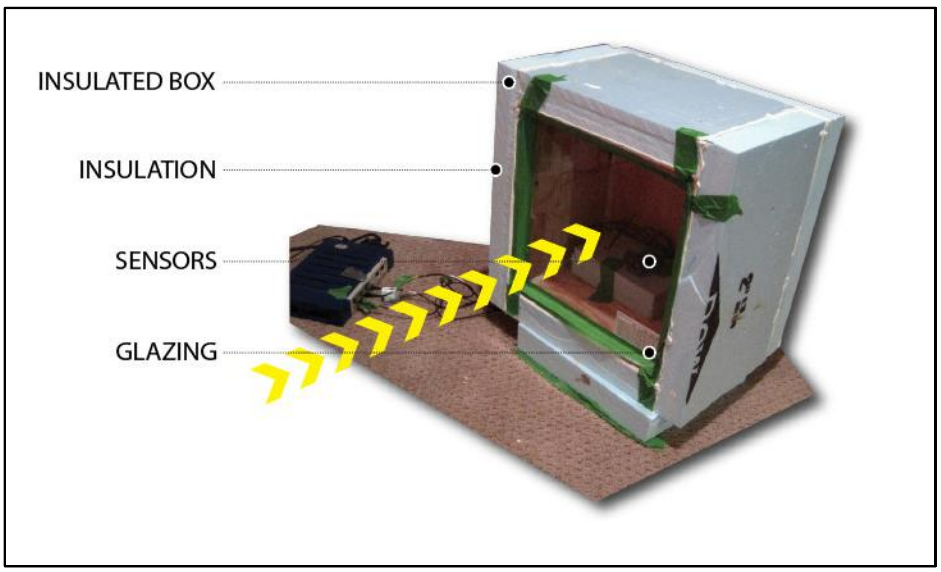

Figure 31 - The hot box test & sensors

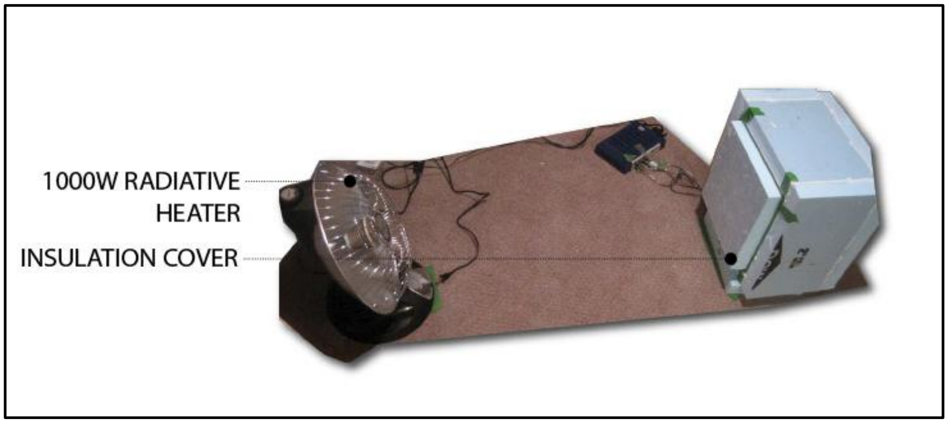

Figure 32 - The insulation over the hot box

Purpose of the Study:

To prove the effect of insulated glazing and thermal mass in a heated enclosure.

Hypothesis:

As glass is a very good conductor, and has a low thermal resistance value, it was hypothesized that insulating the glazing would keep the temperature within the box warmer than letting the glazing remain exposed. The effect of the thermal mass is unknown.

Methods:

The hot box was built and designed around 300mm x 300mm (12"x12") glass samples provided by glazing companies. The design allows for the box to easily interchange glazing samples, in order to easily test a variety of glazing types. The box is made out of 13mm Plywood (1/2") with the joints caulked. The box was covered by 50mm (2") of Dow SM Styrofoam insulation (R=10), again with the joints caulked. One face of the box remained open to accept the glazing types. Caulking was used to reduce infiltration losses around the glazing panels.

The glazing used was Starphire Ultra Clear. The airspace within the box was 305mm x 305mm x 229mm (12"x12"x9") which equals 0.021302725 m^3 or 0.75 ft^3 of air. A solid brick was use as the thermal mass. It was 76mm x 101mm x 203mm. (3"x4"x 8")

Temperature sensor #1 was mounted to the rear of the box, to ensure the exterior temperature remained steady during the test.

Temperature sensor #2 was mounted within the box, to measure the temperature of the atmosphere within the box.

The cabling for the sensors ran out the bottom of the box and was connected to the sensor array and a computer. The hole through which the cabling ran was carefully caulked to minimize infiltration.

Method:

The radiant heater was activated on for exactly 15 minutes. At the 15 minute point, an insulated cover was placed over the glazing for test B,C,D. For test A, the glazing remained exposed.

Test A - Glazing remained exposed

Test B - 50mm (2") insulation (R=10) was placed on the exterior of the glass

Test C - A masonry brick was placed inside the box, to serve as a thermal mass. The brick was acclimatized to the room temperature, prior to the test.

Test D - A masonry brick was placed inside the box, to serve as a thermal mass. The brick was acclimatized to the room temperature, prior to the test. 50mm (2") insulation was placed on the exterior of the glass

Results: Based on the temperature-time graph below, the rate of temperature rise and drop varied in all four tests.

Conclusion:

The internal thermal mass and the placement of an insulating material over the glass after the heat cycle, were both effective in maintaining internal heat. It is interesting to note that the internal mass actually reduced the temperature rise of the interior during the heating cycle but also reduced the rate of heat loss during the cooling phase, thus acting like a capacitor in an electrical circuit. The use of moveable insulation placed over the window was slightly more effective than using a thermal mass for maintaining temperature within the box. Test D, where both movable insulation and thermal mass were used, proved to be most effective in maintaining the interior temperature of the box, after the heating cycle.

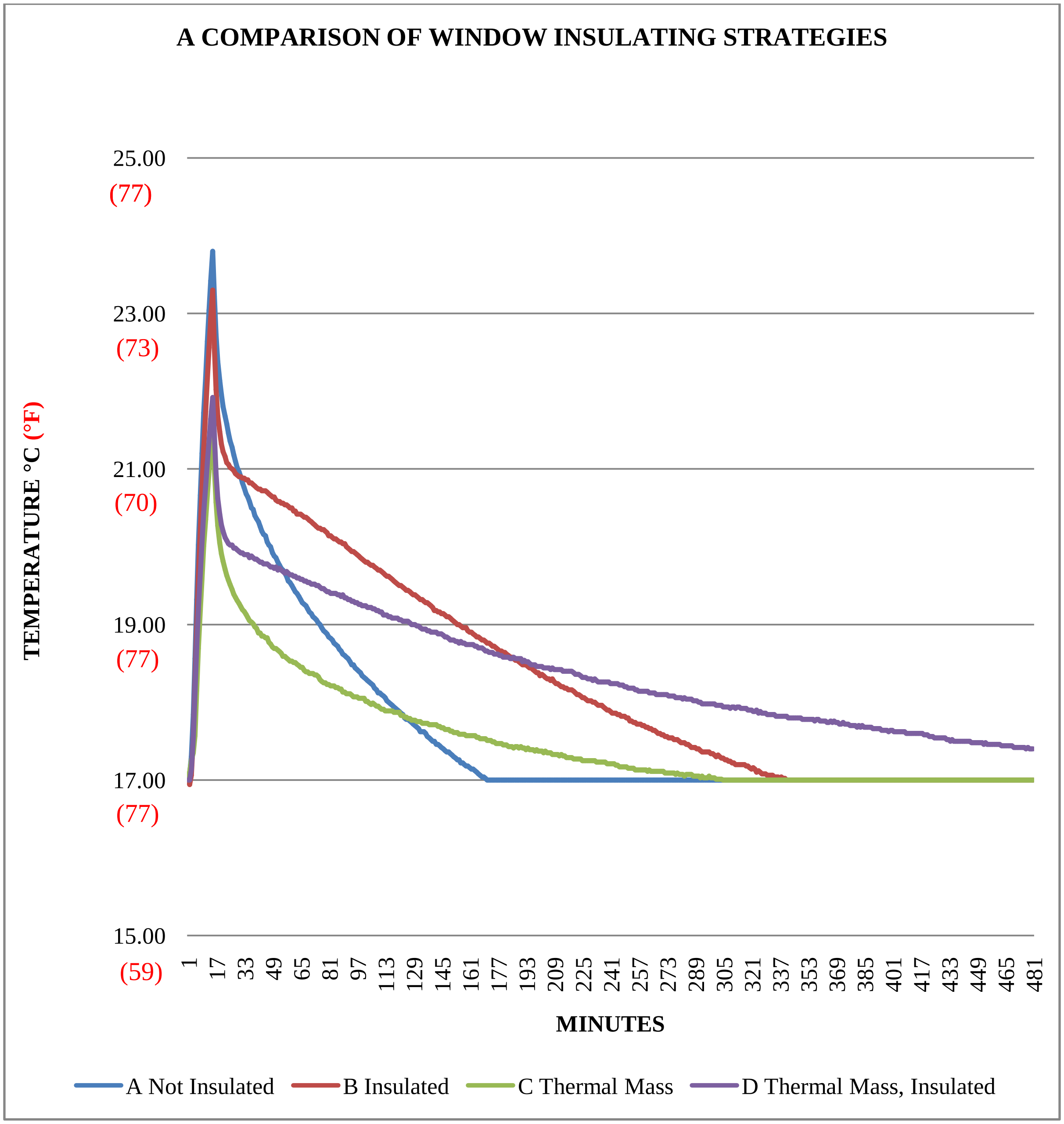

Figure 33 - Graph by Mark Driedger

Conclusion:

Using a combination of thermal mass, and moveable insulation on the windows of a building will offset the thermal losses through glazing.

DIURNAL STORAGE & THERMAL MASS

As shown in the previous sections, it appears that daily storage of energy is limited for a cold climate, e.g. Toronto Ontario. The sun's energy in the winter is not be powerful enough to carry a space through the night, especially when the efficiency losses are added to the equation. Increasing the window size is a possibility, but only if they are insulated during the night time hours. Increased window size will increase energy loss in a cold climate.

Thermal mass, and the seasonal storage of energy, may be the solution to the equation. The summer sun is much more powerful and supplies energy over a longer part of the day, than the winter sun.

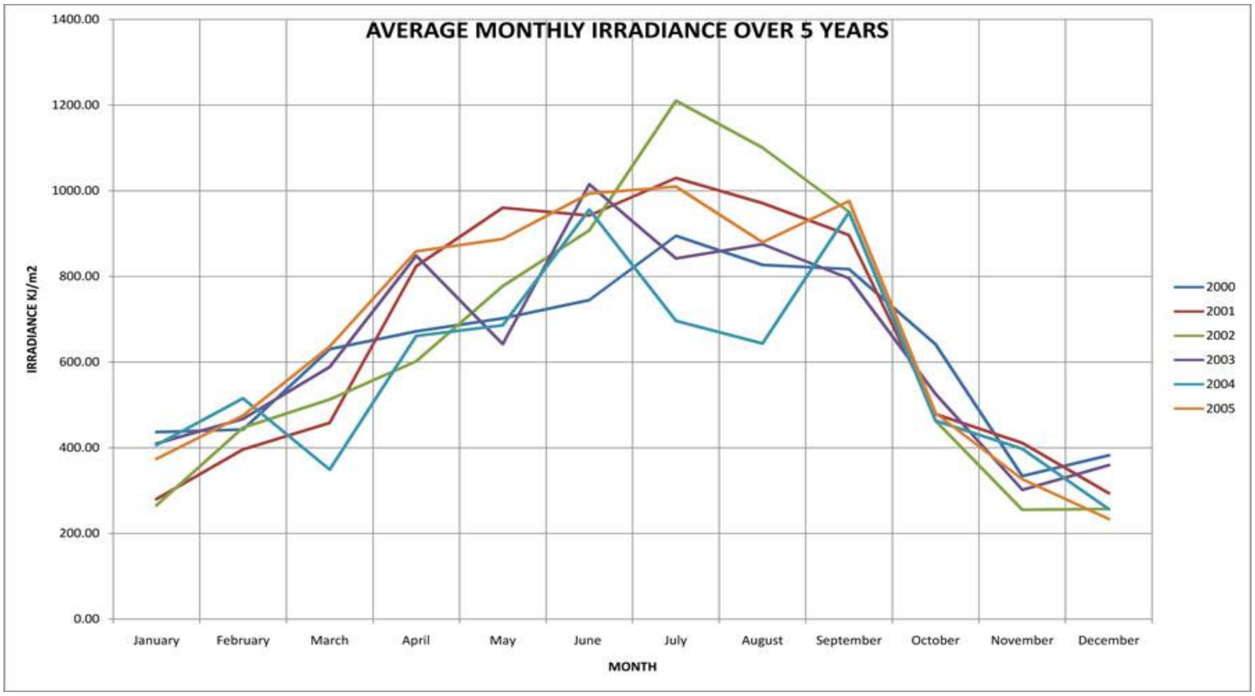

Figure 34 - Comparing the irradiance of the summer sun, with the winter sun from CWEEDS data [43]- Graph by Mark Driedger

As per the Mississauga solar irradiance readings, the sun provides more than twice the maximum irradiance levels in the summer, with significantly fewer overcast days and longer daylight hours. If this energy was stored in a seasonal thermal mass, it may be possible to access the summer heat, during the winter months.

43 http://climate.weatheroffice.gc.ca/prods_servs/index_e.html

THERMAL STORAGE

We can take a cue from nature for storing thermal energy. Large bodies of water typically moderate the temperatures of adjacent areas. Lake water warms the air in the winter, while cooling the air in summer. It should be noted that these large heat sinks (lakes) minimize the actual temperature differential between the heated and the cooled state. The high heat capacity of water makes it an ideal storage medium for energy. Energy storage systems traditionally have used water filled tanks, or natural lakes or aquifers.[44]

Man has used thermal mass for thousands of years, storing sensible heat in mass during times of high energy, only to release it in times of low energy. Adobe construction frequently has been used throughout history as a common method of housing in hot and dry climates. The thick sand and clay walls absorb heat and radiation during the daytime hours and releases it to the interior during the night. Thermal mass is typically a heavy and dense material that has a high specific heat and thus can keep high energy in a relatively small volume.

The specific heat (also called the specific heat capacity) is the amount of heat required to change a unit of mass of substance by one degree in temperature. Different materials have different specific heat values.

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44 Duffie, John A., and William A. Beckman. *Solar Engineering of Thermal Processes*. 4th ed. Hoboken: John Wiley & Sons, Incorporated, 2013. Web.

`	(J/(Kg·°K))	(Btu/lb°F)
Asphalt	920	0.21
Brick	800	0.19
Cement	670	0.16
Glass	750	0.18
Marble	880	0.21
Gypsum	1080	0.25
Sand	800	0.19
Steel	500	0.12
Water	4180	1.0
Perlite	387	0.09
Air	990	0.24

A more effective way to store thermal energy is by latent heat storage through the use of phase change materials (PCM). PCM have the benefits o being able to store greater amounts of energy than sensible heat storage mediums and reduce the range of temperature that a system must operate in. PCMs are most likely the future of energy storage, as they are able to store large amounts of energy within small volumes. To maintain simplicity in the approach of this project, PCM technology will not be the focus.

CHAPTER 7 - ARCHELIO - THE NEXT GENERATION PASSIVE SOLAR SYSTEM

From the research conducted by the author, the following design laws were developed for implementation on the next generation passive solar concept.

Design Law #1 - Reduce Thermal Losses

1.1 Heating - Heating is the largest energy requirement in a cold climate. It is recommended that architects design structures that are inherently easy to heat and require minimal heat input

1.2 Glazing - Glazing is a large source of energy loss for a building. If is recommended that architects reduce the amount of glazing and employ internal thermal mass and movable insulation to moderate inside temperatures. Efforts should be made to reduce heat loss through windows at night. Lighting fixtures are actually much more energy efficient than using large expanses of glass for day lighting.

1.3 Insulation - The lower the U-value of the envelope assemblies, the lower the amount of energy that is lost to the environment. The choice of glazing must be based on U-value and light transmission rather than just aesthetics.

1.4 Wind - Efforts should be made to reduce energy losses associated with infiltration and wind. Prevailing winds must become a factor in design. Wind pressures on the exterior envelope on a building not only reduce the effectiveness of the insulation, but also increase infiltration losses for the building.

1.5 Reduce Transformational Losses - Complexity in any system can breed inefficiency. Mechanical systems that require energy to transform from one form to another will be subject to additional energy losses due to the laws of thermodynamics. An example of this could be the energy lost as heat in the conversion of sunlight to electricity in a photovoltaic panel.

1.6 Reduce Transfer Losses - Complexity in any system can breed inefficiency. Systems that require energy to be transferred from one area to another will be subject to losses due to the transfer. An example of this could be the thermal losses that take place in the transfer of hot water from a hot water heater to a faucet.

Design Law #2 - Harvest Energy From the Sun

2.1 Heliostat - Solar thermal is presently one of the most efficient ways of harvesting energy from the sun.[45] The principles leveraged in solar thermal technology should be incorporated into the design. The heliostat system of reflecting sunlight towards a receiver is a very efficient way of transferring the sun's energy, with few losses. As much of the solar spectrum as possible should be transferred to the receiver.

2.2 Efficient Absorption - Carbon black paint is one of the most efficient ways of absorbing solar energy and approaches the absorption qualities of a black body.[46]

2.3 Span the Seasons With Storage - The power of the sun in the summer must be leveraged for use in the winter. Thermal mass can be utilized to absorb the summer sun as heat, and use this energy in the winter months. Water, because of its high heat capacity, and plentiful nature in the Canadian environment

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45 http://web.ornl.gov/sci/scale/pubs/SOL-05-1048_1.pdf

46 Robert Siegel; John R. Howell. *Thermal Radiation Heat Transfer.* Taylor & Francis, 2002

should be used as the thermal mass. Phase change materials, although possibly more efficient, increase the complexity of the project.

ARCHELIO - THE NEXT GENERATION OF SOLAR DESIGN

A truly sustainable energy-focussed project must take into account all aspects of design law 1 and 2. A designer developing this type of system that stores excess solar radiation from the summer months and then releases it as heat during the colder months, must have an intimate knowledge of the site. An understanding of the micro climate, the heat losses of the building and the limitations of the storage medium all must be completely understood.

A software package and a construction method, "ArcHelio" was designed by the author to meet these requirements. The ArcHelio spreadsheet is discussed in chapter 9. A typical family dwelling was also modelled to assist in the design process.

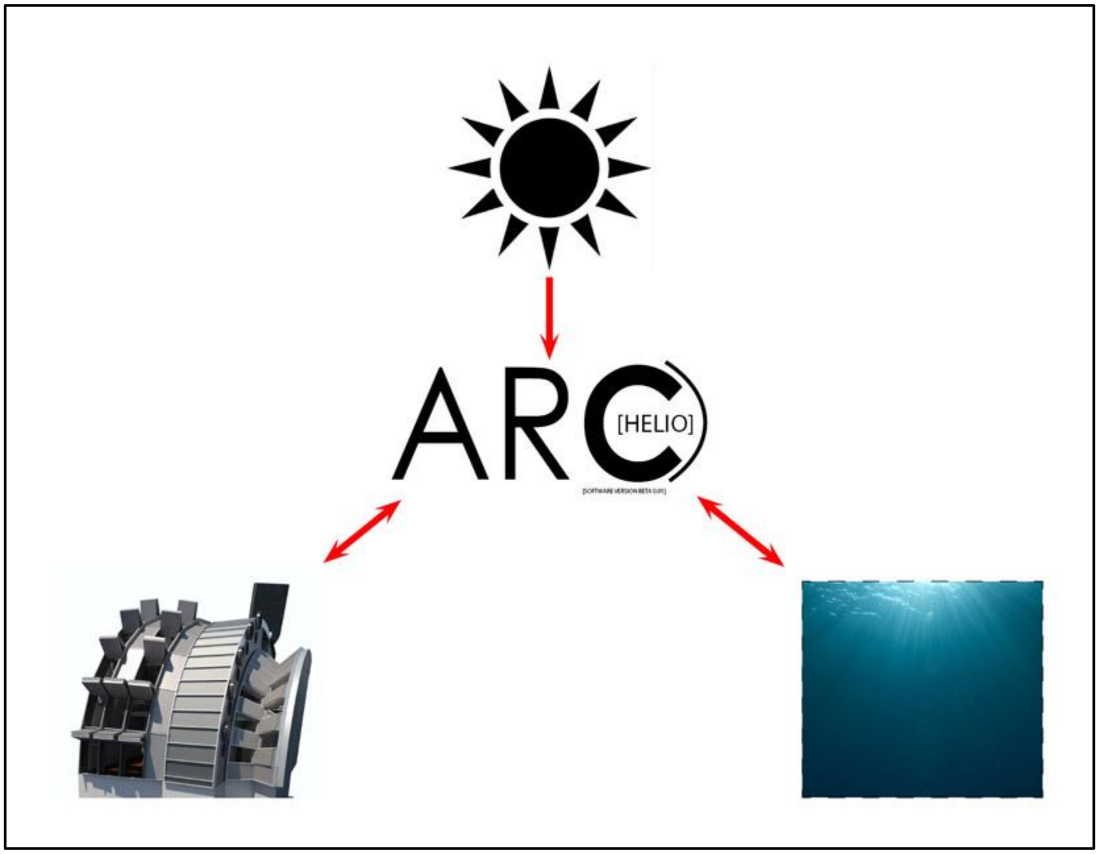

Figure 35 - ArcHelio Software by Mark Driedger

The latest in BIM software, Autodesk Revit© and Autodesk (CFD) Computation Fluid Dynamics© was used to model and calculate the efficiency of the assemblies. Therm©, a software program by Lawrence Berkeley National Laboratory assisted in calculating the U-values for the assemblies.

THE ARCHELIO DESIGN STRATEGY

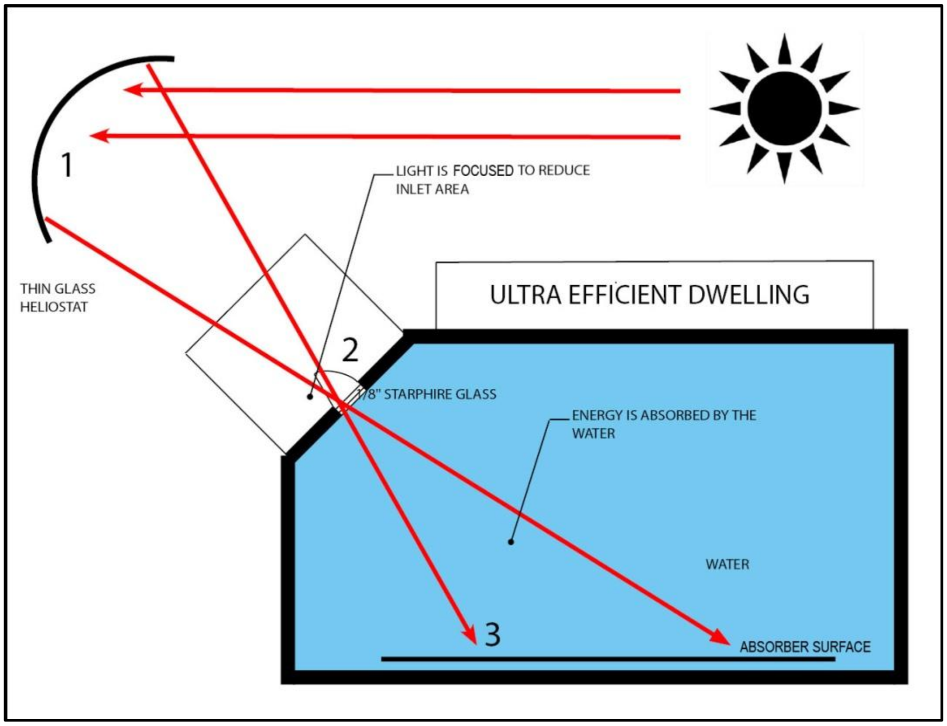

Figure 36 - Energy Capture Strategy

The underlying principle in the ArcHelio design, illustrated above, is simplicity. Energy transformation is kept to a minimum using three main components.

- Heliostat
- Inlet
- Thermal Mass

TRACKING HELIOSTAT DESIGN

A heliostat is normally considered to be a static concave mirror that focuses sunlight (taken from the Greeks). For this design, the heliostat is set up to track the sun as it focuses the sunlight on a target coincident with an inlet to the storage area of the system. Historically, many different types of reflectors have been used as heliostats. It is important that the materials used for the heliostat are able to withstand the exterior environment, while able to provide optimum optical characteristics to limit the loss of energy in certain areas of the spectrum.

Present solar technologies rely on the sunlight to come passively to the building, rather than bringing the sunlight to the building. By remotely locating, tracking and reflecting the sunlight, the sun can be focused as a concentrated beam and sent directly into the storage medium. The amount of sunlight sent to the storage tank is directly related to the orientation, size and number of heliostats. The following describes the research conducted to investigate heliostat performance:

MULTIPLE GLASS HELIOSTATS WITH A RADIOMETRIC LIGHT SENSOR - STUDY 2

Aim of the Study:

Determine if increasing the number of heliostats increases the collection of solar energy and if so, how much?

Hypothesis:

Solar thermal plants typically use multiple heliostats to increase their effectiveness. Increasing the number of mirrors will increase the collection of solar energy.

Materials:

A box (box 1.0) was designed. It was constructed out of plywood with the following dimensions: 200mm x 200mm x 200mm (8"x8"x8"). A 50mm (2") diameter hole was drilled into the box, and temperature sensors were placed within the box.

- Temperature sensor #1 was mounted to the rear of the box.
- Temperature sensor #2 was mounted within the box.
- A radiometric light sensor was mounted within the box, facing the opening.
- Cabling was run out the bottom of the box and to the radiometric light sensor array.
- Ten - 75mm (3") flat glass mirrors were mounted separately on a sheet of plywood on thick movable wire connections so they could be focused independently.
- A 60 watt incandescent light bulb was used as the light source.

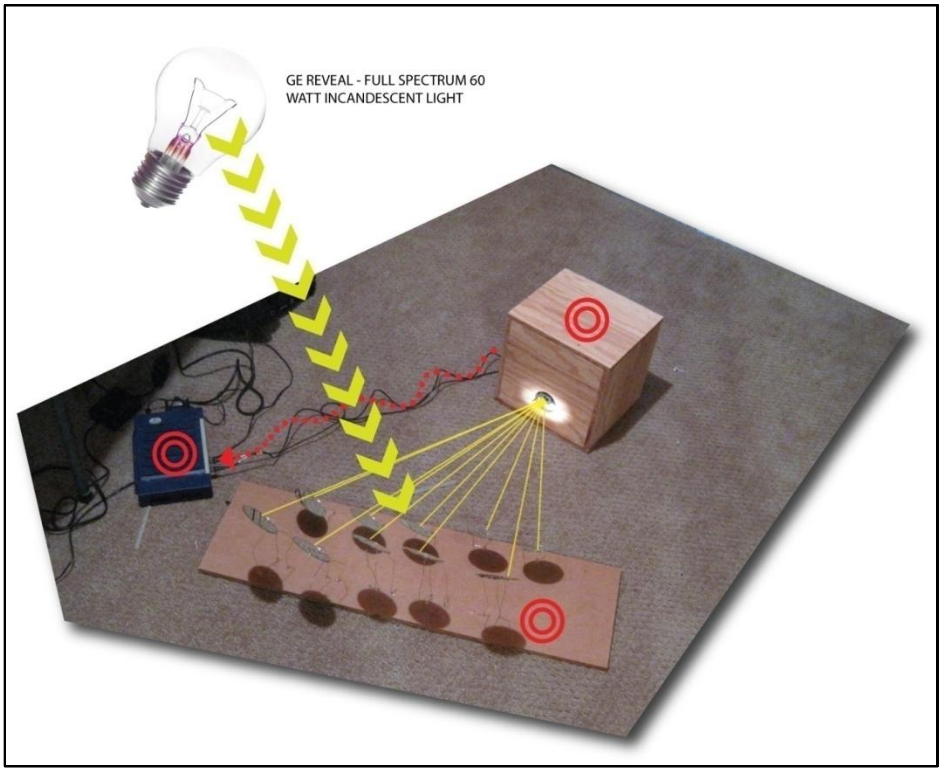

Figure 37 - Multiple Heliostats with a Light Sensor and Receiver Box

Method:

1. The light source and the irradiance sensor were turned on.
2. A single heliostat was positioned to focus the light on the aperture.
3. Additional heliostats were added and positioned to further focus and concentrate the light.

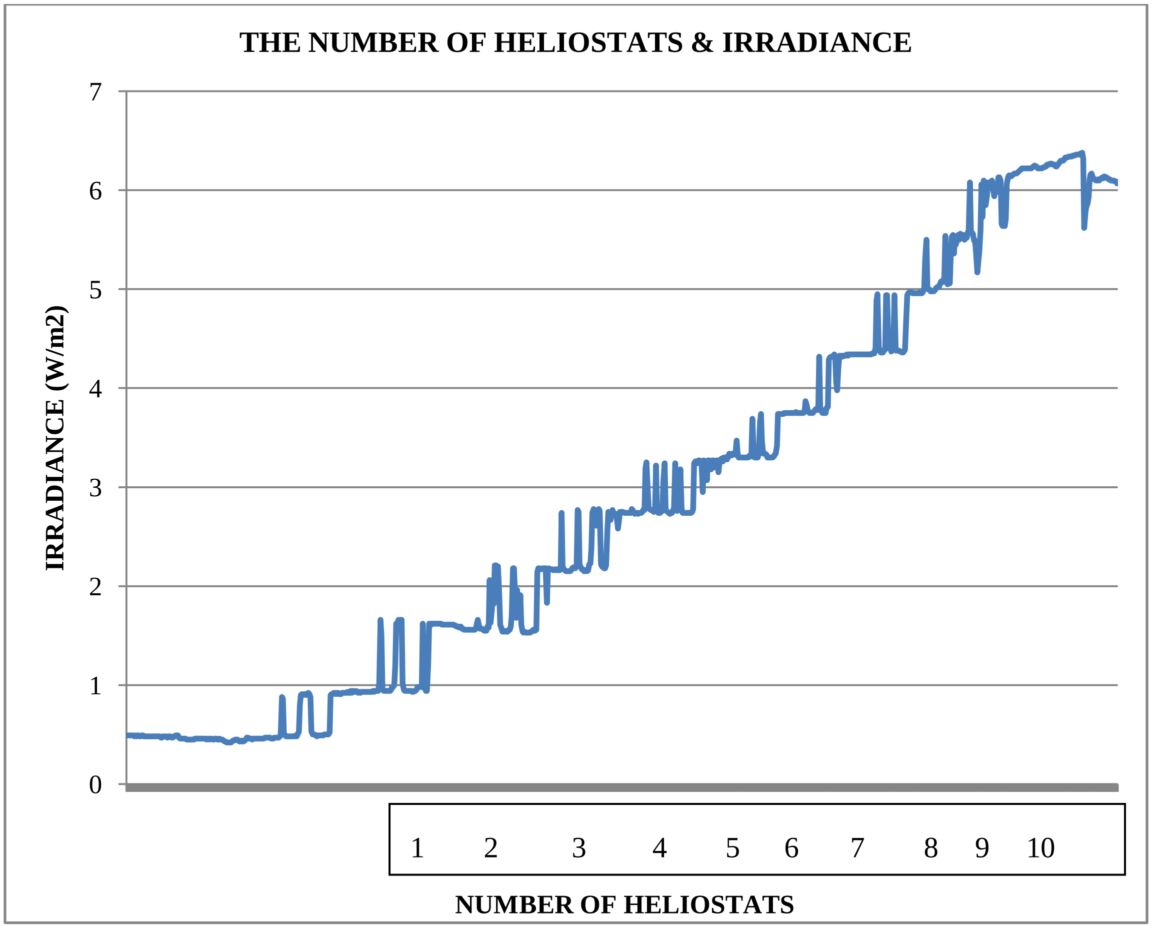

Figure 38 - Plot of Resulting Irradiance Transfer from Multiple Heliostats - Graph by Mark Driedger

Results:

As each heliostat was focused on the opening of the box, the resulting received irradiance went up by roughly 0.5 W/m^2 (0.046 W/ft^2)

Analysis: The relationship between the irradiance and the number of mirrors can be described by the following equation:

$I = I_a + Y N$ I – resulting irradiance, W/m^2

I_a – ambient irradiance in test area, I_o in test area was approximately $1W/m^2$

N – number of mirrors focussed on aperture

Y - irradiance transferred from a single mirror

The inconsistencies in the chart show the adjustments of the mirrors, as they are focused on the light sensor.

Conclusion:

If more energy is required by the heliostat system, either the heliostats can be increased in size, or additional heliostats can be added. Energy transmitted is directly related to the size of the reflective surface.

HISTORICAL USAGE OF HELIOSTATS

In Northern Italy, the small town of Viganella uses mirrors to direct sunlight into the village during the winter months. The town, situated in a deep valley in the Alps, suffered from sun deprivation from November to February of every year. The large computer operated 8m x 5m (26x16ft) mirror turns and tilts to direct sunlight into the town. [47]

47 http://news.bbc.co.uk/2/hi/europe/6189371.stm

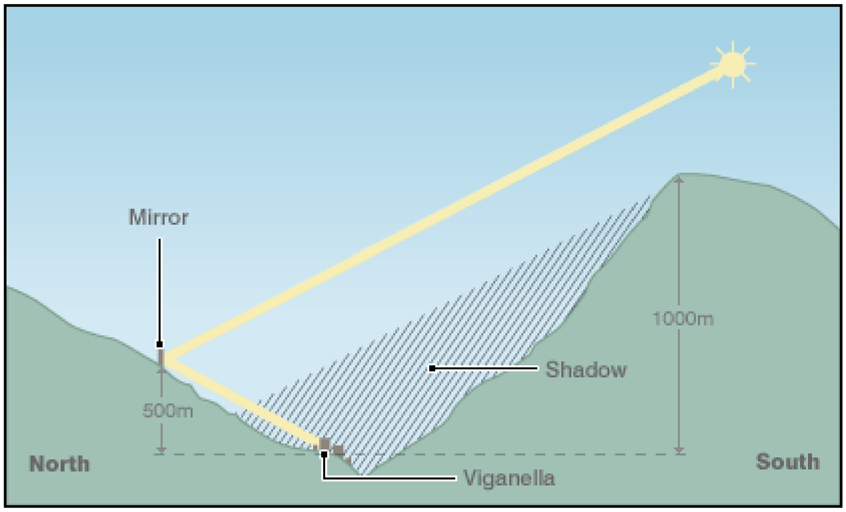

Figure 39 - The Town of Viganella, Italy[48]

NASA is currently funding a study in which a solar array is placed in orbit, to capture a portion of the sun's rays that are currently not striking Earth. The array - a combination of mirrors, will capture the sun's rays and convert them electronically and beam that energy to Earth.[49]

Japanese scientists are working on laser systems that will transmit energy to distant objects. Using microwave energy beams, that puncture the Earth's atmosphere with little efficiency loss, they wish to develop high capacity power stations that are not affected by weather systems. By accessing energy

48 Image from the BBC - http://news.bbc.co.uk/2/hi/europe/6189371.stm

49 http://www.nasa.gov/offices/oct/stp/niac/mankins_sps_alpha.html

that would have been lost to the cosmos, a totally green method of capturing energy could be created, that provides power 24 hours a day. [50] The Japan Space Agency hopes to perfect the technology by 2030.

THE HELIOSTAT IN THE ARC HELIO PROPOSAL

For the purposes of this project a heliostat system was designed and a model set up to efficiently reflect and concentrate sunlight to reduce the necessary collector surface for providing solar heating in a cold climate. Glass absorbs light based on the angle of incidence and its wavelength. Mirrors are no different. If some of the light spectrum is absorbed instead of being reflected, the efficiency of the entire system is reduced. It is important that the heliostats transmit as much of the sun's spectrum as possible.

Losses by the Heliostats can be attributed to the following causes:

- Cosine Losses - Because the angle of the reflectors is not totally perpendicular to the sun's rays, the intensity of the reflected ray is reduced by a larger angle of incidence.
- Shadowing & Blocking - If more than one mirror is part of the system, one mirror could shadow the adjacent mirror, therefore reducing efficiency. This could occur between the sun and the heliostat, or between the heliostat and the receiver.
- Reflective Losses - Because no surface is 100% reflective, there are some absorption losses by the reflectors. Reflection could also occur at the target absorber.

50 http://www.scientificamerican.com/article.cfm?id=farming-solar-energy-in-space

- Attenuation - Depending on the distance to the receiver, and the particulates in the air, energy can be lost because of the distance between the heliostat and the target absorber receiver.
- Spillage - Imperfections in the reflectors, and the imperfect movements of the reflectors can cause some energy loss due to misalignment.

Several different materials have been historically used for heliostats. These materials and the spectrum of light that they reflect are shown below.

1. Thin Glass Reflectors

Thin glass (less than 1mm) mirrors are very fragile and difficult to handle. Hemispherical reflectance is 93% to 96%.

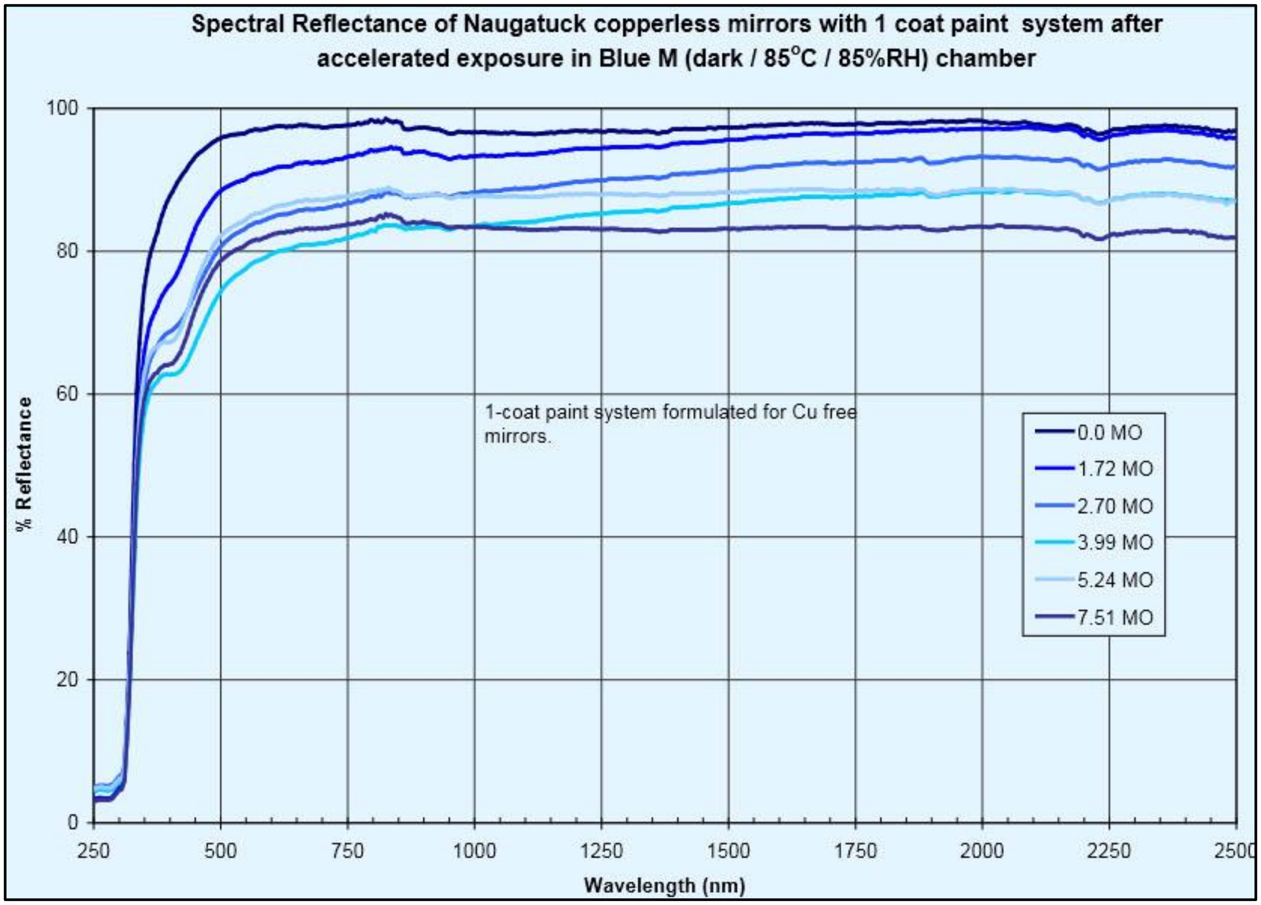

Figure 40 - Thin Glass Heliostats[51]

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51 http://www.nrel.gov/docs/fy08osti/43695.pdf

2. Aluminized Reflectors - Front surface aluminized reflectors are a polished aluminium pan with a protective layer to reduce oxidization. There is a concern these reflectors will degrade because of their exposure to the elements. Hemispherical reflectance is 90%.

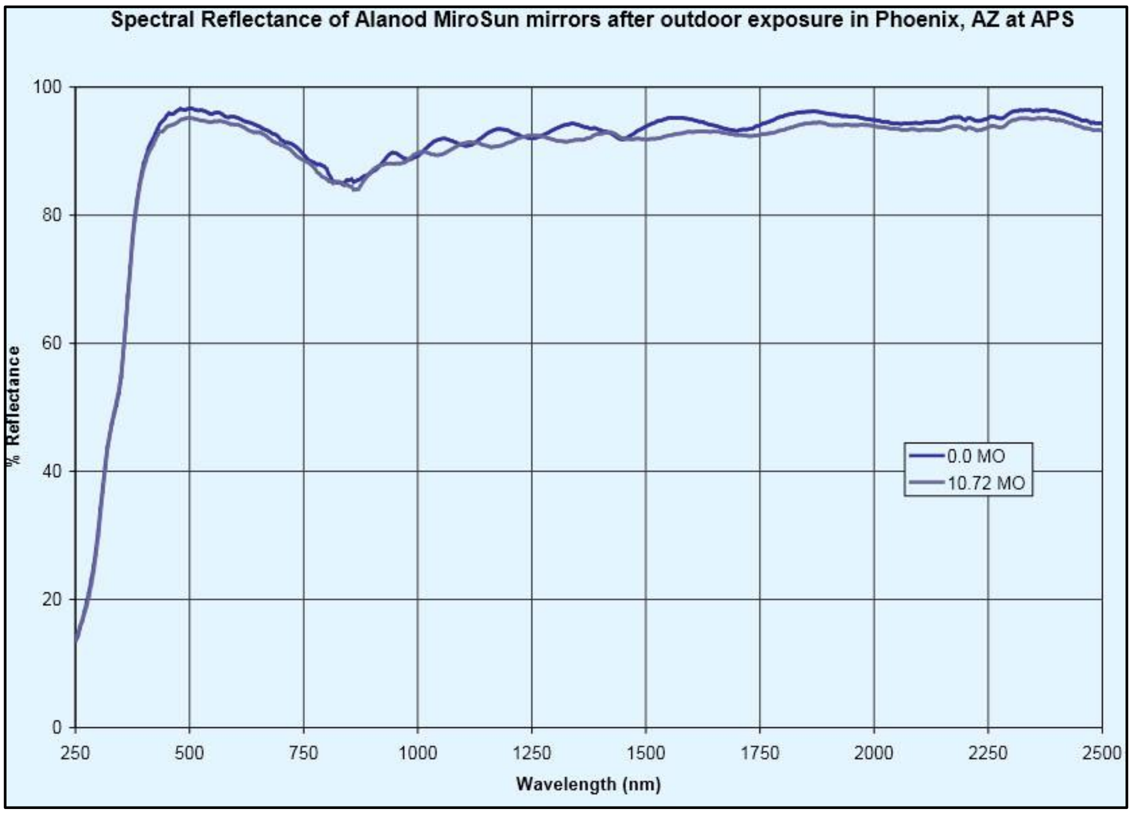

Figure 41 - Aluminized Reflectors[52]

52 http://www.nrel.gov/docs/fy08osti/43695.pdf

3. Silvered Polymer Reflectors - Silvered Polymer mirrors are a composite of several different materials with a silvered acrylic reflector as the reflective surface. They are relatively brittle, however tend to be resistant to environmental elements. Hemispherical reflectance is 96%

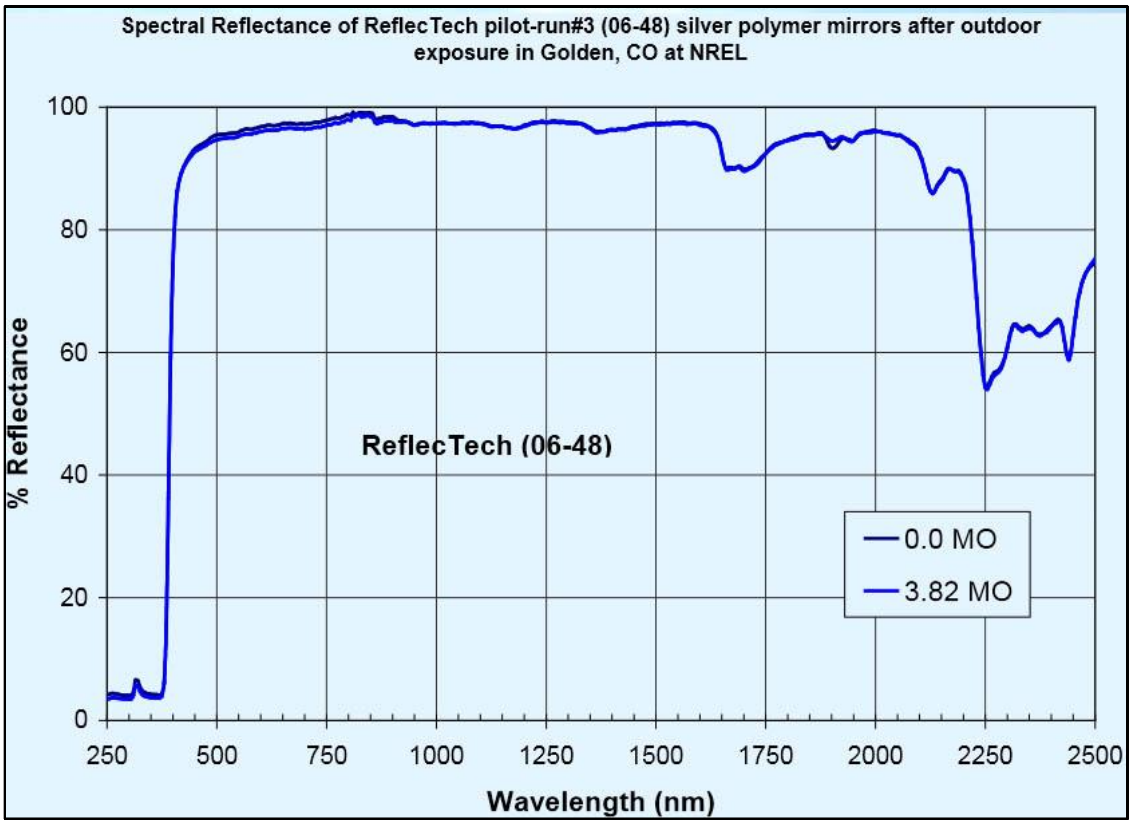

Figure 42 - Silver Polymer Mirrors[53]

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53 http://www.nrel.gov/docs/fy08osti/43695.pdf

Silvered polymer reflectors were used in the Arc Helio energy calculations with a hemispherical reflectance of 96% was used.

INLET DESIGN

The inlet is the "broker" between the focused beam of sunlight from the heliostats, and the water thermal mass. The smaller the inlet, the less energy loss there is from the thermal mass to the exterior. In the design process of the ArcHelio system, a variety of glazing types were tested to see which would perform optimally in the ArcHelio process.

GLAZING COMPARISONS - STUDY 3

Aim of the Study:

Glass is a poor thermal insulator, yet can be very good at reflecting light. A glass for the inlet design must be selected based on its ability to transmit light through it, with little efficiency loss due to reflection or absorption.

Hypothesis:

Glass containing coatings or high amounts of iron will reduce the intensity of light entering the box.

Materials:

A box (box 1.0) was designed. It was constructed out of plywood with the following dimensions: 200mm x 200mm x 200mm (8"x8"x8"). A 50mm (2") diameter hole was drilled into the box, and temperature sensors were placed within the box.

- Temperature sensor #1 was mounted to the rear of the box.
- Temperature sensor #2 was mounted within the box.
- A radiometric light sensor was mounted within the box, facing the opening.
- Cabling was run out the bottom of the box and to the radiometric light sensor array.
- Several different samples of different PPG glass
- A 60 watt incandescent light bulb was used as the light source.

Methods:

1. A plywood box (box 1.0) was constructed to be the following dimensions: 200mm x 200mm x 200mm (8"x8"x8"). A radiometric light sensor was then placed within the box facing the opening. A single thickness of glass was placed in front of the aperture in front of the radiometric light sensor.
2. Ten - 75mm (3") flat glass mirrors, were mounted individually on a sheet of plywood using thick wire connections and focused on the opening aperture of the box.
3. The 60 watt light bulb was used as the light source and the light intensity in the box was recorded with the particular glass plate in place.
4. The glass plate was replaced and step #3 was repeated

Results:

As seen in the chart below, Starphire Ultra Clear Glass was the best performing glazing tested.

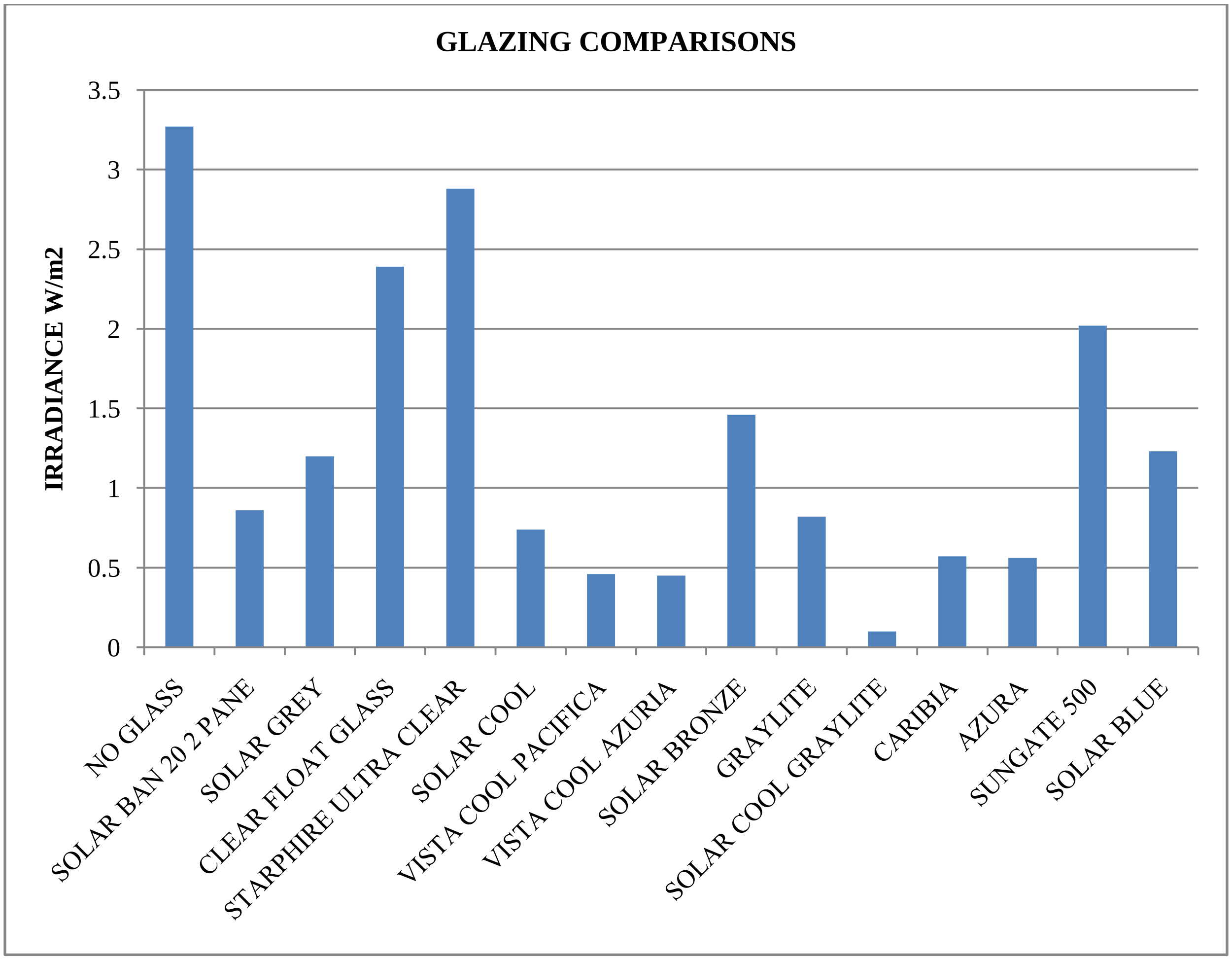

Figure 43 - Metric - Glazing Comparisons Graph by Mark Driedger

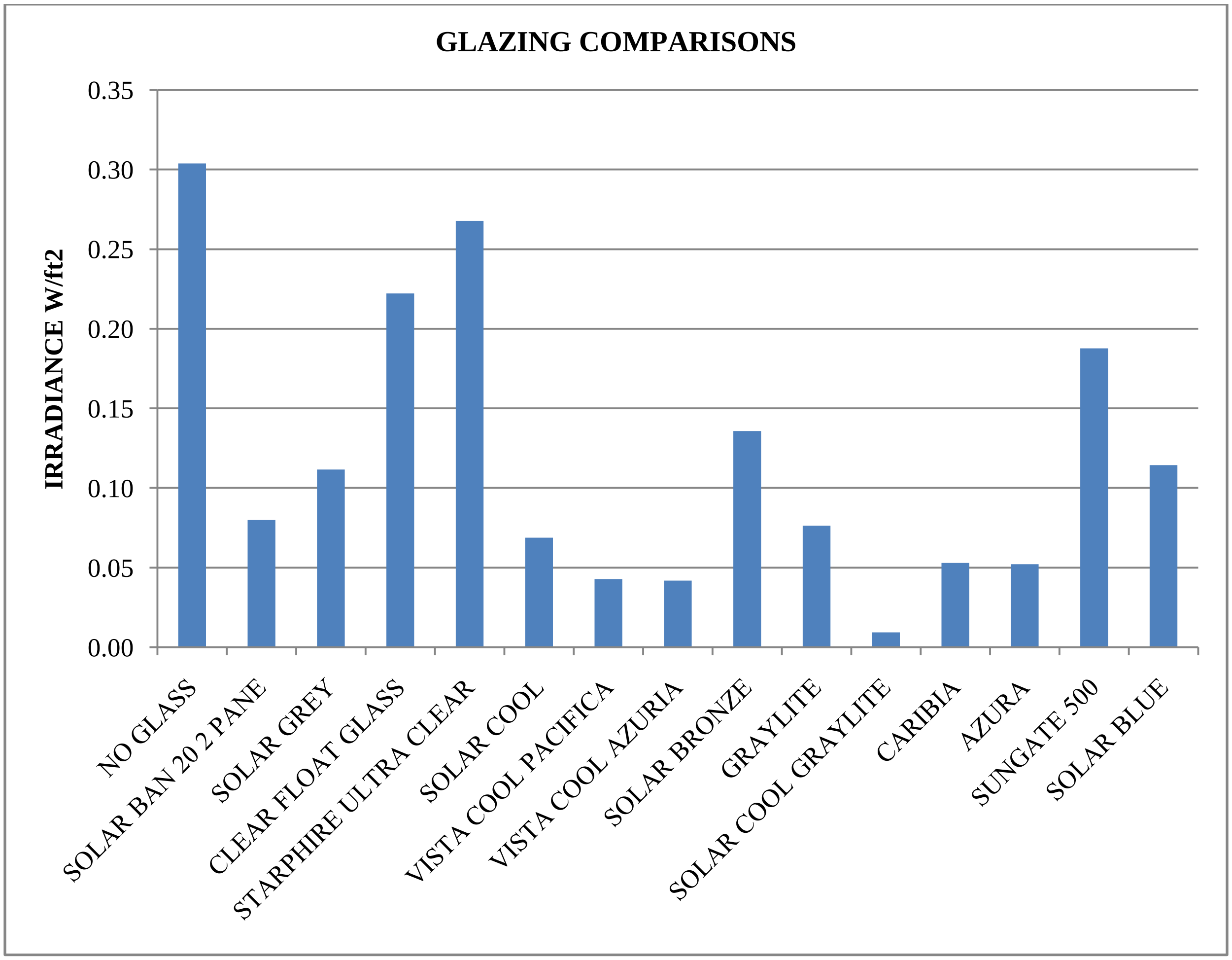

Figure 44 - Imperial - Glazing Comparisons Graph by Mark Driedger

Conclusion:

The inlet has been designed as a single plate glass, made out of PPG's Starphire Ultra Clear Glass. Starphire glass is an ultra-clear glass created by PPG Industries that has a very high light transmittance compared to typical high iron glazing. The data sheet shown below, shows the high level of visible light, infrared and ultraviolet light that is allowed to pass through the glazing. The data also compares the PPG Starphire Ultra Clear Glass with clear glass.

PPG Industries, Inc
Glass Technology Center
Guys Run Road
Post Office Box 38361
Pittsburgh, PA 15238-8361
Customer Services: (800) 872-3157; Fax: (800) 628-0299

Starphire

Product Description: STARPHIRE glass is an ultra-clear soda-lime float glass product. Its high visible light transmittance (>91% at 6 mm) and its brilliant azure edge are two characteristics unique to STARPHIRE glass. This glass is a low iron composition with mechanical and physical properties similar to ordinary clear soda-lime float glass.[1]

Mechanical Properties

Knoop Hardness Number (indentation hardness) indenter load--500 gm	470 kgf/mm^2	
Poisson's Ratio	0.22	
Modulus of Elasticity (Young's)	73.1 GPa	10,600,000 psi
Tensile Strength (Determined as Modulus of Rupture, ultimate)	41.4 MPa	6000 psi
Density at 21°C (70°F)	2.51 g/cm^3	157 lb/ft^3

Thermal Properties

Hemispherical Emissivity at -18 to 66 °C (0 to 150°F))	0.84	
Expansion Coefficient (linear) 20 to 300°C (68 to 572°F)	$9.28*10^{-6}$/ °C	$5.16*10^{-6}$/ °F
Specific heat at 0 to 100°C (32 to 212°F)	858 J/kg-K	0.205 BTU/lb-°F
Thermal Conductivity (k) at 50°C (122°F)	1.00 W/m-K	0.58 Btu/hr-ft-°F
Softening Point	710°C	1310°F
Annealing Point	547°C	1017°F
Strain Point	513°C	955°F
Transformation temperature (Tg)	556°C	1033°F
Yield point (At), (intenerate temperature)	606°C	1123°F

Chemical Properties

SiO_2	73%
Na_2O	15
CaO	11
Trace elements	1

Electric Properties

Dielectric Constant (measured at 1 MHz)	5.7
Surface Resistivity	106-108 ohms/sq.

Refractive Indices and Color

Refractive indices: nF	486.1 nm	1.5245 +/- 0.0005
nD	589.3 nm	1.5183 +/- 0.0005
nC	656.3 nm	1.5158 +/- 0.0005
Abbe number (nD-1)/(nF-nC)	60	
Color at 6 mm : D65, 10 L*	96.5	
a*	-0.24	
b*	0.10	
Dominant wavelength	500 nm	

Approximate weights

Per m^2		Per ft^2	
thickness	weight	thickness	weight
3.3 mm	8.2 kg	1/8"	1.7 lbs
4 mm	9.9 kg	5/32"	2.0 lbs
5 mm	11.9 kg	3/16"	2.4 lbs
6 mm	14.2 kg	1/4"	2.9 lbs
8 mm	19.8 kg	5/16"	4.1 lbs
10 mm	23.8 kg	3/8"	4.9 lbs
12 mm	31.8 kg	1/2"	6.5 lbs

[1] Figures in tables may vary due to manufacturing tolerances.

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Figure 45 - Inlet Glass[54]

54 http://www.jnsglass.com/pdf/Starphire.pdf

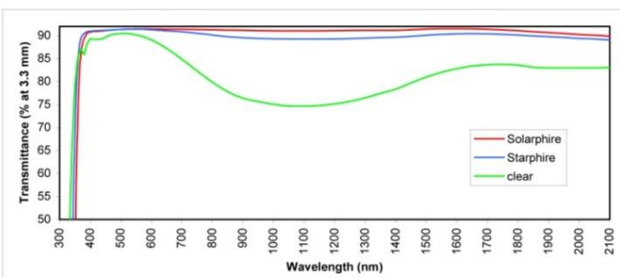
PPG Starphire Glass

Visible and Glazing Performance[2]

Glass Thickness		Trasnmittance				Reflectance		U-value BTU/hr-ft^2		K-value W/hr-m^2		Shading coefficient	Solar Heat Gain Coefficient
inches	mm	Ultra-violet (%)	Visible (%)	Infrared (%)	Visible (%)	Visible (%)	Visible (%)	Winter	Summer	Winter	Summer		
1/8	3.3	65	91	90	90	8	8	1.04	0.94	5.9	5.3	1.04	0.91
5/32	4	63	91	89	90	8	8	1.04	0.93	5.9	5.3	1.04	0.90
3/16	5	60	91	88	89	8	8	1.03	0.93	5.9	5.3	1.04	0.90
1/4	6	58	91	87	89	8	8	1.03	0.93	5.8	5.3	1.03	0.90
5/16	8	54	91	86	88	8	8	1.01	0.91	5.7	5.2	1.03	0.89
3/8	10	52	91	85	87	8	8	1.01	0.91	5.7	5.1	1.02	0.89
1/2	12	49	90	83	86	8	8	1.00	0.91	5.6	5.1	1.01	0.88

Transmittance (% at 3.3 mm/0.129")

Wave-length (nm)	clear	Star-phire	Solar-phire	Wave-length (nm)	clear	Star-phire	Solar-phire	Wave-length (nm)	clear	Star-phire	Solar-phire
300	0.2	0.0	0.0	590	89.4	91.3	91.5	1250	75.7	89.3	91.1
310	1.2	0.1	0.0	610	88.7	91.2	91.4	1300	76.4	89.4	91.2
320	12.9	0.2	0.0	630	88.0	91.1	91.4	1350	77.4	89.6	91.1
330	39.9	12.6	0.7	650	87.2	91.0	91.4	1400	78.4	89.6	91.2
340	64.8	38.3	10.1	670	86.3	91.0	91.4	1450	79.7	89.8	91.3
350	79.0	68.4	40.7	690	85.4	90.9	91.4	1500	81.0	90.1	91.4
360	85.3	84.4	73.3	710	84.4	90.8	91.4	1550	82.0	90.3	91.5
370	87.0	89.4	86.2	730	83.4	90.6	91.3	1600	82.8	90.4	91.5
380	85.8	90.4	89.3	750	82.3	90.5	91.3	1650	83.4	90.4	91.5
390	88.3	90.8	90.5	770	81.3	90.4	91.3	1700	83.6	90.4	91.4
410	89.2	91.0	90.9	800	79.8	90.1	91.2	1750	83.7	90.3	91.2
430	89.2	91.1	91.0	850	77.8	89.8	91.2	1800	83.6	90.1	91.1
450	89.6	91.2	91.1	900	76.4	89.5	91.1	1850	83.1	89.9	90.9
470	90.2	91.2	91.2	950	75.6	89.4	91.1	1900	83.0	89.8	90.7
490	90.4	91.3	91.3	1000	75.1	89.3	91.0	1950	83.0	89.6	90.4
510	90.4	91.4	91.4	1050	74.7	89.2	91.0	2000	82.9	89.4	90.2
530	90.4	91.4	91.4	1100	74.6	89.2	91.0	2050	83.0	89.2	90.1
550	90.1	91.4	91.5	1150	74.8	89.2	91.0	2100	83.0	89.0	89.8
570	89.9	91.4	91.5	1200	75.1	89.3	91.1	2150	82.8	88.7	89.4



[2] Figures may vary due to manufacturing tolerances. All tabulated glazing performance data are based on NFRC methodology using LBL Window 5.2 software. Some variations from previously published data are due to minor changes in the LBL Window 5.2 software versus Version 4.1. Slight changes in transmitted optical properties may occur on exposure to sunlight.

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Figure 46 - Inlet Glass[55]

55 http://www.jnsglass.com/pdf/Starphire.pdf

GEOMETRY OF THE INLET

The inlet must be large enough to allow the focused light to enter the dwelling and strike the absorber receiver but small enough to minimize thermal losses. The concave heliostat was used to compress the reflected light through the inlet opening. To reduce thermal losses, an insulated mechanical shutter was designed to close over the inlet to minimize heat lost.

THERMAL MASS

The thermal mass is designed as a water tank, built below the dwelling, to minimize the thermal losses associated with transferring the energy to another location. The thermal mass is to be well insulated and isolated from both the dwelling and the outside environment. The interior of the tank was painted with carbon black paint to maximize the absorption of solar rays.

It should be noted, that the energy transfer between the rays of sunlight and the water in the tank are simple and natural. Any areas of the target black paint area that are heated, will immediately be cooled by the surrounding water, thus absorbing the heat of the rays. Because the water will constantly be exposed to solar rays, algae may be an issue. The water within the mass will need to be well circulated and possibly need to be chlorinated to ensure the water and inlet remain clear.

ArcHelio software was developed and then used to “size” the thermal mass to ensure the system always operates between the interior temperature of the dwelling and the boiling point of water throughout the year. Boiling water has different thermal properties, and would also increase the pressure in the thermal tank. To reduce steam on the inlet, the water must constantly be against the inlet. The inlet will need to be slightly below the top plane of the water to allow this to happen.

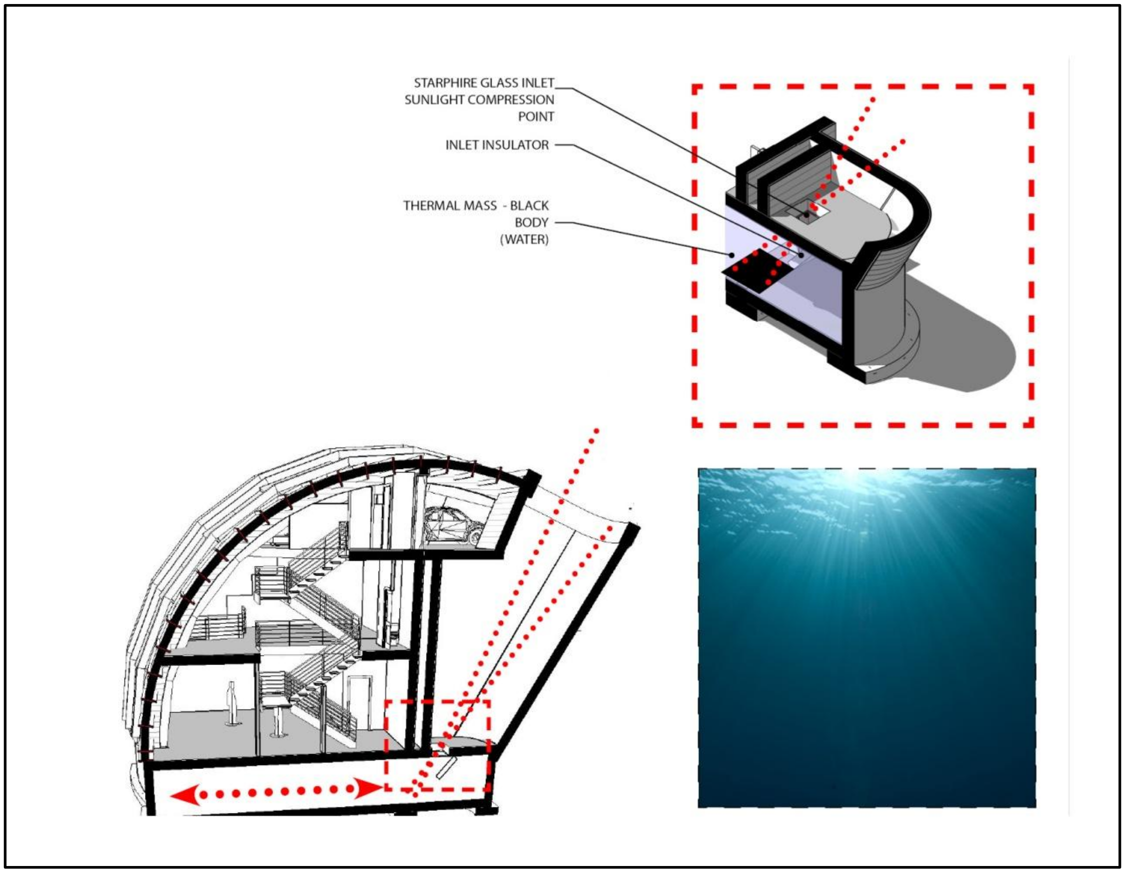


Figure 47 - Inlet Design & Thermal Mass

CHAPTER 8 - MODELLING THE DESIGN OF THE SYSTEM

Several building designs were considered using the ArcHelio software and the aforementioned research. The goal was to design a dwelling that would minimize external losses, in order so as to make the ArcHelio process as efficient as possible. Three of the design iterations are listed below.

DESIGN 1

Design 1 consisted of a 1,200 sq.ft. dwelling constructed around a 200,000 Litre (50,000 gallons) cylindrical thermal mass water tank with heliostats extending to the east and west. The south sloping roof was provided for possible future photovoltaics. In the end, the design afforded too much heat loss to the exterior, because of the large exposed thermal mass tank. The model was tested in the ArcHelio software.

In addition, because of the multiple heliostats at different locations, it was difficult to design an inlet that would allow the entry of light originating from diverse directions. The cylindrical thermal mass also had stratification problems, when modelled in CFD. This is shown in Figure 48.

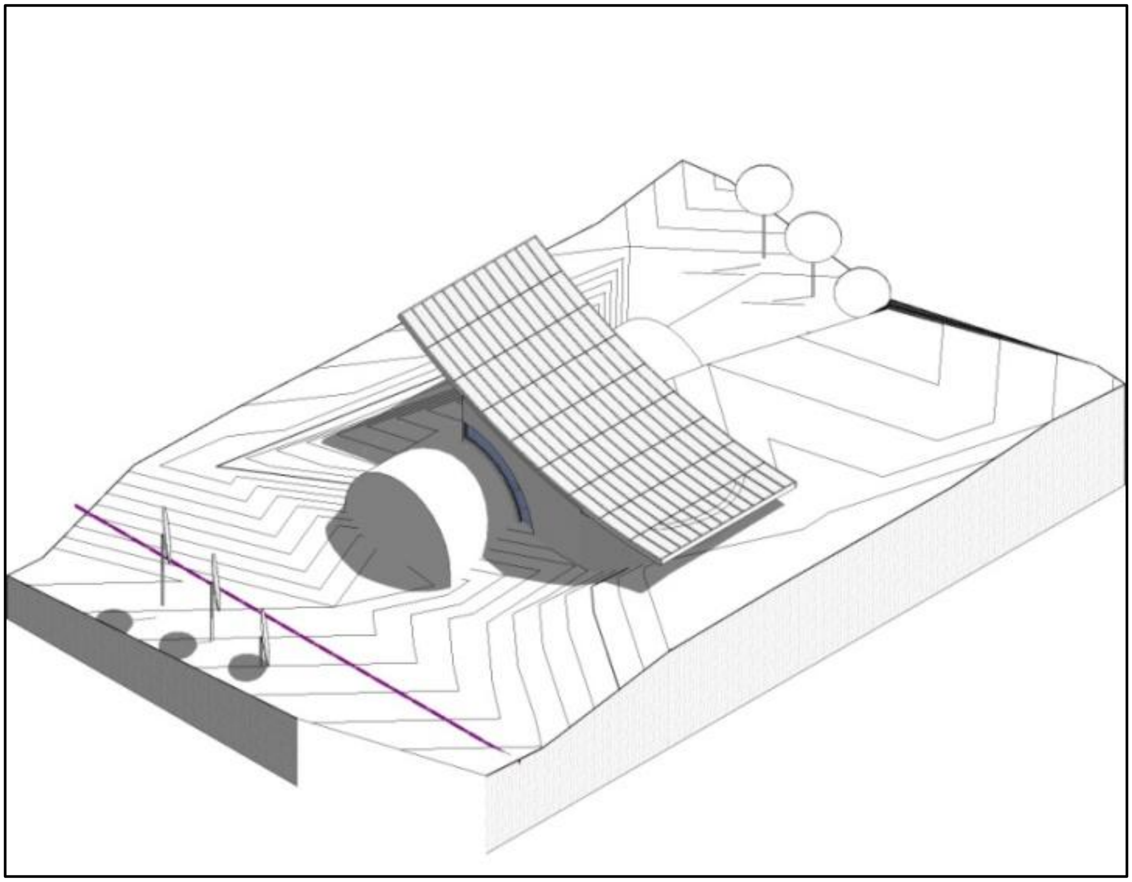


Figure 48 - Design 1

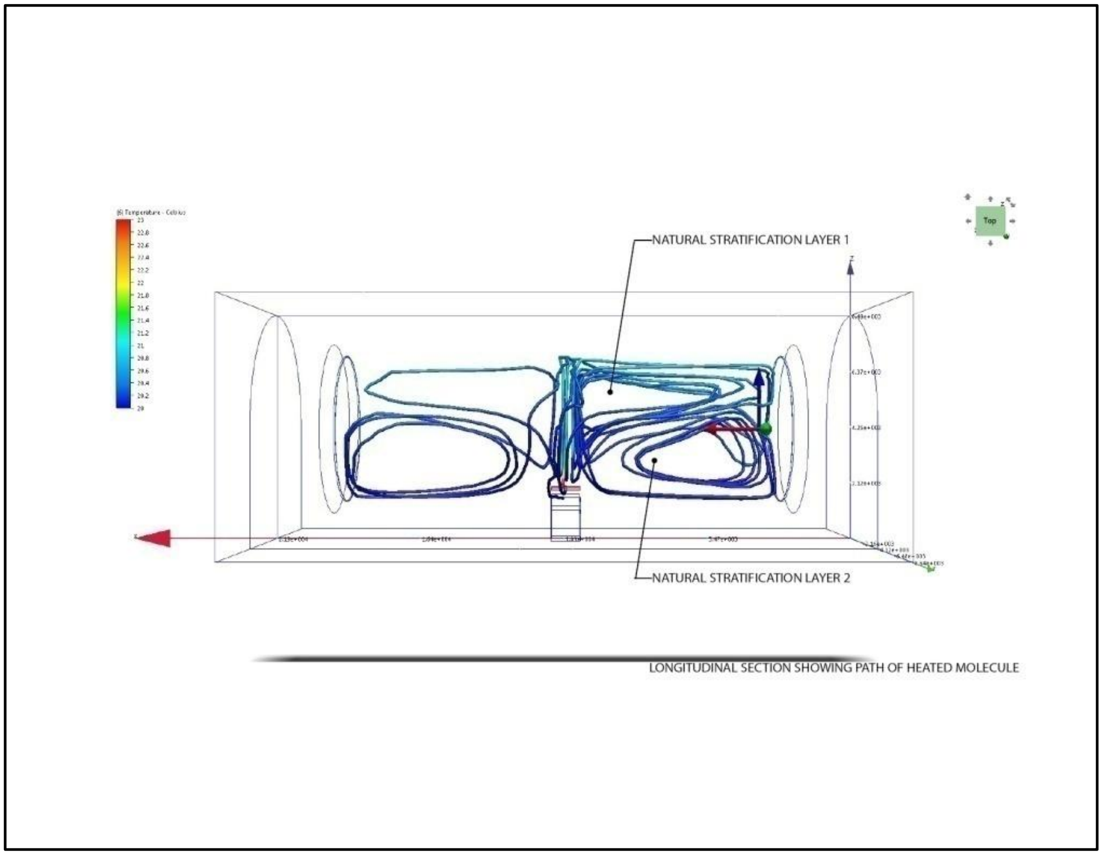


Figure 49 - Stratification of the Tank

DESIGN 2

Design 2 took on a more teardrop shape, an effort to reduce heat losses associated with the wind.. The thermal mass was located below the dwelling to reduce heat loss to the exterior. The tracking heliostats were constructed on the North side of the site, far enough from the house such that they weren't shaded by the structuere. The heliostats were focused on a single inlet, from several different directions. The thermal mass was sized to be approximately 200,000 litres (50,000 gallons) based on the ArcHelio calculations. There were some losses again, due to the differing angles of the 4 heliostats. The system of transferring the energy into the thermal mass were also unnecessarily complex because of the multiple reflections required to get the beam into the basement. With each reflection, there is efficiency loss.

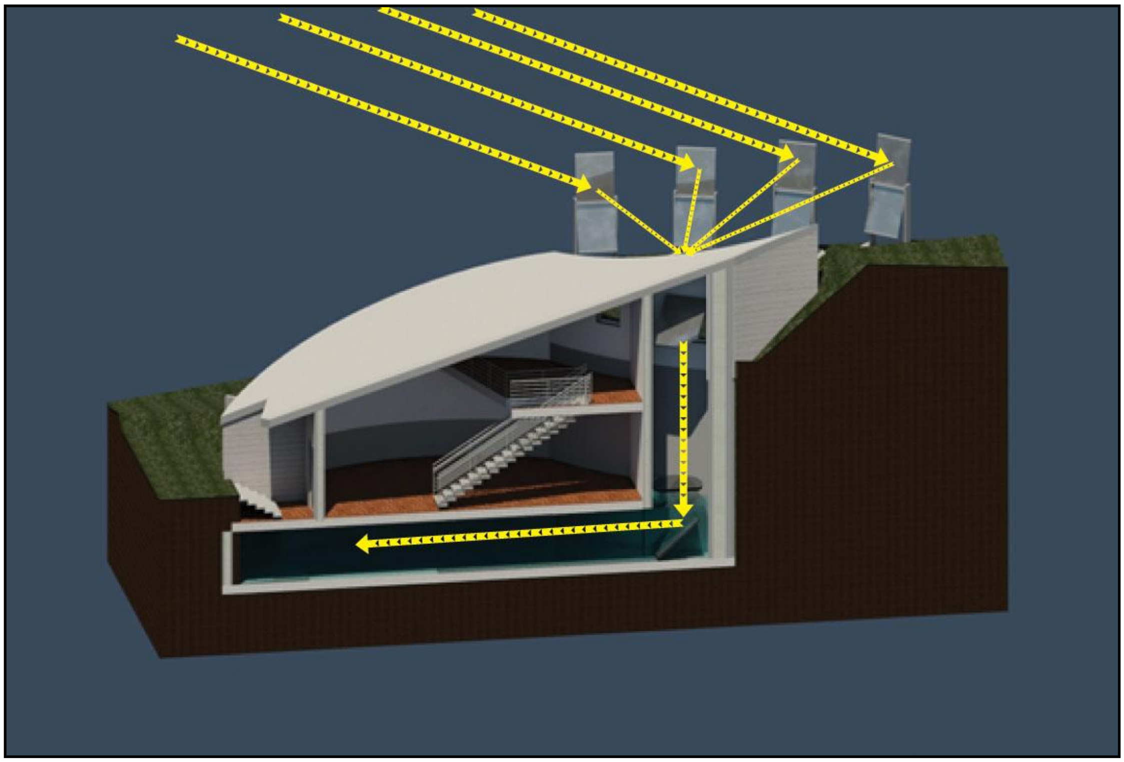


Figure 50 - Design 2 - Tank location

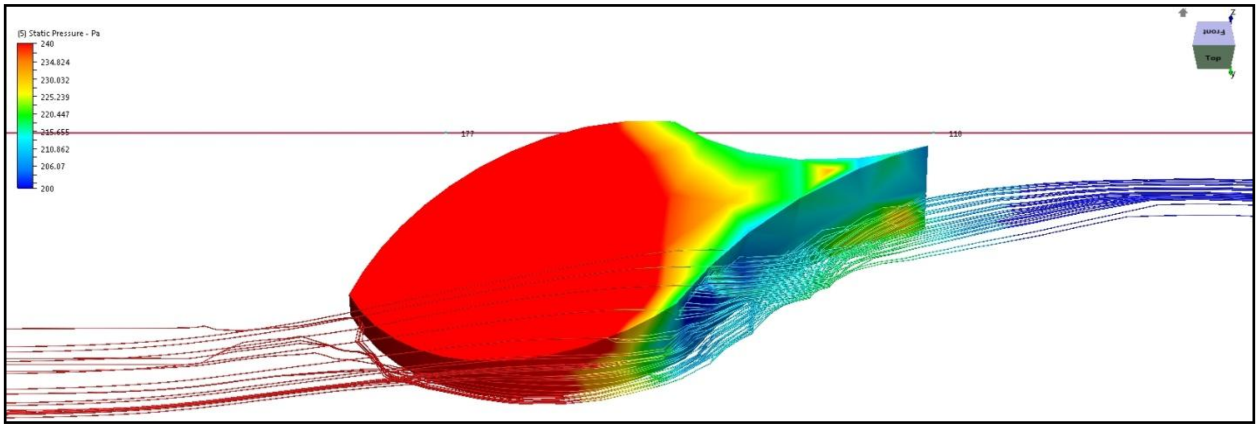


Figure 51 - Wind Analysis on Design 2

DESIGN 3

Design 3 demonstrated the most potential and was carried on through the process. Design 3 was fully modelled in Revit, Autodesk CFD, and Therm, to analyze all points of the heat loss equation. The design was also inputted into ArcHelio and its operation was fully modelled.

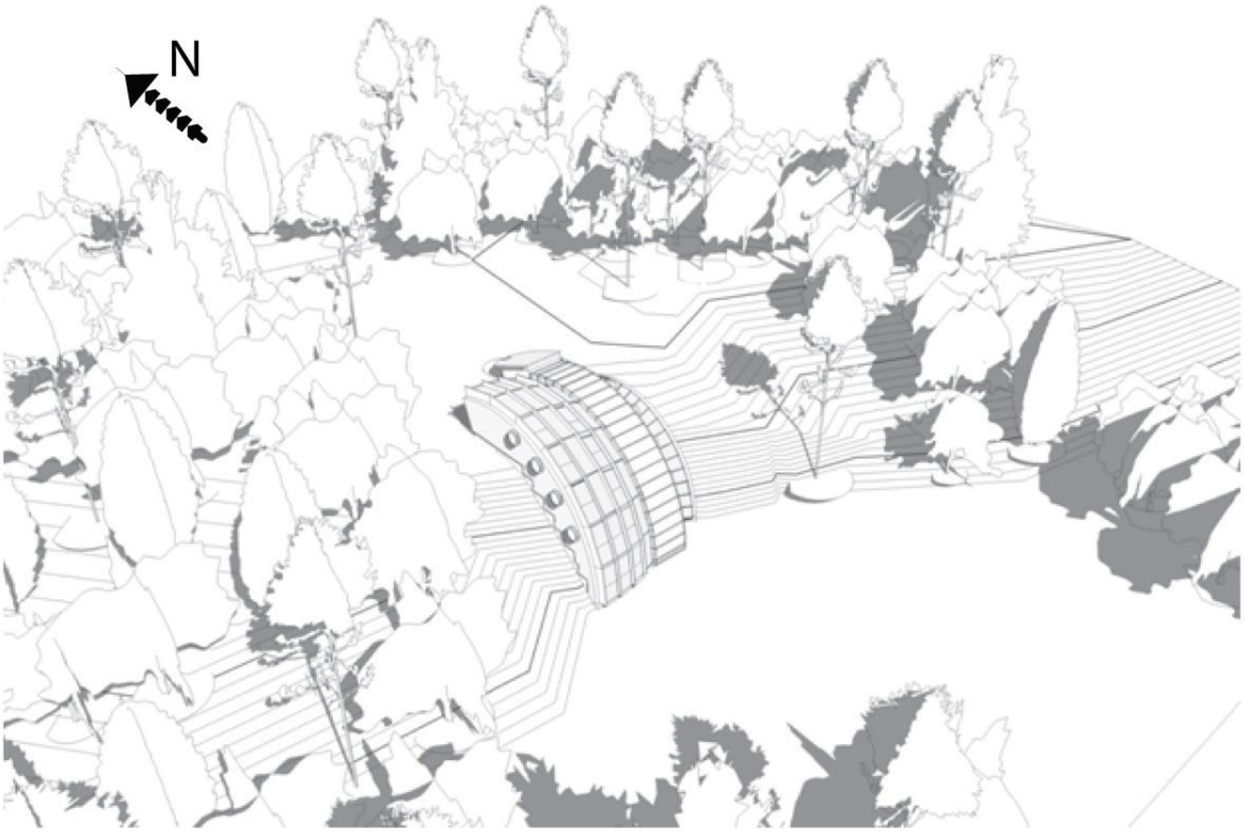


Figure 52 - Design 3

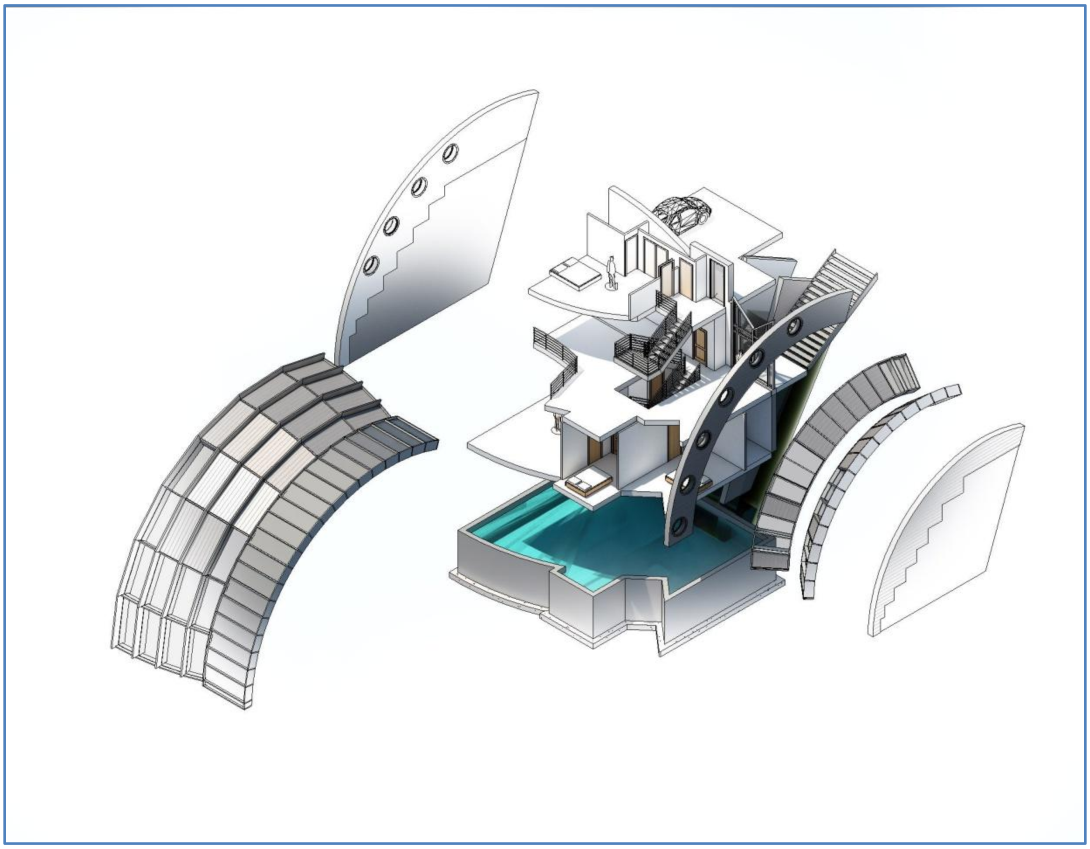


Figure 53 - Design 3 - Blow Out of Components

THERMAL ISOLATION AND WIND PROTECTION

The thermal mass was again placed below the dwelling, in an attempt to reduce as much heat loss as possible to the environment. The shape of the dwelling was chosen after careful consideration viewing the wind patterns for the site. The wind tunnel functions of Autodesk CFD were used to ensure that the wind had a minimum effect on the exposed windows and walls. By reducing the wind pressure on the windows, the protective exterior air layer on the windows will be maintained, therefore reducing heat loss through the windows.

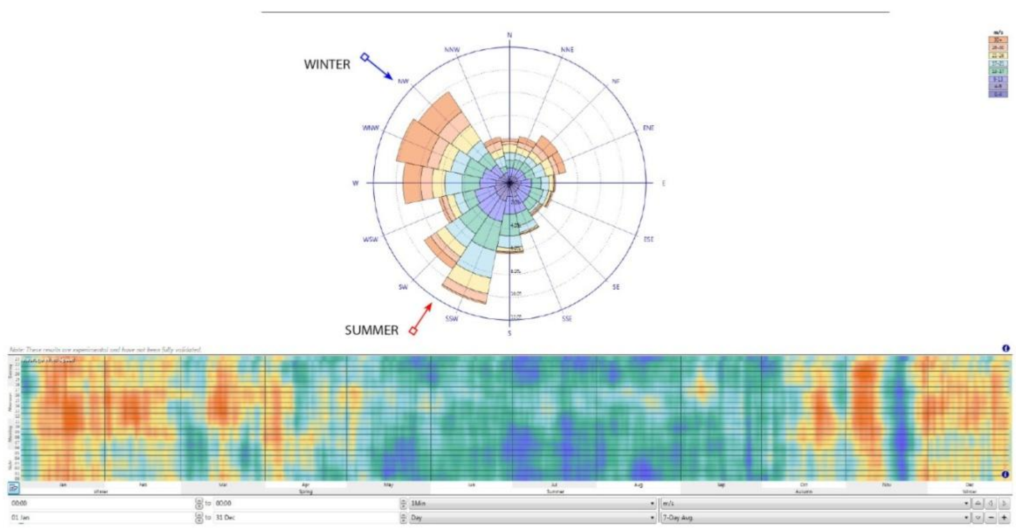


Figure 54 - Wind Frequency in Mississauga Ontario Shown in Wind Rose and Graphic Form[56]

56 Source - Autodesk Ecotect

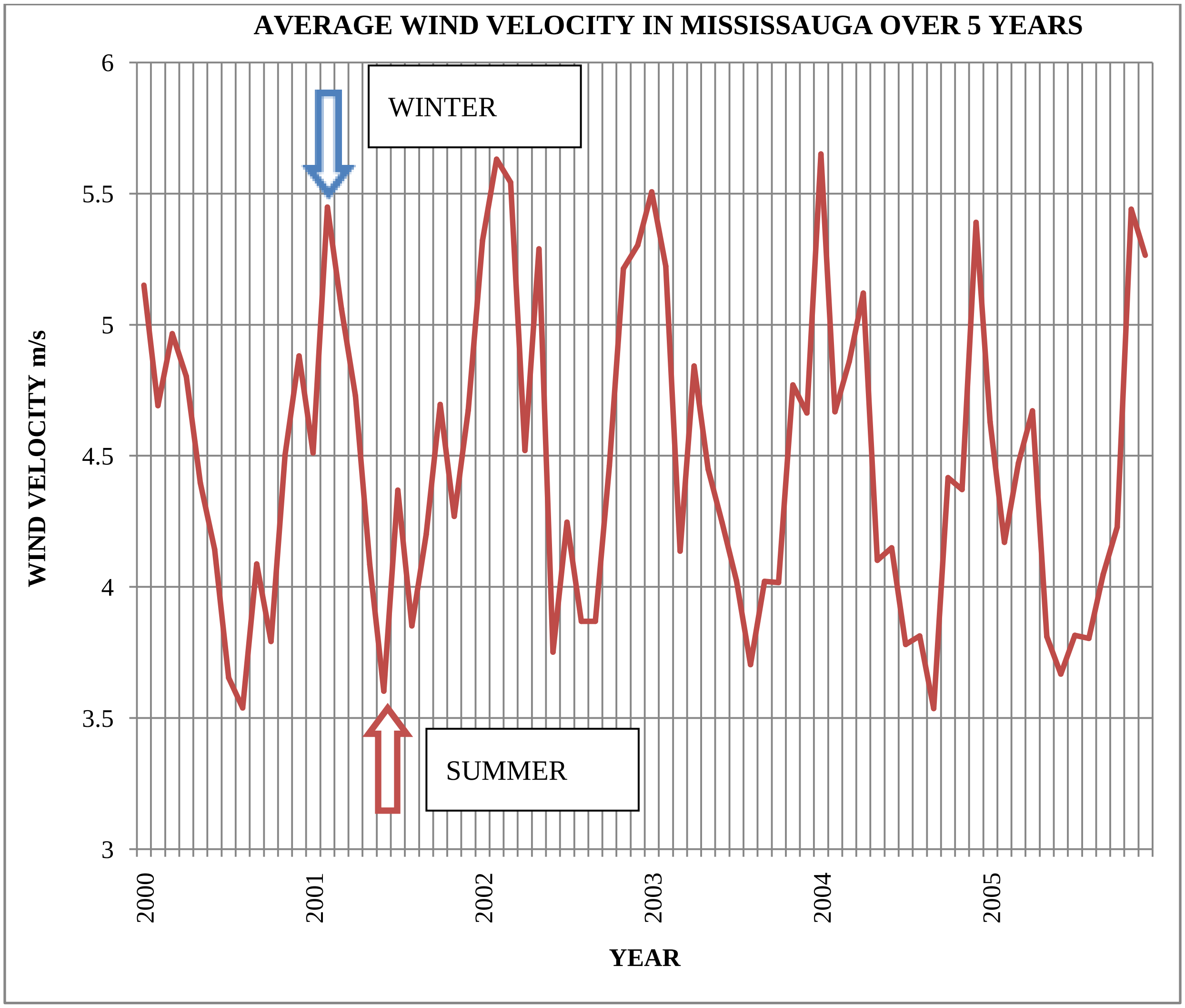
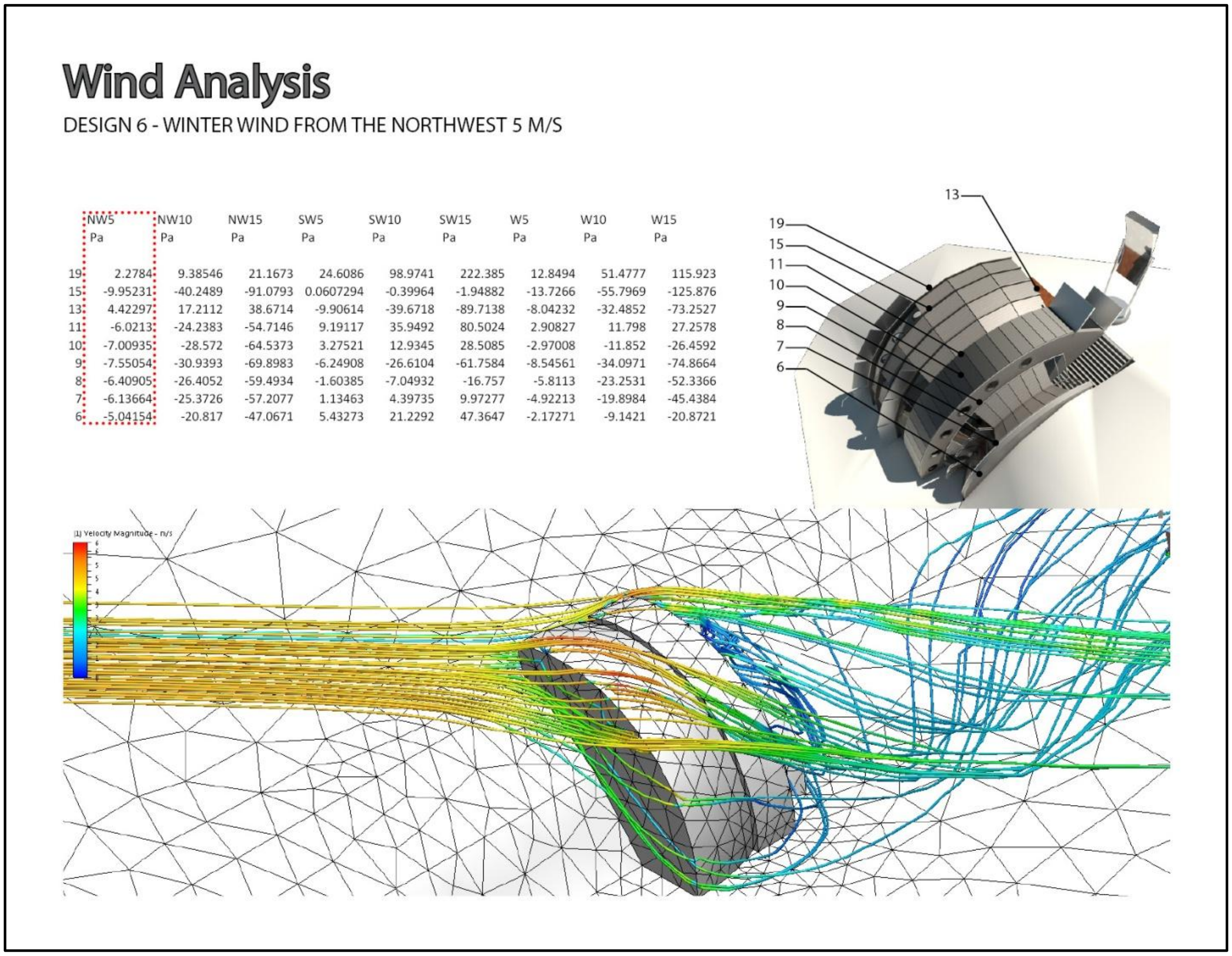


Figure 55 - Wind Velocity over 5 years - CWEEDS Pearson Airport weather data - Graph by Mark Driedger

The winds in Mississauga vary throughout the year in direction and intensity. The winter winds tend to be more powerful than the summer winds and predominantly come from the cold northwest. The majority of winter winds come from the northwest. The building has been designed to minimize the effects of these winter winds. Using Autodesk CFD, the pressures on the exterior envelope of the building have been modelled, and the data inputted into ArcHelio to calculate the resulting losses. The streamlined, curving shape has minimal interaction with the cold northwest wind. By stepping the balance of the building back, the west wall acts as a shield, minimizing the pressures on the other facades.



	NW5 Pa	NW10 Pa	NW15 Pa	SW5 Pa	SW10 Pa	SW15 Pa	W5 Pa	W10 Pa	W15 Pa
19	2.2784	9.38546	21.1673	24.6086	98.9741	222.385	12.8494	51.4777	115.923
15	-9.95231	-40.2489	-91.0793	0.0607294	-0.39964	-1.94882	-13.7266	-55.7969	-125.876
13	4.42297	17.2112	38.6714	-9.90614	-39.6718	-89.7138	-8.04232	-32.4852	-73.2527
11	-6.0213	-24.2383	-54.7146	9.19117	35.9492	80.5024	2.90827	11.798	27.2578
10	-7.00935	-28.572	-64.5373	3.27521	12.9345	28.5085	-2.97008	-11.852	-26.4592
9	-7.55054	-30.9393	-69.8983	-6.24908	-26.6104	-61.7584	-8.54561	-34.0971	-74.8664
8	-6.40905	-26.4052	-59.4934	-1.60385	-7.04932	-16.757	-5.8113	-23.2531	-52.3366
7	-6.13664	-25.3726	-57.2077	1.13463	4.39735	9.97277	-4.92213	-19.8984	-45.4384
6	-5.04154	-20.817	-47.0671	5.43273	21.2292	47.3647	-2.17271	-9.1421	-20.8721

Figure 56 - CFD Wind Analysis

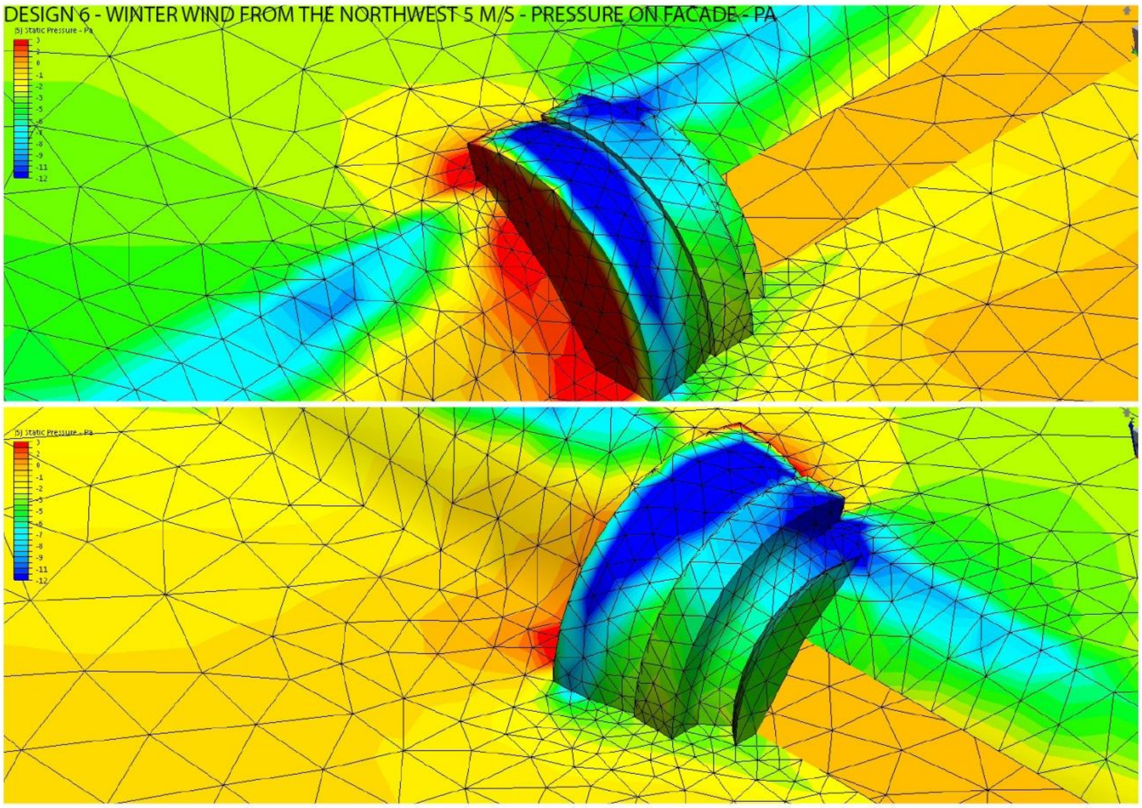
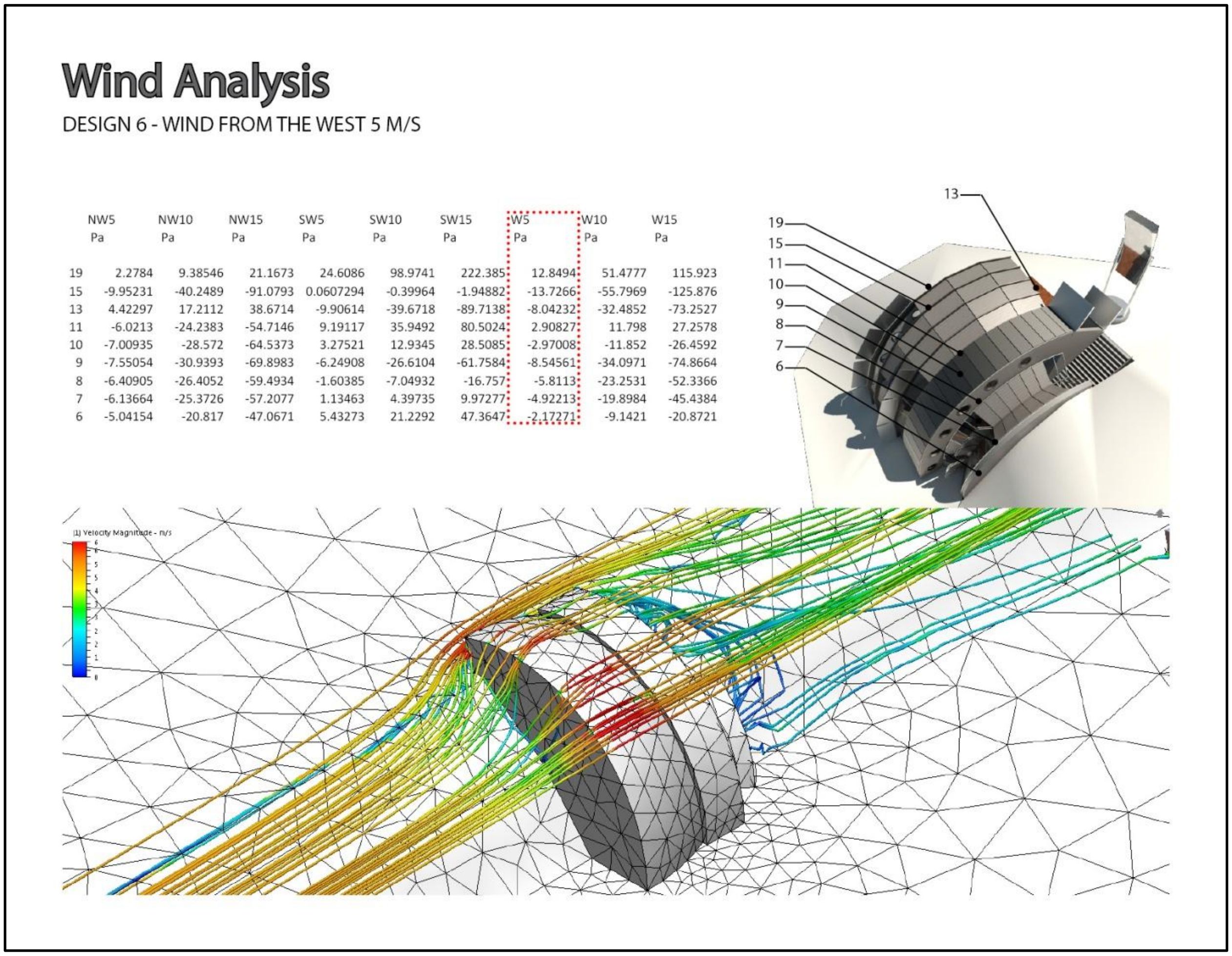


Figure 57 - CFD Wind Analysis

The dark red area in Figure 57, shows the incoming pressures caused by the winter winds. More importantly, the lower pressure blues and greens occur in the glazed areas of the building. The lower the pressure in these areas, the less energy is lost through the glazing.



	NW5 Pa	NW10 Pa	NW15 Pa	SW5 Pa	SW10 Pa	SW15 Pa	W5 Pa	W10 Pa	W15 Pa
19	2.2784	9.38546	21.1673	24.6086	98.9741	222.385	12.8494	51.4777	115.923
15	-9.95231	-40.2489	-91.0793	0.0607294	-0.39964	-1.94882	-13.7266	-55.7969	-125.876
13	4.42297	17.2112	38.6714	-9.90614	-39.6718	-89.7138	-8.04232	-32.4852	-73.2527
11	-6.0213	-24.2383	-54.7146	9.19117	35.9492	80.5024	2.90827	11.798	27.2578
10	-7.00935	-28.572	-64.5373	3.27521	12.9345	28.5085	-2.97008	-11.852	-26.4592
9	-7.55054	-30.9393	-69.8983	-6.24908	-26.6104	-61.7584	-8.54561	-34.0971	-74.8664
8	-6.40905	-26.4052	-59.4934	-1.60385	-7.04932	-16.757	-5.8113	-23.2531	-52.3366
7	-6.13664	-25.3726	-57.2077	1.13463	4.39735	9.97277	-4.92213	-19.8984	-45.4384
6	-5.04154	-20.817	-47.0671	5.43273	21.2292	47.3647	-2.17271	-9.1421	-20.8721

Figure 58 - CFD Wind Analysis

A direct west wind is a little less common, but important nonetheless. Again, the west wall shields the other areas of the building.

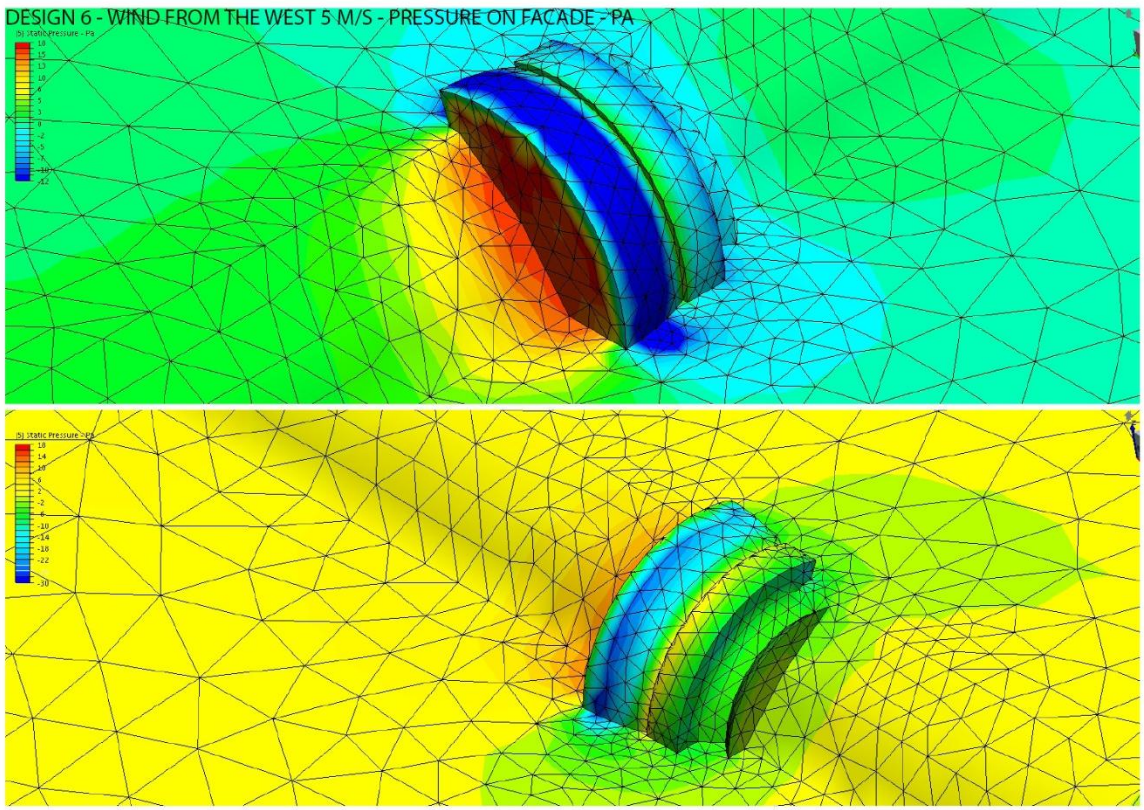
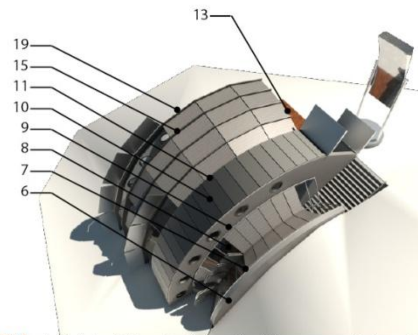


Figure 59 - CFD Wind Analysis

Wind Analysis

DESIGN 6 - WIND FROM THE SOUTHWEST 5 M/S

	NW5 Pa	NW10 Pa	NW15 Pa	SW5 Pa	SW10 Pa	SW15 Pa	W5 Pa	W10 Pa	W15 Pa
19	2.2784	9.38546	21.1673	24.6086	98.9741	222.385	12.8494	51.4777	115.923
15	-9.95231	-40.2489	-91.0793	0.0607294	-0.39964	-1.94882	-13.7266	-55.7969	-125.876
13	4.42297	17.2112	38.6714	-9.90614	-39.6718	-89.7138	-8.04232	-32.4852	-73.2527
11	-6.0213	-24.2383	-54.7146	9.19117	35.9492	80.5024	2.90827	11.798	27.2578
10	-7.00935	-28.572	-64.5373	3.27521	12.9345	28.5085	-2.97008	-11.852	-26.4592
9	-7.55054	-30.9393	-69.8983	-6.24908	-26.6104	-61.7584	-8.54561	-34.0971	-74.8664
8	-6.40905	-26.4052	-59.4934	-1.60385	-7.04932	-16.757	-5.8113	-23.2531	-52.3366
7	-6.13664	-25.3726	-57.2077	1.13463	4.39735	9.97277	-4.92213	-19.8984	-45.4384
6	-5.04154	-20.817	-47.0671	5.43273	21.2292	47.3647	-2.17271	-9.1421	-20.8721



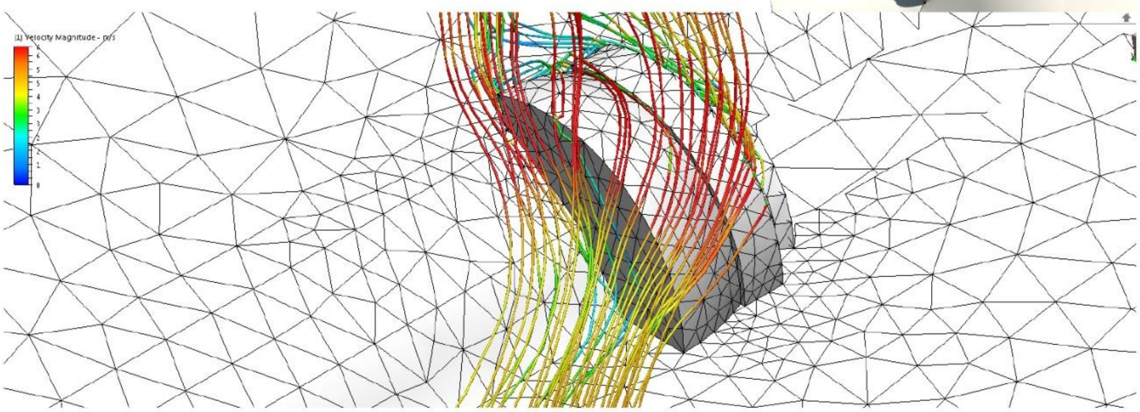


Figure 60 - CFD Wind Analysis

The summer winds come predominantly from the southwest. Although this wind is not as important as the northwest wind in terms of winter energy loss, it is important to see how the west wall shields the balance of the building.

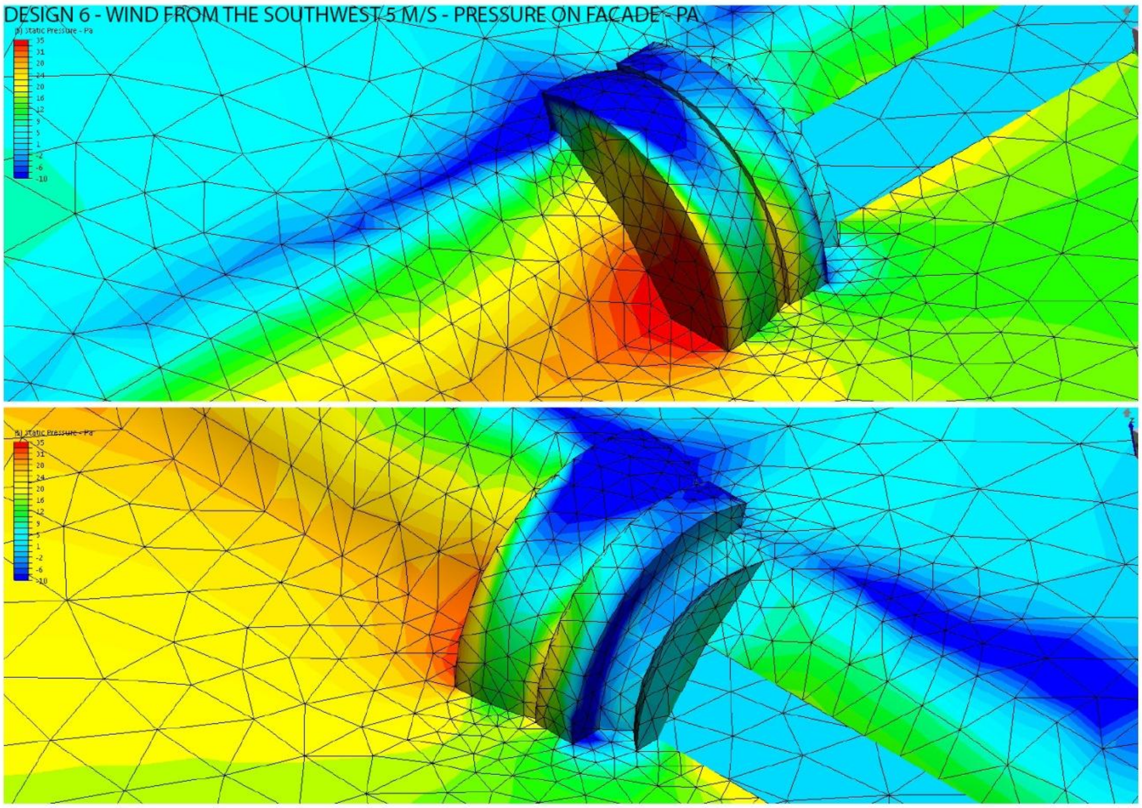


Figure 61 - CFD Wind Analysis

THE PLAN

The building plan itself, is set into a south facing hillside. Although the ArcHelio process is viable regardless of the set direction of the building, provided there is a direct line of sight between the inlet and the heliostat, the goal of this design was to find the optimum configuration for the heliostat location. The layout is almost the reverse of a walk-up three-storey townhouse unit. The 2nd storey houses the kitchen and living / dining areas. An exterior stair will bring the occupants from the 2nd floor to grade at the 3rd floor. The bedrooms are located in both the main floor and in the 3rd floor of the building. The garage access to the building is through the third floor.

The spherical geometry of the building, not only assists with aerodynamics, but also minimizes the volume of air within the building. The less volume of air within the building, the less air there is to heat. The geometry also allows every interior space to be bathed in natural light.

The openings between the floors allow the transfer and sharing of heat energy throughout the interior living space. This minimizes the overheating or overcooling of specific spaces, regardless of the location of the sun, or the direction of the wind.

One large track-able heliostat manages the energy collection for the building. The heliostat is located on the north side of the site, and directs energy to an isolated inlet, deep at the bottom of the dwelling. The heliostat acts as an additional insulating panel, when in the closed position. The heliostat is slightly concave, focusing the energy at the point of the inlet.

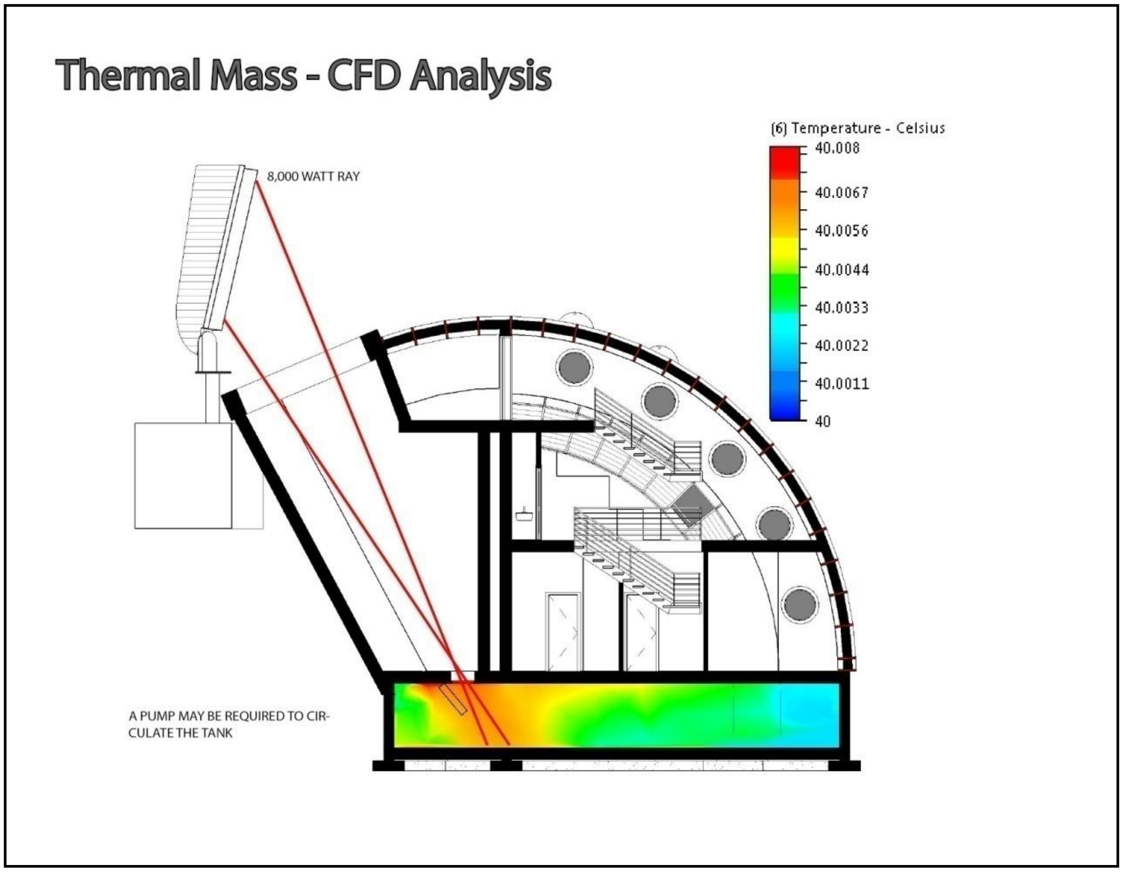


Figure 62 - Section Showing the Location of the Thermal Mass and the Heliostat

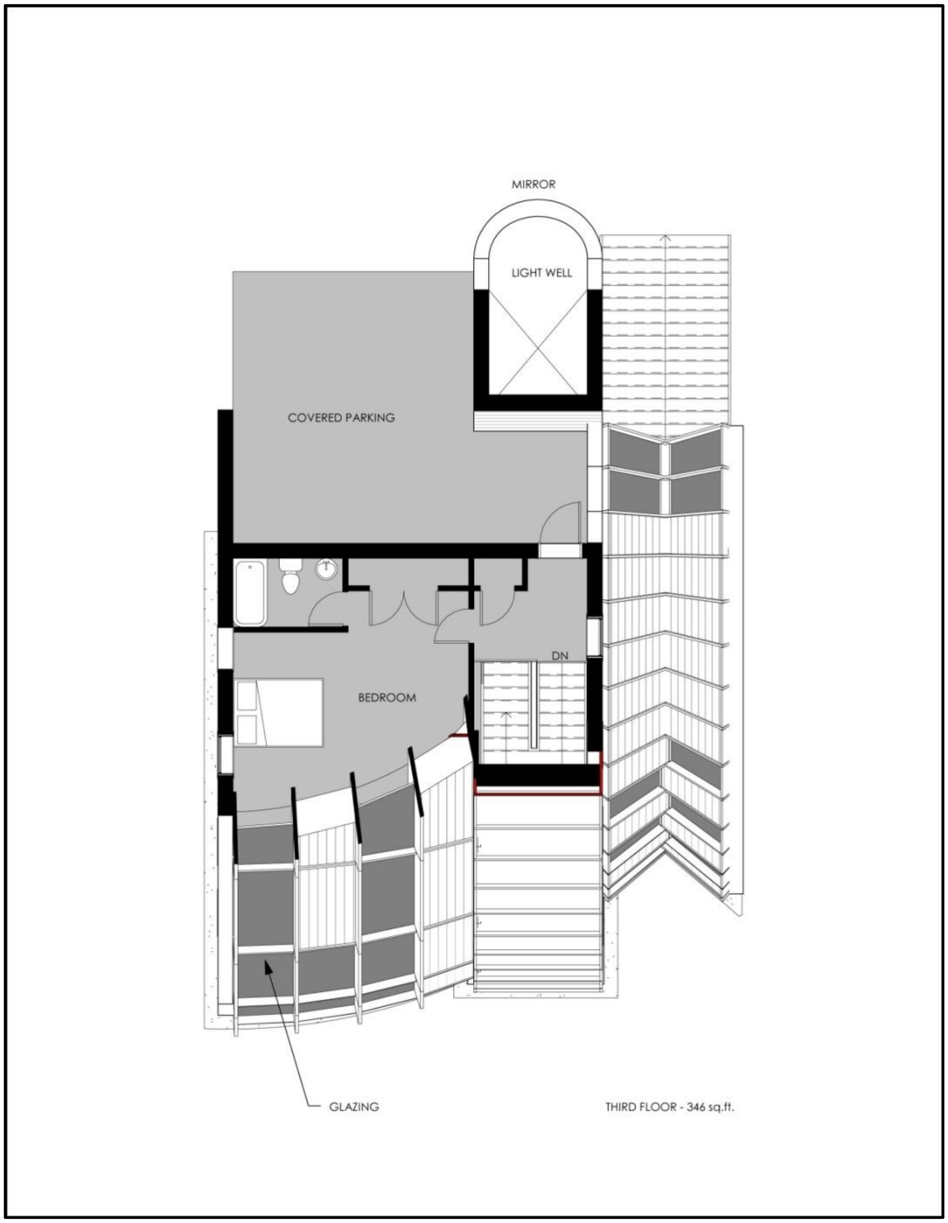


Figure 63 - Third Floor Plan

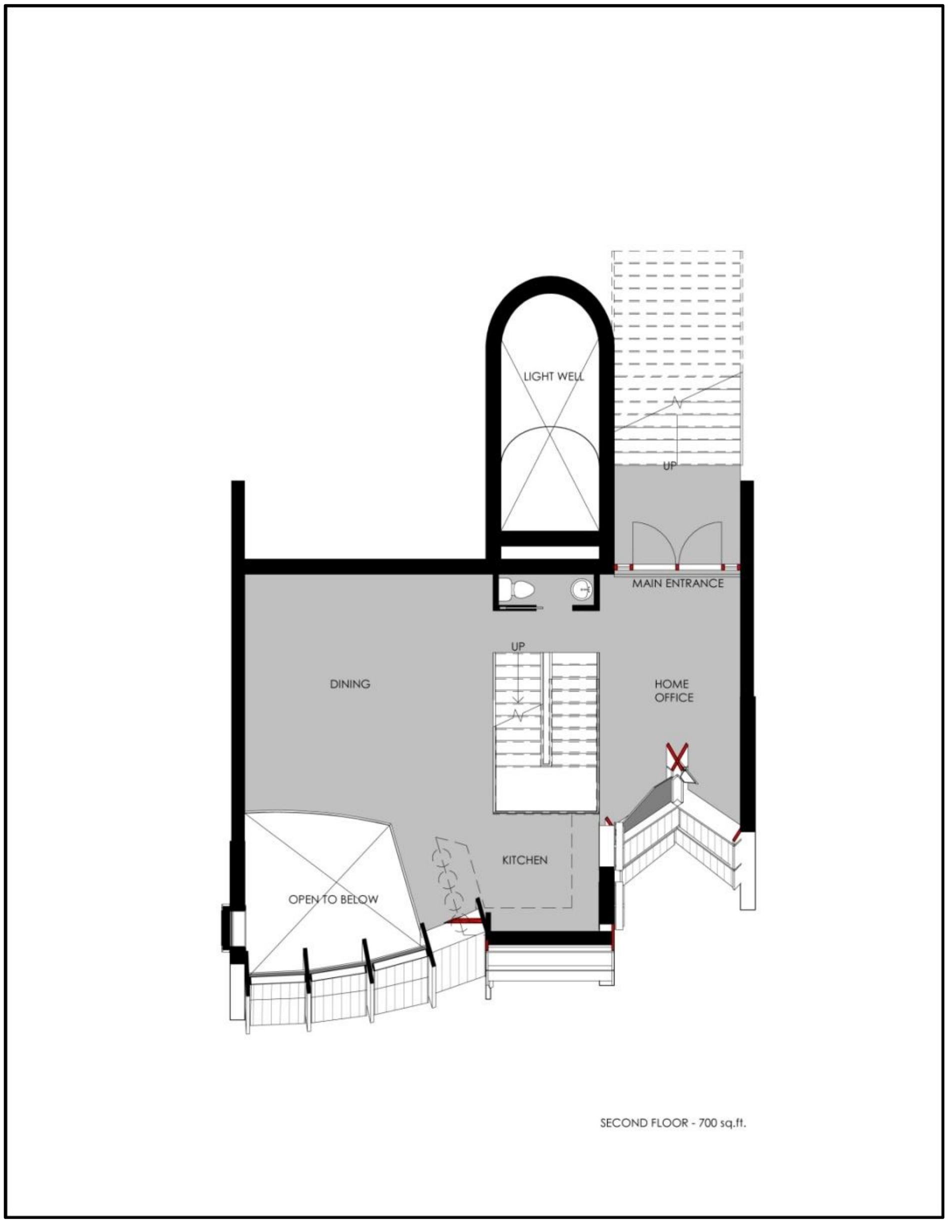


Figure 64 - 2nd Floor Plan

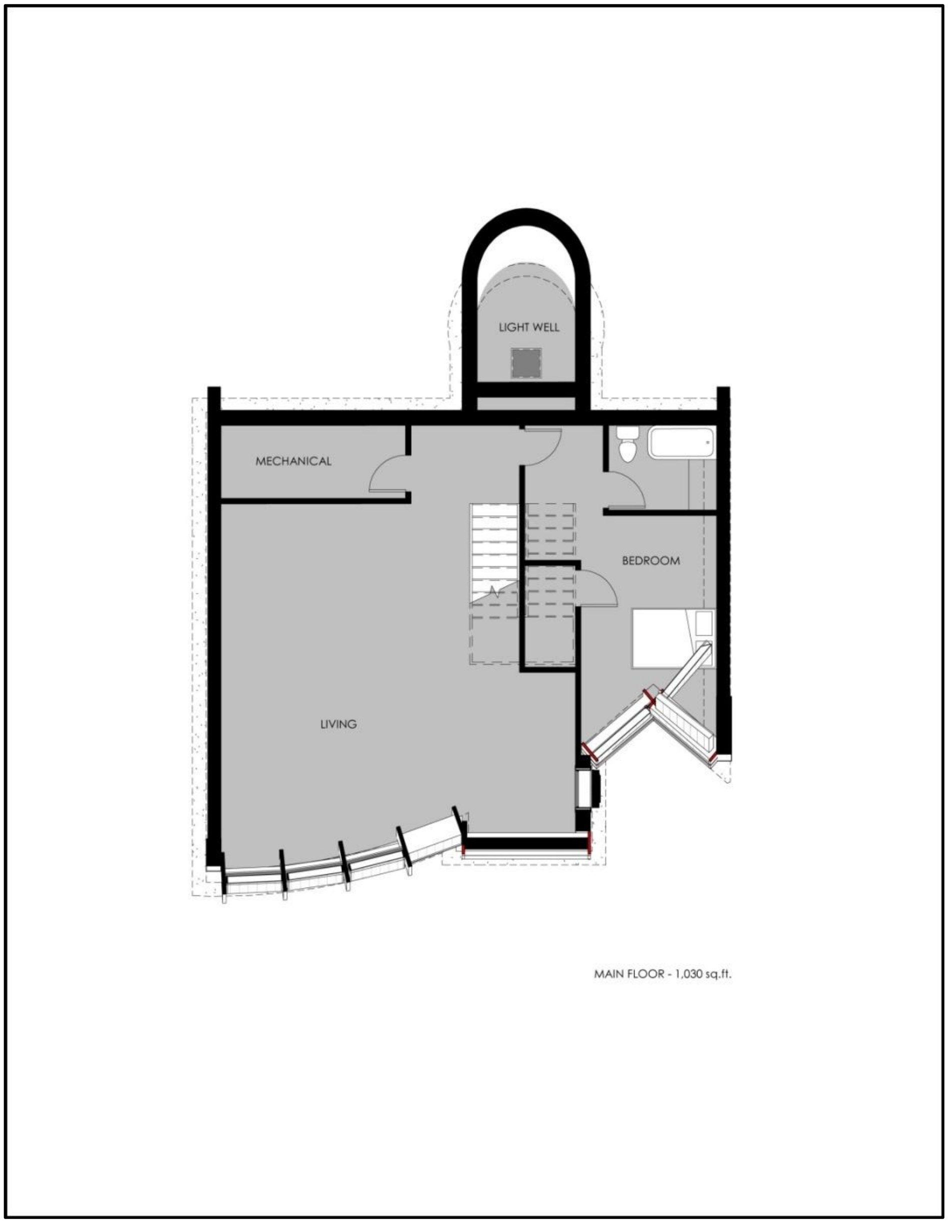


Figure 65 - Main Floor Plan

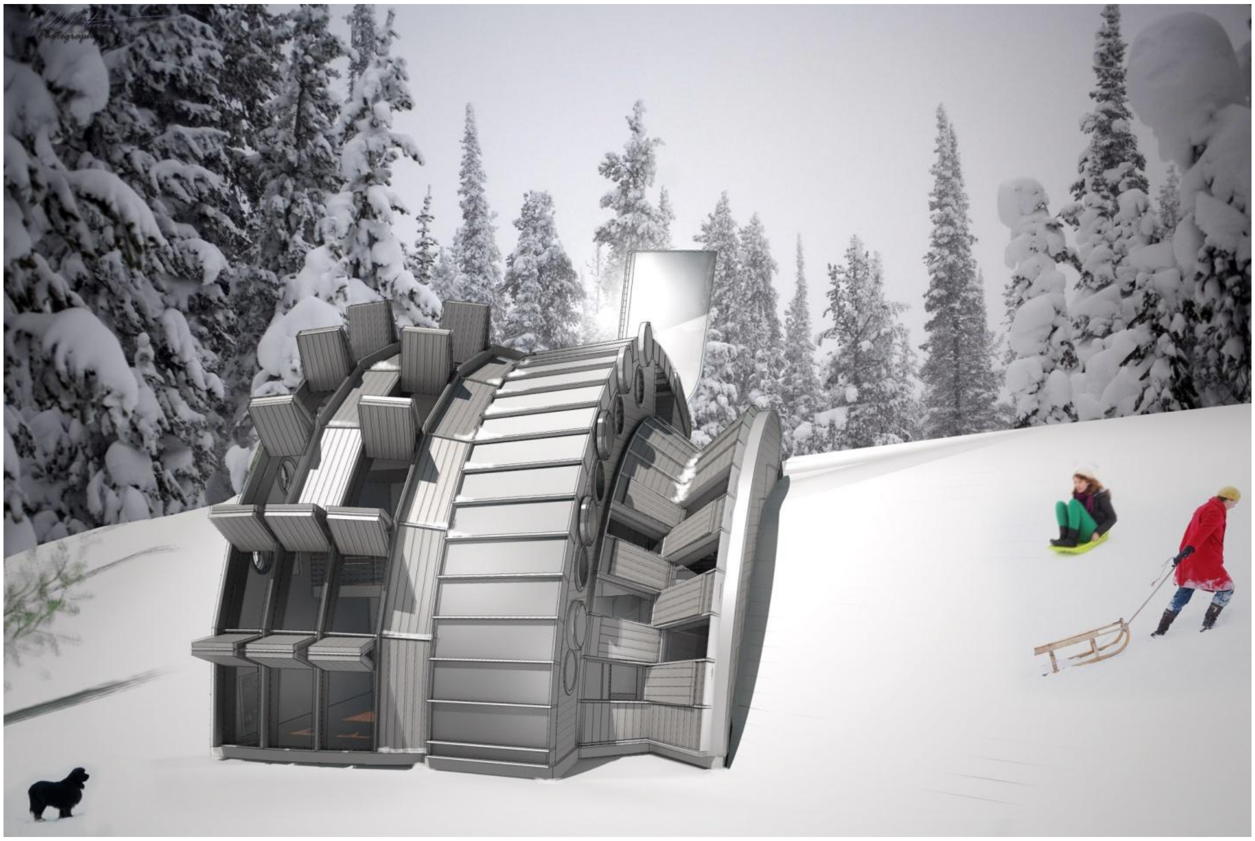


Figure 66 - ArcHelio Final Design Sketch

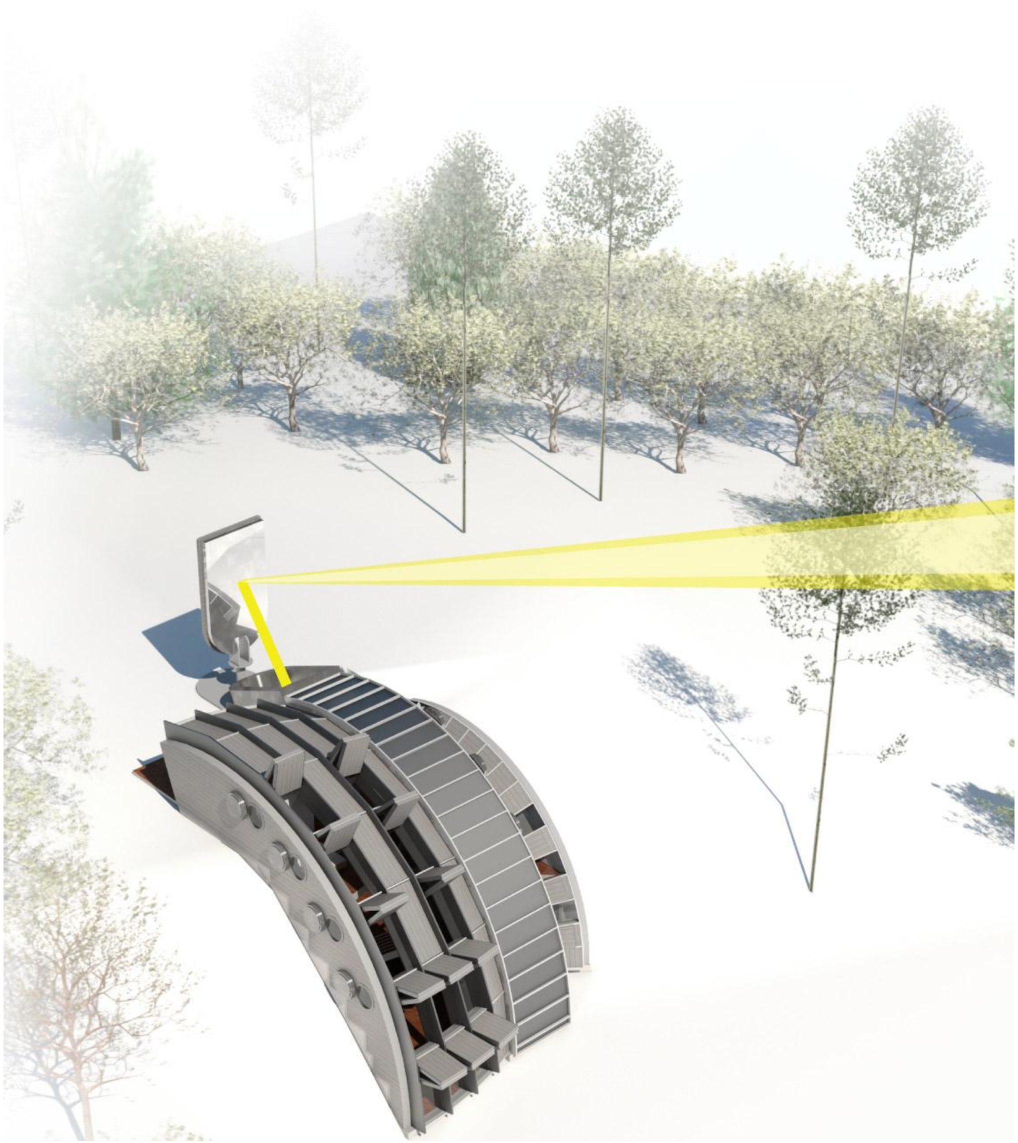


Figure 67 - ArcHelio Final Design Showing the Working Heliostat

DESIGN DETAILS & COMPONENT ANALYSIS

Each component of the exterior envelope was designed and modelled in Therm software to ascertain the U-values of the assemblies. These values were then inserted into ArcHelio software to develop the entire heat loss calculation.

A hybrid wall system was used for the solid part of the envelope. Hollow galvanized structural sections (HSS) were used as both an interior skeleton and an exterior exoskeleton. The exterior structure supports the operable shutters and the exterior steel roofing. The interior structure supports the windows and other openings. By separating the structure on the inside and the outside of the building, most thermal bridges are eliminated, thus greatly reducing heat loss. Structural insulated panels (SIPS) were used as the walls system, and are sandwiched between the exoskeleton and the interior skeleton. The sandwiching also virtually eliminates thermal bridging.

The window frames are fiberglass, and are supported on the interior skeleton. A fiberglass end cap covers the exposed SIPS panel at the window opening. An insulated shutter system has been designed to cover the windows, when natural light is not required and for reducing heat losses when not being used to provide day lighting. The shutters are composed of smaller self-supporting SIPS panels that are designed to simply fold over the windows to offer insulation value when in operation as insulators.

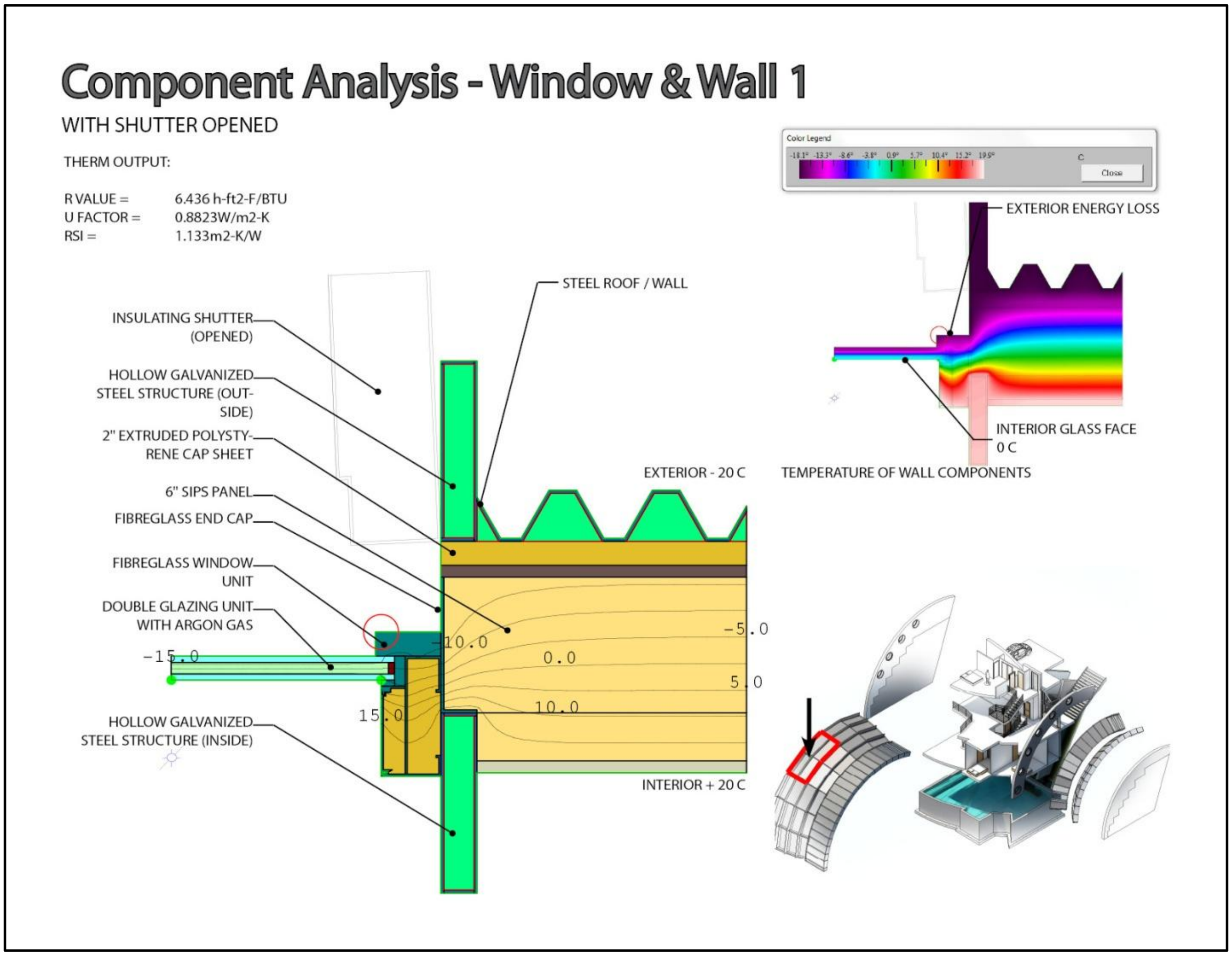


Figure 68 - Window and Wall Section 1 Without Shutter

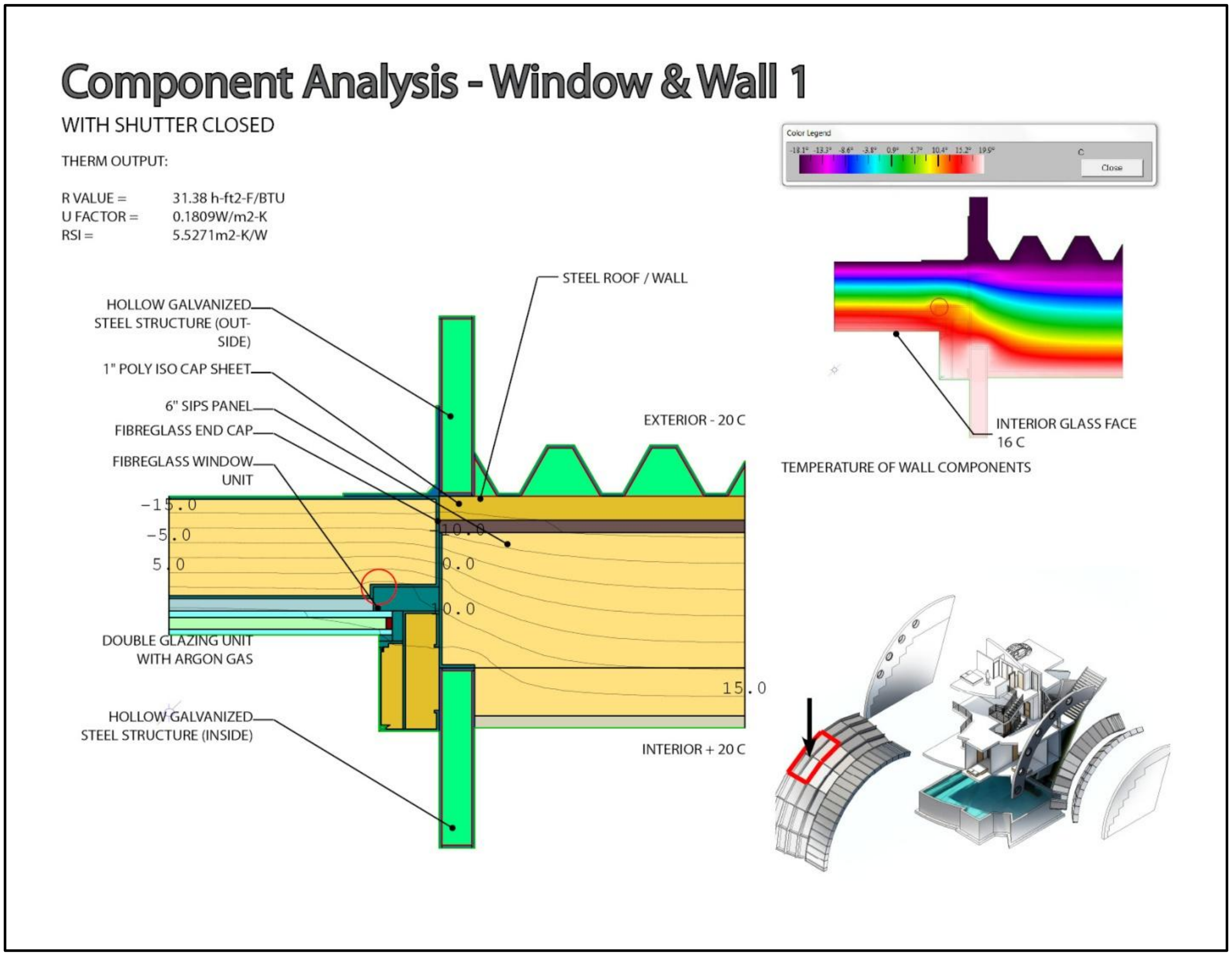


Figure 69 - Window and Wall Section 1 With Shutter

With the shutters closed, the energy loss through the glazing is drastically reduced. Based on the Therm calculations, the thermal resistance of the windows is increased by approximately 5 times. With the shutter closed the U factor is 0.18 W/m^{2}K with an R Value of 31. With the shutter opened, the U factor is 0.88 W/m^{2}K with an R Value of 6.4.

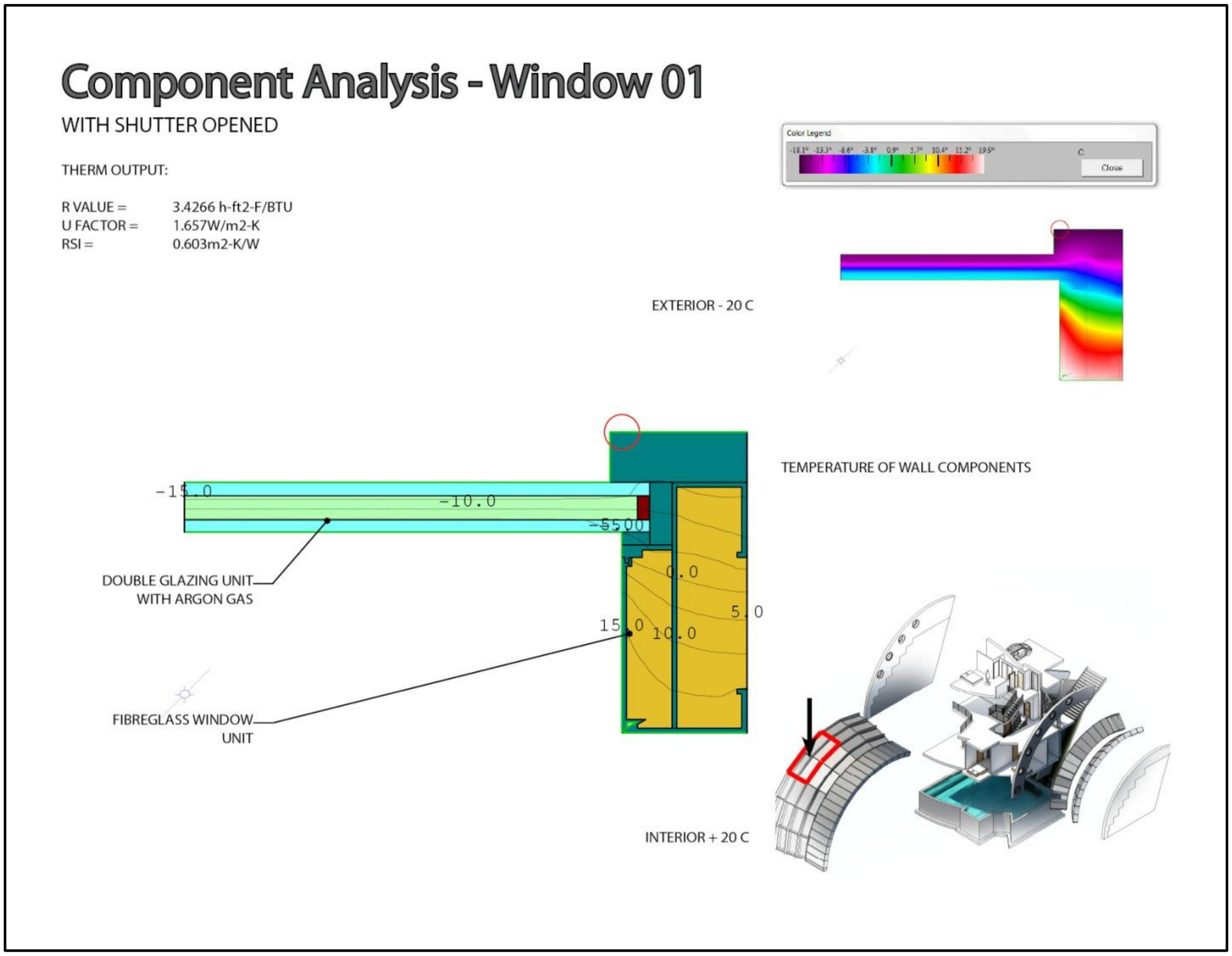


Figure 70 - Window System 1 Without Shutter

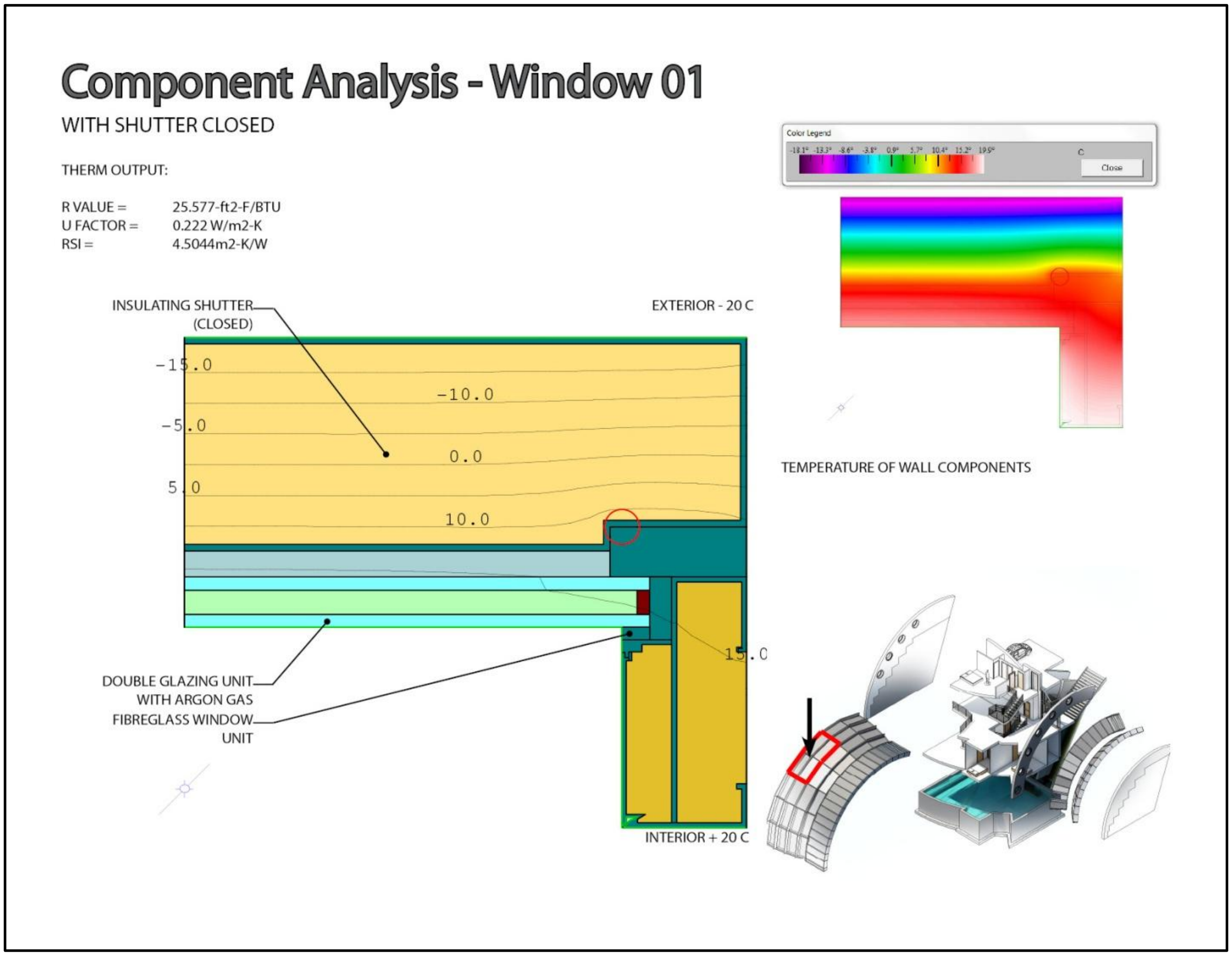


Figure 71 - Window System 1 With Shutter

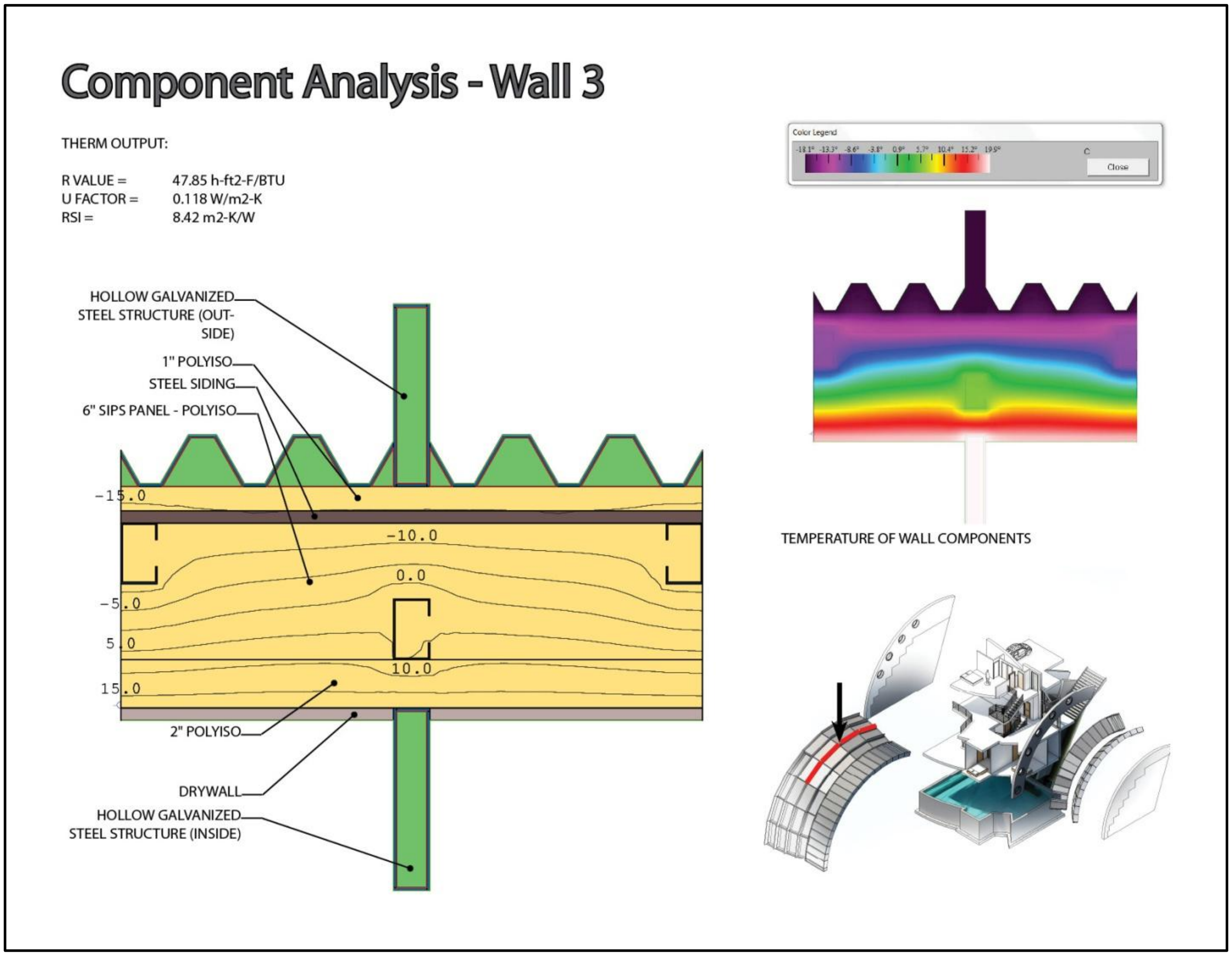


Figure 72 - Wall Section 3

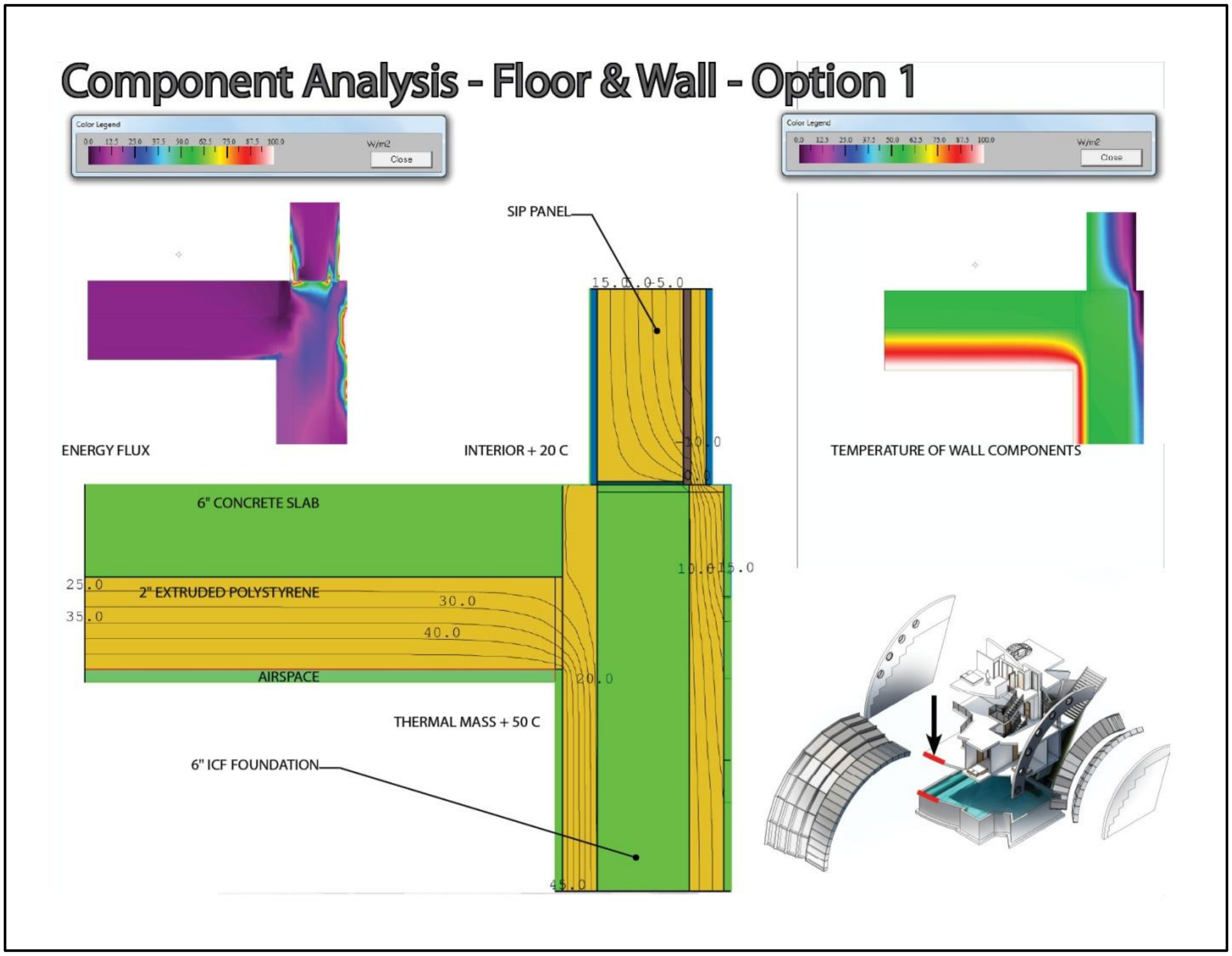


Figure 73 - Floor and Wall Connection 1

The foundation wall and the tank wall have been designed as insulated concrete forms (ICF) because of their exceptional insulation value, and rigidity. The connection between the SIPS panel system and the ICF system is typically a large thermal bridge for a building. See Figure 73. In the energy flux diagram, there is a large energy exchange between the inside of the building, and the outside.

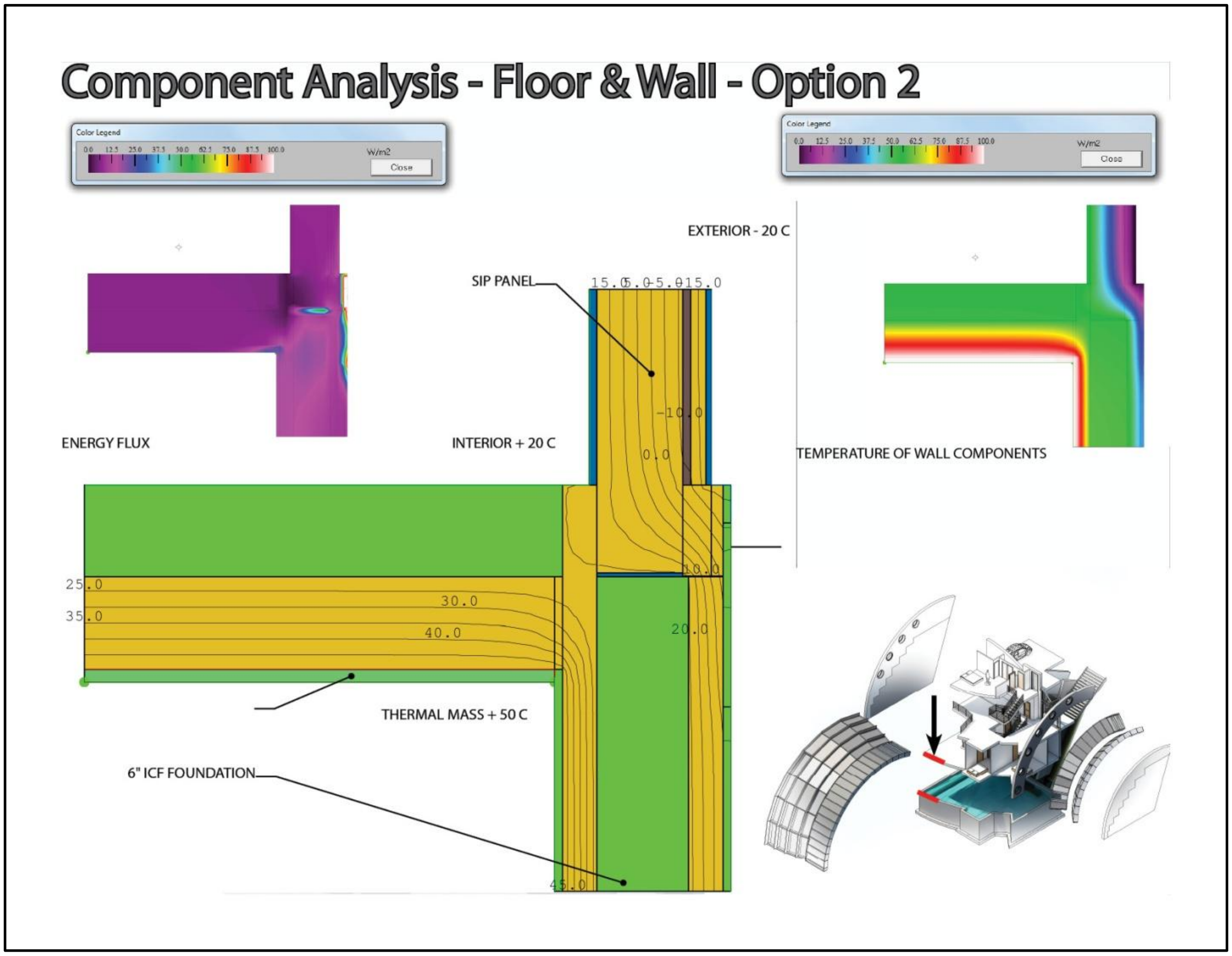


Figure 74 - Floor and Wall Connection 2

By extending the ICF panels 300mm (1'-0") up and integrating with the SIPS panel, the thermal bridge at the connection is drastically reduced, as shown in Figure 74. The energy flux moving through the connection is significantly less.

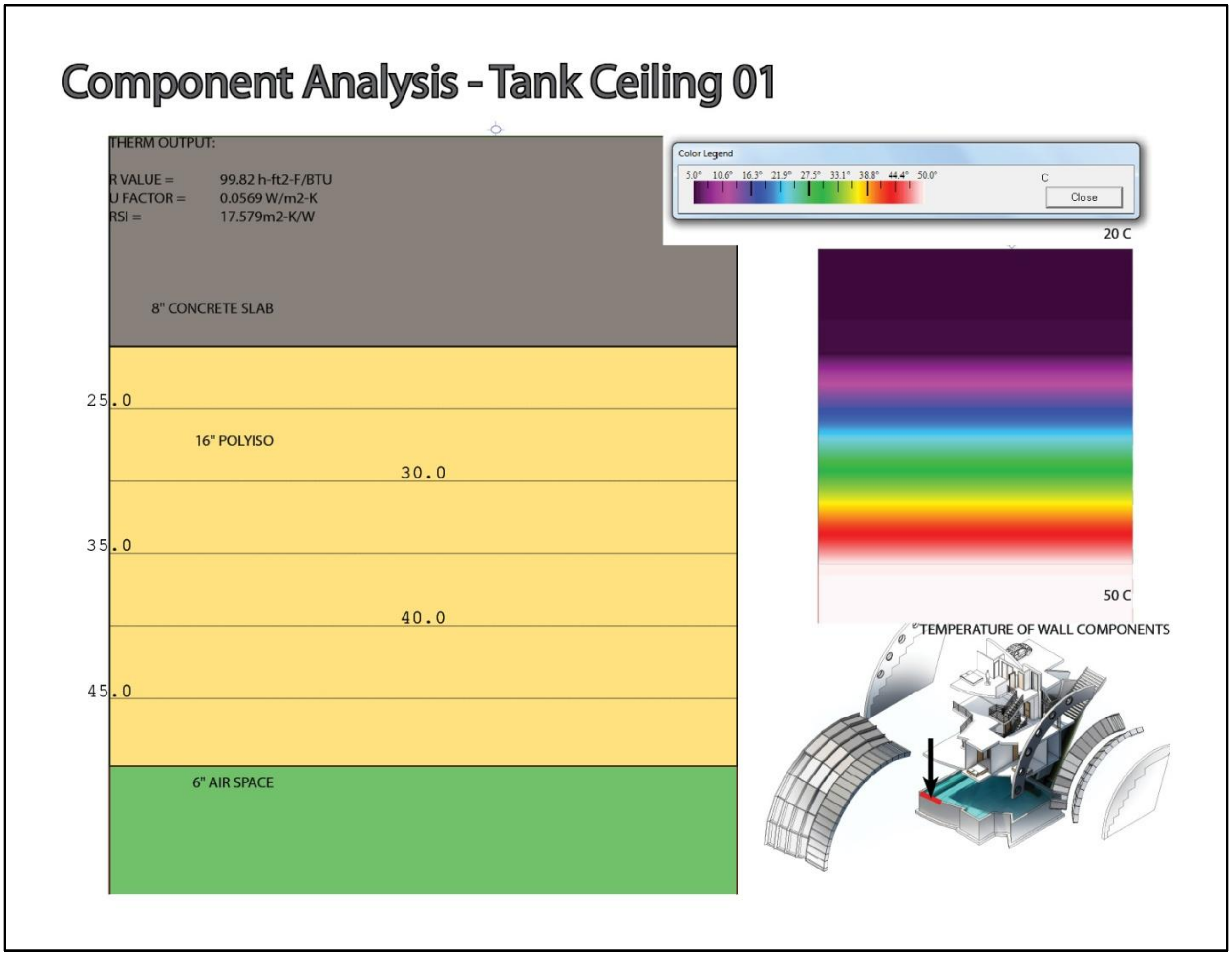


Figure 75 - Tank Ceiling

The tank ceiling and dwelling floor intersection is also critical. Based on the ArcHelio software, the tank temperature can peak 40°C (104°F) above the temperature of the dwelling. To decrease the heat transfer between the thermal mass and the dwelling in the "charging" months, the assembly between the two areas must be extremely well insulated. Figure 75 shows the thermal gradient through this assembly.

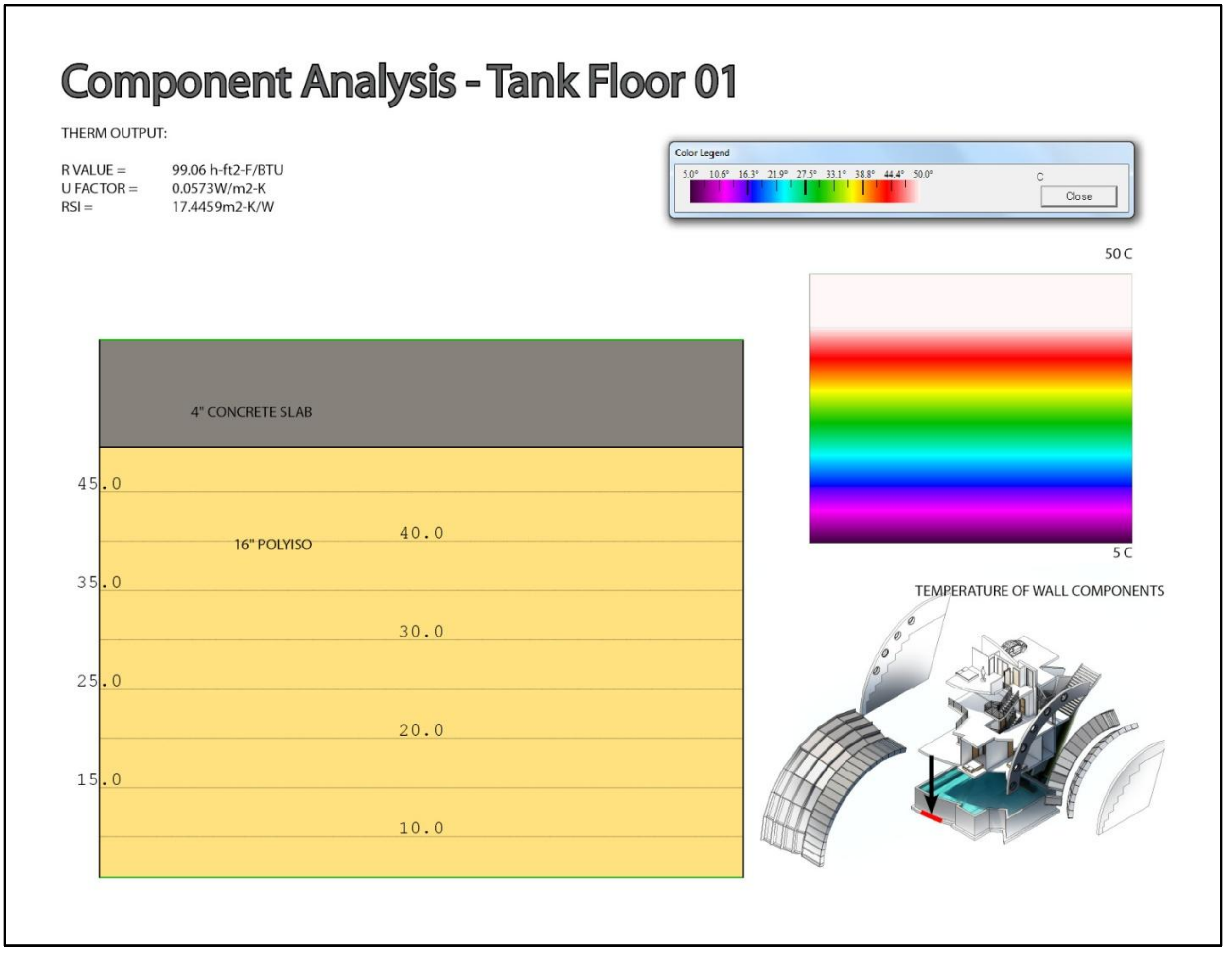


Figure 76 - Tank Floor

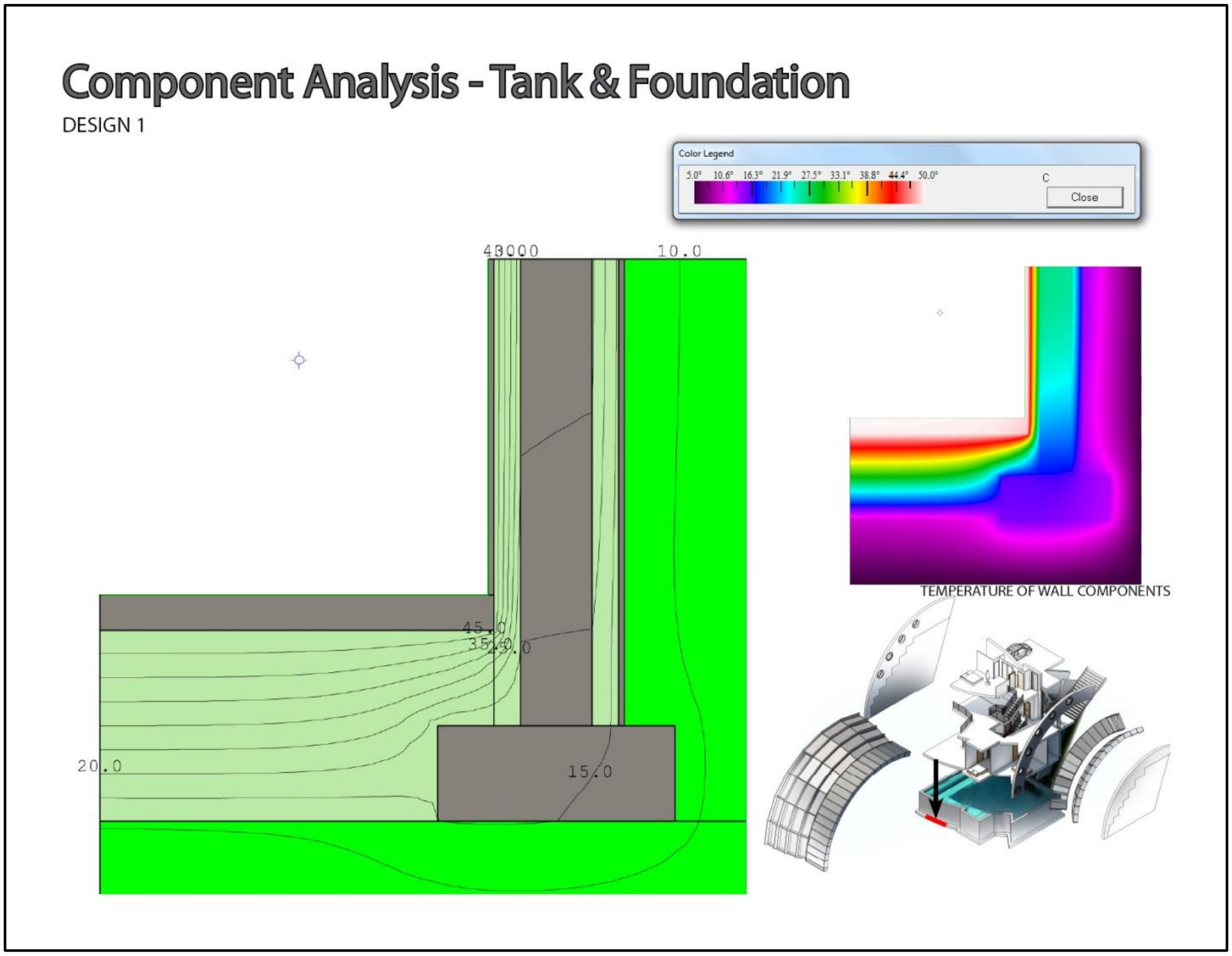


Figure 77 - Tank & Foundation

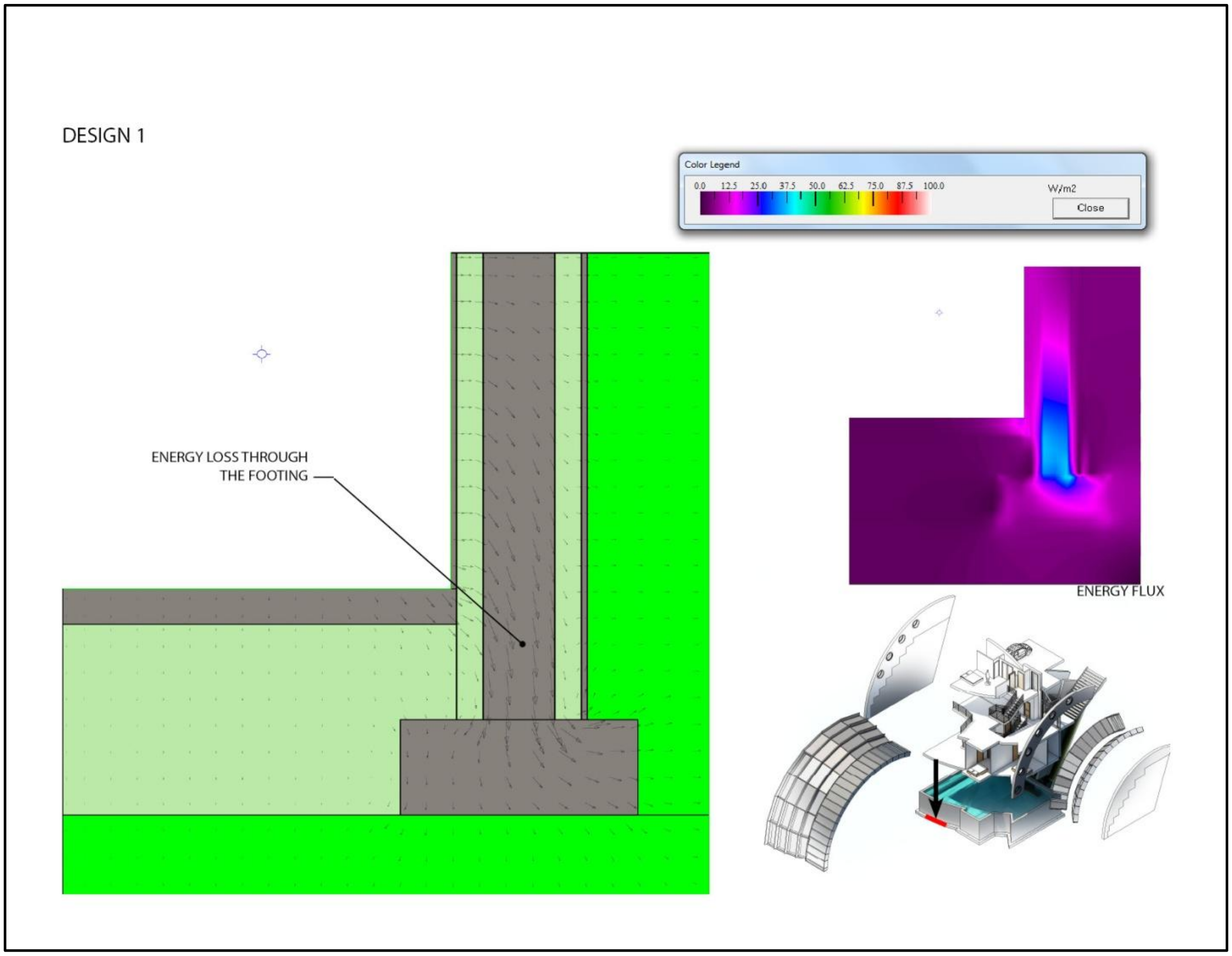


Figure 78 - Tank and Foundation - Therm Vector Diagram

A highly charged thermal mass, embedded below a building will lose a significant amount of energy through the concrete footing. Figure 78 shows the pathway of the energy loss through the ICF / footing connection. Further study is required to reduce these losses.

CHAPTER 9 - ARCHELIO SOFTWARE

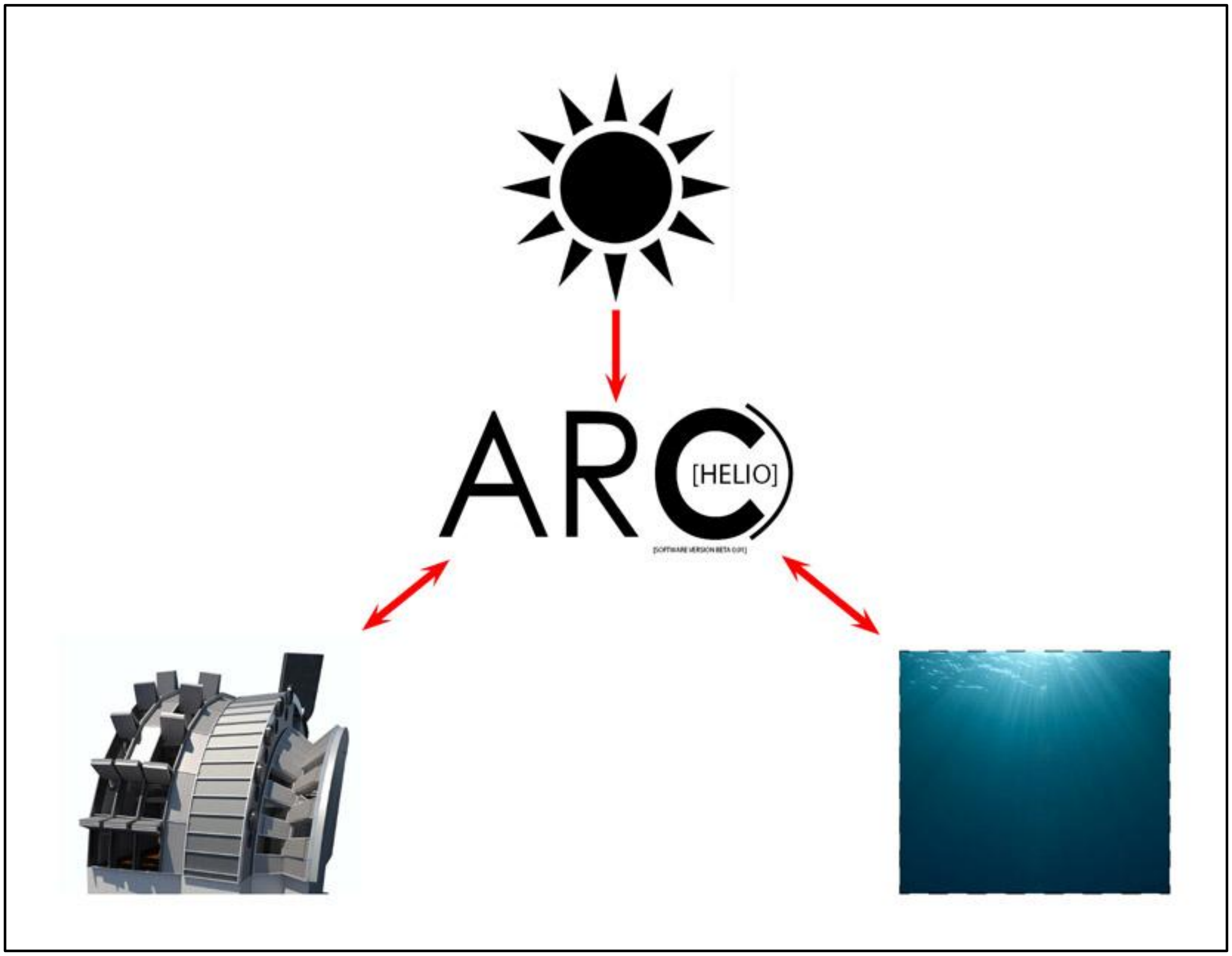


Figure 79 - ArcHelio Software

The HelioArc software mathematically simulates and models the hourly operation and interaction of Design 3, with the historical climate data. The software has been designed to be scalable, so in the future other locations on the Earth and building types can be modelled. The present version of the software takes the following issues into account:

The Heliostat

- The size of the Heliostat
- The type of Heliostat - Heat gain available from the sun less the efficiency losses of the reflector system
- Sky Conditions - Is energy available from the sun at that particular time?
- Do the gains of the system outweigh the losses at a particular time?

The Thermal Mass

- Heat loss to the dwelling under varying temperatures
- Heat loss due to conduction and convection to the exterior under varying temperatures and wind velocities
- Heat loss through the inlet under varying temperatures
- Heat gain from the Heliostat
- Temperature limitations of the mass - The charging of the mass is maintained between room temperature and the boiling point of water

The Dwelling

- Heat loss of the assemblies under varying temperatures
- Window Shutter control - Are the shutters opened or closed?

The program summarizes these components into a single heat loss calculation that ultimately shows the final temperature of the thermal mass at the end of each hour, over a simulated 6 year period. The output is a graph that shows the temperature of the thermal mass at any one time within the 6 year period.

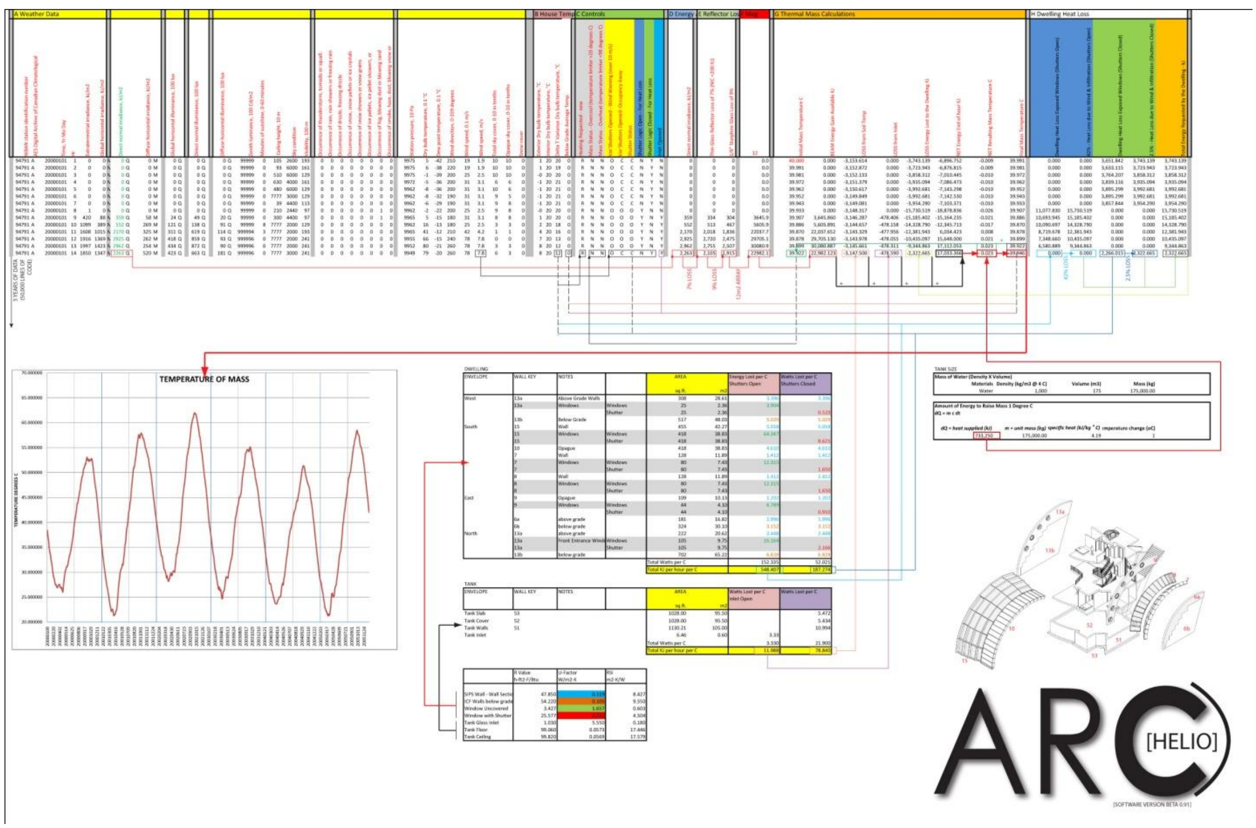


Figure 80 - ArcHelio Software - Software Design Sketch

SIMULATION BASE DATA

The HelioArc base data is derived from historical weather data from the Canadian Weather Energy and Engineering Data Sets (CWEEDS files) and the Canadian Weather for Energy Calculations.

(CWEC files) The files used were revised by the Meteorological Services of Canada and The National Research Council of Canada on October 23, 2008.

THE CWEEDS file sets are hourly data sets of weather conditions occurring at 145 Canadian locations. Some of the locations have been recording data for 48 years. The data set used in this particular instance is for Toronto Pearson Airport. The dataset has been condensed in this instance, using the data between January 1, 2000 and December 31, 2005. This 6 year span was used as it provides a broad representation of the variety of climate conditions for this particular location. Initially the program was set up to simulate 50 years of data, however, that proved to overwhelming for today's CPU's. However, it is important to recognize that the climate of a particular location fluctuates and the conditions one year may vary significantly in the next year. For accuracy and dependability, the HelioArc requires a large set of data. Climate data can vary greatly year to year.

PROGRAM EXPLANATION

To explain the operation of the program, I will show the calculation for a single hour of the operation of the system. The hour chosen, in this case is January 1, 2000 at 12:00 noon. It is listed as cell 14 in the Excel chart, and is shown in red. Each calculation is listed as a step below. At the top of the spreadsheet, the different colors indicate the different sections of the program.

Program Sections:

- Section A - CWEEDS data
- Section B - Dwelling temperatures

- Section C -Controls & Logic
- Section D - Energy Available from the Sun
- Section E - Reflector Losses
- Section F - Magnification of the Heliostat
- Section G -Thermal Mass Calculations
- Section H - Dwelling Heat Loss Calculations

Step 1 - CWEEDS Data

The Direct Normal Irradiance available from the sun, as taken from the CWEEDS file for Toronto Pearson Airport is listed as 2,925 KJ/m^2 (271 KJ/ft^2) See Cell BI14. CWEEDS defines Direct Normal Irradiance as the "portion of the radiant energy received by a pyranometer directly from the sun, during the hour ending at the time indicated in field 003. These are the actual values of the energy available from the sun, for the indicated hour. In this case, the CWEEDS pyranometer at Pearson Airport, tracks the location of the sun throughout the day, by keeping the pyranometer oriented to the incoming rays. The program takes the data at Cell BI14, and transfers the number into Section D - Energy Available from the Sun.

Step 2 - Heliostat Loss

A thin glass reflector, will transmit approximately 93% of sunlight, across all available sunlight frequencies. This is calculated as follows:

Reflector light transmitted = 2925 KJ/m^2 * 93% = 2,720 KJ/m^2 (252 KJ/ft^2) per hour. See cell BP14.

When this equation is applied, it calls for the closing of the heliostat giving a 0 value to all sunlight values when the theoretical reflector light transmitted is under 200 KJ/m^2 (19 KJ/ft^2). This control anticipates that more energy is lost through the exposed inlet than gained in the early morning / late evening hours or in cloud cover conditions. Keep in mind that the heliostat will not function and will provide a 0 value on 100% cloudy days, since diffuse light cannot be concentrated.

Step 3 - Inlet Loss

The light from the sun enters the Starphire glass inlet, which seals the thermal mass from the environment. The glass will reduce the radiant and infiltration thermal losses to the exterior, much the same way a window in a house reduces heat loss. The Starphire glass will allow 91% of all available sunlight frequencies through.

Light Transmission = 2,720 KJ/m^2 * 91% = 2,475 KJ/m^2 (230 KJ/ft^2) per hour. See cell BS14.

Step 4- Size of Heliostat

The present 2,475 KJ/m^2 (230 KJ/ft^2) represents the amount of KJ hitting 1 m^2 (10.7 ft^2). By capturing more than 1 m^2 (10.7 ft^2) of light, you can increase the amount of light reflected based on the multiplying factor.

Therefore a 12m^2 of reflector area would result in:

2,475 KJ * 12m^2 = 29,705 KJ/m^2 (2,759 KJ/ft^2) of energy per hour

The mirror in the design is concave only to reduce the size of the inlet opening. It is important, that from the perspective of the sun, the 12m^2 (129 ft^2) must be the reflected area, no matter where the sun is in the sky. Because the mirror will be at varying angles, the actual captured area will vary throughout the day. This variance is not accounted for in this program and may be available in later editions.

Step 5 - Initial Mass Temperature at start of hour (before beam & losses)

This is the average temperature of the entire thermal mass, before the energy from the heliostat is used.

In this case, it is:

Thermal Mass = 39.924°C (103.8632°F) See cell BW14

Step 6 - Beam Energy Gain Available

If the temperature of the thermal mass is above room temperature 20°C (68°F) and below the boiling point water, in this case, 98°C (208°F) (it is not 100°C (212°F) to provide a 2°C (35.6°F) degree buffer) the new energy is transferred into the thermal mass. By keeping the mass above room temperature, an energy transformation (e.g. using a heat pump) becomes unnecessary. This control is managed the controls section, which is section C of the program. The results of the logic are shown in cell BY14.

Therefore 39,606 KJ * logic control =

39,606 KJ of energy per hour is available

Step 7 - Thermal Mass Loss from Soil Temperature - Heat Loss Calculation

Each hour, there will be loss of the thermal mass to the environment, dependent on the temperature of the mass, and the temperature of the environment. The thermal resistance of the envelope of the mass was calculated using LBNL Therm software. The program has calculated that 78.84 KJ per hour per °C are lost to the environment. See the TAB "HLC & Variables" in HelioArc for details on how the heat loss is calculated. The Equation is explained below:

Q=U*A* ΔT

Q=Energy lost (KJ converted from Watts)

U=U-Factor of material or assembly with air films (W/M^2-K) (Btu/hr-sq ft-°F)

A=Area (M^2) (ft^2)

ΔT=Temperature Difference (°C) (°F)

The ΔT is calculated from the temperature of the mass shown in cell BW - 39.924°C (103.86°F) and the average below grade temperature, in this case shown as 0°C (32°F) in cell BC14. The average below grade temperature varies throughout the year, see column BC in HelioArc for details.

Therefore the ΔT is as follows:

ΔT = (39.924°C(103.8632°F) - 0°C (0°F)

= 39.924°C (103.8632°F)

Therefore the heat loss calculation is:

ΔT*Energy lost per °C per hour

= 39.924°C (103.86°F) * 78.84 KJ

=3,147 KJ lost in that particular hour

Step 8 - Thermal Mass Energy Loss from Inlet - Heat Loss Calculation

When the Heliostat is in operation, additional energy is lost through the Starphire glass inlet. Cell CA14, calculates whether or not the inlet is opened through the controls section. If the inlet is open, HelioArc calculates how much energy is lost through the inlet, again, using the heat loss equation. The heat loss calculation is shown under TAB "HLC & Variables" in HelioArc.

Therefore the heat loss calculation is:

ΔT*Energy lost per °C (°F) per hour

=478.614 KJ lost in that particular hour

Step 9 - Energy lost to the dwelling for heating purposes from the thermal mass - Heat Loss Calculation

This is the main heat loss calculation for the dwelling. It considers whether or not the insulating shutters over the windows are open. CB14 calculates the total heat loss for the dwelling, and therefore the total heat requested from the mass. The calculation also considers the ΔT of the exterior temperature of the dwelling, when compared to the interior temperature of the dwelling. The Heat loss calculation is shown under TAB "HLC & Variables" in HelioArc. There are two columns of losses, one for shutters open and one for shutters closed.

In this case, 10,435.097 KJ are requested from the thermal mass to heat the dwelling.

Step 10 - Net Energy End of Hour

This cell tallies the net gains minus the losses for the hour. At the end of this particular hour, 25,545 KJ will be absorbed by the thermal mass, therefore increasing the temperature of the thermal mass.

Step 11 - Net Resulting Mass Temperature at End of Hour

HelioArc next takes the resulting excess energy completed in Step 10, and apply it to the thermal mass using the specific heat capacity equation.

The specific heat capacity of water is 4.19 KJ/Kg °C (1°Btu/lb_m degR) See HelioArc TAB "HLC & variables" Cell L18.

The equation is as follows:

$dQ = m\ c\ \Delta T$

dQ = Heat Supplied (KJ)

m = thermal mass (kg) (lbs)

c = Specific heat of thermal mass (kJ/kg °C) (Btu/lb_m degR)

ΔT = 1°C (1°F)

dQ = 250,000 kg (551,155 lbs) (of water) * 4.19 KJ/Kg°C (1°Btu/lb_m degR) * 1°C (1°F)

dQ = 1,047,500 KJ

Therefore 1,047,500 KJ of energy is required to raise 250,000 kg (551,155 lbs) of water, 1°C.

Therefore, if only 15,648.000 KJ are available as shown above in Step 10, the mass will only be raised 0.024°C in that particular hour. See Cell CD14, in HelioArc.

Step 12 - Final Mass Temperature at End of Hour

Helio Arc now simply will add the 0.024°C net gain over the hour, to the temperature at the start of the hour. See Cell CE14.

This cell is then transferred down one row into column BS, and the entire process starts again for the next hour.

Results of the HelioArc

The software will output the temperature of the thermal mass, at any given hour, throughout the 6 year analysis period in a graph format. By computerizing the calculation process, the user can vary all of the design elements, including the heliostats, size of the thermal mass, and the dwelling heat loss. The user than can quickly size the elements based on the site conditions. Varying the sizing of elements will have different effects on the calculation results.

Example 1 - 125m^3 (125,000 L) (33,000 gallons) Thermal Mass, 16m^2 (172 sq.ft.) Heliostat

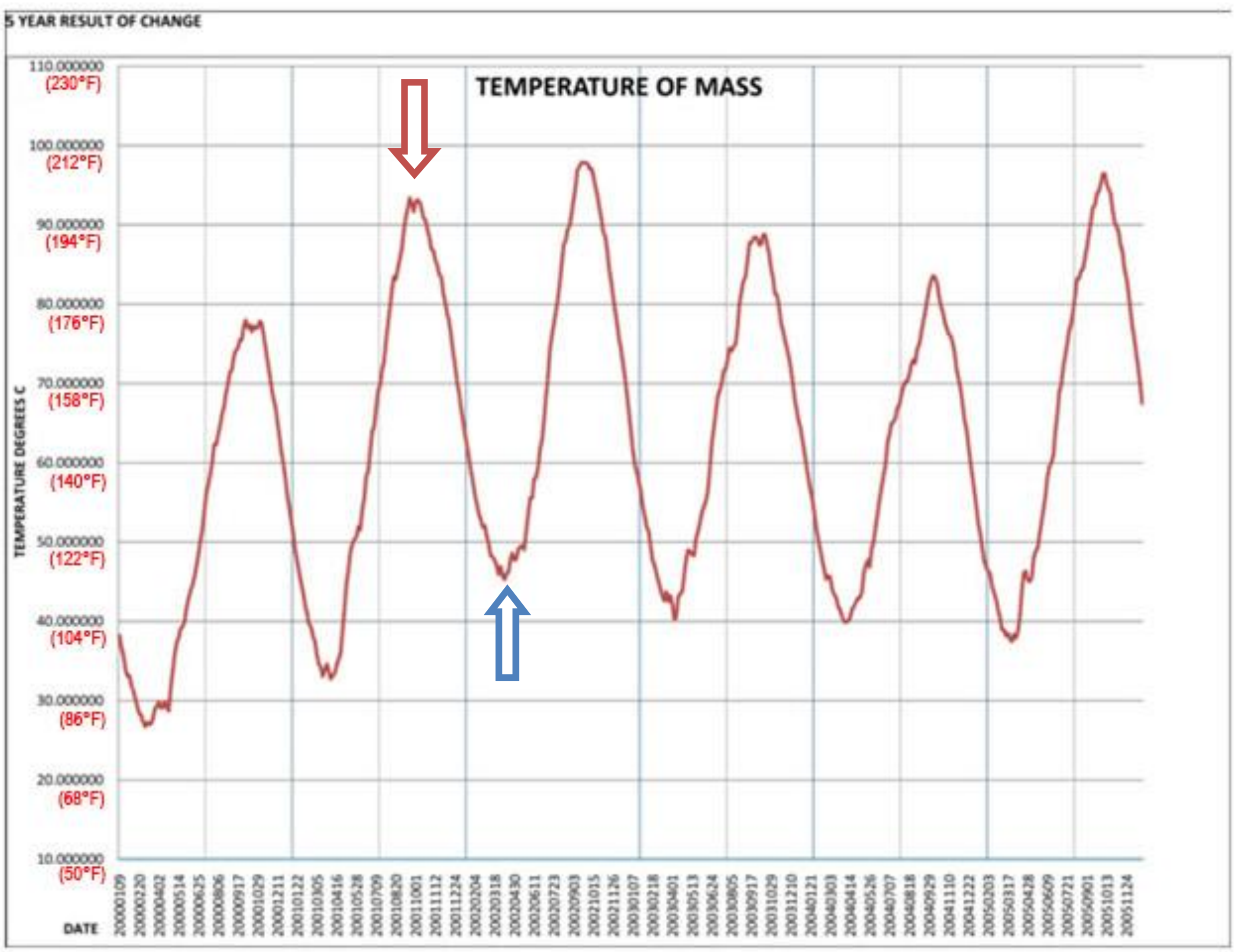


Figure 81 - Example 1 - Graph by Mark Driedger

In example 1, one can see the heating and cooling of the thermal mass over time. The red arrow indicates the end of the thermal mass charging season, and the start of the heating season. From the calculation, this appears to typically take place in October of each year for the designed system in the Toronto area. The blue arrow indicates when the charging of the mass resumes. This is typically in April every year for the designed system in the Toronto area.

Example 2 - 250m^3 (250,000 L) (66,000 gallons) Thermal Mass, 16m^2 (172 sq.ft.) Heliostat

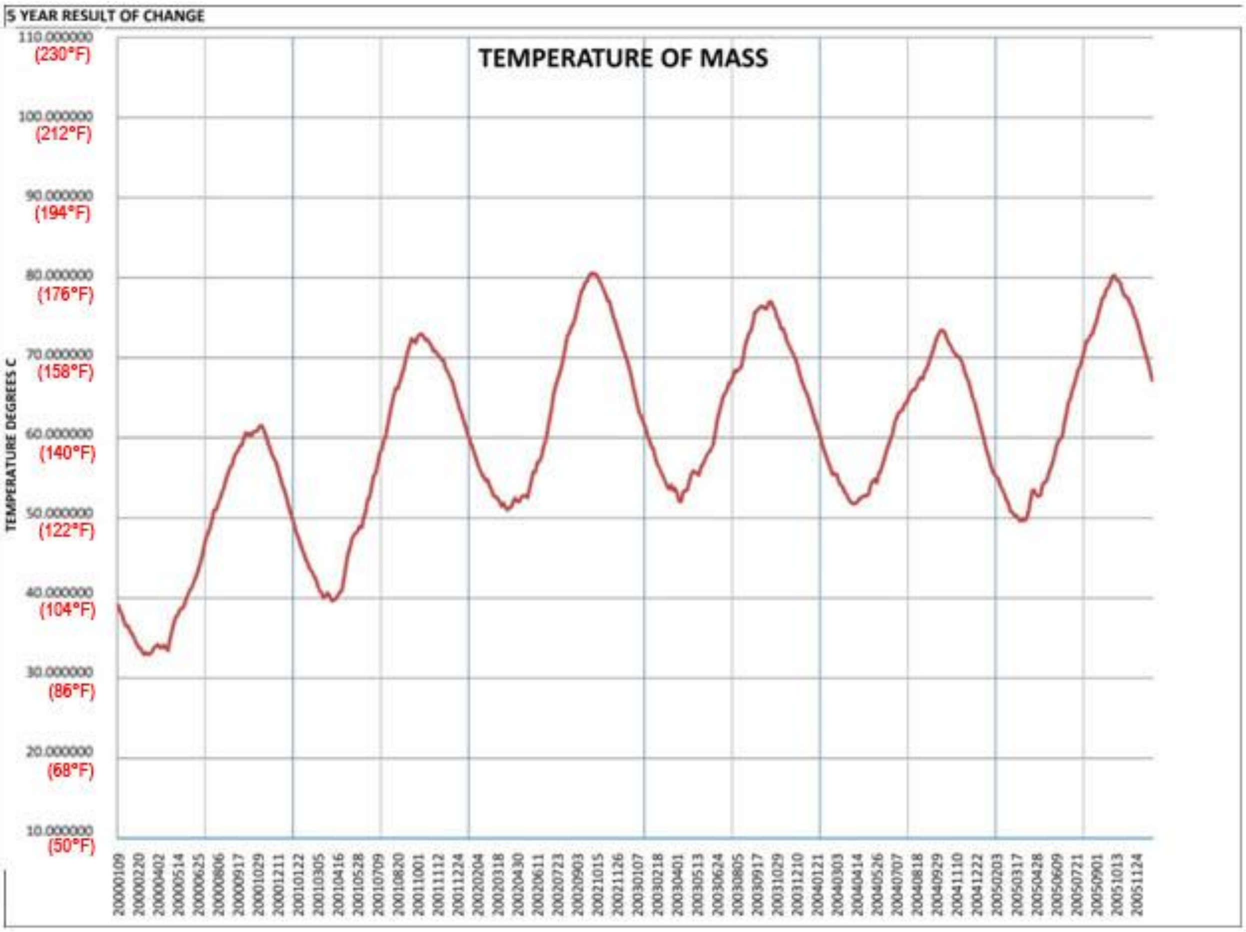


Figure 82 - Example 2 - Graph by Mark Driedger

In Example 2, the thermal mass has been doubled in size. The larger the mass, the less the temperature fluctuates. Lower temperatures, also reduce the temperature differential between the mass and the surrounding environment, leading to improved efficiency and reduced losses to the exterior. A lower temperature mass, may be a more efficient way of storing the energy. However, a larger mass is difficult dimensionally to manage on a site.

Example 3 - 250m^3 (250,000 L) (66,000 gallons) Thermal Mass, 9m^2 (97 sq.ft.) Heliostat

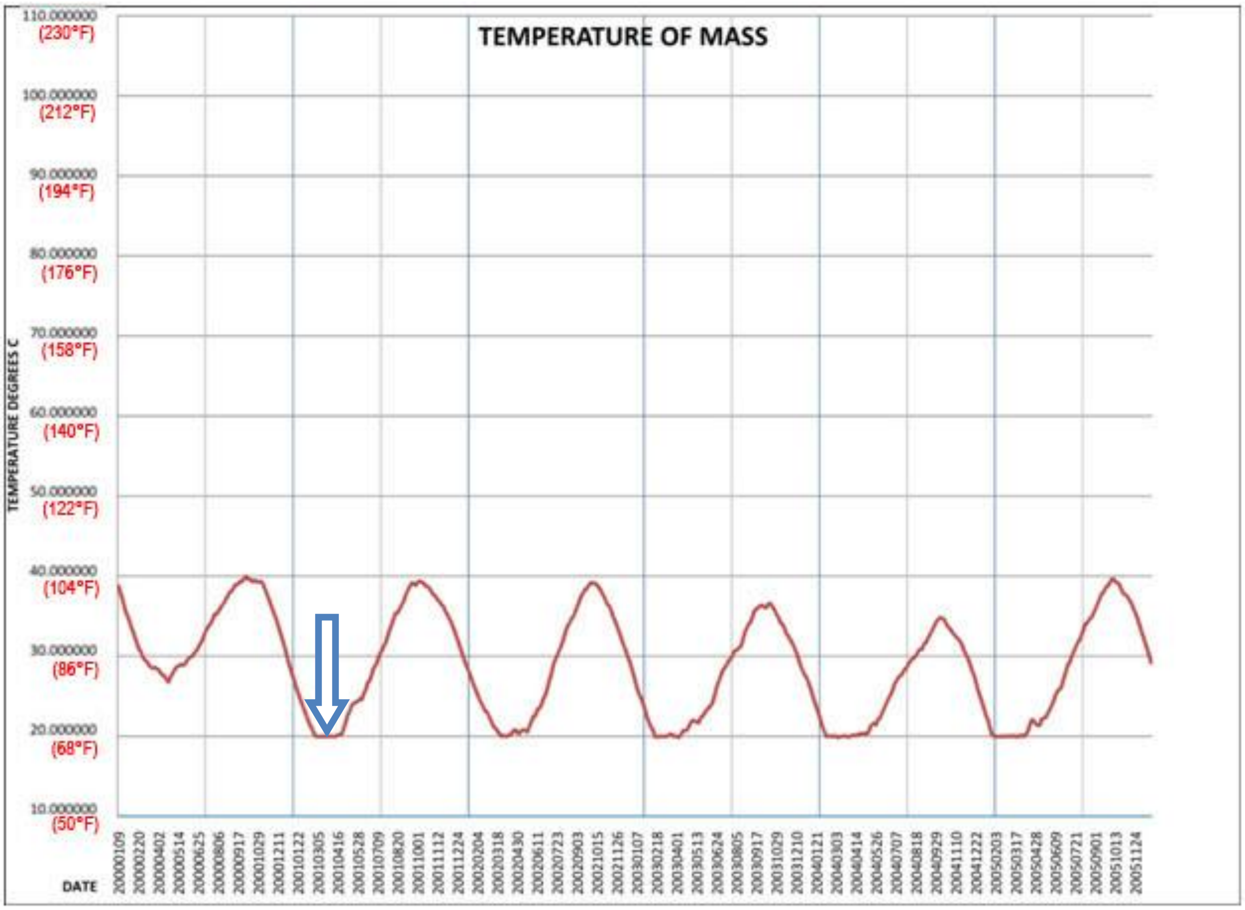


Figure 83 - Example 3 - Graph by Mark Driedger

In example 3, the heliostat has been reduced in size. The temperature of the mass immediately is reduced, however, the control system of the ArcHelio software is in operation, not allowing the building to draw energy from the mass, in late winter, when the mass temperature is below room temperature. The flat section of graph, indicates a failure in the system to provide energy at that particular time. In a situation like this, the heliostats are continuously charging the mass to maintain temperature, although the system is not directing heating energy towards the house.

Example 4 - 125m^3 (125,000 L) (33,000 gallons) Thermal Mass, 9m^2 (97 sq.ft.) Heliostat

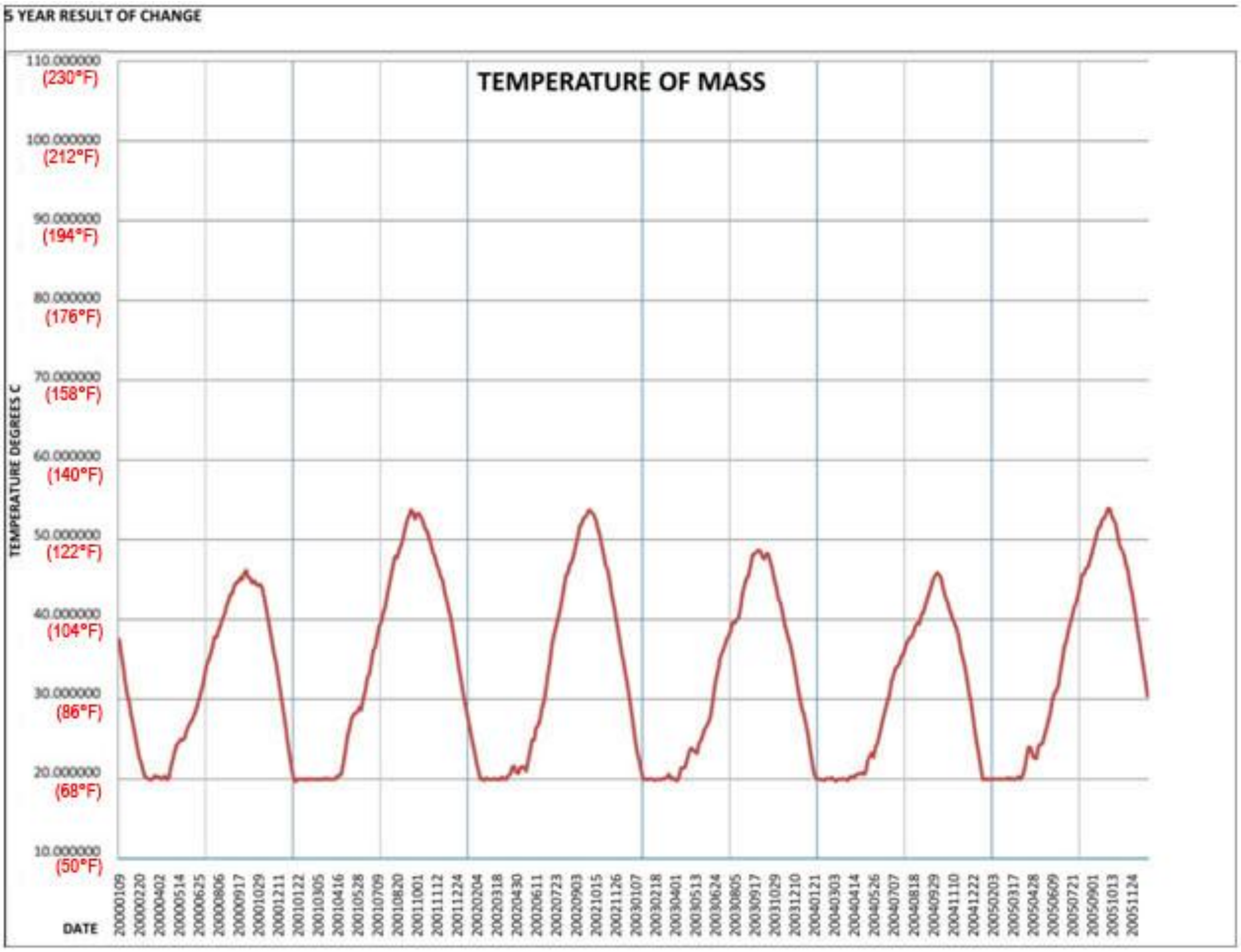


Figure 84 - Example 4 - Graph by Mark Driedger

Example 4 further reduces the size of the mass. This allows for increased temperatures of the thermal mass. The system again, does not have the capacity to carry the temperature through the winter months. The failure occurs earlier than the other examples in January.

Example 5 - 200m^3 (200,000 L) (53,000 gallons) Thermal Mass, 12m^2 (130 sq.ft.) Heliostat

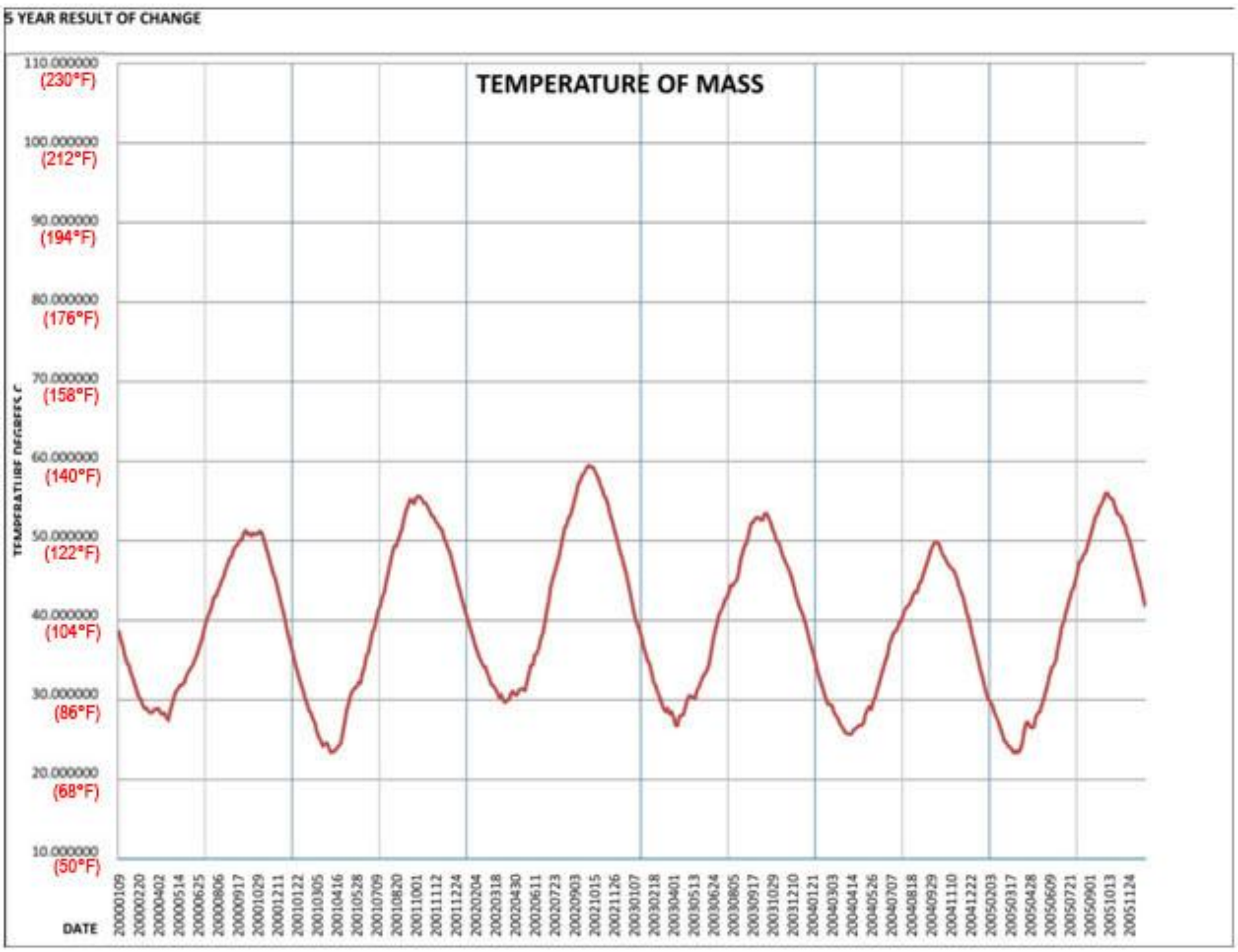


Figure 85 - Example 5 - Graph by Mark Driedger

Example 5 is the ideal situation for an ArcHelio powered dwelling. The temperatures of the thermal mass are relatively low, and far from the boiling point of water. The temperature of the mass approaches, but does not match building temperature in late winter. The heliostats as well are sized to ensure there is a sufficient buffer of spare energy in late winter.

The charging of the mass should be a year round process. Energy is available on sunny days in mid-winter. It is ArcHelio's responsibility to decide whether or not there is enough solar energy to create a net benefit to exposing the inlet to the cold winter air.

CONCLUSION

Although the calculations in ArcHelio are just theoretical at this point, and more experiments are required to test the concept, it appears as though the technology may be able to provide the summer's heat to a well-designed dwelling, in the winter. The system should be able to be adapted to many different configurations and building types. The model shown in this paper takes a very simplistic approach to design in order to find the lowest common denominator. Based on this work, the concept can be scaled up to fit more complicated building types, as long as there is room for the heliostats and a higher capacity thermal mass.

Other building types would also work well with the ArcHelio concept. A more centralized system (district heating) could be designed to manage the heating loads of a group of residences or buildings. Existing heating plants serving campus style arrangements could also be upgraded using this concept. One of the limitations could be energy losses associated with the transfer of the energy to the multiple buildings, which goes against the laws of the system. However the size of the heliostat could be designed to offset these losses.

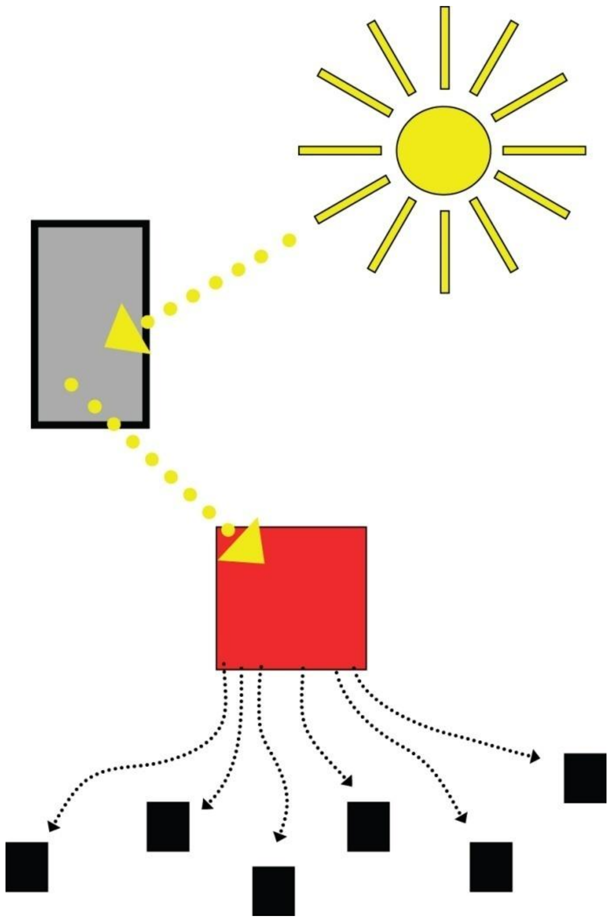


Figure 86 - ArcHelio centralized system for multiple buildings

A standalone system holds the most promise for the ArcHelio process. The process is simple, and the energy transfer is limited. A dwelling could have a control system linked to the ArcHelio software that displays the amount of energy that is stored in the thermal mass battery. The resident could then make calculated decisions whether or not it was a good idea to open the window shutters at that particular moment.

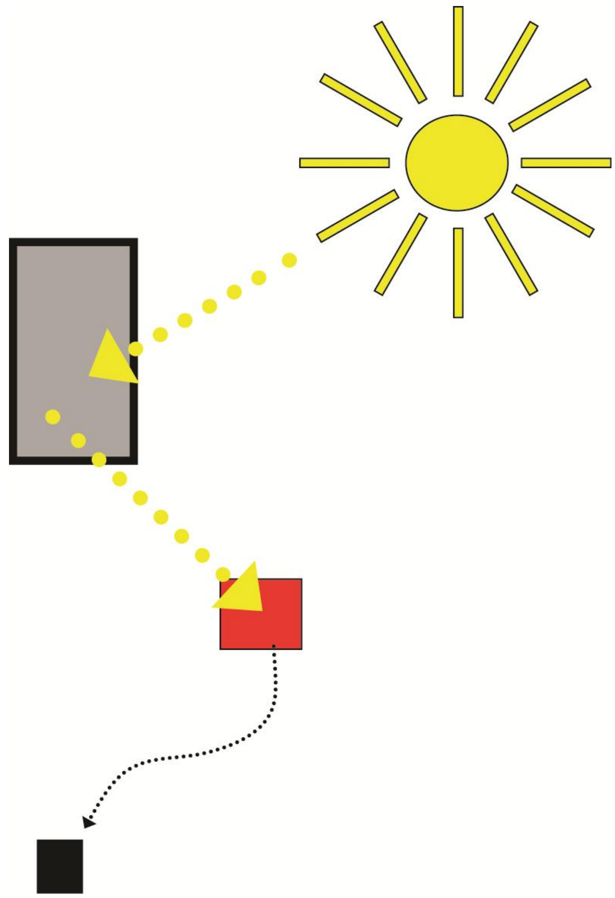


Figure 87 - ArcHelio for a Single Building

The next steps in this research would be to find a partner who would be interested in investing in a scale mock-up of the ArcHelio concept. The resulting tests from this model would be used to verify and updated the loss calculations in the software, increasing the software's accuracy. The ultimate goal would be to have a software system that could create realistic performance models for any area on the planet, integrating the calculations from the different assembly materials used. The software would not only act as a simulation model for the process, but also would form part of the logic for an operating ArcHelio system.

By keeping the system simple and by minimizing both the transfer of energy, and the transformation of energy, it is possible to efficiently harness the power of the sun. With further testing, a properly designed ArcHelio system will provide the means to satisfy all of the heating energy requirements of a building. ArcHelio is a step forward towards the ultimate goal of truly sustainable architecture.

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