Cob Home Performance Report

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Abstract

The function of the Baird's earthen cob home has been assessed as a whole system, monitoring energy inputs from solar thermal, wood gasification, and solar PV, as well as monitoring the indoor environment in relation to the outdoor environment. Inclusive with this research is analysis of the thermal performance of the home and application of concepts in the building codes with relation to building performance. It is common knowledge that cob buildings last for 500-700 years. This preliminary research of year long data collection puts into perspective whether an ancient low embodied energy and natural building concept has a place in the present day environment where energy efficiency, cost and safety are leading qualifiers as to what gets built.

The Cob home was fitted with sensors monitoring indoor/outdoor temperature, dewpoint and RH, along with embedded sensors in the earthen wall measuring temperature and water content. The results demonstrate the exceptional performance of the walls in moderating humidity through all situations and seasons, responding within minutes to the changing respective indoor and outdoor environments. The cob wall acted like an impassible barrier with sponges on each side that could absorb and release moisture without condensation. The walls maintain the suggested moisture equilibrium of 0.4% to 6.0% and the temperature and yearly average indoor relative humidity was 54.9% (range of 47-62%), and indoor temperature average was 20.5^{o}C. The walls have an active and observable effect of taking in and releasing moisture and heat to maintain a balance. The walls responded over duration of 4 hours to an event of 3 hours in the same time frame, to moderate RH and keep it within the normal ranges observed. The cob walls of the Baird home behaved as a selectively permeable membrane responding quickly and effectively to environmental changes to assist in maintaining a desirable and healthy indoor environment.

The solar thermal system performs more efficiently than the manufacturer's published specifications, at over 80% efficiency. Of the energy collected by the solar collector, 80% was used towards supplying the domestic hot water demand and 20% to supply for space heating demand. The wood boiler provided the remaining heating demand. The total space heating for the home was calculated to be 24913.73 kWhrs, which with the heating hours translates to an approximate heat demand of 14167.8 BTUH, consistent with estimations form other earthen and cob homes. A heat dump of 3643 kWhrs (14% of heating demand) was also recorded and suggestions have been made as to reduce this.

It should be noted that due to the short time frame in which the data was able to be analyzed the full properties and response of the thermal mass nature of the home was not fully explored. This is a significant effect and will be looked into further.

The home uses 84.8% less electricity than the average single detached BC residence, has a grid-intertie with BC Hydro, and is a net supplier of energy to BC Hydro of 397kWhr. Results investigate electricity generated, consumed, and sold, the costs and payback period of the system and relates the cost of electricity to that supplied by the provincial utility.

What has become clear is that a conservation lifestyle and occupancy rates together play the biggest role in reducing the energy intensity within the household.

Test Objectives

The data acquired from the test plans allows comparison of the actual performance of the cob home to a theoretical home of the same size and occupancy.

Solar Thermal Collector Performance Monitoring

The objective of monitoring the solar thermal and supplementary wood boiler input is to determine the contribution of solar thermal to the thermal demand of the home, in particular domestic hot water and space heating. Full test objectives and methodology is defined in the test plans [Appendix 2].

The Baird home has two Thermomax solar collectors of 30 heat pipe tubes each. The expected contribution of the collectors will be calculated and measured in relation to the whole heating demand. The wood boiler contribution will also be calculated and compared, as well as the amount of heat dump, if any.

Earth Wall Moisture Monitoring

Historically, earthen cob mass walls regulate humidity to prevent moisture condensation and mold growth. No HVAC systems have been required to regulate this effect, and no vapor barriers are required. Four moisture sensors installed respectively in the north and south earthen mass walls will be used to provide annual data to back up anecdotal evidence of mass wall performance. The objective of earthen wall monitoring is to monitor for one year the indoor and outdoor environment variables of Relative Humidity (RH), temperature and dew point, as well as the wall assembly variables of temperature and water content. Full test objectives and methodology is defined in the test plans [Appendix 1].

The Baird earthen cob walls, insulated with ~30% pumice estimated to increased the R value of the wall from R-10 (regular cob mass wall without pumice) to ~R-20, contributes significantly to a passive solar design by regulating interior temperatures. Anecdotal evidence is to be confirmed with the use of temperature sensors installed in the north and south earthen mass walls and monitored over an annual period. From this data, an energy model will be developed to estimate heat loss load calculations, providing data to allow determination of heating requirements for similar structures.

Expected observations from the data include insight into the relationship between water content within the walls in relation to RH, temperature, and dew point, the three most important variables in any building envelope assembly. Data will also highlight how the daily indoor RH fluctuates in response to changes in outdoor temperature and RH.

The Conventional Home

A house is a building designed to house and sustain human life by maintaining a comfortable healthy temperature and providing protection and stability from the outside elements. Homes were originally developed over time in response to specific cultures, climates and environments. Today many of the homes of this world have become much more generalized and unconnected to the regional climate, culture, and environment.

The modern home is a cookie-cutter box structure, hooked up with a series of supporting systems that bring in water, air, light, and remove waste products. These structures can be mass produced and placed almost anywhere in the world. Unfortunately the disconnection between the environment and climate often results in homes that are artificial and toxic to both the inhabitants and the environment. Materials from the modern home are highly processed, environmentally unsustainable, and not organically degradable.

Moisture, dew point and relative humidity

Air is composed of both dry air (a fairly fixed percentage of oxygen, nitrogen, argon) and water vapor (variable amounts of liquid water in air). Water vapor pressure drives the movement of moisture through building assemblies such as walls and ceilings. Air pressure determines the movement of air (with water vapor) as it flows from higher to low pressure, usually between the interior and exterior elements of the home.

Warm air holds more moisture and the general rule of thumb is that as temperature increases the vapor pressure increases (more water molecules in the air or the more water molecules the air could hold). The amount of moisture in the air is defined in terms of relative humidity (RH). Moisture content varies primarily with RH and not absolute humidity. Absolute humidity is the actual mass of water vapor in a unit volume of air and is equivalent to the density of air. Relative humidity is the percentage or ratio of absolute humidity to the maximum possible density of water vapor in the air at a given temperature.

As warm air cools it loses its ability to hold moisture and will at some point reach 100% RH (saturation). The temperature at which saturation occurs is the dew point temperature. Cooling further past the dew point temperature will result in water condensing out of the air, usually onto a cool surface like a window.

Typically once relative humidity reaches and maintains 80% the adsorbed vapor is able to support fungal growth. Corrosion and decay, to proceed at dangerous rates, require higher levels of humidity (well over 90%) and temperatures over 15C (60F) for months [King].

Baird Framed

For comparison in this report, we will also consider the Baird home built as a typical wood frame in the regional climate. Let’s call this home ‘Baird Framed’. Typical moisture control strategies for the Baird Framed home would include air barriers, drainage planes, vapor retarders, air pressure control, and the use of ventilation and dehumidification to control interior moisture levels. We will examine these strategies in the following sections as a basis of comparison for the earthen home project results. Data still to come.

Envelope Moisture Control

In South-West British Columbia our mean annual precipitation can range between 801-3000 mm, with the southern island region in particular ranging from 801-1400mm. During the period of data collection for this report the annual regional average humidity was 79.23% (moisture content).

Typical homes employ a series of strategies to balance moisture to avoid structural decay and corrosion, fungal growth, and interior damage. Understanding the materials used in home construction and the way moisture moves through the materials is a critical factor in controlling moisture in homes. Moisture degradation is the largest factor limiting the useful life of a building [ASHRAE 23.11].

Moisture accumulation in buildings can be divided into two main categories, (1) liquid water control strategies, and (2) water vapor control strategies. Moisture movement is driven by thermal gradient: from warm to cold, and by concentration gradient: from more to less. Typical strategies to control liquid moisture entry into and out of the building envelope involve keeping moisture from leaking through the roof or foundation, and using an appropriate water control layer to repel wind driven rain and rain splashing. In residential homes, the water control layer is typically on the outside walls of the home with the air control and vapor control layers on the inside.

Typical home building strategies for the structural envelope:

Foundations

- Concrete footing with stem wall, built atop load bearing ground
- Footing is placed below the frost line, and is encircled by a perimeter drain to shunt off moisture in the surrounding ground
- Footing has a moisture barrier coating to stop moisture intrusion through the concrete
- Concrete is insulated to decrease heat loss

Shell

- Exterior siding – receives brunt of weather
- Rain screen layer to provide an air gap between exterior siding and the shell of the house, allows for ventilation/convection to dry moisture that has intruded past the exterior siding
- Water barrier wrap like tar paper of polyethylene (as Tyvek)
- Exterior shell – either shiplap/ 1X8, OSB or plywood, has ventilation openings to allow moisture through as with OSB or Plywood, they are non-permeable
- Stud framing, with 2x6, with infill insulation to decrease temperature differential across interior shell/sheathing
- Vapor barrier – to stop air infiltration and vapor migration – impermeable layer that acts as the dew point within a wall system if conditions allow for such
- Interior finishing (drywall with impermeable paint) – acts as another air barrier if sealed properly

Roof

- Roofing material
- Roofing felt
- Exterior wrap
- Roof sheeting
- Perling/air gap to allow for venting/circulation immediately under the roofing system
- Trusses/supporting structure
- Insulation infill within the supporting structure
- Vapor barrier
- Interior sheeting/finishing

A common cause of moisture problems during the heating season is excessive indoor humidity caused by an improper balance between moisture generation and removal [ASHRAE Fundamentals 24.5].This interior moisture travels to the walls and ceiling and penetrates into the building assemblies if not protected. Once it enters the insulation the moisture will reduce the thermal resistance of the insulation and may condense and freeze. Moisture build up in the interior of the home during cold seasons is critical to control. Moisture barriers are used to prevent moisture from entering the insulation usually placed near the warmest surface protecting the insulation, usually between the inside of the finish layer and the insulation. In the summer moisture is greatest outside the home, reversing the movement of moisture. Summer moisture control is usually controlled through natural ventilation.

It is interesting to note that moisture generated (evaporated indoors) during the summer and adsorbed into hygroscopic materials within the home can remain within the materials until a later time. This stored moisture slows the effect of ventilation and dehumidification because the moisture needs to be removed and released before indoor humidity can be permanently lowered [ASHRAE Fundamentals 24.5].

High indoor humidity in a conventional home is due to inadequate ventilation, inadequate dehumidification, and air conditioning or is due to an unusually large moisture source within the building [ASHRAE Fundamentals 24.5]. In addition, in conventional homes there is very little vapor diffusion through the building envelope.

Heat Load for Conventional (Baird Framed) Home

In Victoria, with an annual heating degree day value of about 3304 (refer to Appendix Table 3-1) taking into account the same size home with conventional high efficiency and insulative materials the calculated heat load is 13.4 BTUH/ft^2. A home with a peak heat load value of 10-15 BTU/ft^2 (including ventilation, like the above values) is considered very good.

The Cob Earthen Home (see appendix 4)

Cob is an earthen mixture that includes clay soil, sand, and straw, wherein clay acts as the binder, sand the aggregate, and straw the tensile strengthener. It is a traditional building material and technique that has been used for centuries, widespread in southwest England alone since the 15th century. It is a technique that does not depend on manufacturing industries, pollution, or unsustainable practices. Cob absorbs high humidity [Minke] and provides thermal mass for solar heating, interior comfort, fire safety, and is environmentally suitable when designed properly. A well designed cob building can weather earthquakes, and wet climates for centuries.

The ideal composition of cob has approximately 30% clay, 60% sand/aggregate and 10% high silica fibrous material (Hemp, oat straw, barley straw, wheat straw). To make the cob, the clay must be hydrated to the point where the clay platelets can be separated via mechanical action and suspended in a moist medium to evenly cover and coat all other materials in the mixture and create a consistency similar to unbaked bread dough. This cob can then be manipulated through several tests (ASTM2392M-10) to demonstrate appropriate consistency for building. As the clay in the cob dries, the moisture between the platelets of clay migrates out, leaving strong molecular level bonds. This bonding is not broken with the re-addition of water.

Cob Envelope Moisture Control & Balance

Many people have difficulty conceiving that a natural building material such as earth need not be processed and that, in many cases, the excavation for foundations provides a material that can be used directly in building. The anxiety that mice or insects might live in earth walls is unfounded when these walls are solid. [Minke]

The primary cause of failure of cob walls is moisture from lack of ventilation, poor design or alterations, or inadequate maintenance. This is the reason drainage around walls and building the walls on a stone or concrete footing is critical. If designed properly the walls will wick and evaporate moisture, allowing moisture to evaporate before it weakens the structure. Natural earthen coatings do not inhibit this wicking effect, and in fact are porous enough to allow water to evaporate as readily as it is absorbed. Owing to ignorance, prejudices against loam (cob) are still widespread.

In conventional homes the purpose of a vapor barrier is to prevent absorption and condensation of moisture. Vapor barriers in a natural building wall interfere with natural plastering, are difficult to install and maintain without puncturing, and introduce a dew point within the wall structure that ordinarily would not be there. One of the strengths of a properly designed earthen wall is its ability to regulate moisture between the interior and exterior as an organic membrane.

Water Movement & Relative Humidity in Cob

The rate of vapor diffusion depends on the porosity of the cob mixture. Adsorption is the tendency of a hydrophilic surface to capture and hold polarized water vapor molecules in the air. Most building materials have internal pores that adsorb water molecules continuously depending on the relative humidity. Once pore surfaces have adsorbed as much vapor moisture as they can, the pores themselves will begin to collect and store water from the air within their spaces via capillary suction, also known as absorption.

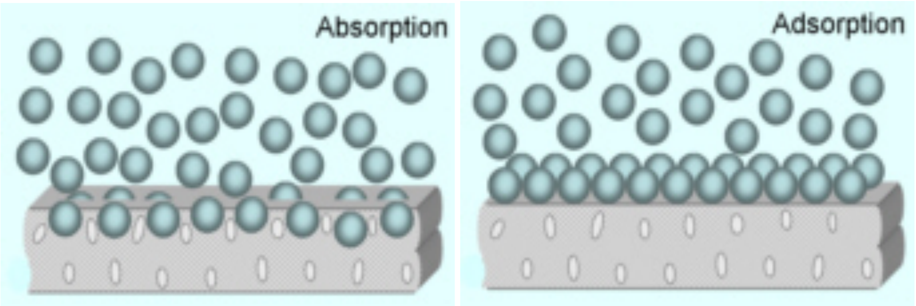


Figure 1 Adsorption and absorption [IFA]

Thermal Mass and Insulation Properties

Dry cob is a very effective insulator. Because of the ability of cob walls to regulate moisture the insulation value of the walls is maintained. It is important to note that the cob walls have significant thermal mass as compared to the walls of a conventional home. In terms of insulation, the more mass a material has, in particular a cob wall, the more heat can be stored when the material is heated. Water, with its high specific heat, can store much more heat than the surrounding material. Any substance that soaks up water will change its thermal properties depending on the amount of water present.

Passive Solar

Passive solar plays an important role in the Baird Eco-Sense home. The home was placed and designed to use energy from the sun to play an important role in the thermal needs of the home, particularly heating and lighting. Implemented properly, it is possible for passive solar concepts alone to reduce energy costs by as much as 40% [PSH]. Passive solar concepts are particularly applicable in buildings with continuous occupancy and in climates that experience more than 1000 degree days (DD).

Passive heating: Collection, storage and distribution

In passive solar the collection of solar energy is usually windows, and sun on the earthen walls. The purpose of designing the collection component of the home is to allow as much winter sun into the home as possible to heat the storage mass. The storage system, the floor and walls, retains the heat based on thermal properties, releasing it later as needed. The key to designing the distribution element of the home it to design the living spaces such that those spaces that need the most heat are closest to the thermal mass.

When the thermal mass is exposed to sunlight energy enters the mass and is stored as heat. How well a thermal mass stores heat is dependent on its thermal storage capacity, thermal conductance, the thickness of the material and the interior temperature. Most passive solar heating systems are designed to release their heat between 4 and 12 hours [PSH].

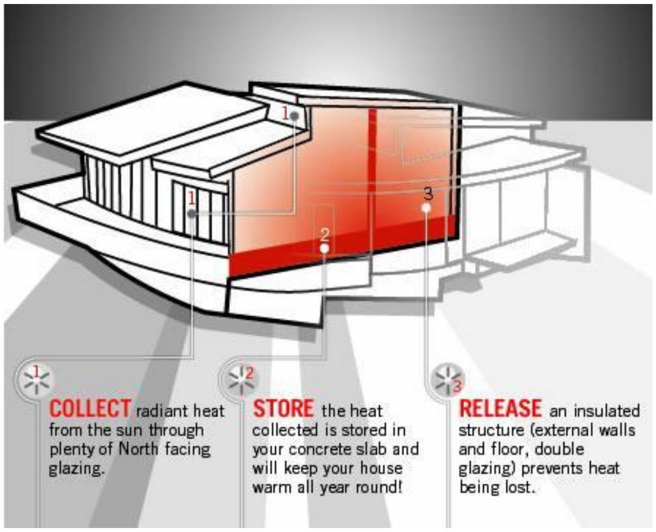


Figure 2 Passive solar concepts [EcoBOB]

The Eco-Sense home employs passive heating (indirect gain) right from the initial design concepts. The collection and storage components of the home (windows and walls) are integrated to collect and store solar energy. Continuous sunlight penetrates the windows and passes through the walls. Even the earthen floors absorb heat from both solar and in floor heating.

Comfort and Health

Thermal comfort in the home is generally defined within a relative humidity range of 20-65% [ASHRAE Standard 55]. There is a fundamental difference between relative humidity measured in the middle of a conditioned space, and the relative humidity found at surfaces due to the significant difference in temperature typically found between surfaces and the air in the middle of a conditioned space [Lstiburek, Building Science Corp. Paper]. In winter month's relative humidity should be kept low around cold condensing surfaces (at surface temperatures lower than 4.4 C). For the cob home, these surfaces would be those with low mass such as windows.

Building Code and Natural Building

There has been resurgence in many parts of the world to try and reincorporate natural building methods and systems into local codes and standards, fueled by volumes of modern research on moisture physics, seismic durability, and thermal performance. The new ASTM standard for earthen building (ASTME2392M-10) released in 2010 refers to standards around the world: from Australia, New Zealand, German, India, and many more.

The building code is a document that looks at individual components as part of a larger system. The metrics specify individual requirements yet fail to provide an overall performance standard, illustrated by a lack of recommendations on energy intensities required for space heating, or whole house air leakage guidelines. The code also fails to recognize traditional materials like cob, despite historic significance around the world, and thus does not cover earthen building metrics. Groups around the world are addressing this, enlisting engineers, architects and builders to supply alternative building methodologies backed by design equations and extensive research.

In regards to structural issues, all load bearing earthen buildings, like the Eco-Sense home, require a structural engineering stamped plans and submission of schedule Bs to the relevant building official. This removes risk and liability from the city/district/municipality.

The issues of greatest concern are those listed in Section 9.25 of the building code, pertaining to thermal and vapor performance and air leakage. This report will show that the Eco-Sense home performs within required guidelines, and in fact highlights a more natural way of living.

For more details on earth building and the Building Code please see Appendix 7, BC Building Code.

Results & Comparisons

There is a high level of activity in the cob home compared to the amount of living space. The home has five occupants with two kitchens and two bathrooms. Each kitchen and bathroom is equipped with its own exhaust fan. Some activities bring in additional moisture, such as drying all washed clothes indoors on drying racks during the winter. Despite the high level of source moisture there is no additional means to decrease the moisture level in the home. The house is well sealed naturally due to the cob/plaster seals integrated at all the junctions in the envelope (windows, doors, roof, foundation), thus eliminating infiltration induced moisture (Blower Door Results: 2.12 ACH@50Pa or the Equivalent Leakage Area of 684 sq cm). The walls are 60 cm thick, providing a significant barrier with the thermal property of a continuous temperature gradient from inside to out, without an impermeable barrier within or on the walls, thus eliminating a dew point within the wall. The wall absorbs and de-absorbs vapor readily, replacing the requirement for a mechanical system to perform the same function.

Cob Walls

We have found that the annual wall moisture content maintains a reliably constant level, wherein humidity plays less of a role in changing wall water content, and temperature directly correlates to absorption. What this is implying is that when a temperature change occurs, such as an increase, the vapor pressure would increase allowing for greater absorption into the wall; as temperature drops, the wall system gives up the moisture, (see Appendix 4 and figures 4-10, 4-11, 4-12).

Humidity

During the period of data collection for this report the annual regional average humidity was 79.23%. The Eco-Sense measured yearly average for the outside humidity is 78.7%; the corresponding inside humidity of the home had an average of 54.9% (see Appendix Figure 4-13). Due to the nature of the mass wall system the inside walls maintain a temperature that is virtually identical to that of the inner air temperature. The average inside temperature inside the home was 20.5 °C, the average temperature 5 cm inside the inner surface of the wall was 19.1 °C. This ensures that the issue of dew point and difference of wall temperature from the center of the living space is of little to no significance, as the inner wall surfaces have an average temperature 17% higher than the dew point.

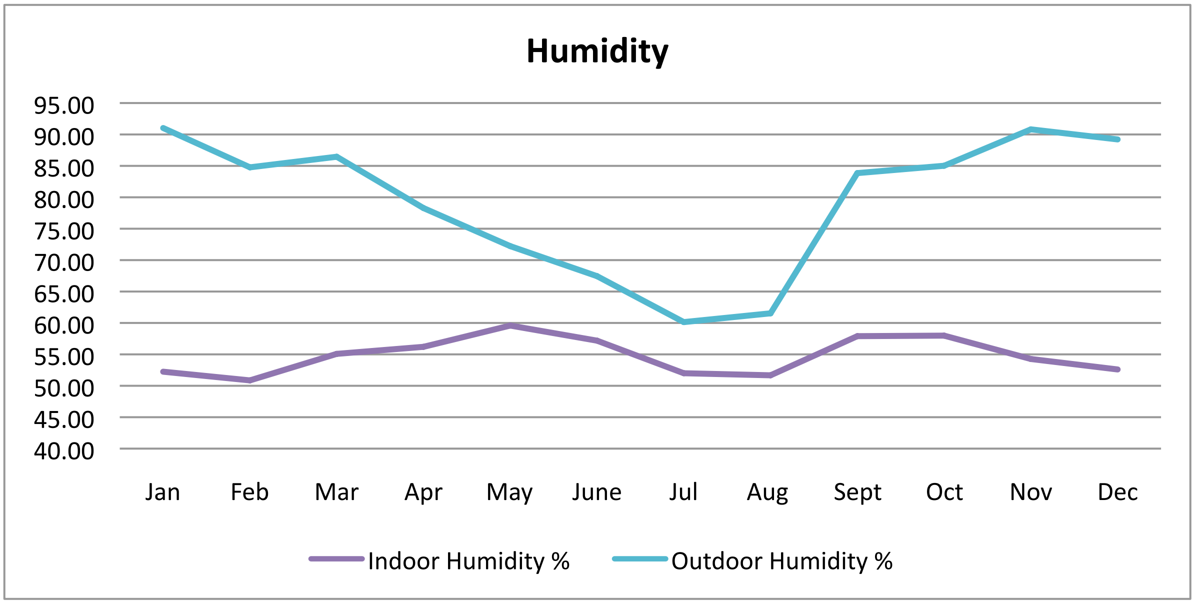


Figure 3 Annual humidity averages

A high relative humidity of up to 70% has many positive consequences: it reduces the fine dust content of the air, activates protection mechanisms of the skin against microbes, reduces the life of many bacteria and viruses, and reduces odor and static charge on surfaces of objects in the room [Minke].

Table 1 Humidity and temperature average

Yearly Regional Outdoor Humidity	79.23%
Yearly Average Outdoor Humidity	78.7%
Yearly Average Indoor Humidity	54.9%
Yearly Average Indoor Temperature	20.5°C
Yearly Average Inner Wall Temperature	19.1°C

The range of RH within the cob home for the period of study was 39.0-68.6%. This is well within the range that is considered comfortable as stipulated by ASHRAE standard 55 (relative humidity range of 20-65%).

Month	Days	C Indoor Temp Average	C Outdoor temp Average	Moisture Content % Indoor Humidity Average	Moisture Content % Outdoor humidity Average
Jan	31	19.55	4.43	52.24	91.03
Feb	28	19.26	3.00	50.86	84.77
Mar	28	19.01	6.48	55.08	86.45
Apr	30	18.35	6.93	56.20	78.29
May	31	19.40	11.50	59.58	72.23
June	30	21.44	15.49	57.18	67.45
Jul	31	22.55	19.49	52.00	60.14
Aug	31	23.13	19.28	51.67	61.53
Sept	30	21.59	14.74	57.90	83.85
Oct	31	21.17	10.96	57.98	85.02
Nov	30	20.28	5.24	54.26	90.81
Dec	31	19.97	4.95	52.60	89.21
					79.23

The following figure shows the outdoor RH variation for the year (min and max for each day), and shows the indoor RH (min and max). The key points of observation are the wide daily difference between the outside RH minimum and maximum and the corresponding very narrow range seen with the indoor RH. Also it is important to note the steady range of the indoor RH.

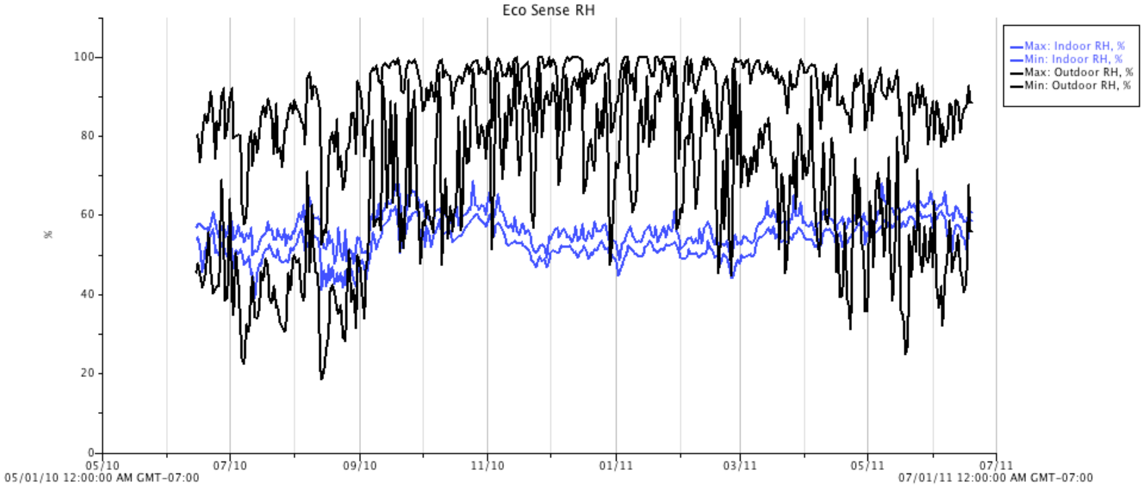


Figure 4 RH variation

		Average Annual RH %	Daily Avg RH % Fluctuation	Daily RH% Range
Indoor Max RH	68.6%	54.81%	4.7%	57.16%-52.46%
Indoor Min RH	39 %			

Outdoor Max RH	100%	78.95%	24.7%	91.30%-66.60%
Outdoor Min RH	18.4%			

Micro adjustments of the relative humidity can be seen in a snapshot of a 24 hr period wherein drastic increases in humidity would be expected. The Figure below (Figure 5) shows the 24 hr period on October 30, 2011, when a sizeable gathering of 60 people was held, from 1pm – 4pm at Eco-Sense. The data shows that the humidity range within the 4 hour period was 58-62%, and was matched with an increase in inner wall water content of 0.22% (from 2.06% - 2.28%) and then equalized down to 2.14%. This demonstrated in real time the instantaneous ability of the earthen walls to moderate the RH.

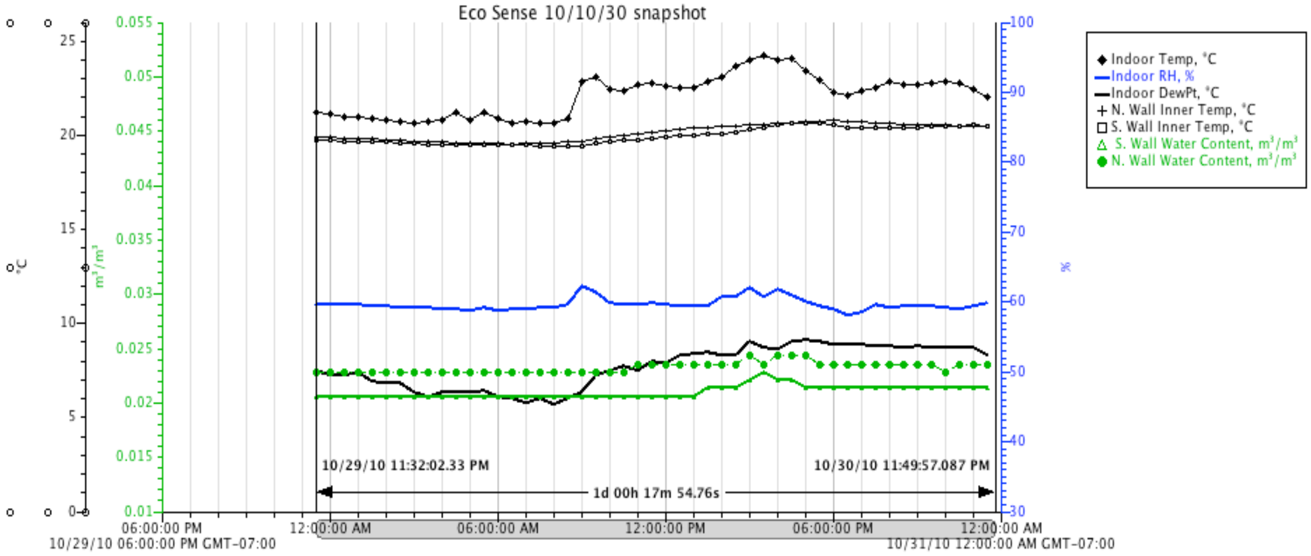


Figure 5 Earthen wall response to RH increase

The average adult is a considerable moisture source, producing an average of 230 g/hr of moisture [ASHRAE Fundamentals 24.5]. Having sixty adults in an enclosed indoor space of less than 1600 square feet, each generating an average of 230 g/hr of moisture in a cold fall month, results in over 13.8 kg/hr of moisture released into the air. Ventilation in the home did not exceed the standard 110-140 cfm. The majority of the moisture from the group was adsorbed into the walls and released, see detailed time of party in Figure below.

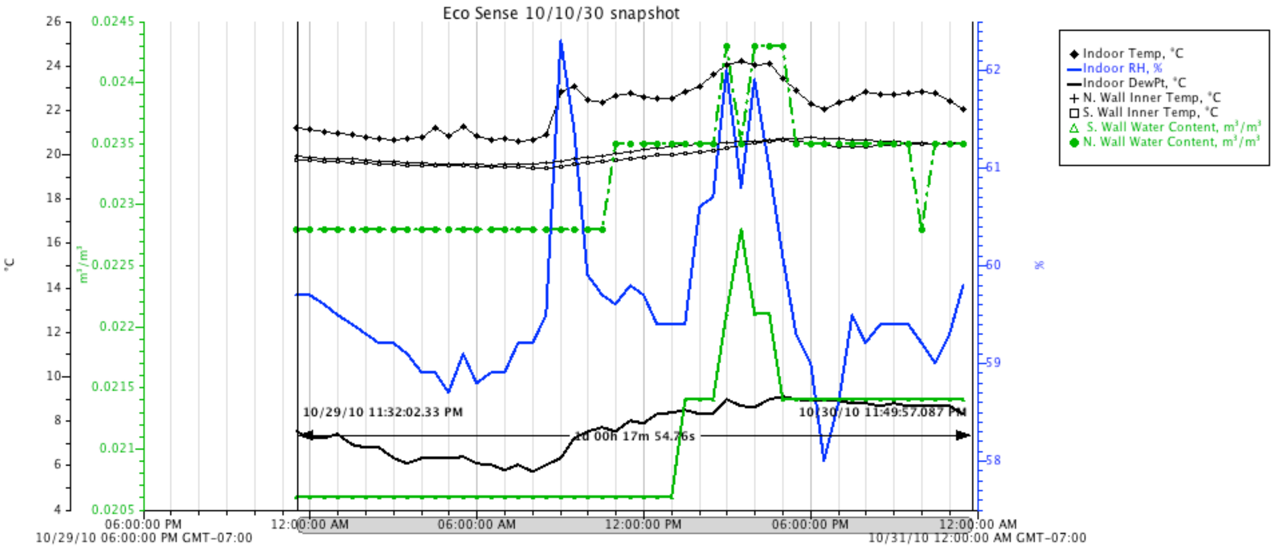


Figure 6 Earthen wall detailed response

Most earthen wall moisture adsorption and de-adsorption occurs within 4 inches (10 cm), within the first 24 hours [Minke]. Since the moisture sensors are located 5 cm deep we can calculate the amount of moisture adsorbed. The S. Inner wall moisture content increased from 0.0206 m3/m3 to 0.0228 m3/m3 for a change of 0.0022 m3/m3; The N. Inner wall had an overall increase of 0.0015 m3/m3. The average increase between the two was 0.0018 m3/m3. Over a wall area of 99.209 m2 with a depth of 10cm, the volume of wall mass implicated in adsorption is 9.9209 m3.

An increase of 0.0018 m3/m3 X wall volume of 9.9209 m3 = 0.017858 m3 of water adsorbed. This converts to 17.858 litres or 17.858 kg. Over the four hour period the rate of adsorption was 4.46kg/hr.

Coldest Day of the year November 23 2010

The outdoor relative humidity varies dramatically during the day, and is inversely related to outside temperature. Relative humidity will decrease with a rise in temperature when no additional moisture is present. On the coldest day of the year, inside the home, the indoor relative humidity has no observable correlation to either outside temp or RH, and stays within a very narrow margin of between 48% and 50% RH, (see Figure 7).

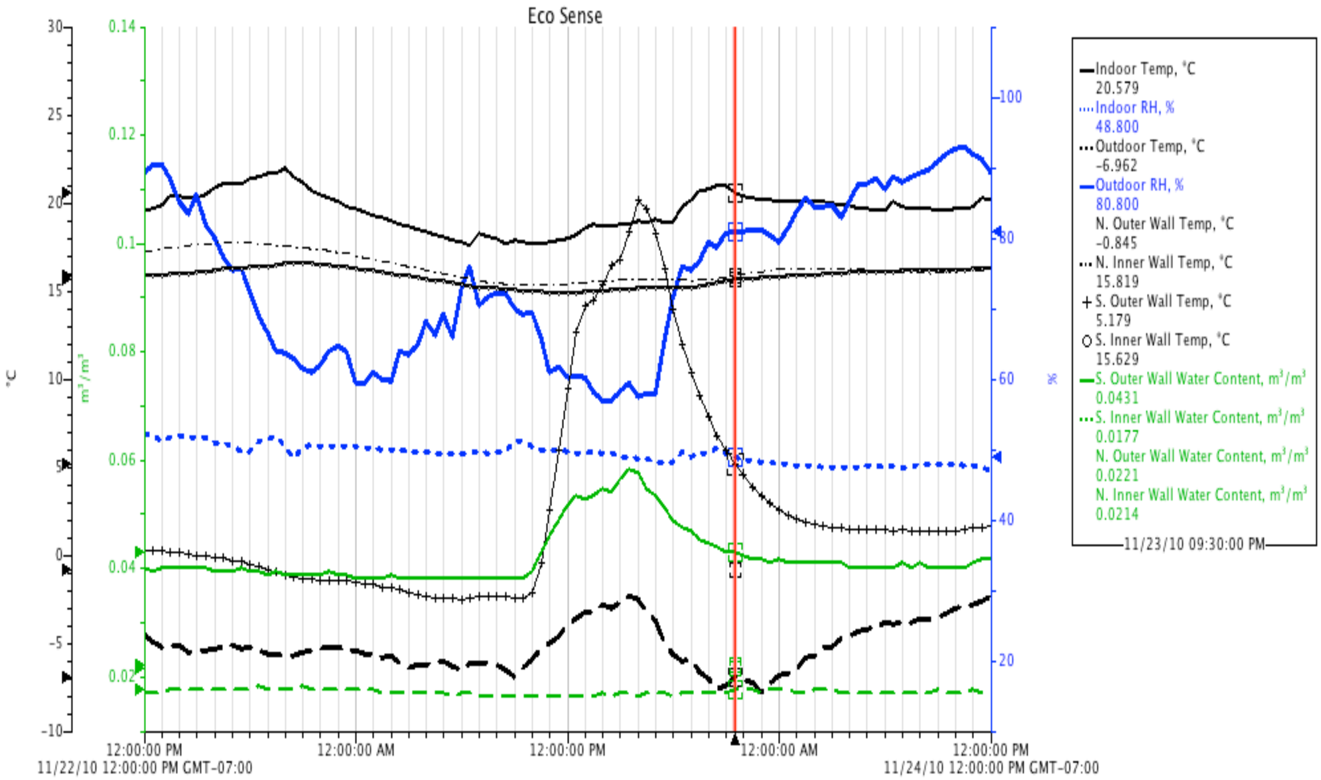


Figure 7 Coldest Day of the year RH observation

Warmest Day of the year July 8 2010

As noted above, there seems to be no connection between the widely variable outdoor RH and that of indoor (see Figure 8). The outdoor RH and Outdoor temperature are inversely related as noted earlier, yet the indoor conditions remain comfortable and stable.

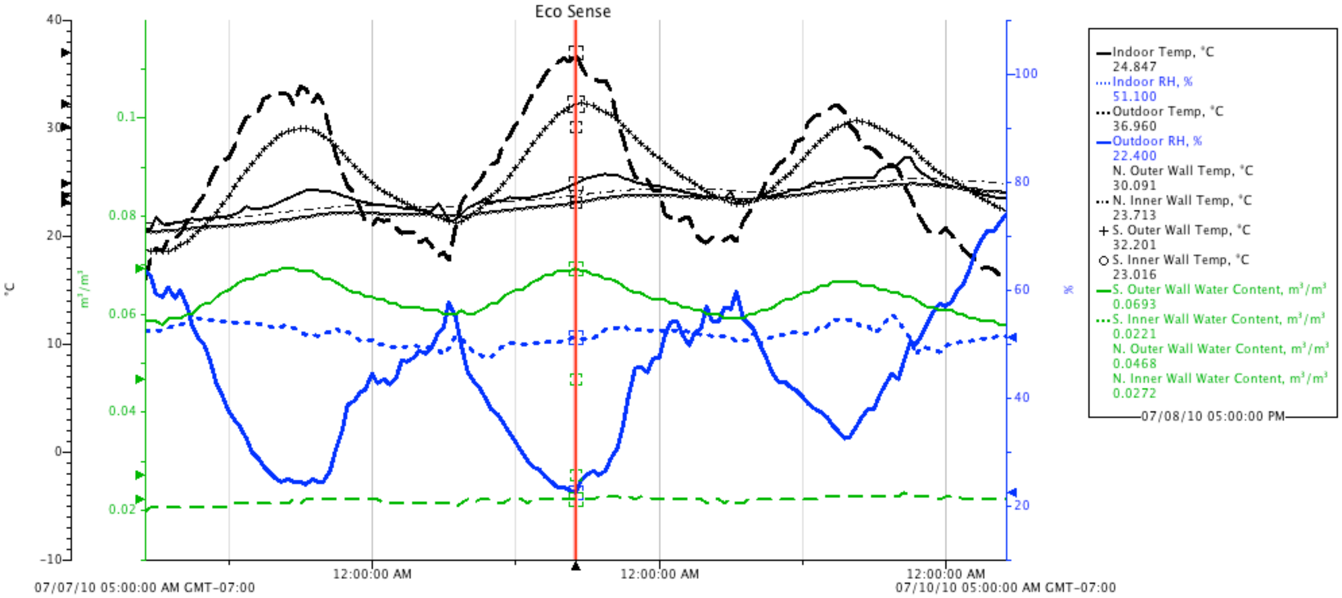


Figure 8 Warmest day – Observation of multiple measurements

Upon closer observation of indoor RH, we are able to see a pattern (Figure 9, below). With all other variables removed there is a slight reverse pattern demonstrated, between Indoor temp and Indoor RH. RH is showing direct sensitivities related to sudden changes in temp, with the overall relationship mirroring temperature, indicating additional moisture is available to raise the RH with the rise in temperature.

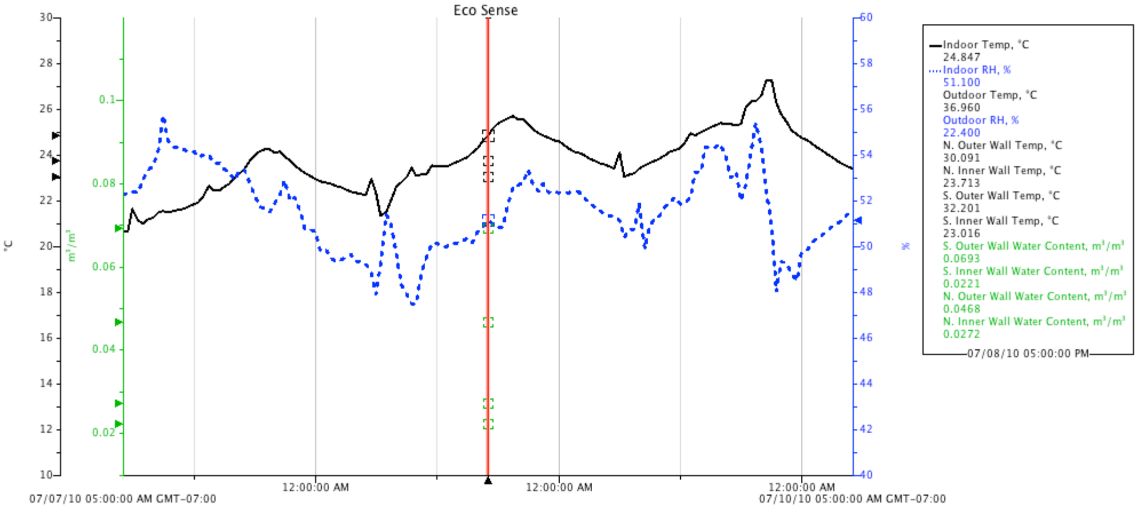


Figure 9 Warmest day – Indoor RH vs Indoor Temp

The relationship is complex, but would follow the common scientific rule that when temperature rises and additional moisture is present the relative humidity will rise. If moisture is not present the relative humidity will fall. Additionally considering the inner wall water content we see a trend of increasing wall moisture with general trend line of increasing indoor temperature, indicating that the wall begins also to absorb the moisture in the air. Exactly what fuels the peaks and valleys of this response has not been analyzed for this report (ie. Occupant activities, etc.).

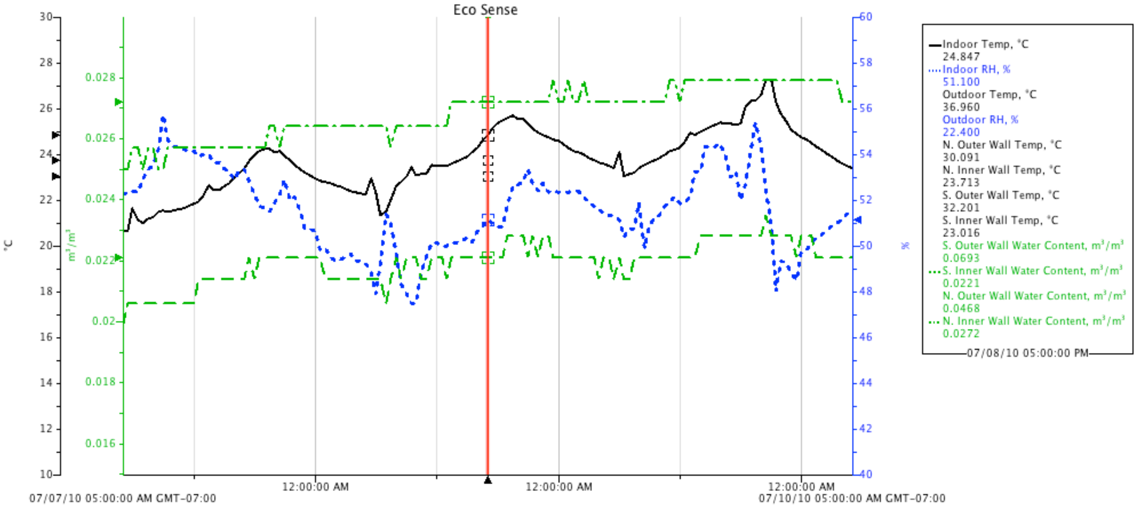


Figure 10 Warmest day – Indoor RH vs Indoor Temp and wall water content

As has been observed the cob house responds well to moderating the effects of moisture and humidity. We can conclude that vapor pressure of RH alone is not responsible for the walls response to adsorb/de-adsorb moisture, that the temperature is a factor, as we are able to measure the walls quantitative water content over a period of time and know it handles drastically changing conditions of temperature and moisture very quickly.

Cob Thermal Conductance

In addition to the measurements taken to monitor water content, relative humidity, dewpoint, and temperature, the thermal conductivity of the cob walls was also monitored. Thermal resistance values had an R value per inch range of 0.19 – 0.39 (see following Table 2).

Table 2 KD2Pro Thermal conductance output

		K	**rho**		Transmittance	Conductivity	Resistance/in	hr ft^2 °F/BTU	hr ft^2 °F/BTU
	# samples taken	**W/(m·K)**	**°C·cm/W**	err reading	BTU/hr ft °F	BTU in/hr ft^2 °F	hr ft^2 °F/BTU in	22 inch wall	12 inch wall
N.W. Wall 1	24	**0.367**	**272.71**	**0.0287**	0.21	2.54	0.39	8.66	4.72
N.W. Wall 2	17	**0.546**	**183.65**	**0.0094**	0.32	3.78	0.26	5.82	3.17
W. Wall 1	26	**0.509**	**196.41**	**0.0128**	0.29	3.53	0.28	6.23	3.40
W. Wall 2	15	**0.476**	**210.24**	**0.0145**	0.28	3.30	0.30	6.67	3.64
S. Wall outr	13	**0.768**	**130.35**	**0.0107**	0.44	5.32	0.19	4.13	2.25
S. Wall innr	10	**0.519**	**193.12**	**0.0155**	0.30	3.60	0.28	6.11	3.33
N. Wall	17	**0.485**	**206.79**	**0.0149**	0.28	3.36	0.30	6.54	3.57
Average		**0.524**	**199.037**	**0.015**	**0.303**	**3.634**	**0.287**	**6.309**	**3.441**

To understand the resulting R values we will illustrate some of the theory as follows. An R value is a measurement of the effectiveness of thermal insulation. It can be expressed in terms ofmetric (SI)or imperial (I) units:

$$R_{SI} = RSI = \left[\frac{m^2K}{W}\right] and R_I = R = \left[\frac{hrft^2F}{BTU}\right]$$

We will continue in this report with the terminology that R denotes the imperial expression. Further understanding of R is assisted with the following expression:

$$R = \frac{1}{thermalconductance/inch}$$

$$thermalconductance = \frac{(BTUsconducted)(inchesofthickness)}{(hroftime)(sq.ftofarea)(deltaF)}$$

From the KD2Pro the results we are particularly interested in are the measured thermal conductivity values (k) which are equivalent to the definition of the U value. We will use the thermal conductivity value k_{RSI}=0.519 [W/mK] to highlight the methodology of deriving the R value. As follows:

$$k = k_{RSI} x\, 6.93 = 3.60 \left[\frac{BTUin}{hrft^2F}\right] Thermalconductance$$

Then to calculate R:

$$\left(\frac{1}{k_{RSI}}\right) = 1.93 \left[\frac{mK}{W}\right] = 193 \left[\frac{cmK}{W}\right] Thermalresistivity$$

$$\frac{R}{inch} = 193\ x\ .00144 = .28 \left[\frac{ft^2hrF}{BTUin}\right]$$

From this we then determine from the KD2Pro results that the outer layers of the cob walls have an average R/inch value of 0.287:

$$\frac{R}{inch} = 0.287 \left[\frac{ft^2hrF}{BTU}\right] perinchofcob$$

The result is an average measured R value of 6.3 for the 22 inch lower cob wall and 3.4 for the 12 inch upper cob wall. The problem with this estimation is that it is a simple snapshot of time in the first few inches of the wall. To better understand the performance of the walls we need to take into account the entire structure, its properties, and behavior. R value relevance is most often useful in climates that experience long cold spells and less relevant for climates with wide diurnal variation in the cold season, such as Victoria.

Since the whole home had a heat load of 14167 BTUH we can estimate from the structural measurements and properties that the thermal resistance of the home is R19.7. This is consistent with measurements used in engineering calculations conventionally (R1 per inch of cob).

This result does not match the steady state R value measurement from the instrumentation in the thermal conductance section, primarily because the usual steady state conservative approach excludes transient heat gains such as solar and internal gains, which may not be present when needed. Energy storage effects are also usually ignored as they are likely not present during the coldest times of the year.

Cob Envelope and Moisture Control Results

The Baird home average cob wall density is 1685 kg/m3, obtained from the test results seen in the table below. Recall that the rate of vapor diffusion depends on the porosity of the cob mixture.

Table 3 – Cob Density

Cob Density	Weight of cylinder	Volume of cylinder	Density [lbs/ft3]	Extrapolated density [kg/m3]
Sample 1	20.7 lbs	339.43 in3	105.38	1688.05
Sample 2	20.4 lbs	339.43 in3	103.85	1663.58
Sample 3	20.9 lbs	339.43 in3	106.40	1704.36
Average	20.67 lbs		105.21	1685.33

Adsorption is the tendency of a hydrophilic surface to capture and hold polarized water vapor molecules in the air. Most building materials have internal pores that adsorb water molecules continuously depending on the relative humidity. Once pore surfaces have adsorbed as much vapor moisture as they can, the pores themselves will begin to collect and store water from the air within their spaces via capillary suction, also known as absorption. The amount of moisture in the air is defined in terms of relative humidity (RH).

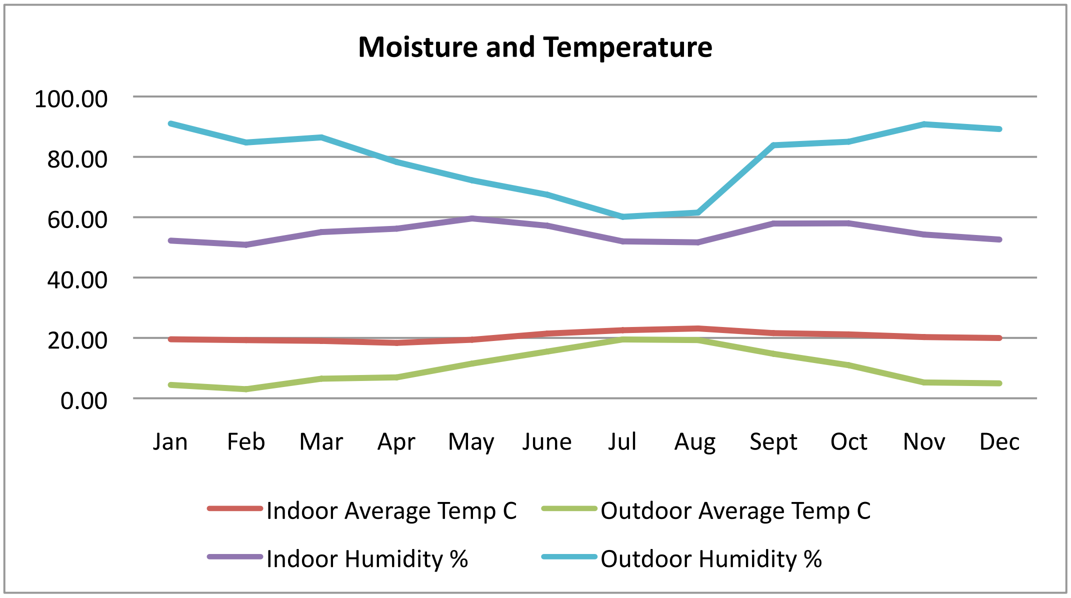


Figure 11 Annual humidity and temperature

We can see that the indoor average temperature remains consistent throughout the year, regardless of season or outdoor conditions. The indoor average temperature ranges from ~ 18-23 C. It can be noted in the figure below that the indoor average temperature peak follow that of the outdoor temperature peak.

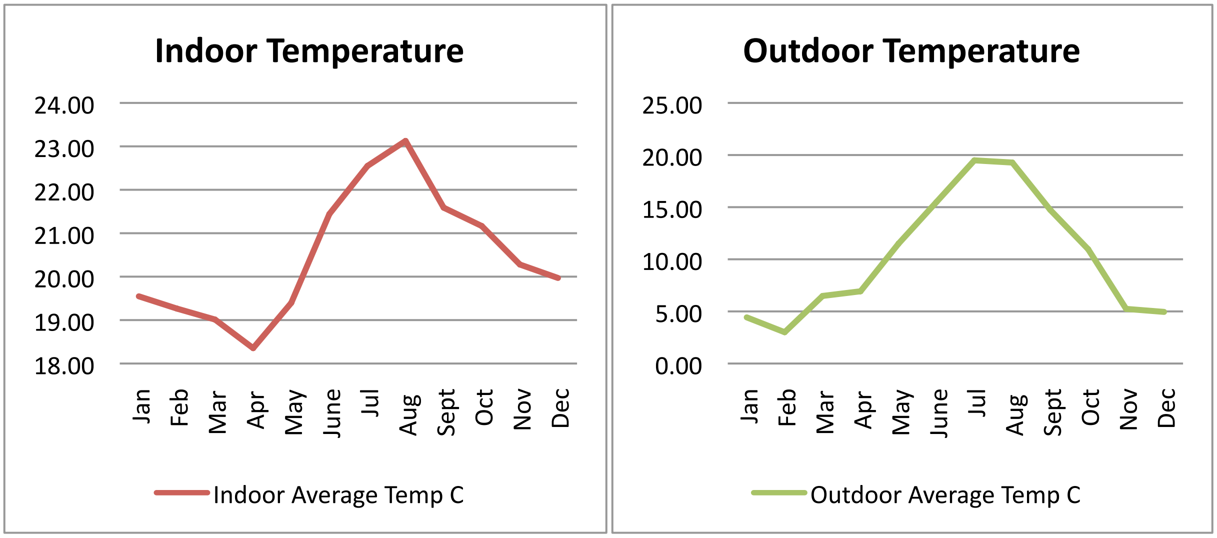


Figure 12 Indoor and outdoor average temperature

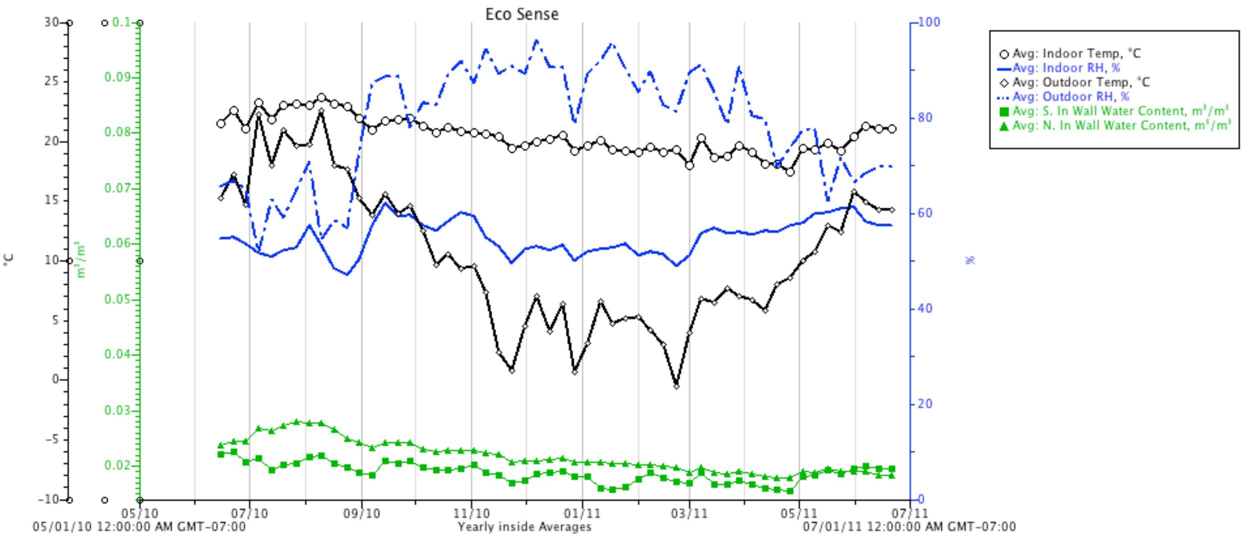


Figure 13 Yearly profile: Outdoor RH & Indoor RH, in relation to Water content and Wall Temp

Wall Water Content

The results of water content (m^3/m^3) in the walls demonstrates the ability of the walls to control humidity yet maintain water content levels that are virtually static, remaining well below the levels required for insect life (> 14%), and fungal growth (>20%). The wall maintains the suggested moisture equilibrium of 0.4% to 6.0% [MInke, Straube]. These moisture levels stayed static for the year, with minor fluctuations attributed to temperature changes.

	Max & Min Moisture content	Average Annual Moisture Content	Daily Avg moisture content (m^3/m^3) fluctuation	Daily Moisture content range
S. Inner Wall	2.35%	1.88%	0.0012 or 0.12%	1.82%-1.94%
	1.41%			

N. Inner Wall	2.93%	2.18%	0.0010 or 0.10%	2.13%-2.23%
	1.70%			
S. Outer Wall	7.73%	5.21%	0.0079 or 0.79%	4.82%-5.6%
	3.81%			
N. Outer Wall	5.55%	3.20%	0.0045 or 0.45%	2.98%-3.42%
	2.21%			

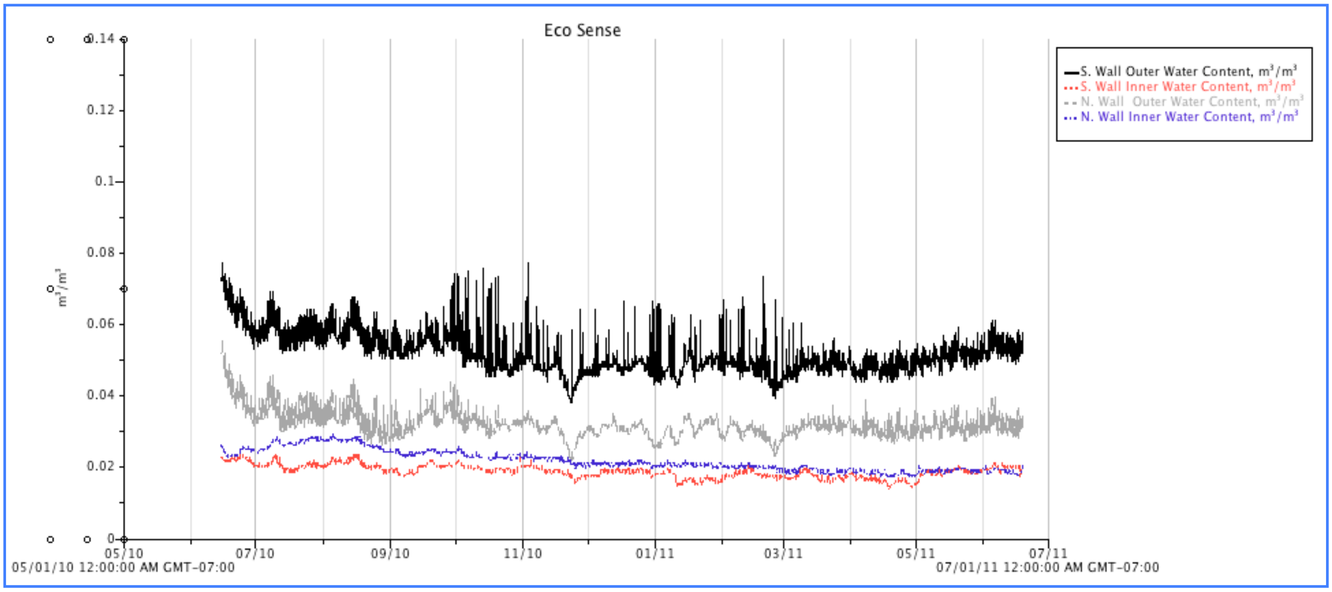


Figure 14 Yearly water content

The figure above, (Figure 14), represents the water content for the year. The research data results on the walls clearly illustrates that on the inside of the home (the wall surface with the highest vapor pressures) the moisture level does not exceed 3%. This was unexpected, as we predicted it would be greater on the inside due to heating loads and living activities.

	m^3/m^3	Percentage
Max S. Inner Wall Water Content	0.0235	2.35%
Max N. Inner Wall Water Content	0.0293	2.93%
Max S. Outer Wall Water Content	0.0773	7.73%
Max N. Outer Wall Water Content	0.0555	5.55%

Wall Dewpoint vs wall water content

The dewpoint is the temperature at which water vapor in the air condenses into a liquid. The following Figures are of the outer wall assembly performance in relation to outside dewpoint and relative humidity. Of particular note is where the wall temperatures drop below the dewpoint as it is at these times that we would expect drastic changes in the moisture content in the walls, such as condensation.

Moisture levels stay well within the < 3% range. The expectation was that at some point in the day the dew point would be at its maximum, providing the best chance for the wall to come nearest the dewpoint. During this same period we know that a wall experiences its minimum temperature. The graphs below observe the maximum dewpoint in relation to the minimum wall temperature.

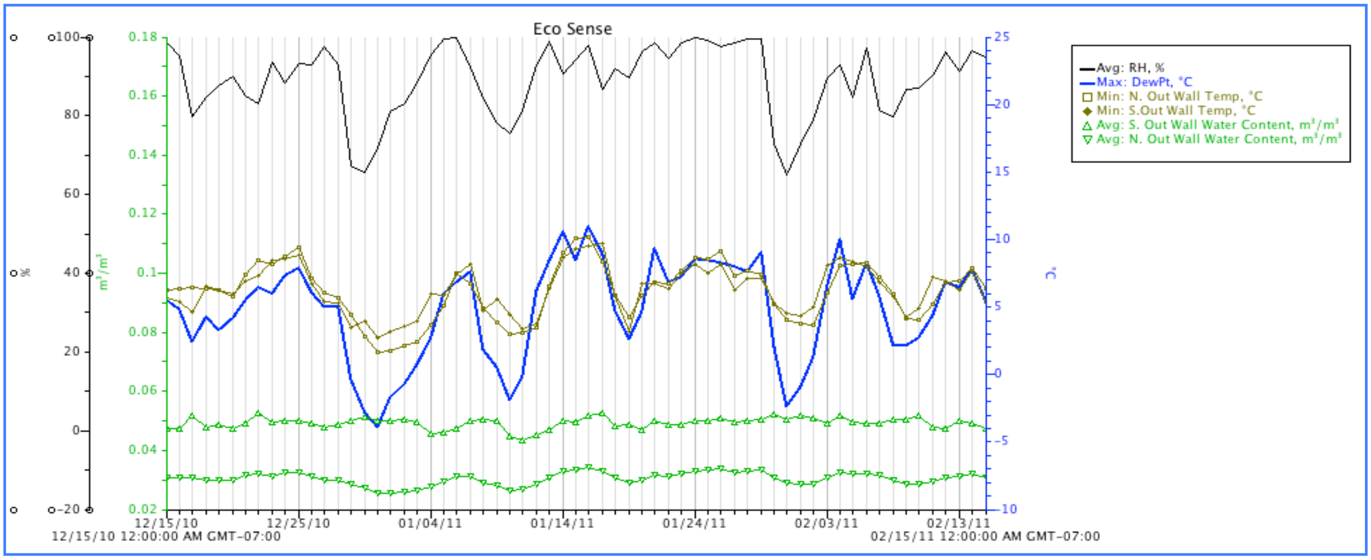


Figure 15 Winter dewpoint and water content results

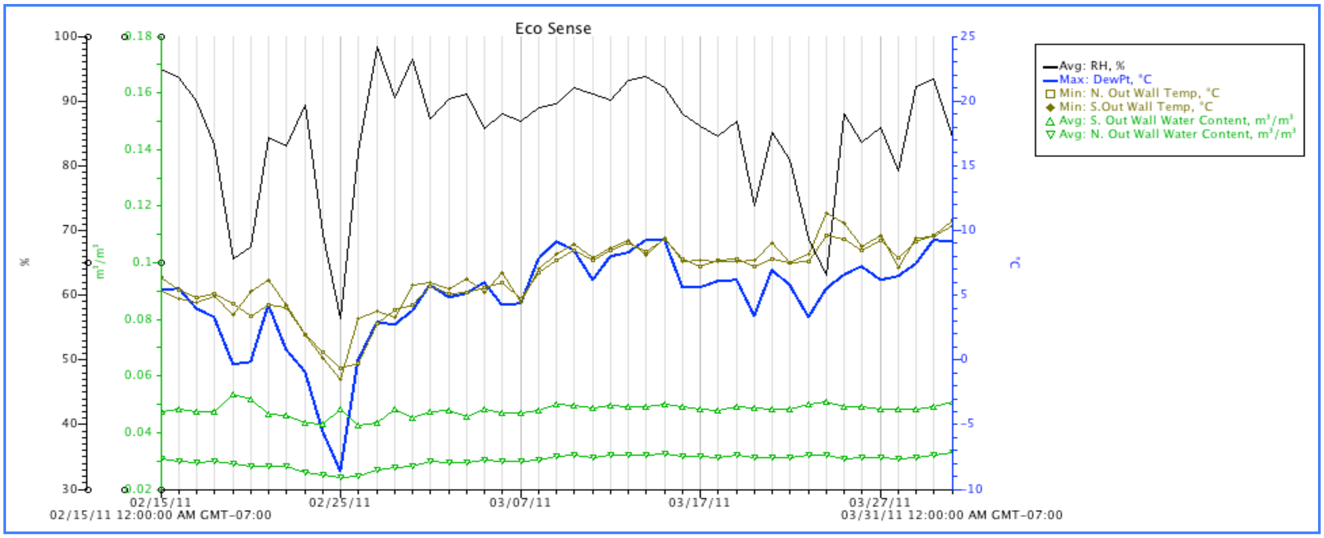


Figure 16 Spring dewpoint and water content results

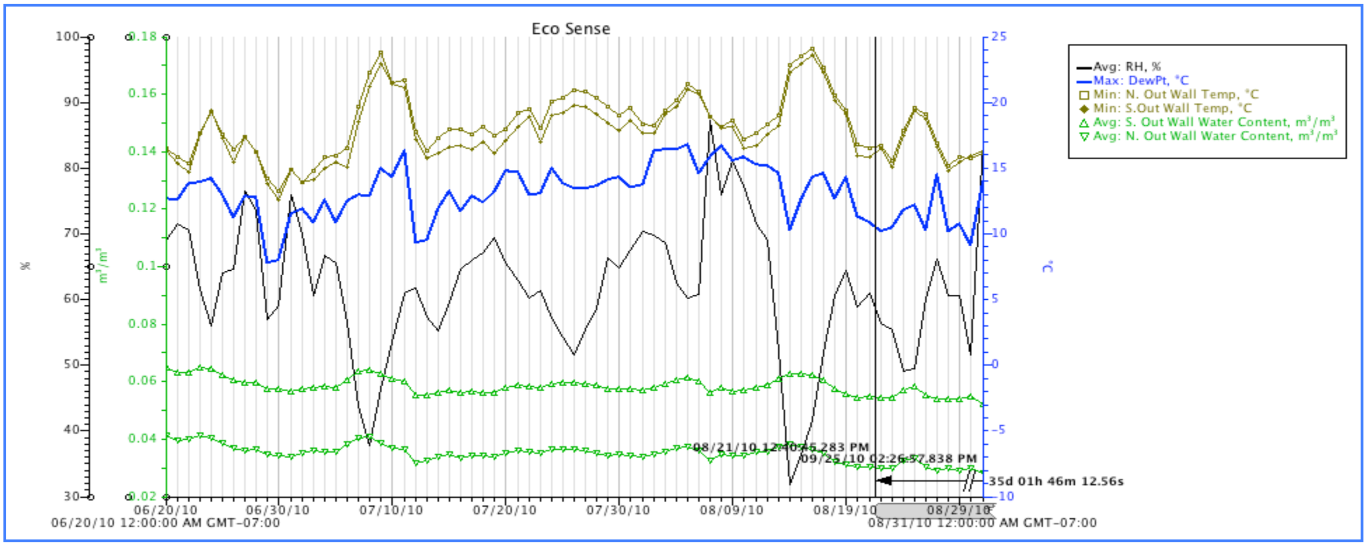


Figure 17 Summer dewpoint and water content results

It is concluded that the porous nature of cob allows for large volumes of adsorbed water which is easily attached and released. The walls are so effective at adsorption that absorption does not take effect at these temperatures and hence water does not condense on or within the walls.

Wall Temperature and Moisture Content

It was noted that in periods where wall temperatures increased sharply from the normal range, such as when sun heated up the south outer wall, there was correlated increase in outer wall water content, indicating moisture was available in the air for the wall to adsorb. The following Figure compares the moisture and temperature of the North Outer Wall to that of the South Outer wall in November (winter), wherein the sun has shone on the south wall during a day where temperature is below 0°C

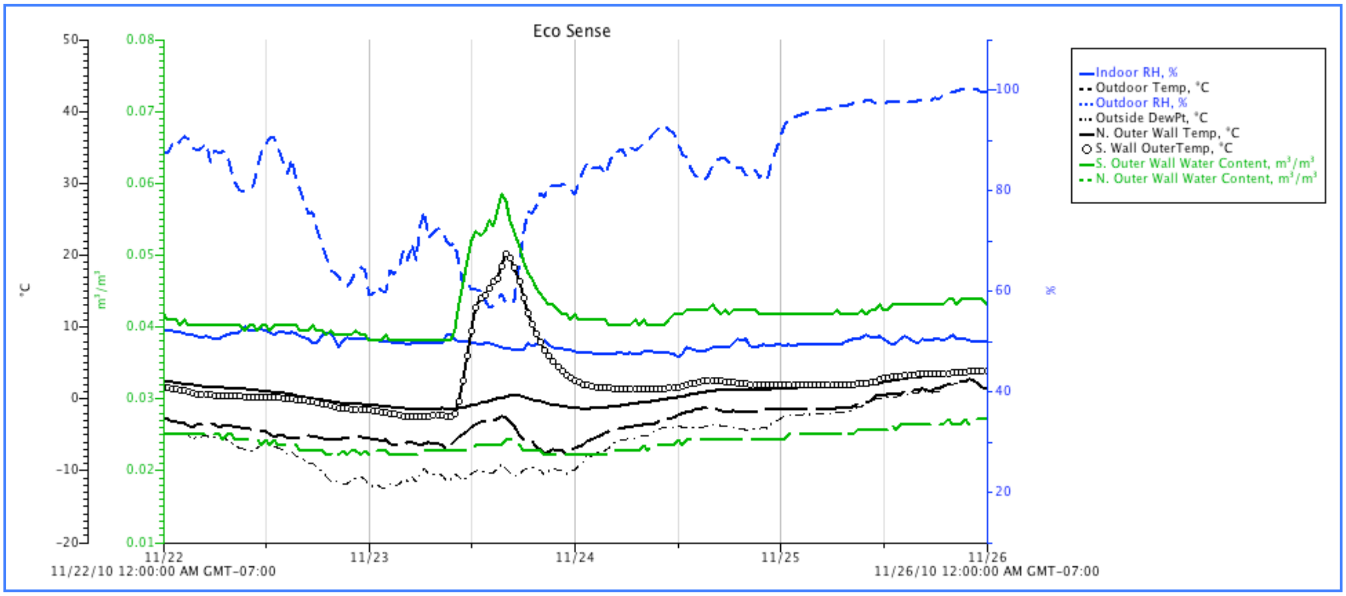


Figure 18 Temp and Water content

Temperature Moderation

Results thus far have shown the temperature moderating effect of the cob wall wherein interior temperatures maintain shallower amplitude between daily extremes, than those experienced outdoors. The below Figure denotes the South Wall over a 7 day period showing the heating and cooling exterior temperature cycles. Of importance in this observation is the time shift seen between S. Wall outdoor peak and the S. Wall indoor peak, which is several hours' difference, a time lag.

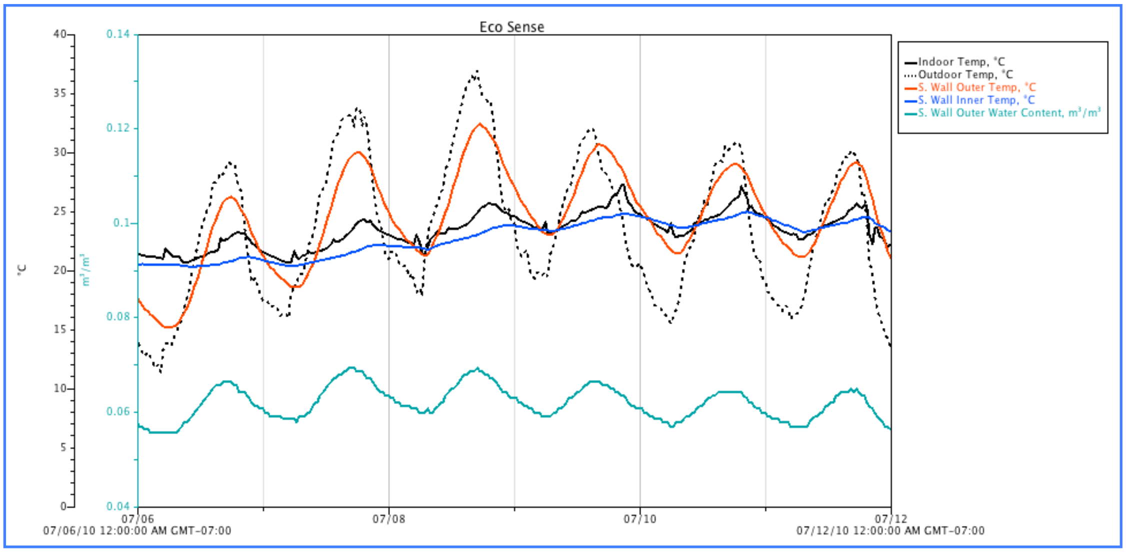


Figure 19 Temperature variation over 7 day period

The absorbed energy from solar gain provides a significant construct in the functioning of the wall assembly. As the sun hits the wall surface the wall absorbs energy to a depth we estimate to be 10 cm. With a specific heat capacity based on an average water content of 3%, a 3m X 3m section can adsorb 0.45651 kWhrs for every degree C increase, (refer to Table 4 , in Passive Solar section).

In a day with good solar exposure we see the S. Outer wall temperature increase from 12.63 C to 41.04 C, a difference of 28.41C. This translates into an increase in stored thermal energy of 12.97 kWhrs. The time lag to reach this peak energy store was 8 hours. The corresponding time lag to give up the gains is 15.5 hours. All temperature profiles on the wall systems show the ability to quickly and readily absorb thermal energy, dissipating slowly with time.

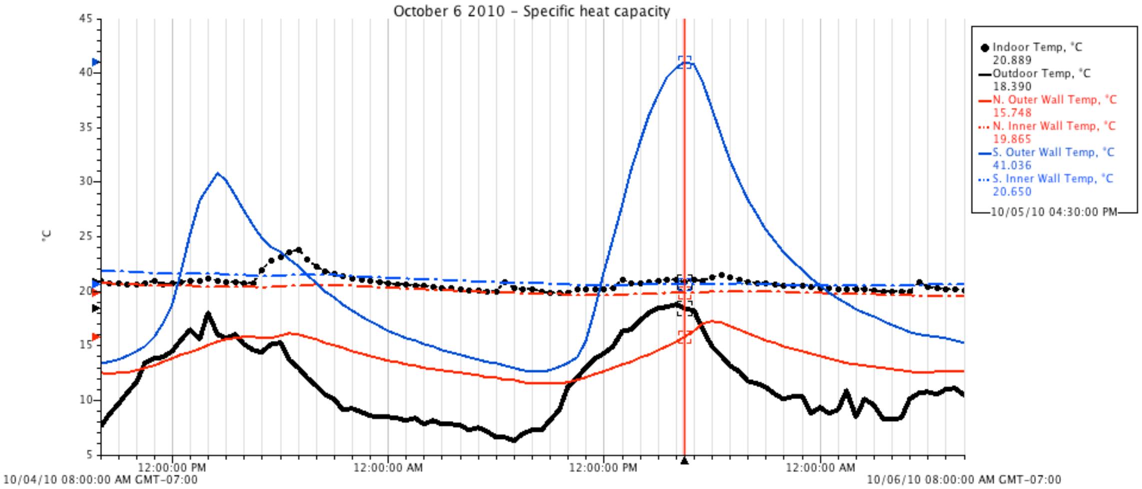


Figure 20 Oct 5 4:30 pm – Peak temp outer wall; took 8 hours to reach maximum temp

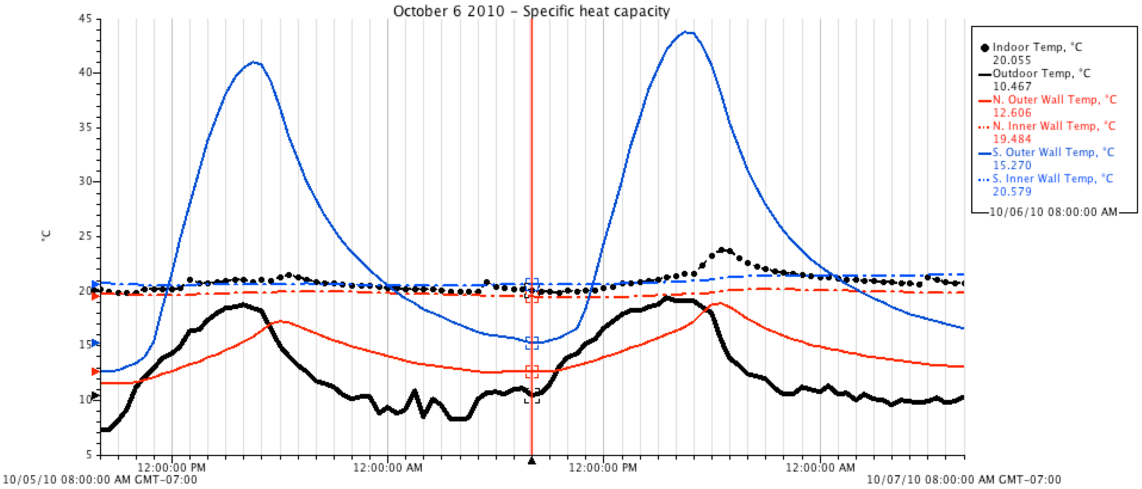


Figure 21 Oct 6 8:00 am – 15.5 hour lag to lose the previous day solar gain

The wall assembly readily stores thermal energy and releases it over long periods. The energy composition of the outer wall fluctuates with variations of outer temperature and moisture, and thus we see a moderate thermal energy transfer from the inside of the wall to the exterior.

Baird Heat Load

The peak heat load equations do not take into account the thermal contributions from thermal mass/passive solar, nor is there any factor for type of heating system used such as radiant flooring/solar thermal. The strengths of the cob home lie in the cob walls, the cost per square foot, and the efficiency of the entire home as a system.

Rule of Thumb

Using conventional heat load analysis techniques the Baird Cob home peak loss heat load was calculated. To start the analysis the general rule of thumb of R1 per inch of cob was used, giving an R22 for the 22 inch lower wall, and a R12 for the 12 inch upper wall. For the upper stud wall the R28 value is reduced by 1/3 to R18.7 to compensate for thermal bridging by the studs.

Calculated heat load of Baird cob home is 11.1 BTUH/ft^2. For a conventional home exactly like the Baird's but built with conventional high efficiency and insulative materials the calculated heat load is 13.4 BTUH/ft^2. A home with a peak heat load value of 10-15 BTU/ft^2 (including ventilation, like the above values) is considered very good.

Rule of Thumb	Upper Wall R	Lower wall R	Peak Heat Load	Home BTU/ft2
Cob Home	R12	R22	23816 BTUH	11.1 BTUH/ft2
Conventional	R15	R15	28911 BTUH	13.4 BTUH/ft2

Note that the peak heating load values compare well with other homes calculated using conventional engineering methods and software:

Home	Heat Load	Square footage	Load per ft^2
Baird Cob	23816 BTUH	2150	11.1 BTUH
Baird Conventional	28911 BTUH	2150	13.4 BTUH
Gaber Cob	22889 BTUH	1022	18 BTUH
Robinsons (light clay/cob)	24523 BTUH	1280	16 BTUH

Note that the Gaber cob home is much smaller, with a square footage less than half that of the Baird cob home. The Robinsons light clay/cob home is also only about 60% of the area of the Baird cob home.

Degree Day Method Estimation

The original degree-day procedure was based on the assumption that on a long term basis, solar and internal gains for a residential structure will offset heat loss when the mean daily outdoor temperature is 18C (65F). It is further assumed that the fuel consumption will be proportional to the difference between the mean daily temperature and 18C. A serious shortcoming is the inability to model equipment whose performance depends on outdoor ambient conditions.

Considering that internal heat gains have increased due to improved insulation and construction a mean daily outdoor temperature less than 18C/65F should be used, but data is still based on 65F. The general relation for fuel components using this procedure is:

$$F = \frac{24(DD)\dot{q}C_D}{\eta(t_i - t_{oi})H}$$

Where:

F = the quantity of fuel required for the period desired (85MBTU from measured data)
DD = degree days for period required F-day or C-day.
q= total calculated heat loss based on design conditions it and to, BTU/hr or W (design system to 50-60% of peak load value – matches actual usage data Jason has).
n= an efficiency factor that includes the effects of rated full load efficiency, part load performance, over sizing, and energy conservation devices. Value of 0.9 used in consideration of high efficiency equipment.
H = heating value of fuel, Btu or kWhr per unit volume or mass (1000 BTU/ft^3)
CD = interim correction factor for degree days based on 18C (0.6 from reference graph).
Ti-to = 70F-25F or 45F

Solving this equation for q give us an approximate heat loss value of 44000 BTUH. We know this equation is designed for peak coldest day. We also know that the operating load rarely reaches this limit and in conventional calculations it is known that the formula overestimates by a factor of two. Based on this we find it reasonable to say the peak heat loss load is estimated at 22 000 BTUH, giving us a value of 10.2 BTUH/ft^2. This value gives us an overall peak coldest R value of 8.5.

Measured Envelope Heat Loss

The rule of thumb of R1 per inch of cob is a conventional starting point. From our data we can take a different look at what the actual space heating demand measurement. To start, as an intellectual exercise we take a look at the overall envelope R value to provide a basis of comparison.

The annual number of BTUs used for space heating is 85MBTU (or 24913 kWhr). The run time of the heating system was calculated to be 5808 hours. From these two values we get a heat load loss value of 14636 BTUH for the envelope, giving us an approximate envelope R value of 14.6.

We can then set up a weighted average equation to determine the R value of the walls:

$$\left(\frac{Wall\ Area}{Total\ Envelope\ Area}\right)(Est.Wall\ R) = \left(\frac{Window\ Area}{Total\ Envelope\ Area}\right)WindowR$$

$$+\left(\frac{Door\ Area}{Total\ Envelope\ Area}\right)Door\ R + \left(\frac{Roof\ Area}{Total\ Envelope\ Area}\right)Roof\ R$$

Solving for the unknown gives us an estimated wall R value of 24.5.

R Value Summaries

Here are the summary values determined thus far. We know the degree day method does not recognize that internal heat gains that offset heating requirements may vary from one building to another. Thus, from the table and the calculated weighted average we can conclude that the Baird cob walls are a very effective insulator and the rule of thumb method is not unreasonable.

Method	**R value**
Rule of Thumb	R1 per inch
Degree Days	Envelope R8.5 (peak coldest)
Weighted Average	Overall Wall R24.5

Passive heating

Specific heat is the amount of energy required to raise a unit of mass through one degree of temperature. Generally, the higher the density of the material, the higher the specific heat. The closer the particles in a mass are connected the faster heat travels through it. A rule of thumb is that heat travels through cob at an inch an hour, so that energy that shines on your foot thick cob wall at 9am will be warming you at 9pm [L. Collins].

Substance	Specific Heat - c_p -	
	$(cal/gram^{o}C)$	$(J/kg^{o}C)$

Air, dry (sea	0.24	1005
Asphalt	0.22	920
Bone	0.11	440
Ice (0°C)	0.50	2093
Granite	0.19	790
Sandy clay	0.33	1381
Quartz sand	0.19	830
Water, pure	1.00	4186
Wet mud	0.60	2512
Wood	0.41	1700

The measured specific heat capacity of the cob is 879 J/(kg C), just above quartz sand and below asphalt in the table above. When this is adjusted for 3% moisture content the adjusted values are 975 J/(kg C). The measured density of the wall is 1685 kg/m3. As the moisture content in the wall varies with environmental conditions, the walls can increase their specific heat capacity. For every degree C increase the clay walls serve as a battery and can store ~975J/(kg C) of heat.

Table 4 Specific Heat Capacity of cob sample

	MJ/(m3 K)	J/(kg K) where m3 is 1685kg	kWhr/(m3 k)
KD2	1.482	879	0.41666
With 3% WC		975.34 (average)	0.45651

The absorbed energy from solar gain plays a significant part in the functioning wall assembly. As the sun hits the wall surface the wall absorbs energy to an estimated depth of 10 cm. With a specific heat capacity based on an average water content of 3%, a 3m X 3m section can absorb ~975J/(kg C) or 0.45651 kWhrs for every degree C increase in wall temperature.

Heat travel through wall

A fall day with good solar exposure shows the S. Outer wall temperature increasing from 12.63 C to 41.04 C, a difference of 28.41C. This translates into an increase in stored thermal energy of 12.97 kWhrs. The time lag to reach this peak energy store was 8 hours. The corresponding time lag to give up the gains is 15.5 hours. All temperature profiles on the wall systems show the ability to quickly and readily absorb thermal energy, with long energy dissipation. The significance of this is that the stored heat in the wall thermal mass heats the house through the night.

The following figure shows the relationship between the external and internal temperatures (see solid blue and black lines). It is also worthwhile to note that the indoor conditions maintain steady conditions.

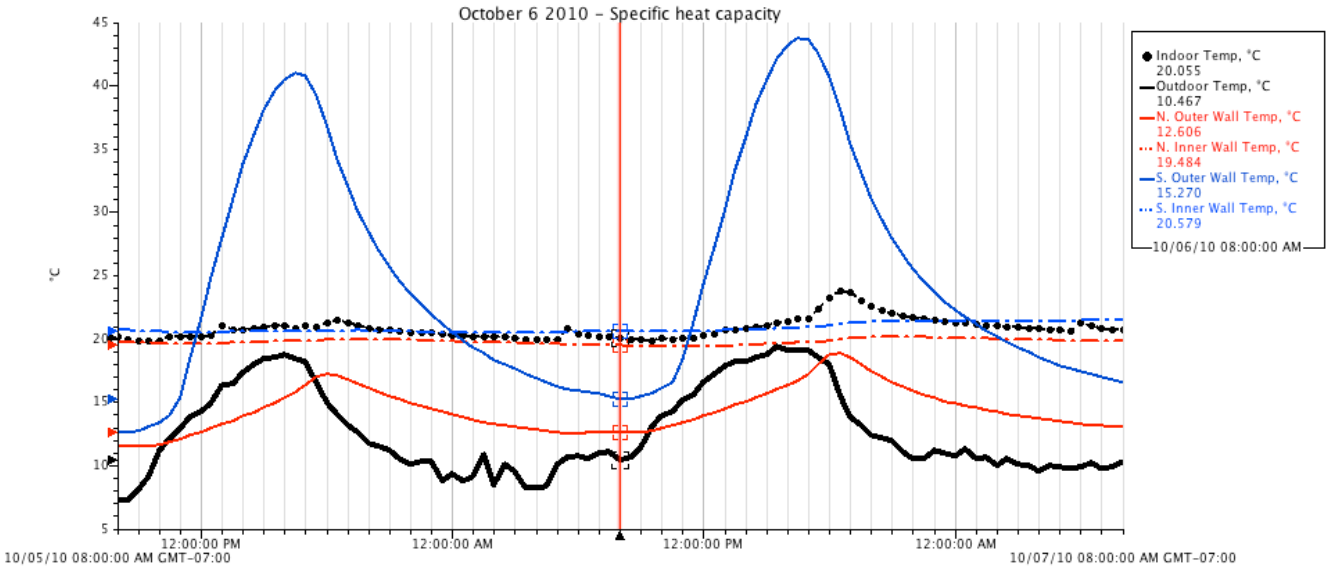
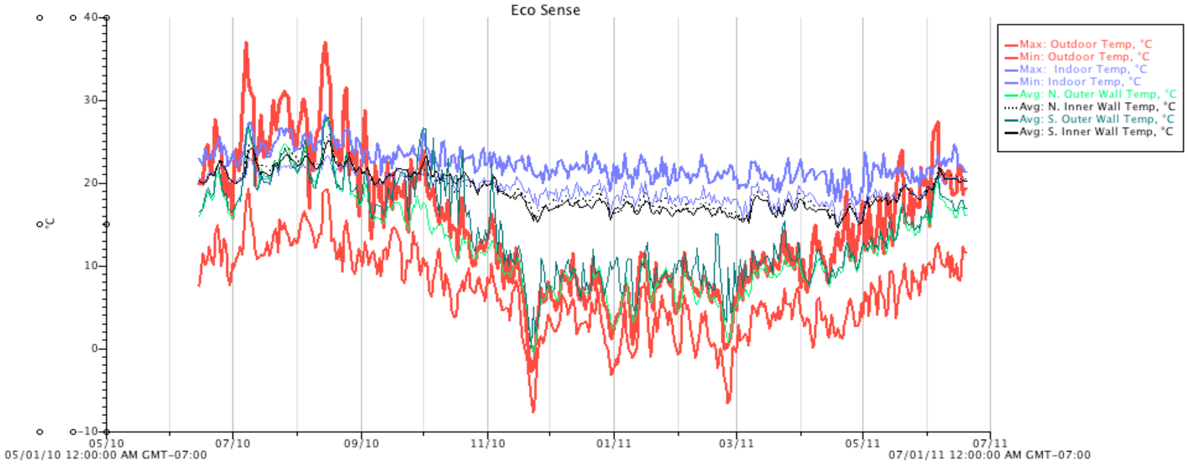


Figure 22 Specific heat capacity thermal lag

The relevance of this in understanding the thermal performance of the wall is that the energy composition of the outer wall fluctuates with variations of temperature and moisture, and thus directly impacts the flow of thermal energy between the inside and the exterior, which means the functional R values greatly vary depending upon the state of the exterior wall.

Relating specific heat and R values… Still in progress

In the following graph the Max. and Min. of Outdoor and Indoor temperatures are displayed. This shows the drastic variability in the daily variance of outdoor temp, contrasted to the very narrow range displayed by the indoor temp. Also visible is the consistency throughout the year of the indoor temp.



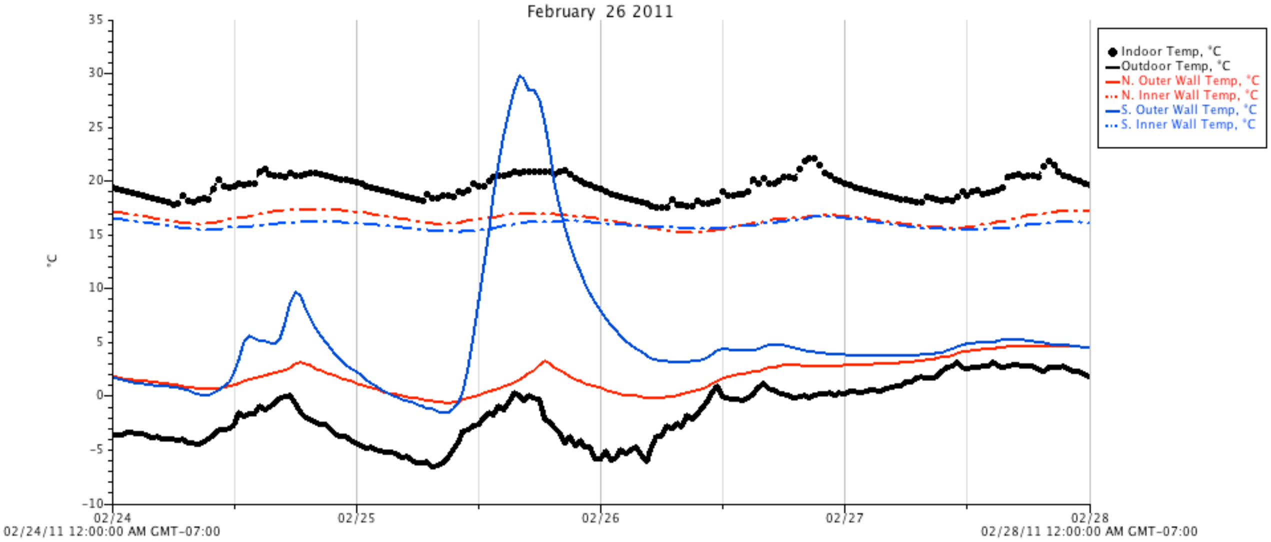


Figure 24 Temperature variation over winter days

Note the extreme heat that the south outer wall reaches is due to solar gain, as the sun is lower on the horizon and shines on the wall. As with the other results, we see the wall maintains a fairly steady temperature range, sensitive to the indoor temperature with a small thermal lag, suggesting that the walls act as a very efficient insulator.

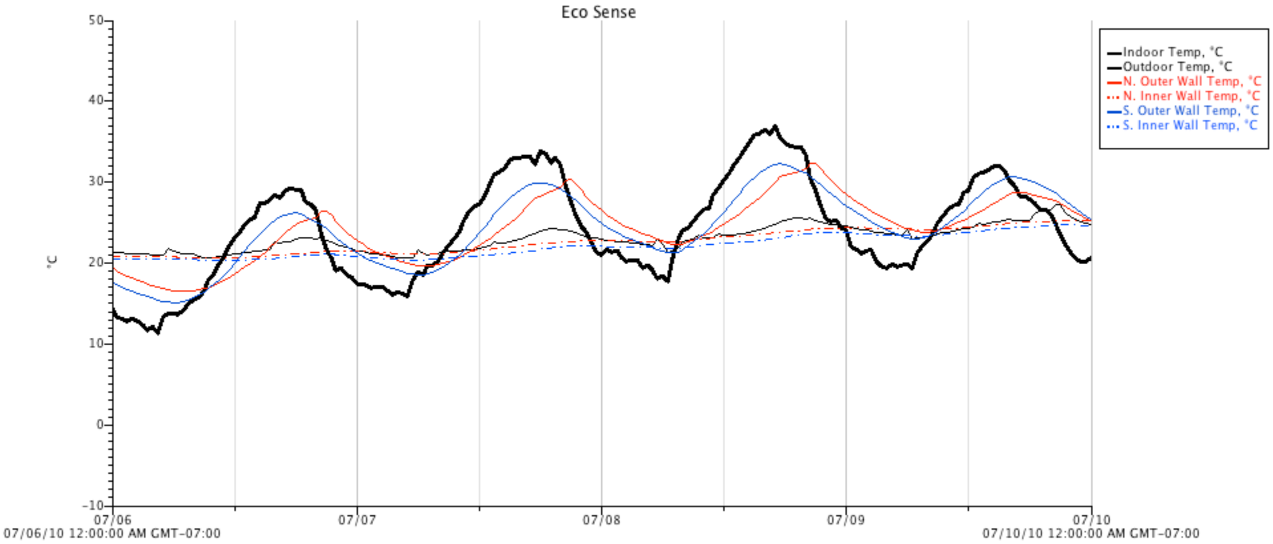


Figure 25 Temperature variation over summer days

The summer daily variations show a strong response to the outdoor temperature. The high outdoor temperature is closely reflected by the outdoor wall temperature. Note the consistency of the indoor temperatures. The walls are heating in response, but slowly.

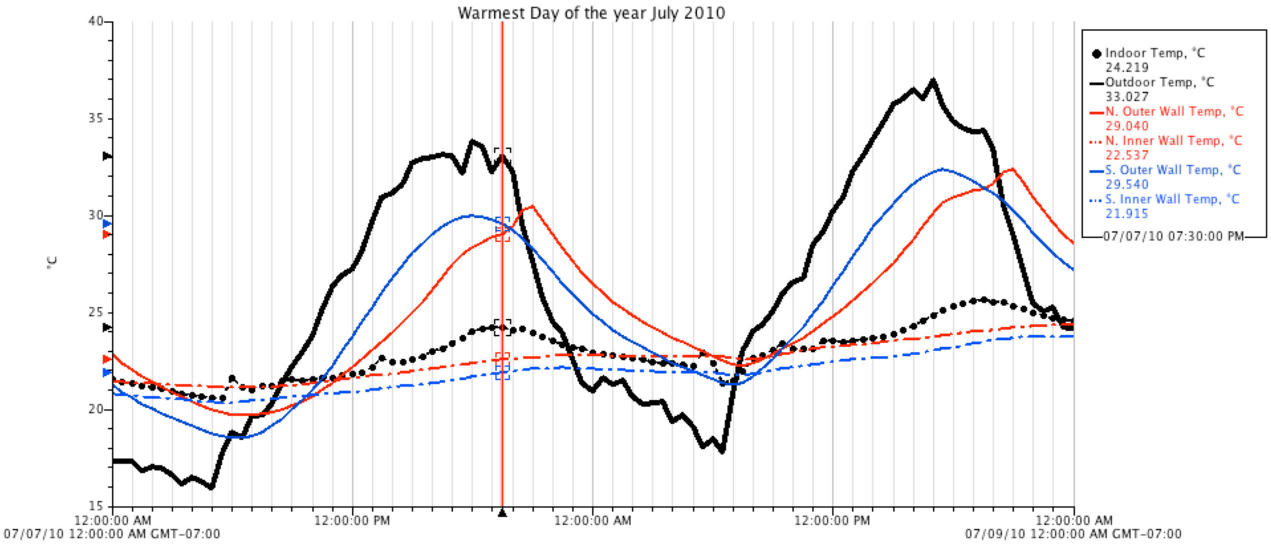


Figure 26 Warmest day of the year temperatures

Daily peak day results: Outdoor Max temp was 33.8 C, indoor Max temp was 24.2 C with a lag time of 1.5 hours. The inner walls respond primarily to indoor temp. As noted Max indoor temp was 24.2 C; the N. Inner Wall Max temp (22.8 C) occurred 3.5 hours after, and S. Inner Wall Max temp (22.13C) had a lag of 3.0 hours.

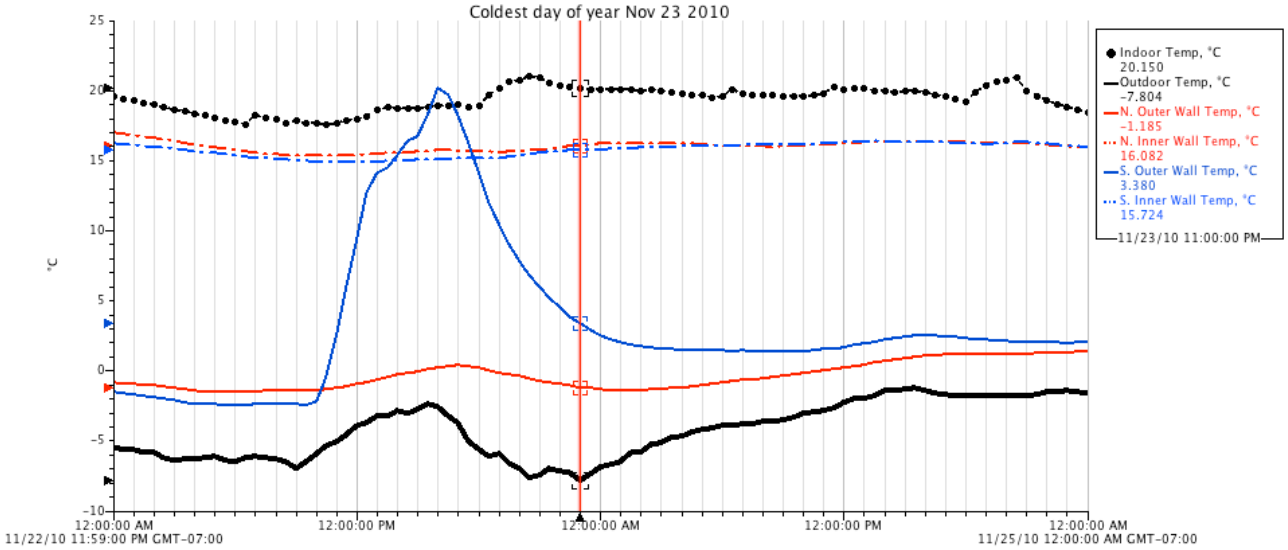


Figure 27 Coldest day of the year temperatures

In the coldest day of the year we see the blue peak of sun exposure on the outer south wall. The Warmest outdoor temperature of the day -2.4 C was followed by the N.Outer Wall warmest temp of 0.4 C; the time lag was 1.5 hours. Again we see a small response of the inner and outer wall temperatures, almost insignificant.

The pattern that appears is that the interior of the home stays consistently within a few degrees throughout the year, throughout all thermal inputs. The wall responses are fascinating in that there is a noticeable but small thermal lag. The interior temperatures of the wall respond most to interior air conditions, with the equivalent true for the outdoor air. The suggestion is that the outer layer of the walls acts as breathable surface layers storing heat and moisture and releasing them according to temperature and moisture gradients. The small thermal lags suggest the walls are extremely effective thermal insulators, with little to negligible transmission of heat and moisture.

Solar thermal (see appendix 6)

Of important note about the year of data collection from Eco-Sense, was the abnormal decrease in solar insolation for the region. The average yearly insolation is 1242.71 kWhr/m2 (refer to Appendix Note 6-1); what was observed was 1050.82 kWhr/m2 (refer to Appendix Note 6-1), 191.89 kWhr/m2 short from the norm, or approximately 15% less sunshine. This virtually equates to missing 2 months of solar insolation. The months that showed the largest actual decrease were the shoulder months (spring and fall), when reliance on the solar thermal insolation for heating is paramount.

	Actual Monthly Insolation (kWh/m2)	Average Insolation for Lat/Log from NASA (kWhr/m2/day)	AverageMonthly Insolation for Lat/Log from NASA (kWhr/m2)	Average difference from Normals expected for the month
Jan	21.54	1.04	32.24	-33.2%
Feb	35.60	1.91	53.48	-33.4%
Mar	62.12	2.93	90.83	-31.6%
Apr	102.76	4.2	126.00	-18.4%
May	137.39	5.17	160.27	-14.3%
Jun	172.68	5.67	170.10	1.5%
Jul	193.74	6.08	188.48	2.8%
Aug	147.61	5.4	167.40	-11.8%
Sep	83.13	4.07	122.10	-31.9%
Oct	56.59	2.25	69.75	-18.9%
Nov	20.88	1.18	35.40	-41.0%
Dec	16.79	0.86	26.66	-37.0%
	1050.82		1242.71	

With the actual daily insolation known we are able to determine the actual efficiency of the collectors based on the amount of heat they collected. The Figure below shows the averaged monthly relationship between insolation and actual collected energy.

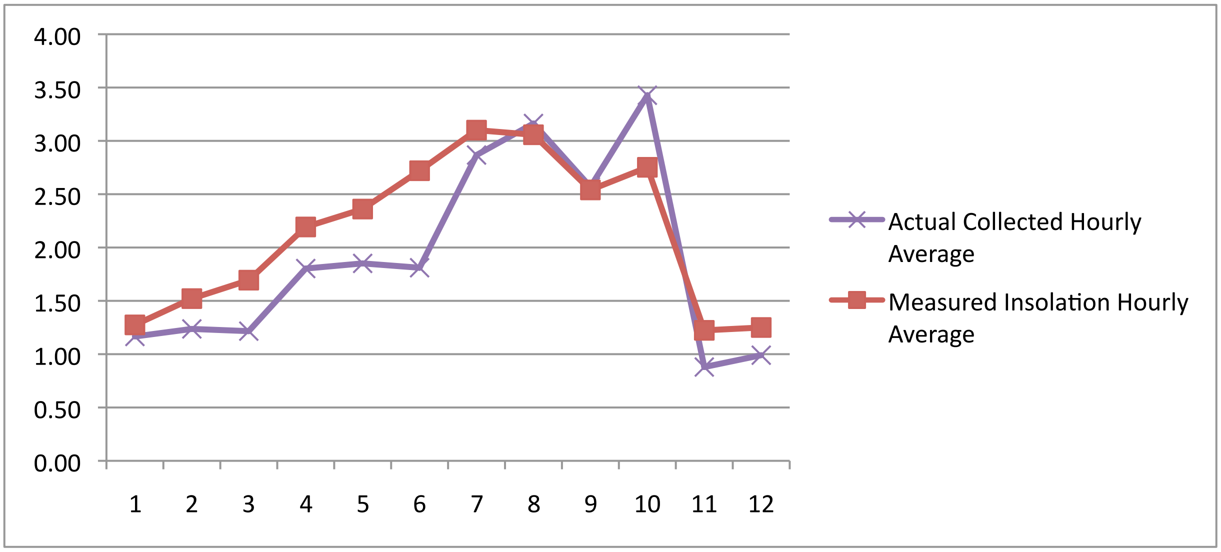


Figure 28 Available insolation and collected solar energy

The actual annual efficiency of the solar collectors was calculated to be 87%. This outperformed the forecasted solar fractions of the collectors from RETScreen and Thermomax of 70%. Note the November 'actual collected' peak was due to a moderate equipment malfunction.

The data collection for the solar thermal tubes performed better than expected and data was collected except for a one week period when the laptop reading the data from the controller was unable to collect data. The lost data was of no issue due to the fact that the Calleffi controller logged and stored the lost data, and we were able to take the lump total collected over those days and determine the average daily gain. On November 3 an air lock was generated in the manifold causing the manifold to over heat (recording very high temperatures), and the pump to run without pumping fluid, creating an errant reading for that one day. This can be seen in the following two graphs.

Total kWhrs produced from the Solar Thermal Systems was 9318.5 kWhrs

Table 5 Comparison of Measured Solar thermal and Insolation to Theoretical availability via Webgraph

Monthly Solar kWhr SUM		DAILY	DAILY	MONTHLY	MEASURED	MEASURED	DAILY	MONTHLY		
		Collected	Collected Hourly	Collected	Insolation	Insolation Daily Hr.	Estimated Coll.	Estimated Coll.	Insolation	collector
Month	Days	Daily Ave.	Ave.	Ave kWhr	Daily Ave	Ave	Webgraph	kWhr	Hours	efficiency
Jan	31	10.49	1.17	325.28	11.47	1.27	7.91	245.19	9	91.48
Feb	28	13.60	1.24	380.88	16.73	1.52	13.89	388.86	11	81.31
Mar	28	15.81	1.22	489.97	22.02	1.69	17.71	495.89	13	71.78
Apr	30	27.04	1.80	811.32	32.89	2.19	21.49	644.61	15	82.23
May	31	29.62	1.85	918.13	37.77	2.36	25.27	783.23	16	78.41
June	30	30.78	1.81	940.47	46.24	2.72	24.92	747.47	17	66.56
Jul	31	48.74	2.87	1510.98	52.71	3.10	28.67	888.90	17	92.47
Aug	31	47.44	3.16	1470.78	45.86	3.06	27.05	838.48	15	103.46
Sept	30	30.82	2.57	924.65	30.48	2.54	25.51	765.23	12	101.12
Oct	31	34.28	3.43	1062.57	27.52	2.75	16.73	518.62	10	124.55
Nov	30	7.91	0.88	237.43	11.01	1.22	10.18	305.33	9	71.88
Dec	31	7.92	0.99	245.61	10	1.25	7.08	219.54	8	79.23

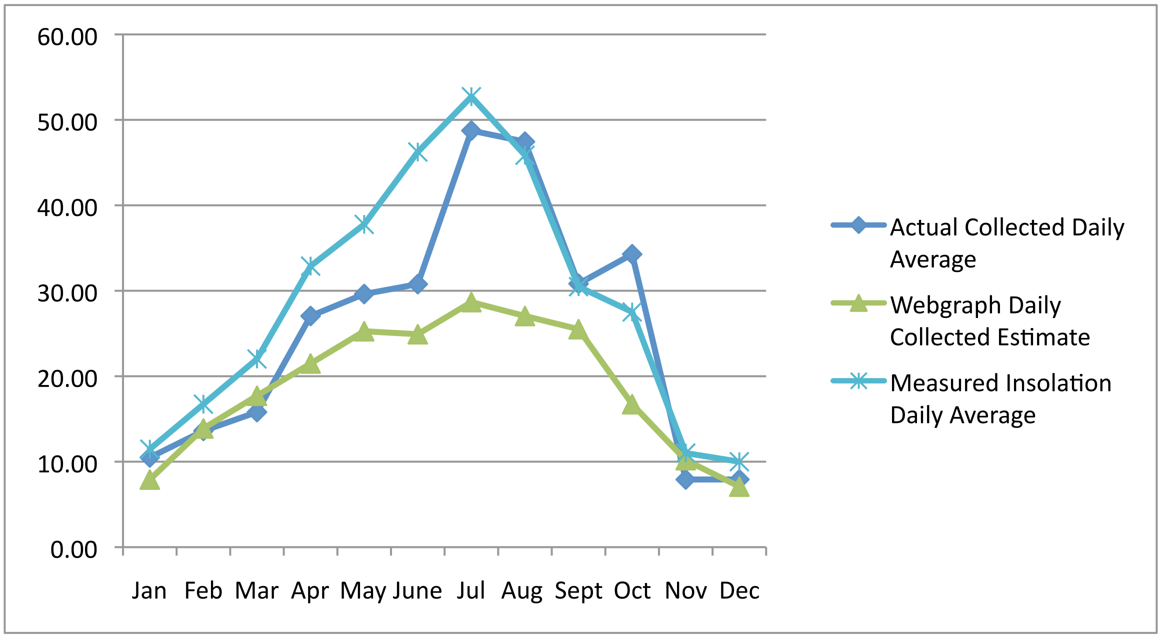


Figure 29 Comparison of the average Actual collected Solar thermal to Webgraph Estimate, and to Actual insolation

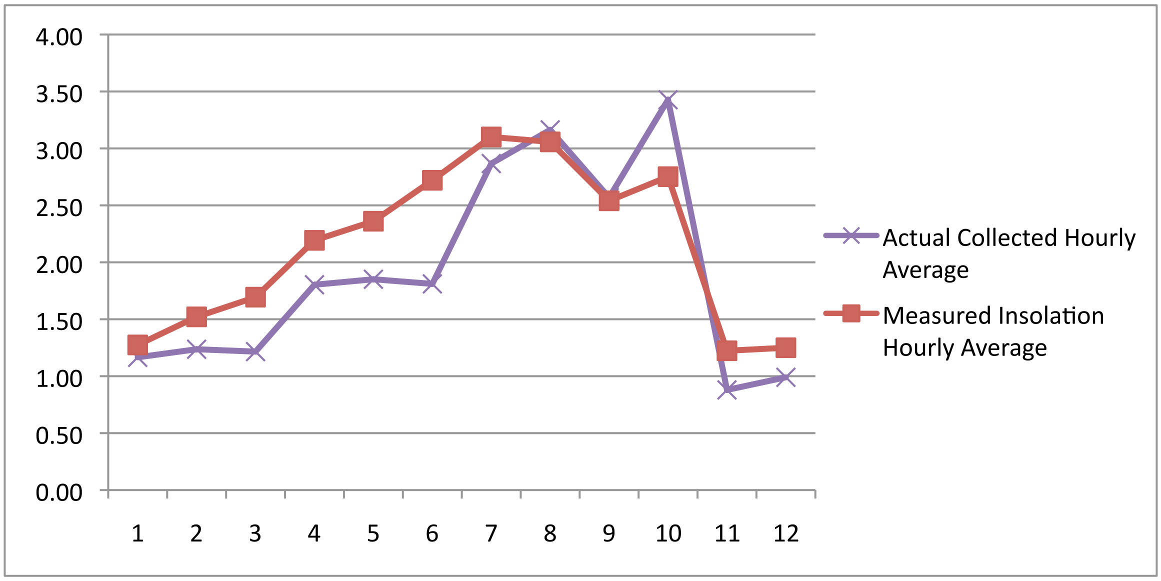


Figure 30 Comparison of Hourly Average Solar Thermal collected to the measured insolation

Note: The peak at the end of October is due to an errant reading wherein ther was an airlock.

Monthly collected totals are shown in Appendix Table 2-6.

Table 6 Comparison between Solar Thermal & PV generation

Solar Thermal Monthly	Solar Thermal Monthly (kWhrs)	Solar PV Generated (kWhrs)	Difference b/n Solar Thermal over Solar PV kWhrs
January	325.28	107.33	67.0%
February	380.88	107.38	71.8%
March	489.97	206.05	57.9%
April	811.32	272.80	66.4%
May	918.13	313.95	65.8%
June	940.47	397.75	57.7%
July	1510.98	339.35	77.5%
August	1470.78	312.05	78.8%
September	924.65	248.65	73.1%
October	1062.57	197.83	81.4%
November	237.43	97.08	59.1%
December	245.61	69.73	71.6%
Totals	9318.05	2669.93	69.0%

Of the two sustainable energy input sources, of solar thermal and solar PV, the solar thermal consistently adds more energy to the house, on average 69% more energy (Table 6, Figure 31). With the price per kWhr of PV being $0.82 when amortized over the lifespan of the system, solar thermal (20 years at a cost of $17,000), has a price tag is $0.091/kWhr.

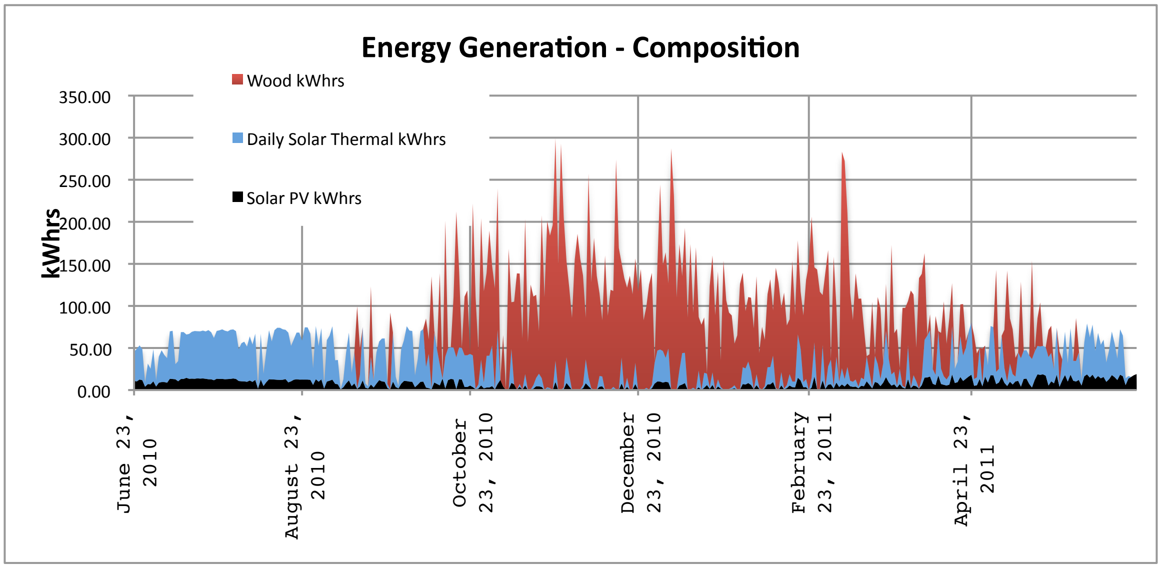


Figure 31 Energy contribution profile

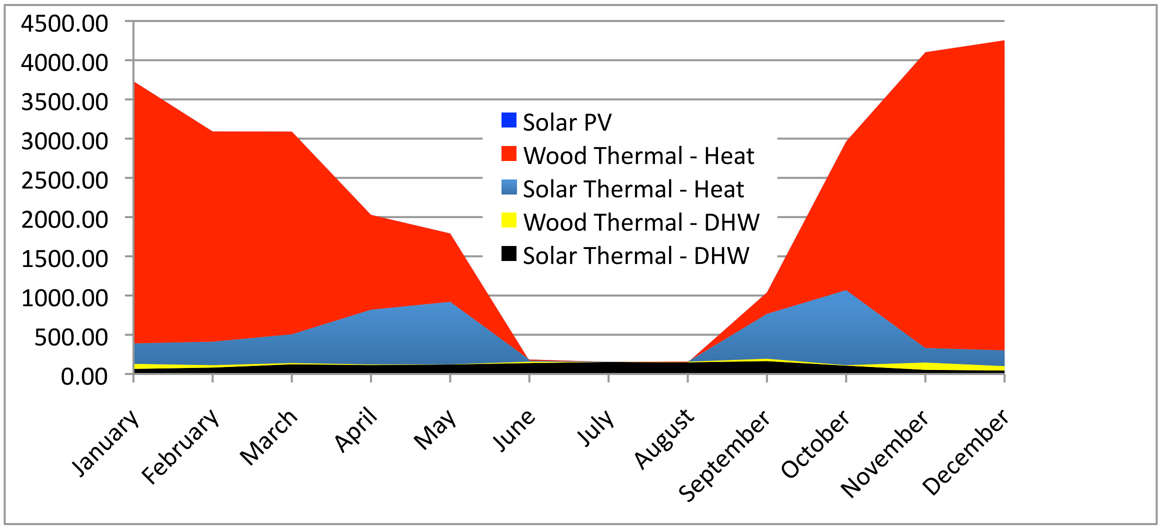
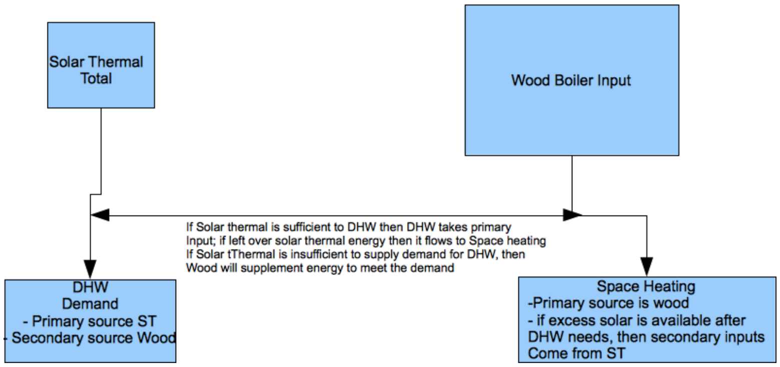


Figure 32 Energy Contribution to end-use

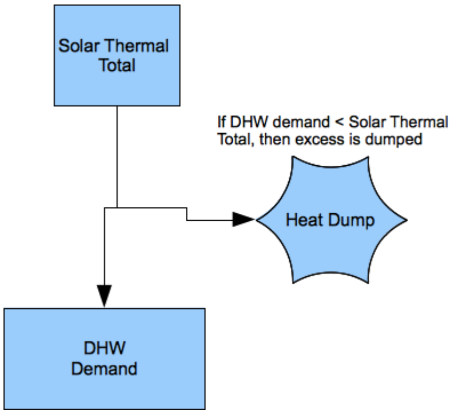
Solar thermal contribution as a percentage of total energy inputs for space heating was greatest in the shoulder seasons. In the winter the insolation is diminished and solar thermal collection contribution is limited. In the summer season there is less demand for heating, primarily DHW only, thus the excess solar thermal energy is dumped by running it through the dormant wood boiler, (see Figure 32); methodology of the extrapolation is explained in Appendix Note 6-3 and 6-4.

The following flowchart shows the thermal energy flows within each of the two phases, winter heating season, and summer season. Each End-use (DHW, space heating) draw upon the total energy inputs, but vary slightly in has they are dispersed depending on the phase.

Heating Season



Summer Season



See Appendix Note 6-5

Table 7 End-Use energy profile of thermal energy inputs (solar thermal & wood)

Solar Thermal Monthly	Solar Thermal Monthly (kWhrs)	Insolation (W/m2)	Solar Thermal used for heat (kWhrs)	Wood Used for Heat (kWhrs)	Solar Thermal Used for DHW (kWhrs)	Wood used for DHW (kWhrs)	Un-Utilized Solar Thermal (kWhrs)	Solar Thermal Contribution to Space Heat (%)
January	325.28	21.54	260.61	3342.00	64.67	65.18	0.00	7.2%
February	380.88	35.60	299.31	2679.76	81.57	31.08	0.00	10.0%
March	489.97	62.12	366.59	2583.67	123.38	16.70	0.00	12.4%
April	811.32	102.76	698.01	1208.76	113.30	8.55	0.00	36.6%
May	918.13	137.39	797.41	870.94	120.72	2.36	0.00	47.8%
June	940.47	172.68	26.41	-14.57	139.01	18.53	775.04	0.0%
July	1510.98	193.74	0.00	0.00	153.47	0.00	1357.50	0.0%
August	1470.78	147.61	0.00	-9.27	148.27	9.27	1322.50	0.0%
September	924.65	83.13	571.93	272.63	164.01	30.84	188.70	67.7%
October	1062.57	56.59	956.36	1894.83	106.21	6.46	0.00	33.5%
November	237.43	20.88	184.69	3770.11	52.74	93.86	0.00	4.7%
December	245.61	16.79	201.57	3951.99	44.05	56.40	0.00	4.9%
Totals	9318.05	1050.82	4362.89	20550.84	1311.4	339.22	3643.75	

The total solar thermal energy that could not be utilized, and dumped was 3643 kWhrs. This is approximately 14% of the total heat demand used within the home. As the table above illustrates, the total space heating (heat load) demand for the home is measured to be 24,913.73 kWhr over ~6000 heating hours (estimated from equipment), giving us a heat load of 14167.8 BTUH. Refer to Appendix Notes 6-3 & 6-4 for methodology)

Source	Space Heating Demand	DHW Heating Demand
Wood Boiler	20550.84 kWhr	339.22 kWhr
Solar Collector	4362.89 kWhr	1311.40 kWhr

Of the total demand the solar collectors provided 80% of the domestic hot water demand (DHW) and 20% of the space heating demand. The remainder was supplied by the backup wood boiler system. These numbers also allow us to estimate a whole house heat loss comparison. Since the whole home had a heat load of 14167 BTUH we can estimate from the structural measurements and properties that the thermal resistance of the home is R19.7. This is consistent with measurements used in engineering calculations conventionally (R1 per inch of cob).

This result does not match the steady state R value measurement from the instrumentation in the thermal conductance section, primarily because the usual steady state conservative approach excludes transient heat gains such as solar and internal gains, which may not be present when needed. Energy storage effects are also usually ignored as they are likely not present during the coldest times of the year.

The Baird's solar thermal system was found to be functioning above the manufactures specifications, which may be due in part to having the manifolds plumbed in parallel, and being able to draw heat out of their tank quickly for space heating thus allowing a cooler tank to better able absorb new and continuous thermal inputs efficiently because of larger temperature differentials between inputs and tank temperature.

It was found that the solar thermal system really plays a role in the shoulder seasons, and thus design considerations could be implemented to increase storage capacity to better utilize otherwise lost (dumped) thermal inputs.

Based on its present level of functioning and the life expectancy, the low cost of $0.09 kWhr of solar thermal energy far surpasses what is garnered from solar PV, and virtually compares to what BC Hydro's charge would be for the same energy.

The obvious conclusion is that the workhorse of the home jumps into action in the winter months to top up space heating, this is the wood boiler. At the time of writing this paper the Baird's were in the process of researching a Daikin Altherma air-to-water heat pump with a Coefficient of Performance (COP) of 4.5. The addition of this would in effect cut down the energy requirements in kWhrs from wood source by 75%, a drastic decrease, and the energy would be derived from a lowered carbon footprint source.

Due to the design of solar thermal and wood source systems, and their nature, it has been learned that owners should acquire the basic knowledge to service the components, if even on a yearly schedule.

DHW comparison to Conventional

Water heating is generally controlled by the usage patterns of the residents. The BC average energy per person per BC household is 2148.64 kWhr; the Eco-Sense average is 330.13kWhrs. The is a dramatically different usage pattern than that of the average BC resident wherein Eco-Sense on a per person basis uses 84.6% less energy to heat its domestic hot water on a per person basis. And of the water that is heated, the majority is from solar thermal collection.

2008 BC Average Total usage/household (kWhrs)	Eco-Sense Total household usage (kWhr)	2008 BC Average Intensity / m2 (kWhr/m2)	Eco-Sense Intensity / m2 (kWhr/m2)
5371.61	1650.63	35.96	8.22
Avg usage /Person (kWhr)	Usage / person (kWhr)		
2148.64	330.13		

Space Heating Comparison to Conventional

The average residence in BC uses 19739.07 kWhrs of energy to heat space, for an energy intensity of 105.14 kWhrs/m2; whereas Eco-Sense used 24948.72 kWhrs for an intensity of 124.31 kWhrs/m2. This demonstrates that the envelope is possibly performing less well than the average single detached residence, with an increased energy intensity usage of 18.2%. Also what may account for this additional energy usage may be in part the decreased solar insolation of 15% and the subsequent increase in HDD by 17%. Note: The Eco-Sense data is not for an average year but is compared to data from an average year.

Single Detached 2008 (kWhr)	Space Heating intensity (kWhr/m2)	Eco-Sense Space Heating (wWhr)	Eco-Sense Space Heating Intensity (kWhr/m2)
19739.07	105.14	24948.72	121.99

The Eco-Sense home heating system would benefit from the addition of an air-to-water heat pump with a Coefficient of Performance (COP) of 4.5. The addition of this would in effect cut down the energy requirements in kWhrs from wood source by 75%, a drastic decrease, and the energy would be derived from a lower carbon footprint source.

Solar PV

Eco-Sense Started the test year with 12 Sharp 175w panels, providing a 2kW array. On Oct. 12, 2010 the panels were tilted to their winter position and 4 new 175w panels were added. On March 20, 2011 the panels were tilted back to the summer angle. Summer angle is 60 deg; winter angle is 35 deg.

All 16 panels are wired to feed two parallel Outback MX 60 Charger controllers, an 800 amp hour sealed AGM battery bank, 3500W Outback Grid-Tie inverter, and linked to the BC Hydro grid. There is no generator backup power supply. When batteries are fully charged and the panels are producing extra kW, they are fed into the BC Hydro grid. When the house is using electricity and drawing the batteries down, the inverter will keep the batteries topped up either from the solar PV or the BC hydro grid. Everyday, the BC Hydro net meter sells and buys electricity with Eco-Sense. (Refer to Appendix Figures 5-1, 5-2, & 5-3 for additional visual graphs/notes).

Summary of Solar PV	Measured kWh
Total Yearly Production	2699
Total Yearly Consumption	2302
Average Daily Consumption	6.33
Average Daily Production	7.42
Net zero surplus for the year	397
Refer to Appendix Tables 5-1, 5-2 & 5-3	

It is very difficult to compare the electricity usage of the Baird home with the conventional or average single detached residence in BC (SDR), as there is a very different energy profile. The make up of energy consumption shows a drastically decreased use of electricity, using only 18.3% of the average BC SDR. A summary of energy intensity inclusive with electricity follows:

	BC Avg Single Detached Residence (NRCAN	Eco-Sense (kWhr)

	NEUD 2008)	
Energy Use by Energy Source (kWhr)		
Electricity	12731.12	2324.85
Natural Gas – LP Gas (Appendix Note 3-1)	16235.09	1263.00
Heating Oil	204.40	0
Other2 (inclusive of Solar Thermal)	262.80	5709.29
Wood	2452.78	20890.7
Total Energy (kWhr)	31886.19	30187.84
Shares (%)		
Electricity	39.9%	7.6%
Natural Gas	50.9%	4.2%
Heating Oil	0.6%	0.0%
Other2	0.8%	18.9%
Wood	7.7%	69.2%
Average Floor Space (m^2)	187.74	200.67
Energy Intensity (GJ/m^2)	0.61	0.54
Energy Intensity (GJ/household)	114.70	108.7
Energy intensity per person m^2 (per detached residence)	0.24	0.11
Energy intensity per person per detached residence	45.88	21.70
Energy Intensity (kWhr/m^2)	169.44	150.43
Energy Intensity (kWhr/household)	31861.11	30187.84
Energy intensity per person m^2 (per detached residence) (kWhr/m2)	67.78	30.09
Energy intensity per person per detached residence (kWhr)	12744.44	6037.57

The strategy the Baird home uses to make the implementation of solar PV cost effective is conservation. This is represented in having less electronic devices to plug in and for those that they do use, to invest in very efficient choices. An example of energy saving choices includes:

- Corded phones - (no battery chargers and no phantom load)
- Laptops instead of desktop computers
- 12 DC chest fridge -(uses 157 Whr/day or 57 kWhr/year compared to Energy Star minimal for comparable fridge which is 377 kWhr/year. The sundanzer has an energy consumption of just 15% of the standard meaning it is 84.8% more efficient)
- LED lighting – bulbs range in power from .8W to 3.2W
- Use of Natural Lighting – (The home has five light tubes installed acting as a main light source in both main living areas)
- 24 VDC wiring – the home tries to minimize efficiency losses from inverting power from DC to AC, thus using it in the form it is collected and stored.

- Efficient mechanical systems: DC pumps, valve and controllers – the hydronic and solar thermal systems use Ivan Labs El Sid pumps as circulators; Belimo 24 VDC actuator valves, and Caleffi/Resol 12VDC controllers.

PV/BC Hydro Net Metering - Payback

The Baird home is a net supplier to BC Hydro on an annual basis wherein it sells to BC Hydro at the same price it purchases energy, at $0.0812 /kWhr (8.12cents/kWhr). For the period of research the Baird's would have earned 397kWhrs X $0.0812, the equivalent of $32.24; this compared to the average home that uses 12,731 kWhrs at a yearly cost of $1033.75/year.

The solar PV panels have a warranty period for 25 years, the batteries a period of 10 years. Using an amortization period of 25 years for the system less batteries ($40,180), and 10 years on the batteries ($4836), where the total cost of the alternative energy system is $45,016 (depreciation and net present value not accounted for), the yearly costs of energy generation to meet needs is:

Main system

$40,180/25 yrs = $1607.2/yr

$1607.20/2554 Avg yearly kW generated = $0.63/kW

Batteries

$4,836/10 yrs = $483.6/yr

$483.60/2554 Avg yearly kW generated = $0.19/kW

$2090.80/year which when converted to cost per kWhr ($0.63 + $0.19) is $0.82/kWhr (this is based on the average yearly production over the past three years of 2554 kWhr/year).

BC Hydro presently pays $0.0812/kWhr, thus the Baird system costs them 10 times the price for their electricity than those whom are using BC Hydro. Of interesting note, the Province of Ontario, at the time of this report, had a feed in tariff program where they are paying customer's $0.82/kWhr, the same calculated cost that the Baird system comes in at.

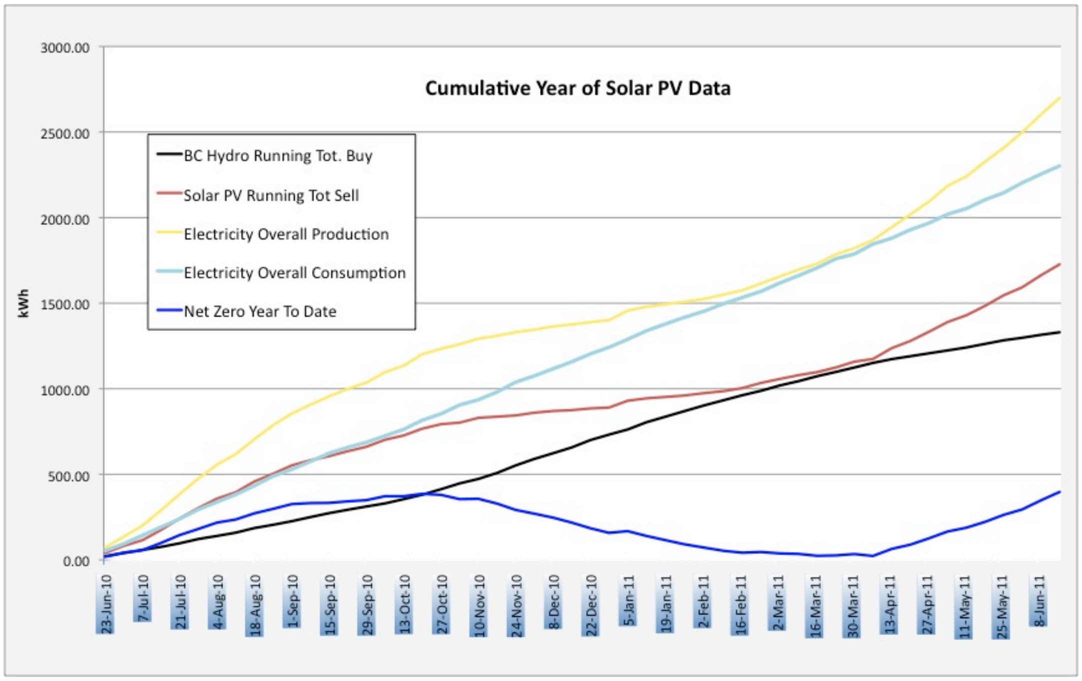


Figure 33 cumulative solar PV data

Note Eco-Sense was net zero electricity for the entire year and the Figure above shows the flow of electricity to/from BC Hydro with relation to Eco-Sense production and consumption.

Summary and Recommendations

The analysis on the data in this report has been preliminary due to time constraints. Analysis and research will continue. The initial conclusions that can be formed are as follows.

The results demonstrate the exceptional performance of the walls in moderating humidity through all situations and seasons, responding within minutes to the changing respective indoor and outdoor environments. The cob wall acted like an impassible barrier with sponges on each side that could absorb and release moisture without condensation. The walls maintain the suggested moisture equilibrium of 0.4% to 6.0% and the temperature and yearly average indoor relative humidity was 54.9% (range of 47-62%), and indoor temperature average was 20.5°C. The walls have an active and observable effect of taking in and releasing moisture and heat to maintain a balance. The walls responded over duration of 4 hours to an event of 3 hours in the same time frame, to moderate RH and keep it within the normal ranges observed, without any requirement of mechanical systems to perform this function. Under no circumstances even extremes, does condensation develop within the wall assembly. The cob walls of the Baird home behaved as a selectively permeable membrane responding quickly and effectively to environmental changes to assist in maintaining a desirable and healthy indoor environment.

The solar thermal system performs more efficiently than the manufacturer's published specifications, at over 80% efficiency. Of the energy collected by the solar collector, 80% was used towards supplying the domestic hot water demand and 20% to supplying the space heating demand. The wood boiler provided the remaining heating demand. The total space heating for the home was calculated to be 24913.73 kWhrs, which with the heating hours translates to an approximate heat demand of 14167.8 BTUH, consistent with estimations form other earthen and cob homes. A heat dump of 3643 kWhrs (14% of heating demand) was also recorded and suggestions have been made as to reduce this. It was also found that the cost of energy generated from the solar thermal system was $0.09/kWhr, vastly cheaper than the $0.82/kWhr of solar PV. The Eco-Sense home heating system would benefit from the addition of an air-to-water heat pump effectively cutting down the energy requirements in kWhrs from wood source by 75%.

The thermal performance of cob was measured two different ways; component testing of the cob walls varied significantly to the actual system performance of the cob walls. Regular metrics and testing of the specific component did not account for the thermal mass, and when the extrapolation was performed, the walls demonstrated a performance of R 24. This follows the general rule of thumb that cob performs at R 1/inch, which has been used in the geographic area for performing heat loss load calculations on other cob buildings

The home uses 84.8% less electricity than the average single detached BC residence, has a grid-intertie with BC Hydro, and is a net supplier of energy to BC Hydro of 397 kWhrs. Results investigate electricity generated, consumed, and sold, the costs and payback period of the system and relates the cost of electricity to that supplied by the provincial utility.

This report comes with 7 appendices and is written in conjunction with five other reports:

1. Comparisons for energy consumption, energy intensities and carbon analysis
2. Full solar PV analysis.
3. Wall performance report
4. Water use report
5. Key stakeholders report

Of the most obvious is that a years worth of data collection on every aspect of the home, has lent to an enormous amount of data. This report only barely scratches the surface. Due to the large volume of data, at the deadline for submission, thermal conductance not been completed. What was found, and will be reported on, is the functioning of the wall assembly and how it can be used in the creation of modeling data for other earthen homes.

What has become clear is that a conservation lifestyle and occupancy rates together play the biggest role in reducing the energy intensity within the household.

Other research that can be pulled from the data set in the future include:

- Applicability of earthen architecture for affordable housing both on initial costs, system maintenance, and full lifecycle costs.
- Relationship between R value and moisture
- Specific recommendations for the Building Code for creation of guidelines for earthen architecture resulting from the drastically different and opposing metrics that apply to earthen wall systems
- Future modeling to incorporate solar hot water for space heating of both earthen and conventional wall systems.
- Applicability of using earthen components in conventional homes to address moisture control
- Documentation for the Home Warranty providers, enabling builders to contract new builds

- Direct application potential of integrating sustainable energy systems into earthen architecture for adaptation to Climate change
- Long-term heath benefits of indoor air quality within an earthen home as it relates to the human respiratory system, household air borne pathogens, dust control, and dramatically reduced toxic off gassing from manufactured products.
- Full lifecycle cost analysis for human health, embodied carbon footprint, operational carbon footprint, and eventual deconstruction costs.

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