THERMAL COMFORT OF GLOBAL MODEL EARTHSHIP IN VARIOUS EUROPEAN CLIMATES

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ABSTRACT

This paper explores the thermal performance of the Global Earthship design. Earthship is an autonomous earth-sheltered home utilising passive solar principles. Hourly monitoring data of the indoor temperature in such a building in Taos, New Mexico, were used to calibrate a simulation model of the building. Using the calibrated model, the performance of this design is investigated in other locations: Paris, Albacete, Seville, Valladolid, and London. The results show that the Global Earthship is able to provide thermal comfort without heating and cooling provided there is adequate solar irradiance but where overcast conditions prevail, a small amount of backup heating is necessary. The study also finds that the ground temperature has a large influence on indoor air temperature and indicates the need for further research in simulating Earthship designs.

INTRODUCTION

The Earthship concept was developed by US architect Michael E Reynolds as a response to growing concerns about the negative effects of conventional housing on the environment and on peoples' health and wellbeing (Reynolds 1990). The Earthship is an autonomous home which utilises passive solar principles, earth-sheltered design and innovative "off-grid" systems to provide the occupants with shelter, thermal comfort, food, water, electricity and wastewater treatment. It is constructed substantially from consumer waste and natural materials, in particular the main load bearing walls are made by compacting earth into used car tyres and then rendering with adobe. The wall building system is easily learned but is labour intensive and consequently it is often undertaken by community groups or in an educational setting, however mechanised methods have also been developed.

It is claimed that these houses will require minimal or no active heating or cooling in almost any climatic condition, however, very few scientific studies have tested this claim. On the contrary recent monitoring and anecdotal evidence from Earthships built in Europe and the UK has questioned the claim (Hewitt & Telfer 2012).

The study presented in this paper tests these claims. The indoor thermal performance of the Global Earthship design has been investigated through monitoring and simulations while the performance of the same design located in five other locations/ climates are explored through further simulations. It is expected that this study will begin to provide a better understanding about the thermal performance of the Global Earthship design.

METHODOLOGY

In this study, hourly indoor air temperature and humidity in a Global Earthship building (Figure 1) located in Taos, New Mexico, USA, were measured and recorded for the entire 2012 calendar year. The building was occupied for only short periods during the winter but was occupied throughout the rest of the year. Sensors and data loggers were positioned at 2000mm above floor level in the main bedroom, 150mm from the rear adobe rendered tyre wall, and in the greenhouse, 600mm from the angled, double glazed facade. Outside air temperature and relative humidity were measured with sensors located 1000mm above ground level (of the berm). Solar radiation data was supplied by Weather Analytics (Keller & Khuen 2012).

The indoor air temperature data were then used to calibrate the DesignBuilder/EnergyPlus simulation model in conjunction with ground temperature modelling equations developed by Williamson (1994). To measure the accuracy of the simulated model, the Coefficient of Variance of the Root Mean Square Error CV(RMSE) between the simulated indoor air temperatures and hourly measured data were calculated. It is acknowledged that this approach was commonly applied to compare hourly simulated energy use to measured data (ASHRAE 2002); however, this approach is perceived to be adequate to be applied in this study. Typically a CV(RMSE) of less than 30% is considered acceptable; however, this study aims to achieve a much lower CV(RMSE), i.e. between 10-20%, as suggested by Bou-Saada and Haberl (1995).

Using the calibrated model, the performance of this Earthship design is investigated in five European locations: Paris, France (maritime temperate), Albacete, Spain (arid/semi arid), Seville, Spain (warm summer Mediterranean) Valladolid, Spain (hot summer Mediterranean) and London, (marine west coastal). Simulation results are then presented in terms of annual/seasonal indoor comfort conditions and, where applicable, energy use. These results are discussed in the context of previous studies of Earthship thermal performance in Europe.

Figure 1 Global Earthship, Taos, SW View

STUDY 1: TAOS EARTHSHIP

The DesignBuilder model was created using architectural drawings of the Earthship supplied by the architecture/building company, Earthship Biotecture. Figure 2 illustrates the sensor location and the general layout of the building, which is oriented to capture morning sun at 10 degrees East of South. It has approximately 100m^2 floor area not including the greenhouse (an extra 60m^2).

Construction materials for each type of building element used in the model are listed in Table 1 from outside layer to inside layer. U-values are reported with no bridging effects. As built, the Earthship exterior wall construction is made from tyres filled with rammed earth. A layer of polystyrene is positioned vertically in the berm about 1200mm from the tyres. Such a construction poses some challenges to heat transfer modelling necessitating a series of simulations aimed at assessing the validity of various approximations about this wall construction. EnergyPlus uses one-dimensional heat transfer functions through "layers" of materials (US Department of Energy 2012) and is therefore not capable of modelling the heat flow through an earth filled tyre due to its (toroid) geometry. One solution is to model the tyre as two layers of 10mm thick rubber positioned approximately 650mm apart, with compacted earth between the rubber layers (Kruis & Heun 2007). This was the initial approach adopted in this study and previous studies (Freney, Soebarto & Williamson 2012), however, a simplified method was developed which yielded comparable results. It was found that the insulated, bermed tyre wall could be accurately represented as a 1600mm layer of compacted earth (density 1900kg/m^3) with adiabatic (zero heat flow) conditions at the outside surface of the wall, and by calculating ground temperatures using assumptions consistent with the construction of the berm and floor.

The "under-slab" ground temperature was found to be an important factor that was highly influential to the simulated indoor air temperature. This is not surprising given the earth-sheltered design of the Earthship. A model developed by Williamson (1994) *TgroundES* for calculating ground temperatures was further evolved in this study to account for the peculiar slab edge condition in an Earthship arising from the presence of the greenhouse. A relationship between measured temperatures of the greenhouse and outdoors was used to refine the predicted ground temperatures and the heat flow path (length) was increased to account for the modelling assumption that the outside surface of the wall was adiabatic.

Schedules for the opening and closing of vents in the greenhouse roof were informed by occupant surveys and on advice given by the architect. The vents are generally open in the warmer months to exhaust hot air from the greenhouse which in turn draws cool air from underground "earth tubes" (located in the berm) into the living space. The effect of the earth tubes was not modelled however.

The simulated results of this building were compared to the measured results over the entirety of 2012 using hourly data and analysed using statistical methods which calculate the CV(RMSE) of the two data sets (Kreider & Haberl 1994).

Table 1
U Value and Composition of Construction

TYPE	DESCRIPTION	U-VALUE (W/M2-K)
Floor, interior	100mm thick concrete	3.355
Floor, greenhouse	25mm sand, 25mm flagstone	3.904
Glazing, exterior/ interior	Double glazed, 4mm clear, 16mm air, 4mm clear	2.715
Roof	0.4mm steel, 200mm Polyisocyanurate (PIR), 25mm softwood	0.110
Exterior Wall	1600mm earth, 25mm adobe render	0.613 not inc. berm
Interior wall	50mm concrete	3.382

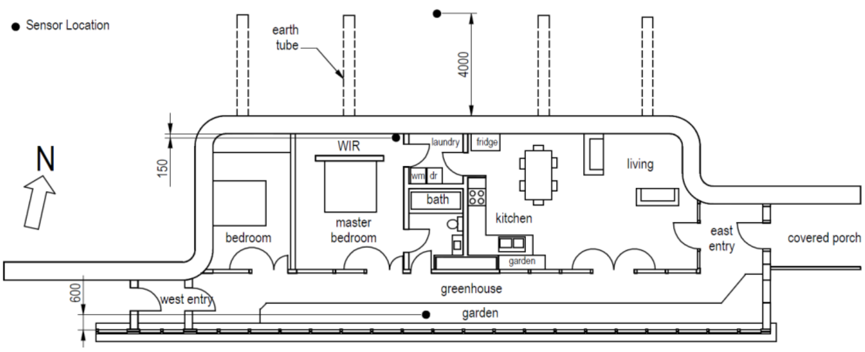

Figure 2. Location of sensors in the master bedroom, greenhouse and outside

Study 1: Monitoring Results & Discussion

Figure 3 presents the measured temperature in the Earthship compared to the acceptable temperature in a naturally ventilated building based on the adaptive model as per ASHRAE 55-2010 Standard, addendum D (ASHRAE 2012). Section 5.3 of this Standard describes a method for determining thermal conditions (that would be acceptable to 80% of people) in occupant-controlled naturally conditioned spaces. One of the criteria for using this method is that the prevailing mean outdoor temperature is greater than 10°C and less than 33.5°C. Unfortunately the Standard does not specify how to determine the thermal comfort range when the prevailing mean outdoor temperature is outside this range, as it is for the colder half of the year in Taos. Consequently the graphs show the thermal comfort acceptability limits that adhere to this criterion in dark grey shaded area (“T80%adapt”), however, a light grey shaded area (“T80%extrap”) has been used to indicate an extrapolation of the acceptability limits for the purposes of discussing the results of this study. This has been done by plotting the minimum and maximum limits for a 10°C mean monthly outdoor temperature for all months with mean monthly temperatures less than 10°C.

In Figure 3 it can be seen that the average maximum and minimum bedroom air temperature (“TaveMaxBR” and “TaveMinBR” respectively) stayed within the acceptability limits for the months where the acceptability limits could be calculated (April to September). In the colder months, the average minimum is within the extrapolated acceptability limits although occasionally the extreme maximum (“T96%ileMaxBR”) was even warmer than the comfort range. Note that there was no active heating or cooling employed in this building.

The greenhouse, which is intended as an uninhabited and infrequently used space (it serves as an air-lock entry/corridor), had average maximums and minimums either side of the acceptability limits indicating that it is generally not suitable for habitation. However, although the greenhouse temperature reached an average maximum that is well above the acceptability limit, the average minimum is often just within the acceptability limit indicating that there were many periods (generally each day) when the greenhouse provided thermally comfortable conditions.

To give an overview of the temperature profile measured in the Earthship bedroom and to compare with the simulated results, Figure 5 shows the percentage of time the indoor temperature remained in each temperature band for the total monitoring/simulation period. The measured results show that for 80% of the time bedroom air temperature was very comfortable, between 20 and 24°C; 8.5% at 19-20°C; 6.6% at 18-19°C; 2.1% at 17-18°C; and 0.06% (5 hrs) at 16-17°C. For 2.4% of the time the temperature was between 24-25°C and the remaining 0.4% between 25-28°C. Closer analysis shows that the coldest temperatures were only experienced briefly (less than an hour) early in the morning (6-8am) followed by a steady rise in temperature until comfort level was attained. This indicates that active heating is unnecessary as the temperature naturally rises to the comfort range within the hour thereby making a heater redundant.

The simulated results generally indicate slightly higher temperatures than the measured results, and the extreme outlying temperatures that were measured are not predicted by the simulation. This is consistent with the acceptability limits analysis (Figure 3 and 4) which also showed the simulation results were slightly higher than measured.

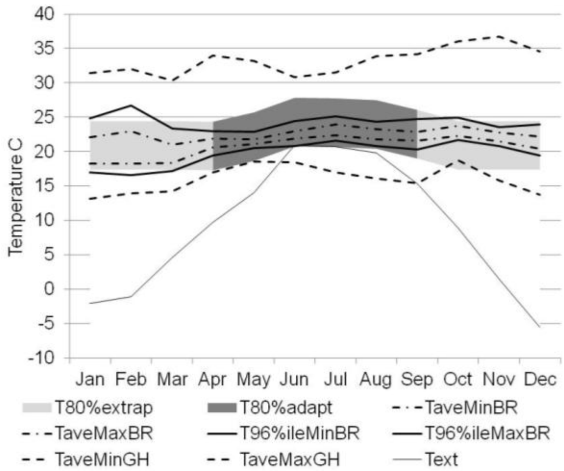

Figure 3– Measured indoor temperatures in Taos compared to acceptable adaptive temperatures

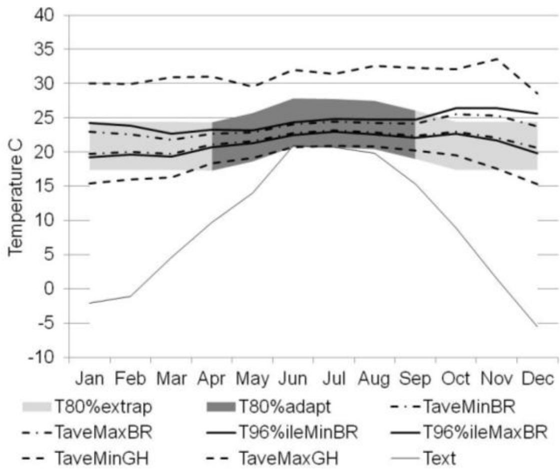

Figure 4 – Simulated indoor temperatures in Taos compared to acceptable adaptive temperatures

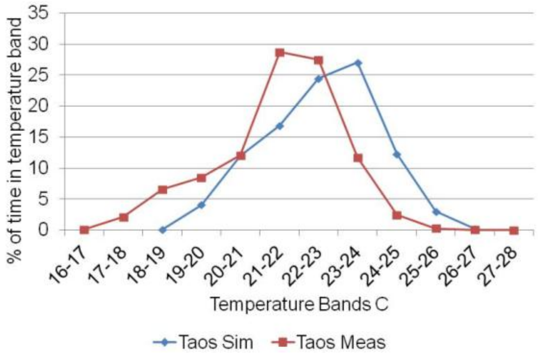

Figure 5. Simulated and Measured, Frequency in Temperature Bands

Study 1: Simulation Results & Discussion

Figure 4 shows the simulated results versus the ASHRAE acceptability limits. In the warmer months the results for the bedroom are very similar although the simulation tends to underestimate the maximum 96%ile extreme and overestimate the minimum 96%ile extreme. In the cooler months the simulation is towards the warmer side of the acceptability limits whereas the measured data indicates that in reality there is a wider range of temperatures which are slightly towards the cooler side of the limits.

In the greenhouse the simulated average maximum is slightly lower than measured, and the simulated average minimum is slightly higher than measured.

The coefficient of variance of the root mean square error CV(RMSE) between the simulation results and measured data was 6.3% for the bedroom and 13.7%. for the greenhouse respectively. These results are substantially less than the prescribed 30% threshold (ASHRAE 2002) and within the value suggested by (Bou-Saada & Haberl 1995).

Selected simulation results are presented in Figures 6-7. Figure 6 shows a week of simulation versus measured results during the winter when there were some discrepancies. The simulated temperatures in the greenhouse were generally 1-2°C lower than measured with the exception of the midday peak where simulated results were up to 6°C lower than measured. Figure 7 shows a week of simulation versus measured results during the summer with a high level of agreement for both the bedroom and the greenhouse.

During the colder months the simulated temperatures in the bedroom were often 2°C higher than measured. An incorrect ground temperature assumption was the likely cause of this as the general character of the two graphs are similar and experiments in which the ground temperature was lowered corrected this simulation error.

Thus, further work is required to develop more accurate ground temperature predictions. A study by Ip and Miller (2009) has begun this research in the Brighton, England climate, in which monitoring of the under slab and in-berm temperature of an

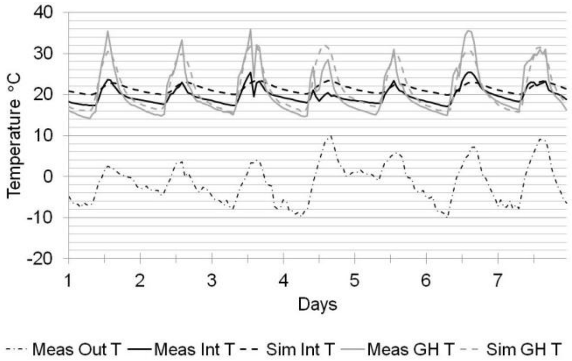

Figure 6. Taos 5-11 Feb2012

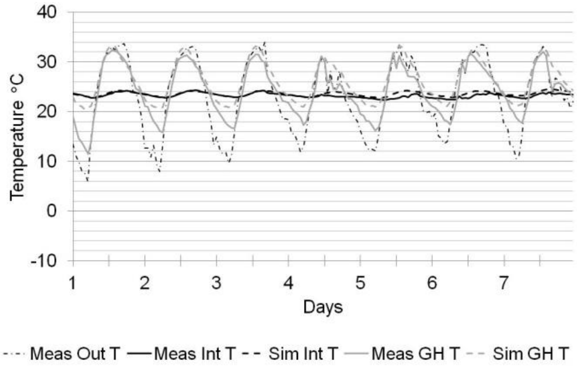

Figure 7. Taos 25 Jun – 1 Jul 2012

Earthship has been measured and this data has been used to generate ground temperatures for some of the locations in study 2 described below. Aside from measuring underfloor temperatures, data regarding earth type and moisture content throughout the year would also be very useful.

Furthermore, to achieve more accurate and reliable simulations of Earthships and similar earth sheltered designs, it is suggested that improvements are needed to EnergyPlus and DesignBuilder. Although EnergyPlus' "slab" utility is capable of generating ground temperatures based on differing core and edge slab parameters this is not sufficient to model the unusual construction of an Earthship wall. Such walls often have rainwater tanks within them with water levels that vary on a daily basis. The tapering shape of the berm provides for far greater earth sheltering at the base of the wall than the top of the wall, and the characteristics of the earth in the berm may vary in terms of density, and moisture content, the latter on a daily basis according to snowmelt, rainfall, irrigation et cetera thereby effecting the conductivity of the berm. The geometry of the tyre which is non-planar (most construction materials are planar) has already been noted as being problematic for EnergyPlus heat transfer calculations. The inclusion of a layer of polystyrene in the berm is also problematic for EnergyPlus: an EnergyPlus error message encountered while experimenting with Earthship wall simulations stated "Highly conductive or highly resistive layers that are alternated with high mass layers may also result in problems."

However despite these limitations of the tools and the information available, the simulations have shown a high degree of agreement with the measured results.

Furthermore, the comparison to the adaptive thermal comfort acceptability limits indicate similar results for both the measured and simulated results and therefore give some confidence that further simulations in other climates are likely to be reasonably reliable for predicting the performance of an Earthship built in these locations.

The overall assessment of the calibrated model's results is that they are very accurate in the warmer months; however, in the cooler months they tend to over estimate the indoor (bedroom) temperature by 2°C on average, possibly due to inaccurate ground temperature predictions during the winter months.

STUDY 2: EARTHSHIPS IN EUROPE

Using the calibrated model from Taos, simulations were conducted in five European climates: Paris, France (maritime temperate), Albacete, Spain (arid/semi arid), Seville, Spain (warm summer Mediterranean), Valladolid, Spain (hot summer Mediterranean) and London (marine west coastal). The Köppen classifications stated in the EnergyPlus weather data STAT files are Cfb, BSk, Csa, Csb, and Cfb respectively. These simulations presented a number of challenges. Ground temperatures were recalculated for each location using the *TgroundES* model. This software calculates heat transfer equations developed by Williamson (1994) which are a function of the average monthly outdoor temperature and the monthly average predicted indoor temperature.

Various options are available regarding the latter: (1) an assumption that the internal temperature equates to the ASHRAE neutral temperature, (2) correlations measured between external and internal temperatures in a large sample of Australian houses and (3) correlation between the measured external and internal temperatures for the Earthship in Taos. Experiments with these various options indicated that the last option (3) produced ground temperatures that lead to simulated indoor temperatures closest to the measured Taos data. In contrast to the other methods for calculating ground temperatures, this (last) method does not require the input of a minimum indoor temperature but uses a correlation specific to an Earthship.

However, simulation experiments in which the Taos correlation was used in London produced indoor air temperatures results that seemed far too high, well above those reported for the Brighton Earthship (Ip & Miller 2009). Using published data from the Brighton Earthship (Miller & Ip 2005) correlations were calculated for the interior versus exterior temperature and greenhouse versus exterior temperature and used to generate the London Earthship ground temperatures. This produced more realistic indoor air temperatures results, similar to those reported by Ip & Miller (2005). Furthermore this method produced monthly ground temperature results within 1.2°C of those measured in the Brighton Earthship.

Thus the correlation between indoor, greenhouse and outdoor air temperatures seems to be specific to climate and not to the Earthship design per se and it seems likely that the critical factor affecting indoor temperatures and hence "under slab" ground temperatures is not outdoor temperature but solar radiation: Taos is extremely cold in the winter yet it receives abundant solar radiation whereas London is not as cold but receives very little winter solar radiation.

Another factor affecting the correlation is the effect of occupant behaviour, however these correlation factors (for London and Taos), were calculated from data measured in buildings that were frequently unoccupied. The Brighton Earthship a visitors centre (unoccupied at night and minimal casual loads) and the Taos Earthship was sporadically occupied as it was nightly rental tourist accommodation for much of the monitoring period.

As indoor temperature data was not available for an Earthship in all the various European locations, this created a dilemma for calculating the ground temperature at each location. One approach would be to estimate a minimum indoor temperature to calculate the ground temperatures (i.e. using option one or two of *TgroundES*) and this was the approach used for the energy modelling study because when energy is modelled it can be assumed a minimum indoor temperature is maintained by the HVAC system. However estimating a minimum indoor temperature did not seem very "scientific" for a free running Earthship and therefore it seemed reasonable to use the correlation calculated for London in Paris (which has similar cool and cloudy conditions) and to use the Taos correlation for the Spanish locations which are more similar to Taos in terms of their solar radiation.

Aside from changing the ground temperatures, no other alterations were made to the calibrated model. The model was simulated in each location in both free running mode and with HVAC installed using ground temperatures calculated via option 3 and 2 respectively.

Thermostat settings were set according the ASHRAE acceptability limits for each location i.e. the heater switched on at 17.5°C for all locations and the cooler switched on at 27°C for London and Paris, 28°C for Valladolid, 28.5°C for Albacete and 29.5°C for Seville. Natural ventilation occurred if indoor temperature was 21°C or higher and the outdoor temperature was cooler than indoors for the months May to October.

Results for the free running Earthships were output in hourly format and analysed using the same methods used in Study 1. Results for the Earthships with HVAC installed are reported in terms of heating and cooling load in kWh/m2 for each month and the annual total.

Study 2: Free Running Simulation Results & Discussion

The free running simulation results are presented in Figures 8-11 showing the average maximum and minimum predicted indoor temperature in the bedroom versus the acceptable temperature limits based on the adaptive model as in ASHRAE 55-2012 (ASHRAE 2012).

With reference to the discussion comparing the simulation and measured results in Taos (Figures 6 and 7) the results for the Spanish locations should be considered in a similar manner, that is, the simulations for the cooler months maybe slightly overestimated (2°C) and have a wider range of averages and extremes than indicated, whereas the results for the warmer months can be considered to be very accurate. This is due to the use of the Taos interior/exterior temperature correlation which was also used for the Spanish locations.

In London (Figure 8) the Global Model Earthship simulation shows indoor air temperatures below the acceptability limits during winter while in the summer the minimum average indoor air temperature is within the limits. As mentioned previously this is consistent with the performance of the Brighton Earthship.

In Paris (Figure 9) the results are very similar to London, perhaps not surprisingly given their very similar mean monthly outdoor air temperature and monthly solar irradiance.

The free running simulation of the Spanish Earthships: Valladolid (Figure 10), Albacete (Figure 11) and Seville (Figure 12), indicate comfort conditions throughout the year.

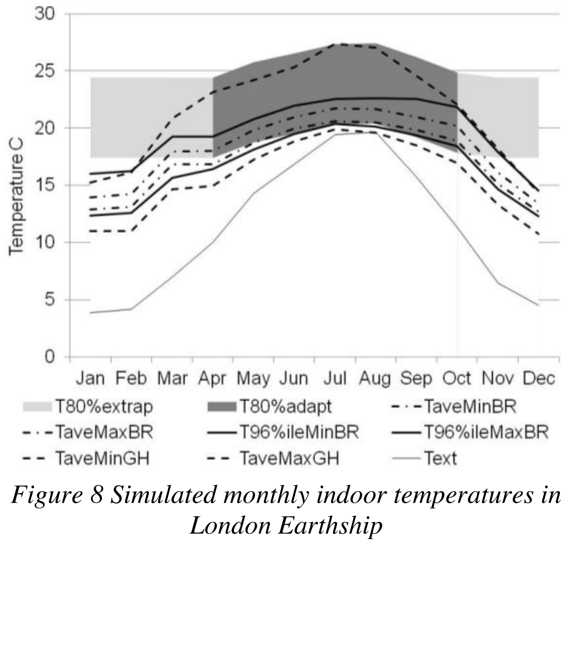

Figure 8 Simulated monthly indoor temperatures in London Earthship

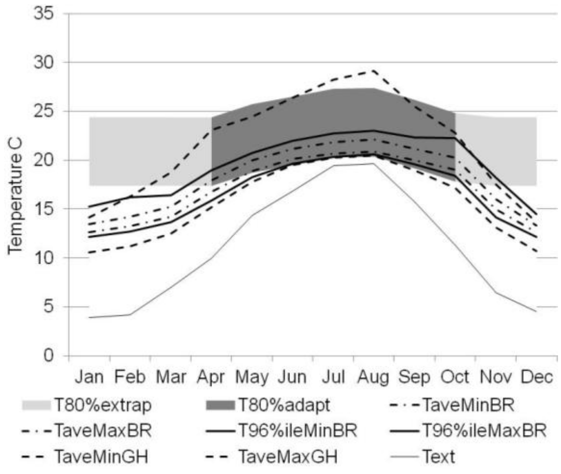

Figure 9. Simulated monthly indoor temperatures in Paris Earthship

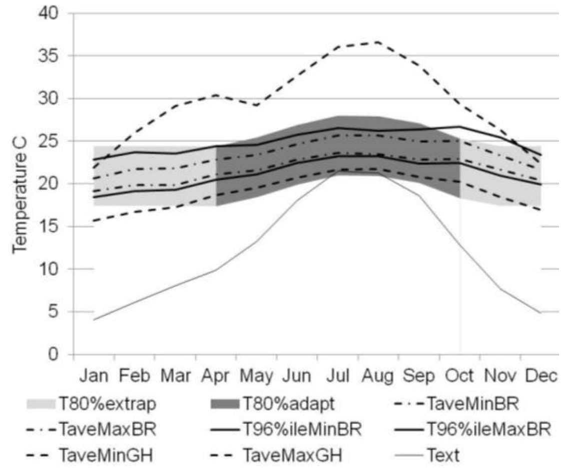

Figure 10. Simulated monthly indoor temperatures in Valladolid Earthship

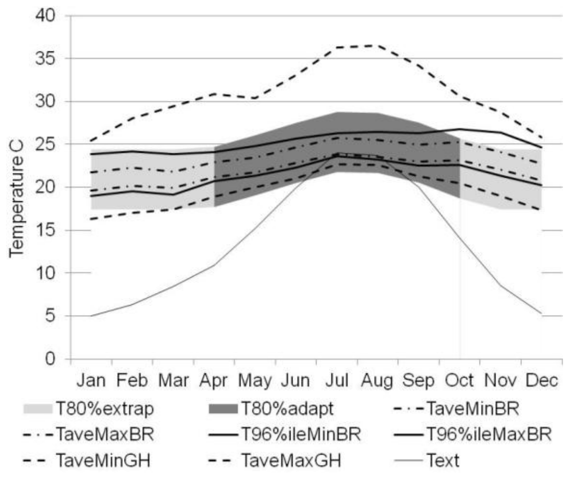

Figure 11. Simulated monthly indoor temperatures in Albacete Earthship

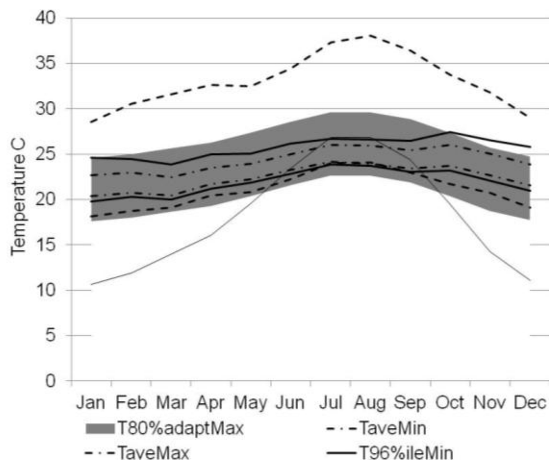

Figure 12. Simulated monthly indoor temperatures in Seville Earthship

Figure 13 plots the simulated free running indoor temperature in the bedroom in terms of the percentage of time spent in each temperature band over the whole year. This highlights the similarity between the Earthships in Valladolid and Albacete, the cooler indoor air temperatures in the Paris and London Earthships and the warmer conditions in the Seville Earthship.

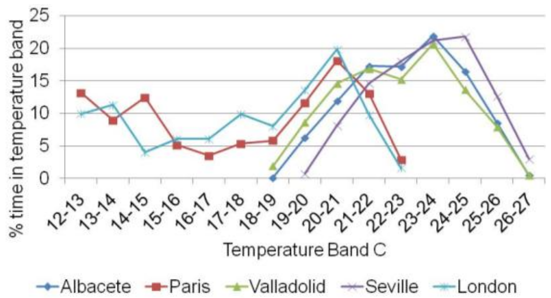

Figure 13. Simulated European Earthships – Frequency in Temperature Bands

In Brittany, France, an Earthship inspired home called the Brittany Groundhouse has been constructed. It features a bermed tyre wall similar to the Global Model Earthship although it does not have a greenhouse. Instead it has an operable, double glazed, south facing façade and an insulated hydronic floor with slow combustion heater. The owners have written a book in which average seasonal temperatures are reported: Winter 18.7°C; Spring 19.9°C; Summer 22°C and Autumn 20.6°C (Howarth & Nortje 2010). Brittany has the same Koppen climate classification as Paris therefore comparison with the Paris simulation seems reasonable although the different design and construction prevents a closer comparison. The Paris simulation produced seasonal averages of: Winter 13.2°C; Spring 17.1°C; Summer 21.1°C and Autumn 18.5°C. The warmer conditions in the Groundhouse are due to its use of a heater, which, according to the Paris simulation, is necessary.

The Brighton Earthship is similar in design to the Global Model Earthship although a significant difference impacting the thermal performance is that the greenhouse does not extend the full length of the building. Another notable difference is the local soil type which is chalk. The results reported by Ip and Miller (2009) indicate that the Brighton Earthship often suffered from indoor temperatures below the acceptability limits and occasionally overheating (above the limits). In this study, the same problem of low indoor temperatures is evident, however the overheating problem is not. This is possibly due to the Global Model design's full length greenhouse which is ventilated constantly through roof vents during the summer and is isolated from the living space by double glazing.

In Valencia, Spain, an Earthship that suffered from overheating in the summer solved this problem by the use of external block-out blinds (Hewitt & Telfer 2012).

Study 2: Energy Modelling Results & Discussion

Energy modelling was conducted in all locations regardless of the free running results as this provided a means for comparing the simulation results arising from two different ground temperature modelling methods: the free running simulations used the correlation between indoor, greenhouse and exterior air temperatures whereas the energy modelling used a relationship based on minimum monthly indoor air temperature.

The heating and cooling energy use of this 100 m^2 Global Model Earthship in the European locations was generally very low with no need for cooling in the study locations with the exception of Valladolid which required cooling during June-September although this small cooling load (0.9kWh/m^2.yr) might be met by the effect of earth tubes which were not modelled. Backup heating was indicated for Paris (12.6kWh/m^2.yr) and London (14.3kWh/m^2.yr) during the colder months. Valladolid also required small amounts of backup heating (4kWh/m^2.yr) although far less than London and Paris. Albacete's heating load was negligible (0.06kWh/m^2.yr). Seville required no heating or cooling whatsoever.

For comparison to existing standards and aspirations, in France the *Réglementation Thermique 2012* specifies a "primary energy consumption" maximum for French homes of 50kWh/m^2.yr (65 in the north east, 45 in the Mediterranean and 45 in the south west) (French-property.com 2013). In the UK a low-carbon strategy to reduce UK housing emissions (Boardman 2007) quotes household energy use as 21-22,000 kWh.yr of which roughly 65% is for space heating. Even the "passivhaus" concept requires up to 15kWh/m^2.yr of energy for its heat recovery ventilation system and backup heating (Feist et al. 2001) putting it on par with the Global Earthship for energy use in cold, overcast climates.

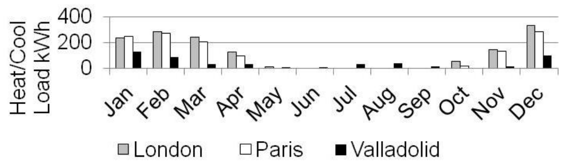

Figure 14 Simulated heating/cooling load

CONCLUSIONS

In Taos, the monitored Global Model Earthship performs as per anecdotal evidence and claims by the architect: it does not require heating or cooling.

The Taos simulation model can be considered to be calibrated as the discrepancies with the measured data is well within the CV(RMSE) limit; however, further improvements might be realised by modelling the earth tube and by recording accurate data regarding occupant control of ventilation. Moreover, improvements to ground temperature modelling would assist as this is a big uncertainty and it can be demonstrated that this is the main cause of error in the results. Measurements of under-floor and behind-wall (in berm) temperatures would be very useful as would be accurate data regarding soil type and seasonal moisture content. Measuring indoor and outdoor temperatures of Earthships would also assist with calibrating ground temperature models.

This study did not investigate how different designs might improve performance, for example in cold climates insulating the floor has been suggested (Hewitt & Telfer 2012) and in warm climates shading may further improve indoor comfort conditions during the summer. Further simulations and monitoring studies are planned to ascertain this. This study indicates that backup heating systems are necessary in cold and cloudy climates (as per the Groundhouse); however, the energy use is likely to be extremely minimal, on a par with passivhaus heating energy requirements, due to the Earthship's capacity to store and release heat. In summer, over-heating reported by other studies may be mitigated by natural ventilation of the greenhouse and shading.

Through the use of onsite renewable energy systems (intrinsic to Earthship) the relatively minimal energy use required for backup heating could be offset resulting in a zero energy building. Thus with basic climate specific adaptations, the Global Earthship may live up to its name of providing zero to low energy comfort in a wide variety of climates all over the globe.

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