The Ger Plug-in Housing Prototype: Thermal Comfort and Energy Consumption from Field Testing and Numerical Simulation

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Abstract

This report focuses on the thermal performance of the Ger Plug-in, an affordable housing prototype that combines a *ger* – the traditional nomadic structure and most ubiquitous form of housing in Mongolia – with new construction. The hybrid structure provides the *ger* with the functions that it currently lacks, including central heating, toilet and shower systems. Currently the Green Climate Fund is offering low interest green mortgages through two Mongolian entities: Xac Bank, and the Mongolian Sustainable Finance Association who act as an intermediary between the government and local banks. Each of these entities have specific performance criteria that new housing products have to meet in order to be eligible for the lower interest rate loans.

For Xac Bank the criteria is a 20% reduction of energy consumption compared to a baseline of 393 kWh/m^2/year for a typical detached house in the ger districts.

For the Mongolian Sustainable Finance Association (MSFA) the criteria is less than an annual energy consumption of 252 kWh/m^2/yr

The project was constructed in 2017 and on site field measurements together with numerical simulation has been used to generate a figure for Energy Use Intensity (EUI).

Key Findings

The average simulated EUI was found to be **211 kWh/m^2/yr.**

This is: **<u>46%</u>** lower than the Xac Bank base line AND

<u>16%</u> lower than the MSFA baseline

This report evidences how this figure was derived and the methodologies that substantiate its verification.

1. Introduction

1.1 The Context: The Ger Districts of Ulaanbaatar, Mongolia

The ger is a resilient, engineered artefact that has evolved in direct correlation to the demands of nomadic life. It is designed for portability, can be easily disassembled and reassembled without any mechanical fixings, and all of its component parts are prefabricated and can be bought at everyday markets. A *ger* costs between 600USD-1000USD, making it the most economical form of housing in the city. Its ease of transportation, affordability and reproducibility in large numbers have been one of the main contributing factors to the speed and extent of the urbanization process in the city of Ulaanbaatar.

Figure 1. Ger districts in Ulaanbaatar, Mongolia, Rural Urban Framework

The population of the city has increased by 230% in the last 20 years (National Statistical Office, Mongolia, 2013) resulting in the creation of sprawling districts with no basic infrastructure that nevertheless house over 70% of the city's population. The cold winters mean that each ger district household uses around 3.8-5 tonnes of unrefined coal as their main heating source, contributing to toxic air pollution reaching levels reported to be 133 times higher than the World Health Organization (WHO) guideline. (National Center for Public Health and UNICEF, 2018). Water is collected from water kiosks with families making at least 8 trips per week, collecting approximately 500 litres of water; 95% have access only to pit latrines, (The World Bank, 2017). As the population of migrants grows by 35,000 each year, the urban risks associated with this form of settlement are becoming increasingly threatening, particularly with respect to sanitation, freshwater supply and air quality.

1.2 The Prototype: Ger Plug-in

The Ger Plug-in addresses the lack of basic urban infrastructure in the Ger districts in Ulaanbaatar. The Plug-in connects to an existing ger of standard dimensions. The Ger Plug-In fuses the traditional structure of a ger with typical timber house construction. A new truss suspends the ger from above, allowing the centrally placed columns to be removed and the stove to relocate within the thermal mass of a brick wall. This liberates the ger as a free-space providing the family with more options for how they wish to live. The project improves the environmental performance of the household testing low-tech, off-grid systems providing a septic treatment system and WC; water tank and shower; underfloor heating; an electric boiler and a passive solar trombe wall made of black PVC pipes filled with sand. Together these systems act to provide much needed basic infrastructure to the ger and reduce coal consumption.

Figure 2. The Ger Plug-in, Ulaanbaatar, Mongolia

Observations on the living quality after being inhabited by a couple for 1 year:

- The plug-in allows the couple to use electricity to heat their home. They do not have to use coal.
- They use electricity for radiators, underfloor heating, and heating water for the shower. The electrical costs were 36,000 MNT per month on average for the winter (Nov 2018 – May 2019)
- The temperature is more stable throughout the day and stays warm for longer periods.
- The couple do not have to go the bathhouse. They take three showers a week in winter, and every day during summer.
- They also share the shower with other families in the district.
- During the harsh winter they no longer have to leave the house to access the toilet.
- Instead of having to walk 30 minutes to collect water every day the residents have access to a 1 ton water tank which is filled by a truck once every 10-14 days.
- During the winter, the residents used an estimated 93% less coal than their previous year living in a ger, an estimated 0.266 tonnes compared to an average of 3.8tonnes, a coal reduction of 3.534 tonnes. If each of the 104,000 ger households (Mongolia Real Estate Report 2017, Asia Pacific Investment Partners) was replaced by a Plug-In this would result in an estimated saving of 27,664 tonnes of coal per year.

2. Methodology: Objective of this study

The objective is to evaluate the thermal performance of the existing Plug-In, and to suggest improvements in the use of construction materials to better the future performance of subsequent versions. By establishing a verified figure for the Energy Use Intensity (EUI), the aim is to prove that the Plug-In meets the eligibility requirements for green mortgages for thermal performance as set by the Mongolian Sustainable Finance Association and so can be offered to the market as a viable housing solution.

To establish the performance of the Ger Plug-in design, on-site measurement and numerical modeling were used. The field data measured the temperature inside the house against the outside temperature to show that the thermal environment is suitable for living and to monitor any temperature fluctuations. The design was analyzed through the study of the construction material used and the actual operation profiles when the occupants were inside a tested house. The numerical modeling was used to analyze the housing design in order to suggest improvements to the performance and to find if any elements were underperforming and therefore could be removed. For example: to verify the optimum thickness of insulation. The measured temperature data was also used to correlate and validate the numerical model.

2.1 On-site Measurements

Six HOBO UX100 data loggers were installed into the Plug-in in October 2017. They have been logging temperature data at four hour intervals daily from October 2017 to October 2018. Data from four traditional *gers* also collected between 06 October 2017 and 18 December 2017. Two data loggers have been relocated to a traditional *ger* to collect simultaneous data sets for comparison, data between June and August 2019 have been extracted. Extracted data can be seen in Figures 6A – 6D.

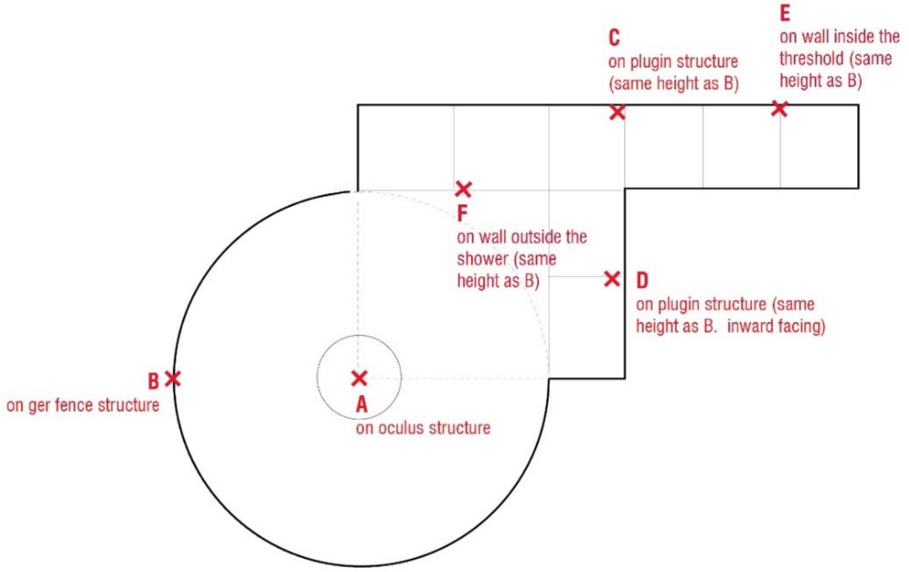

Figure 3A. Location of data loggers in the Ger Plug-in (Oct 2017 - Oct 2018)

Figure 3B. Data loggers installed into the Ger Plug-in

2.2 Construction Material and Operation Profiles

The Ger Plug-in was built with material selected for a balance between performance and cost. For example: increased thickness of insulation increases performance but also cost. According to the construction materials for different parts of the building, IESVE model has been built using its library of materials with thermal properties, and two figures are used to illustrate the surfaces modeled (Walls – S1 to S7, Floor – S8, S9, and Roof – S10, S11). Table 1 summarizes the material and the estimated building operation parameters used in the Ger Plug-in.

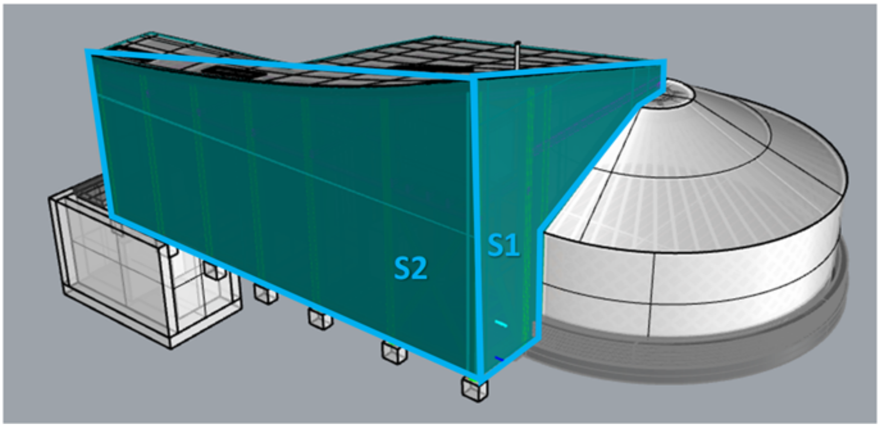

Figure 4A. Surfaces notation for the simulation model

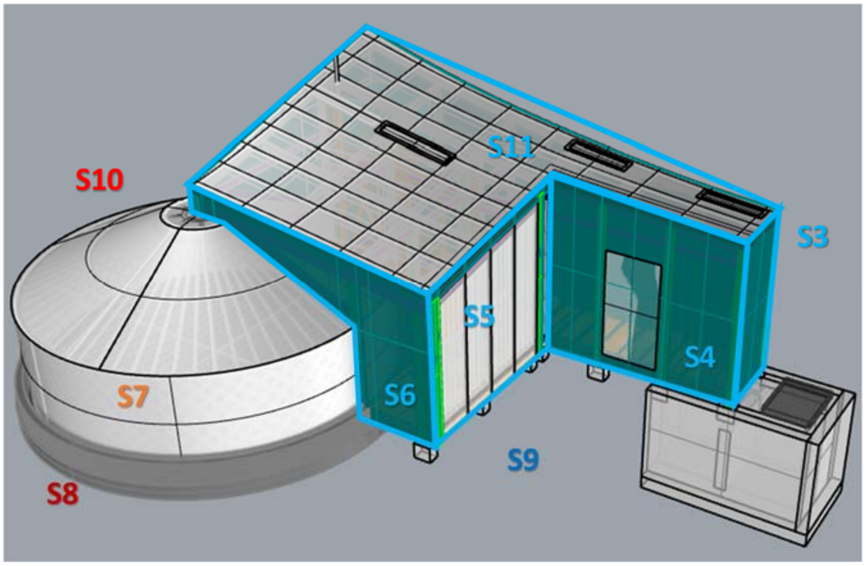

Figure 4B. Surfaces notation for the simulation model

Table 1. Construction Material

		Surface Reference	(Inside to outside)	Thickness	Conductivity	Density	Specific Heat Capacity	Vapour Resistivity	Note
				mm	W/(m-K)	kg/m3	J/(kg-K)	GN-s/(kg-m)	
Wall_A	**Insulated Sandwich Panel**	*S1, S2, S3, S4, S6*	OSB Panel	20	0.011	620	2500		
	U=0.42 W/(m2-K)		Rockwool Insulation	80	0.045	90	820		
			Waterproofing	2	0.13	500	1600		
			OSB Panel	20	0.11	620	2500		
			Rubber Cladding	5	0.23	1100	1000		
			Canvas	2	0.13	500	1600		
				129					
Window_B	**Glazing**	*S5*	Triple glazed panels						With black pvc pipe trombe wall behind
	U=1.4 W/(m2-K)		Inner Pane	6	1.06				
			Cavity	12					Argon
			Mid Pane	6	1.06				
			Cavity	12					Argon
			Outer Pane	6	1.06				
			Timber Shutters						Closed at night
Wall_C	**Ger Cladding**	*S7, S10*	Ger Fence						
	U=0.57 W/(m2-K)		Rockwool Insulation	70	0.045	90	820		
			Waterproofing	3	0.13	500	1600		
			Canvas	2	0.13	500	1600		
	Total			75					
Floor_D	**Ger Base**	*S8*	Concrete Foundation	270	2.3	2300	1000		
	U=0.11 W/(m2-K)		Waterproofing	3	0.13	500	1600		
			Solid Foam Insulation	220	0.025	700	1000		
			Screed	70	1.15	1800	1000		With cast in place underfloor heating pipes
	Total			563					
Floor_E	**Timber Base**	*S9*	OSB Panel	20	0.011	620	2500		
	U=0.35 W/(m2-K)		Rockwool Insulation	100	0.045	90	820		
			Waterproofing	2	0.13	500	1600		
			OSB Panel	20	0.11	620	2500		
			Rubber Cladding	5	0.23	1100	1000		
	Total			147					
Roof_F	**Plug-in Roof**	*S11*	OSB Panel	20	0.011	620	2500		
	U=0.29 W/(m2-K)		Rockwool Insulation	130	0.045	90	820		
			Waterproofing	2	0.13	500	1600		
			OSB Panel	20	0.11	620	2500		
			Rubber Cladding	5	0.23	1100	1000		
			Canvas	2	0.13	500	1600		
	Total			179					
Door_A	**Main Door**		Plywood	37	0.13	500	1500		
	U=2.2 W/(m2-K)								

2.3 Integrated Environmental Solutions – Virtual Environment (IESVE)

This study used a dynamic simulation software, Integrated Environmental Solutions - Virtual Environment (IESVE), which is an approved energy simulation software for LEED® Certification Programme. IESVE was used provide a detailed understanding of its energy performance. IESVE is a software for integrated building performance analysis, providing tools for solar, external temperature, thermal analysis, heating/cooling load calculations, energy cost, life-cycle, airflow, lighting, in one integrated system.

Simulation results were compared with the results of other simulation software or results of standard tests in the process of validation of any simulation tools (Beevor, 2010 & Chinnayeluka, 2011). Through the comparison of model predictions against real measurements, a reasonable level of confidence in the IESVE has been achieved (Booth, 2009). It has been demonstrated that the IESVE model is capable of making estimates and predictions to a reasonable level of accuracy for the purpose of examining design changes.

IESVE uses first-principles models of heat transfer process which are driven by real weather data. The model uses 3-dimensional geometry of the house to be studied, together with the following data:

- Site location and local weather data;
- Layer-by-layer thermo-physical properties details of building elements including the wall, roof, floor and glazing;
- Sensible and latent gains from lights, equipment and occupants;
- Natural ventilation and infiltration;
- Plant operation profiles, efficiency and fuel characteristics; and
- Properties of house façades and roof.

With the calculations of solar impacts, indoor loads, system and building construction details, IESVE can evaluate the building performance in a variety of output aspects including:

- Internal load distribution;
- Thermal performance of the building, room, surface and glazing;
- Energy and/or fuel consumption details in hourly, monthly and annually basis; and
- Surface temperature and room temperature.

The IESVE model simulated the impact of the building thermal insulation performance on the building energy consumption. The IESVE models were conducted for the Ger Plug-in.
Figure 6 illustrates the simulated geometry and here is the summary of input parameters:

- Building geometry based on building layout;
- Construction material details;
- Home equipment and small power of the houses; and
- Estimated occupancy density, occupancy profile and equipment operating profile.

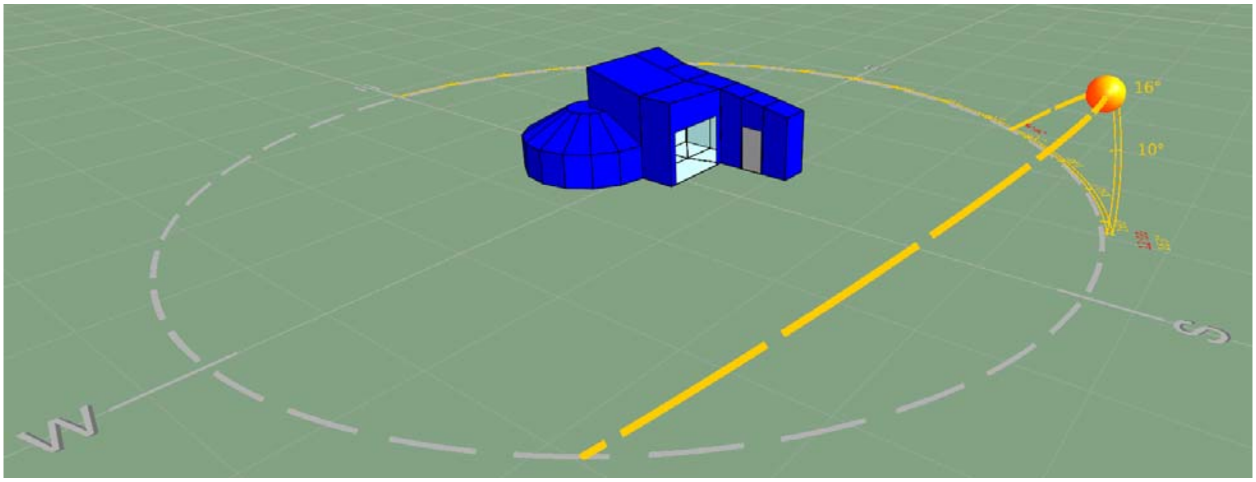

Figure 5. Simulated model

3. Results and Discussions

3.1 Findings from On-site Measurement

Key initial findings from the data recorded between October 2017 and October 2018 with the data loggers, and the comparative data from Summer 2019:

- From Oct 2017 to Dec 2017, when the external temperature was between -9.9°C and -19.8°C. The Plug-in was 2.48°C warmer than that of a traditional ger.
- The average daily temperature fluctuation is a traditional ger is 10.2°C, whereas it is only 4.1°C in the Plug-in.
- There was a period when the Plug-in was unoccupied during February 2018 (external temperatures average between -12.5°C and -23.4°C). Heat loss occurred primarily in the threshold by the door (Logger E), then at the glazed area (Logger D) and the brick cavity wall (Logger F). Overall, it took five days for all parts of the interior to reach negative temperatures.
- Once the heating is switched off, the Plug-in remains at comfort level (above 15°C) for up to 12 hours.
- The Ger Plug-in also reduces the extremes in Summer. Between June 2019 to August 2019, the temperature range in a traditional *ger* is from 10.2°C to 32.2°C, where as it was 12.0°C to 20.8°C in the Ger Plug-in.

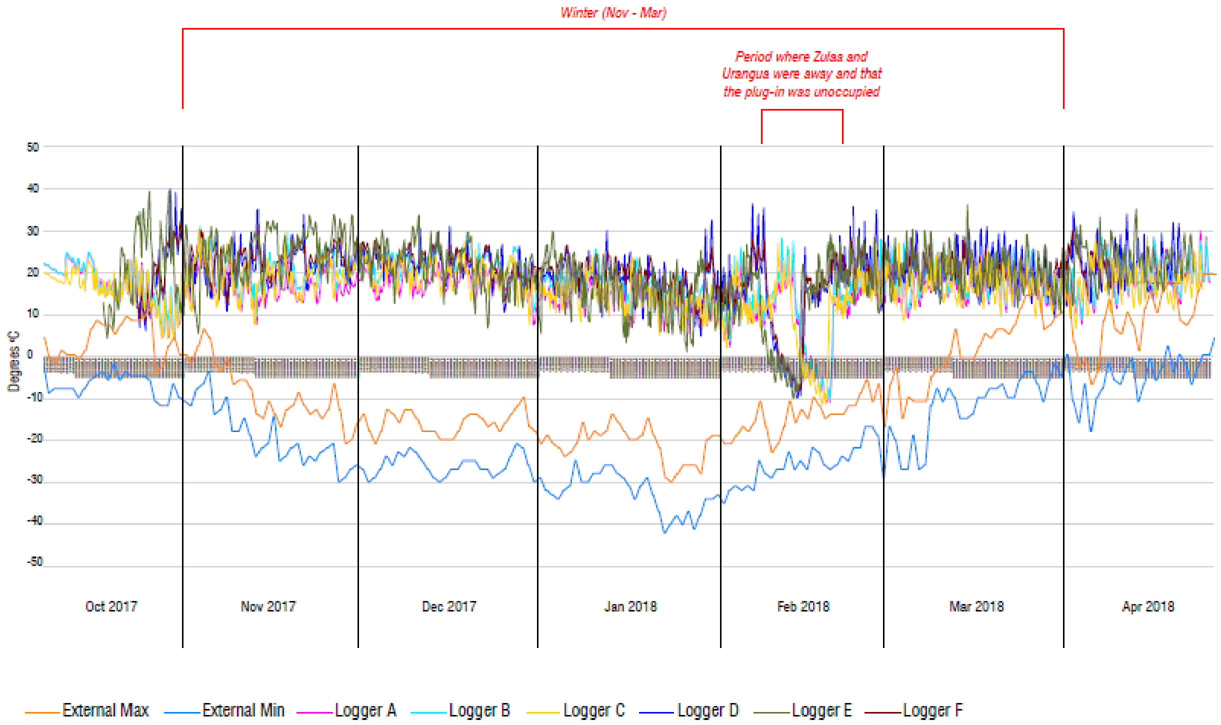

Figure 6A. Measured Temperature for Ger Plug-in (October 2017 – April 2018)

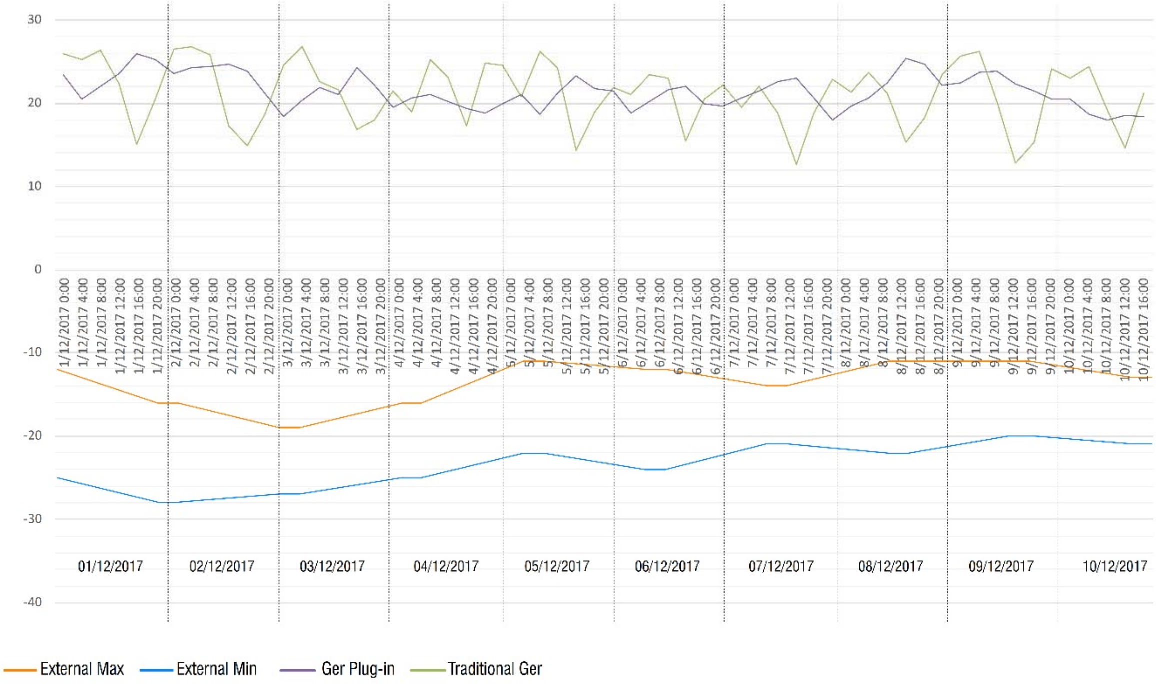

Figure 6B. Measured Temperature for Ger Plug-in vs Traditional ger (1-10 December 2017)

Figure 6C. External temperature vs.Traditional Ger and Ger Plug-in (October 2017 – April 2018)

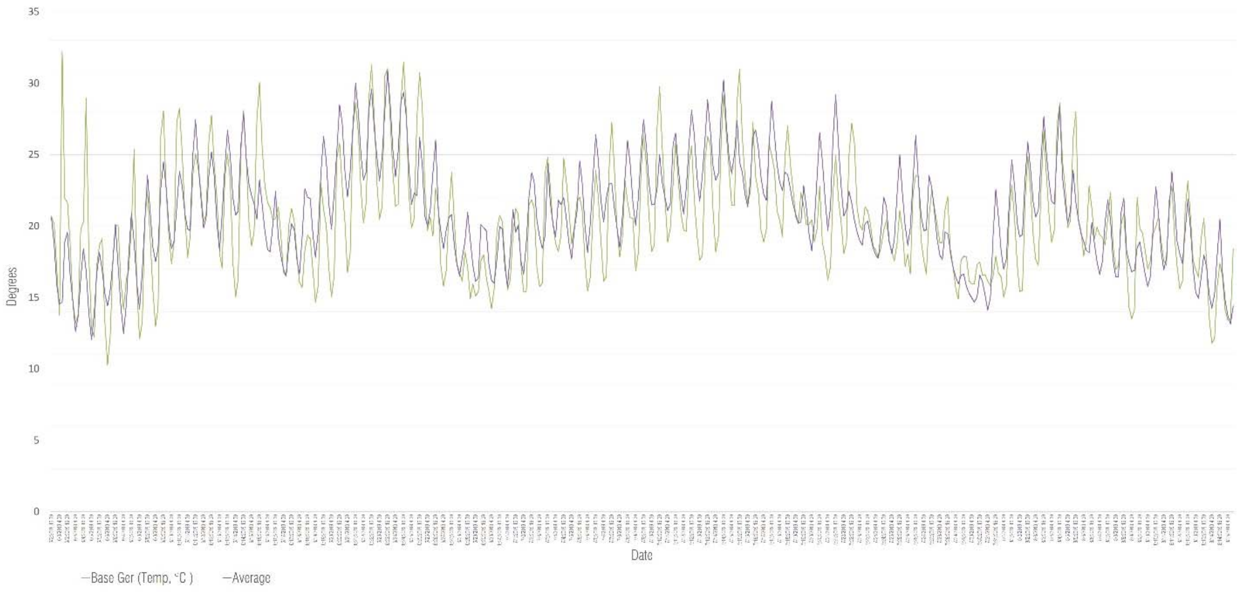

Figure 6D. Traditional Ger and Ger Plug-in (June – August 2019)

3.2 Findings from Simulation

With the test data from Jan 2018, we were able cover the temporal and spatial variations with our simulation and the results are subsequently used by a correlation method. Along with the discussed simulation process, the energy used and the resulted temperature for the Ger Plug-in is determined. With the average simulated results against the average test data, the Energy Use Intensity (EUI) is 211 kWh/m^2/yr. (Based on the modeled floor area of 47 m^2). Given that the actual situation is complicated for the simulation process, it is helpful to estimate the possible lower and upper bounds for EUI for understanding of the uncertainty. The EUI lower and upper bounds are estimated to be 171 and 244 kWh/m^2/yr.

3.3 Correlation and Verification of Results

Taking into accounts both the measured data and simulated results, correlation is carried out to confirm the usability of the numerical prediction. The comparison helps to identify a few of the uncertainty parameters, like the occupant’s profile, and the results can be used to verify the numerical prediction. The following chart shows the simulation results and the test data; and the two curves suggests they are reasonable shows the same level of the temperature within the Ger Plug-in.

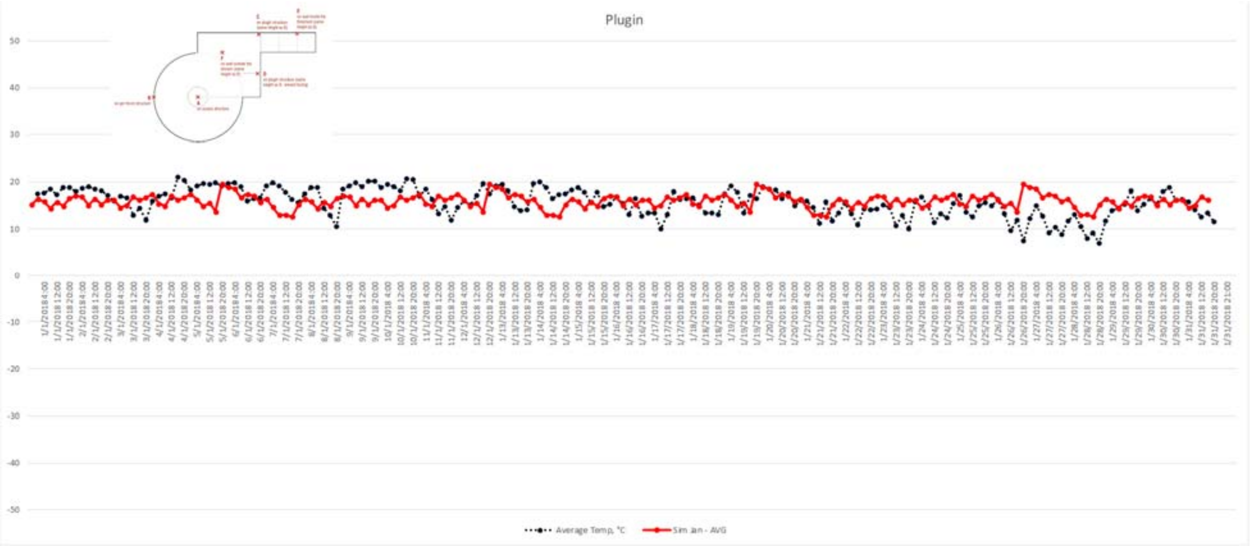

Figure 7. Comparison of Temperatures (measured vs simulated) for Ger Plugin

4. Conclusion and Recommendations

Numerical simulation and field measurement are necessary activities to demonstrate the performance of the Ger Plug-in. The correlation process used in this study verifies the validity of the numerical simulation to predict the annual energy use and the energy use index.
The findings are as follows:

- With the average simulated results against the average test data, the average Energy Use Intensity (EUI) is 211 kWh/m^2/yr
- The lower and upper bounds of the EUI are estimated to be 171 and 244 kWh/m^2/yr
- By increasing the insulation from 80mm -100mm the average EUI is 198 kWh/m^2/yr
- Changing the ger floor from concrete floor to insulated timber floor the average EUI is 234 kWh/m^2/yr
- By using double glazing instead of triple glazing the EUI is 240 kWh/m^2/yr

  Note: based on the modeled floor area of 47 m2

The upper and lower EUI figure of the built structure of 171 and 244 kWh/m^2/yr are still below the 252 kWh/m^2/yr stipulated in the MSFA requirements.

For the Xac Bank baseline of 393 kWh/m^2/year, the lower EUI represents a 56% reduction whilst the upper represents a 38% reduction. Both fall well within the requirements of the 20% reduction criteria.

Compared to a typical ger, which Xac bank's baseline is 550 kWh/m2/year, the Ger Plug in is able to reduce energy consumption by 62% based on the yearly average EUI.

Even by using double glazing instead of triple glazing the results still meet the criteria which could bring down construction costs.

By using an insulated timber floor as opposed to concrete does not significantly alter the performance however could reduce time for construction and allow construction to take place in the winter months.

Limitations

Although the study provides a good sense of the overall thermal performance of the plug – in it is not able to provide clear conclusions on whether design moves such as the internal brick wall or the experimental trombe wall system were effective.

Next Steps

This report demonstrates that the Plug-In meets the criteria set by both financial organisations and so should be eligible for low interest rate mortgages.

The next steps are to test its viability in the market to prove demand and affordability. Additionally, we will further investigate how to optimize construction costs and other methods of prefabrication to further reduce costs through scalability and to limit on-site construction time.

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Biography

Joshua Bolchover is an Associate Professor at The University of Hong Kong. His current research focuses on the complex urban-rural ecology of cities. He set up Rural Urban Framework with John Lin in 2005 with the remit to create a not-for-profit agency as a platform for design and research. Their projects have been internationally exhibited at the Venice Biennale 2018 and 2016, the Design Museum London 2016, and The Chicago Biennale 2015. RUF's work has been awarded the RIBA International Emerging Architect Award 2016 for the Angdong Hospital, The Curry Stone Design Prize 2015, The Ralph Erskine Prize 2014 and has received third place commendations for the Architectural Review's Healthcare and Schools Award. Joshua's recent publications include Border Ecologies: Hong Kong's Mainland Frontier, Birkhauser, 2016, Designing the Rural: A Global Countryside in Flux, Architectural Design 2016, and Rural Urban Framework: Transforming the Chinese Countryside, Birkhauser 2013.

Dr. Jimmy Tong is East Asia Energy Skill Leader and an Associate at Arup focusing on Building Sustainability. An industry leader in the energy business, Dr. Tong has applied his expertise in energy systems in various sectors, including wind and renewable energy, infrastructure and building services, and product and system development in the manufacturing of electronics, ventilation equipment, and filtration equipment for more than 18 years. Dr. Tong's current focus is creating and transforming buildings toward a greener future. He obtained a Ph.D. specializing in computational fluid flow and heat transfer from the University of Minnesota.

Prior to joining Arup, Dr. Tong was General Manager at Avantis Limited in Hong Kong leading wind projects and assessment for more than 8 GW capacity around the World, (Argentina, Australia, Brazil, Canada, Dominican Republic, Italy, Kazakhstan (Chilik Corridor), Lithuania, Pakistan, Poland, Romania, Russia (Murmansk), South Africa, Spain, Sweden, Ukraine, Uruguay, USA), with focused on Asia (China, India, Philippines, Thailand, Vietnam). He served as a subject-matter expert at Lockheed Martin Maritime Systems and Sensors, Thermal Analysis Partners LLC, Jacobs Civil Inc., Donaldson Company, and XeteX, Inc. in the U.S.

He is also a guest lecturer at several universities in Hong Kong on the subject of energy and sustainability and co-authored book publication and book chapters and publications in archival, refereed journals. Dr. Tong has taught a course in thermal case studies using a commercial software ANSYS/CFX at the University of Minnesota. He also serves as a mentor and advisor at the American Society of Mechanical Engineers (ASME), in few universities in Hong Kong and Friend of the Earth (HK).