Correlation between simulations and measurements of an eco-house design for Mongolia

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Abstract

Mongolia is experiencing unprecedented urbanization along with recent economic growth. Ulaanbaatar is known to be the coldest capital in the world and heating demand is very high during the long winter season. Due to the increase of coal burning to provide heat, there is an urgent need to improve housing and to reduce energy use and air pollution. Currently, there is a revitalization of the Ger area of Mongolia and this presents a good opportunity to redevelop the region into an ecologically designed district with sustainable housing. Such a redesign will result in energy saving and air pollution reduction. With this goal in mind, a pilot project called Create Accord Living Environment (CALE), was developed to demonstrate living conditions with a new house design that is cost effective for Mongolia. This paper presents the house performance using an energy simulation and the results are correlated with measurement data taken during the wintertime. The average energy use intensity (EUI) for 5 CALE houses was found to be 112 kWh/m^2/yr. This is a 71% energy savings compared to a typical detached house with a modern and efficient house design. If it is possible to redevelop 1000 houses in the Ger area, an estimated 6.5 kton/yr in carbon emission can be saved. In addition, a parametric study was conducted to investigate the impact of different construction materials, craftsmanship quality, and occupants' behavior on the house's energy efficiency. The proposed housing structures, which provide a comfortable living space with significantly reduced energy utilization, serves as a potential model for development both within Mongolia as well as for other similar climates.

Keywords: Detached Houses, Sustainable Design, Building Energy Use, Air Pollution, Fossil Fuel Reduction

1. Introduction

Since the 1990s, Mongolia has experienced an average growth rate of 5.5% in Gross Domestic Product (GDP); Mongolia's GDP expanded 6.1% in the first quarter of 2018, according to a World Bank study [1]. Another study [2] by the Asian Development Bank also adjusted upwards, by 1.0-1.5%, their forecasts over previous projections reflecting an optimism in the economy of Mongolia. However, with the recent growth, many challenges have emerged relating to the environment, economy, and housing, caused by rapid urbanization and land and urban planning, according to a study [3] by UN-Habitat. One of the major emerging problems is increased air pollution and high energy demand associated with economic growth. A major energy demand is from heating residences and other building types. For instance, the capital city of Ulaanbaatar faces almost half of a year with outdoor temperatures below 0^{o}C. Consequently, the heating demand is very high. Because the major heating source is the burning of fossil fuels, both greenhouse gas emissions and local airborne pollution emissions rise during the winter time causing Ulaanbaatar to have among the worst air quality in the world.

Previous studies [4,5] showed the severity of the pollution problem, reporting monthly average winter concentration levels of SO_2 over the period of 1996–2009 exceeding the WHO 24-hour mean limit of 20 μg/m^3. A review of the sources of the pollution emissions found that heating demand in the Ger areas is one of the major contributors. One study [6] estimated that there are almost 100,000 Gers and 120,000 detached houses with a 700,000 population in the Ger areas in Ulaanbaatar. A number of studies [6,7] have reported a strong correlation between local pollution levels and health effects, especially experienced by the young and elderly. In general, multiple health studies [8,9] suggest premature mortality owing to lung and heart illness, and long-term respiratory

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and cardiovascular diseases associated with exposure to air pollution. Figure 1 illustrates the pollution in the capital city of Ulaanbaatar, Mongolia during recent winters.

Traditionally, Mongolians lived in Gers, which are portable “Yurt” tent like dwellings. There have been a number of studied [10-12] of energy consumption and thermal comfort of these structures. However, since more Mongolians have settled down in the traditional Ger areas, many have moved into detached houses next to their Ger. As the residential buildings in the Ger areas to contribute pollution emissions, it is important to look into the potential for improving housing design and operation. A few studies [13-18] in Mongolia and others in the similar climates [19-21] have investigated the energy consumption levels and have proposed various improvement strategies. Specifically, for a typical detached house, the average energy use intensity (EUI) is about 400 kWh/m^2/yr [14] although others have reported lower levels from 315.36 to 210.64 kWh/m^2/yr [20]. Taking examples from other parts of the world, a low carbon retrofit and zero energy house performance is possible when current technologies are applied [22,23]. This is a common challenge faced by many old cities that are undergoing revitalization [24-26]. Improving the efficiency of housing, particularly in a large area such as Ulaanbaatar, is not an easy process. It is necessary to take account of the cultural context, as the stakeholders need to adopt to any transformation. There are multiple strategies [27-29] that have been proposed specifically for Ulaanbaatar, and various stakeholders are in the process for gaining the support to move forward.

Figure 1 Air Pollution Problems in Mongolia

This paper summarises an eco-housing development study that uses computer simulation, measurements of housing performance, correlation and validation between the two processes, and a parametric study to investigate the various impacts of different variables. The ultimate goal is to Create Accord Living Environment (CALE) by redeveloping “Khashaa Baishin” with an affordable eco-housing solution and with an engineering infrastructure based on a public-private partnership. In the Ger area, parcels of land, called "Khashaa", are allocated for private residential use for an individual family. As the first pilot project in Mongolia, Khashaa Baishin, it will demonstrate the potential of carbon reduction in individual detached houses and encourage community engagement through participation and education. When applied at a city, or even national scale, significant carbon reductions can be achieved and air pollution can be greatly reduced. The aims of CALE are to balance cost and green factors for affordable living, and to increase income from rental rooms and shops.

A five-house complex with four-car garages was built in the Phase one demonstration. All five houses used different technologies for measuring, comparing, and finding the most suitable solution for their future use. Two of the houses were designed with the concept of possible micro-business operation. This housing complex model is our vision of a Ger district redevelopment of Ulaanbaatar city. The project began in 2014, with heat loss measurements being carried out in 124 houses at 21 locations across 6 districts in Ulaanbaatar. During the design phase, the team identified over 430 possible technologies and solutions, with over 40 technologies and solutions then selected and tested the solutions in five different houses. Comparative measurements and verification of heat loss and energy usage were conducted. Lastly, a calibrated energy simulation was set up to check that the actual building performance meets the designed performance, and to identify the energy performance gap and improve the building performance. Figure 2 shows the houses before (left) and after (right) the development.

Figure 2 Khashaa CALE Project in a Ger Area (before, left and after right development). The house shown in yellow box was renovated, where the other houses were newly built.

2. Methodology

The energy performance optimisation of the Khashaa development was carried out with reference to the internationally recognized standards and guidelines for measurement and verification (M&V), namely, the International Performance Measurement and Verification Protocol (IPMVP) [30,31] and American Society of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE) [32]. After the eco houses in Khashaa had been operating for a period of time, the following works were carried out according to the standards and guidelines:

- Acquire information regarding the building energy utilization;
- Determine the energy consumption characteristics with respect to the outdoor climate and operating conditions of the building;
- Develop a Key Performance Index (KPI) system for the building energy performance; and
- Develop an energy accounting system for the building complex to facilitate the electrical bill apportionment.

During the M&V stage, data acquisition was conducted to collect the operational data of the system using on-site measurements and data log records, from which a comprehensive system operation database was established. With the system operation database, an intensive analysis of the system operation data, also known as data mining, was conducted to identify the optimisation parameters of the system, including the operation set-point of the individual system and equipment, the occupant behaviour and the operation and maintenance schedule.

On-site measurements were conducted to establish a database of the current situation, relating to the insulation performance of the detached houses in the study area. Subsequently, the energy modelling software, IESVE, was used to evaluate the impact of the building interior surface temperature and the building construction on the energy consumption of individual houses. To ensure the accuracy of the model, correlations were conducted against on-site measurements of internal wall surface temperatures and energy consumption records. Figure 3 shows a flow chart of this process.

The validation process of the energy model was based on the desired tolerance from a statistical comparison between energy simulations and the on-site measurements. Referring to the ASHRAE Guideline 14-2014 [32], two statistical indices were used for this purpose: hourly mean bias error (MBE) and coefficient of variation of the root mean squared error (CV(RMSE)) [33-35]. It was important that the simulated quantities be compared over the same days that the observations were made. Acceptable tolerances for this comparison were determined to have a range from ±10% for MBE to ±30% for CV(RSME) of the energy use and/or demand quantity when using hourly data, and 5% to 15% using monthly data. An average of 10% tolerance from the energy model and on-site measurement results was considered acceptable.

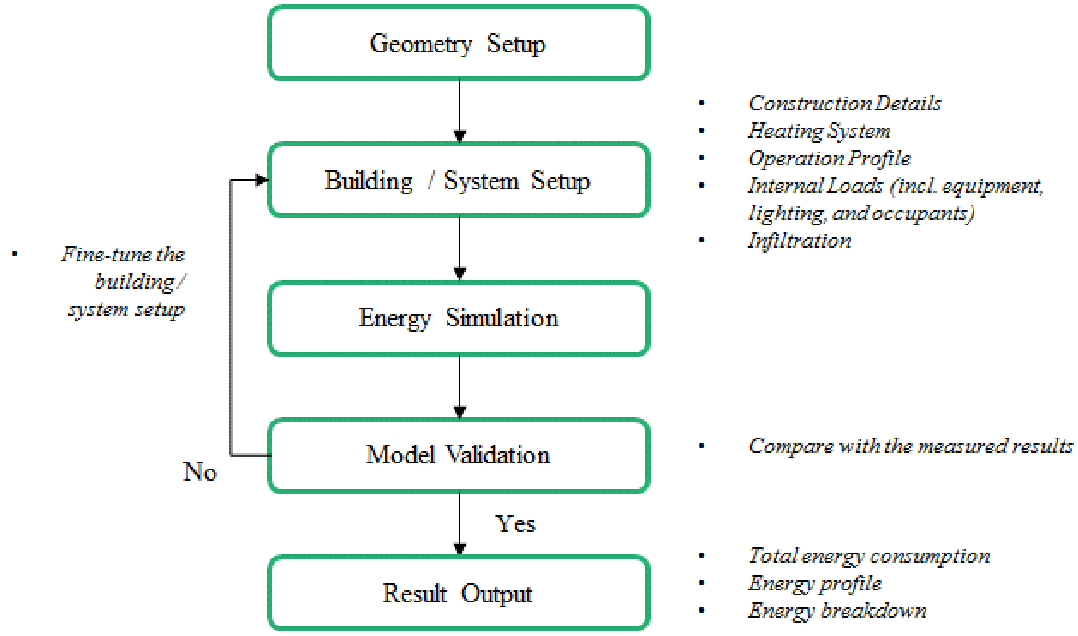

Figure 3 Flow Chart of the Measurement and Verification

2.1 Construction Material and Operation Profiles

A Mongolian property developer, Gund, invested MNT 340 million to build a five houses complex with four car garages fully integrated with the infrastructure. Two out of the five houses were designed with the option of a possible micro-business operation. According to the construction materials for different parts of the building, the IESVE model was set up using its library of materials thermal properties. Table 1, Table 2, and Table 3 summarise the material and the estimated building operation parameters used in the CALE project simulation. For the ventilation system, a flowrate of 0.8 l/s/m^2 outside air supply was assumed. The efficiency of the water heater/boiler was 80%.

Table 1 Construction Materials

Component	Type	Thickness (mm)	U Value (W/m^{2}K)
Wall Insulation	Polystyrene foam	105	0.21
Wall	Autoclaved aerated concrete	64	
Siding	Polystyrene foam insulated metallic siding	50	
	Fiberglass armature	13	
Window	Double glazing	20	1.25
	Polystyrene foam insulated magnesium panel	12	
Foundation insulation (floor)	Polystyrene foam	177	0.13
Foundation	Stepped reinforced concrete (2steppes)	100	
Lintel	Concrete filled U block	50	
Armature for foundation	Iron armature	20	
Roof insulation	Wool	63	0.40
Roof	Wooden roof	163	

Table 2 Lighting, Equipment and Small Power Loads

Electronics	House 1			House 2			House 3			House 4&5		
	Power (watt)	Daily usage (hours)	Weekly usage (frequency)	Power (watt)	Daily usage (hours)	Weekly usage (frequency)	Power (watt)	Daily usage (hours)	Weekly usage (frequency)	Power (watt)	Daily usage (hours)	Weekly usage (frequency)
1. TV	170	6-8	7	NA			215	6	7	215	6	7
2. Washing machine	345	1-2	1	NA			100	2	1	350	4	2
3. Refrigerator	69	24	7	NA			120	24	7	120	24	7
4. Stove	7800	1-2	7	NA			2100	1	7	2100	2	7
5. Vacuum cleaner	1800	0.16	7	NA			1600	0.16	7	2800	0.16	2
6. Iron	1000	0.32	1	NA			1400	0.32	1	2200	1	1
7. Water boiler	700	1-2	7	NA			100	1	7	250	0.32	7
8. Lighting	140	5-6	7	NA			166	5	7	140	6	7

Table 3 Number of Occupancy, Occupancy Profile and Infiltration

House	Number of people	Occupancy Profile
House 1	2	Around 6 hours per day
House 2	0	0 hours per day
House 3	2	Around 6 hours per day
House 4	0	0 hours per day
House 5	2	Around 6 hours per day
Infiltration: 0.3 ACH		

The U-values of the project have been compared to regulations established in other countries such as China, UK, and Germany. It was noted that the U-values for walls, windows and floors exceed the minimum requirements for most of the compared countries. For the roof, it complies with the insulation requirements of China. Table 4 below summarizes the comparison results.

Table 4 Comparisons of the Project U-value with Regulations of Other Countries

		Current Project	China	UK	UK	Germany
Government's Policy		Khashaa Baishin	Design Standard for Energy Efficiency in Residential Buildings in Severe Cold and Cold Zones	Building Regulations 2010	Wales, Scotland, England, Ireland	Energy Conservation Regulations (EnEV)
Insulation Requirements – U-value (W/m2K)	Wall	0.21	0.33-0.48	0.30	0.18	0.28
	Window	1.25	0.70	2.00	1.40	1.30
	Floor	0.13	0.48	0.25	0.13	0.35
	Roof	0.40	0.33-0.40	0.20	0.13	0.20

2.2 On-site Measurements

On-site measurements were conducted and two months of data spanning January and February of 2018 were recorded. The on-site measurements included:

1. Outdoor air temperature;
2. Air humidity;
3. Internal surface temperature of the building wall;
4. Ceiling temperature;
5. Indoor temperature; and
6. Electrical consumption.

During the on-site measurements, a calibrated Thermal Imaging Infrared Camera was used to measure the interior surface temperatures inside all five houses. Multiple infrared temperatures were averaged to a single value. The temperature measurements were carried out using a FLIR i5 Compact Thermal Imaging InfraRed Camera, with the image resolution of 100 x 100 pixels, a temperature range of -20°C to 250°C, a thermal sensitivity of <0.10°C @25°C and an accuracy of ±2% or 2°C. In addition, a LondiSun LS-207 Electronic Thermo/hygrometer, with a temperature range of -50°C to 70°C and an accuracy of ±1.5% max, was also used to measure air temperature and relative humidity. The two sensors were used to calibrate against each other, and agreement was found. The measurement locations and sample infra-red photos are shown in Figure 4 below for reference. There were more than 1200 images taken by the IR camera. Figure 4 shows some example thermal images illustrating the surface temperature variation at the specification locations. For instance, the two pictures (lower row from the right in Figure 4) were taken outside on the windows (Point #9) to show the cold temperature of House 4 at 8am and House 1 at 10pm during a day in January, where the picture on the right shows the indoor temperature on the ceiling (Point #C) of House 1 around 10pm in a day in January.

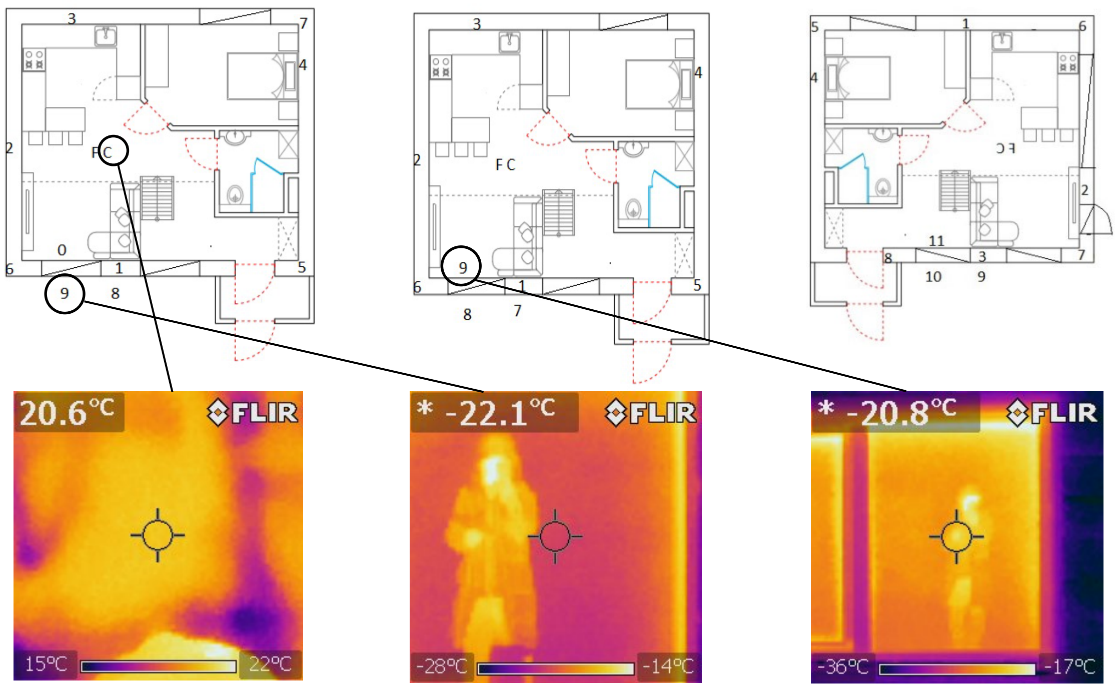

Figure 4 Measurement Point Locations: 1st & 3rd (Left); 4th (Mid) 5th (Right) House Layouts and Sample Images of Infrared Sensor Photos

2.3 Integrated Environmental Solutions – Virtual Environment (IESVE)

Many building energy simulation tools are commercially available, such as DesignBuilder, DeST, DOE-2, Equest, EnergyPlus, IES-VE, TAS, and TRNSYS. While each of the tools has advantages and disadvantages, Integrated Environmental Solutions - Virtual Environment (IESVE) [36] was selected for use for this study. IESVE has been approved by the LEED® Certification Programme. Studies [37-39] have also been conducted using IESVE which have demonstrated the effectiveness of this tool. IESVE was used in this study to provide a thorough understanding of the energy performance and the flow of heat through the houses. IESVE uses first-principle-models of heat transfer processes that are driven by real weather data. The software uses a 3-dimensional geometrical representation of the house. Further inputs to the software are listed in Table 5. With the calculations of solar impacts, indoor loads, system and building construction details, IESVE can evaluate the building performance for a variety of outputs, as shown in the table.

Table 5 IESVE Inputs and Outputs

Inputs	Outputs
• 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.	• 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 was used to carry out simulations for all five houses in order to study the impact of the insulation performance on building energy consumption. Figure 5 illustrates the simulated geometry and compares the reconstructed geometry to the 3D rendered image of the project. The input parameters included:

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

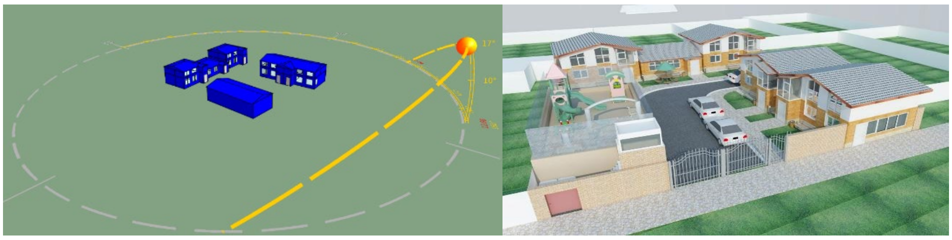

Figure 5 IESVE Geometry vs Actual Design (sun path included)

2.4 Baseline Correlation and Parametric Study

The results from the simulation modelling were compared to the measurement data. It was difficult to obtain a full record of the occupancy behaviour and to keep track of the variation of the internal load throughout the entire measurement period. Therefore, only general trends of simulated and measured energy consumption were compared. Once the simulation models yielded results that matched the measurement, these correlated models provided a baseline for further simulations. These further simulations form a parametric study to investigate how each of the factors impacts the overall energy performance. The five studied factors and the range of each factors are listed in Table 6. Although five houses were simulated, only three of them were selected as the representatives for the study; and the chosen ones were House 1, House 3, and House 4/5; House 2 was not chosen because only minimum renovation was done. Lastly, multi-variable linear regression was used to show the relative impacts of the various input parameters.

Table 6 Studied Factors and the Corresponding Study Range

Factors	Parameters	Unit	Study Range
Vertical wall insulation performance	U-value	W/m^2K	0.15 (better insulated) – 0.42 (less insulated)
Roof insulation performance	U-value	W/m^2K	0.10 (better insulated) – 0.80 (less insulated)
Ground insulation performance	U-value	W/m^2K	0.11 (better insulated) – 0.35 (less insulated)
Window	U-value	W/m^2K	1.14 (triple glazing) – 3.00 (double glazing)
Infiltration rate	Air Change per Hour (ACH)	hr^{-1}	0.1 (better sealed) – 3 (less sealed)

3. Results and Discussions

Following the Measurement and Verification procedure described in the preceding section, daily measurements including overall energy, Energy Use Intensity (EUI), energy distribution, energy and carbon savings were tabulated from the measurement and simulations and will be discussed here. Other findings from the parametric study will also be presented.

3.1 Findings from Measurement and Verification

To ensure that the energy simulation is accurate, a validation process, which is illustrated in Figure 3, has been adopted. From a sun-path analysis, shown in Figure 5, the low-angle sun in winter (azimuth angle from 125^o to 235^o), will overshadow the buildings while the situation in summer (azimuth angle from 53^o to 308^o) is slightly better. In both cases, the solar flux is still relatively low compared to other modes of heat transfer in the studied buildings. From previous work [15], the heat loss apportionment was 28-39% through walls, 23-27% through the roof, 13-15% through the floor, 9-10% through the windows, and 16-19% through air infiltration. Similar results were found in the present study.

A comparison is made between the simulated and measured temperatures, as will now be discussed. Figure 6 illustrates the temperature in the living rooms on the 1st and 2nd floors for the measurement and simulation. The average measured temperature for House 1 in January was 16.9^{o}C (10.4^{o}C min and 23.0^{o}C max) whereas the average simulation temperature for the same period was 15.9^{o}C (9.1^{o}C min and 21.2^{o}C max) – an excellent agreement with a 6% difference. The simulation models have been correlated with the measured data for January. It is found that the energy patterns and the energy consumption of the simulation models show a good match with the measured results as well, as the differences between the simulations and the measurements for the new houses are within 4%, which is lower than the required limit of 10% from the standard protocol. Details of the correlations can be found in Figure 7 below. The comparison is reasonable (especially for House 3) in terms of the range of energy use, and we would expect some differences due to occupancy.

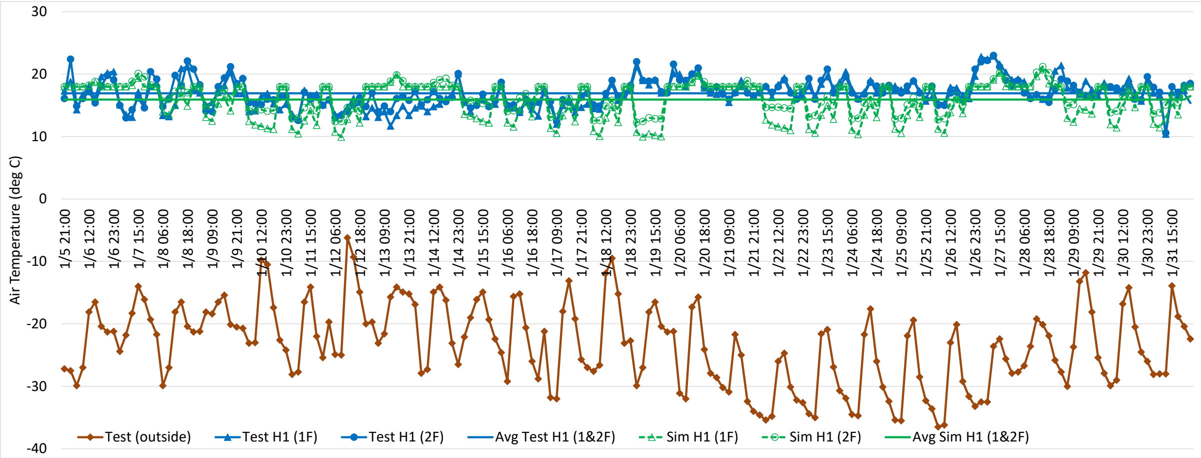

Figure 6 Measured with Simulated Temperatures for House 1 in January 2018

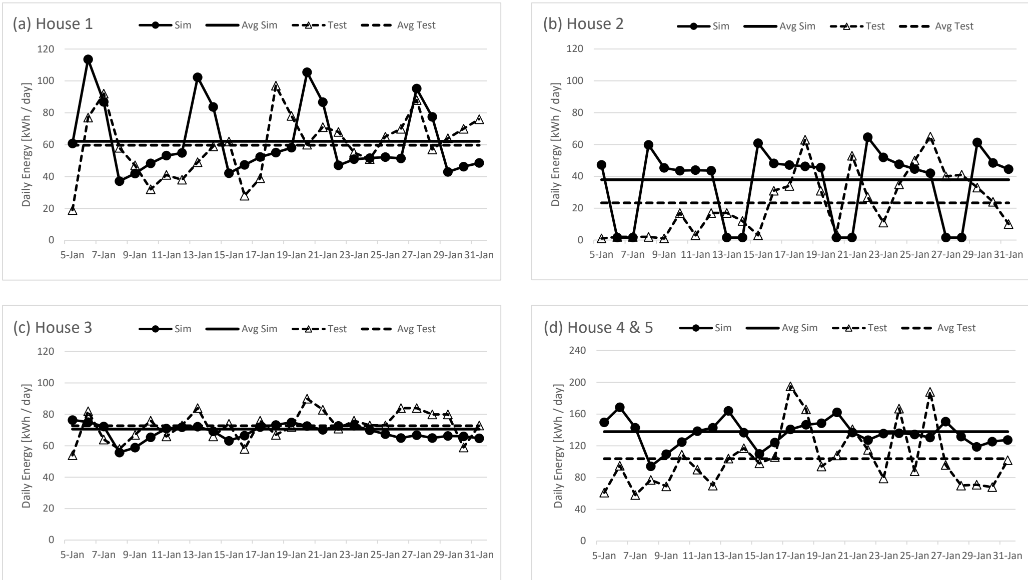

Figure 7 Correlation of Daily Energy Consumption Measurement with Simulated Results

The energy consumption comparison between the simulations and measurements for January is summarised in Table 7. For Houses 1, 3 and 4&5, indicating that the accuracy of the simulated models is found to be acceptable with the difference of less than 4%. This agreement is within the usual recommended level of 10% [30,31]. For House 2, the difference between simulated and measured values is slightly greater than that of the other houses. The error is about 18.1%, but since the house is only slightly renovated and is not regularly occupied, the accuracy is of less interest for this study.

Table 7 Correlation Results for the Total Energy Consumption for January

	House 1	House 2	House 3	Houses 4&5
Modelled (kWh/day)	60.28	28.44	71.24	107.92
Modelled (kWh/m^2/day)	0.49	0.32	0.52	0.39
Measured (kWh/day)	59.67	23.30	72.70	103.78
Error (%)	1.0%	18.1%	-2.1%	3.8%

Following the validation exercise, the simulation was expanded to further evaluate the energy performance of the houses throughout the year. The total annual energy consumption for the five houses ranges from 12.20 MWh to 30.04 MWh. The energy performance for each simulated model has been summarised in Table 8. The table includes the modelled area, liveable area (only for reference), total annual energy consumption and Energy Use Intensity (EUI).

Table 8 Annual Energy Performance and EUI for the CALE House

	House 1	House 2	House 3	Houses 4 & 5
Modelled Floor Area (m^2)	124.00	89.10	136.06	273.52
Liveable Floor Area (m^2)	68	40	79.7	160
Total Annual Energy Consumption (MWh/yr)	12.20	4.68	25.23	30.04
EUI (kWh/m^2/yr)	98.40	52.56	185.44	109.82

The energy apportions for the project houses are illustrated in Figure 8. As mentioned before, the apportion for House 2, which was unoccupied, is quite different from the others. House 1 and Houses 4&5 are most similar. The results show that most of the energy is used by the boilers for heating ranged between 40% to 86% of the total energy used.

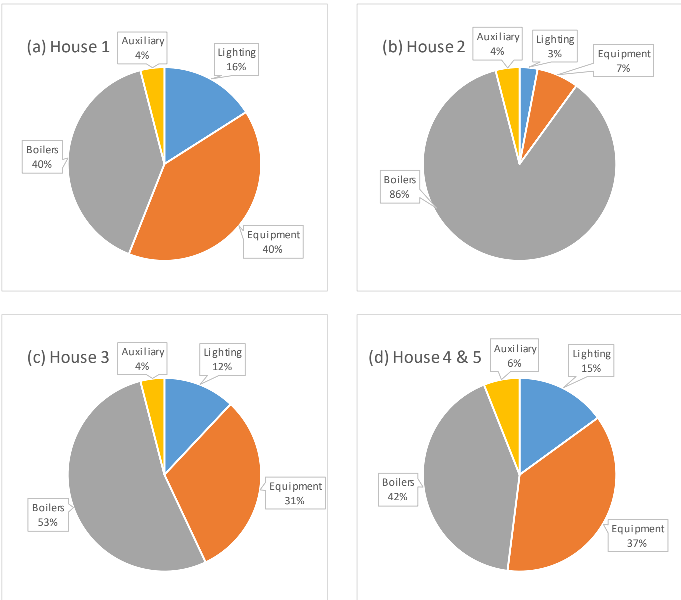

Figure 8 Energy Distribution for the CALE Houses

The overall average EUI for the whole CALE development, i.e. Houses 1, 2, 3 and 4&5, is 112 kWh/m^2/yr, which is about 71% lower than the energy consumption for reference non-apartment buildings (around 395 kWh/m^2/yr). The results reported here compare reasonably well with other studies [16]; which reported 8.97-9.69 MWh (8 months, Oct-May) as the simulated thermal energy supplied to a case study house of 48 m^2, leading to an EUI of 187-202 kWh/m^2/yr. When compared to a target set by foreign investors, like Asia Development Bank (ADB), of 150 kWh/m^2/yr, the CALE development is 23% more energy efficient than the target value.

If the CALE project is expanded to cover 1000 houses, as an expected redevelopment scale, the total saving in CO_2 emissions is about 6.51 ktons/yr. A summary of the calculations is provided in the following list:

- Baseline energy consumption (for non-apartment buildings [14]): 395 kWh/m^2/yr
- Average energy consumption from CALE development: 111.5 kWh/m^2/yr
- House size (liveable area): 80 m^2
- Targeted CALE project coverage: 1000 houses
- Total energy saving: 39,116 MWh/yr
- Assumed heating load: 50% of the total building energy consumption
- Conversion factor for CO_2 emission [40]: 333 kg/MWh
- Total saving in CO_2 emissions: 6.51 ktons/yr

3.2 Findings from the Parametric Study

Five design parameters were varied from the baseline models (House 1, House 3, and House 4/5; as mentioned earlier, House 2 was not chosen since only minimal renovation was done). The value of each factor an upper and lower bound for each simulation of this parametric study (as highlighted in each row in Table 9). With the five factors and their upper and lower values listed, the EUI of the 10 simulated cases can be summarized in Table 9. As seen in the table, Cases 2 to 6 were the simulations with the lower bound of the selected factors whereas Cases 7 to 11 were with the upper bound values. Results are also expressed as a ratio to show the normalized impact. In each case, the magnitude of each change in the inputs were less than the magnitude for each of the outputs.

Table 9 Simulated Results of the Parametric Study

					Modeled Area [m2]	House 1 124	House 3 136.06	House 4/5 136.76
Case	Input Wall [W/m2K] V1-Wl	Input Roof [W/m2K] V2-Rf	Input Floor [W/m2K] V3-Fl	Input Window [W/m2K] V4-Wd	Input Infiltration [ACH] V5-If	Output EUI [kWh/m2/yr]	Output EUI [kWh/m2/yr]	Output EUI [kWh/m2/yr]
1 Base	0.21 100%	0.4 100%	0.13 100%	1.25 100%	0.3 100%	98.40 100%	185.44 100%	109.82 100%
2 V1-L	0.15 71%	0.4 100%	0.13 100%	1.25 100%	0.3 100%	92.65 94%	184.56 100%	106.78 97%
3 V2-L	0.21 100%	0.1 25%	0.13 100%	1.25 100%	0.3 100%	85.00 86%	184.38 99%	102.33 93%
4 V3-L	0.21 100%	0.4 100%	0.11 85%	1.25 100%	0.3 100%	97.48 99%	185.29 100%	109.07 99%
5 V4-L	0.21 100%	0.4 100%	0.13 100%	1.14 91%	0.3 100%	97.36 99%	185.32 100%	108.96 99%
6 V5-L	0.21 100%	0.4 100%	0.13 100%	1.25 100%	0.1 33%	85.53 87%	184.13 99%	100.48 92%
7 V1-H	0.42 200%	0.4 100%	0.13 100%	1.25 100%	0.3 100%	118.58 121%	193.07 104%	120.98 110%
8 V2-H	0.21 100%	0.8 200%	0.13 100%	1.25 100%	0.3 100%	114.56 116%	188.26 102%	122.85 112%
9 V3-H	0.21 100%	0.4 100%	0.35 269%	1.25 100%	0.3 100%	109.03 111%	188.39 102%	118.20 108%
10 V4-H	0.21 100%	0.4 100%	0.13 100%	3 240%	0.3 100%	115.32 117%	189.68 102%	123.84 113%
11 V5-H	0.21 100%	0.4 100%	0.13 100%	1.25 100%	3 1000%	273.35 278%	355.64 192%	281.68 257%

To understand the impact how each of the factors affect the results, the results listed in Table 9 were put into a multi-variable linear regression. The calculated coefficients for each of the modelled houses are listed in Table 10 and the coefficients can be used in the linear equation, shown in Eqn (1) to determine the EUI for any combination of input variable values.

Table 10 Coefficients of Eq. (1) from the Multi-Variable Linear Regression of the Parametric Study

	House 1 Coefficients	House 3 Coefficients	House 4/5 Coefficients
C : Intercept	2.872	21.522	7.556
m_1 : V_1-Wl	11.974	3.909	6.897
m_2 : V_2-Rf	5.209	0.684	4.036
m_3 : V_3-Fl	6.069	0.763	4.757
m_4 : V_4-Wd	1.209	0.191	1.037
m_5 : V_5-If	8.041	8.447	8.655

$$EUI = m_1 \cdot V_1 + m_2 \cdot V_2 + m_3 \cdot V_3 + m_4 \cdot V_4 + m_5 \cdot V_5 + C \qquad \text{Eqn (1)}$$

To further explore the relationship between each of the factors and the houses, it is possible to make a few more observations:

1. All the coefficients are all positive, which means each parameter is positively correlated to EUI.

2. For all the houses, the U-values of the wall (V_1-Wl) are highest, followed by the ACH of infiltration (V_5-If), the U-values of the floor (V_3-Fl), roof (V_2-Rf), and the U-value of window (V_4-Wd) is the smallest. This order shows the order of importance from each factor to the EUI results.
3. The coefficients for House 3 are lower than those for House 1 and House 4/5, which indicates a lower energy impact. When House 3 is compared with House 4/5, the layout and usage are seen to be different. While House 3 is used as a home, part of House 4 has apartment units and part of House 5 has a microbusiness shop. House 3 and House 1 are both used for home living, but the occupant schedules are the major differences.

4. Conclusion

The aim of this project was to Create Accord Living Environment (CALE) by redeveloping "Khashaa Baishin" with affordable eco-housing solutions. Due to the extremely cold temperatures during the winter in Mongolia, keeping a comfortable living condition for homes can be very challenging. Houses that can balance affordability and sustainability are needed to ensure a highly efficient operation, with less coal burning and reduced emission of pollutants. Efficient operation was facilitated by the careful choice of construction materials and quality workmanship, with U-values of 0.21, 1.25, 0.13, and 0.40 W/m^2K for the walls, windows, floors, and roof, respectively.

This project has validated an affordable eco-house design based on measured data collected during real-life conditions and predicted data through simulation. The CALE results showed an average EUI of 112 $kWh/m^2/yr$, which is significantly better than 187 to 202 $kWh/m^2/yr$ for improved houses from other quoted work, and superior to that of a traditional house of 395 $kWh/m^2/yr$. The validation shows that a 71% energy savings can be achieved with new, efficient house designs. In terms of pollution impact, a total reduction of 6.51 ktons of carbon emissions could be achieved if the eco-house design of CALE is applied to a targeted scale of development of 1000 houses in Ulaanbaatar. Moreover, the differences between the simulations and the measurements for the new houses (Houses 1, 3, 4&5) are within 4%, which is lower than the required limit of 10% from the standard protocol. With the correlated simulated models, the energy distribution was determined, and the energy used in heating accounted for the highest share, ranging from 40% to 86%. Lastly, a parametric study of five factors was conducted; for the current design, it is found that the U-value of the wall has the biggest influence on the energy performance of the houses.

The findings of this paper serve as a roadmap to support further development plans for CALE, and potential investors/interested parties can fit into a bigger picture of the eco-district redevelopment in Ulaanbaatar. This information can be used to develop a financial model for CALE houses and to propose a roadmap for CALE to be implemented at scale, to transform the Ger districts of Ulaanbaatar into a modern eco and sustainable city.

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Reference

[1] Nganou, J.P., Batsuuri, D., Nyanzi, S., & Shiilegmaa, A. (2018). Mongolia Economic Update: Fiscal space for growth - the role of public investment spending efficiency: main report. Mongolia economic update. Washington, D.C.: World Bank Group. Retrieved from http://documents.worldbank.org/curated/en/648031532963732140/main-report

[2] ADB. (2017). Asian Development Outlook (ADO) 2017 Update: Sustaining Development Through Public-Private Partnership. Asian Development Bank. Retrieved from https://www.adb.org/publications/asian-development-outlook-2017-update

[3] UN-Habitat. (2016). Mongolia Habitat-III National Report. Retrieved from http://habitat3.org/wp-content/uploads/Mongolia-HABITAT-III-Report-25.04.2016-english-final.pdf

[4] M.E. Luvsan, R.H. Shie, T. Purevdorj, L. Badarch, B. Baldorj, & C.C. Chan. (2012). The Influence of Emission Sources and Meteorological Conditions on SO2 Pollution in Mongolia. Atmospheric Environment, 61, 542-549.

[5] Y.K. Huang, M.E. Luvsan, E. Gombojav, C. Ochir, J. Bulgan, & C.C. Chan. (2013). Land use patterns and SO2 and NO2 pollution in Ulaanbaatar, Mongolia. Environmental Research, 1-6.

[6] Hill, L., Edwards, R., Turner, J., Argo, Y., Olkhanud, P., & Odsuren, M. et al. (2017). Health assessment of future PM2.5 exposures from indoor, outdoor, and secondhand tobacco smoke concentrations under

alternative policy pathways in Ulaanbaatar, Mongolia. PLOS ONE, 12(10), e0186834. doi: 10.1371/journal.pone.0186834
[7] National Center for Public Health and UNICEF. (2018). Mongolia's Air Pollution Crisis: A call to action to protect children's health. Retrieved from https://www.unicef.org/mongolia/Mongolia_air_pollution_crisis_ENG.pdf
[8] Brook, R. D., Rajagopalan, S., Pope III, C. A., Brook, J. R., Bhatnagar, A., Diez-Roux, A. V., ... & Peters, A. et al. (2010). Particulate matter air pollution and cardiovascular disease: an update to the scientific statement from the American Heart Association. Circulation, 121(21), 2331-2378.
[9] Wu, Y., Benjamin, E. J., & MacMahon, S. (2016). Prevention and control of cardiovascular disease in the rapidly changing economy of China. Circulation, 133(24), 2545-2560.
[10] Bayandelger, B., Ueda, Y., & Adiyabat, A. (2020). Experimental Investigation and Energy Performance Simulation of Mongolian Ger with ETS Heater and Solar PV in Ulaanbaatar City. Energies, 13(21), 5840. https://doi.org/10.3390/en13215840
[11] Purev, U., & Hagishima, A. (2020). A Field Survey of Traditional Nomadic Dwelling Gers Used as Urban Habitats in Ulaanbaatar, Mongolia. Evergreen, 7(2), 155-171. https://doi.org/10.5109/4055214
[12] Badarch, A. (2017). An Elementary Thermal Analysis of a Mongolian Ger by the Lattice Boltzmann Method. Proceedings of the 13th International Conference of Technology and Innovation, 88-91.
[13] Ganchimeg, G. (2014). Energy consumption and household's wealthy: case of herder household in Mongolia. Mongolian Journal of Agricultural Sciences, 11(2), 103-109.
[14] GIZ (2013). The thermo-technical rehabilitation of public and apartment buildings in Ulaanbaatar / Mongolia. Retrieved from https://www.unescap.org/sites/default/files/Mongolia_UB_1311_%2016%20Khoroo%20Project%20Design%20Document.pdf
[15] Tong, J.C.K., Tse, J.M.Y., & Jones, P.J. (2018). Development of Thermal Evaluation Tool for Detached Houses in Mongolia. Energy and Buildings, 173, 81-90. doi: 10.1016/j.enbuild.2018.05.026
[16] Rosato, A., Erdenedavaa, P., Ciervo, A., Akisawa, A., Adiyabat, A., & Sibilio, S. (2019). A Solar Thermal Application for Mongolian Detached Houses: An Energy, Environmental, and Economic Analysis Based on Dynamic Simulations. Buildings, 9(8), 185. https://doi.org/10.3390/buildings9080185
[17] Gado, T., & Games, T.S. (2018). A Parametric Study to Optimize the Thermal Performance of Mongolian Self-built Houses in Terms of Energy Efficiency: Towards a Cleaner Environment for Ulaanbaatar. In PLEA 2018: Smart and Healthy within the 2-degree Limit, 262-267.
[18] Erdenedavaa, P., Adiyabat, A., Akisawa, & A., Otgonjanchiv, E. (2018). Performance Analysis of Solar Thermal System for Heating of a Detached House in Harsh Cold Region of Mongolia. Renewable Energy, 117, 217-226.
[19] Ren, G., Heo, Y., & Sunikka-Blank, M. (2019). Investigating an Adequate Level of Modelling for Retrofit Decision-Making: A Case Study of a British Semi-Detached House. Journal of Building Engineering, 26, 100837.
[20] Shao, T., Zheng, W., & Jin, H. (2020). Analysis of the Indoor Thermal Environment and Passive Energy-Saving Optimization Design of Rural Dwellings in Zhalantun, Inner Mongolia, China. Sustainability, 12(3), 1103.
[21] Li, W., & Chen, Q. (2021). Design-Based Natural Ventilation Cooling Potential Evaluation for Buildings in China. Journal of Building Engineering, 102345.
[22] Li, X., Lannon, S.C., & Jones, P.J. (2015). Modelling-based low carbon retrofit house design. Urban Flux, 42 (2), 34-50,
[23] Wang, L., Gwilliam, J.A., & Jones, P.J. (2009). Case study of zero energy house design in UK. Energy and Buildings, 41 (11), 1215-1222.
[24] Castanheira, G., Bragança, L., & Mateus, R. (2013). Defining best practices in Sustainable Urban Regeneration projects. Portugal SB13-Contribution of Sustainable Building to Meet EU 20-20-20 Targets, 435-442.
[25] Nadkarny, S., & Anderson, M. (2013). Slum Upgrading in Thailand: CODI. Retrieved from http://healthycities.berkeley.edu/uploads/1/2/6/1/12619988/thailand.pdf
[26] Johnson, K., & Nadkarny, S. (2013). Slum Upgrading in Mumbai. Retrieved from http://healthycities.berkeley.edu/uploads/1/2/6/1/12619988/india.pdf
[27] ADB. (2018). 49169-001: Ulaanbaatar Affordable Housing and Urban Renewal Project. Asian Development Bank. Retrieved from https://www.adb.org/projects/49169-001/main
[28] World Bank. (2015). Land Administration and Management in Ulaanbaatar, Mongolia. Retrieved from http://www.worldbank.org/en/country/mongolia/publication/land-administration-and-management-in-ulaanbaatar-mongolia

[29] AHI. (2014). Affordable Housing Strategy for Ulaanbaatar. Affordable Housing Institute. Retrieved from http://www.usip.mn/uploads/reports/en/Affordable.pdf
[30] EVO. (2012). International Performance Measurement and Verification Protocol: Concepts and Options for Determining Energy and Water Savings Volume I, EVO-10000-1.2012. Efficiency Valuation Organization.
[31] EVO. (2006). International Performance Measurements and Verification Protocol: Concepts and Options for Determining Energy Savings in New Construction, Volume III, EVO-30000-1.2006. Efficiency Valuation Organization.
[32] ASHRAE. (2014). ASHRAE Guideline 14-2014 for Measurement of Energy and Demand Savings. American Society of Heating, Refrigeration and Air Conditioning Engineers, Atlanta, GA.
[33] Kreider, J.F., & Haberl, J.S. (1994). Predicting Hourly Building Energy Use: The Great Energy Predictor Shootout-Overview and Discussion of Results. ASHRAE Transactions, 100(2), 1104-1118.
[34] Kreider, J.F., & Haberl, J.S. (1994). Predicting Hourly Building Energy Usage: The Results of the 1993 Great Energy Predictor Shootout Identify the Most Accurate Method for Making Hourly Energy Use Predictions. ASHRAE Journal, 36(6), 72-81.
[35] Haberl, J.S., & Thamilseran, S. (1996). Predicting Hourly Building Energy Use: The Great Energy Predictor Shootout II, Measuring Retrofit Savings-Overview and Discussion of Results. ASHRAE Transactions, 102(2), 419-438.
[36] Integrated Environmental Solutions Limited. (2015). Construction Database User Guide - VE 2015.
[37] Jannat, N., Hussien, A., Abdullah, B., & Cotgrave, A. (2020). A Comparative Simulation Study of the Thermal Performances of the Building Envelope Wall Materials in the Tropics. Sustainability, 12(12), 4892.
[38] Al-janabi, A., Kavgic, M., Mohammadzadeh, A., & Azzouz, A. (2019). Comparison of EnergyPlus and IES to Model a Complex University Building Using Three Scenarios: Free-Floating, Ideal Air Load System, and Detailed. Journal of Building Engineering, 22, 262-280.
[39] Barbosa, S., & Ip, K. (2016). Predicted Thermal Acceptance in Naturally Ventilated Office Buildings with Double Skin Façades under Brazilian Climates. Journal of Building Engineering, 7, 92-102.
[40] U.S. Energy Information Administration. (2015). How much carbon dioxide is produced when different fuels are burned? Retrieved from http://www.eia.gov/tools/faqs/faq.cfm?id=73&t=11. [Accessed 2015].