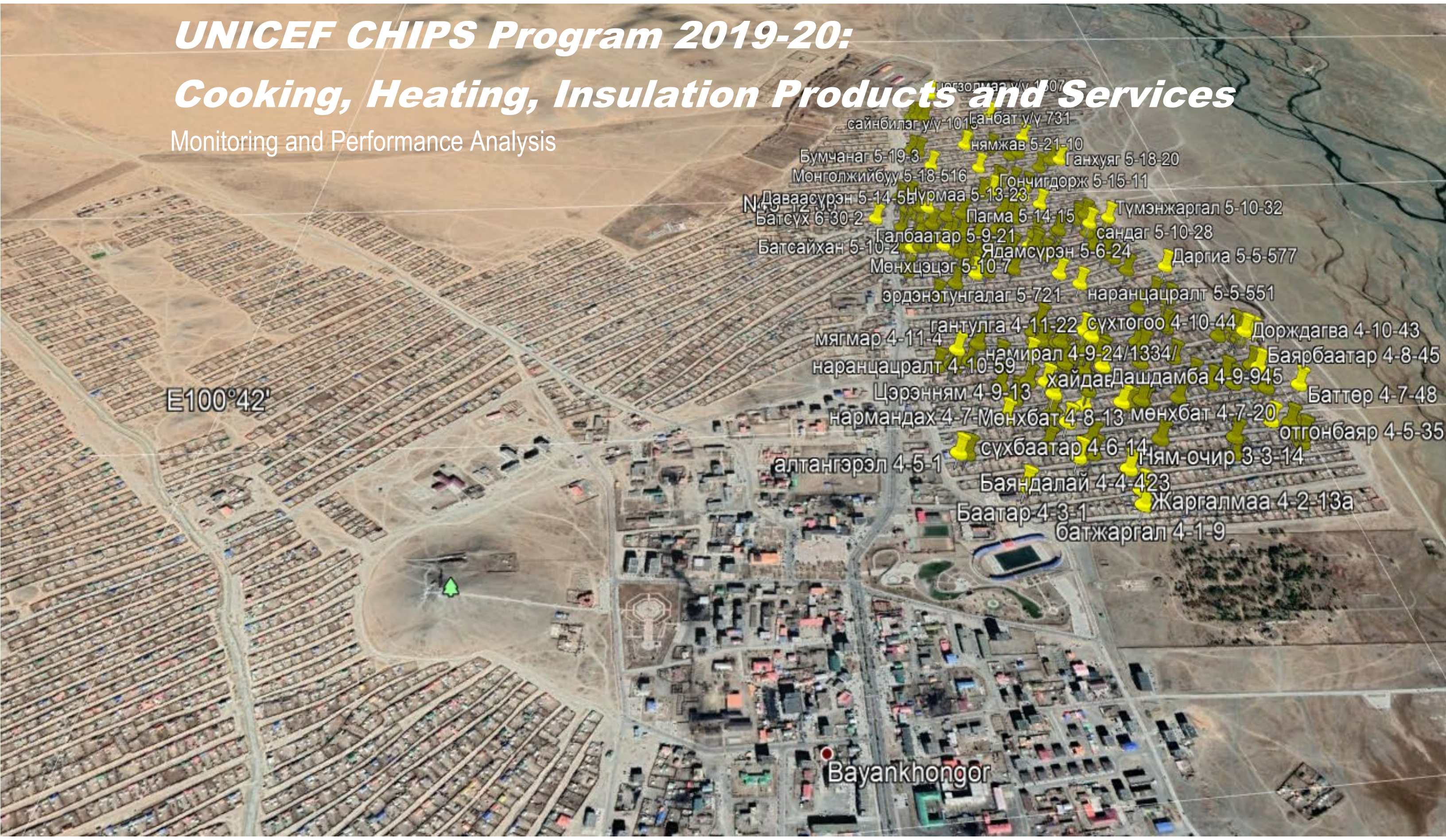
UNICEF CHIPS Program 2019-20:
Cooking, Heating, Insulation Products and Services

Monitoring and Performance Analysis



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Executive Summary

For UNICEF's "Ger for the 21st Century" project in the winter of 2018-19, the thermal behavior of twelve Mongolian ger were studied in detail: five Occupied Ger in Ulaanbaatar, six Test Ger at a "ger ranch" outside the city, and one highly instrumented Penn Ger at the University of Pennsylvania in Philadelphia. The study was conducted in support of programs by UNICEF and Ger Hub to reduce or eliminate coal consumption in the ger district. The result of that study confirmed that a better insulated ger could be heated affordably with electricity.

For the winter of 2019-20, UNICEF moved to test the approach on a larger number of occupied ger in Bayankhongor, Mongolia, a provincial capital southwest of Ulaanbaatar. The project was organized as a collaboration between UNICEF's Mongolia office, the CEBD at the University of Pennsylvania, the Building Energy Efficiency Center at the Mongolian University of Science and Technology (MUST), and an air pollution research group at Washington University in St. Louis. This project took insights from the "Ger for the 21st Century" project and used them to develop a comprehensive "Cooking, Heating, and Insulation Product System" (CHIPS) for Mongolian ger. CHIPS were applied to nearly 200 ger in Bayankhongor, while a selection of nine pilot households were more intensively monitored and studied: 4 occupied ger with CHIPS, 3 occupied without CHIPS, 1 stick-built bashin, and an unoccupied ger with CHIPS. For the CHIPS program there are three general aspects of performance to evaluate: energy consumption and costs, thermal comfort, and indoor air quality.

Energy consumption and costs. There are three valuable observations we can make about the energy performance of the nine pilot households. First, ger with CHIPS perform better than those without CHIPS, and in the case of BKH Ger 2, it actually outperforms ger E, the best ger from the 2018-19 study, which is quite a feat for an occupied ger. Second, as one would expect, the ger with heat pumps use somewhat less electricity than the those with other heaters. The data is too noisy for a final conclusion about heater choice, but this observation is consistent with heat pump performance. Third, all but one of the ger in this study cost less to operate with electricity than the average ger usually spends on wood, coal, and electricity.

Thermal comfort. The second criteria for the success of CHIPS are the levels of comfort they provide. The use of the electric heater provides a more consistent and generally comfortable interior temperature than experienced in ger heated with coal stoves. The warmth of the ger is related to the levels of insulation, with the CHIPS ger maintaining higher air and wall temperatures.

Indoor air quality. Urban air pollution was a key concern for this project and we sought to understand the impact that CHIPS have on indoor air quality. PM 2.5 concentrations in the ger district are largely driven by the burning of coal for domestic heating, but it was not clear whether the PM 2.5 in the ger came from inside or outside, or both. This study demonstrates that indoor concentration of PM 2.5 closely follows the pattern of outdoor pollution with a modest time lag depending on the air-sealing of the ger. In other words, the use of electric heaters does not reduce indoor concentrations of PM 2.5. The measurements of indoor air quality also demonstrated that the CHIPS ger were more tightly sealed, reducing rates of air infiltration, which contributed to greater energy efficiency and lower cost.

In summary, CHIPS successfully reduces energy consumption, heating ger through a Mongolian winter at similar or lower cost than typically expended on wood, coal, and electricity. The CHIPS construction also reduces air infiltration and increases thermal comfort. The surprising result of the study was the CHIPS did not reduce indoor concentration of PM 2.5, which is almost entirely determined by the levels of outdoor pollution.

1. Introduction

Following Mongolia's formal break from the Soviet Union in 1990, the country has been going through a tumultuous transition into a modern democratic market economy (Diener & Hagen, 2013). This, of course, has implications beyond the realm of the purely political and economic spheres. For example, the population of the capital Ulaanbaatar has nearly tripled from 571,692 in 1990 to 1,552,654 in 2019 (World Bank, 2020b). The population increase is largely due to people moving from the countryside to the city because of socioeconomic and environmental pressures (Park et al., 2019). Due to a lack of housing infrastructure in the city center, many new arrivals to Ulaanbaatar live in ger in the informal peri-urban areas that surround the city and house about 60% of its residents (Cousins, 2019; Diener & Hagen, 2013; Guttikunda et al., 2013). Figure 1. The Mongolian ger (also called "yurt" in Russian) is traditionally a light-weight, easy-to-assemble, tent-like dwelling used by nomads living a pastoral lifestyle, but in recent years, many ger have become permanent dwelling, particularly in Ulaanbaatar (Paddock & Schofield, 2017). Additionally, these informal settlements or ger districts have limited access to public utilities and sanitation services, so people living there are vulnerable to disease, contamination, and air pollution (Park et al., 2019).

Figure 1. A ger in the ger district north of Ulaanbaatar being used as a permanent dwelling

In 2011 and 2017, the World Health Organization (WHO) listed Ulaanbaatar as one of the cities with the worst air quality in the world, citing high PM 2.5 concentrations (Guttikunda et al., 2013; Kerimray et al., 2017). PM or particulate matter refers to small quantities of organic and inorganic solids and liquids (the main components are sulfate, nitrates, ammonia, sodium chloride, black carbon, mineral dust, and water) that are suspended in the air (Ambient (Outdoor) Air Pollution, 2018). Particulate matter is classified by the aerodynamic diameter of the particles, and PM 10 (particles less than or equal to 10 micrometers in diameter) and PM 2.5 (particles less than or equal to 2.5 micrometers) are two common categories (Ambient (Outdoor) Air Pollution, 2018; Guttikunda et al., 2013). PM is often reported as a concentration with units $\mu g/m^3$ (micrograms of particulate matter found in a cubic meter of air) (Air Quality: EPA's 2006 Changes to the Particulate Matter (PM) Standard (RL33254), n.d.; Ambient (Outdoor) Air Pollution, 2018). Both PM 10 and PM 2.5 can be inhaled and damage the lungs, but PM 2.5 can also cross from the lungs into the blood stream affecting the cardiovascular system as well (Ambient (Outdoor) Air Pollution, 2018; Cousins, 2019). Even in low concentration, PM 2.5 is dangerous, and has been linked to respiratory disorders, cardiovascular problems, and premature death (Cousins, 2019).

PM 2.5 concentration is commonly used as a proxy measurement for air quality because it has a bigger impact on people's health than any other air pollutant (Ambient (Outdoor) Air Pollution, 2018). Additionally, particulate matter produced by domestic heating and cooking, vehicle emissions, energy production, and industrial and construction activities is one of the main pollutants in Ulaanbaatar (Enkhbat et al., 2016). WHO's recommended annual average exterior PM 2.5 concentration is less than or equal to 10 $\mu g/m^3$, and the daily average on a given day should not exceed 25 $\mu g/m^3$ (Ambient (Outdoor) Air Pollution, 2018). Meanwhile, the United States Environmental Protection Agency (US EPA) has an annual standard for exterior PM 2.5 concentration of 15 $\mu g/m^3$ and a daily standard of 35 $\mu g/m^3$ (Air Quality: EPA's 2006 Changes to the Particulate Matter (PM) Standard (RL33254), n.d.). However, the mean annual exposure for PM 2.5 in Mongolia in 2017 was 40.1 $\mu g/m^3$, about four times higher than WHO's maximum recommendation (World Bank, 2020a). In 2011, Ulaanbaatar's annual average exterior PM 2.5 concentration was about 120 $\mu g/m^3$, and in 2014, the winter time average exterior PM 2.5 concentration was 250 $\mu g/m^3$ (Guttikunda et al., 2013; Hill et al., 2017). More troublingly, in 2011 the annual average exterior PM 2.5 concentration in areas in the ger districts were between 200 to 350 $\mu g/m^3$ (Kerimray et al., 2017). It is easy to see that the exterior PM 2.5 concentration in Ulaanbaatar and Mongolia generally are well above what is considered healthy.

Another dimension to consider is indoor air quality. Indoor PM 2.5 concentration is a major source of exposure for ger residents during the wintertime because they are spending more time indoors due to the shorter days and colder exterior temperatures (Enkhbat et al., 2016). One study estimated that the wintertime indoor PM 2.5 concentration in ger is about 98 $\mu g/m^3$, a second study estimated that the indoor PM 2.5 concentration in Ulaanbaatar is three to five times lower than the outdoor PM 2.5 concentration, and a third study conducted in January and February 2015 measured indoor PM 2.5 concentrations in ger to be 100 $\mu g/m^3$ (Enkhbat et al., 2016; Hill et al., 2017; Kerimray et al., 2017). Guidance from either WHO or the US EPA is not readily available for acceptable levels of indoor PM 2.5 concentration, but all three PM 2.5 concentrations reported in the above-mentioned studies are much higher than their recommended maximum outdoor PM 2.5 concentrations. Major sources of indoor PM 2.5 generation in ger include cooking or heating with solid fuels (coal, wood, dung, etc.), smoking indoors, and polluted outdoor infiltrating to the inside (Hill et al., 2017; Household Air Pollution and Health, 2018), and it is estimated that 98% of families living in ger burn coal for heating during the winter (Kerimray et al., 2017). Additionally, it was estimated that household combustion of solid fuels for heating in the ger district north of the city is responsible for 50% of the total air pollution in Ulaanbaaatar and 60% of the PM 2.5 generation in the city (Guttikunda et al., 2013; Kerimray et al., 2017). Furthermore, in the February 2019 World Health Organization Bulletin, Dr Delgermaa Vanya explains that " 'The coal used in the stoves is a primary cause of Ulaanbaatar's air pollution. . .much worse than other sources of pollution such as cars and trucks or waste. . .accounting for about 80% of Ulaanbaatar's winter pollution'" (Cousins, 2019).

The high indoor and outdoor PM 2.5 concentrations seen in Mongolia can be linked to poor public health outcomes. Studies have shown strong statistical correlations between elevated PM 2.5 concentration in the air and cardiovascular mortality, spontaneous abortion, and lung cancer (Kerimray et al., 2017). Additionally exposure to PM 2.5 has been shown to impede fetal growth and negatively impact children's general health (Enkhbat et al., 2016). Household indoor air pollution was estimated to have caused 3.5 million premature deaths worldwide in 2010 and 4.3 million in 2014 (Bruce et al., 2015). Specifically, in

Mongolia, in 2009 it was estimated that 10% of the total deaths in Ulaanbaatar are attributable to poor outdoor air quality (Allen et al., 2013). Another study in 2016 estimated that roughly 3,300 Mongolian people (or about 0.1% of the country's total population) died that year from diseases attributable to poor indoor and outdoor air quality (Cousins, 2019). Furthermore, the negative health externalities are concentrated in the ger districts where the residents are most vulnerable to pollution and poor air quality (Hill et al., 2017). However, if the concentration were to decrease, some of these consequences might be mitigated. Reducing the annual average PM 2.5 concentration from 35 $\mu g/m^3$ to 10 $\mu g/m^3$ could decrease pollution related mortality rates by as much as 15% (Ambient (Outdoor) Air Pollution, 2018). Therefore, reducing the indoor and outdoor PM 2.5 concentration would represent a major public health boon in Mongolia.

With the health hazards of poor air quality as a backdrop, the Ger of the 21st Century project was launched in 2018 as a collaboration between UNICEF's Mongolia Office, the Center for Environmental Building and Design (CEBD) at the University of Pennsylvania, a local Mongolian NGO GerHub, the Philadelphia based architecture firm Kieran Timberlake, The North Face, and Arc'teryx. Initially, the goal of this project was to improve indoor air quality for people living in ger in Ulaanbaatar. One approach considered by the team was to ignore the outdoor air quality problem and focus on solutions that could directly impact indoor air quality, and, encouragingly, some work has been done in this area. For example, one survey of kitchens burning solid fuels found that while several interventions were able to decrease indoor the PM 2.5 concentration from the baseline level, but the new levels were still often in the hundreds of micrograms per cubic meter (Bruce et al., 2015). Another study in non-ger households in Ulaanbaatar (where smoking is the largest source of PM 2.5 generation) showed that using high efficiency portable air filters was potentially able to reduce indoor PM 2.5 concentrations by 29% (Barn et al., 2018). While the PM 2.5 reductions of these interventions are not trivial, it is not possible to have good indoor air quality if the outdoor air quality is bad (Bruce et al., 2015). Therefore, a robust solution must decrease emissions from ger, as well as decreasing the generation of indoor pollution.

Another approach is to use electric heating in the ger, which should decrease emissions. The three largest coal power plants in Ulaanbaatar supply electricity to the 40% of the city's residents who live downtown, and account for only about 27% of the total PM 2.5 pollution in the city (Guttikunda et al., 2013). If all that electricity was used for residential heating, electric heating per person would account for 0.0000435% of the total PM 2.5 generation in the city. On the other hand, using the numbers previously cited (60% of the population live in the ger district, and burning of solid fuels in ger accounts for 60% of the PM 2.5 generation in the city), heating by combusting solid fuels per person would account for 0.0000644% of the total PM 2.5 generation in the city. In this case, switching the ger to electric heaters would represent a 32% decrease in total PM 2.5 emissions in Ulaanbaatar. In reality, this decrease would be much higher because not all of the power generated in the factories is used just for residential heating. Furthermore, cleaner power sources could be used in the future to further decrease the pollution associated with heating ger. For example, the Rural Energy Access Project (REAP) in Mongolia was able to supply solar and wind power to several rural parts of Mongolia, and even speculated that it would be possible to heat ger with clean electricity, but that was ultimately too expensive (Sovacool et al., 2011). Additionally, in a 2009 study, it was estimated that heating ger with district electricity would be twice as expensive as heating them with coal stoves (Kerimray et al., 2017). Thus, given the current situation, electric heating does not seem cost effective for ger residents.

Finally, the team explored the effect of increasing the level of thermal insulation in ger, which decreases the amount of energy required to heat them. Ger requiring less energy use less fuel and produce fewer emissions, ultimately leading to getter air quality (Kerimray et al., 2017). Furthermore, if less energy is required to heat them, the cost to heat a ger with electricity would go down, and electric heating could become economically viable. Therefore, improving the thermal insulation of ger became a central focus of the Ger of the 21st Century project. During the summer of 2018, several ger interventions were designed to improve the insulation, air tightness, and long-term durability of ger to be used as permanent dwellings. These interventions were built in unoccupied test ger in the countryside near Ulaanbaatar, and an experiment was conducted on them during the 2018-2019 winter. All the unoccupied test ger were heated with electric heaters, and their energy consumption, as well as thermal characteristics were measured. Based on that data, energy efficiencies and were calculated along with cost of heating estimates.

The results of that experiment led to three main insights for improving the thermal insulation of ger. Firstly, and perhaps most obviously, adding another layer of felt insulation to the envelope of the ger increased the level of thermal insulation of the walls and roof and decreased the amount of energy required to warm ger. Next, air infiltration is a major pathway of heat loss in the ger. Ger are not perfectly sealed structures, and some warm air from inside will leak out and be replaced by cold exterior air, cooling down the interior air. However, better insulation around the door and toono (the circular oculus at the top of the ger) can decrease the amount of air infiltration and the amount of energy required to warm ger. Figure 2. Finally, improving insulation around the perimeter of the floor further increased the thermal insulation of the ger and decreased the amount of energy required to keep ger warm.

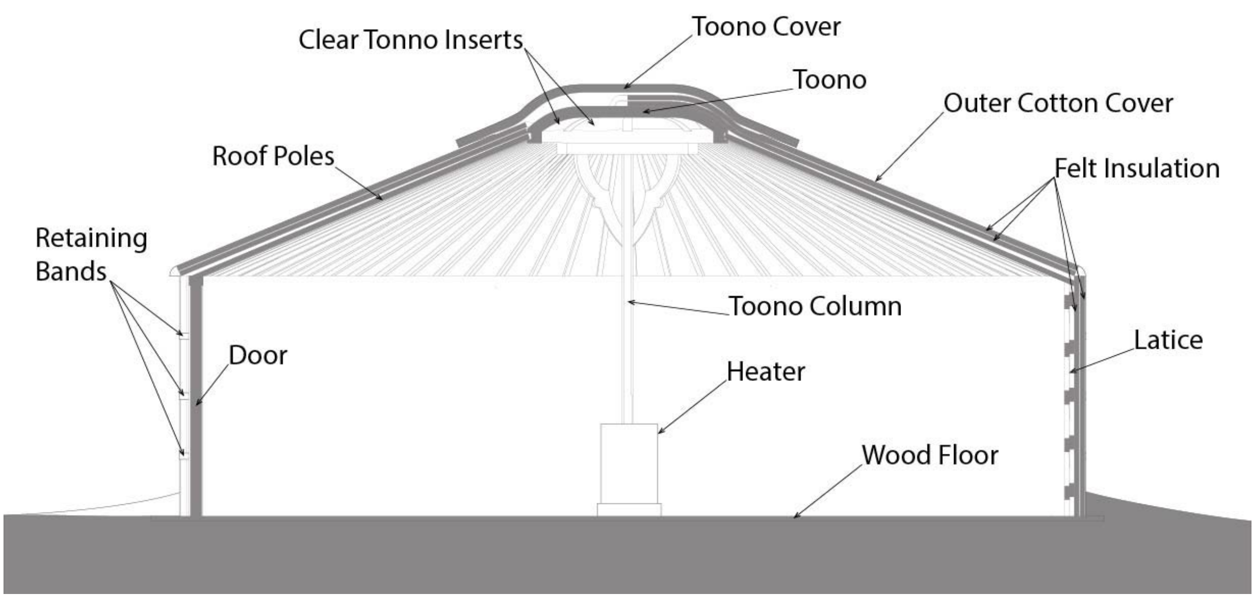

Figure 2. Parts of a traditional ger

With these insights, a new collaboration started in 2019 between UNICEF's Mongolia office, the CEBD at the University of Pennsylvania, the Building Energy Efficiency Center at the Mongolian University of Science and Technology (MUST), and Professor Jay Turner's research group at Washington University in St. Louis. The goal of this new group was to take the insights learned in the 2018-2019 winter and use them to create and test Cooking, Heating, and Insulation Product Systems (CHIPS) that would be tested during the 2019-2020 winter in Bayankhongor, a provincial capital southwest of Ulaanbaatar. The experiment during the 2019-2020 winter set out to demonstrate that the CHIPS were able to decrease the amount of energy required to heat the ger and if heating ger with electric heaters could be cost effective.

2. CHIPS program in Bayankhongor

The 2019-2020 CHIPS program in Bayankhongor consisted of installing CHIPS in about 200 households in the ger district northeast of the town. Surveys were given to each of these households at the end of the winter to evaluate the cost of electric heating and the thermal comfort of the occupants.

Figure 3. Location of 200 CHIPS installations in Bayankhongor

Nine pilot households were selected to be studied in greater detail. Table 1. One was an unoccupied ger with the CHIPS installed (BKH Innovation Ger). Four more of the pilot households were occupied ger with CHIPS installed (BKH Ger 1-4). An additional three of the pilot households were occupied ger without CHIPS to serve as a point of comparison for the energy efficiency and performance of CHIPS (BKH 5-7). Finally, a small, three-room stick-built house, called a bashin, was included (BKH Bashin 1). All nine of the pilot households were heated with one of four kinds of electric heaters. Monitoring equipment was installed in each to collect data on electric energy consumption, thermal characteristics, and indoor air quality. Locations are indicated in Figure 4. Details of each of the pilot households are illustrated in Appendix A.

Table 1. Details of the ninepilot households

Name	Type	CHIPS	Heater
BKH Bashin 1	Bashin	no CHIPS	Table Convector
BKH Ger 1	5 Wall Ger	with CHIPS	Hybrid Heater
BKH Ger 2	5 Wall Ger	with CHIPS	Heat Pump
BKH Ger 3	4 Wall Ger	with CHIPS	Table Convector
BKH Ger 4	4 Wall Ger	with CHIPS	Radiant Cylinder
BKH Ger 5	5 Wall Ger	no CHIPS	Radiant Cylinder
BKH Ger 6	5 Wall Ger	no CHIPS	Heat Pump
BKH Ger 7	5 Wall Ger	no CHIPS	Table Convector
BKH - Innovation Ger	5 Wall Ger	with CHIPS	Table Convector

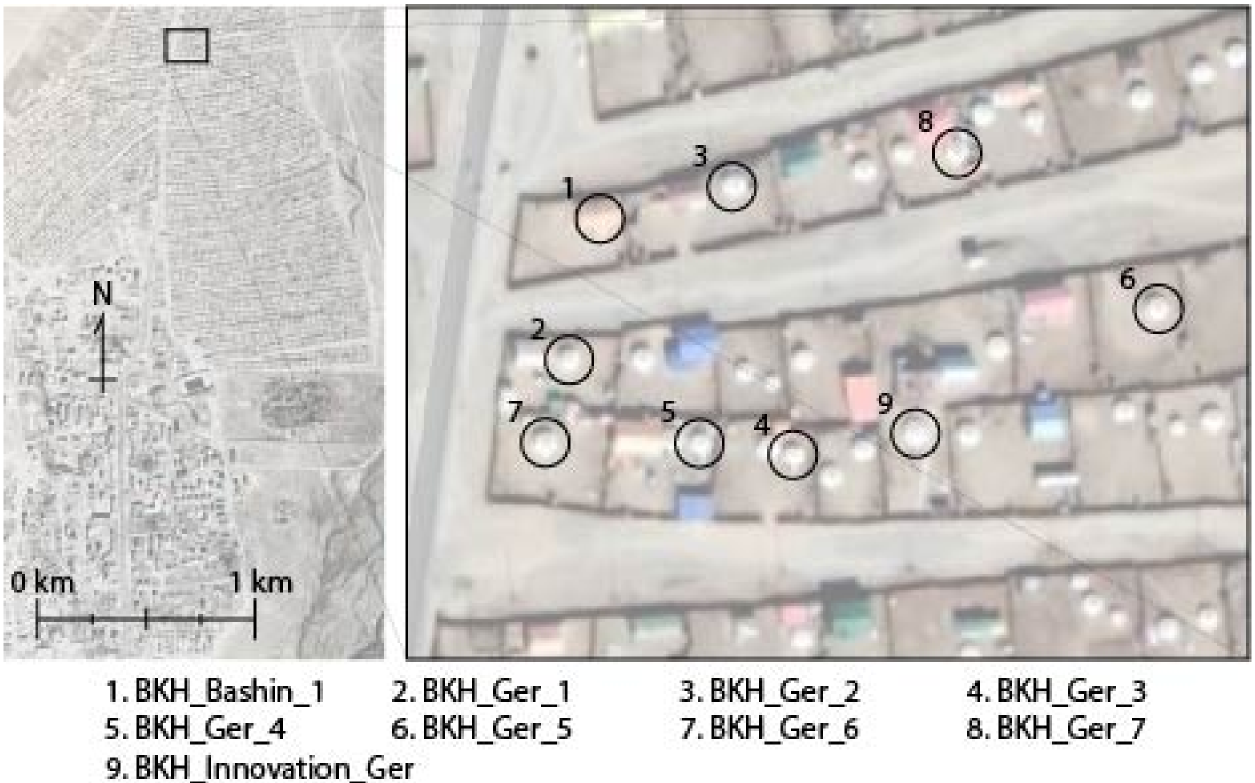

Figure 4. Locations of 9 pilot households on a map of Bayankhongor, Mongolia

ХБХДБҮ
Хоол бэлтгэл, Халаалт, Дулаалга, Бүтээгдэхүүн, Үйчилгээ

CHIPS
Cooking, Heating, Insulation, Production and Service

2.1. CHIPS Design and implementation

The ger has a ten thousand year history and the CHIPS program represents an incremental improvement in a durable and flexible form of construction. Over that long history, Mongolians have used different method to better insulate ger: An extra layer of felt on the walls and roof (up to 3 or 4), felt insulation for toono and door, lower edge insulation, waterproof textiles for water and wind protection, floor insulation, paper layer for wind protection, wool blankets, and external entrance rooms. For heating and cooking they traditionally used a trivet for fire, a simple stove burning dung, wood, etc., a stove for burning coal, and an electric cooker and pot.

CHIPS is package of improvements provided to residents to help reduce air pollution, reduce costs, and provide greater comfort. The main concept of the CHIPS packages is to make the improvements as easy as possible for residents, providing materials that are already quality tested, locally produced and serviced, and above all, affordable.

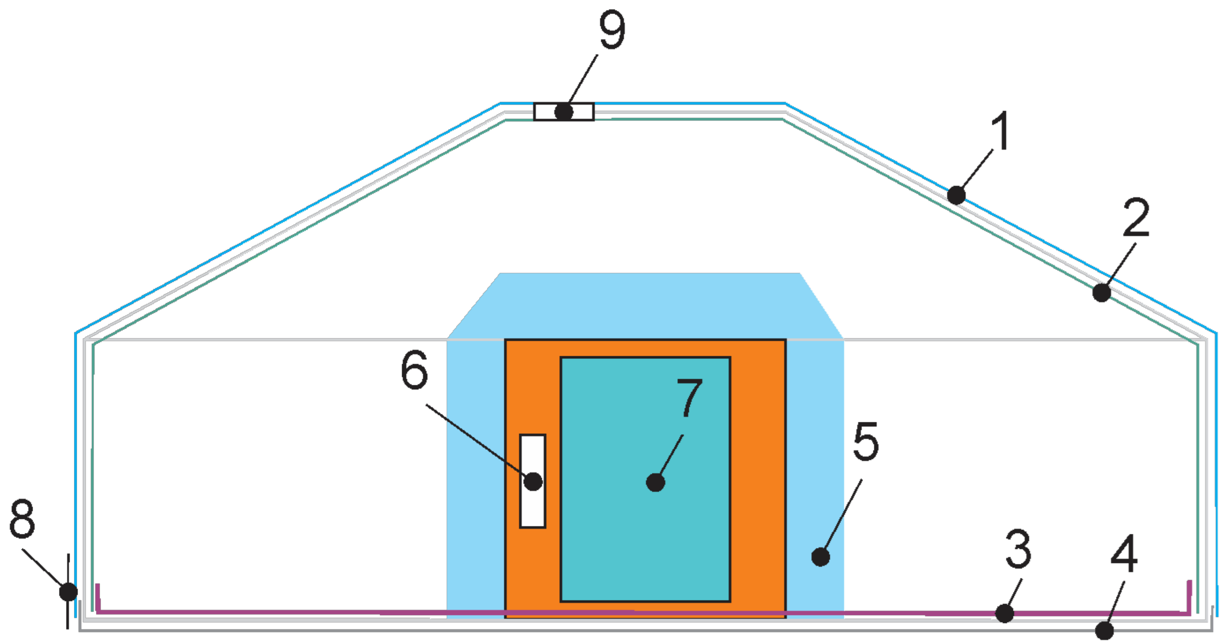

Figure 5. Elements of the CHIPS program for ger

The basic elements of the insulation package include some or all of the follow elements:

1. Water and wind proof layer (external)
2. Internal vapor proof layer
3. Floor insulation with vertical parts
4. Vapor proof layer between floor and from ground
5. Door side insulation
6. Air inlet opening with filter and flow control
7. Door insulation
8. Bottom edge insulation
9. Air exhaust opening with flow control

The basic requirement for the felt insulation was that it include at least 3 layers of sheep wool or recycled textile fabric of greater than 3 cm in thickness, and that it be dry and odorless.

Four different electric heaters were chosen for the project: a hybrid heater, a table convector, a radiant cylinder, and a heat pump, shown below. Figure 6.

Figure 6. Electric heaters used in the CHIPS program

2.2. Data Collection

To determine the energy efficiency and cost effectiveness of each of the nine pilot households, data was collected from each one over the course of the winter. This data was collected in one of two ways: either by installing monitoring equipment and directly measuring quantities with sensors or through surveys and estimation. Generally speaking three types of information were collected: electric energy consumption related data, thermal environment data, and air quality data. The following sections will detail how each of these types of data was collected.

2.2.1. Electric Energy Consumption Monitoring

The nine pilot households were all heated with electric heaters, so it is necessary to accurately measure the electric energy consumption, however there were different sources and degrees of resolution for the electric data, so uncertainty about the total consumption remains for some of the ger. In general, the electric energy consumption falls into two categories: electricity for the electric heater and electricity for all other non-heating appliances (such as irons, cooking pots, televisions, refrigerators, etc.). Even though the non-heating appliances perform other functions, the energy that they consume will eventually degrade into heat after the appliances have performed their function (conservation of energy). So, it is important to gather data on both categories of energy consumption.

Three methods were developed to measure the electric energy consumption in the pilot households. First, energy consumption by the electric heater was directly measured at one-minute intervals using an Onset EG4115 power logger. Second, the local electric utility provided daily electric usage for each household as part of their regular billing procedure. Subtracting the energy for the heater from the total electricity should give the electric consumption for the non-heater appliances. Third, estimates were developed for the power consumption of the non-heater appliances observed in each ger. This was done as a check on the data provided by the utility and to confirm that that all the electricity was ending up as heat inside the ger. As the data in Section 3 will show, for some of the ger we were unable to reconcile the total electric usage with the more detailed data we recorded and the equipment observed.

Heater power. In each household, single phase power from the grid flows into the main breakers of the house. The output of the main breaker is split into two circuits. Figure 7. The first circuit is for the non-heating appliances in the household, and the second circuit is for the electric heater. The second circuit was monitored by the EG4115 with a JD sensing 50 mA current transducer (Onset part number T-EG-0630-0050). The configuration is shown in Figure 8. Data was downloaded from the EG4115 at a one-minute sampling interval. This was similar to the procedure used to collect electric heater power consumption data from the winter 2018-2019 unoccupied test ger.

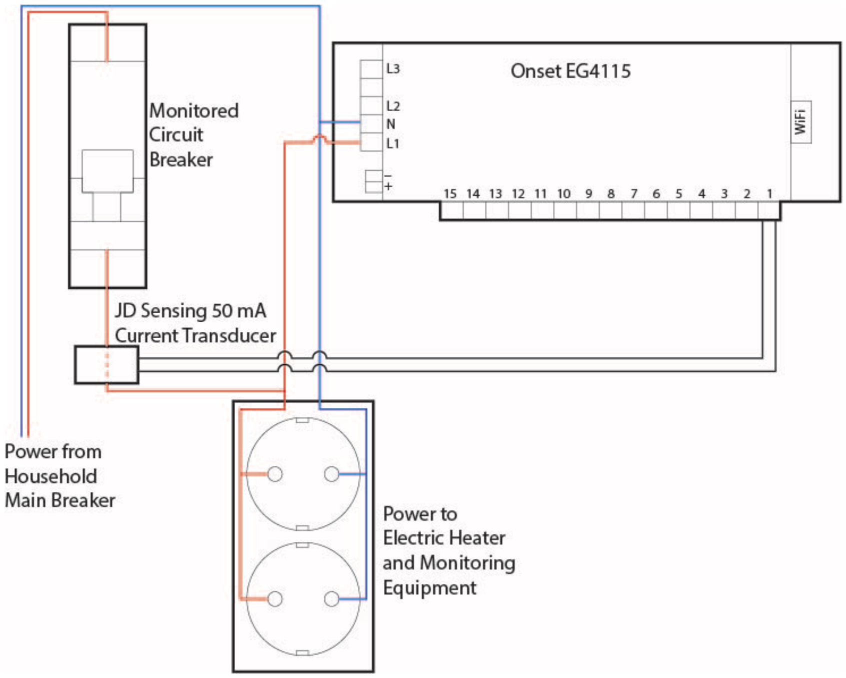

Figure 7. EG4115 Configuration Diagram

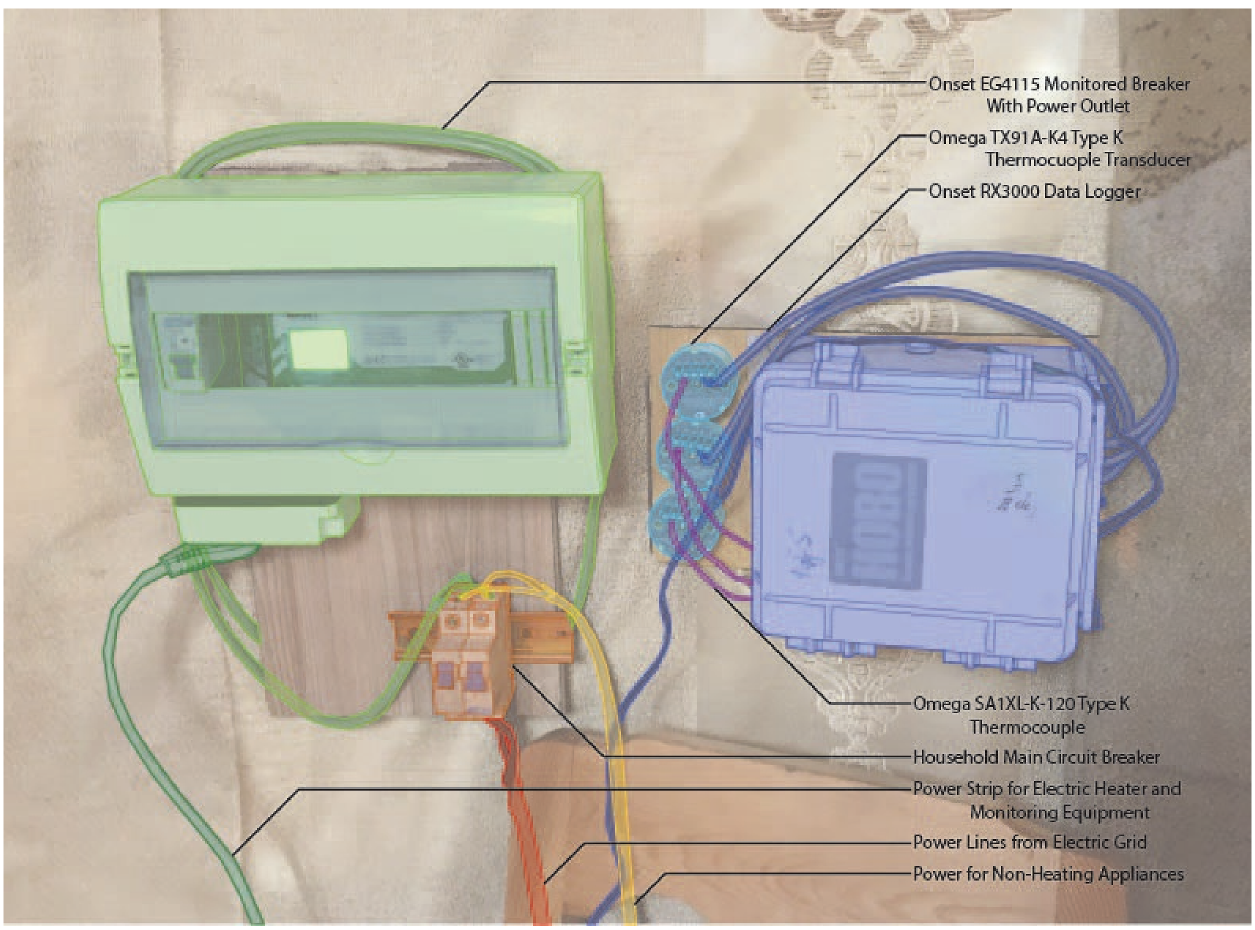

Figure 8. Diagram of Monitoring Equipment in Ger 6

However, because it was important that the power supply not be disturbed for the data logging equipment and the WiFi router, an Onset RX3000 data logger, and a Huawei E5563Cs WiFi router were also powered by the second circuit. Per the manufacturer's specifications, the maximum instantaneous power draw of the Huawei E5563Cs is 3.5 W, and while the operating power is not listed, based on the expected battery life, it is between 0.02 W and 0.95 W. Meanwhile, Onset lists the maximum instantaneous current draw of a RX3000 as 2 A at 4.5 V, which yields a maximum instantaneous power draw of 9 W. The operating power of an Onset RX3000 is variable, but based on the battery capacity and expected battery life, it should be around 0.1 W. By comparison, the EG4115's measured an average of 320 W to 980 W when the heaters were in use. Figure 9. So the maximum possible instantaneous power draw of the both non-heater devices is 12.5 W is quite small compared with the average power consumption measured by the EG4115's, and the operating power draw of both devices (about 1 W or less) is negligible. Therefore, the power consumption measured by the Onset EG4115's is all attributed to the electric heater.

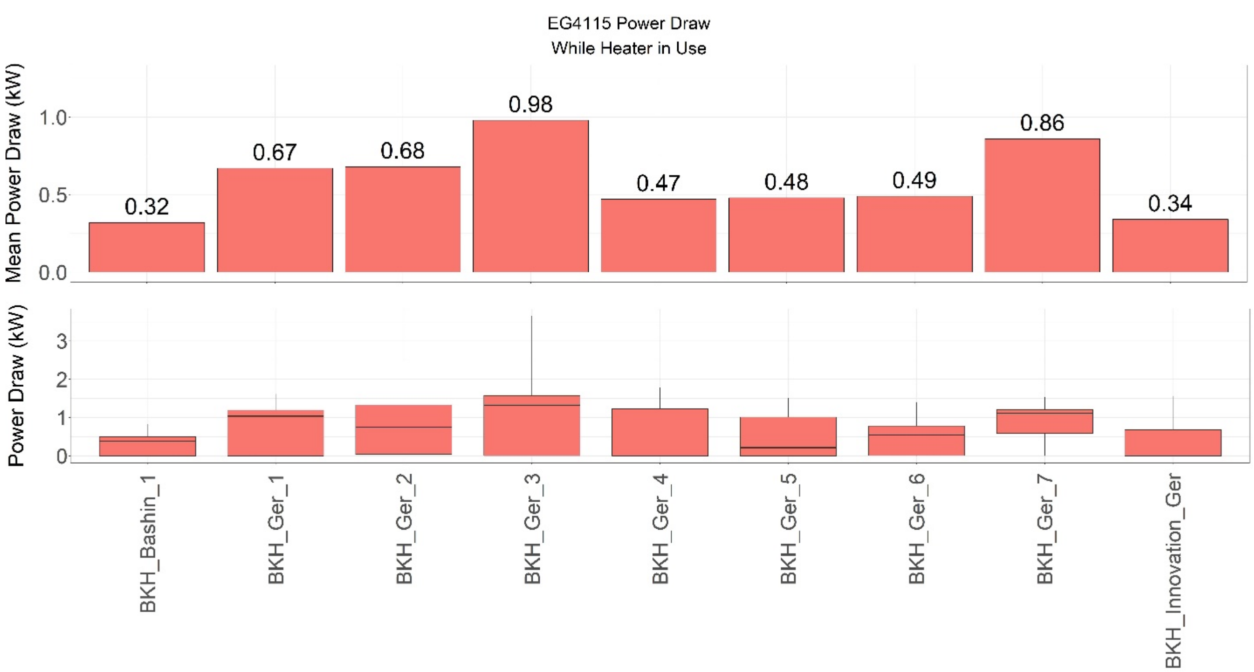

Figure 9. Power draw measured by the EG4115's when the heaters were in use

Total electric consumption. Data for the daily and monthly total energy consumption by each household was provided by the local power utility in Bayankhongor. This was delivered in batches and is not complete for all the ger.

Appliance electric consumption. The electric energy consumption by the non-heating appliances was determined in two ways. First it was calculated by subtracting the heater energy consumption from the total energy consumption reported by the utility. Second, as an additional check on the data, and to understand where the electricity was going and whether it would end up as heat inside the ger, the appliance consumption was estimated. The number and types of non-heating appliances in each household were recorded and the hours of usage per week were estimated. Power ratings for each of the non-heating appliances were documented where available and estimated when they were not. The hours of use per week was then multiplied by the power rating to arrive at the estimated weekly energy consumption of the non-heating appliances in the pilot households. It was believed that these three methods would effectively describe the electric energy consumption by the electric heater and of the non-heating appliances.

Data validation. For a number of the ger, the total electric consumption reported by the utility was larger than the total of the heater energy and the estimated electric consumption by appliances. There are many possible reasons for this discrepancy. The list of appliances might be incomplete or they could be used more intensively. It is also possible that there are issues with the electric company meter or power may be diverted to other uses outside the household. For this report, the analysis will consider the implications of both totals, but further validation of the data is being pursued.

One check on the estimate of the appliance energy is the usage in summer, when the heaters are not used. Monthly totals for the rest of the year were provided by the utility and were used to evaluate the amount consumed by appliances, which does appear to vary from summer to winter.

2.2.2. Thermal Environment monitoring

Data about the temperatures inside the ger were also recorded. This was done for two reasons. First to determine how well the heating system was performing and second to evaluate how comfortable the interior conditions were. The purpose of stoves and heaters is to keep the interior of the ger warm and a big advantage of electric heaters is that they can be operated by a thermostat to keep the interior at a steady temperature. Better insulation and air sealing not only reduce the amounts of energy required to keep the ger warm, but also make the interior temperatures more even, which can make people more comfortable. To determine how well the heaters perform, we measured a variety of temperatures inside and outside of the ger.

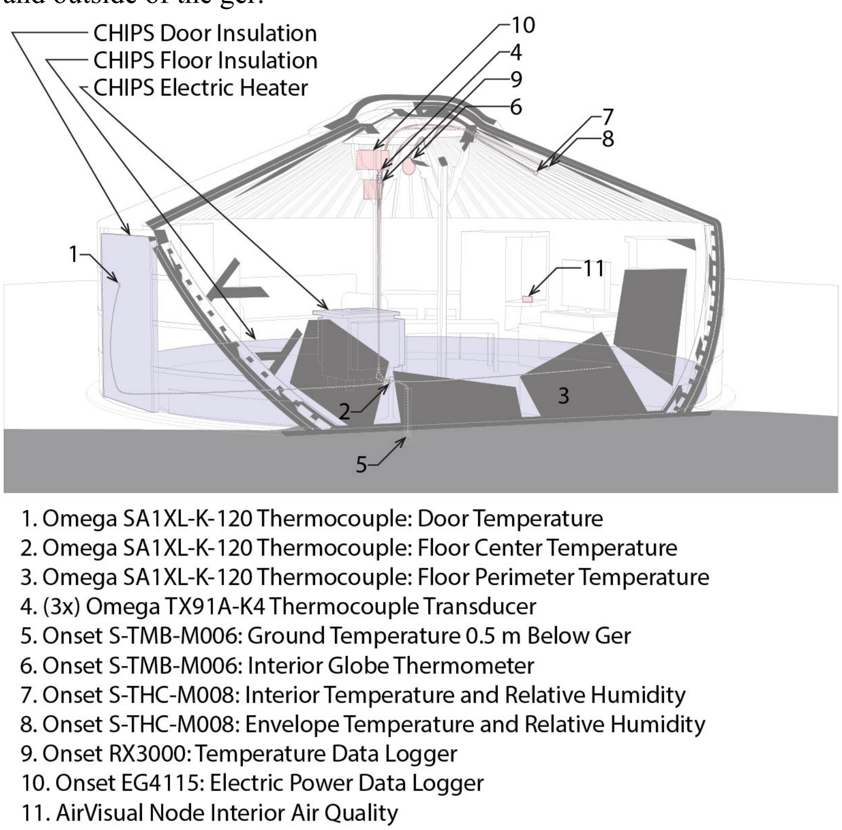

Figure 10. Typical Sensor Layout in Ger

The outside temperature were recorded by an Onset weather station with the following sensors: wind speed and direction, solar flux, ambient temperature and relative humidity, and three embedded ground temperature at 0.25 m, 0.50 m, 1.00 m depth.

In the interior, the following comfort temperatures were measured: air temperature, relative humidity, and a “globe” temperature, which is a temperature sensor inside a black metal globe used to evaluate the radiant temperature of the interior, located either near the perimeter of the ger or toward the center of the ger close to the roof. In addition a series of surface temperatures were recorded with sensor embedded in the wall, floor, door, and the ground below the ger. Interior temperatures were logged with Onset RX3000 data logger using Onset S-TMB-M006 temperature sensors, Onset S-THB-M008 temperature and relative humidity sensors, and Omega TX91A-K4 type k thermocouples using Omega SA1XL-K-120 thermocouple transducers. Figure 10.

2.2.3. Air Quality Monitoring

One of the key motivations of this project is to address the air quality crisis in Mongolia. While the CHIPS program is mostly focused on decreasing the amount of energy required to heat ger, so they can be heated affordably with electric heaters, the overarching goal is to improve indoor air quality. In addition to the thermal and electric monitoring equipment, indoor air quality was measured in each of the nine pilot households with an AirVisual Pro. The AirVisual Pro is a low cost air quality monitor, which measures PM 2.5 concentration, CO_2 concentration, temperature, and relative humidity in the ambient air (AirVisual Pro Technical Specifications, 2020). Because of the other thermal monitoring equipment, only the PM 2.5 and CO_2 concentrations were taken from the AirVisual. In each of the pilot households, the AirVisual Pro was placed on a table or shelf about 2 feet off the ground near the perimeter of the ger (or in the living room of the bashin). Data collected by the AirVisual Pro is stored at an irregular sampling interval, so it was averaged to a consistent 10 minute sampling interval, using a start-of-hour based convention where each data point represents the average of the readings from the subsequent 10 minutes. The data was used for the indoor PM 2.5 and CO_2 concentrations in the pilot households.

Concurrent with this experiment, Professor Jay Turner’s research group from Washington University in St. Louis conducted a study of outdoor air quality in Bayankhongor, Mongolia. They installed several air quality monitors both indoors and outdoors in various locations in Bayankhongor. They provided the CEBD team with data from three PurpleAir PA-II air quality monitors, located outdoors near the innovation center and three PurpleAir PA-II air quality monitors and three AirVisual Pro air quality monitors located at a reference site in town. Figure 11. The PurpleAir PA-II is another low-cost air quality monitor, which can measure PM 2.5 concentration, temperature, pressure, and relative humidity in ambient air (PurpleAir PA-II Technical Specifications, 2020). Because an outdoor weather station was placed near the innovation center, only PM 2.5 concentrations were taken from the PurpleAir PA-II devices and PM 2.5 and CO_2 concentrations were taken from the AirVisual Pro devices. Each set of three sensors were collocated measuring outdoor air quality in the same location. The data provided to the CEBD team was averaged to a 10 minute sampling interval using the same start-of-hour based convention described above. The main interest in this data was to compare to indoor and outdoor PM 2.5 and CO_2 concentrations, so the values from each of the sets of three sensors were averaged to create three sets of data for exterior PM 2.5 concentration and one set of data for exterior CO_2 concentration at the reference site.

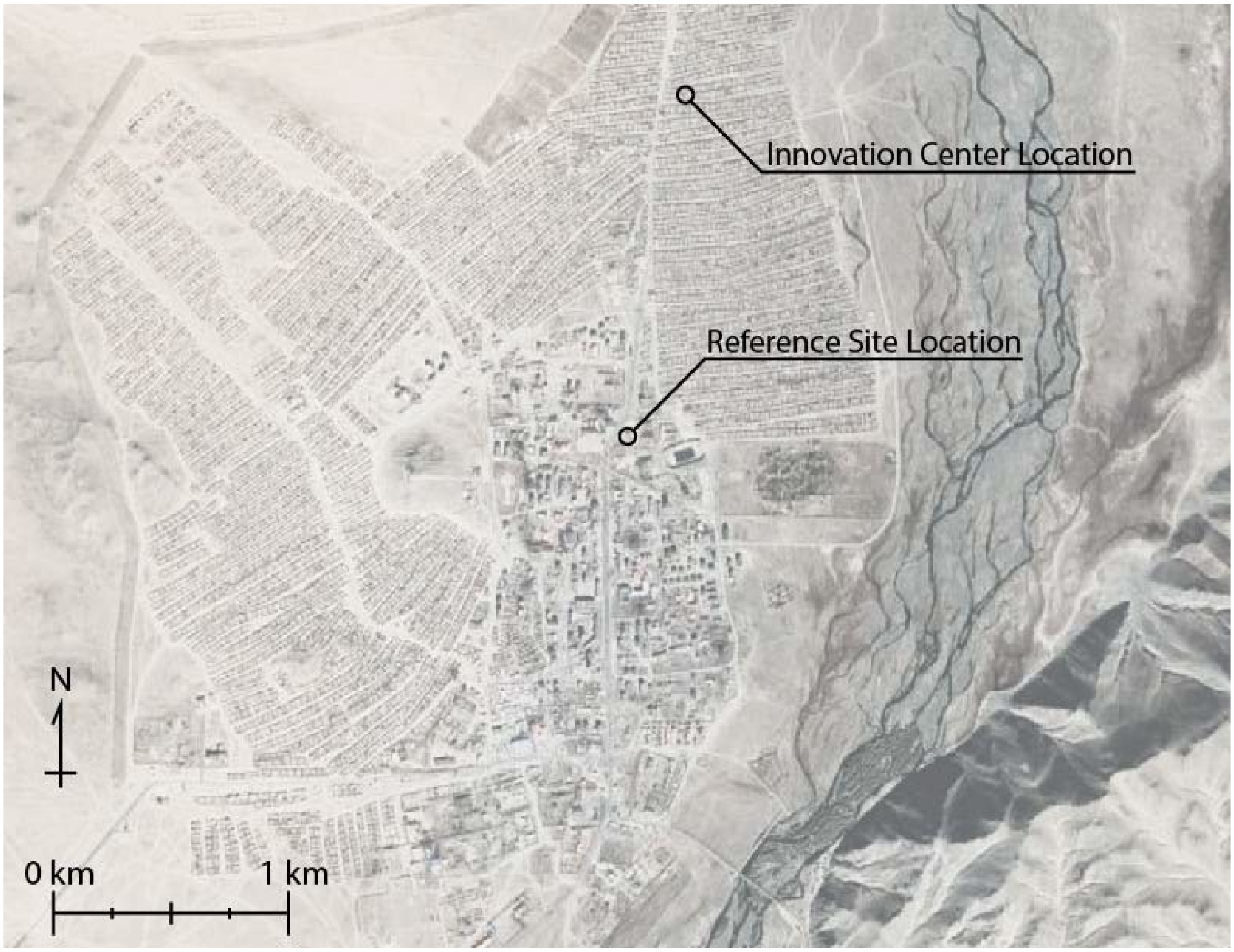

Figure 11: Map of Outdoor Air Quality Monitoring Locations in Bayankhongor, Mongolia

While the PurpleAir PA-II and the AirVisual Pro are both low-cost air quality monitors, a growing body of research has examined the accuracy of low-cost air quality monitors, including the AirVisual Pro and the PurpleAir PA-II. One study compared the PurpleAir PA-II to a highly accurate Beta-Attenuation Monitor (BAM)—a device used as a Federal Equivalent Method (FEM) for measuring PM 2.5 concentration—and found that after applying a correction factor, the PM 2.5 concentration measured by the PurpleAir PA-II was accurate to the PM 2.5 concentration measured by the BAM within 3-4 $\mu g/m^3$ (Magi et al., 2019). Another study showed that the AirVisual Pro was able to measure PM 2.5 concentrations with about 86% accuracy compared with a DataRAM pDR-1200—another highly accurate PM 2.5 monitor (Zamora et al., 2020). Additionally, a further study of a BAM FEM device with twelve low-cost air quality sensors and found that the PM 2.5 concentrations measured by the AirVisual Pro and the PurpleAir PA-II had an R^2 greater than 0.7 relative to the BAM device, noting that this data can be useful if it is interpreted correctly (Feenstra et al., 2019). Furthermore, PM 2.5 concentration measured by an AirVisual Pro was shown to be highly correlated to the measurements of an FEM device for major cooking and combustion sources (Singer & Delp, 2018).

While these low-cost air quality monitoring systems are less accurate than the more expensive ones used for calibration, Professor Turner's work demonstrated they provide a reasonably accurate measure of PM 2.5 concentration. For this project, we were interested in daily and seasonal trends in PM 2.5

concentration, and especially indoor to outdoor PM 2.5 concentration comparison. To that end, the AirVisual Pro and the PurpleAir PA-II were deemed sufficiently accurate for the purposes of the experiment.

3. Results & Discussion

For the CHIPS program there are three general aspects of performance to evaluate: energy and its costs, thermal comfort, and indoor air quality.

3.1. Energy Accounting

This section reports on the electric energy consumed to keep the ger warm, which includes both the electricity used by the heater and also that used by the many appliances. As described in section 2.2.1. there were some inconsistencies between the total electric consumption reported by the utility and the estimated consumption of the appliance. Both results are reported and their implications considered.

3.1.1. Total Energy Consumption

The average total daily electric consumption of each of the nine pilot households is shown in Figure 12. The red bar is the electric heater consumption, the yellow bar is the consumption estimated for the appliances, and the black line indicates the total amount of electricity billed by the utility. The full record of power consumption for each of the ger is reported in Appendix B: Daily energy consumption. As the chart below indicates, the sum of heater and estimated appliance is similar to the total billed for only two of the ger (2 & 3), however the pattern of usage for the totals closely follows the recorded and estimated usage, so our operating assumption is that additional appliances were being used or used more frequently.

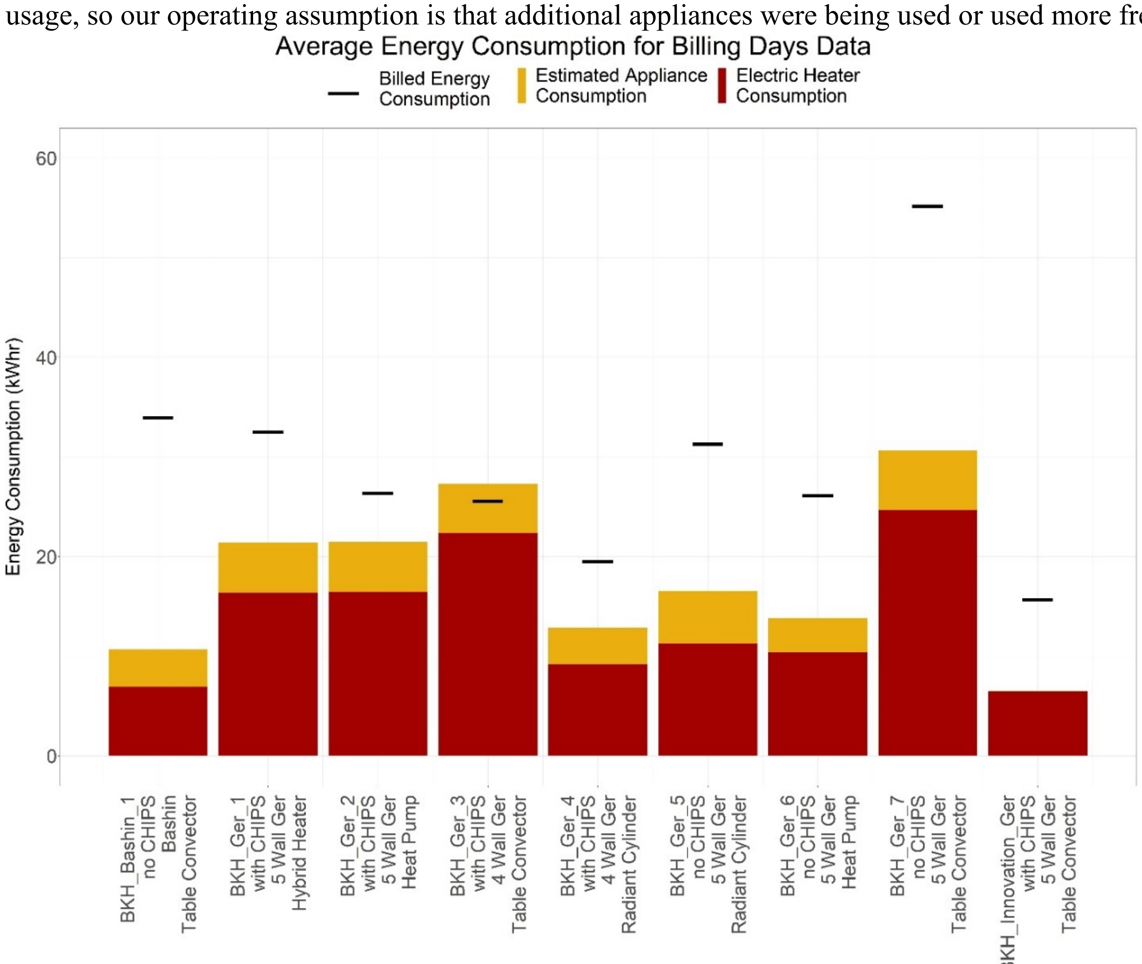

Figure 12. Average daily total electric consumption for the nine pilot households

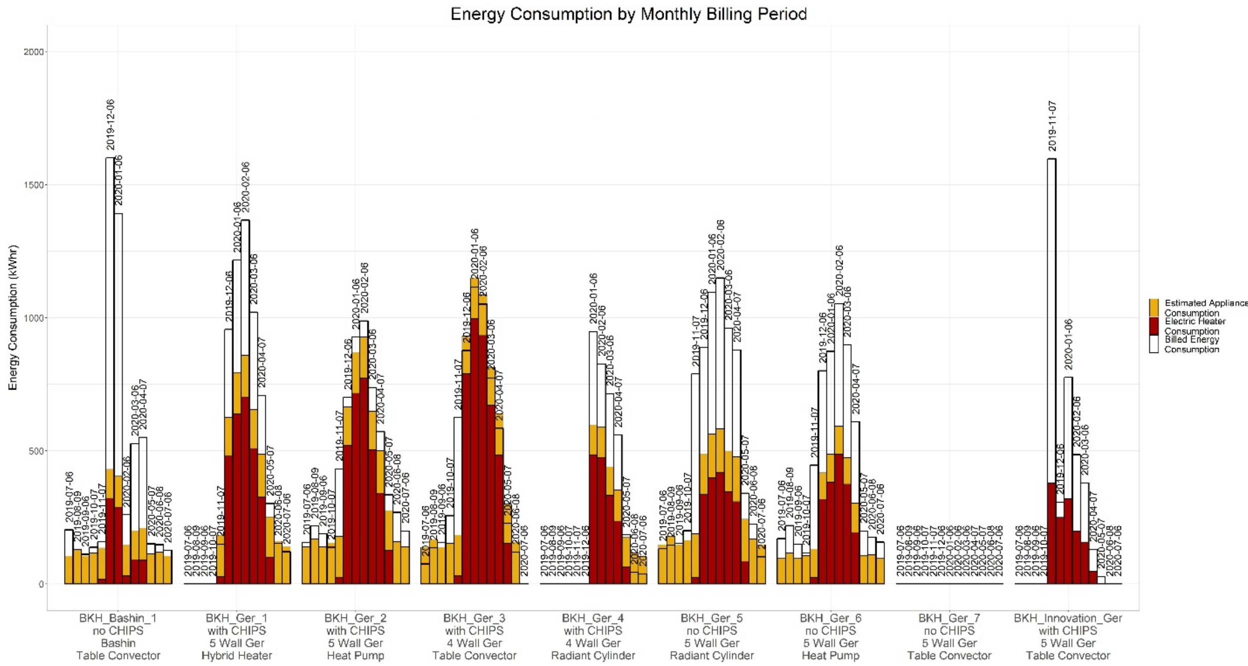

Figure 13. Total electric energy consumption by month, showing months with and without heater

Figure 13 shows the total electric consumption by month for the whole year from July 2019 to July 2020, which includes months when the heater was not used. The amounts of electricity billed in the non-heating months is very close to the estimated appliance use, but then grows larger in the winter months. This could indicate more intensive use of appliances or the introduction of additional appliances over the period.

It is also worth noting that that ger 7 stopped using the electric heater early in the program and the bashin started using a coal heater to supplement the electric heater as the winter got colder, because the electric heater was unable to keep it warm. These are both visible in Figure 13.

The general pattern of use indicates that the ger with CHIPS perform better than those without it, but to fully understand the performance, we have to account for the level of heating provided in each ger.

3.1.3 Heating Normalized to Temperature Difference

The purpose of an electric heater is to keep the inside warmer than the exterior, so the best performance measurement is the temperature difference maintained between inside and outside. The greater the temperature difference, the warmer the interior, the more effective the heater, and the better the envelope is at retaining the heat. For each ger we divide the electric energy consumed by the temperature difference to obtain a performance metric. These are shown for each ger in Appendix C: Normalized energy consumption per degree temperature difference. Figure 14 shows the heating per degree temperature difference by month.

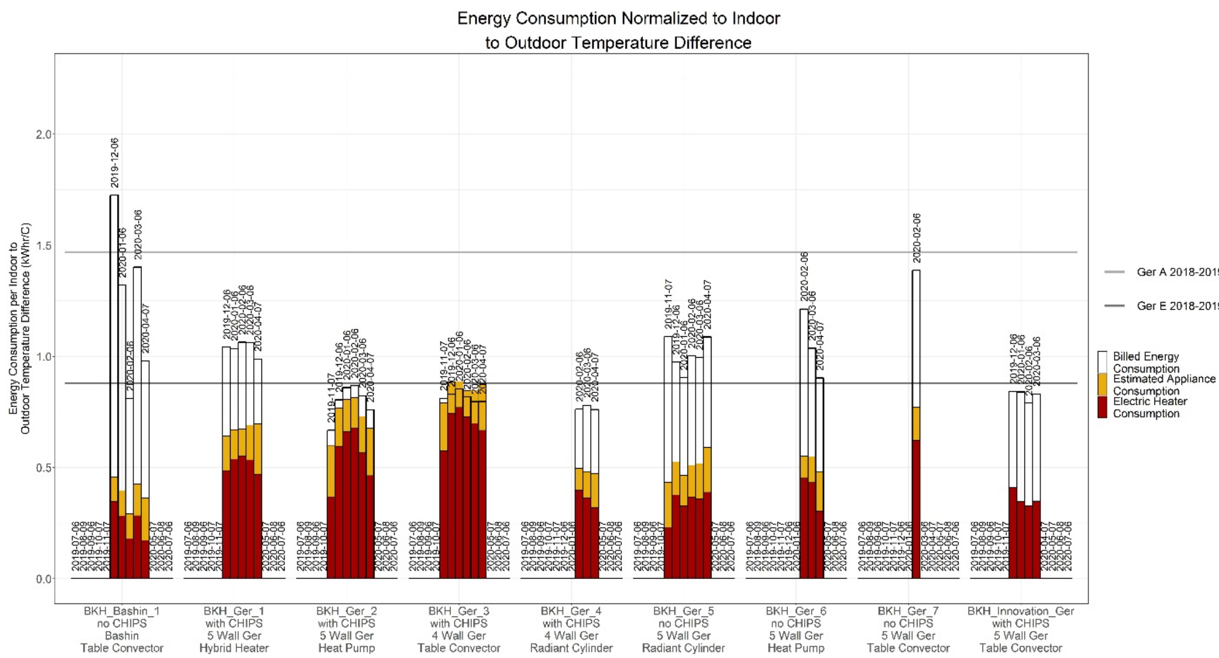

Figure 14. Monthly heating energy normalized to temperature difference

3.1.3. Heating Normalized to Temperature Difference and Area

However this still doesn't provide a true comparison between the different households because two of the ger (BKH Ger 3 and BKH Ger 4) are smaller than the others, so require less heat, and the bashin is larger, so would require more. To compensate for these differences, we divide the electricity per degree temperature difference by the floor area, giving the results shown in **Error! Reference source not found.**. Added to that chart are the average consumption for two of the test ger monitored in 2018-19. These were unoccupied ger, so did not have any appliances or interior activity such as opening and closing doors or toono, but they provide a valuable reference for the CHIPS program. Ger A was configured as a typical ger from the district around Ulaanbaatar, while ger E had almost all the improvements used in the CHIPS program. As the chart indicates, if we consider the total billed electricity, most of the nine pilot households fall in the range between the ger A and ger E, with BKH Ger 2 performing slightly better than ger E. If we consider the total of measured heater energy and estimate appliance consumption, the results are puzzling because the ger with CHIPS perform substantially better, so this would support the working hypothesis that either additional appliances or even an additional heater were used in these ger to keep them warm.

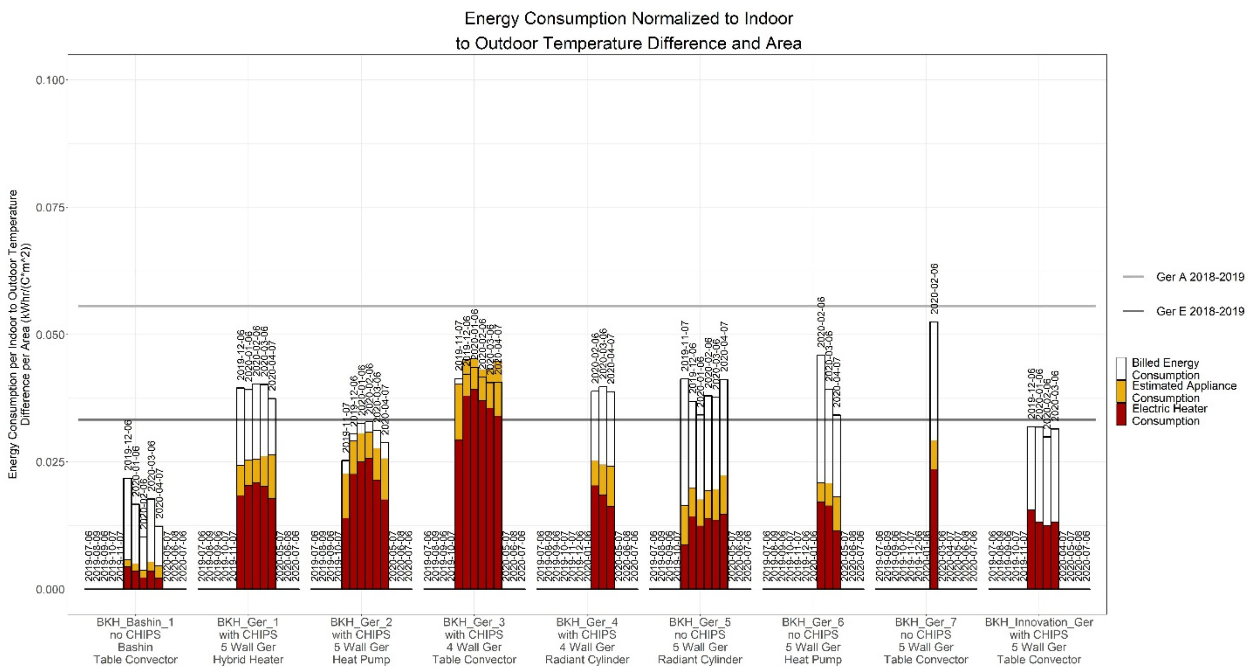

Figure 15. Monthly energy consumption per degree temperature difference and area

Even with the uncertainty, there are two general conclusions we can draw from the electric consumption. First, ger with CHIPS do perform better than those without CHIPS, and in the case of BKH Ger 2 actually outperform ger E, which is quite a feat for an occupied ger. Second, as one would expect the heat pump uses somewhat less electricity than the other heaters. The data is too noisy for a final conclusion, but this is consistent with their performance.

3.1.4. Heating Costs and Affordability

For the average ger occupant, heating costs are probably the most important measure of performance. According to data developed during the 2018-19 project, the daily cost for average ger in Ulaanbaatar is about ₮7,500 ($2.67) on wood, coal, and electricity, of which about ₮6,000 ($2.11) is for wood and coal. For a 6 month heating season, that average cost would total ₮1,400,000 ($480).

In the 2018-19 study, Ger A, the worst of the test ger, would cost about ₮1,703,400 ($600) to heat with electricity through the winter, while Ger E, the everything" ger, would cost about ₮922,675 ($325), so the cost of heating Ger E with electricity would cost much less than the average total cost of wood, coal, and electricity, while Ger A would cost somewhat more. Figure 16 shows the average daily cost of electricity for the heater and appliances the nine pilot households. However, as mentioned previously, the bashin was using a coal stove for supplemental heating, so that number is not representative of the total heating cost. Additionally, data for energy consumption from ger 4 was only available from December 7, 2019 to April 7, 2020, and data for energy consumption for ger 7 was only available for January 9, 2020 to January 28, 2020. Therefore, these estimates are heavily weighted to colder parts of the winter, and their actual heating costs may be lower. That being said, with the exception of Ger 7, the heating costs of all of the pilot households was well below the expenditures of a typical ger household on coal, wood, and electricity. Perhaps even more surprisingly, they were all lower than the ger E, the best of the unoccupied ger from the 2018-2019 winter. This leads to the conclusion that it should be possible to cost effectively heat ger with an electric heater.

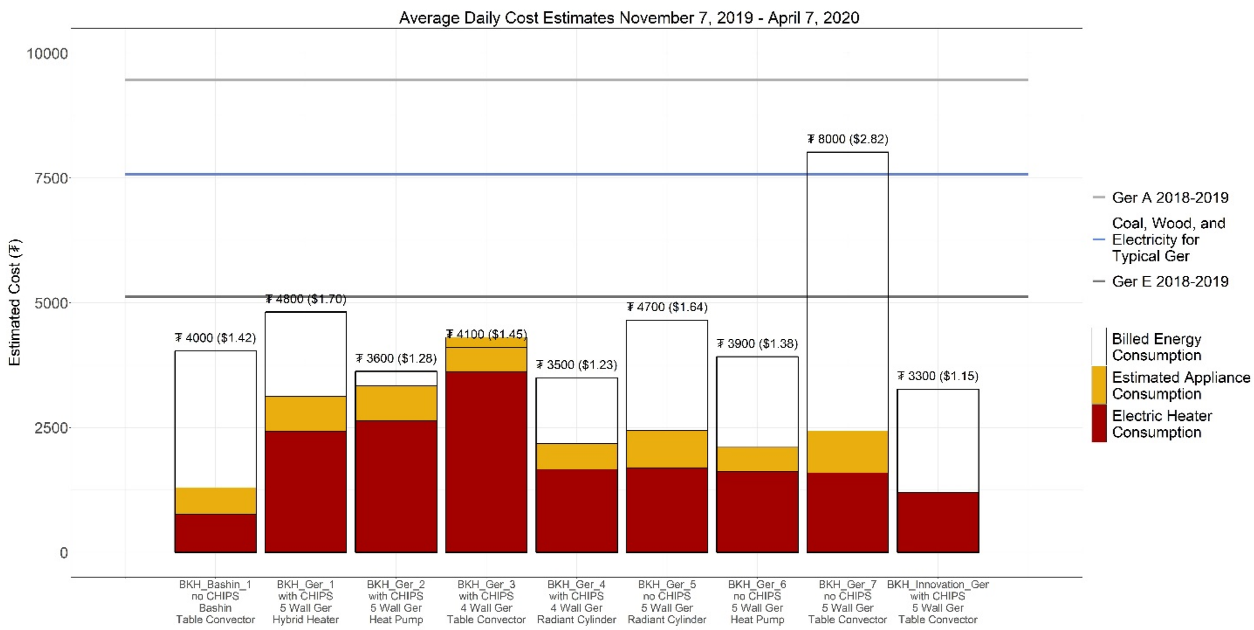

Figure 16. Average daily heating costs for nine pilot households

3.2 Occupant Comfort

The second criteria for the success of CHIPS are the levels of comfort they provide, which are determined by evaluating the temperatures through the day. Figure 17 shows the average daily temperature variances for the 9 pilot households, all of which were heated with electricity, and the average of the five occupied ger from the 2018-19 study, which wer heated with coal. The temperature variance of the coal heated ger is immediately visible with the wide temperature swings following the usage of the coal stove, which is fired in the morning and later in the day, and then the ger cools overnight. As a basic conclusion, the use of the electric heater provides a more consistent and generally comfortable interior temperature.

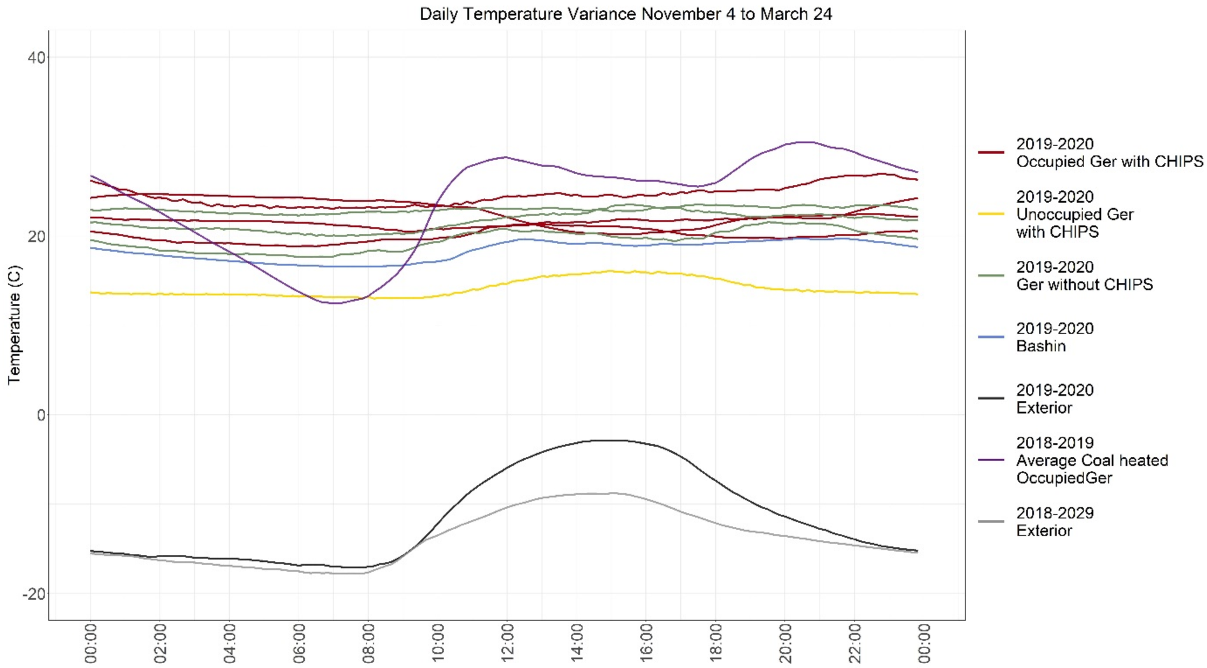

Figure 17: Daily Temperature Variance for CHIPS Pilot Households

The temperature plots of the different ger are also slightly different, depending on how effectively insulated they are and how many other appliances are being used. As a general rule, the ger with CHIPS are notably warmer. The most visible contrast is the consistently lower temperature of the unoccupied Innovation ger, which has no occupants or additional appliance use, so it represents the average temperatures that could be achieved by the heater alone. It is worth observing that the daytime temperatures in Ulaanbaatar were slightly cooler than Bayankhongor, though the nighttime temperatures are similar.

Figure 18 shows the temperature variations in the 9 pilot households over the heating season, which shows the same distinctions among the ger, with the unoccupied ger running at a much cooler temperature as does the bashin. Different periods of occupancy are also visible.

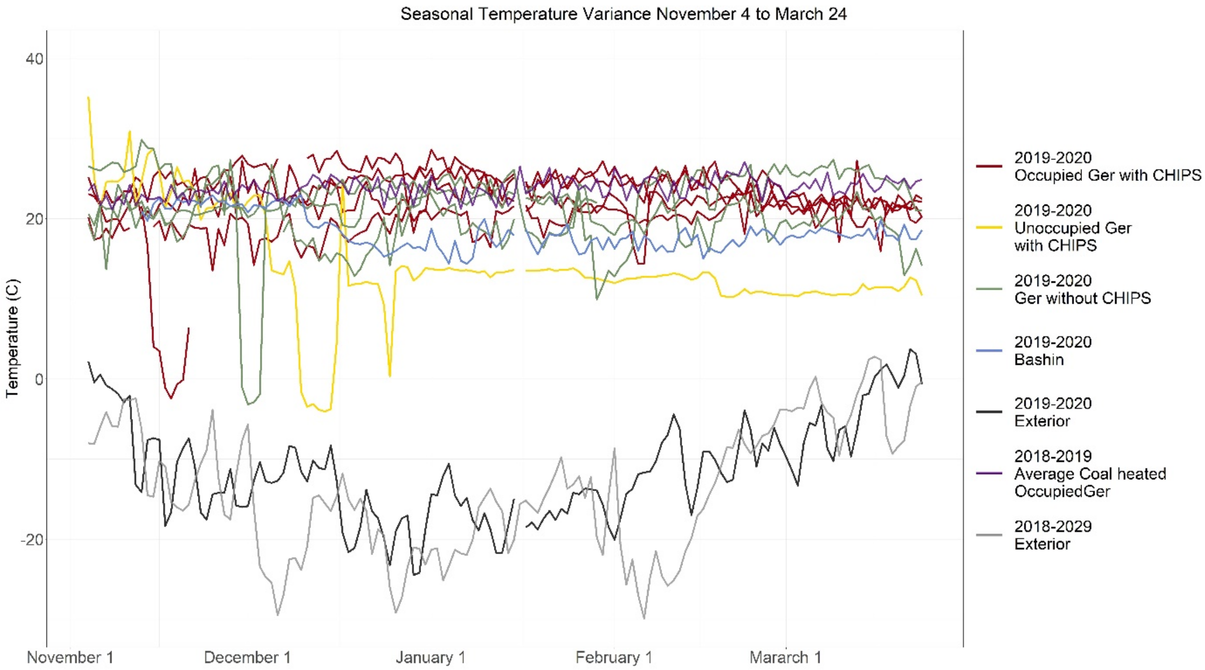

Figure 18: Seasonal Temperature Variance for CHIPS Pilot Households

Average variance of all the temperature data is available in Appendix D: Average daily temperature variances. It shows the full range of temperatures experienced by the ger residents, from the air temperature and the globe thermometer temperature to the temperature of the walls and roof (envelope) and of the ground below the floor. The globe thermometer temperature is the warmest closely followed by air temperature (except in the innovation center ger, where the interior temperature is warmer than the globe thermometer temperature), while the envelope is cooler and follows the exterior temperature, and the ground temperature is even colder, but very stable. The globe thermometer temperature provides the best approximation of the temperatures experienced by the occupants, combining air and radiant temperatures. The consistently high globe thermometer temperatures suggest that the pilot households provided a high degree of thermal comfort.

3.3. Indoor Air Quality & Infiltration Rates

Urban air pollution was a key concern for this project, and we sought to understand the impact that CHIPS have on indoor air quality. PM 2.5 concentrations in the ger district are largely driven by the burning of coal for domestic heating, but it was not clear whether the PM 2.5 in the ger came from inside or outside, or both. This study demonstrates that indoor concentration of PM 2.5 closely follows the pattern of outdoor pollution with a modest time lag depending on the air-sealing of the ger. This lag also provides an empirical measure of the improved air-sealing of the CHIPS ger.

Because exterior temperatures change daily and seasonally, fuel combustion also varies on those cycles, and seasonal and daily patterns can be observed in indoor and outdoor air quality data. To investigate the correlation between the indoor and outdoor patterns of pollution, seasonal and daily variances were determined for PM 2.5 and CO_2. Seasonal variances show the change over time in the daily PM 2.5 or CO_2 concentration. Daily variances show the hourly change over the course of an "average day." This yields a descriptive set of data that can be used to understand characteristic patterns.

Graphs of the seasonal CO_2 and PM 2.5 variances are shown in Figure 19 and Figure 20 which reveal the increase of PM2.5 as temperatures get cooler and more coal is burned in the area. The CO_2 concentrations show little seasonal variation and seem mostly determined by occupancy, as suggested by the close alignment of levels of CO_2 in the unoccupied Innovation ger with the exterior levels.

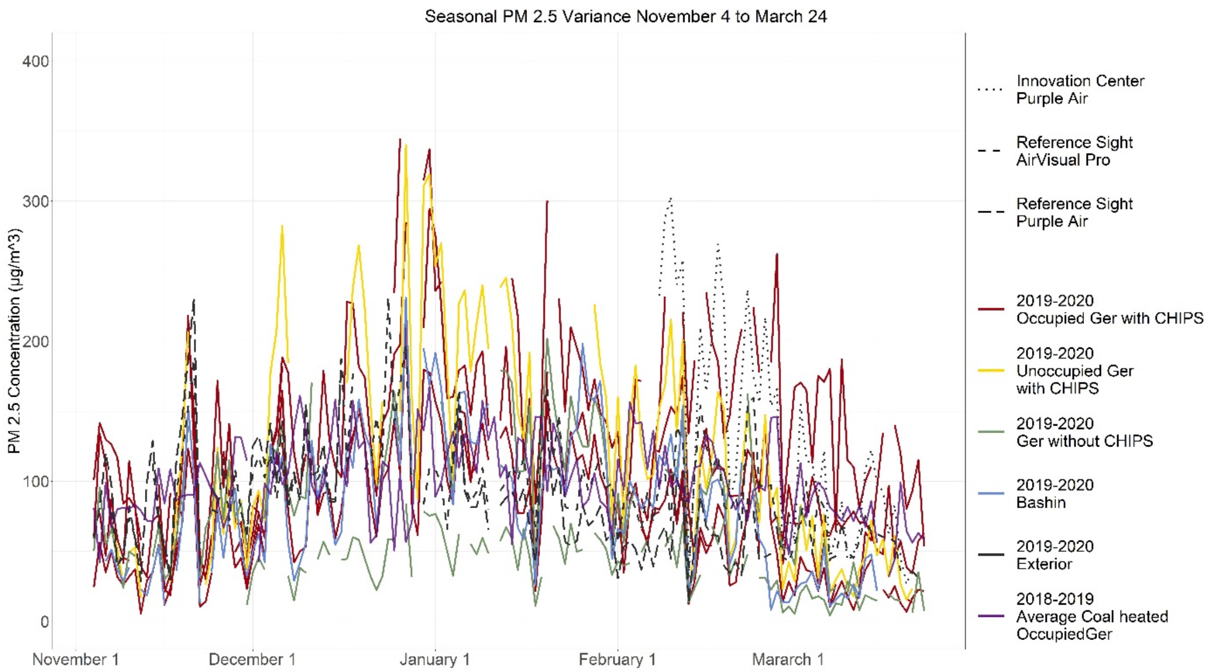

Figure 19: Seasonal PM 2.5 Concentration Variance for CHIPS Pilot Households

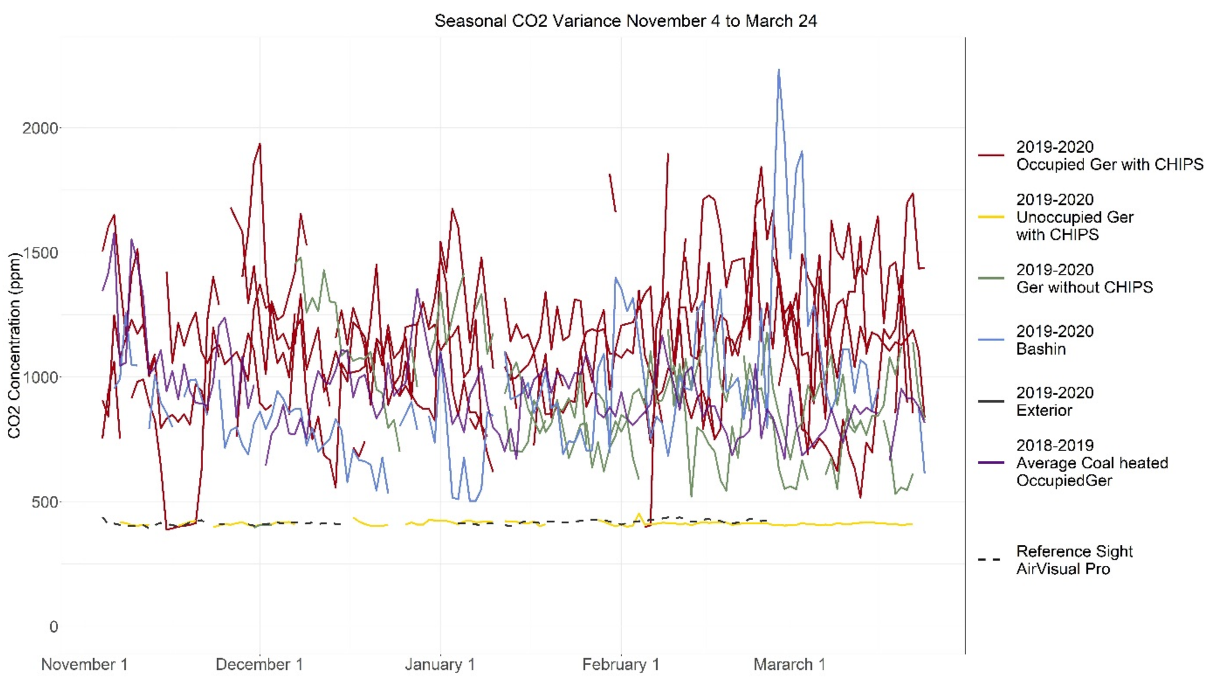

Figure 20: Seasonal CO_2 Concentration Variance for CHIPS Pilot Households

It is worth noting that the daily average indoor and outdoor PM 2.5 concentrations are frequently above the WHO's 24-hour recommended level of 25 µg/m^3 and the US EPA's 35 µg/m^3 (Air Quality 2018). Table 2 summarizes the percent of days above each of these thresholds. While there is some uncertainty about the accuracy of low-cost air quality monitors used for this study, the extremely high daily average concentrations of PM 2.5 and the high percentage of days with unhealthy air quality indicate that the winter 2019-2020 air quality in Bayankhongor was very unhealthy. This result agrees with the findings of previous studies observing poor indoor air quality in ger as well as poor outdoor air quality in Mongolia.

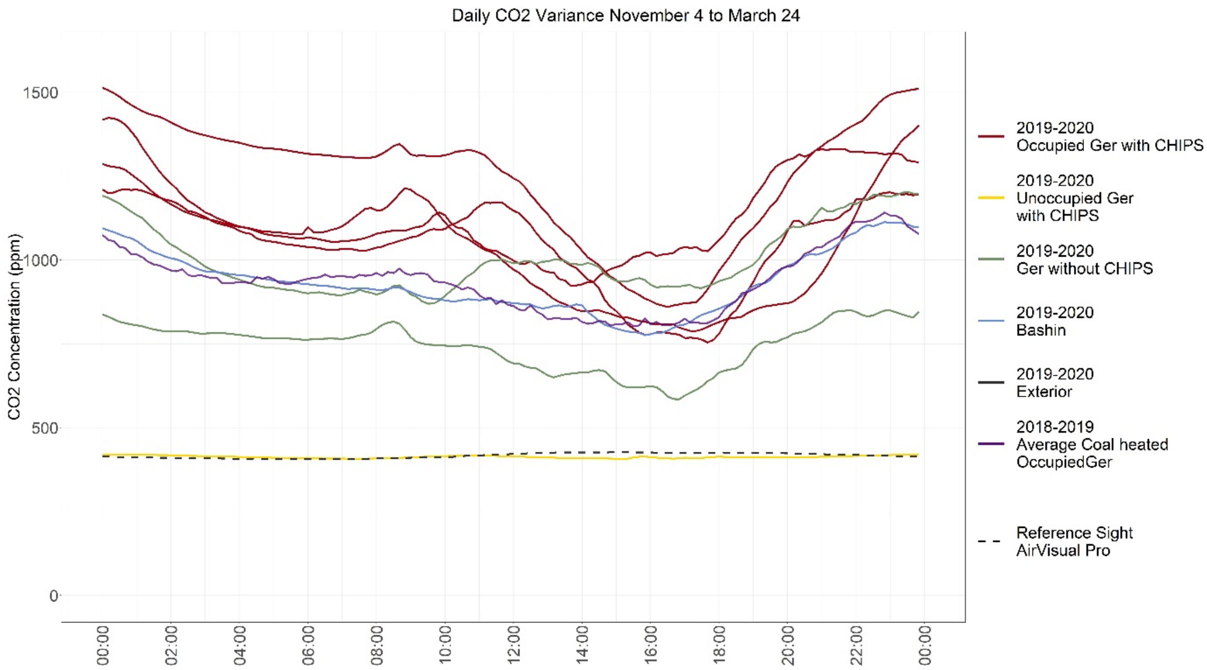

Figure 21: Daily CO_2 Concentration Variance for CHIPS Pilot Households

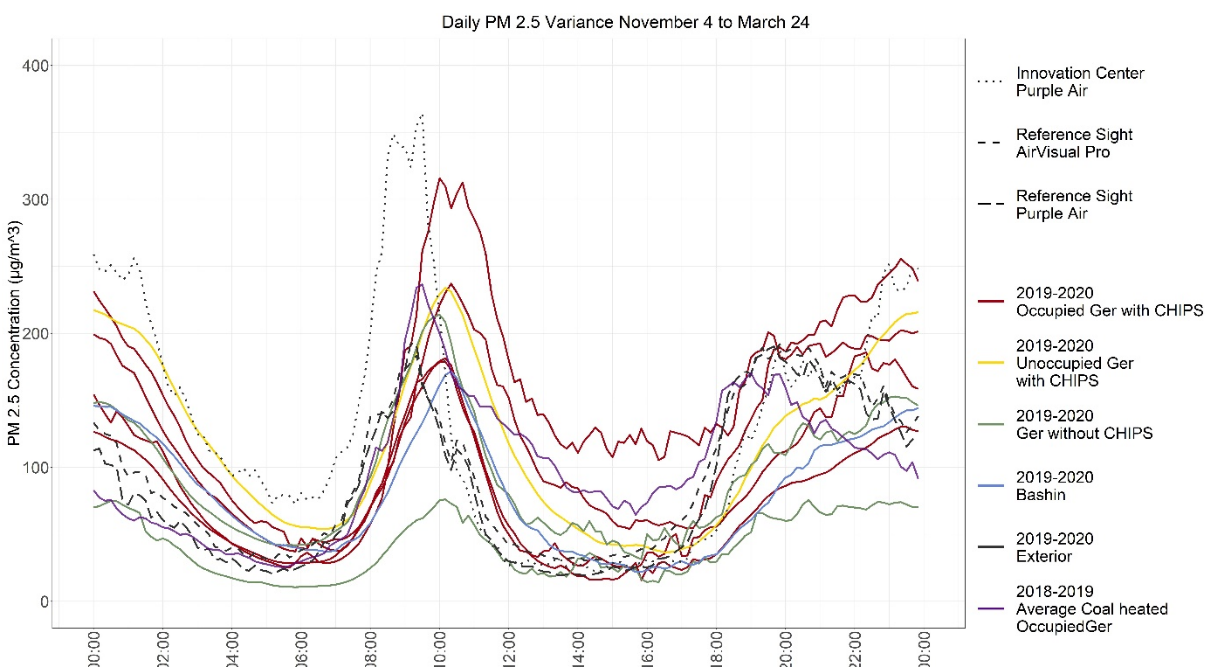

Figure 22: Daily PM 2.5 Concentration Variance for CHIPS Pilot Households

With this data it is not possible to decisively separate the effect of cooking inside the ger from the infiltration of outdoor air, since we have no way to determine when meals are prepared inside. We can assume that the pattern of cooking is similar to that in the many other ger burning coal that produce the outdoor spikes in PM2.5, with the peak of indoor cooking occurring well before the indoor peak in pollutants. But in any case, the indoor generation of pollutants is outweighed by the infiltration of pollutants from the outside. Since the cooking in the CHIPS ger uses electricity, we should be able to detect the patterns of cooking with the more detailed electric monitoring package we propose for 2020-21.

The most important result is that the indoor and outdoor PM 2.5 concentrations follow a remarkably similar pattern, as demonstrated in Figure 22. PM 2.5 concentrations spike during the morning (8 to 11 am) and during the evening (around 6 pm), with lower concentrations during the afternoon and night. This is consistent with the typical firing cycles of coal stoves in the ger district, indicating that PM 2.5 concentrations are largely driven by residential combustion of coal. The evidence that the indoor concentrations come from outdoor air can be seen in the daily PM 2.5 variance in the innovation center ger (the yellow line in Figure 22). The innovation center ger was, for the most part unoccupied and heated by an electric heater. There should be no indoor PM 2.5 generation in the innovation center ger, but not only is the PM 2.5 concentration in the innovation center ger quite high, but it closely follows the trend of the other pilot households and the exterior PM 2.5 concentrations. This indicates that the primary driver of indoor PM 2.5 is outdoor PM 2.5.

Table 2: Percent of Days that CHIPS Pilot Households have Unhealthy PM 2.5 concentrations

Measurement Location	Number of Days with Observed PM 2.5 Concentration (out of 142)	Percent of Days with PM 2.5 Concentration > the WHO recommended 24-hour average of 25 μg/m³	Percent of Days with PM 2.5 Concentration > the US EPA recommended 24-hour average of 35 μg/m³
Bashin, AirVisual Pro	126	87%	81%
Ger 1, AirVisual Pro	131	100%	98%
Ger 2, AirVisual Pro	135	82%	73%
Ger 3, AirVisual Pro	71	92%	85%
Ger 4, AirVisual Pro	90	98%	94%
Ger 5, AirVisual Pro	97	72%	57%
Ger 6, AirVisual Pro	96	95%	89%
Ger 7, AirVisual Pro	0	-	-
Innovation Center Ge, AirVisual Pro r	114	93%	85%
Reference Site, PurpleAir PA-II	132	100%	98%
Reference Site, AirVisual Pro	93	99%	94%
Innovation Center Exterior, PurpleAir PA-II	45	100%	98%

As noted, the CO_2 concentration in the unoccupied innovation center ger tracks very closely to the exterior CO_2 concentration, but the remaining 8 pilot households show fluctuating CO_2 concentrations well above the outdoor concentration. These CO_2 concentrations are often between 500 and 2,500 ppm, which exceeds the generally recommended levels. While decreases in concentration and decision making ability have been shown in people exposed to CO_2 concentrations between 2,000 and 5,000 ppm, CO_2 is not typically dangerous below 20,000 ppm (Satish et al., 2012). Although the elevated concentrations of CO_2 observed in the CHIPS pilot households are higher than we would like, they do not pose as much of a health risk as the concentrations of PM 2.5. CO_2 concentrations are typically reduced by increasing ventilation with outdoor air.

Air Infiltration. CO_2 measurements are commonly used as a proxy measurement for human occupancy and air exchange rates. Indoor CO_2 concentrations are mostly driven by occupancy behaviors, such as human respiration or cooking. For example, daily CO_2 concentration in the occupied pilot households show lower CO_2 concentrations during the afternoon and elevated levels during the evening to late morning. More importantly for this study, the households with CHIPS (ger 1-4) have higher indoor CO_2 concentrations than the ger without CHIPS (*ger* 5 & 6) or the bashin. This elevated level suggests that there is either higher CO_2 generation in these households or that less of the CO_2 is able to escape, so it accumulates to a higher level. The higher levels in ger with CHIPS indicates that they have lower rates of air infiltration (outside air entering the ger through cracks and pours in the walls, door, etc.).

Further evidence of lower air infiltration rates in CHIPS ger can be seen in the daily PM 2.5 concentration variance in Figure 22. The morning peaks of indoor PM 2.5 concentration occur shortly after the morning peaks of outdoor PM 2.5 concentration. The mechanism by which the outdoor air with a higher PM 2.5 concentration enters the ger is called infiltration, but the process is not instantaneous. A better sealed ger, will have a longer delay between the indoor and outdoor peaks. To generalize this a bit, the indoor and outdoor PM 2.5 concentrations can be mathematically described as wave function that has a characteristic one-day time scale. If the outdoor PM 2.5 concentration is driving the indoor PM 2.5 concentration, then the indoor concentration should be able to be modeled as a function of the outdoor concentration and a time delay. That time delay or lag is a measure of how out of phase the two waves are from each other. A statistical method for estimating how well one set of time series data can be used to predict another set of time series data is a cross correlation function, which measures how well one set of time series data can be used to predict another set of time series data at different lag times.

Cross correlations were conducted between the indoor PM 2.5 concentrations in each of the pilot households and the outdoor PM 2.5 concentration measured by the PurpleAir PA-II outside of the innovation center. The concentration at the innovation center was selected because it is most representative of the outdoor air in the immediate vicinity of the CHIPS pilot households. Data from this sensor is available from February 8, 2020 to March 22, 2020, though there were some gaps in the data from the AirVisual Pros inside the CHIPS Households. Cross correlations require complete time series data with no gaps. The indoor and outdoor PM 2.5 concentration data tends to be rather continuous with few dramatic short time scale variations, so for short gaps under 4 hours, linear interpolations were done to impute the missing data. Then, cross correlations were conducted between the indoor and outdoor PM 2.5 concentrations for all available periods of data.

Complete graphs of the cross-correlation functions are shown in Appendix E: Cross correlations for PM 2.5 Concentrations and a summary of the optimal cross correlation and lag time are shown in Table 3: Cross Correlations and Optimal Lags for CHIPS Pilot Households Interior PM 2.5 Concentration to Outdoor PM 2.5 Concentration (above). The negative values of the optimal time lag of the cross correlation simply indicate that the outdoor PM 2.5 concentration spikes before the indoor PM 2.5 concentration. A couple of valuable conclusions can be drawn from these results. Firstly, the cross-correlation values observed for the pilot households are all statistically significant. This implies that while there may be other factors influencing the indoor PM 2.5 concentrations, the outdoor PM 2.5 concentration is a significant driver. Second, the innovation center ger has the highest cross correlation value of the CHIPS pilot households. This can probably be explained by the fact that it has no interior PM 2.5 generation, so the indoor PM 2.5 can only come from outside. The value of the correlation is enhanced by the fact that the PM 2.5 concentration measured by the PurpleAir PA-II is located right outside of the innovation center.

Table 3: Cross Correlations and Optimal Lags for CHIPS Pilot Households Interior PM 2.5 Concentration to Outdoor PM 2.5 Concentration

Household	Has CHIPS	Size (Walls)	Dates	Optimal Lag (minutes)	Cross Correlation
Bashin	n/a	n/a	2/8/2020 - 3/17/2020	**50**	0.684
Ger 4	yes	4	2/12/2020 - 3/15/2020	**50**	0.293
Innovation Center Ger	yes	5	2/8/2020 - 3/22/2020	**50**	0.852
Ger 1	yes	5	2/8/2020 - 3/22/2020	**40**	0.535
Ger 2	yes	5	2/8/2020 - 3/22/2020	**30**	0.587
Ger 3	yes	4	2/27/2020 - 3/22/2020	**30**	0.281
Ger 5	no	5	2/8/2020 - 2/15/2020	**20**	0.693
Ger 5	no	5	2/25/2020 - 3/20/2020	**20**	0.251
Ger 6	no	5	2/9/2020 -3/4/2020	**10**	0.63

The critical observation for this study is that the ger with CHIPS have longer lag times between outdoor and indoor concentration than the ger without CHIPS. The ger with CHIPS have time lags of 50 to 30 minutes, while those without CHIPS have lags of 30 to 10 minutes. These agree closely with the measured infiltration rates of the test ger in 2018-19, which had air change rates of 0.5 to 1.8 total air changes per hour (a complete air change replaces all the indoor air with outdoor air, at which point it would have the same PM 2.5 concentration as the outside). This indicates that the CHIPS improved the air tightness of ger and decreased the air infiltration rate, which reduces energy consumption and makes the ger warmer.

4. Conclusions

This project took insights from the 2018-2019 "Ger for the 21st Century" project and used them to develop a comprehensive "Cooking, Heating, and Insulation Product System" (CHIPS) for Mongolian ger. CHIPS were applied to nearly 200 ger in Bayankhongor, while a selection of nine pilot households were more intensively monitored and studied: 4 occupied ger with CHIPS, 3 occupied without CHIPS, 1 stick-built bashin, and an unoccupied ger with CHIPS. For the CHIPS program there are three general aspects of performance to evaluate: energy consumption and costs, thermal comfort, and indoor air quality.

Energy consumption and costs. There are three valuable observations we can make about the energy performance of the nine pilot households. First, ger with CHIPS performed better than those without CHIPS, and in the case of BKH Ger 2, it actually outperformed ger E, the best ger from the 2018-19 study, which is quite a feat for an occupied ger. Second, as one would expect, the ger with heat pumps use somewhat less electricity than the those with other heaters. The data is too noisy for a final conclusion about heater choice, but this observation is consistent with heat pump performance. Third, all but one of the ger in this study cost less to operate with electricity than the average ger usually spends on wood, coal, and electricity.

Thermal comfort. The second criteria for the success of CHIPS are the levels of comfort they provide. The use of the electric heater provides a more consistent and generally comfortable interior temperature than experienced in her heated with coal stoves. The warmth of the ger is related to the levels of insulation, with the CHIPS ger maintaining higher air and wall temperatures.

Indoor air quality. Urban air pollution was a key concern for this project and we sought to understand the impact that CHIPS have on indoor air quality. PM 2.5 concentrations in the ger district are largely driven by the burning of coal for domestic heating, but it was not clear whether the PM 2.5 in the ger came from inside or outside, or both. This study demonstrates that indoor concentration of PM 2.5 closely follows the pattern of outdoor pollution with a modest time lag depending on the air-sealing of the ger. In other words, the use of electric heaters does not reduce indoor concentrations of PM 2.5. The measurements of indoor air quality also demonstrated that the CHIPS ger were more tightly sealed, reducing rates of air infiltration, which contributed to greater energy efficiency and lower cost.

In summary, CHIPS successfully reduces energy consumption, heating ger through a Mongolian winter at similar or lower cost than typically expended on wood, coal, and electricity. The CHIPS construction also reduces air infiltration and increases thermal comfort. The surprising result of the study was the CHIPS did not reduce indoor concentration of PM 2.5, which is almost entirely determined by the levels of outdoor pollution.

Team and Sponsors

The project was funded by UNICEF with resources and in-kind contributions from the Center for Environmental Design + Planning (CEBD).

The research team included a diverse mix of experts.

At the CEBD at the University of Pennsylvania, Professor William W. Braham served as Co-PI with Max Hakkarainen leading the monitoring, data collection, and analysis.

At the McKelvey School of Engineering at Washington University in St. Louis, Professor Jay Turner led a parallel project to monitor and analyze air pollution in the area, in the CHIPS ger, and in kindergartens operated by UNICEF. Zhiyao Li organized the monitoring, data collection, and data analysis.

At the Mongolia University of Science and Technology Professor Munkhbayar Buyan, Director of Building Energy Efficiency Center, served as Co-PI and developed the CHIPS modifications and coordinated the data collection. Mrs. Tseetuya, Manager of Innovation center oversaw data collection.

At UNICEF Mongolia, the project was overseen by Alex Heikens and managed by Sunder Erdenekhuyag and Altantsetseg Sodnomtseren.

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Appendix A: CHIPS pilot households

Figure 23. BKH Bashin 1 Exterior

Figure 24. BKH Bashin 1 Interior

Figure 25. BKH Ger 1 Exterior

Figure 26. BKH Ger 1 Interior

Figure 27. BKH Ger 2 Exterior

Figure 28. BKH Ger 2 Interior

Figure 29. BKH Ger 3 Exterior

Figure 30. BKH Ger 3 Interior

Figure 31. BKH Ger 4 Exterior

Figure 32. BKH Ger 4 Interior

Figure 33. BKH Ger 5 Exterior

Figure 34. BKH Ger 5 Interior

Figure 35. BKH Ger 6 Exterior

Figure 36. BKH Ger 6 Interior

Figure 37. BKH Ger 7 Exterior

Figure 38. BKH Ger 7 Interior

Figure 39. BKH - Innovation Ger Exterior

Figure 40. BKH - Innovation Ger Interior

Appendix B: Daily energy consumption

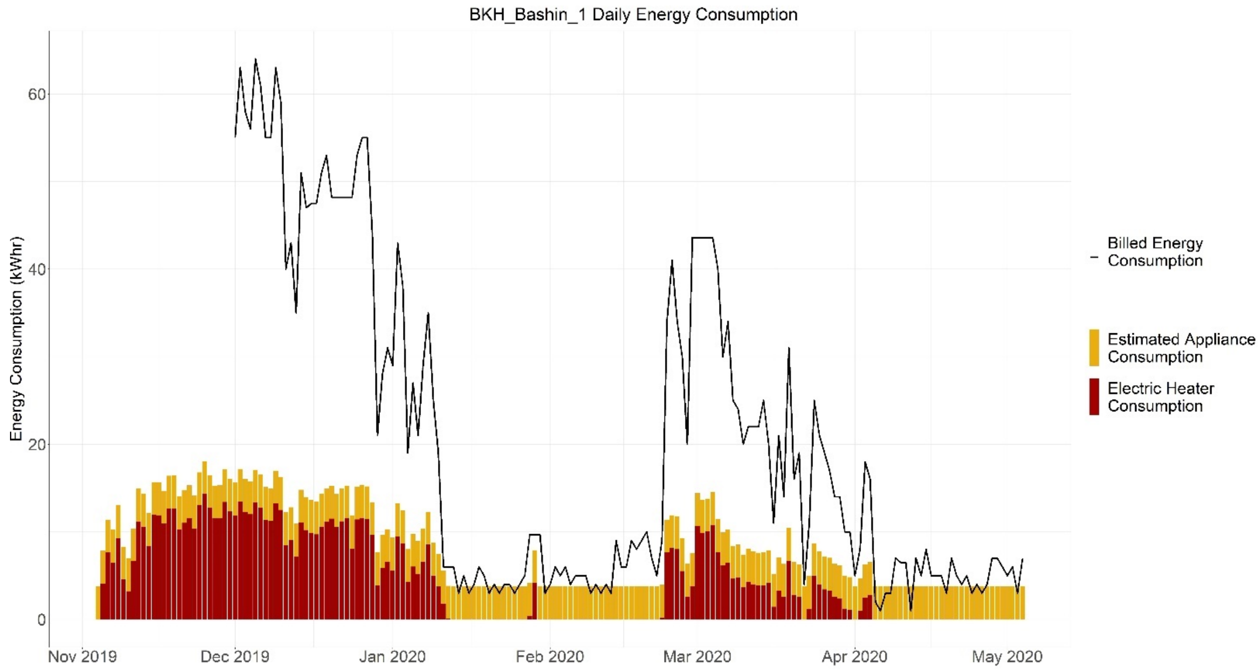

Figure 41. BKH Bashin 1: Daily Energy Consumption

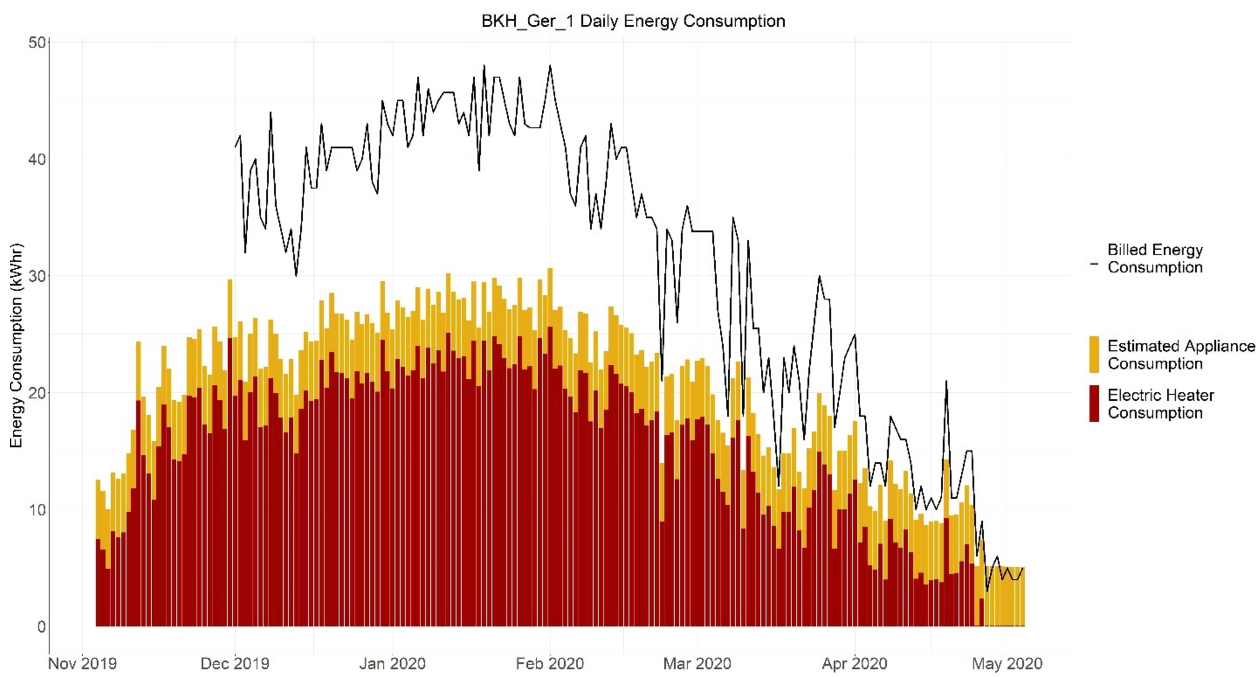

Figure 42. BKH Ger 1: Daily Energy Consumption

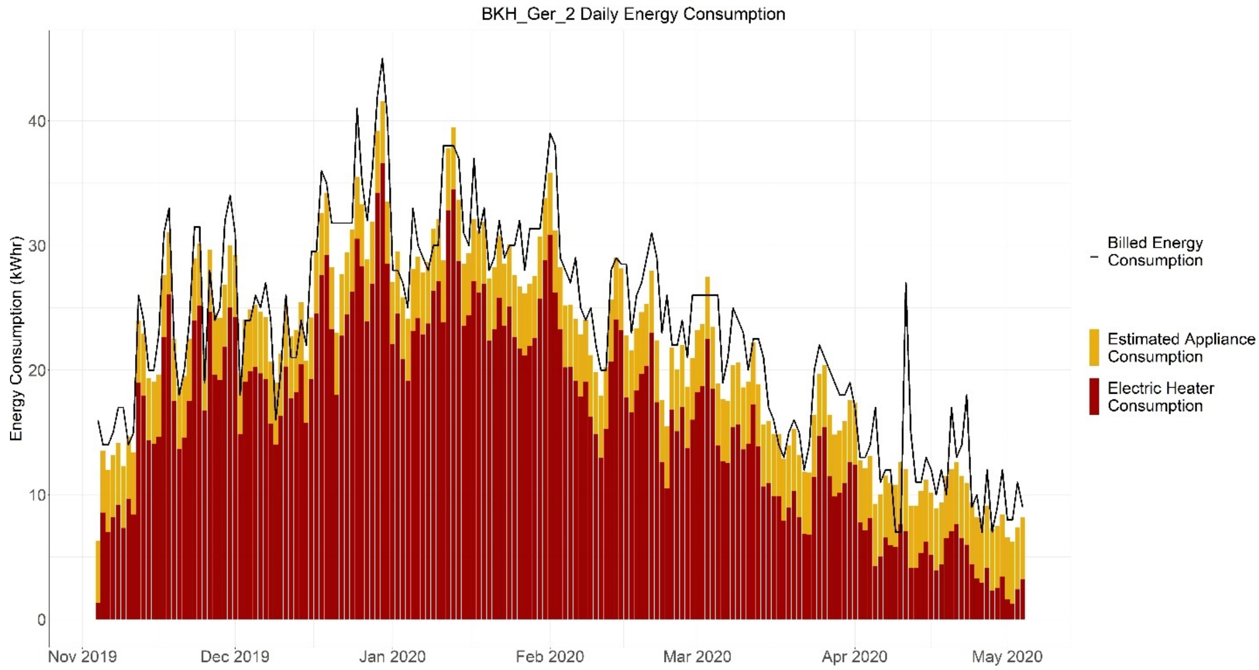

Figure 43. BKH Ger 2: Daily Energy Consumption

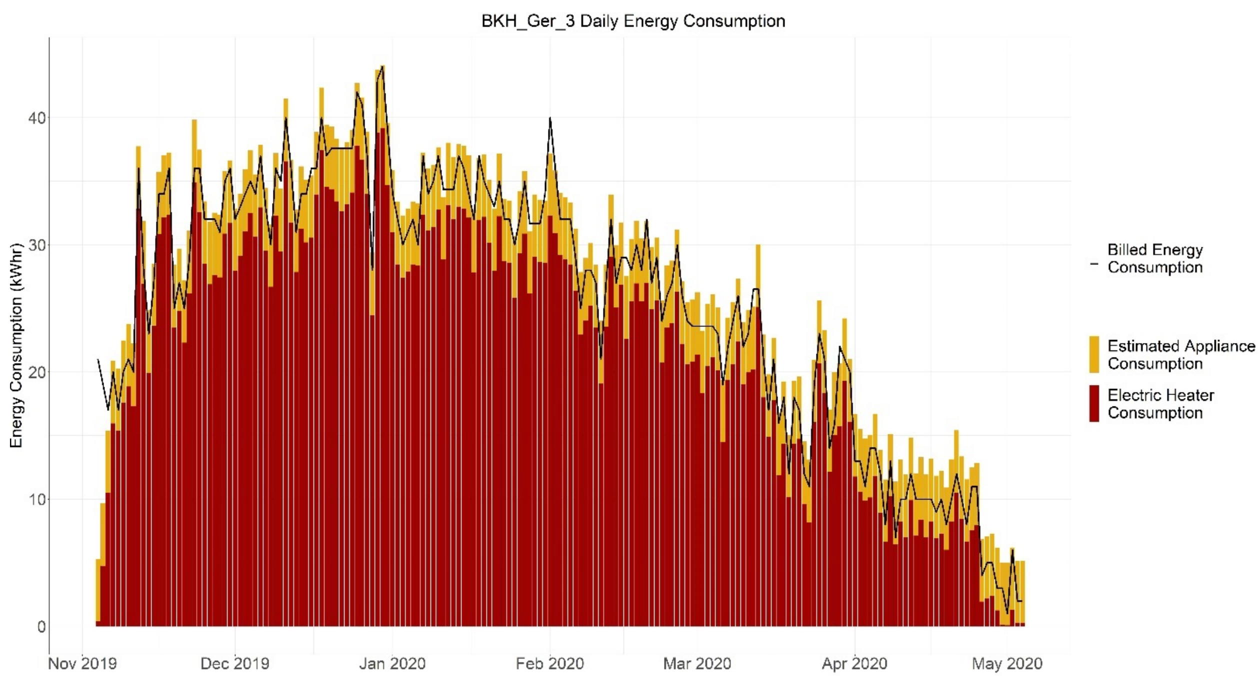

Figure 44. BKH Ger 3: Daily Energy Consumption

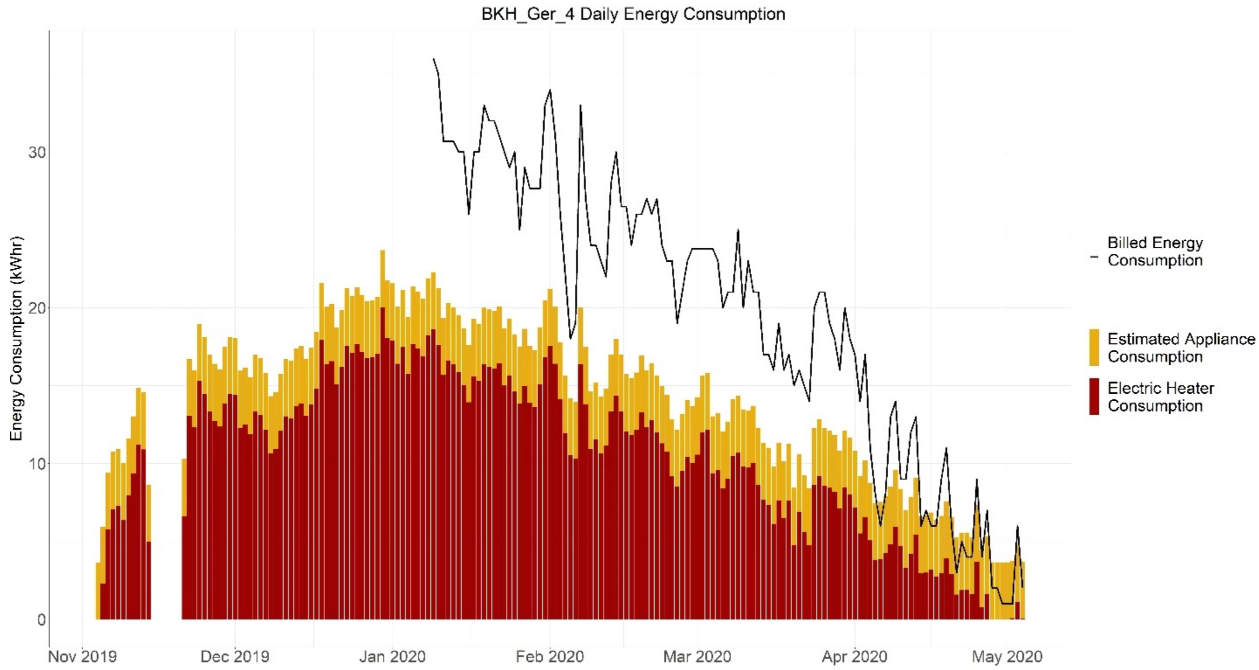

Figure 45. BKH Ger 4: Daily Energy Consumption

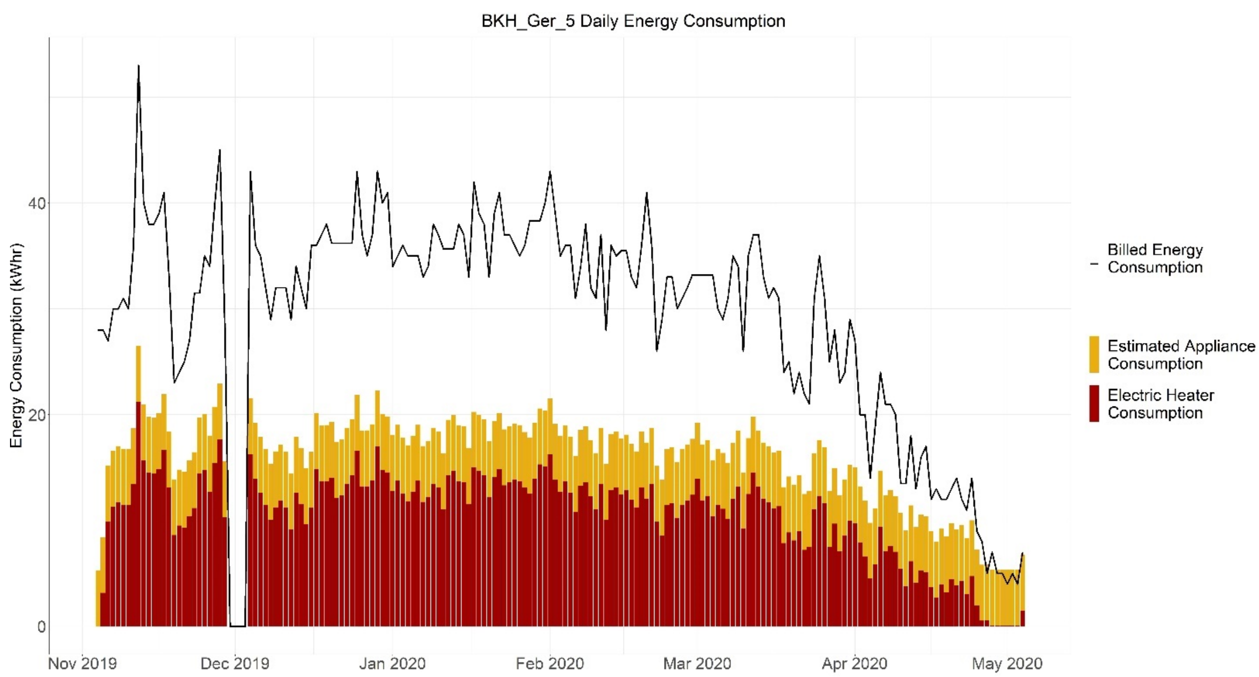

Figure 46. BKH Ger 5: Daily Energy Consumption

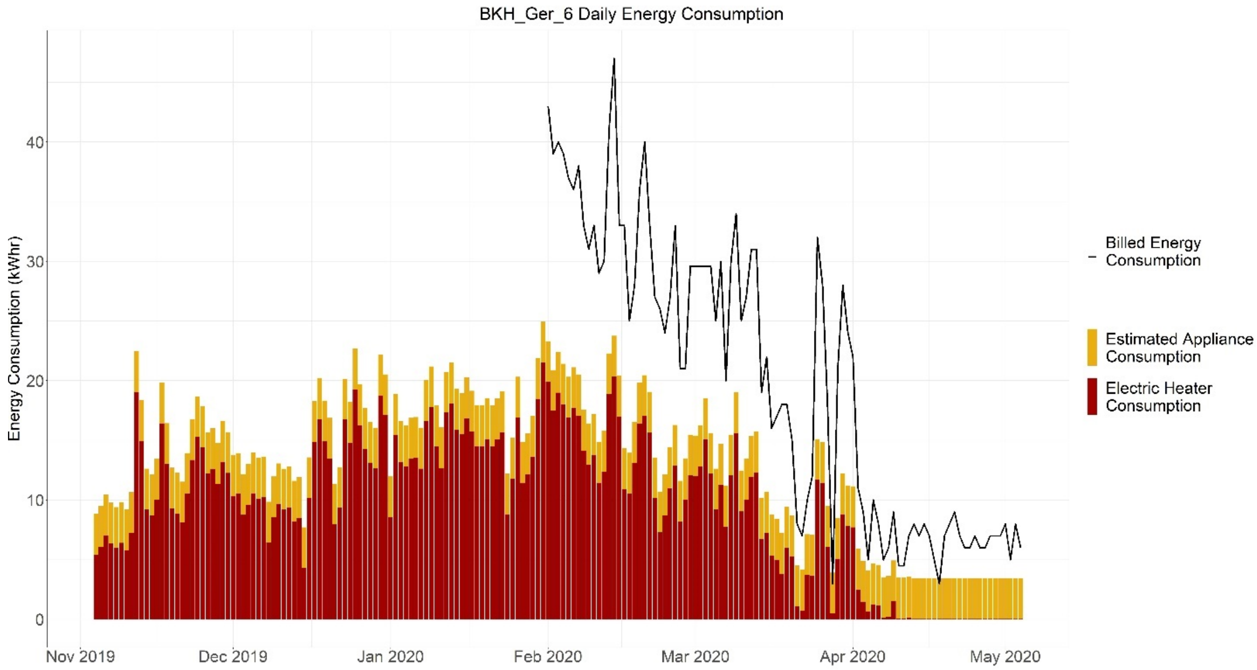

Figure 47. BKH Ger 6: Daily Energy Consumption

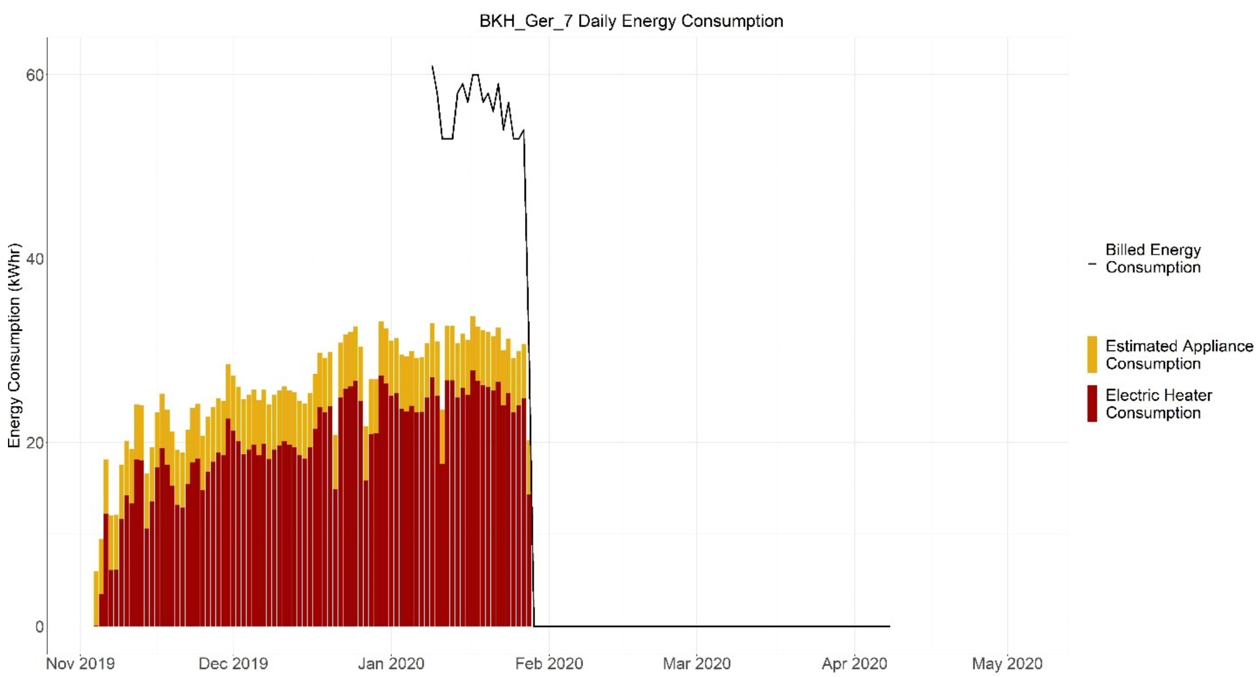

Figure 48. BKH Ger 7: Daily Energy Consumption

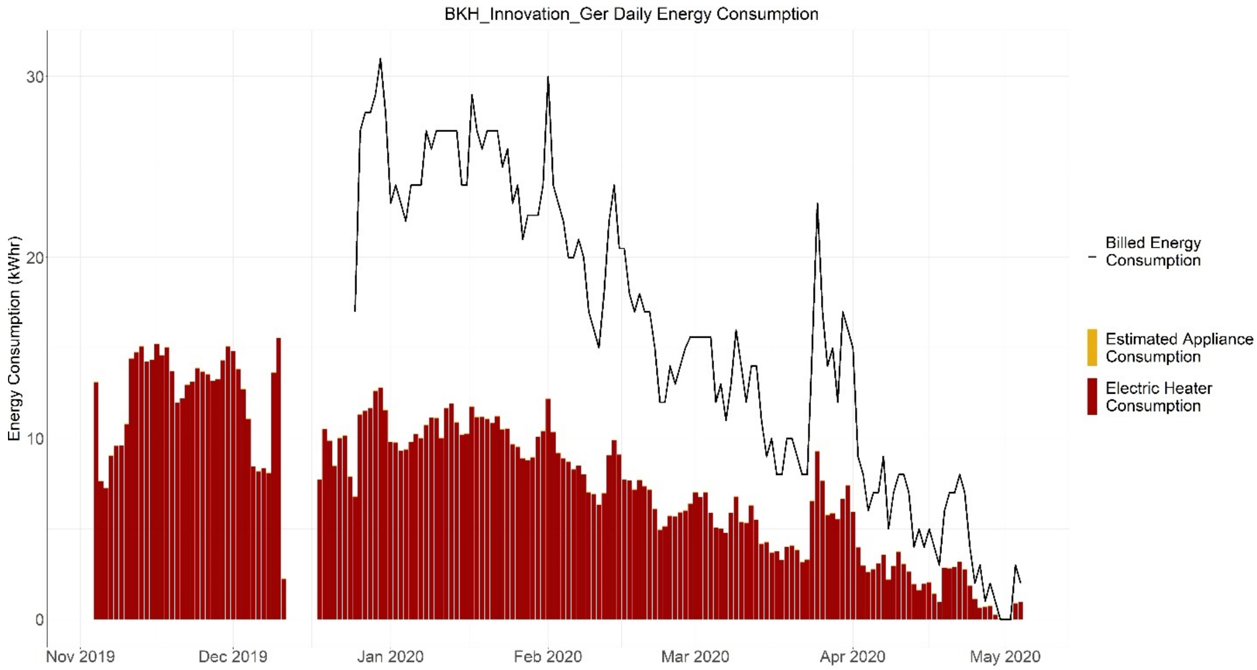

Figure 49. BKH Innovation Ger: Daily Energy Consumption

Appendix C: Normalized energy consumption per degree temperature difference and area

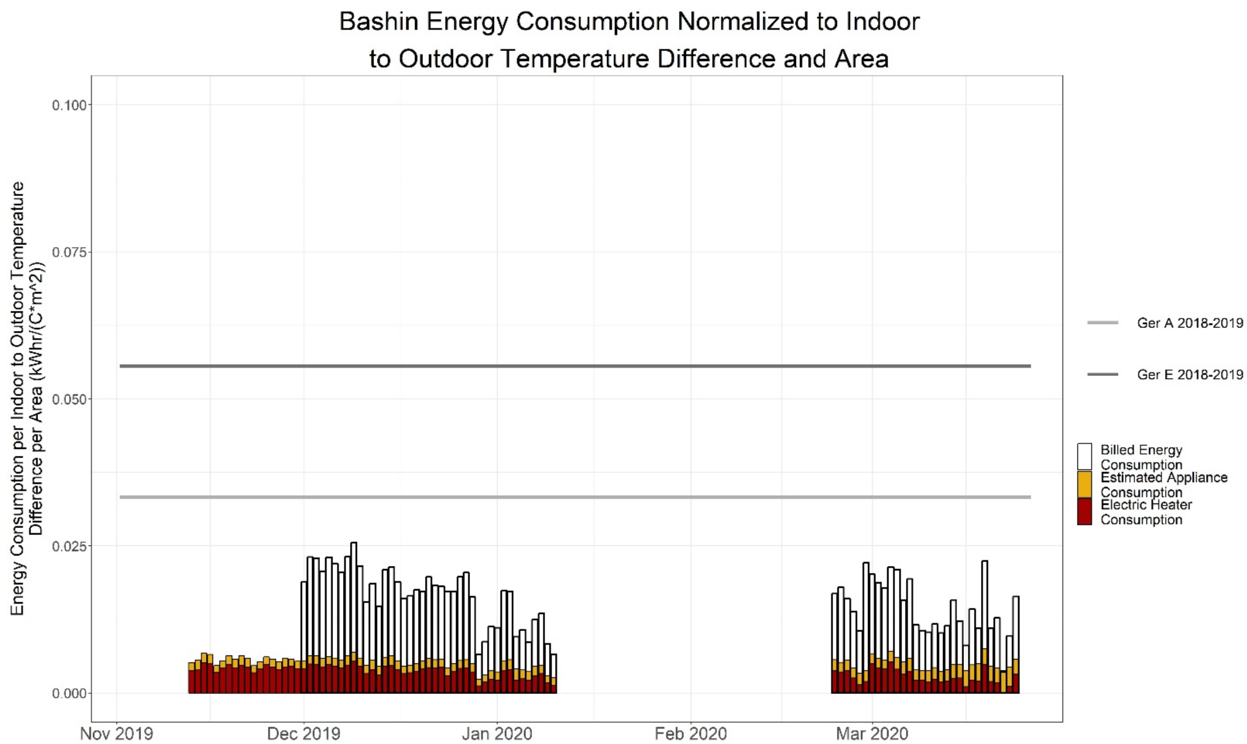

Figure 50. BKH Bashin 1: Normalized energy consumption per degree temperature difference and area

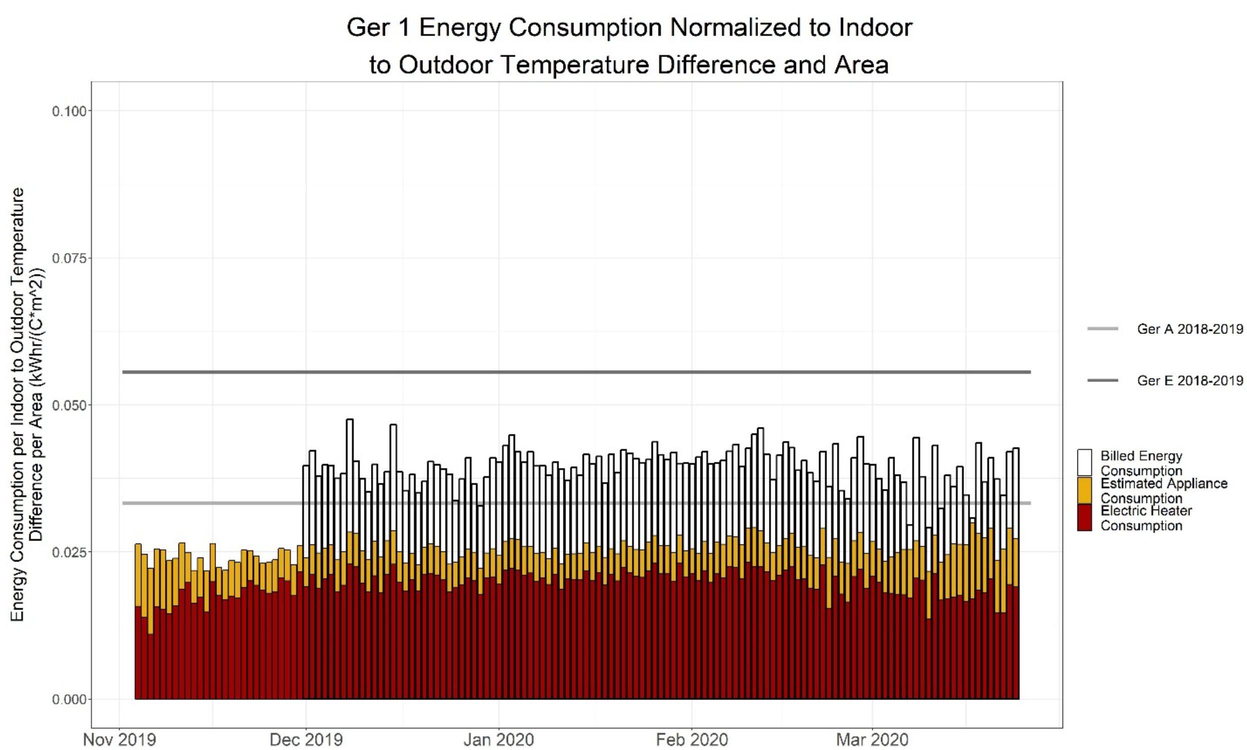

Figure 51. BKH Ger 1: Normalized energy consumption per degree temperature difference and area

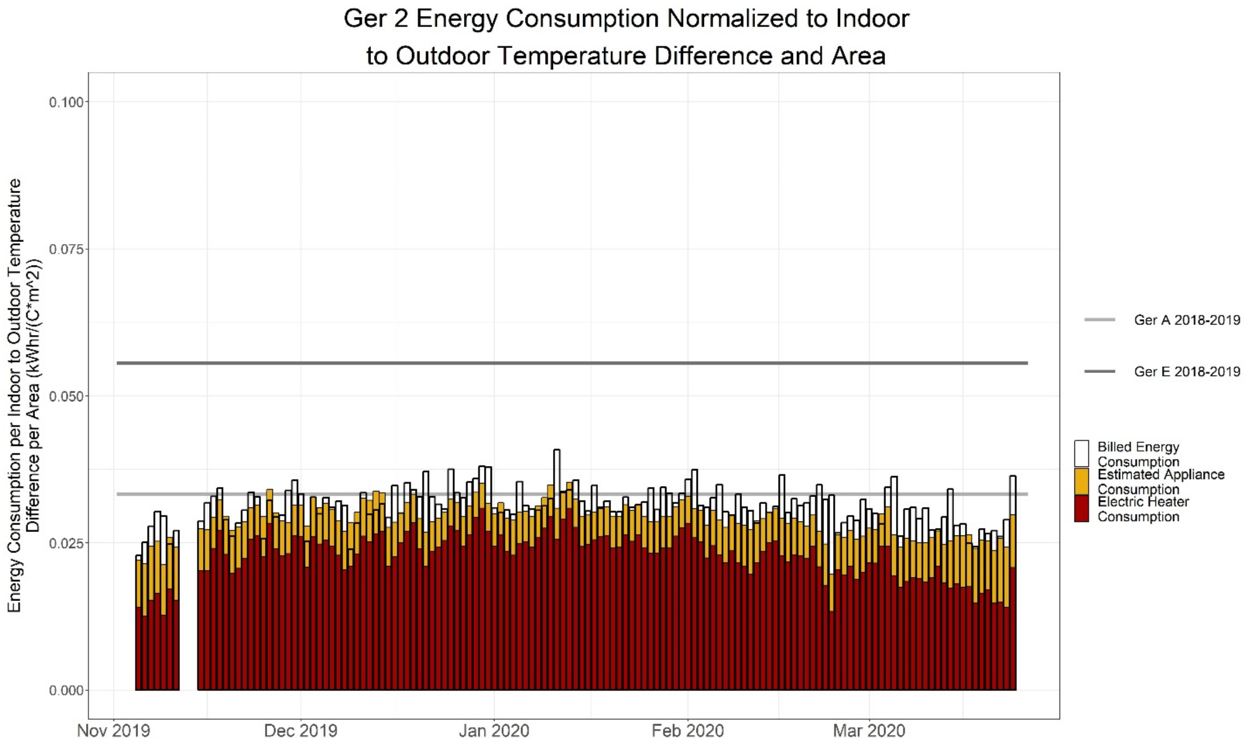

Figure 52. BKH Ger 2: Normalized energy consumption per degree temperature difference and area

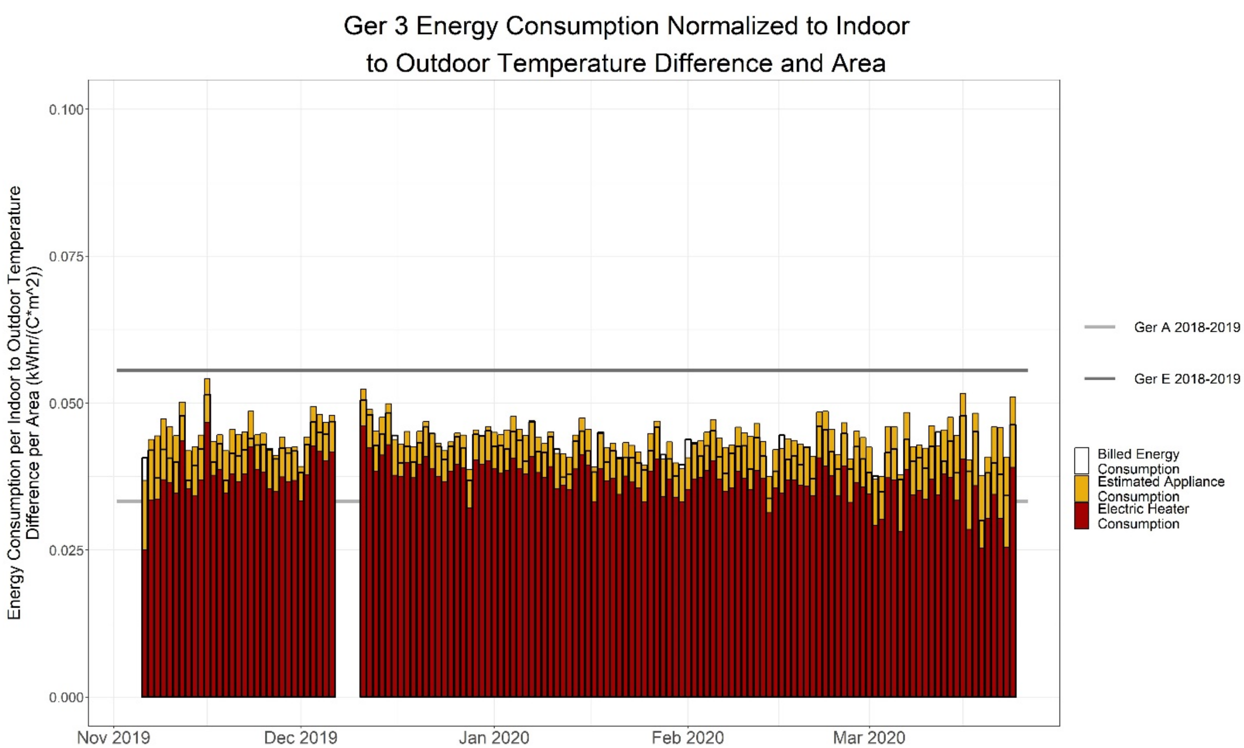

Figure 53. BKH Ger 3: Normalized energy consumption per degree temperature difference and area

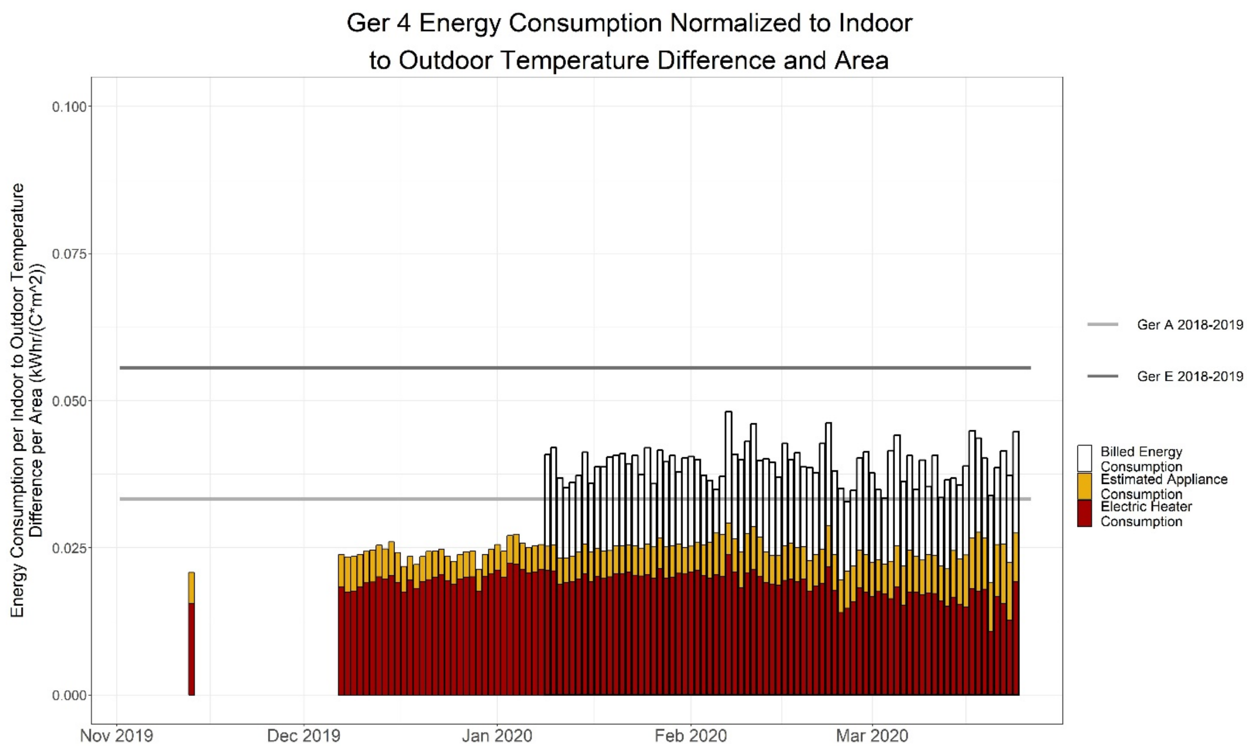

Figure 54. BKH Ger 4: Normalized energy consumption per degree temperature difference and area

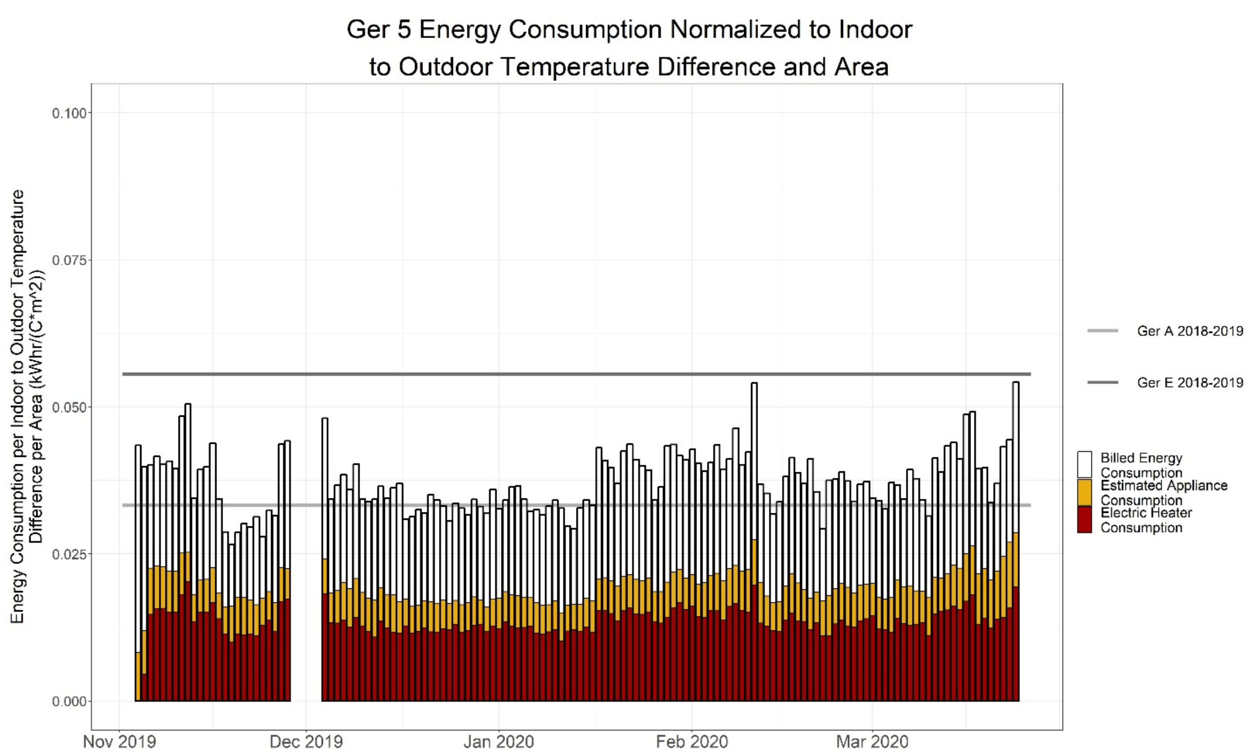

Figure 55. BKH Ger 5: Normalized energy consumption per degree temperature difference and area

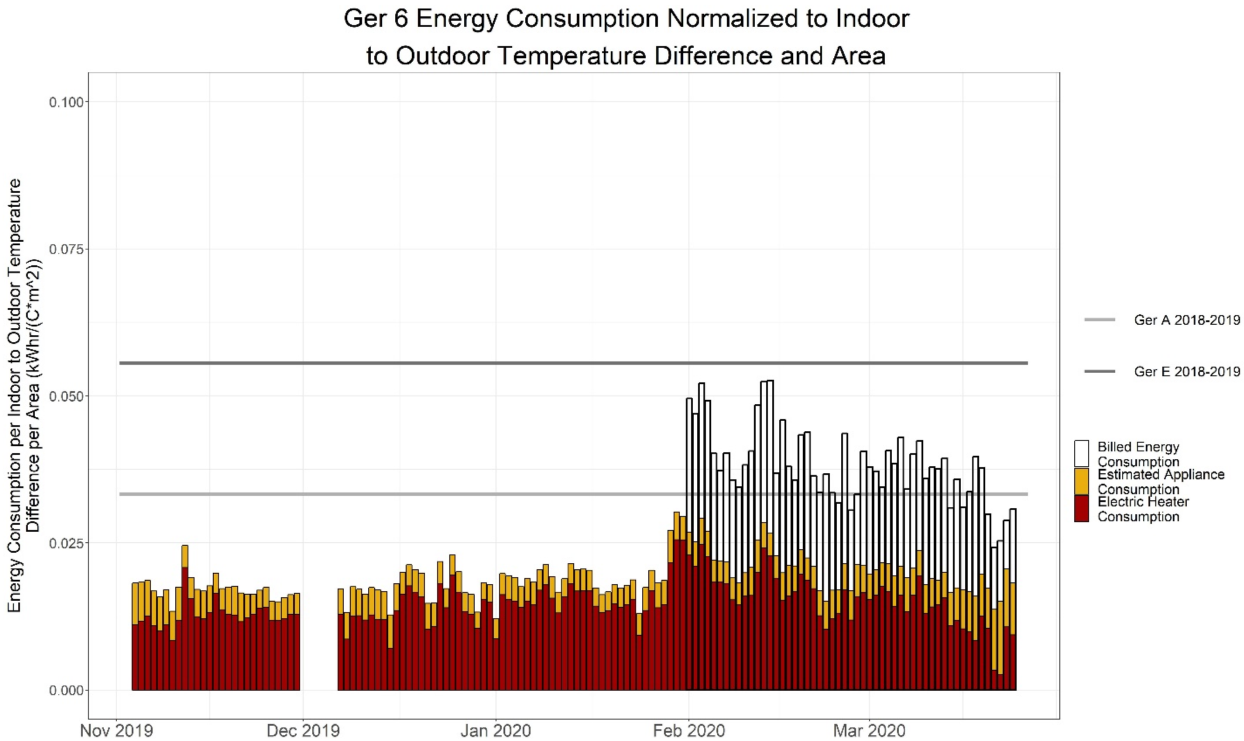

Figure 56. BKH Ger 6: Normalized energy consumption per degree temperature difference and area

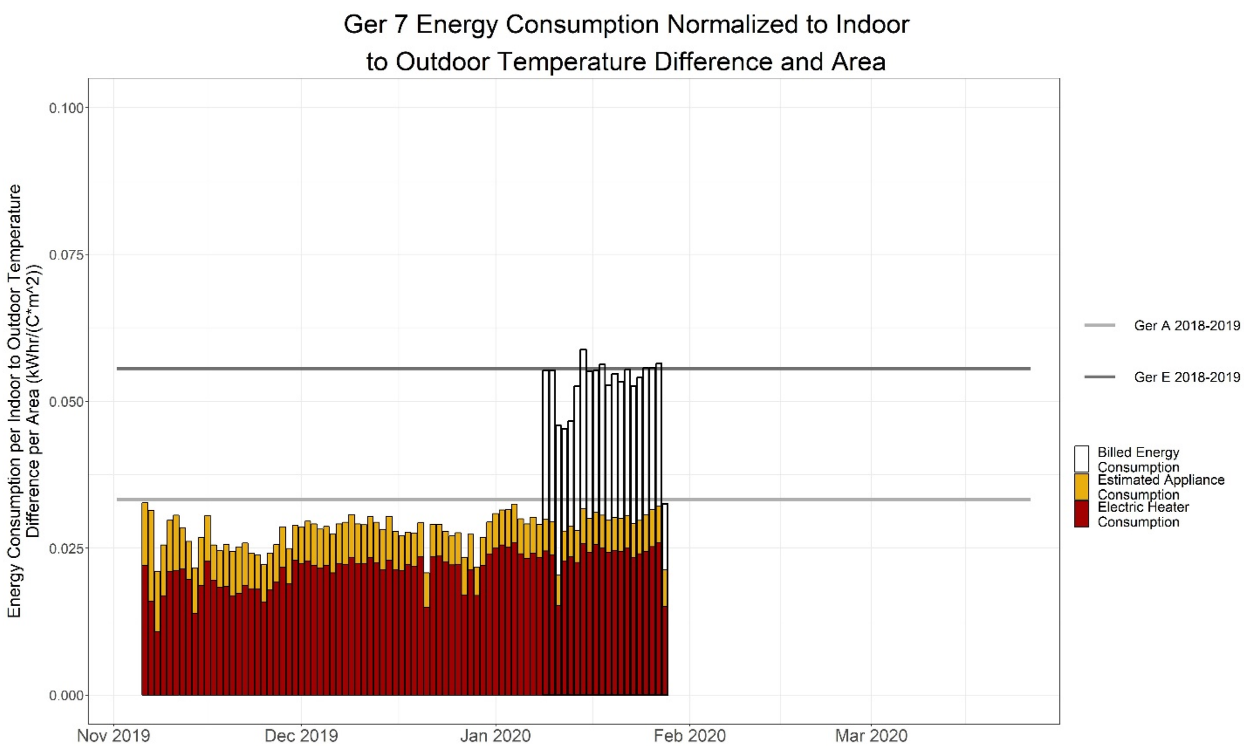

Figure 57. BKH Ger 7: Normalized energy consumption per degree temperature difference and area

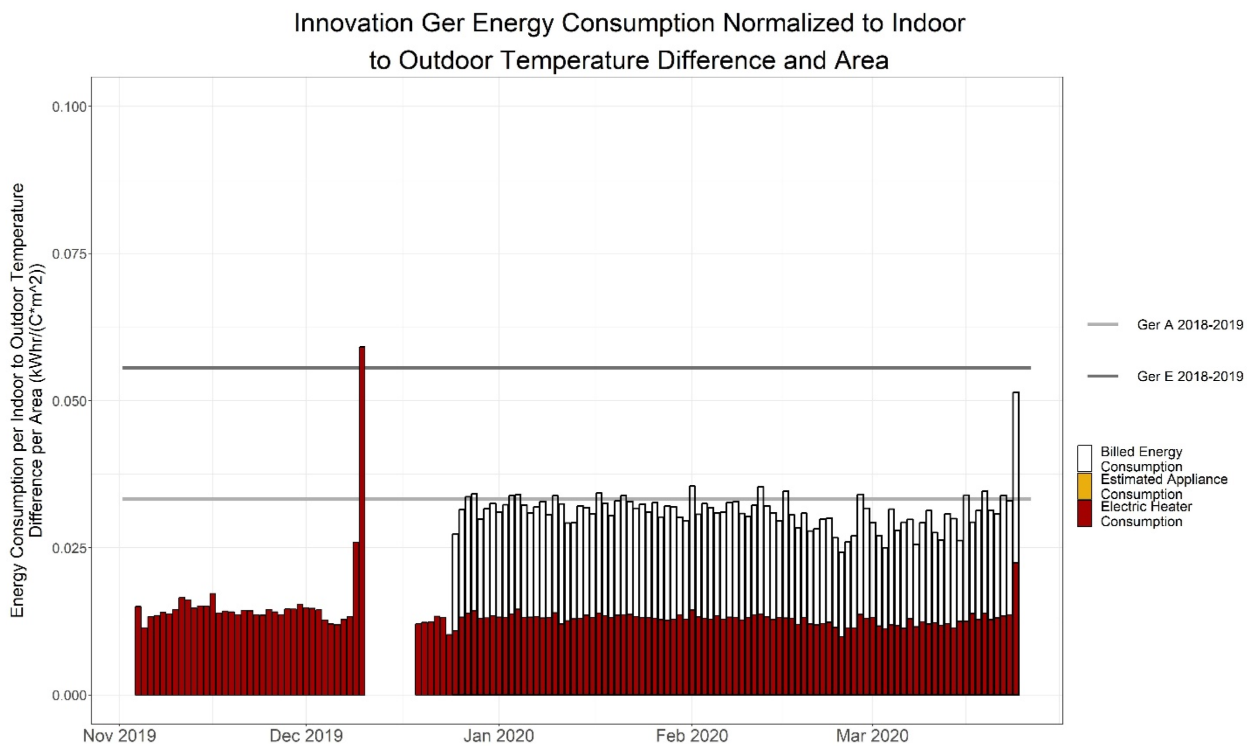

Figure 58. BKH Innovation Ger: Normalized energy consumption per degree temperature difference and area

Appendix D: Average daily temperature variances

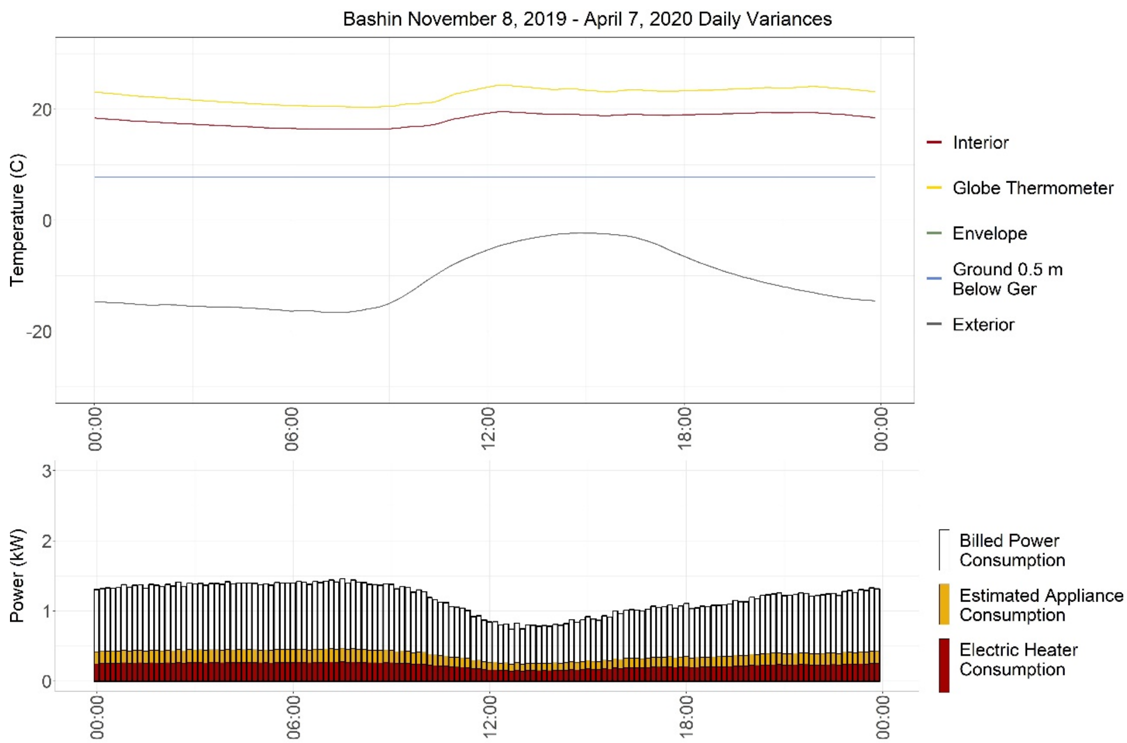

Figure 59. BKH Bashin - daily temperature variances

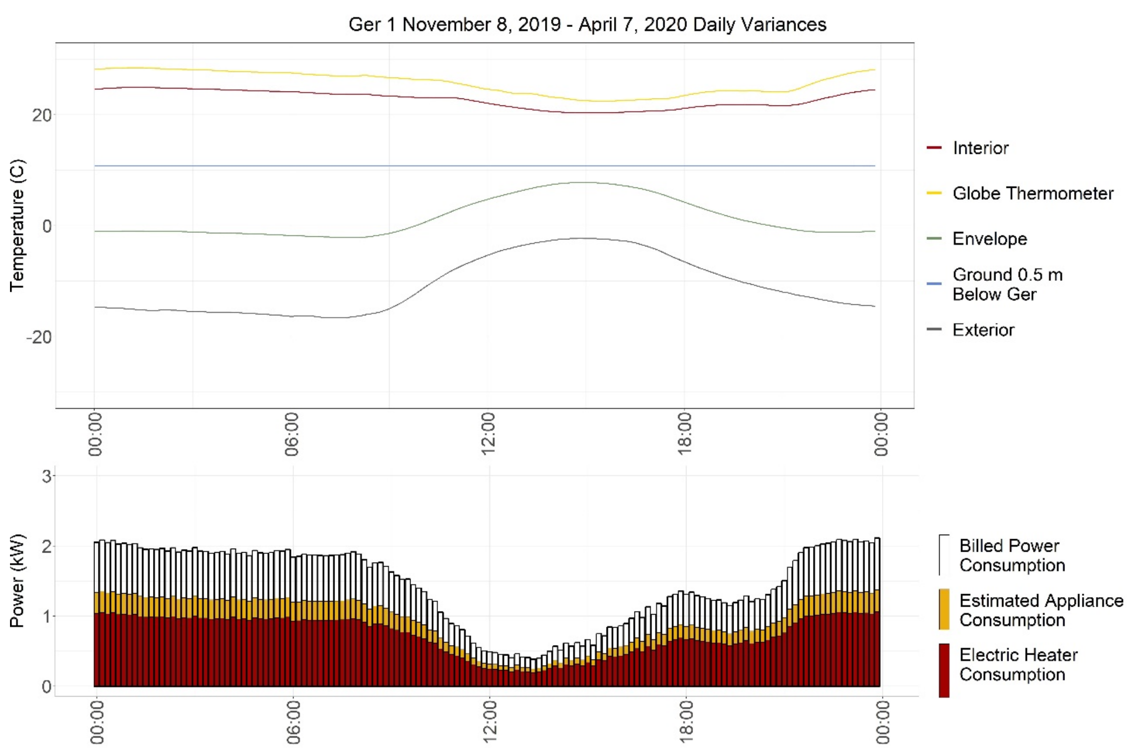

Figure 60. BKH Ger 1 - daily temperature variances

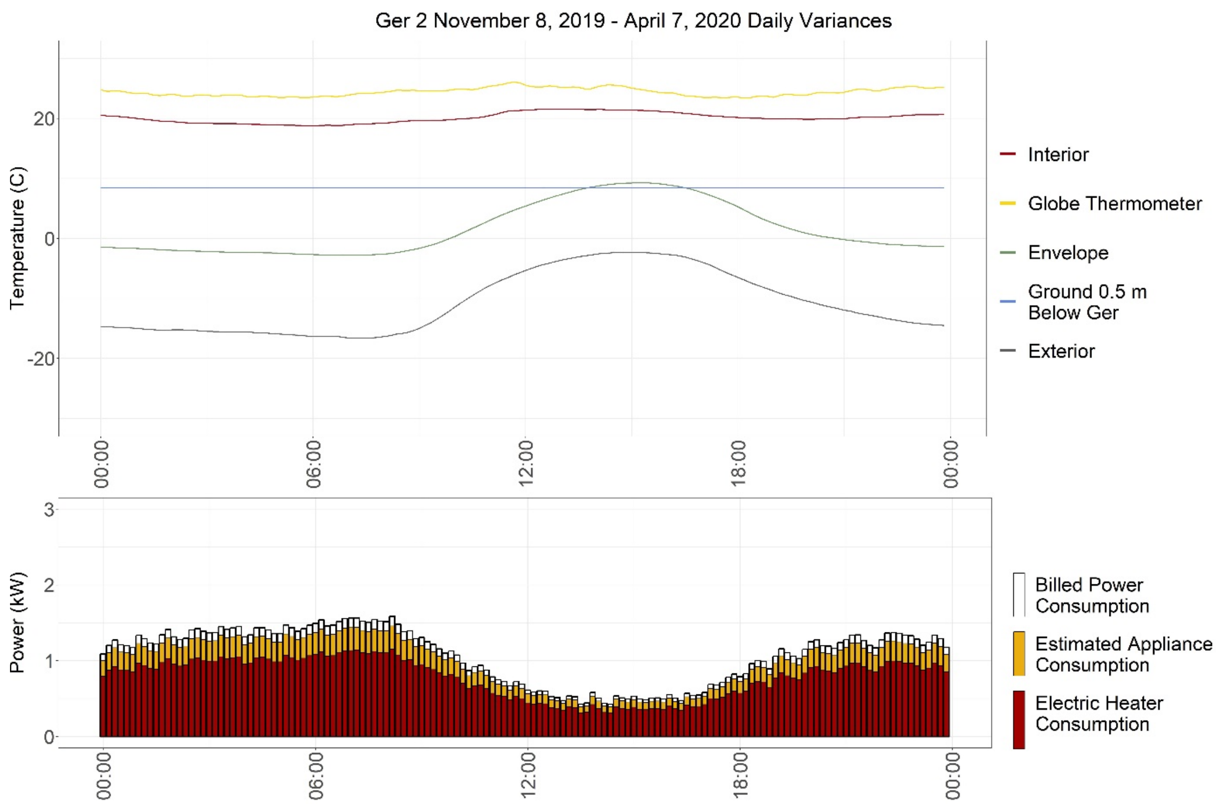

Figure 61. BKH Ger 2 - daily temperature variances

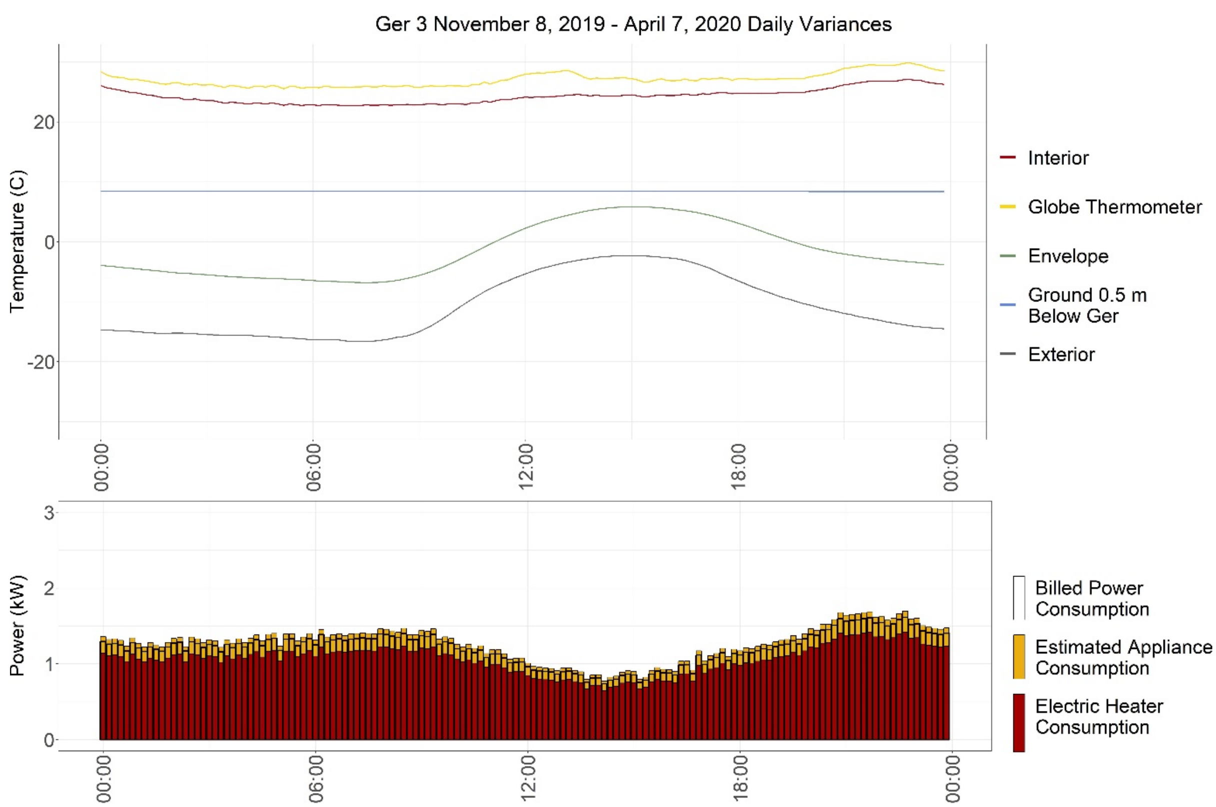

Figure 62. BKH Ger 3 - daily temperature variances

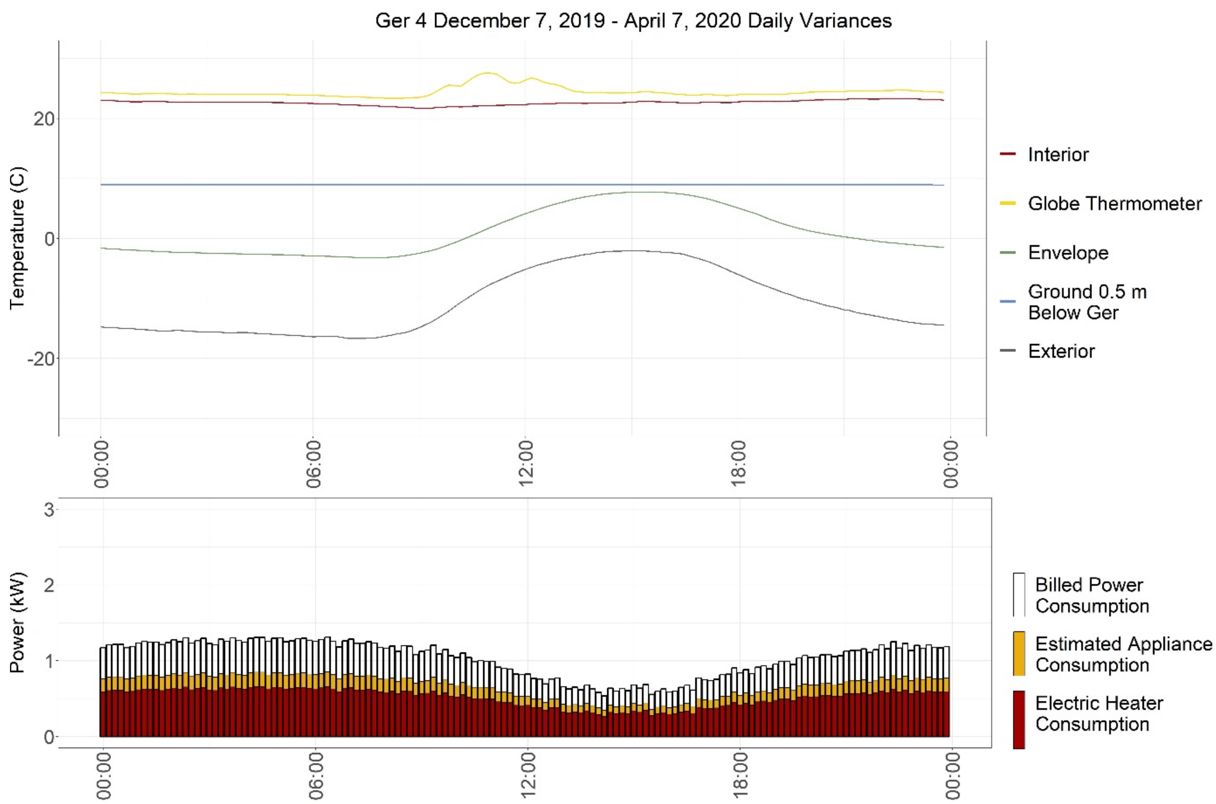

Figure 63. BKH Ger 4 - daily temperature variances

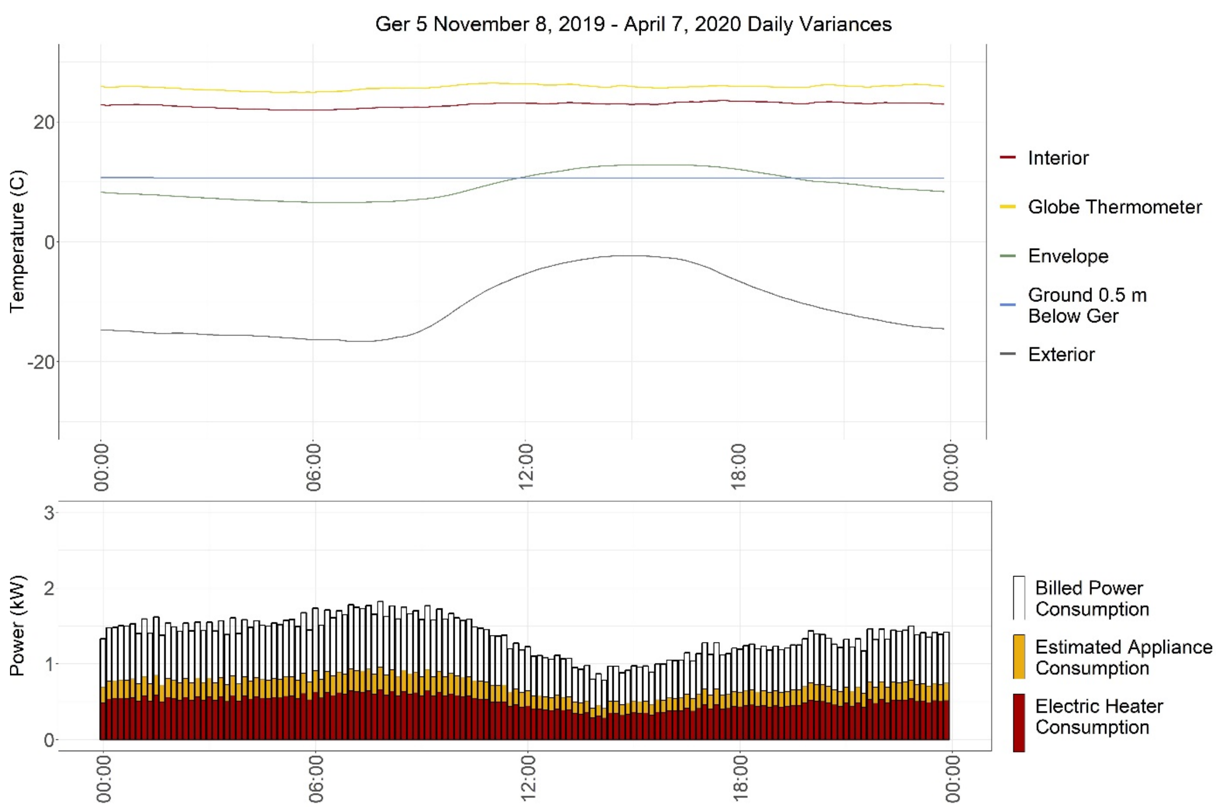

Figure 64. BKH Ger 5 - daily temperature variances

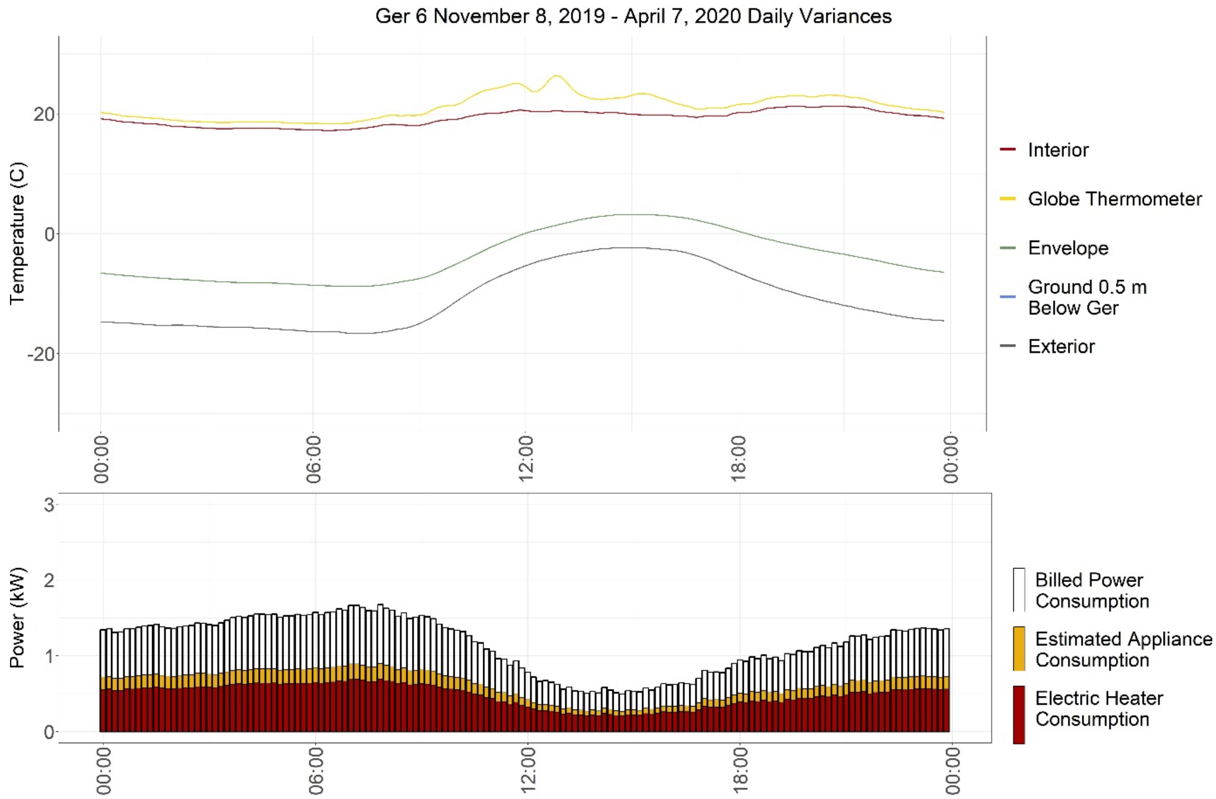

Figure 65. BKH Ger 6 - daily temperature variances

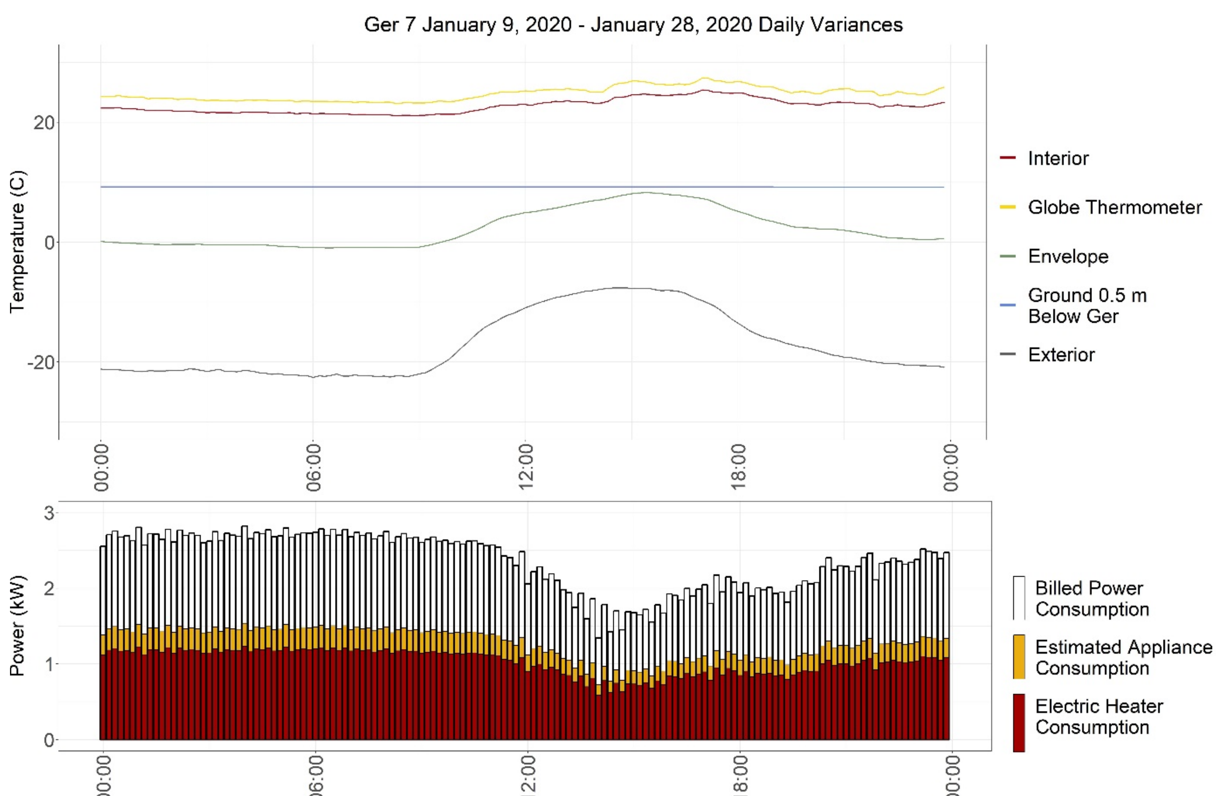

Figure 66. BKH Ger 7 - daily temperature variances

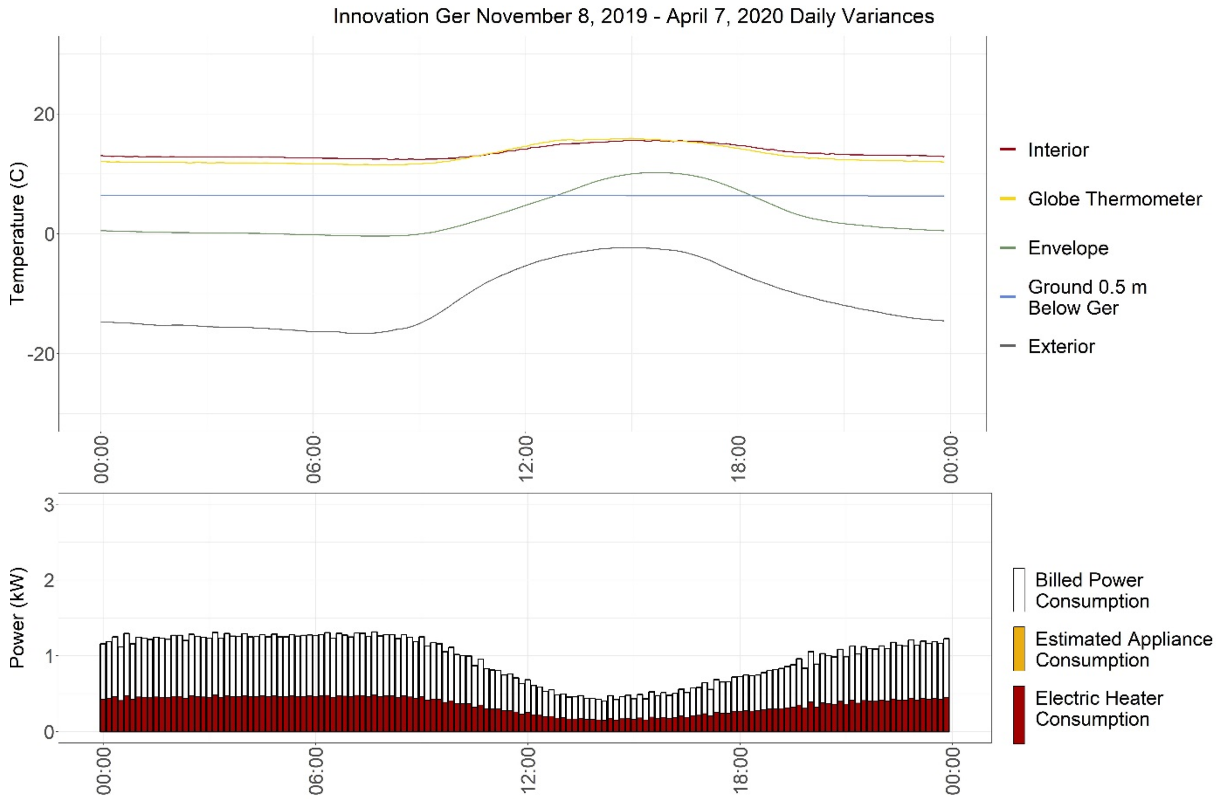

Figure 67. BKH Innovation Ger - daily temperature variances

Appendix E: Cross correlations for PM 2.5 Concentrations

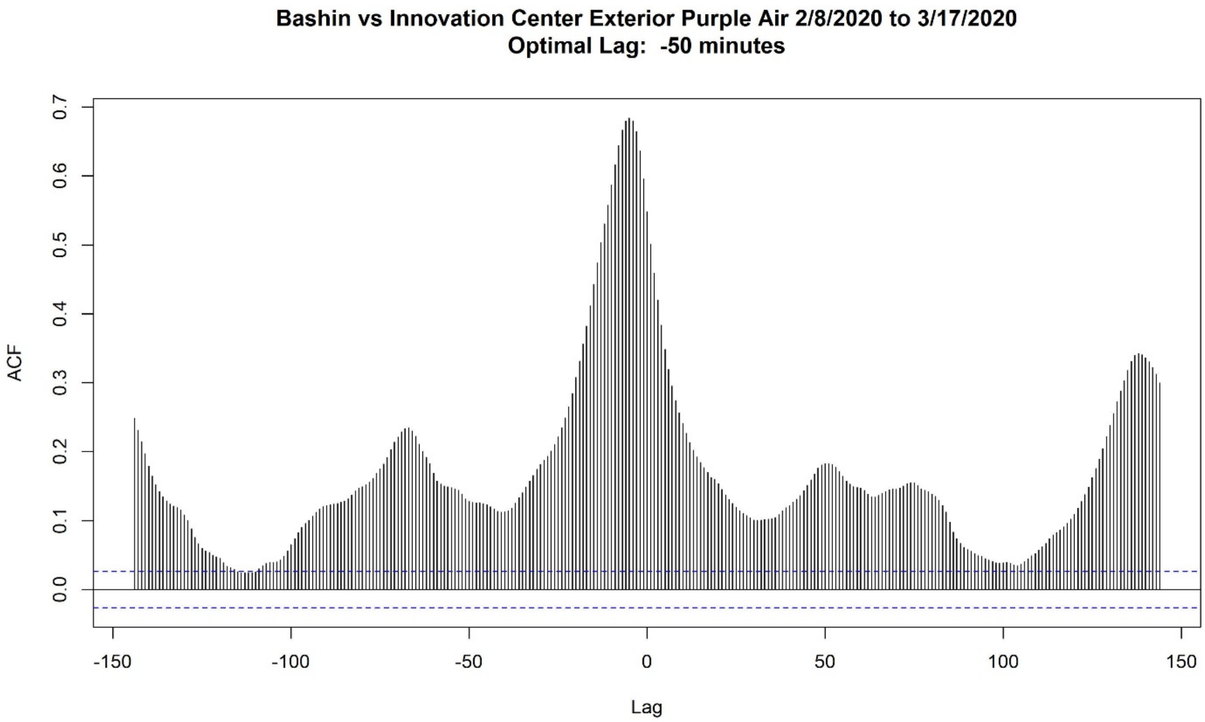

Figure 68. BKH Bashin: Cross correlations for PM 2.5 Concentrations

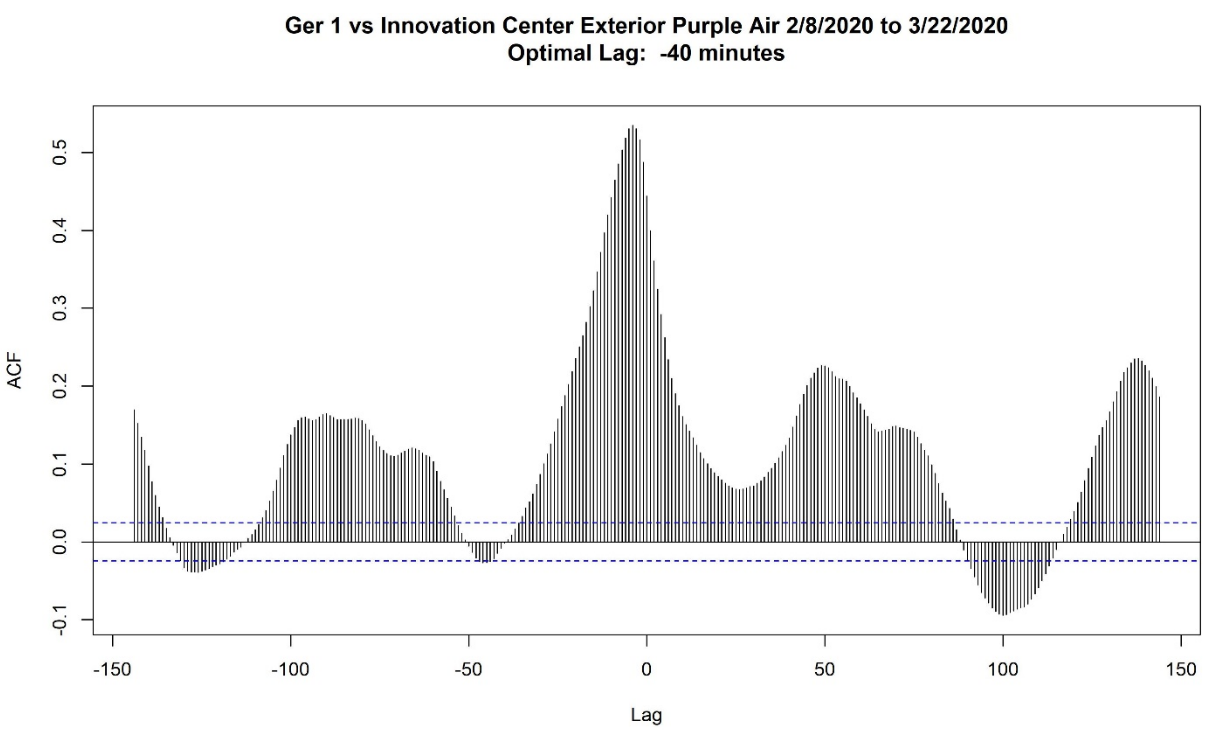

Figure 69. BKH Ger 1: Cross correlations for PM 2.5 Concentrations

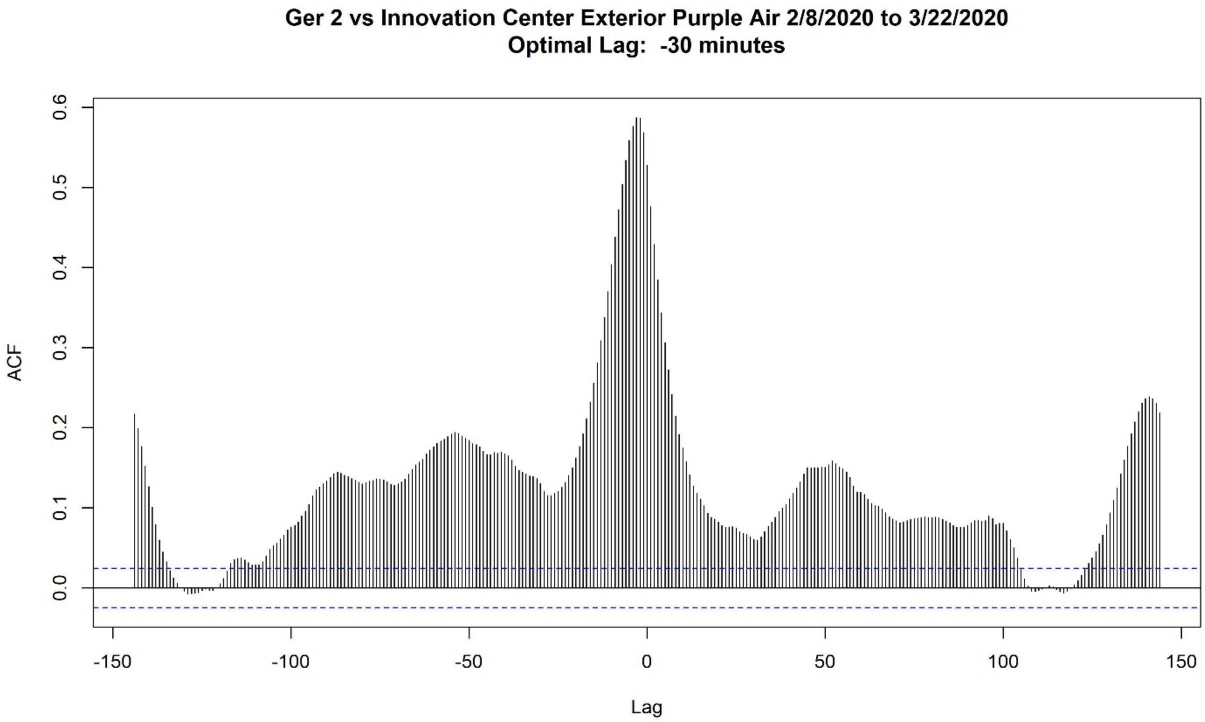

Figure 70. BKH Ger 2: Cross correlations for PM 2.5 Concentrations

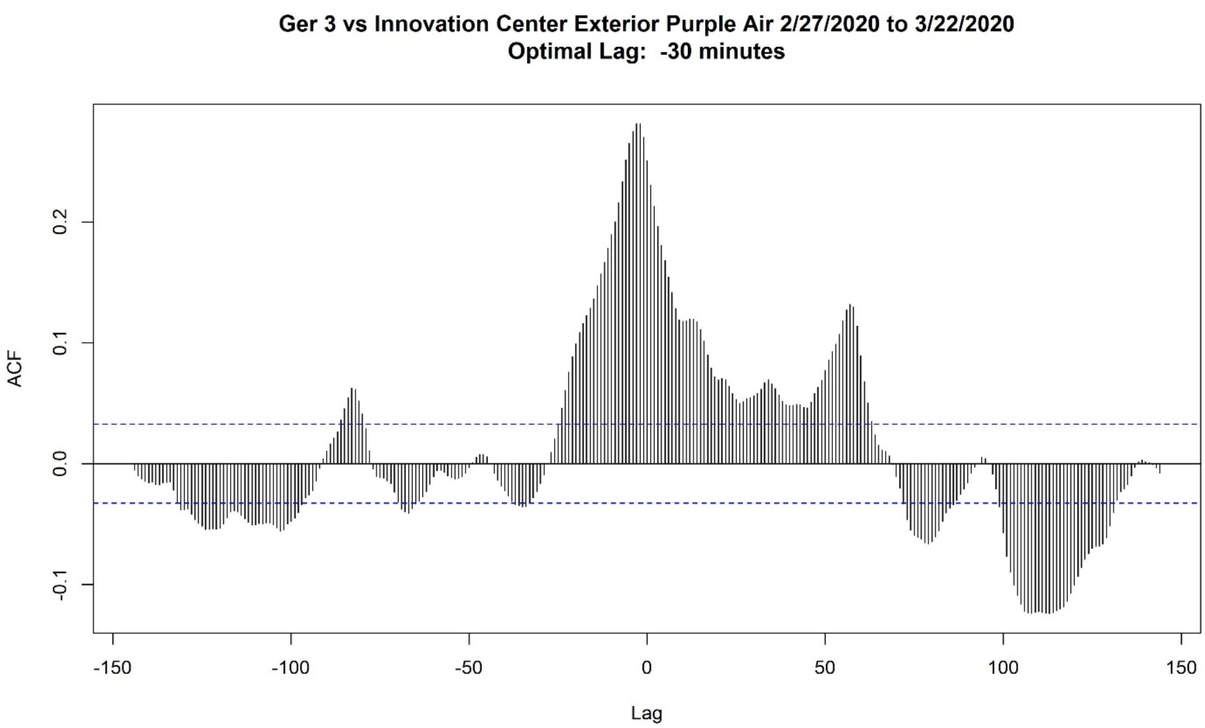

Figure 71. BKH Ger 3: Cross correlations for PM 2.5 Concentrations

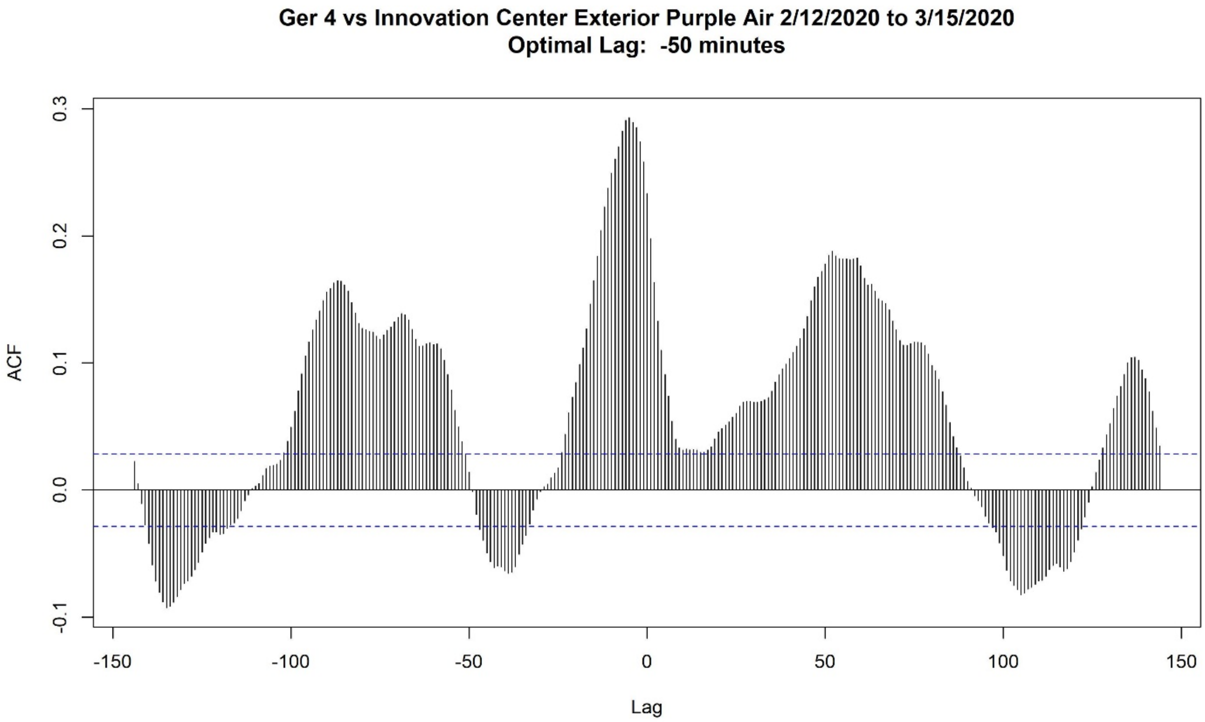

Figure 72. BKH Ger 4: Cross correlations for PM 2.5 Concentrations

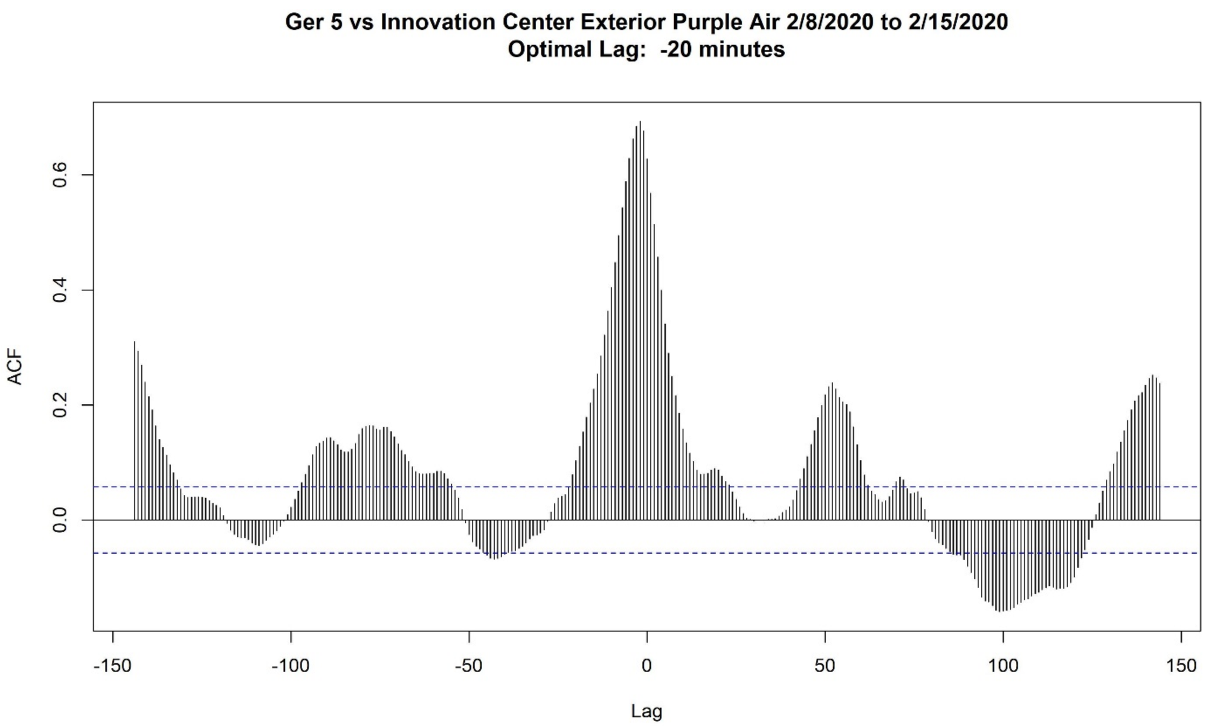

Figure 73. BKH Ger 5: Cross correlations for PM 2.5 Concentrations

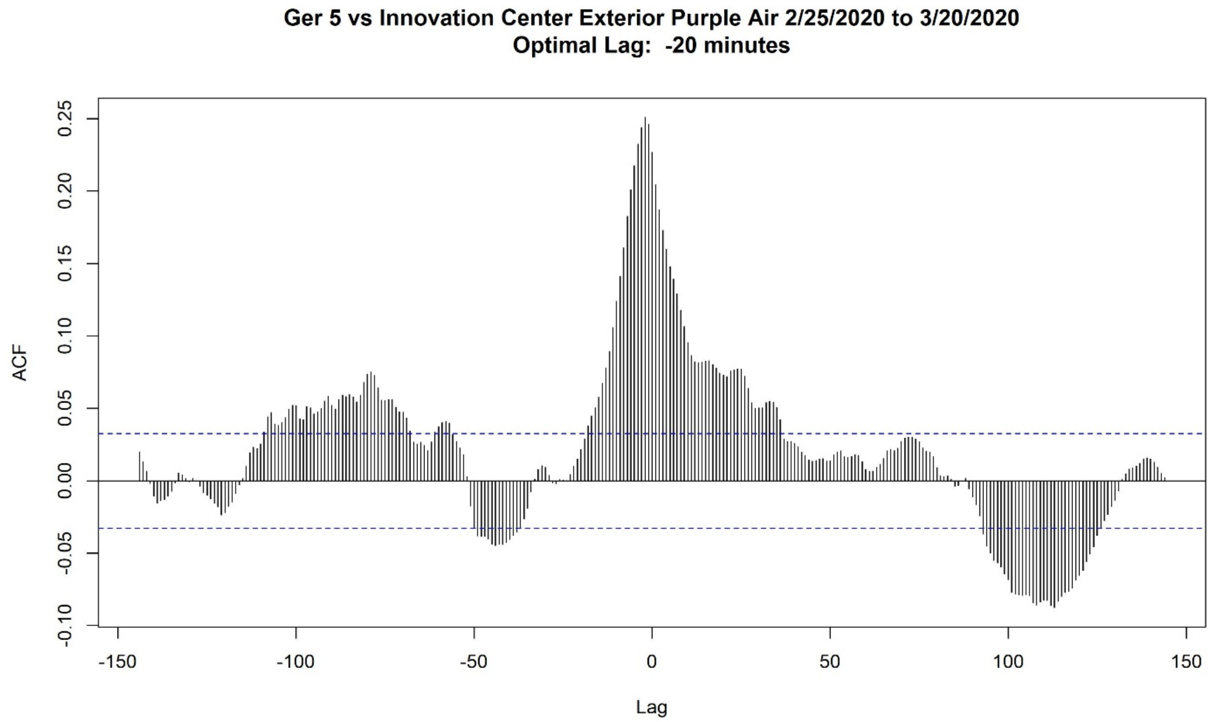

Figure 74. BKH Ger 6: Cross correlations for PM 2.5 Concentrations

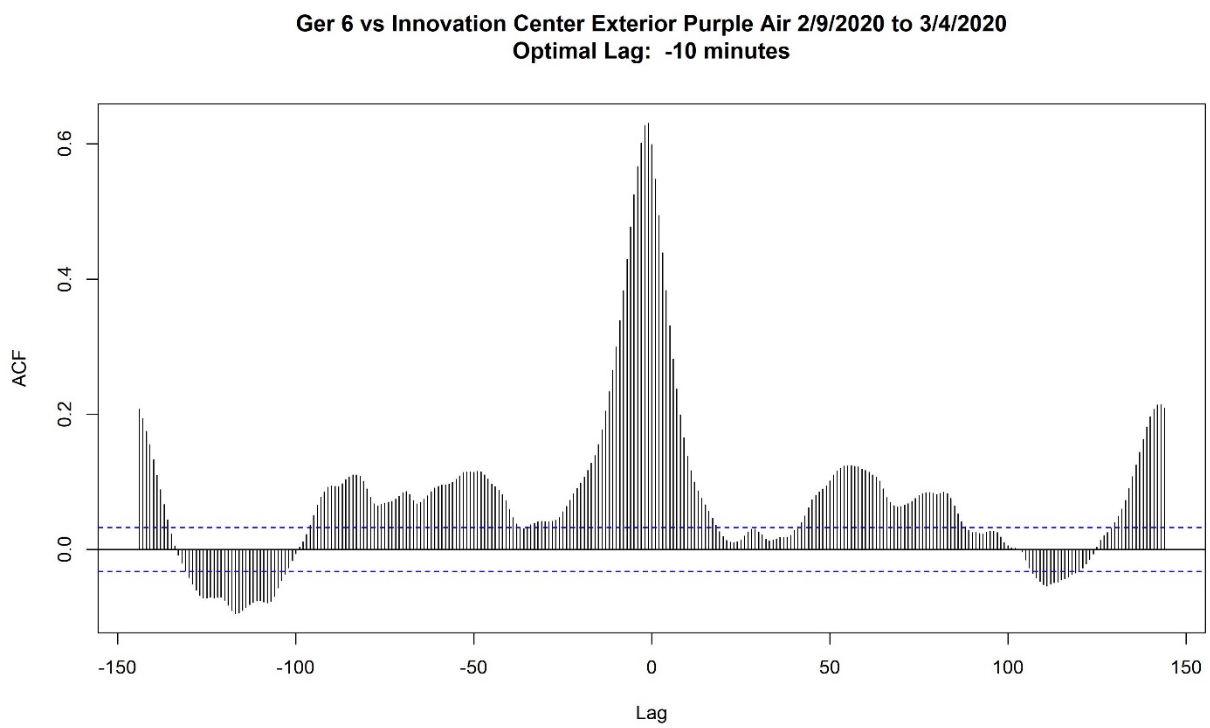

Figure 75. BKH Ger 7: Cross correlations for PM 2.5 Concentrations

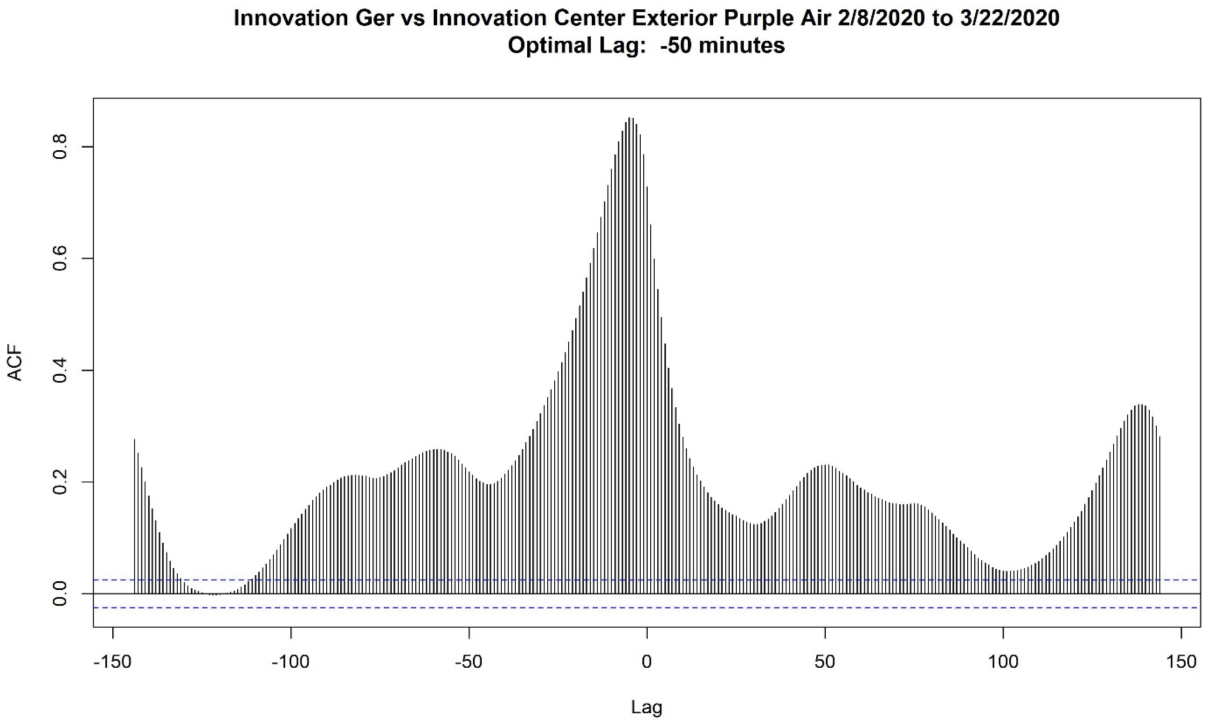

Figure 76. BKH Innovation Ger: Cross correlations for PM 2.5 Concentrations