Environmental Research 176 (2019) 108381

Contents lists available at ScienceDirect

Environmental Research

journal homepage: www.elsevier.com/locate/envres

Short communication

Advanced household heat pumps for air pollution control: A pilot field study in Ulaanbaatar, the coldest capital city in the world

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ARTICLE INFO

Keywords:
Household heating
Mongolia
Air pollution
Electricity
Coal
Energy transitions

ABSTRACT

Ulaanbaatar - the coldest capital in the world - is home to half of Mongolia's population, much of which uses coal for household heating, contributing to high wintertime air pollution. We piloted two-stage air-to-air heat pumps in 2017, when temperatures dropped to −39 °C. These heat pumps were reliable and efficient, with an average coefficient of performance of 1.86 on the coldest days. Heat pumps' recurrent costs were similar to those of coal stoves and lower than those of resistive heaters.

1. Introduction

Ulaanbaatar (UB), the capital city of Mongolia, presents difficult and fairly unique air pollution challenges. Over the past decade, it has grown rapidly due to urban migration and is now home to more than 1.4 million of the country's 3.1 million people (National Statistical Office of Mongolia, Populatio and Housing National Report, 2015, 2017). New migrants to UB – who often move into small, relatively dispersed homes – have been encouraged by the government to live in the valleys in and around the city. These valleys are characterized by low inversion heights and low wind speeds in winter (National Center for Public Health and UNICEF, 2018; World Bank, 2013).

UB is the coldest capital city in the world (temperatures visualized in Supplemental Information [SI] Fig. S1); Mongolia has no readily accessible petroleum or gas resources of its own, yet has abundant coal, which fuels both its power plants and simple stoves in homes. As such, much of the population heats their homes with coal combusted in simple stoves (National Statistical Office of Mongolia, Population and Housing National Report, 2015, 2017) that produce large volumes of pollution (Lim et al., 2018). The resulting urban $PM_{2.5}$ concentrations are among the worst in the world, mainly in winter (World Health Organization, 2018; Allen et al., 2013; Barn et al., 2018) when the pollution penetrates all major indoor and outdoor environments in which people spend time.

To address this situation, cleaner-burning coal stoves have been introduced, often as part of government and NGO-led assistance. For example, stoves imported from Turkey were deployed as part of an intervention, but this did not change the pollution situation appreciably (Greene et al., 2016). Previously, we modeled the health impacts from all sources of pollution in UB and projected scenarios for improvements (Hill et al., 2017). We found that no potential improvement in household coal burning would likely significantly improve the situation over the next decade; major improvements in fuel supply or other emissions-reducing technologies would be needed. Similar conclusions have been reached by other studies, although efforts are still being made to find ways to burn coal cleanly (Asian Development Bank, 2017; Edwards, 2017).

Electric solutions – including resistive heaters and ground-to-air or air-to-air heat exchangers – have relatively poor penetration in UB. Traditional air-to-air electric heat pumps (HPs), which can be highly efficient space heating systems in more temperate climates (Ma et al., 2017), have not been widely deployed in UB because of the long periods of temperatures below −30 °C, occasionally dipping to −40 °C. These traditional HPs work down to about −20 °C, but offer no advantage over simple resistance heating at lower temperatures. New "two-stage compression" HPs – that operate down to −40 °C with a coefficient of performance (COP) above 1.0 (see SI Fig. S2) – have been developed and deployed in China in recent years (Ma et al., 2017, 2018). A COP

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https://doi.org/10.1016/j.envres.2019.03.019
Received 18 January 2019; Received in revised form 6 March 2019; Accepted 7 March 2019

higher than 1.0 means it is more energy efficient than direct electrical heating.

As with other household energy interventions, a small series of pilot studies can be useful to evaluate the feasibility of interventions prior to their full deployment (Mukhopadhyay et al., 2012). Outside of laboratory testing, these advanced air-to-air heat pumps had not been used in harsh climates, such as those found in UB. Thus, in late fall 2017, our team arranged import of seven of these two-stage compression heat pumps for evaluation in households in UB by the end of December. The HPs used in this pilot are commercial products with sales in the tens of thousands in northern China (Ma et al., 2018). Part of our team has several years' experience deploying and measuring HP performance in China.

2. Methods

2.1. Study site and participants

Because our project was initiated at the beginning of the winter season, we needed to find potential household participants quickly. We worked in one area of UB where our partners at the Mongolian Ministry of Energy had contacts. We chose a convenience sample of five separate modern-style households (bungalows) and two traditional *ger* households (round insulated tents common in Mongolia) in Sukhbaatar District. Characteristics of participating households are described in Table 1.

2.2. Enrollment

Households were approached by field staff from the Mongolian University of Science and Technology and asked if they were willing to participate in the study. As part of the recruitment and consent process, households were offered free electricity through the winter until March and were allowed to retain their coal stoves, but asked not to use them unless necessary. Coal stoves were inspected weekly for any signs of usage. At the end of the study, households could either keep or return their HP.

2.3. Heat pump intervention

Two types of two-stage compression heat pumps with different capacities were utilized (see SI Table S1 for specifications). Larger capacity heat pumps were utilized in the bungalows, while smaller units were utilized in the gers. Each HP consisted of an outside unit installed on the wall of the house and connected directly to an inside unit with a small internal fan to spread heat within the room. Installations were performed by technicians licensed by the HP manufacturer. The HPs logged performance data and transmitted it to servers at the manufacturer's headquarters in southern China via the cellular network. A number of parameters were logged automatically, including indoor and outdoor temperatures, temperature setpoint (controlled by the household), fan speed (controllable by the household), and power consumption. These parameters were used to estimate instantaneous COP (see description in SI, based on (Ashrae, 2017)). We also directly monitored indoor and outdoor temperatures and power consumption to verify data reported by the wireless system.

As the peak power demand of the HPs exceeded the normal power load for households in the study area, the local electric utility upgraded power to the households to 4 kW or 8 kW. All households chosen were within 150 m of a transformer.

We gave short trainings to the households about the operation of the HPs and a phone number to call anytime in case of urgent problems. Local technicians were prepared to react quickly if there were any issues. Our team visited each week to check on the HPs, to evaluate use of the coal stoves, and to download data from the temperature loggers.

2.4. Statistical analysis

All descriptive and statistical analyses were performed in R 3.5.1. Minute-to-minute data were summarized by household at hourly and daily scales. Linear models were created to evaluate the relative impact of various parameters – including outdoor temperature, temperature setting, fan speed, calendar date, and heat pump size – on estimated COPs. The performance of each parameter was evaluated by (1) estimating the Pearson correlation coefficient between the parameter and COP, (2) by estimating the parameter's influence on model R^2, and (3) by estimating the partial correlation of the parameter and COP.

3. Results

Every household used their HP successfully. We found no use of coal stoves based on both questionnaire data and weekly inspection. Power outages during the pilot period were short (reported as never beyond a few minutes).

Fig. 1 shows the performance of each heat pump in the seven participating households. Mean indoor temperatures were maintained at approximately 20 °C for all households, no matter the outside temperature. Measurements from household 6 indicated anomalously cold indoor temperatures around March 1, which were due to the absence of participants from their household during this period. The lowest outdoor temperature recorded by our dataloggers during the sampling period was −39 °C (see SI Fig. S3 for a breakdown of temperatures during this monitoring period).

Overall COPs are plotted in Fig. 2 against outside temperature. They were all above 1, and during the coldest days (< −20 °C), ranged between 1.05 and 5.40, with an average COP of 1.86 on days with an average outdoor air temperature of −23.3 °C.

Total electricity consumption, estimated local electricity costs, and cost per square meter are shown in Table 1. Considering the houses were not well insulated, the energy consumption data look comparable to data reported in better insulated homes and less harsh climates in China (Ma et al., 2018).

Table 1

Electricity consumption and costs across the entire heating season, from Sept. 15th to May 15th of the following year. Occupant behaviors, such as the temperature setting on the heat pump, the fan speed, and whether or not the heat pump is left on when no one is present have an impact on energy consumption. The electricity cost is 0.054USD/kWh.

#	Residents	Home area (m^2)	Temp setting (C)	Fan speed	Energy (kWh)	kWh per m^2	Electricity cost ($)	USD per m^2
1[a]	1	28	17–20	Med	4453	159	241	8.6
2[a]	3	28	20–26	Med	4807	172	260	9.3
3	3	19	24–30	Med	3934	207	212	11.2
4	4	39	24–27	Med	6924	178	374	9.6
5	6	28	27–30	Med	5835	208	315	11.3
6	2	27	26–28	Med	5598	207	302	11.2
7	4	42	30	High, Low	9792	233	529	12.6

[a] Ger-type residence (all others are bungalows). Gers were equipped with a small 4 kW HP, while bungalows were equipped with an 8 kW HP.

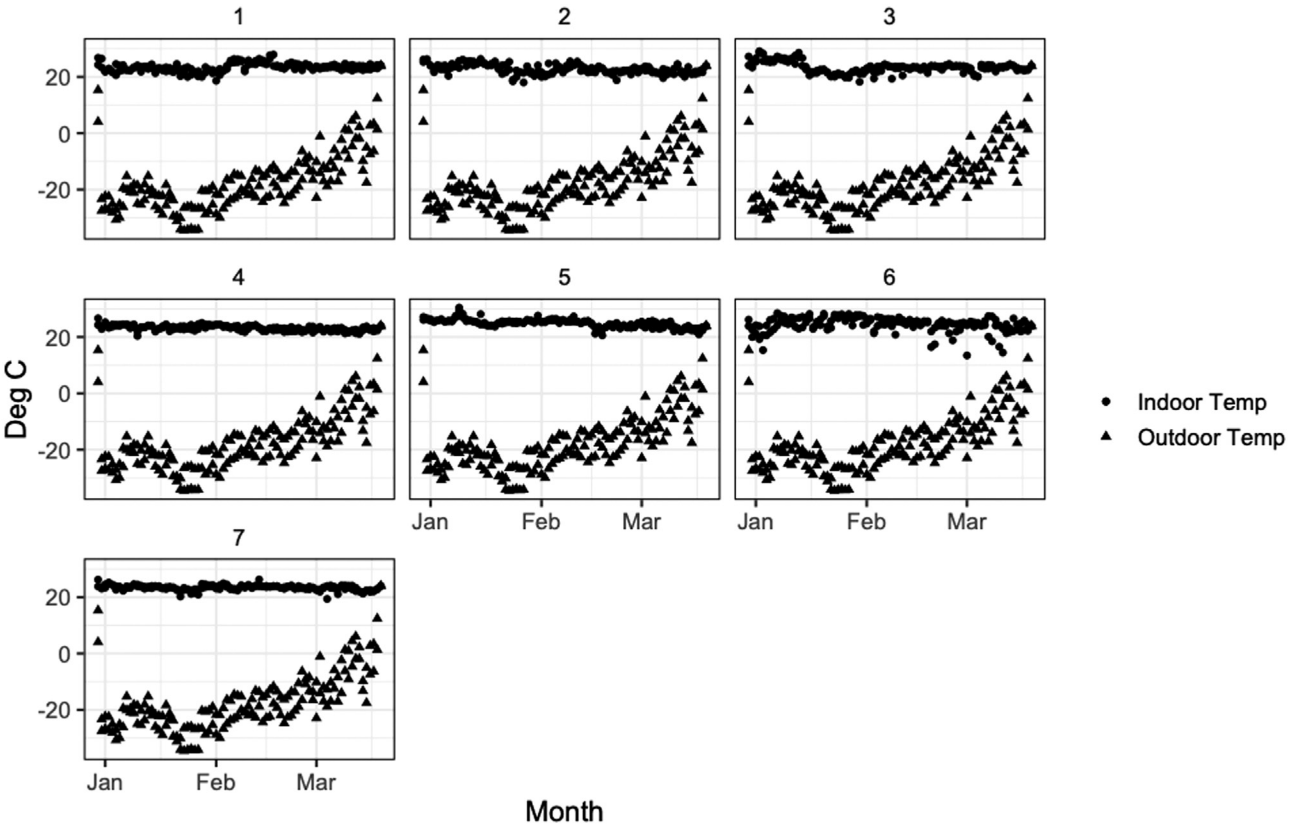

Fig. 1. Measured Indoor and outdoor temperature of heat pumps by household. Mean daily indoor and outdoor temperatures during the study period.

Operator behavior modified HP performance. Examples of these modifying behaviors are shown in SI Table S2. Some households kept the fan at low or medium settings, which lowered COPs (Table S2 rows 1 and 2). These households used lower fan speed due to noise created by the fan, which was perceived as a nuisance. The impact of this behavior on COP was consistent across households and heat pump types (Fig. S4).

Linear models evaluating the impact of average outdoor temperature, the temperature setting, fan speed, and calendar date on COP were created. The strongest predictor of COP was average outdoor temperature, with an R^2 value of 0.80. Including the temperature setting in the model increased the adjusted R^2 to 0.83; including both the temperature setting and the calendar date increased the R^2 to 0.84. Mean-squared errors were similar for the univariate model and the model including temperature setting (0.15), and slightly lower for the model including outdoor temperature, the temperature setting and day

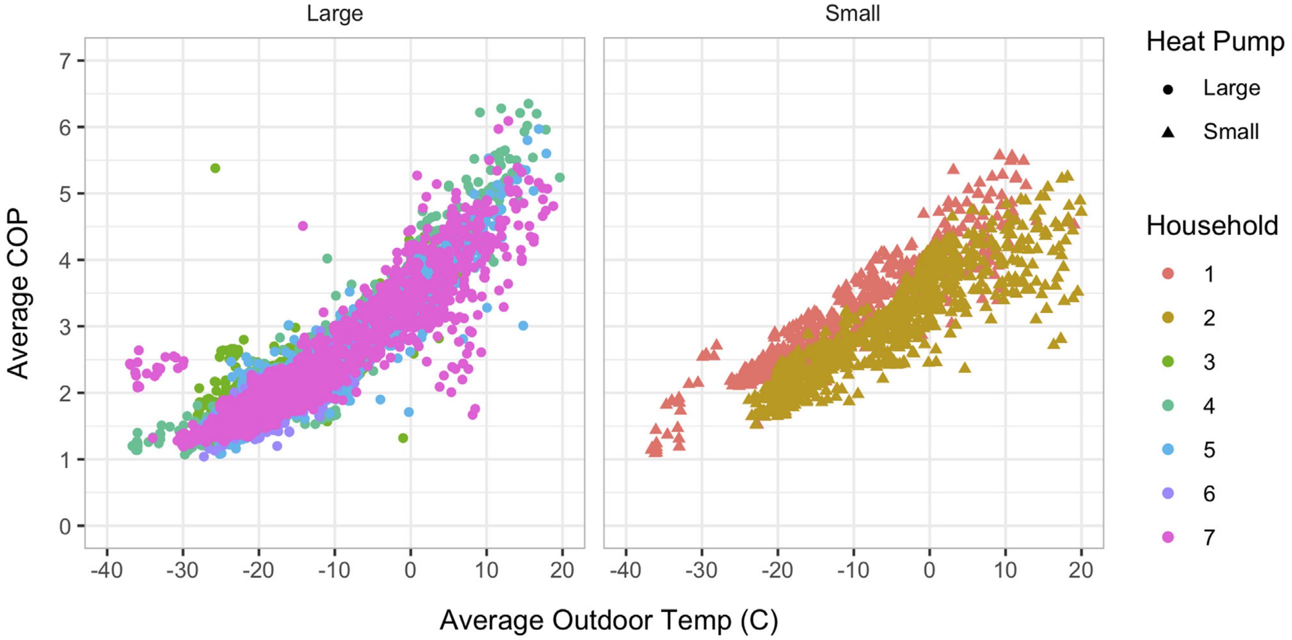

Fig. 2. Hourly average Coefficient of Performance versus hourly average ambient temperature. Each point is the average hourly COP and outdoor temperature.

Table 2

Comparison of variable costs for common heating methods in a Ger of 28 m^2 over an 8-month heating season. Two scenarios are presented for the heat pumps – one based on average values for Gers from this study and a second, more conservative estimate based on the least efficient heat pump (in terms of kWh/m^2) from all households in this study at a higher than expected electricity tariff.

	Consumption	Tariff	Total (USD)	\$/m^2
Coal	3.5 tons[a]	71 USD/ton[b]	248.5	8.88
Direct Heating	12,960 kWh[a]	0.0375 USD/kWh[c]	486	17.36
Heat Pumps (this study)	4634 kWh[d]	0.0375 USD/kWh[c]	173.8	6.21
Heat Pumps (conservative)[e]	6524 kWh	0.043 USD/kWh	280.5	10.02

[a] Average coal consumption was estimated to be 3.5 t in Ger households in Ulaanbaatar by the World Bank, as reported in (Bank, 2009). The same report also evaluated the cost of heating with electricity, used in the “Direct Heating” scenario.

[b] The average price of coal was reported to be approximately 71 USD per ton in January 2018 (Xinhua, 2018).

[c] The cost of electricity was reported by the Ministry of Energy of the Government of Mongolia in August 2018 (Ministry of Energy - Government of Mongolia, 2018) with two rates, one for daytime (0.043 USD/kWh) and another for nights (0.032 USD/kWh). The mean value was used for the “Direct Heating” and “Heat Pumps (this study)” estimates.

[d] Electricity usage is based on the average kWh/m^2 among Ger households.

[e] The upper bound of electricity costs (Ministry of Energy - Government of Mongolia, 2018) was used in this scenario. To estimate consumption, the value of kWh per m^2 from the least efficient household from this study was used.

(0.13) A table of regression coefficients and semipartial, partial, and Pearson correlation coefficients for each included variable is in SI Table S3.

4. Discussion

We report on the performance of two-stage compressor heat pumps in the cold climate of Ulaanbaatar, Mongolia. While our findings are highly promising, our sample is too small to justify a major investment in HPs to address UB's air pollution situation. These findings, however, do justify a larger demonstration project which is currently being planned and which will include more objective measures of coal stove and energy use and will measure the impact of HPs on indoor and outdoor air pollution.

Table 2 shows an approximate variable cost comparison of a HP under two scenarios and two other alternative heating options in the city for a typical ger of 28 m^2. With the assumptions shown (derived from the work reported here and from the World Bank (Bank, 2009) and the Mongolia Ministry of Energy), HPs are substantially cheaper to operate than simple resistance heating – about half the cost. They are between approximately one-quarter cheaper and slightly more expensive than the cost of using a coal stove, but substantially cleaner. The upfront cost of the HP itself and upgrades to the power system in many neighborhoods would need to be incorporated into any large-scale assessment of costs (as was done for electric heaters in (Bank, 2009)), but the variable costs seem manageable compared to current practice, i.e. the purchase of coal.

The heat pumps used in this study are designed to produce a more uniform temperature profile in the room where they are installed when compared to other options, like coal stoves or resistive heaters. This is partly achieved by the location of inlets and outlets, ensuring better distribution of warm air throughout the indoor environment (see photos in SI Fig. S5). This produces a substantially different temperature profile than do coal stoves, however, which are very hot near the stove with colder areas in other parts of the room. We believe that the high temperature setting observed in some homes may be because (1) people tried to recreate the temperature profile of the coal stove and (2) households were not paying for power during this study and thus had no incentive to optimize between energy conservation and comfort.

Operator behavior appears to influence the cost of using the HPs; any large-scale introduction of them should consider field-tested training and education, in particular so the households understand how much money they could save if temperatures are set at reasonable levels (20–22 °C) and the fan speed is kept on high. Like many other modern heaters and air conditioners, the HPs evaluated in this study can be programmed so that settings change automatically at preset times, perhaps making these types of behaviors easier to implement and enforce.

Air-to-air HPs have advantages beyond being clean at the household level. They circulate warm air more uniformly throughout the room, as previously mentioned. Unlike other options, they have no hot temperatures anywhere in the system and thus pose lower fire and burn risks. They are not damaged by freezing temperatures and they can be transferred from one house to another if a family moves, since they require no special piping, as do geothermal-type heat pumps. They offer flexibility in control and can be switched to a cooling (air-conditioning) mode in summer.

A concern with large-scale implementation of these types of HPs is the strain it may put on the grid during peak demand periods. Performance and power use data from the heat pumps we evaluated go in one direction to inform the central facility about performance; they are capable of bidirectional communication, which would enable HPs to be turned on and off as part of a demand management system to manage peak load. As long as the indoor air and walls are heated, homes with space heating will likely not cool down over a short period of time due to the thermal inertia of the building (Le et al., 2017). This type of cycling may enable flexibility by enabling peak power load regulation.

Beyond its small sample size, our study had additional limitations. First, because we provided free electricity to households, we were unable to assess switching between heat pumps and coal that may occur. Future interventions should evaluate use of both stoves and measure coal and electricity consumption to provide more refined estimates of cost and behavior. Second, a larger sample size would have enabled more sophisticated statistical modeling at the household level. Future work should evaluate different size heat pumps in different housing styles to establish if a single heat pump size is sufficient across housing types in UB. Finally, our cost analysis was based on average values of variable costs throughout a winter season. Future work should better characterize fuel and electricity use cases for different heaters and how they change over a winter, as the temperature profile changes. It should also consider the cost of upgrades to the electricity distribution system and any additional generation that would be required to meet the needs of a large-scale deployment.

Introducing electricity-based clean heating, of course, raises a set of complex issues involving cost, imports, power supply and balance, reliability, climate-relevant emissions, the shift of emissions from households to power plants, household behaviors, and potential changes in air pollution concentrations and exposures. While the current study's sample size is small, it provides enough confidence to move forward with a more thorough evaluation of HPs in UB.

Acknowledgements

We thank our participating households and field teams from Hurgult Service and the Mongolian University of Science and Technology. We greatly appreciate the assistance of Gree Corporation of Zhuhai, which provided heat pumps at a substantial discount and arranged for their shipment and installation. They also provided weekly data reports on performance of the installed heat pumps. Gree had no role in writing this paper or in the analysis of data. We appreciate the cooperation of the Ministry of Energy and the UB Electricity Authority. We also acknowledge the support of and insights gleaned from Dr. Oyun Sanjaasuren.

Supporting information

Supporting Information is available and includes information about calculation of the Coefficient of Performance and additional figures and tables.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.envres.2019.03.019.

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