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Impact Evaluation Results of the MCA Mongolia Energy and Environment Project Energy-Efficient Stove Subsidy Program

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Impact Evaluation Results of the MCA Mongolia Energy and Environment Project Energy-Efficient Stove Subsidy Program

Prepared by Social Impact, Inc.
for the Millennium Challenge Corporation

August 20, 2014

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IV. ACRONYMS AND TERMS

ALRI	Acute lower respiratory infection
CO	Carbon monoxide
CO_2	Carbon dioxide
CH_4	Methane
DALY	Disability-adjusted life year
DEM	Data entry monitoring
DPE	MCC Department of Policy and Evaluation
DQM	Data quality monitoring
EC	Elemental carbon
EEP	Energy and Environment Project
ERR	Economic rate of return
Ger	Traditional house structure typically used by nomadic Mongolian herders, also found in peri-urban areas
GC FID	Gas chromatography flame ionization detector
GHG	Greenhouse gases
GIS	Geographic information system
HH	Household
HOB	Heat-only boiler
IE	Impact evaluation
JVRIPSL	Joint Venture of Robust and Institute of Philosophy, Sociology, and Law
ITT	Intention to treat
Khoroo	Administrative unit of Ulaanbaatar representing a subdivision of a district analogous to a neighborhood
MCA	Millennium Challenge Account, Mongolia
MCA stove	MCA Mongolia-supported energy-efficient stove
MCC	Millennium Challenge Corporation
MCEEIF	Millennium Challenge Energy Efficient Innovation Facility
MMITT	MCA-Mongolia Indicator Tracking Table
MUST	Mongolian University of Science and Technology
NAMHEM	National Agency for Meteorology Hydrology and Environmental Monitoring
NIST	National Institute of Standards and Technology
OC	Organic carbon
PCA	Principal component analysis
PIU	Project Implementing Unit
$PM_{2.5}$	Particulate matter sized below 2.5 micrometers
PMT	Proxy means test
PSM	Propensity score matching
SD	Standard deviation
SE	Standard error
SEET	Stove Emissions and Efficiency Testing laboratory, Asian Development Bank
SI	Social Impact
SUM	Stove use monitor
THC	Total hydrocarbons
UB	Ulaanbaatar, Mongolia

V. ACKNOWLEDGMENTS

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VI. EXECUTIVE SUMMARY

Ulaanbaatar, Mongolia (UB) has been called both the coldest capital city and the second most polluted city in the world (World Bank, 2012; Walsh, 2011). Air quality is worst in the winter, when daily temperatures can drop below -40 °C and average daily concentrations of fine particulate matter ($PM_{2.5}$) can be 15 times higher than the WHO guidelines established to minimize morbidity and mortality risk (Allen et al., 2013; Correia et al., 2013). During the winter months (approximately October-March), residents of Ulaanbaatar's peri-urban "ger district" [4] typically use coal-burning stoves to heat their homes on a nearly continuous basis (Figure 1). The heavy use of coal in residential stoves is a major source of pollution, estimated to contribute up to 70% of $PM_{2.5}$ in the ger district (World Bank, 2009). Visibly poor air quality is of critical concern to residents of UB, the Mongolian Government, and global air quality experts. The economic burden of stove fueling is also seen as an impediment to poverty reduction, as annual fueling expenses can amount to 40% of income within the poorest wealth quintile (World Bank, 2009).

Figure 1. Residential stove smoke in Ulaanbaatar's ger district

To address this issue, the U.S. Millennium Challenge Corporation (MCC), through its compact[5] with the Government of Mongolia, introduced the Energy and Environment Project (EEP) in 2011 to reduce air pollution in part through limited financial support for commercially viable energy efficient appliances, such as stoves. Through consumer subsidies to encourage the purchase of energy-efficient stoves, this activity aimed to reduce stove emissions of PM, thereby reducing health expenses and lost productivity due to air quality-related illness. In addition, the increased stove efficiency was posited to reduce fuel use and, as a consequence, fuel expenditures. These effects were expected to contribute to economic growth and poverty reduction. This report presents findings and conclusions from the data collection and results of the impact evaluation of this portion of the program,

[4] Gers are round traditional Mongolian homes, referred to as yurts in other countries, which can be disassembled and transported to accommodate a nomadic lifestyle. Many migrants to the capital city have established their gers in outskirt areas of UB, thereby receiving the name "ger district." However, both gers and standard houses are located in these areas.

[5] Compacts are large five-year grants awarded by MCC to countries that meet its eligibility criteria.

conducted by Social Impact during the 2012-2013 winter.

vi.i. Overview of Compact and Intervention

The consumer subsidy program was part of a five-year USD $285 million compact between MCC and the Mongolian Government, which ended in September, 2013. It was one component of the Energy and Environment Project's Millennium Challenge Energy Efficiency Innovation Facility (MCEEIF), which provided consumer subsidies to encourage adoption of energy-efficient and lower-emissions products and homes, among other activities. More specifically, the project also included consumer subsidies for ger insulation, consumer subsidies for approximately 100 energy efficient homes in place of gers, implementation of a large greening program in the ger districts, replacement of inefficient heat-only boilers at 10 ger district sites, and the displacement of 50MW of coal-fired electric generating capacity, the impacts of which are not evaluated. Approved as part of a compact restructuring activity, the Project Implementing Unit (PIU) was not formed until April 2010. As part of its initial activities, the PIU reviewed, selected, and tested various energy-efficient stove models and selected those meeting a set of criteria, such as lowered emissions and coal use, cost-benefit analysis, and market viability. Four stove models were selected: Ulzii (Silver mini) and Khas (Silver turbo) stoves, manufactured in Turkey and distributed in Mongolia by the Selenge Construction company, and Dul (Royal Single) and Golomt (Royal Double) stoves, manufactured in China and distributed in Mongolia by the Royal Ocean company. All stoves except Golomt (the "MCA stoves") were included in this evaluation, as Golomt was supported with project subsidies in 2011-2012, but not supported with project subsidies in 2012-2013, since its production was discontinued.

For optimal efficiency, MCA stoves ("top-lit-up-draft" design) required modified operating procedures. While traditional stove users typically pour coal on top of lit kindling and add coal to the burning stove as needed, the MCA stoves are most efficient when the stove is fully loaded with coal and kindling is lit atop the pile of coal. Fires should be completely extinguished prior to refueling the stove with coal (i.e., only cold starts and no warm refuelings). These modified procedures place the combustion zone on top of the coal where volatile gases and particulate matter from heating unburned fuel pass through the combustion zone, thus reducing $PM_{2.5}$ emissions; unlike traditional stove usage procedures where heat travels up through the coal bed. Since the combustion zone is at the top, this limits the heating of unburned coal underneath, thus preventing all coal burning at the same time (as in traditional stoves). This slows coal consumption, reduces excessive loss of heat to the atmosphere, keeps the dwelling warmer for longer, and reduces coal use. Laboratory tests commissioned by the PIU found that Ulzii, Khas, and Dul stove models are capable of reducing $PM_{2.5}$ emissions by 70-89% and coal consumption by 11-26%. However, consumers' failure to comply with modified operations procedures in addition to fuel type, loads, incorrect adjustment of air intake registers, etc. could limit these impacts.

Once MCA stoves were selected and subsidy levels set, they were marketed widely through the Project's Public Awareness

Activity and made available for purchase through product centers, temporary showrooms established by the PIU in ger districts, and hosted by marketing staff and subsidy transfer agent (participating banks) staff, each compensated by the Project. Additional products to improve ger insulation were also available through this program, including ger vestibules and packages of two felt insulation layers. While not the primary subject of this evaluation, this report presents some data on the influence of vestibules and felt insulation on the impact of the stoves.

vi.ii. Evaluation Type, Questions, and Methodology

This impact evaluation assessed stove performance and impacts under real-world usage conditions. It was designed to answer the following questions:

Evaluation question 1: How do energy-efficient products impact ambient air pollution levels, and health and income of residents in Ulaanbaatar? Specifically:

1. How does the use of MCA stoves affect fuel usage and expenditures?
2. Does the use of MCA stoves affect available household income?
3. What is the impact of MCA stoves on emissions of CO and PM2.5?
4. What is the impact of MCA stoves on indoor concentrations of CO and PM2.5?
5. What would be the estimated change in health for Ulaanbaatar residents?
6. How do MCA stoves affect household expenditures related to respiratory health problems?

Evaluation question 2: How do different MCA stove models and different patterns of usage affect the level of impact on ambient air pollution, and the health and income of households with MCA stoves? Specifically:

1. Do different MCA stove model types impact fuel expenditures, income, and PM2.5 emissions, under typical usage behavior?
2. Do deviations from expected MCA stove usage patterns impact air pollution, health, and income of households with MCA stoves?
3. Did the MCA stove program result in differential impacts on men and women?
4. Does possession of additional energy efficiency products such as vestibules or additional ger insulation modify the impact of MCA stoves on ambient air pollution, health, and income?

Since this program was a market-based intervention, households chose whether to purchase an MCA stove. Because a randomized intervention assignment was not possible and the evaluation was implemented after the project had started, a **quasi-experimental propensity score matching (PSM) design** was used to adjust for differences between those who did and did not choose to purchase an MCA stove. Matching on propensity scores enabled construction of treatment and comparison groups that were balanced along the observed characteristics, thereby providing a counterfactual for the intervention.

Pilot data were collected in the second half of the 2011-2012 winter in order to calibrate measurement methods and sample sizes for the full evaluation. The full evaluation was conducted during the 2012-2013 winter heating season, and its results are presented in this report. Data were analyzed from several sources:

1. Panel data from three **household surveys** of 1,057 randomly sampled gers and houses with traditional or MCA stoves provided data on fuel consumption and stove usage patterns over the course of the winter, demographic and economic characteristics, dwelling characteristics, and stove perceptions.
2. Electronic **stove use monitors (SUMs)** recorded fueling event and temperature data, used to triangulate household survey findings. SUMs obtained stove temperature measurements at 10-minute intervals in a random subsample of 421 households and room temperature measurements in 396 households over more than 100 days of the winter.
3. **Household stove emissions and indoor air quality measurements** of PM2.5, CO, and other pollutants were obtained from a random subsample of 143 gers and houses throughout the winter using a variety of sampling equipment.
4. **Ambient air quality modeling** estimated changes in stove contributions to ambient PM2.5 levels in light of MCA stove sales throughout UB, compared to a hypothetical counterfactual in which all households were still using traditional stoves. The modeling utilized this evaluation's emissions measurements and household survey coal consumption data, combined with population and meteorological data and geographic locations of MCA stove purchasers.

vi.iii. Key Findings

vi.iii.i. Air pollution

Participants in the EEP stove subsidy program had 65% lower emissions of $PM_{2.5}$ and 16% lower CO emissions, both statistically significant, compared to traditional stoves under typical usage conditions. These reductions were calculated from household emissions measurements weighted by the MCA stove sales in UB. Ulzii stoves significantly reduced $PM_{2.5}$ emissions by 74% in houses and 83% in gers. Smaller reductions were also observed for Khas stoves in houses (46% reduction) and Dul stoves in both houses and gers (reductions of 31% and 38%, respectively) compared to traditional stoves, but the Khas and Dul results were not significant, potentially due to low sample sizes which reflected fewer sales of these models. Moreover, there was evidence that MCA stoves reduced indoor CO concentrations and the associated health risks compared to traditional stoves.

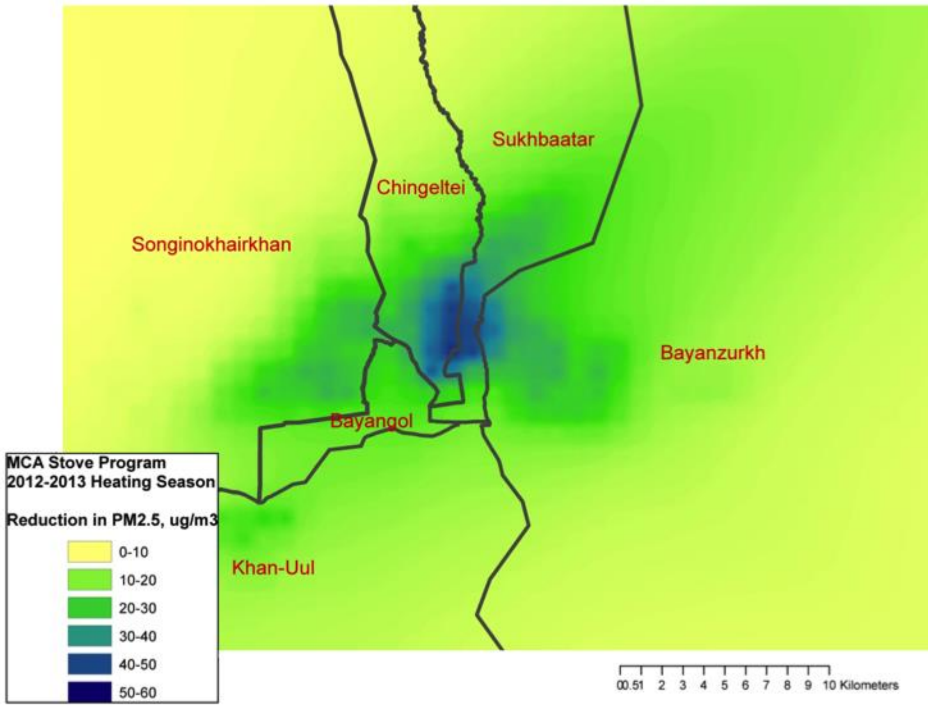


Figure 2. Average reductions in ambient $PM_{2.5}$ mass concentration resulting from the MCA stove program, modeled for the 2012-2013 heating season (October-March).

The EEP stove subsidy program reduced ambient $PM_{2.5}$ concentrations over UB attributable to heating stoves by an estimated 30%, with largest reductions in highly polluted areas that were more heavily targeted by the program. Air quality modeling calculated the reductions in pollutants under current conditions, compared to a hypothetical counterfactual of all households using traditional stoves (Figure 2). Reductions of up to ~50 $\mu g/m^3$ (at the location of maximum impact) and ~20 $\mu g/m^3$ (population weighted across the city) were estimated for the entire heating season.

vi.iii.ii. Stove usage patterns

Factors known to affect coal consumption differed systematically between Ulzii, Khas, and Dul stove users, including greater usage for cooking among Dul stove owners. Different types of households purchased different models of MCA stoves. Since Khas stoves were marketed as appropriate for larger houses, 91% of Khas stoves were found in houses; only 17 were in gers. Per usage recommendations, Ulzii were generally used in smaller homes with main rooms measuring 59 cubic meters (m^3), on average, whereas Dul and Khas owners had larger homes, on average: 66 m^3 and 93 m^3, respectively. While 81% of traditional stove owners used their stoves for cooking and heating (Figure 3), only Dul stove owners used stoves in a similar way, with 79% using their stove for both purposes. Only 54% of Ulzii and 61% of Khas owners used their stove for both purposes.

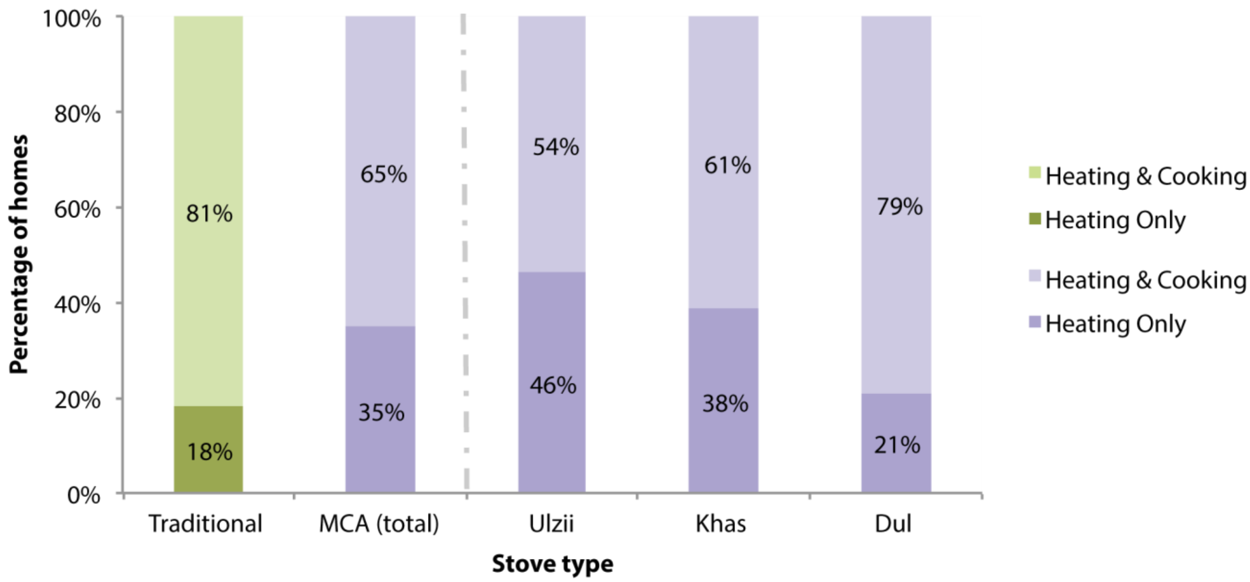


Figure 3. Stove usage for cooking and heating by stove type (winter average).

vi.iii.iii. Satisfaction and demand

The EEP stove subsidy program achieved high demand for energy-efficient stoves and satisfaction among stove users; however, some stove limitations remained barriers to satisfaction. Among those without an MCA stove, 78% wished to acquire one, citing fuel savings, pollution reduction, and longer heating duration as the top reasons. Only 7% cited the subsidized price as a compelling factor. The large majority of MCA stove owners believed their stove was superior to a traditional stove in terms of appearance, pollution reduction, fuel economy, ash maintenance, and maintaining heat longer. Areas of dissatisfaction included difficulties cooking with MCA stoves, higher burn risk, and greater effort required to start a fire. Opinions of MCA stove performance compared to traditional stoves were nearly the same between male and female stove tenders; the rating differences between men and women were three percentage points or less for most categories. Among traditional stove owners, many factors driving demand for MCA stoves were similar between male and female-headed households; however, the greatest differences between these groups related to financial concerns. More female-headed households than male-headed households cited fuel expense savings as a reason for wanting an MCA stove (86% versus 74%). Female-headed households with traditional stoves who did not plan to purchase an MCA stove were more likely to cite a lack of funds as a reason (18% versus 2% of male-headed households).

vi.iii.iv. Coal consumption

The EEP stove subsidy program did not achieve significant reductions in daily coal consumption under typical usage conditions. MCA stove owners fueled their stoves less often, but with more coal per fueling, resulting in no significant differences from traditional stoves in coal consumption. Averaged across three data collection phases, MCA stove users performed 0.33 fewer daily fueling events than traditional stove users ($p<0.001$) but utilized 0.72 kg more coal (p=0.001) on average at each fueling (a 14% increase), thereby equalizing total daily quantities of fuel used by the two groups (Figure 4a-c). Results were largely consistent across data collection phases, stove types, dwelling types, heating wall presence, the sex of the stove tender, and after adjustment for the volume of the heating space.

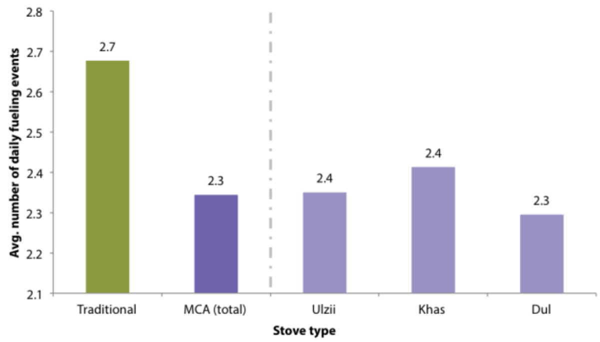


Figure 4a. Average daily fueling events, by stove type.

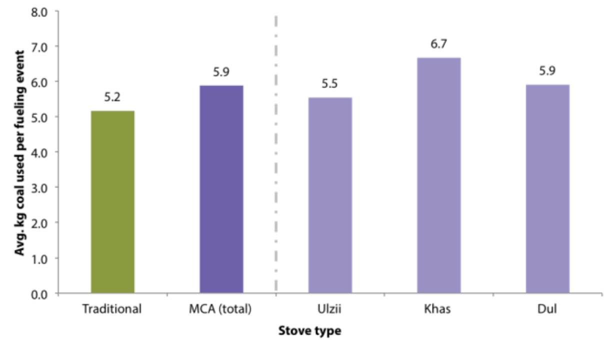


Figure 4b. Average quantity of coal used per fueling event, by stove type.

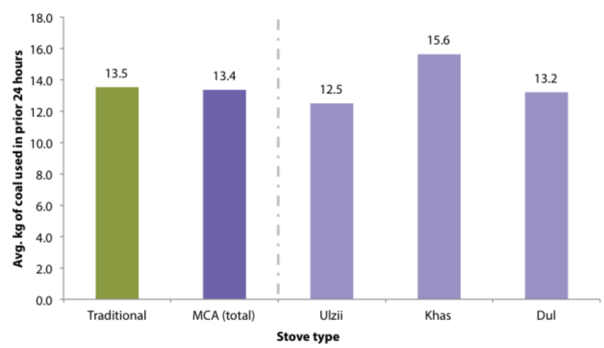


Figure 4c. Average daily quantity of coal used, by stove type.

vi.iii.v. Compliance with operation instructions

Very low compliance with MCA stove operation instructions may have contributed to lack of reduced coal consumption. Only 4% of MCA stove owners were consistently compliant with stove use instructions, reporting no warm refuelings the prior day and lighting their stove from the top of the coal bed in all three data collection phases. Compliance varied over time, dropping sharply in the coldest part of winter. On average, MCA stove owners reported 1.64 warm refuelings and 0.69 cold starts each day, implying that many households were only conducting warm refuelings (Figure 5). The poorest 40% of households, defined using a wealth asset score, were significantly less likely to be compliant than more economically advantaged MCA stove owners. Compliance with both cold start and top-light instructions throughout the winter was reported by 2% of the poorest households, compared to 6% of the wealthiest households (p=0.012). One possible reason for this finding is that dwelling construction quality may be lower among the poor, resulting in reduced insulation efficiency. Compliance did not differ significantly between male and female stove tenders.

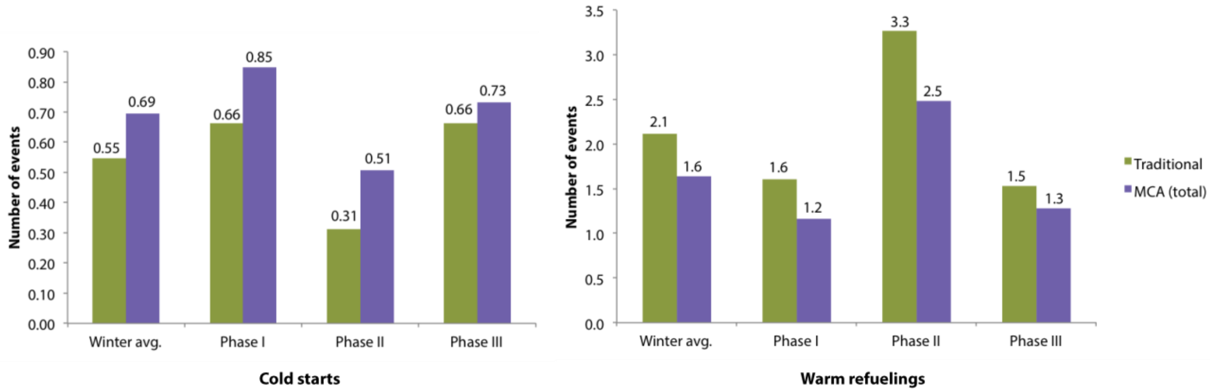


Figure 5. Average daily cold starts and warm refuelings, by phase.

Significant reductions in coal use were observed when households used MCA stoves according to instructions. When fuel consumption was compared between MCA stove users correctly following use instructions and traditional stove users, MCA stove users were observed to have highly significant, 17% reductions in daily coal consumption ($p<0.01$). For this subgroup, reductions in coal consumption compared to traditional stoves projected across the winter approached laboratory findings: Ulzii stoves reduced coal consumption by 24% ($p<0.01$); Khas by 7% (not significant); Dul by 13% (Phase I-II not significant; Phase III $p<0.01$).

Households using MCA stoves enjoyed significantly higher indoor temperatures, suggesting that users may be sacrificing fuel economy for comfort. In spite of using approximately the same quantities of coal daily, MCA stove owners kept their homes up to 2 °C warmer, on average, than traditional stove owners. This suggests that while MCA stove owners may be able to maintain the same temperatures as traditional homes with less coal, they either choose to maintain a more comfortable home temperature, are accustomed to following coal use and purchasing habits previously practiced with traditional stoves, or otherwise have not succeeded in changing their behavior. This may be evidence of a *rebound effect* in which consumers reduce net energy efficiency improvements by compensating with inefficiencies in other areas. Alternatively, in light of the lack of fuel reductions, temperature differences provide evidence that MCA stoves were burning hotter, but not over a longer duration (i.e., specific coal consumption rates were not reduced).

vi.iii.vi. Fuel expenditures

There is no evidence that the EEP stove subsidy program achieved reductions in overall coal expenditures. No significant differences in spending on coal were observed between MCA and traditional stove owners. Among the poorest 40% of households, MCA stove owners spent an average of MNT 7,184 more on coal each month ($p=0.052$). Similarly, among female-headed households, MCA stove owners spent MNT 10,614 more on coal per month (p=0.056). While the reasons for these effects experienced by the disadvantaged groups are not known, government coal subsidies at the time of the evaluation may have affected the fuel market such that coal expenditure estimates may be unreliable or difficult to understand. Without further investigation, it is not possible to draw decisive conclusions about the program's impact on fuel expenditures from this evaluation or why particular trends are observed. Since the study finds no overall difference in daily coal consumption, minimal change in fuel expenditures are expected.

vi.iii.vii. Effect of home insulation

MCA stove owners in gers with better insulation used less coal than traditional stove owners. MCA stove owners in gers with three or more layers of felt insulation used 2.23 kg less coal each day than traditional stove owners with the same level of insulation (p=0.093). Those with two or fewer layers used approximately the same quantity of coal as traditional stove owners. This suggests that insulation may be a key factor that can either facilitate or inhibit fuel saving benefits of energy-efficient stoves. The presence of a vestibule at the door did not have a significant impact.[6]

vi.iii.viii. Health impact

Observed emissions reductions may have contributed to substantially fewer cases of air pollution-related respiratory illness and related costs. Health impacts were not directly measured by the data collection efforts but were based on estimates of population-weighted annual exposures to $PM_{2.5}$ using methods developed for a health burden assessment commissioned by the Ministry of Environment and Green Development (MEGD, 2014). The analysis of premature mortality and morbidity for 2012 utilizes the results of the Comparative Risk Assessments of the Global Burden of Disease Project (Burnett et al., 2014; Lim et al., 2012; Smith et al., 2014), which quantify $PM_{2.5}$ dose-response functions for five primary diseases: lung cancer, acute lower respiratory infection for ages 0-4 years (ALRI), chronic obstructive pulmonary disease, ischemic heart disease, and stroke. Under a scenario with the MCA stove program compared to a scenario with all traditional stoves, the MCA stove program reduced population-weighted annual average exposures to $PM_{2.5}$ in Ulaanbaatar by an estimated 11.5%. For 2012, this exposure reduction would imply a 9% reduction in the incidence of air pollution-related lung cancers, an 8.3% reduction in the incidence of air pollution-related chronic obstructive pulmonary disease, an 8.1% reduction in the incidence of air pollution related ALRI in children between 0-4 years old, a 4.9% reduction in the incidence of air pollution related ischemic heart disease and 2% reduction in the incidence of air pollution related strokes. Overall this would result in a reduction of 47 deaths and 1,643 DALYs, which under the ERR assumptions of the MCA project would result in 3.9 million USD in productivity gains for the 2012-2013 heating season. It is important to note that these estimates focus only on one year of impacts (2012-13), and the overall impacts of the stove program should be assessed over the functional lifetime of the MCA stoves.

[6] It should be noted that the project team considered bundling the products (e.g., buying the stove and insulation together would result in a higher subsidy than the sum of the two), but this program feature was ultimately not implemented.

vi.iv. Recommendations for Future Programs and Studies

- **Barriers to compliance with cold start procedures should be studied and addressed to achieve expected fuel savings.** While all MCA stove owners reported receiving stove operation instructions and were likely aware that they should utilize only cold starts with MCA stoves, compliance appears challenging in UB's extreme cold conditions. Waiting for the stove to be fully extinguished prior to refueling may be highly uncomfortable, especially in poorly insulated homes. This might be especially challenging for poorer households if they reside in dwellings that are of lower quality. Future interventions could consider complementing stove acquisition with higher insulation efficiency to facilitate cold start compliance and optimal fuel savings. Compliance with instructions may also be challenging if the stove is being used to cook, requiring the refueling of an already burning stove to enable cooking at a desired time. Qualitative research among both high and low compliers may illuminate strategies to improve future interventions, usage training, information outreach, or stove design.
- **Future work should evaluate the performance of MCA stoves with different coal types.** The coal varieties used by residents in stoves during the 2012-2013 winter varied greatly. This evaluation did not capture enough specific data to assess directly the influence of coal type on stove performance. Each coal type has unique calorific value and emissions potential. Emissions levels are affected by both the stove and the coal type used; therefore, it is important to assess the impact of various types of coal and other fuels on stove efficiency, especially those that may be considered for marketing or subsidy in the future.
- **Future studies could measure fueling behavior with higher detail and precision.** Though triangulated data support the accuracy of recall of fueling events by respondents, uncertainty remains. Future studies could use a more detailed survey of fuel consumption with documentation and direct weighing of each fuel type present in the home over a period of several days. The use of SUMs was found to be highly valuable to help estimate fueling behavior and is recommended for future studies.
- **Future studies should investigate gender differences in stove usage and project impacts.** While gender impacts of cookstove projects in other regions have been documented, these findings may not be fully applicable in Mongolia, where stoves are primarily used for heating and where there is greater gender equity than in many African or Asian countries.[7] Further qualitative exploration of gender differences in this Mongolian context would provide valuable information to the sector and help answer the questions raised in this evaluation. This evaluation shows few gender differences in stove preferences and use. A key exception is the higher fuel

[7] Source: http://datatopics.worldbank.org/gender/country/mongolia

expenditures among female-headed households, for which explanations should be investigated further. It would also be beneficial to examine whether MCA stoves result in time usage efficiencies, particularly for women, who represent the majority of stove tenders.

- **Future studies should better quantify assumptions used in estimating the impact of stoves on air quality.** While stove emission testing in this impact evaluation was conducted using best-practice methods, the actual emissions would also include additional PM formed when the stove chimney exhaust mixes with the cold outdoor air. Heating stove emissions estimates from this study do not account for this process, which is particularly relevant in the presence of extreme cold conditions of Ulaanbaatar in the wintertime. This effect needs to be quantified to better understand heating stove contributions to air quality in Ulaanbaatar and the impact of adopting improved stoves.
- **Future studies should seek better measures of household income and expenditures, to yield more accurate estimates of income effects.** Reported household income as measured in our study is likely to be unreliable and underreported. Expenditures on food and household goods from the prior month proved highly difficult for respondents to estimate, particularly around the time of Lunar New Year celebrations when household expenses were atypical. A wealth asset score constructed using the household's ownership of various luxury items was found to be the most reliable, though imperfect, measure of household wealth, but could not be used to estimate income effects. Further study is also warranted to examine reasons behind the higher coal expenditures for poor households and female stove tenders with MCA stoves.

1 INTRODUCTION

Ulaanbaatar, Mongolia has been called the coldest capital city in the world, with average winter temperatures ranging from -20 °C during the day to -40 °C at night (World Bank, 2012; Norwegian Meteorological Institute, 2013). Residents of Ulaanbaatar's peri-urban "ger district"[8] settlements typically use coal-burning stoves to heat their homes throughout the winter months (October-March).

The heavy use of coal in residential stoves has been cited as a major contributor to the deterioration of air quality in UB (see Figure 6), with one report estimating 70% of $PM_{2.5}$ in the ger district attributable to residential heating. Automobile emissions, municipal heat and power plant emissions, and dust are among other sources. Air quality is the subject of heightened attention and concern among residents of UB, the Mongolian Government, and global air quality experts. A recent study found annual average concentrations of $PM_{2.5}$ (fine particulate matter pollution) more than seven times above the World Health Organization guideline of 10 $\mu g/m^3$, and wintertime averages were nearly double the annual averages (Allen et al., 2013). UB has been called the world's second most polluted city (Walsh, 2011). Air pollution, at levels much lower than that of UB, has well established, consistent associations with increased morbidity and mortality, incurring substantial economic costs (Correia et al., 2013).

The cost of fuel in this context can represent a substantial economic burden, particularly for the many lower income households. At the height of the heating season, ger households may spend an estimated 1,750MNT (USD $1.05) per day on fuel, a substantial financial commitment for poor families (Office of the Mayor of Ulaanbaatar, 2008). One study estimated that for people in the lowest wealth quintile of Ulaanbaatar (UB), fuel amounted to up to 40% of income, with the average ger household consuming approximately 4.2 tons of raw coal and 4.7 cubic meters of wood for heating and cooking during a full heating season (winter) (World Bank, 2009).

Photo: Rufus Edwards

Figure 6. Winter afternoon smog seen from UB's Sukhbaatar Square.

To address these critical public health issues and the economic implications of continued residential heating, the U.S. Millennium

[8] Gers are round traditional Mongolian homes, referred to as yurts in other countries, which can be disassembled and transported to accommodate a nomadic lifestyle. Many migrants to the capital city have established their gers in outskirt areas of UB, thereby receiving the name "ger district." However, both gers and standard houses are located in these areas.

Challenge Corporation (MCC), through its compact[9] with the Government of Mongolia, introduced a subsidy program to encourage the purchase of energy-efficient, low-emission residential heating stoves to replace less efficient traditional stoves. In order to measure the impact of this program on fuel consumption and air pollutant emissions, among other outcomes, a rigorous impact evaluation was conducted during the winter of 2012-2013. This report presents the results and conclusions of this evaluation.

1.1 Overview of Mongolia Compact and Energy and Environment Project

In 2007, MCC signed a USD $285 million compact designed to increase economic growth and reduce poverty through investments in land tenure, health, vocational education, and transportation in Mongolia. As with all MCC compacts, priorities were driven by the local government. In 2010, the compact was amended to reflect an additional $45.3 million investment priority focusing on energy and the environment: the Energy and Environment Project (EEP), representing 16% of the total compact investment. The Millennium Challenge Account, Mongolia (MCA), managed the implementation. On September 17, 2013, the five-year Mongolian compact officially ended.

The EEP aimed to reduce air pollution in UB by financially incentivizing the adoption of energy-efficient technology, as well as displacing up to 50MW of coal-fired electricity generating capacity by upgrading the electrical transmission and distribution network. This project consisted of three activities:

1. The **Millennium Challenge Energy Efficiency Innovation Facility (MCEEIF)**, which provided consumer subsidies for the purchase of energy-efficient and lower emissions products and homes, technical assistance in assessing the viability of such technologies, and funds to replace existing outdated heat-only boilers (HOBs) that contribute to air pollution.
2. The **Wind** activity, which provided electric transmission and distribution facilities upgrades to facilitate the introduction of wind power, expected to produce at least an additional 50 megawatts of power.
3. A **Public Awareness** activity, which aimed to increase consumer awareness of renewable energy, energy efficiency, and its benefits; timeliness and availability of subsidies; and participating partners from whom they could seek products.

This evaluation is designed to evaluate only the stove and insulation components of the MCEEIF. The primary goal for the MCEEIF is to reduce air pollution and associated health problems and expenditures, and to increase available income through financial savings associated with reductions in fuel expenditures by helping the residents of Ulaanbaatar adopt more energy-efficient and lower emissions technologies. These effects are anticipated to contribute to economic growth and reduce poverty. The implementation of the MCEEIF included several components:

[9] Compacts are large five-year grants awarded by MCC to countries that meet its eligibility criteria.

1. Energy-**efficient household wood/ coal stoves:** Subsidies were provided to consumers of 103,255 stoves to be used for heating and cooking (MCA-Mongolia, 2013).
2. **Extra layers of ger insulation:** Over 20,000 subsidized sets of two additional ger insulation layers made of felted wool (Figure 7) were sold (MCA-Mongolia, 2013).
3. **Vestibules at ger entrances:** More than 5,000 subsidized vestibules (Figure 7) were sold (MCA-Mongolia, 2013). These are small structures at the entrance of a ger designed to separate inside and outside air to prevent heat loss, as with storm doors.
4. **Heat-only boiler (HOB) replacement:** Fifteen highly inefficient HOBs were replaced at 10 sites across UB (MCA-Mongolia, 2012).
5. **Energy-efficient homes:** Ninety-nine small houses were built with advanced technology to save thermal energy and reduce fuel consumption and particulate matter (PM) (MCA-Mongolia, 2013).
6. **Greening:** Thirteen small grants were awarded to winning project proposals for UB greening and air quality research activities (MCA-Mongolia, 2012).

This evaluation focuses on energy-efficient stoves; however, ger insulation, and vestibules were examined to the extent possible.

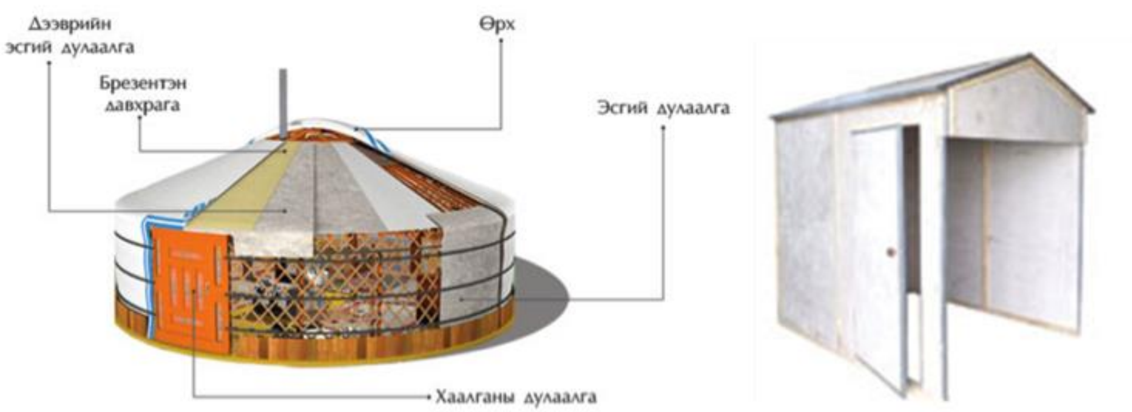


Figure 7. Ger insulation layers (left); ger entrance vestibule (right). *(Source: MCA promotional materials)*

1.2 Stove Replacement Project Logic

The introduction of subsidized energy-efficient, low-emission stove options, in conjunction with widespread marketing through various media, was expected to increase ownership and usage of these improved stoves across targeted sub-districts among the most air-polluted in Ulaanbaatar. According to manufacturers and limited laboratory and field-based testing, if energy-efficient stove models are used according to manufacturer instructions, these stoves have lower emissions, utilize less coal and lead to decreased fuel expenditures.

Figure 8. Typical traditional stove fueling behavior.

Typically, in a traditional stove, Mongolians first light wood and other kindling and then add a pile of coal to the top (Figure 8). Additional coal is added to the burning stove throughout the day to ensure continuous heating. This placement of coal on top of the combustion zone increases the quantity of volatiles released from the coal, including particulate matter and carbon monoxide, which are discussed below. Conversely, energy-efficient stoves are designed so that users place coal in the stove first and then create a combustion zone of wood and kindling on top, which radiates heat down through the coal to keep the stove burning (Figure 9). Stove fires are to be completely extinguished prior to refueling, as the addition of coal to an ignited pile of coal would replicate traditional stove operation. Improved stove design (restriction of the coal burn) is meant to retain heat for longer-lasting effects, thereby requiring only approximately two “cold start” fueling events per day and reducing the quantity of coal necessary. Failure to follow instructions could decrease the reductions in coal use and emissions (Maddalena et al, 2012).

Figure 9. Energy-efficient stove design.
(Source: “Royal Stove Firing Instructions”)

As shown in Figure 10, the program logic follows that reductions in stove emissions and in coal use would contribute to the EEP compact-level goal of reducing air pollution, therefore improving respiratory and cardiovascular health outcomes, thus reducing associated costs of medical care and lost productivity. In addition, decreases in the amount of coal use would directly lead to fuel cost savings and increased available income for other purposes.

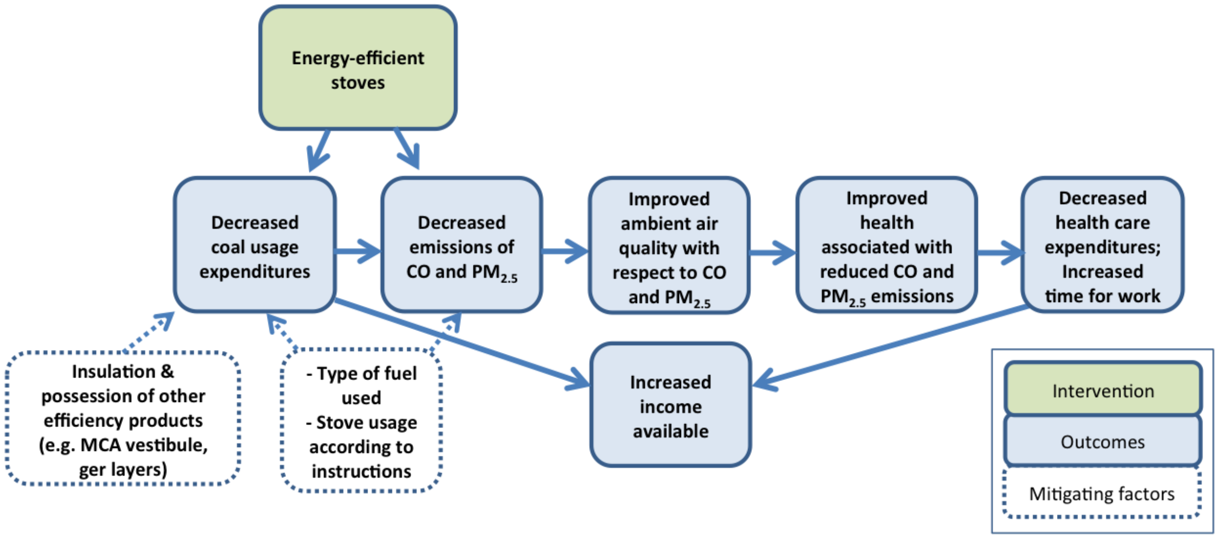


Figure 10. Program logic model for MCEEIF stove subsidy program.

1.3 Link to Economic Rate of Return

MCC calculated an economic rate of return (ERR) for the stove subsidy program based on a variety of assumptions including an anticipated 5% reduction in fuel expenditures and a 35% reduction in stove emissions. Following expected emissions reductions, the ERR accounted for anticipated reductions in the annual cost of treating respiratory illness, and improvements to productivity (measured in disability-adjusted life years, or DALYs). On average, the ERR projected that households using selected energy-efficient stoves would save MNT 279,396 (approximately $165) on fuel beginning in 2011, with savings reaching up to MNT 838,056 (~$495) in 2013. Accounting for inflation, population growth, the expected rate of stove adoption, an estimated 10-year stove lifespan, and numerous other factors, the ERR was expected to be up to 246% through 2023. This evaluation will enable MCC to update the underlying assumptions in a subsequent revision of the ERR.

1.4 Implementation Summary

The stove project was implemented by MCA Mongolia's Project Implementing Unit (PIU), which began with a product review process to identify commercially viable energy-efficient stove models, test emissions and efficiency performance, and assess cost-benefit and market viability. As a market-based intervention, one goal of the project was to provide consumers with a variety of stove models and other energy efficiency measures from which they could choose to meet their household needs rather than just one that performed most efficiently. The final field of stove candidates was tested by a team from the Mongolian University of Science and Technology (MUST) and the Ulaanbaatar City Air Quality Office with technical support from the Lawrence Berkeley National Laboratory. Stoves that met performance criteria in the temporary lab were then subjected to field-testing by MUST. The testing results, in combination with market and economic analysis, were used to select four stove models for the program: Ulzii (Silver mini) and Khas (Silver turbo) stoves, manufactured by Silver Company in Turkey and distributed in Mongolia by Selenge Construction company; and Dul (Royal Single) and Golomt (Royal Double) stoves, designed and distributed by the Royal Ocean company in Mongolia and manufactured in China (Figure 11).

Figure 11. Millennium Challenge Account Mongolia stove models.

MCA subsidy levels were established for each stove type based on performance and market analysis (Table 1). The Government of Mongolia added additional subsidies to supplement the MCA subsidies, amounting to an additional 5-96% of the MCA subsidy, and in effect setting the final price. After all subsidies, the consumers paid between 7-14% of the original stove price. Most subsidized stove prices were less than traditional stoves, which range from approximately USD $25 to USD $40. Prices, subsidy levels, and Government additions established for the initial rollout in the winter of 2011-2012 were adjusted the following winter. Golomt stoves were not supported by MCA in the winter of 2012-2013, due to discontinued production, and are therefore not included in the present evaluation.

Table 1. Subsidy structure for MCA stove models

	Stove name	Original price*	MCA subsidy	Government of Mongolia subsidy	Final price	US dollar equivalent*	% of original price paid by consumer
2012-2013 winter	Ulzii	357,720	279,000	51,220	27,500	$16.29	8%
	Khas	484,560	223,600	203,260	57,700	$34.18	12%
	Dul	283,767	244,100	11,367	28,300	$16.77	10%
2011-2012 winter	Ulzii	325,068	250,768	50,000	24,300	$14.40	7%
	Khas	459,250	208,450	200,000	50,800	$30.09	11%
	Dul	275,000	209,800	40,000	25,200	$14.93	9%
	Golomt	330,000	245,000	40,000	45,000	$26.66	14%

**All numbers are in Mongolian currency (MNT) unless otherwise noted. USD conversion based on rate at time of report*

MCA contracted a firm to market energy-efficient products through television and newspaper ads, brochures, personal outreach through community leaders, and other methods. Marketing materials advertised air quality and fuel savings benefits, based on the results of PIU managed testing, as well as the reduced stove prices (Figure 12). A gift card program was introduced for the benefit of the most vulnerable members of the community.

MCA administered subsidies and monitored sales of energy-efficient products through two Mongolian banks: Xacbank and Khan Bank. Consumers would first visit product centers—gers established throughout the ger districts to obtain information about stoves, vestibules, and ger insulation products, as well as view prototypes. Interested consumers who resided in districts slated for stove sales: Bayanzurkh, Chingeltei, Khan-Uul, Songino Khairkhan, and Sukhbaatar, were eligible to purchase a stove. After obtaining a purchase order at the product center, the consumer would visit a participating bank branch to pay the down payment. The stove was then delivered to the purchaser's home, and the traditional stove was removed and destroyed. The banks then intermediated payment to the producers from the consumer and MCA-Mongolia.

Xacbank began intermediation and monitoring of sales of vestibules, ger insulation, and project stoves in June 2011. By the end of March 2012, Xacbank had overseen 58,339 project stoves purchases in 47 sub-districts across five districts (Xacbank, 2012). Khan Bank's sales intermediation and monitoring began in August 2011 in only 3 sub-districts. In May 2012, Khan Bank had recorded sales of 4,590 project stoves (Khanbank, 2012). A total 103,255 stoves were delivered by the end of the project. XacBank reported demographic data for consumers purchasing stoves. Approximately 40% of those purchasing the stoves were female, and 29% of consumer households were female-headed. 75% of the clients lived in gers, and half of consumers reported a monthly household income of 151,000-350,000 MNT. A monthly income of 150,000 MNT or less was reported by 22% of households (XacBank, 2012). A survey by Khan Bank identified 34% of their consumer base as female compared to 66% male. The age distribution of consumers was largely evenly balanced (Khanbank, 2012).

Figure 12. Marketing materials on consumer benefits of MCA stoves.

1.5 Background

1.5.1 Health effects of $PM_{2.5}$ and CO

The burning of raw coal releases carbon monoxide (CO) and particulate matter (PM) both into homes and the outside air. CO is an odorless and colorless gas, while PM contains both liquid and solid matter, composed of acids, organic chemicals, and dust. Exposure to high levels of CO can lead to dizziness, chest pain, impaired vision, and even death. The negative effects of PM on health are related to the size of ambient particles (Figure 13). PM_{10} are inhalable particles with a diameter lower than 10 micrometers that can lodge in the nose and throat. Particles of this size and smaller are associated with reduced lung function, asthma, coughing, difficulty breathing, and more serious cardiovascular disease. PM with diameters less than 10 micrometers, but greater than 2.5 micrometers, are coarse particles that can lodge further down into the respiratory system. $PM_{2.5}$, called fine particles, are generally emitted through combustion. They can become lodged in parts of the lung and are associated with the greatest health risks. Therefore, $PM_{2.5}$ is the primary focus of air quality studies concerned with health, and the particle size measured for this evaluation. Health effects associated with $PM_{2.5}$ include fatal and nonfatal cardiovascular events such as heart attacks, chronic obstructive pulmonary disorder (COPD), and all-cause and cardiopulmonary mortality (Pope & Dockery, 2006). In its predictive economic rate of return calculations, MCC accounted for costs associated with cases of general respiratory illness, amounting to approximately $60 per year.

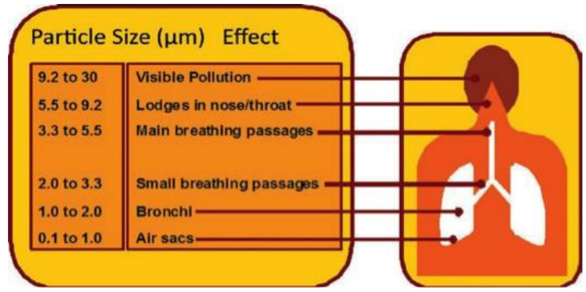


Figure 13. PM accessibility to human respiratory tract.

In a seminal 1993 study, researchers established a robust, significant association between air pollution and mortality (Dockery et al., 1993). This was the first study to control for individual risk factors, such as cigarette smoking and other health risks, and used survival analysis to estimate the adjusted mortality-rate ratio for the most polluted of six cities compared to the least polluted. The study suggested that the strongest correlate of mortality was air pollution with fine particulates ($PM_{2.5}$). In addition, air pollution was found to be associated with lung cancer and cardiopulmonary disease deaths. In the last twenty years, a growing body of evidence has established clear linkages between fine particulate matter and a variety of cardiopulmonary and other morbidity and mortality.

Subsequent research summarizes evidence accumulated since 1997 that illuminate the nature of the relationship between PM and health (Pope & Dockery, 2006). One key finding based on results from nine different studies is that there is extensive evidence of a linear relationship between PM and mortality risk with no safe threshold of exposure. This implies both that any level of exposure increases risk and that any level of PM reduction is likely to reduce mortality risk. However, none of the studies cited were conducted in locations with levels of PM as high as in UB; therefore, the mortality risk response for minor PM increases, or reductions, at such a high scale of exposure is not fully understood. This review also highlights evidence of the increased impacts associated with longer-term exposure to $PM_{2.5}$ and the particular vulnerability of children (including those in utero), elderly, and immuno-compromised individuals. In the case of residential stoves, women may be more vulnerable since they are more likely to tend stoves. This also suggests that women are in a position to benefit more than men from improved, better-insulated stoves that may reduce indoor $PM_{2.5}$ exposure.

Ambient air pollution is responsible for a large fraction of the global disease burden. One study calculated the deaths and DALYs attributable to 67 separate risk factors over two decades (Lim et al., 2012). The study found that household air pollution from solid fuels ranked as one of the highest risk factors for global burden of disease, the fourth leading cause of disease in 2010, and second in 1990. The contribution of different risk factors to the global disease burden has shifted substantially over time, with some of the greatest risk shifting from communicable disease risk in children towards non-communicable disease risk in adults. One of the main drivers of this trend is changes in risk factor exposures, including ambient particulate matter pollution. Household air pollution is one of the main causes of adult chronic disease, including cancer.

1.5.2 Ulaanbaatar context

Ulaanbaatar's PM concentrations are among the highest in the world. Given UB's topographical features, during the winter pollutants that are produced at ground level are caught between the mountains and unable to disperse. Ger districts (Figure 14) are thought to be responsible for 75 to 95% of UB's ambient PM emissions, and are located at the edges of the city, housing close to 60% of UB's population (World Bank, 2011). Ambient PM concentrations vary across the city since ground level emissions are localized. Annual average $PM_{2.5}$ concentrations for June 2008 – May 2009 were 200-350 $\mu g/m^3$ in the monitored ger areas and 75-150 $\mu g/m^3$ in the monitored central city areas (World Bank, 2011). An analysis for the year 2010 attributed 42% of $PM_{2.5}$ emissions (excluding windblown dust) to domestic stoves (Guttikunda, Lodoysamba, Bulgansaikhan, & Dashdondog, 2013). The same study conducted air quality modeling and attributed 53% of the population-weighted ambient $PM_{2.5}$ concentration across UB to domestic stoves.[10] Stove contributions to ground-level $PM_{2.5}$ levels are disproportionately high compared to their contribution to overall emissions because emissions from elevated sources such as power plant and heat-only boiler smokestacks are more widely dispersed before reaching the ground.

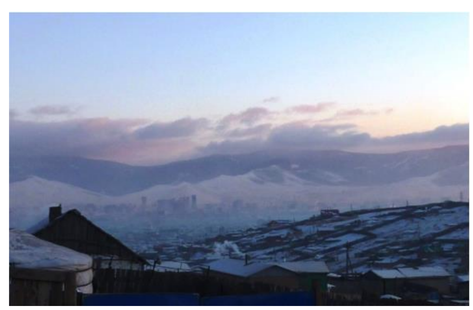


Figure 14. Ulaanbaatar ger district.

[10] Guttikunda et al. (2013) reported a combined contribution of 56% from domestic stoves and kiosks. The domestic stove contribution is estimated using the emissions split 95% from domestic stoves and 5% from kiosks that was also reported in that study.

A 2013 study used a land use regression model to estimate mortality attributable to $PM_{2.5}$ measured in UB (Allen et al., 2013). Using data from a central UB monitoring station from June 2009 – May 2010, daily $PM_{2.5}$ concentrations drastically exceeded global guidelines in the winter months with a December – February average of 148 $\mu g/m^3$ (Figure 15). These researchers estimated that 29% (95% CI, 12–43%) of cardiopulmonary mortality and 40% (95% CI, 17–56%) of lung cancer deaths in UB are attributable to ambient air pollution, representing almost 10% of total mortality in UB.

Mongolia's population is expanding at 4% per year and has rapidly urbanized (Guttikunda, 2008). The number of households in the ger areas has increased by 42,000 between the end of 2007 to 2013 (World Bank, 2013). As more residents migrate to UB and settle in ger areas, UB's air quality has continued to deteriorate. There were approximately 103,000 stoves in the UB ger areas in 2007 (World Bank, 2009). Later data showed stove use for heating in UB reported at 172,055 stoves (World Bank, 2013).

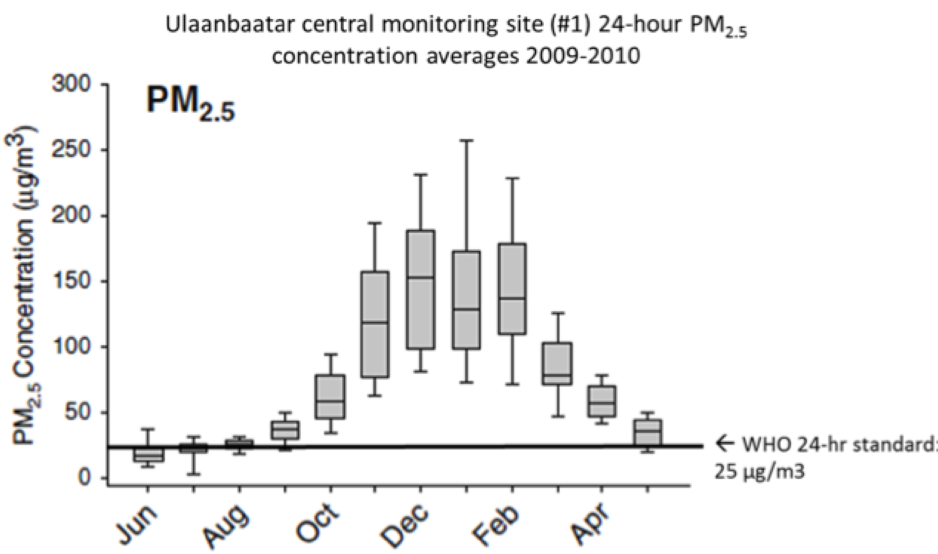


Figure 15. $PM_{2.5}$ concentrations at UB Station #1 2009-2010.
(Modified from: Allen et al., 2013)

These issues have captured the attention of the Mongolian Government, which has introduced several initiatives to improve air quality, including the EEP. Other initiatives underway or under discussion within the government and other groups include technology upgrades to coal-fired power plants, incentives to encourage relocation of households from the ger district to apartments connected to a central heating system, weekly restrictions on automobile use, tax incentives and penalties based on emission-related behavior, additional subsidized low- or no-emission heater and stove sales programs, among others (Air Pollution and Health Workshop, 2013). EEP's energy-efficient stove subsidy activity has maintained a high profile among UB residents including policy makers. Since subsequent laboratory tests performed by others confirmed EEP laboratory test findings, and based on the EEP's success in stove distribution, the World Bank and the Government of Mongolia through the Clean Air Fund have funded the continuation of up to 40,000 more subsidized energy-efficient stoves in UB during the winter of 2013-2014. Policy makers and implementers seek evidence of this technology's effectiveness under typical usage conditions to inform future scale-up opportunities to include at least Mongolia's second largest city, Darkhan. This impact evaluation provides that evidence; however, sustainability of the market, particularly MCA stove replacement, remains uncertain.

The impact of a residential stove sales program is thought to potentially affect males and females differently, in part because the majority of stove tenders are typically female. In its 2012 review of its Mongolia Gender Integration Plan, MCC identified potential threats to equitable benefits from this program. It was hypothesized that women and particularly female-headed households, often poorer groups and lacking knowledge about loans and banking processes, might have less access to the program. Upon examination of consumer records at participating banks, MCC discovered that females made up 40% of the banks' overall consumer base, but that 46% of loan consumers were female (MCC, 2013). While female-headed households comprised 29% of the stove consumers, 38% of these women opted to purchase stoves through loans. These data suggest that females and female-headed households were not underrepresented in the program, as the program did reach these vulnerable populations. This evaluation examined the gender composition of the sampled population and additional gender dynamics of stove preferences and usage.

2 EVALUATION DESIGN

The objective of this impact evaluation was to quantify both the direct and indirect impacts of the energy-efficient stove sales component of the MCEEIF activity. In addition to answering programmatic questions about the effectiveness of the intervention and benefits accrued to population sub-groups, the evaluation provides information that may inform future MCC programming to improve the effectiveness and efficiency of investment decisions. By documenting and substantiating impact with rigorous research methodology, the evaluation provides useful and actionable information to MCC, policymakers, project managers, beneficiaries, implementers, evaluators, and other evaluation stakeholders.

2.1 Evaluation Questions

This MCA stove subsidy project impact evaluation was designed to answer the following questions:

Evaluation question 1: How do energy-efficient products impact ambient air pollution levels, health, and income of residents in Ulaanbaatar?

1. How does the use of MCA stoves affect Ulaanbaatar's ambient air pollution, health, and income of its residents?
2. Does the use of other energy-efficient products affect Ulaanbaatar's ambient air pollution, health, and income of its residents?
3. What are the impact pathways (e.g., is there evidence to support the *a priori* causal pathways proposed in the project logic model?)

Specifically, several sub-questions were addressed:

a. Income:
   i. How does the use of MCA stoves affect fuel usage and expenditures?
   ii. Does the use of MCA stoves affect available household income?

b. Ambient air pollution:
   i. What is the impact of MCA stoves on emissions of CO and $PM_{2.5}$ outdoors?
   ii. What is the impact of MCA stoves on indoor concentrations of CO and $PM_{2.5}$?

c. Health:
   i. What are the estimated health impacts for Ulaanbaatar residents based on the health estimates used in the ERR?
   ii. How do MCA stoves affect household expenditures related to respiratory health problems?

These primary evaluation questions focus on assessing the overall impact of the EEP stove subsidy activity and measuring how the intervention contributed to MCC's broader goals of economic growth and poverty alleviation. It is important to note that maximum program benefits may not be achieved if intervention participants do not use stoves as instructed. In addition, differences in the availability of various stove models may contribute to variation in use patterns and pollution emission profiles. The use of other EEP products for home insulation by households may also alter the impact estimates of the evaluation. The following questions and sub-questions address whether these factors affect impact estimates.

Evaluation question 2: How do different MCA stove models and different patterns of usage affect the impacts on ambient air pollution, health, and income of households with MCA stoves?

1. Do different MCA stove model types have differential impacts on fuel expenditures, income, and CO and $PM_{2.5}$ emissions, under typical usage behavior?
2. Do deviations from expected MCA stove usage patterns affect the level of impact on air pollution, health, and income of households with MCA stoves?
   a. To what extent are households following the recommended operation instructions for the MCA stoves?
   b. Are households using the MCA stove models appropriate for their dwelling?
   c. Have households altered their chimney connection?
   d. Are households using the appropriate fuel and the appropriate fueling procedures for their stoves?
   e. For what purposes do households use each MCA stove model?
   f. Do deviations from prescribed usage (cold starts, warm starts, and refueling) attenuate the impact of MCA stoves on CO and $PM_{2.5}$ emissions?
   g. Do deviations from prescribed usage (cold starts, warm starts, and refueling) attenuate the impact of MCA stoves on fuel use and related expenditures?
   h. Did the MCA stove activity result in differential impacts on men and women?
3. Does use of additional energy efficiency products such as vestibules or additional ger insulation modify the impact of MCA stoves on ambient air pollution, health, and income?

2.2 Evaluation Timeline

The impact evaluation was implemented in three stages. In the first stage, the SI team worked with MCC Department of Policy and Evaluation (DPE) and Economics staff, the MCA monitoring and evaluation team, the PIU, and other evaluation stakeholders to develop a proposed evaluation design and an implementation plan. In the second stage, pilot data were collected in the second half of the winter of 2011-2012. During this stage, SI tested and refined the household survey instrument, tested and adjusted household air pollution emissions measurement protocols and equipment for the local context, produced preliminary data from which required sample sizes for the full evaluation were calculated, and identified and refined propensity score matching factors (described later in this report). Pilot results were presented in a previous report (Social Impact, 2013). The third stage, and the subject of this report, entailed the impact evaluation of the stove subsidy activity, completed over the course of the 2012-2013 winter heating season. This included household surveys conducted in three phases and continuous measurement of household stove emissions and indoor air quality as well as stove temperature fluctuations throughout that time period. Conducting the evaluation a full year after stoves were first distributed in 2011 has allowed time for market penetration as well as time for purchasers to become accustomed to using the new stove models. Figure 16 shows a timeline of these activities.

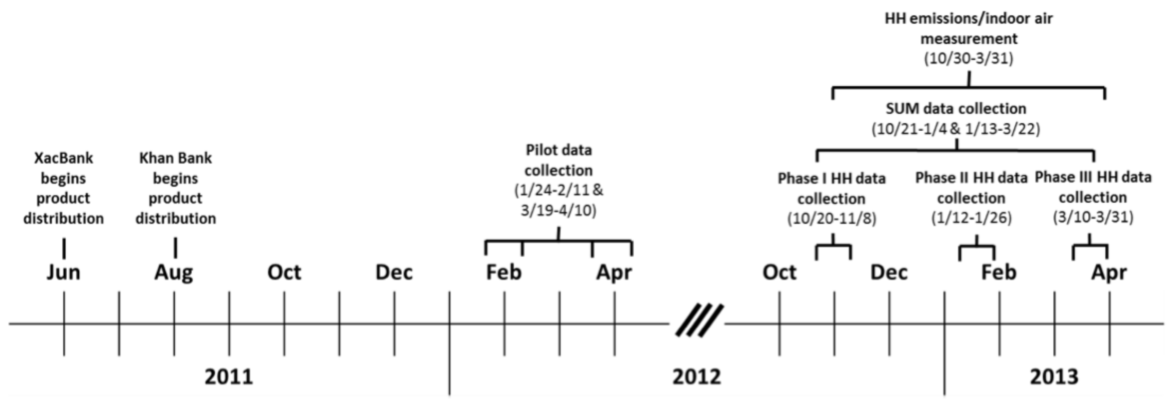


Figure 16. Impact evaluation timeline.

2.3 Propensity Score Matching Design

The hallmark of an impact evaluation is that it aims to identify the impacts that can be *attributed to* an intervention. This requires a suitable comparison group to serve as the *counterfactual* (a demonstration of what would have happened in the absence of the intervention). While randomized intervention assignment is the ideal way to ensure the intervention and comparison groups are truly similar, this was not possible for this evalu ation. Since this was a market-based intervention, households could choose whether to purchase MCA-supported stoves at the subsidized price (MCA-supported stoves are henceforth referred to as "MCA stoves"). Households that decided to purchase the MCA stove may systematically differ from those that did not. For example, they may be wealthier or more fuel-conscious than non-participating households. If so, differences in outcomes between participating and non-participating households might be explained by *selection bias*, and may not be attributable to the use of the MCA stove. In order to control for these differences, this IE uses a statistical technique called propensity score matching (PSM), which efficiently matches intervention and comparison observations based on certain household and dwelling characteristics (Rosenbaum & Rubin, 1973). This allows the estimation of the differences in outcomes between participating and non-participating households, while controlling for observed differences between these groups on a variety of characteristics that predict the probability that a household adopts an MCA stove. By matching on propensity scores, we were able to construct treatment and comparison groups that are balanced along the observed characteristics, even in the absence of randomization (Heckman, Ichimura, & Todd, 1997). However, PSM, as any regression approach, is only able to account for observed characteristics. The omission of any potentially predictive unobserved characteristics that may influence a household's adoption of the intervention, and outcomes of interest, could thus still contribute to potential bias.

While the most robust evaluations use a baseline to help measure changes due to an intervention, this was not possible because MCA stoves were available on the market before a baseline could be conducted. This is another reason the PSM approach was chosen as the best method for the evaluation, as matching can be based on non-baseline characteristics that are unlikely to have been affected by adoption of an MCA stove.

3 EVALUATION METHODS

3.1 Household Survey Sampling Methods

The study population included residents of Ulaanbaatar's Bayangol, Bayanzurkh, Chingeltei, Khan-Uul, Songino Khairkhan, and Sukhbaatar Districts. With the exception of Bayangol, these areas were targeted for stove sales in order to achieve the highest reductions in PM throughout the city, as they are the most heavily polluted areas in the city (Figure 17). While there is a raw coal ban in effect in Bayangol District, its residents were included in the study because this district was targeted by the program for the other energy-efficient products, with the exception of stoves. In addition, there was an expectation of leakage of a small number of project stoves into this area, and many households were still using raw coal due to a lack of other alternatives.

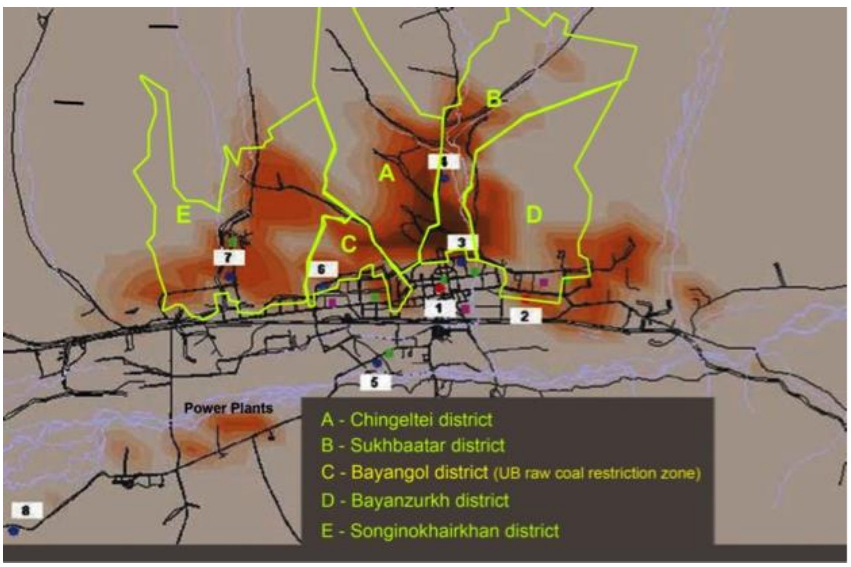


Figure 17. Sampled districts capture the most polluted areas, represented by orange shading. *(Source: World Bank 2009)*

The sampling frame was drawn from multiple sources. MCA stove owners were randomly selected from complete stove sales lists of Khan Bank and Xacbank. Traditional stove owners were randomly selected from the Ministry of Labor and Social Welfare's 2010-2011 Proxy Means Test (PMT) data, a census of all Ulaanbaatar ger area households that was designed to assess poverty levels. Addresses in the PMT data that were also present in the bank lists (i.e., MCA stove owners) were removed prior to sampling; however, the PMT list addresses were used to validate the location of households derived from the bank lists. Some participants (n=195) were selected from the January-April 2012 EEP pilot study sample. These pilot households were sampled from lists compiled by the same distributing banks and from khoroo governors in the six districts. When

PMT data became available for the winter 2012-2013 evaluation, this dataset was used to overcome the limitations of the pilot sampling methods, as discussed in the pilot evaluation report (Social Impact, 2013). This was the most comprehensive and recent data source that was available. The sample frame included only complete records, with non-missing names, addresses, and registration numbers. The complete records from the Bank and PMT lists were stratified by dwelling type (ger or house) and stove type (Dul, Khas, Ulzii, or traditional), and households were randomly sampled within each stratum.

3.1.1 Sample size requirements

Household survey sample sizes were powered to detect effects for each MCA stove type as compared to traditional stoves. While additional stratification by dwelling type ensured representativeness on this critical variable, the sample was not powered to detect differential impacts by dwelling type. Stata software's *sampsi* procedure was used to conduct power calculations using matched differences in means and standard deviations (SD) for key outcomes observed during the pilot (Table 2). MCA stove means were combined for sample size calculations, as pilot results were similar for each MCA stove type. Calculations assumed 85% power, 15% attrition, a two-sided hypothesis—with no assumptions made about which group would have better outcomes—and a significance level of 5%. Upon consultation between SI and the data collection firms, the attrition buffer was subsequently increased to 22% to account for potentially higher than expected non-response.

Table 2. Household survey power and sample size estimates for key indicators

	Daily coal use (kg)		Number of reported fueling events		Number of reported cold starts		Number of reported warm refuels		Avg. kg of coal per fueling event	
	mean	SD	mean	SD	mean	SD	mean	SD	mean	SD
Pilot results: MCA stove	21.4	11.9	3.0	1.6	2.1	1.1	0.8	1.7	7.6	2.8
Pilot results: Traditional stove	25.0	13.6	4.3	1.9	1.0	1.0	3.4	1.7	5.9	2.8
Minimum sample size required per stove type	225		32		15		11		49	
Statistical power of minimum sample	85%		85%		85%		85%		85%	
+ attrition buffer (22%)	49		7		3		2		11	
Total sample needed, per stove type (minimum + buffer)*	274		39		18		13		60	

**Final sample size allows detection of at least the same magnitude of differences in daily coal use found in first phase of pilot survey (January-February, 2012)*

Since reported coal use over a 24-hour period required the largest sample size, the final sample size was based on this indicator. These calculations indicated that a sample size of 225 households per stove type was required to detect, at a minimum, the same differences between traditional and MCA stoves found during the pilot, with up to 274 households per group to account for attrition. The underlying power calculation formula for the detection of a difference between means is as follows:

$$1-\beta = T_\nu\left(t_{\alpha/2,\nu}\,\middle|\,\frac{\delta}{\sqrt{\sigma_1^2/n_1+\sigma_2^2/n_2}}\right) - T_\nu\left(-t_{\alpha/2,\nu}\,\middle|\,\frac{\delta}{\sqrt{\sigma_1^2/n_1+\sigma_2^2/n_2}}\right)$$

Where 1-β refers to the power; T_v is the T statistic parameter with v degrees of freedom; $t_\alpha/2,v$ is the value of the t distribution value given the desired 2-tailed level of precision (α/2) and degrees of freedom (v); $\delta = \mu_1 - \mu_2$ where μ_1 is the anticipated parameter mean of the outcome for project stove users and μ_2 is the anticipated parameter mean for traditional stove users; σ_1^2 is the variance of the outcome for project stove users; σ_2^2 is the variance for traditional stove users; and n_1 and n_2 are the sample sizes for each group.

While the sample was initially divided equally into dwelling and stove type strata, this allocation was adjusted during data collection since it was found that very few gers had Khas stoves, because the Khas stove was marketed as more suitable for houses due to its larger size. The Ger-Khas stratum was therefore reduced to only 15 observations. This allowed a reallocation of the survey sample to the other groups, increasing the size of the other strata to at least 150, thus increasing power. The final sample stratification for the intended household sample size and resulting power estimates are presented in Table 3.

Table 3. Final target sample stratification after ger-Khas stratum reallocation

	Traditional	Ulzii	Khas	Dul	Total
Ger	150	150	15	150	**465**
House	181	150	150	150	**631**
Total	**331**	**300**	**165**	**300**	**1096**
Revised power to detect a 3.6 kg difference in daily coal use	91%	100%	100%	100%	**100%**

3.2 Household Survey Data Collection Methods

Household data were collected in three phases to capture changes in stove usage patterns throughout the winter of 2012-2013 to account for temperature fluctuations. Data collection was contracted by MCA to be conducted by a joint venture between Robust LLC and the Institute of Philosophy, Sociology and Law (JVRIPSL). The data collection was implemented by 15 teams of two enumerators each, managed by three supervisors. All enumerators completed a three-day training prior to Phase I that covered research ethics, data collection instruments, and protocols. One-day refresher training was provided before Phases II and III of data collection.

3.2.1 Household survey instrument

The household survey (Annex 2) was administered to the individual most responsible for tending the stove, although other household members could assist in answering demographic questions if necessary. After obtaining informed consent, enumerators gathered information on each dwelling's physical characteristics such as construction materials and insulation. Enumerators measured dimensions of the room in which the main stove was located to allow estimation of the heating space volume. Demographic characteristics were collected for the full household roster, including information on age, gender, education, marital status, as well as employment status and income in the prior month from work, pensions, and other allowances for every household member. A general household expenditures section was added to the survey during Phases II and III to further document potential economic impacts beyond changes in income. Though the survey methods and the sample size were not designed to measure health outcomes reliably, respondents were asked to report current respiratory, cardiac, and dermal symptoms experienced by household members in vulnerable age groups (<5 and >60 years old), to collect some data on symptoms that could be associated with air pollution. However, by design, no precise conclusions with regard to health could be made from these data, as these data represented self-reported symptoms rather than disease incidence. Rather, the main health impacts were inferred separately from dose-response curves used in WHO methodologies for burden of disease estimates for ambient $PM_{2.5}$ reductions.

The survey captured the ownership and use of up to three stoves within each home, as well as any other heating and cooking devices. In addition, data were gathered on stove usage for cooking and heating, any modifications made to MCA stoves, and criteria-based personal preferences between MCA and traditional stoves. To determine whether MCA stove owners were compliant with lighting instructions, respondents were asked an open-ended question about how they light their stove, and enumerators recorded pre-coded responses.

Respondents reported recent expenditures on truckloads of coal and wood since the last data collection visit (for Phase I data collection, since June). The types of coal and wood purchased were also reported. Enumerators showed photos of truck sizes to help the respondent estimate the quantity purchased. Total purchases of coal and wood by the sack were also reported for the previous week and the past two weeks. Types of coal and wood and the per-sack prices for the most recent purchase were also reported.

To estimate the quantity of fuel used daily and the number of fueling events, cold starts, and warm refuelings, enumerators asked the main stove tender to recall the times of each fueling event in the 24 hours preceding the interview. For each event, enumerators asked the respondent the time, purpose (heating, cooking, or both), whether the stove was still warm or had unburnt coal or embers present, and the quantities of each fuel type used. Any fuelings in which embers or unburnt coal were present were considered warm refuelings. To further verify fuel quantities, respondents were asked to put the amount of coal they used into a bag or bucket, which enumerators then weighed with handheld digital scales and recorded after subtracting the weight of the container (Figure 18). The same procedure was followed for wood. Household survey data quality monitoring procedures are described in Annex 3.

Figure 18. Enumerators weighing coal quantities at survey respondents' households.

3.2.2 Stove use monitors

To triangulate the number and types of fueling events with physical measurements reported in the household survey, enumerators installed time stamped temperature recorders called stove use monitors (SUMs) on the leg of the stove within a subsample of 419 gers and houses (Berkeley Air Monitoring Group, 2012)[11]. The SUMs used in this study were Maxim iButtons model 1922L, which are smaller in diameter than a penny (Figure 19), making them inconspicuous and convenient to place in dwellings. Each SUM records time-stamped temperatures between -40 °C and 85 °C and can store up to 8,192 temperature readings, at ten-minute intervals (Maxim Integrated, 2013). These data are then uploaded to a computer using an adapter. In order to compare approximate energy efficiency of homes, another SUM was placed on the wall (in houses) or on the ceiling 0.5 meters above the wall (in gers) in a subsample of 318 households with stove SUMs. Wall SUMs measured ambient temperature, which was compared to stove temperatures to estimate relative heat efficiency of homes. Each SUM recorded a temperature and time stamp every ten minutes from the Phase I visit for approximately 57 days. SUMs were placed during Phase I, retrieved during Phase II to download the data, and then replaced at the same households for continued data collection until the Phase III visit.

Figure 19. Size comparison of SUM.

3.3 Data Entry and Analysis

Household survey data were checked by JVRIPSL supervisors for completeness and adherence to protocol, and JVRIPSL performed double data entry using CSPro software. Electronic databases were checked by both JVRIPSL and SI for discrepancies in double data entry, internal consistency, and corrections were made where possible. Audio recordings of interviews were also used to verify actual responses. SI conducted data cleaning and analysis using Stata 12 and 13 software.

[11] Data was collected from 419 stove SUMs in the first phase and 435 stove SUMs in the second phase.

3.3.1 Key variable creation

All fueling events reported in the 24-hour recall section of the household survey were aggregated to calculate the total daily fueling events. Fuelings were considered to be "cold starts" if the respondent reported no burning coal or embers in the stove prior to adding fuel. Otherwise, they were coded as "warm refuels." Weights of coal at each fueling event were added to calculate the total daily quantity (kg) used for each data collection phase. Total fueling events and total fuel quantity were used to calculate an average amount of coal per fueling event. In cases where more than one stove was used the prior day, fueling events and coal from both stoves were included in the aggregate estimates for the household. This was done to fulfill the intent of the evaluation to determine the impact of the program under real-world usage conditions. The few cases in which MCA stove owners used a second stove indicate those households did not find the MCA stove to sufficiently fulfill their heating and cooking needs. That the use of an MCA stove triggered the perceived need to use a second stove is a condition attributable to the MCA stove itself. Therefore, total coal consumption from both stoves in these cases should be attributed to the MCA stove's impact.

The total cost of coal purchases during the winter was estimated by adding purchases by truck and by sack. Due to limitations associated with the availability of fuel expenditure data (which could be collected only at three time points), total winter fuel expenditures were estimated using key assumptions, particularly with regard to coal purchases by the sack. The number of sacks purchased in the past one and two weeks was used to estimate weekly averages and assumed to remain constant throughout that data collection phase. This was multiplied by the per-sack price paid at the last purchase to estimate the total weekly cost of coal purchased by sack, assuming constant coal types and prices during that phase. If households reported purchasing more than one type of coal at different prices at last purchase, the average per-sack price was calculated as a proportional average based on the number of sacks purchased of each type. The per-week average coal expenditure was then multiplied by eight weeks to cover the two-month time period, to represent each data collection phase throughout the six-month winter season. In cases where the respondent did not recall the price of coal, the price was imputed using averages specific to the same coal type, district, and data collection phase, as coal prices vary with these factors. In addition to the limitations inherent in the assumptions listed above, coal sack sizes were not recorded but, according to anecdotal reports, varied widely.

Monthly income reported for each household member was added to calculate the overall monthly household income per phase. Assets, including alternative heating and cooking devices, were collected in a newly added section in Phase III, and then combined into one asset index using principal component analysis (PCA) (Vyas & Kumaranayake, 2006). This metric was divided into quintiles for analysis and was used to assess the validity of reported household income.

The volume of the main heating space in gers and houses was calculated using geometrical dimensions of the room in which the main stove was located. While gers have a uniform shape, in cases where the main room of a house was atypical, the enumerators sketched the shape and noted dimensions to allow for volume calculations of more complex spaces.

3.3.2 Calculating and using the propensity score

The first step in PSM analysis was to identify variables *a priori* that could be logically associated with whether a household would choose to purchase a subsidized MCA stove. Only Phase I characteristics not likely to have changed as a result of a stove purchase were used to estimate the propensity score, with the exception of household assets reported in Phase III, as these characteristics were not available in Phase I. Frequencies of these variables were reviewed, and certain variables were not included in the model if they negatively affected the balance of the propensity score model due to collinearity or highly skewed distributions that did not provide relevant information (e.g., characteristics present in <0.01% of households). Stata's *pscore* procedure was then used to calculate a single propensity score based on all variables included. Intervention and comparison households were matched based on this propensity score using a specific algorithm (Becker & Ichino, 2002). Specific variable inclusion and algorithm selection methods, as well as sensitivity analyses of matching, are discussed in the Results section.

3.3.3 Analysis

Separate analyses are presented for outcomes at each data collection phase along with averages of all phases to approximate impacts for the entire winter. When possible, fueling-related results are further stratified by variables affecting fuel consumption such as dwelling type, use of a heating wall, and fuel type. First, simple means and standard deviations of physical and demographic household characteristics and stove usage behavior were calculated to draw preliminary comparisons between groups.

Stove fueling behavior and other key impact measures were next compared using PSM. Stata's *psmatch2* command was used to perform matched comparisons of differences in means between intervention and comparison groups (Leuven & Sienesi, 2003). Such non-parametric analysis is possible because the matching attempts to adjust for other measurable biases, thereby creating groups equivalent in most respects except for stove ownership. Means, mean differences, standard errors, and p-values were calculated for each matched analysis. p-values of less than 0.05 were considered highly statistically significant; and those less than 0.01 were considered highly significant and are highlighted in results.

3.4 Emissions and Indoor Air Pollution Monitoring Methods

3.4.1 Sample selection

Emissions and indoor air measurements were assessed over an approximately 14-hour period from early evening through the next morning in a randomly selected subsample of homes drawn from the household survey sample. To facilitate the derivation of typical emissions factors, households with family size close to the average size for Ulaanbaatar and a typical dwelling structure were selected, to the extent feasible. Household fuel use was estimated by field workers during sample collection and recorded on data sheets.

Table 4. Prevalence of MCA stove purchases in Ulaanbaatar

	Ulzii	Khas	Dul
Gers	46%	0%	16%
Houses	13%	15%	6%
Undetermined	2%	0%	1%
Total no. of stoves	**58,886**	**15,162**	**23,035**
Overall prevalence	**61%**	**16%**	**24%**

Sample size estimates were based on the prevalence of the stove types purchased in Ulaanbaatar (Table 4), the sample sizes required to detect statistical differences between traditional and MCA stoves within dwelling groups (Table 5), and practical budgetary and time constraints, since it was not feasible to test all possible stratifications. Calculations aimed to achieve 80% power to detect a significant two-tailed (i.e., either positive or negative) difference between groups, with a significance level of 5%. Since the number of homes in the pilot was small, there was substantial uncertainty in the sample size estimate. Calculations showed that a sample size of 20-25 homes would be required to detect at least the same magnitude of differences in g $PM_{2.5}$/kg fuel observed in the pilot phase for three major comparisons:

1. Traditional compared to Ulzii stoves in gers;
2. Traditional compared to Ulzii and Khas stoves in houses, grouping dwellings with and without heating walls[12];
3. Overall statistical comparison for all stoves, weighted by the overall distribution of stove sales.

Table 5. Sample sizes for air quality measurements, by dwelling type

	Emissions		Indoor air	
	$PM_{2.5}$	CO	$PM_{2.5}$	CO
Gers	19	19	40	65
Houses, no heating wall	**	**	*	*
Houses with heating wall	30	**	35	

** No differences in pilot*
*** Estimates of variability and difference between means not robust due to sample size*

Since the number of sample losses due to equipment failure and other factors was greater than anticipated, the sample size for the emissions measurements was increased to 216 in the course of data collection. The final sample of measurements for which complete data was obtained, after excluding sample losses, was 143. The distribution of the samples is presented in Table 6. As shown in Table 7, the majority of equipment failures were the result of intermittent power supply to the Testo and dilution pumps used for measurements, which were powered by electricity from the home. In addition, the batteries from the low-flow pumps decayed during the course of the study, leading to loss of data due to pump failure. In some homes no refueling events were recorded, as the residents had refueled prior to the enumerator team's arrival; in several homes the probe was removed from the flue by the household members.

[12] Although the initial intent was to keep these groups separate, survey data showed that the majority of households with traditional stoves had heating walls whereas the majority with MCA stoves did not. This supports anecdotal reports that residents of houses were reducing or removing parts of the heating walls to accommodate MCA stoves. A simple comparison of houses with and without a heating wall would bias results if house residents removed heating walls when they installed MCA stoves.

Table 6. Distribution of emissions measurements, by stove and dwelling type

	Traditional	Ulzii	Khas	Dul	Total
Gers	20	26	0	16	**62**
Houses	19	22	23	14	**78**
Total	**39**	**48**	**23**	**30**	**140**

Table 7. Emission sample results and equipment failure rates

Sample summary	Frequency	Percentage
Valid samples	143	66%
Samples not used:		
Testo failure	39	18%
Lowflow/filtermass failure	16	7%
Dilution pump failure	6	3%
Pump fault	2	1%
Sampling duration too short	3	1%
No refueling performed	3	1%
Incorrect probe position	2	1%
Filter damaged	1	0%
No fuel weight	1	0%
Total	**216**	**100%**

3.4.2 Methods for measurement of household emissions

Emission samples were collected by two teams, each comprised of three student data collectors from the Mongolian University of Science and Technology (MUST) and Health Sciences University of Mongolia (HSUM), who were trained in the use of the equipment. One student was responsible for scheduling the appointments, and a professor at MUST managed the team and the logistics. SI technical advisors provided the technical protocols, training, and oversight. The study placed particular importance on building the capacity of Mongolian personnel, should stakeholders choose to perform continued assessment of program impact.

Each team visited one sampled household per evening to obtain informed consent, set up equipment, and document the weight of fuel to be used by the household overnight (using the same demonstration and electronic weighing method used for the household survey). Emissions and indoor sampling trains are shown in Figure 20. Stove emission samples were collected directly from the stove's flue with a metal sampling probe inserted approximately 70 cm above the stovetop into the center of the flue. $PM_{2.5}$ gravimetric sampling was conducted using 37 mm PTFE (Teflon) 2.0 μm pore size filters (pre-weighed and loaded into cassettes) using BGI Triplex Cyclone and SKC PCXR8 Pump. Real-time CO_2 and CO measurements were conducted using either a Testo 350 M/XL or 350 Flue Gas Analyzer with a low pressure drop HEPA filter capsule placed before the analyzer. Flue gas analyzers were factory calibrated prior to the study. Testo sampling regimes were set for five minutes of sampling followed by ten minutes of purge time with clean air. Water Traps were used inline within the sample train before the sampling equipment. All flow rates were set using Dry Cal flow meter primary standard. Pre and post weights of filters for particulate matter were performed in an environmentally controlled microbalance room after equilibration for at least 48 hours. Nine field blanks were collected.

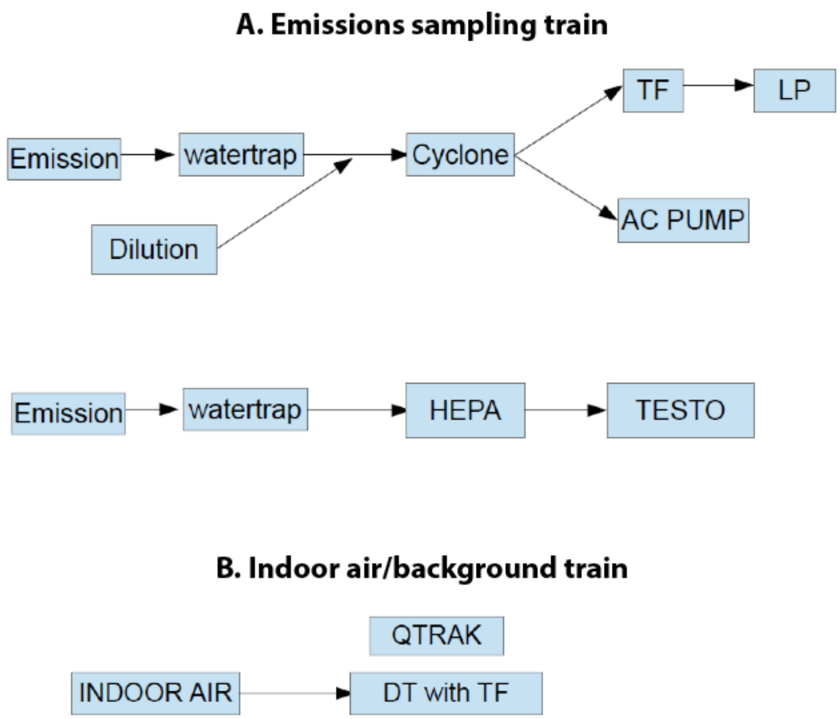


Figure 20. Emissions and indoor air sampling trains.

Background or indoor air concentrations in gers were sampled simultaneously at flow rates similar to the emissions samples. $PM_{2.5}$ indoor air concentrations were assessed using simultaneous gravimetric and semi-continuous $PM_{2.5}$ measurements with a TSI DustTrak (DT) II Aerosol Monitor. The gravimetric samples were then used to calibrate the DustTrak semi-continuous data response. Semi-continuous CO/CO_2 measurements were conducted using a TSI Q-Trak 7565/7575 CO & CO_2 Monitor.

Households were re-visited the following morning to retrieve equipment, and DustTrak, Q-Trak, and Testo data that had been recorded electronically were uploaded to a Sharepoint site.

3.4.3 Estimation of emission factors

To calculate the emission factors, first the background concentrations were subtracted from the emission concentrations to estimate the net emissions from the stove. This subtraction accounts for concentrations of pollutants in the indoor air that enter the stove and are emitted in the flue, but are not directly the result of the combustion at that specific time interval. $PM_{2.5}$ and CO emissions factors were determined by estimating the net amount of carbon used in each home, by subtracting the estimated moisture and ash content from the weight of fuel used in the home during the monitoring period. The assumptions used in the calculations included: (1) the moisture, carbon and ash content of the coal, obtained from stove performance testing in a stove laboratory in Mongolia, Lawrence Berkeley National Laboratory testing, and from communication with the Mongolian Mining Institute; (2) the carbon content of the particulate matter, obtained from historical measurements from coal burning stoves; and (3) the carbon content of the fuel wood used to light the stove, obtained from historical measurements of fuel wood.

Table 8. Distribution of coal types reported within emissions measurement sample

Coal type	Frequency	Percentage
Baganuur	33	15%
Nalaikh	70	32%
Alagtolgoi	5	2%
Baganuur/ nalaikh	80	37%
Baganuur/ alagtolgoi	5	2%
Nalaikh/ alagtolgoi	3	1%
Nalaikh/ alagtolgoi/ baganuur	4	2%
Alagtolgoi/ semicoke	1	0.5%
Omnogovi/ baganuur	1	0.5%
Ovorhangai bayanteeg/ baganuur	1	0.5%
Oyu tolgoi/ nalaikh	1	0.5%
Semicoke	1	0.5%
Semicoke/ baganuur/ nalaikh	1	0.5%
Semicoke/ nalaikh	1	0.5%
Sharin gol/ nalaikh	1	0.5%
Tavan tolgoi	1	0.5%
Tavan tolgoi/ nalaikh	1	0.5%
Tavan tolgoi/ nalaikh/ baganuur	1	0.5%
Not reported	5	2.3%
Total	**216**	**100%**

An additional complication for the emissions estimates from homes was the variability in types of coal used by the households, who often used different fuel types throughout the heating season (Table 8). Since many households reported multiple coal types in the survey around the time when the emissions measurements were conducted, the average coal composition was estimated based on a combination of the coal types present in the home.

The amount of fuel used during evening refueling was weighed directly in the home. Morning refueling amounts were obtained from the household questionnaire's 24-hour fueling event recall, in which the respondent reported the time of each fueling event and filled a bucket with the estimated amount of coal used at each fueling for subsequent weighing. Total quantities of coal reported for the morning refueling(s) were added to the evening quantities weighed by the emissions data collectors to determine total coal used during the air quality sampling period. Emission factors for $PM_{2.5}$ and CO were calculated by weighting the net carbon utilized per kg of coal by the ratios of the carbon measured in emissions samples as CO_2, CO, and $PM_{2.5}$ and are reported as grams per kilogram fuel burned (g/kg). While hydrocarbon emissions have not been included in the computation, CO_2, CO, and particulate matter account for the vast majority of emitted carbon species. Additional sampling in a subset of homes included estimation of hydrocarbon emissions by gas chromatography flame ionization detector (GC FID), which can be used to assess the sensitivity of the emissions estimates in further analyses to include these species in the calculation. In addition, measurements of elemental carbon and organic carbon fractions of particulate matter were also conducted in the subsample that assessed hydrocarbon emissions, which can also be used to assess the sensitivity of the emissions estimates to the carbon content of the particulate matter.

3.4.4 Subsample for quartz filter and gas analysis

In a subsample of 86 homes, additional quartz filters for elemental carbon (EC) and organic carbon (OC) and gas bags for analysis of CO_2, CO, methane (CH_4) and non-methane hydrocarbons using a GC FID were used. For gas analysis and quartz filters, samples were drawn by a low flow sampling pump through Teflon tubing to a 47 mm pre-fired quartz filter before going to a 200 liter Kynar bag, a small sample of which were transferred to metal lined bags for shipping to the United States for subsequent analysis. Gas sampling bags were purchased for the study and purged three times with zero air prior to transport to the field. Spiked control samples of gas bags with a National Institute of Standards and Technology (NIST) traceable gas standard mixture of CO_2, CO, and CH_4 in a helium balance were used to determine sample loses in metal-lined multilayer bags. The multilayer Tedlar (MMT) bags have been demonstrated to maintain stability of CO_2, CO, CH_4, and total hydrocarbons for three months. OC/EC analyses were performed using a Sunset analyzer. Blanks were performed daily, and the analysis automated a calibration with methane gas after each sample. A three-point calibration using sucrose was conducted weekly.

3.5 Ethical Precautions

The household survey and emissions data collection protocols, data collection instruments, and consent forms for this evaluation were approved by the Social Impact Institutional Review Board. Each respondent provided informed written consent agreeing to participate in the study. A modest incentive of a MNT 2,000 (~USD $1.20) pre-paid phone card was provided to each participant at each household survey visit to thank and compensate each for time spent responding to the lengthy survey. The same incentive was given to each household visited for data quality monitoring verification. Each household selected for emissions measurements was compensated with a MNT 10,000 (~USD $6) phone card to offset the greater inconvenience of noisy sampling equipment operating overnight. These small payments were given to provide a gesture of appreciation without being so high as to coerce participation. Stove chimney parts that were drilled to fit the sampling probe during emissions sampling were immediately replaced after sampling by the emissions team at no cost to the participant.

3.6 Ambient air quality evaluation methods

If MCA stoves effectively reduce emissions, it is expected, all else being equal, that ambient air quality would improve and lead to health benefits. Unfortunately, it is unlikely that all else remains equal. Changes in weather, other emissions sources, economic conditions, and behavior, among other factors, are likely to exert significant influence over ambient air quality, such that observed changes from one year to the next would be difficult to attribute to any one intervention. Moreover, reliable, source-apportioned[13] data over time do not currently exist. To facilitate this analysis, air pollution levels were estimated under two scenarios: (1) the existing scenario, in which the MCA stoves had been distributed (intervention case), and (2) a hypothetical counterfactual (base case) in which all households were still using traditional stoves as if the project stoves had never been distributed. In each case, air pollution levels were estimated based on the study's emissions measurements and fuel consumption data.

3.6.1 Ambient air quality modeling methods

The objective of this analysis was to determine how the MCA stove subsidy program has affected outdoor air quality across UB. The change in outdoor (ambient) air quality was quantified by modeling ambient $PM_{2.5}$ concentrations from residential heating stove emissions in the absence (base case) and presence (intervention case) of the MCA stove subsidy program. Heating stove emission factors and coal use estimates, generated as part of this impact evaluation, were used in conjunction with MCA stove sales data to determine the total release of $PM_{2.5}$ from MCA stoves into the ambient air. Air quality modeling was conducted to disperse these emissions over the city as dictated by the meteorological conditions. The *absolute change* in ambient $PM_{2.5}$ concentrations is determined by running the model with MCA stove emissions and comparing to the hypothetical case, in which all MCA stoves would be traditional stoves. The *relative change* in heating stove contributions to ambient $PM_{2.5}$ concentrations was determined by estimating the total number of residential heating stoves in UB and running the model with and without the intervention.

Air quality modeling for the October 2012 – March 2013 heating season was conducted for three separate periods – late fall, winter, and early spring. The dates for these periods were determined using the ambient temperature time series and household (HH) survey phases shown in Figure 21. The goal was a one-to-one mapping between modeling periods and HH survey phases to ensure there was adequate survey data to support the modeling inputs. Persistent changes in ambient temperature were used to define the precise transition between the three modeling periods (hereafter referred to as seasons).

[13] Source apportionment examines the chemical composition "fingerprints" of ambient particulate matter and emission source categories to characterize the relative contributions of different sources, such as cars, stoves, factories, etc., to ambient air quality.

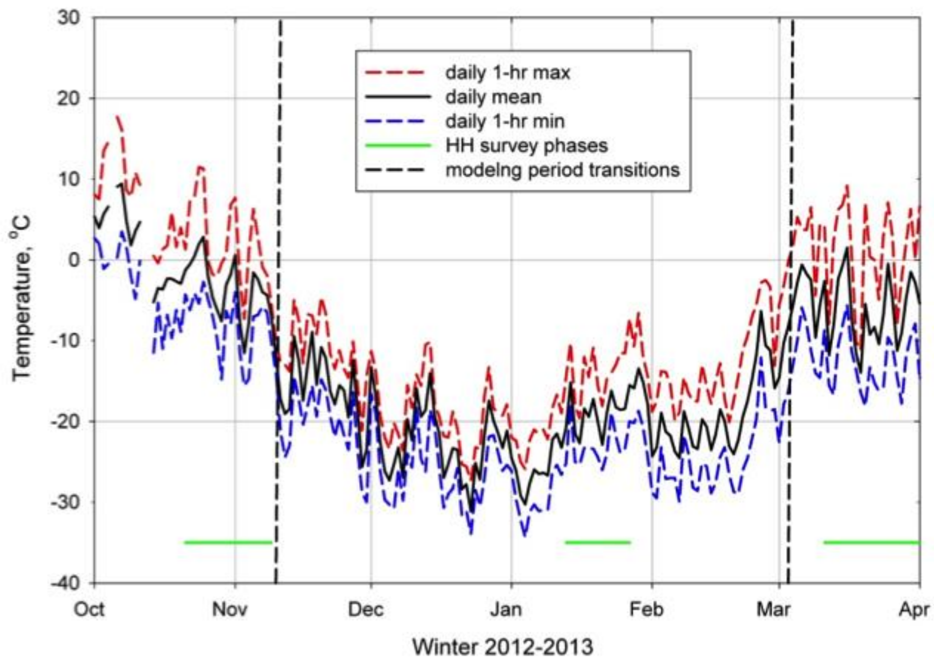


Figure 21. Daily temperature metrics at National Agency for Meteorology Hydrology and Environmental Monitoring air quality monitoring station #4.

(The household survey phases are noted with horizontal green lines, and the transition dates of November 8-9 and March 2-3 delineate the three air quality modeling phases, noted by dashed vertical lines.)

3.6.1.1 Temporal allocation of emissions

$PM_{2.5}$ emission factors (g $PM_{2.5}$/kg coal) calculated from the household measurements (see Table 29 and Table 30) and daily fuel use rate (kg coal/day) from the HH survey (see Table 13) were used to estimate daily $PM_{2.5}$ emission rates (g $PM_{2.5}$/stove/day). Both the emission factors and fuel use rates were stratified by stove type (i.e., traditional, Ulzii, Khas, and Dul). Emission factors were assumed to remain constant across seasons, whereas fuel use rates varied by season but were assumed to be constant within each season.

Daily emission rates were further allocated to hour of the day using the fueling profiles shown in Figure 22. These profiles were constructed from the 24-hour recall data in the HH survey and varied by season. Variations by stove type within each survey period were examined and the differences were deemed to be inconsequential.

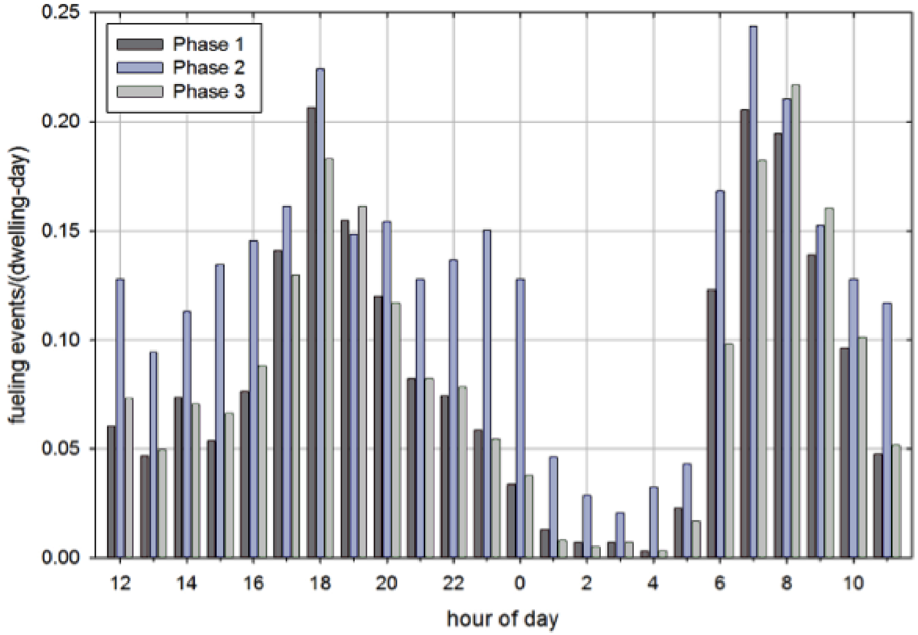


Figure 22. Time of day distribution of heating stove fueling events from the household survey.
Survey phases (Phase 1 = late fall, Phase 2 = winter, Phase 3 = early spring);
Hour (12 = noon, hour 0 = midnight., etc.) is the start of the one-hour period.

3.6.1.2 *Spatial allocation of emissions*

Residential stoves were modeled as area sources.[14] The banks distributing MCA stoves provided stove sales data that included information on the stove type and residential location (address, khoroo, and district) per sale. Geographic coordinates of residences (i.e., latitude, longitude) were provided by only one of the two banks, and thus the locations of MCA stoves were aggregated at the khoroo level for this analysis. Aerial images of UB were used in a geographical information system (GIS) to clip the boundaries of khoroos to exclude large, uninhabited areas. Otherwise, if the population and stoves were uniformly distributed over khoroos with relatively large uninhabited areas, ambient PM concentrations in the inhabited areas would be underestimated and the population-weighted concentrations would be biased down. The stoves assigned to each khoroo were uniformly distributed within the clipped khoroo boundaries. MCA stoves by khoroo (Figure 23), which shows actual khoroo boundaries rather than the clipped boundaries) and stove type were spatially allocated to a network of 1 km × 1 km modeling grids over UB using area-weighted sums.

[14] An "area source" approach combines the emissions from all stoves in given area (1 km × 1 km grids in this case) and treats the emissions as being uniformly released across that area. This is distinguished from modeling each stove individually as a discrete point source of emissions. Area sources have emission rates of mass/(area·time) such as μg $PM_{2.5}$/(km^2-hr).

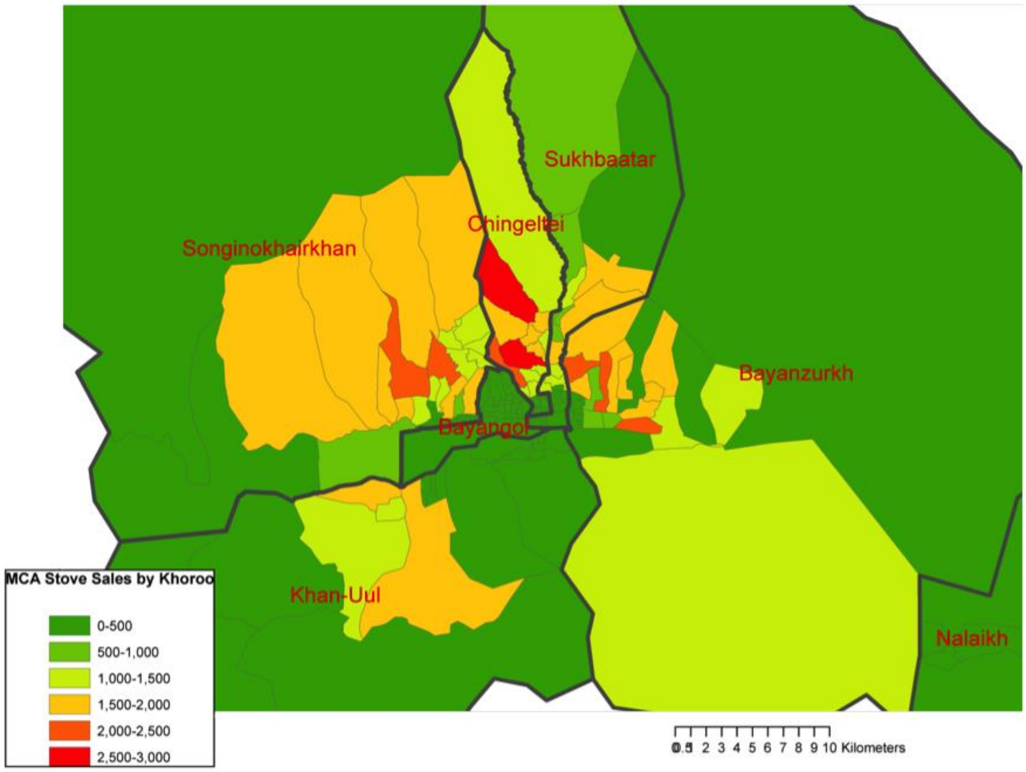


Figure 23. MCA stove sales by khoroo.

Total residential heating stoves by khoroo were estimated using the 2012 household census. These data are stratified by ger and house dwelling types.[15] It was assumed that each household had only one dwelling. However, multiple lines of evidence suggest this underreports the number of residential stoves that are in use. Many households have both a ger and house within the same compound and thus the number of dwellings is likely to be systematically biased downwards. JICA used satellite images to count the number of dwellings for one khoroo in each district and estimated that the 2010 household census underestimated the number of dwellings by about 20% (JICA, 2013). Thus, for this model, a multiplier of 1.2 was used to estimate the number of residential stoves from the 2012 household census. This assumes that dwellings are occupied and are using stoves during the heating season, whereas in practice some dwellings may be used seasonally (e.g., a household may use a house in the winter and a ger in the summer). The modeling also assumes one stove per dwelling. This assumption is supported by the HH survey, in which only ~2% of dwellings reported having two or more stoves. Stoves were spatially allocated by the protocol described above for MCA stoves.

[15] The census data dwelling types include gers, regular houses, luxury houses, and apartments. Heating stoves are assumed to be present only in gers and regular houses.

3.6.2 Ambient air quality model

Ambient $PM_{2.5}$ concentration fields over UB from residential stove emissions were estimated using the Industrial Source Complex Short-Term, version 3 (ISCST3) dispersion model (USEPA, 1995). This level of modeling sophistication is consistent with prior World Bank modeling that was used to develop the MCA stove rollout strategy and by JICA in their capacity development project for air quality management in UB (Guttikunda, 2007; JICA, 2013).

Figure 24. Location of meteorological monitoring stations used in the air quality modeling.

Modeling was conducted at hourly resolution. Meteorological data used to drive the model included hourly temperature, wind speed and wind direction from air quality monitoring station #4 (UB04) in the National Agency for Meteorology Hydrology and Environmental Monitoring (NAMHEM) monitoring network (Figure 24), and mixing layer height[16] and solar radiation estimates from the NOAA HYSPLIT model (Draxler & Hess, 1997). The wind speed and solar radiation data were used to assign an atmospheric dispersion stability class to each hour. Figure 25 shows the hourly wind rose for the 2012-2013 winter season, and Figure 26 shows the daily time series of morning mixing layer height. Surface winds at UB04 are primarily from the northeast and secondarily from the southwest. However, there was also considerable within-season variability in the prevailing surface winds. Twelve percent of the hours were calm conditions (operationally defined as wind speeds less than 1 m/s), and these hours could not be modeled. Morning mixing layer heights are less than 100 m for the deep winter period.

[16] "Mixing layer height" is the top of the layer in which ground-level emissions will mix. A low mixing layer height means the emissions will remain trapped near the ground while a high mixing layer height means the emissions are diluted over a larger layer air volume. The mixing layer height tends to be a minimum during the nighttime and a maximum during midday.

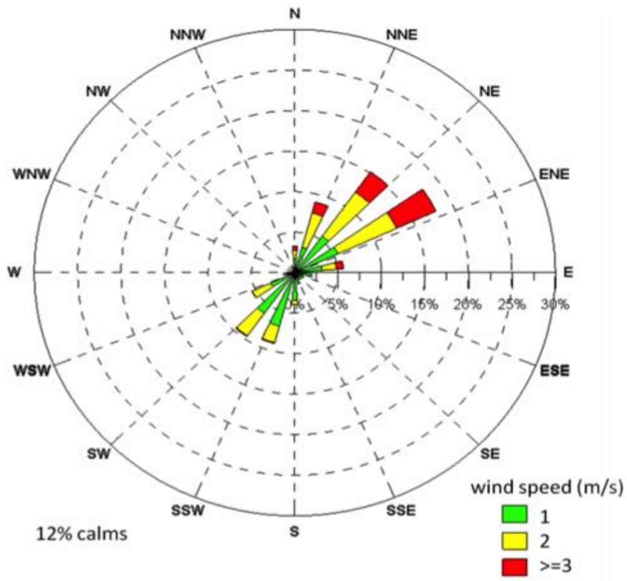


Figure 25. Hourly wind rose at National Agency for Meteorology Hydrology and Environmental Monitoring station #4: October 2012-March 2013.

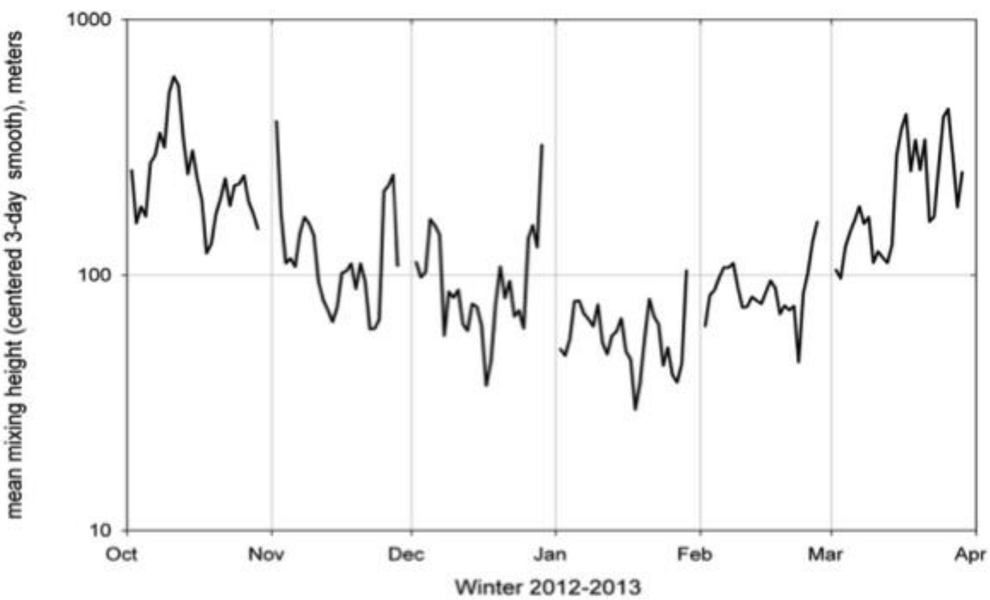


Figure 26. Daily 6-10 AM mixing layer height estimates from the HYSPLIT model.

4 HOUSEHOLD SURVEY DESCRIPTIVE RESULTS

4.1 Sample Selection

At the start of Phase I data collection, a variety of challenges required that 35% of sampled households be replaced (Table 9). First, there were numerous discrepancies in the household addresses within the bank and PMT lists on which the sampling framework was based. Of the households that data collectors attempted to interview, 13% identified through either list were actually living at another address, either because they moved or because an incorrect address was given or recorded in the lists; 4% of the listed addresses could not be located at all. In 34 cases, enumerators discovered that the sampled home was actually an apartment building or business address, which were not eligible for the stove evaluation. While some of the households sampled from the PMT list would have moved since the time of the PMT survey two years prior to this evaluation, this would only explain a portion of discrepancies.

If a sampled household refused to participate or used a low-pressure boiler or an improved stove model not approved by MCA as the main heating stove, it were replaced with another randomly sampled household from the same sampling frame strata. Enumerators arranged to revisit up to two times if the main stove tender (the intended respondent) was not present to answer questions. Failure to interview after three visits also resulted in replacement of the sampled household.

There were also numerous discrepancies between the dwelling and stove type recorded in the data sources and those actually found upon arrival at the sampled home. During the first weeks of Phase I data collection, such households were replaced in the sampled list. However, since this type of dwelling and stove mismatch continued to be a common problem, in order to minimize bias from re-sampling while minimizing the number of replacements, it was decided that for the remainder of the study, households that had different dwelling or stove types than expected would still be surveyed. In addition, those households in which the listed residents had moved outside the district or were renting their home to others, the current residents at that address would be invited to participate.

Table 9. Phase I data collection sample summary

	n	%
Reasons for non-interview (replacement sample used):		
Household not found	76	4%
Relocated outside of district	225	13%
Inappropriate dwelling (e.g. apartment, business)	34	2%
Address duplication in list (already sampled)	11	1%
Not home at any of 3 visits	60	3%
Refusal to participate	53	3%
Uses other non-MCA improved stove, low-pressure boiler, electric heater	65	4%
Does not use expected stove or live in expected dwelling	80	5%
Total	**604**	**35%**
Completed interviews:		
Correct information	917	52%
Mismatch dwelling type	79	5%
Mismatch stove type	129	7%
Total	**1125**	**64%**

The enumeration team encountered far more cases than expected of household relocation and mismatched residence and stove types, which may support anecdotal reports that some households were providing false addresses to the participating banks to purchase subsidized stoves for family members outside of Ulaanbaatar. However, our limited data cannot confirm the degree to which misreporting had occurred. Sample bias could have been introduced if the characteristics, stove satisfaction, and fueling behaviors of the unsurveyed households differed from those successfully interviewed, but it is difficult to estimate the direction of this potential bias.

Interviews were completed with 1,125 households in Phase I, 208 of which had different stove or dwelling types than expected. Two households were removed from the final sample because they were using Golomt stoves, a model subsidized by MCA during 2011-2012 but not sold in sufficient numbers to be a focus of this evaluation. The final sample of completed household surveys throughout each of the data collection phases is shown in Table 10. There was a 6% attrition rate from Phase I to III, largely due to respondent fatigue, relocation, or continued absence of the intended respondent from the home. The geographic distribution of the sample largely reflected stove distribution patterns (Figure 27).

Table 10. Stove distribution in the final sample, by phase

		Traditional	Ulzii	Khas	Dul	Total
Phase I	Ger	105	173	18	175	471
	House	106	186	182	178	652
	Total	**211**	**359**	**200**	**353**	**1123**
Phase II	Ger	104	166	18	170	458
	House	102	180	166	173	621
	Total	**206**	**346**	**184**	**343**	**1079**
Phase III	Ger	102	161	18	165	446
	House	99	179	162	171	611
	Total	**201**	**340**	**180**	**336**	**1057**

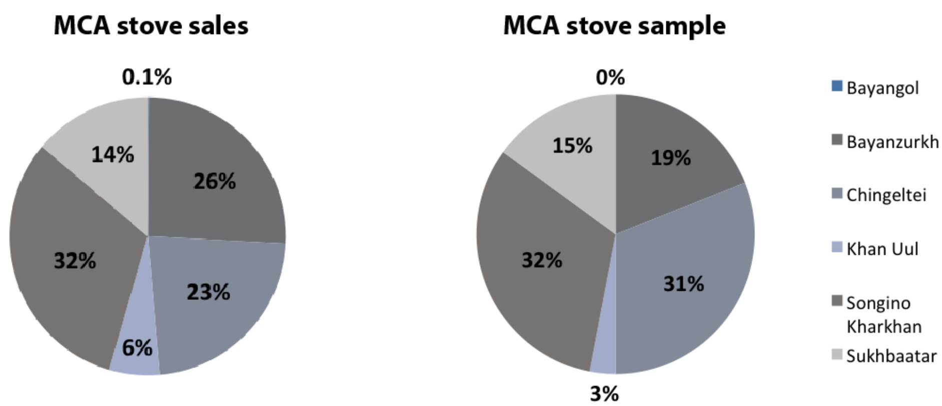


Figure 27. Comparison of MCA stove sales to sample, by district.

4.1.1 Intervention assignment of the final sample

Analyses were conducted to compare the overall intervention (MCA stoves) versus comparison (traditional stoves) groups, and each MCA stove type (Ulzii, Khas, and Dul) versus traditional stoves. As with randomized control trials, this IE aimed to assess the impact of the program under an approximation of an intention to treat (ITT) model. This means the intervention status (stove type) was established based on the stove types recorded during the Phase I household visits. If a household owned only a traditional stove at Phase I, it was included in the comparison group throughout the three data collection phases, regardless of whether the household adopted an MCA stove after Phase I. Figure 30 shows how households changed stove types throughout the duration of the study. Likewise, if the survey recorded an MCA stove at a household in Phase I, that stove type was considered the intervention status for the duration of the evaluation, even if the household also used a traditional stove at any time during the winter or stopped using the MCA stove. In the 13 cases where households owned two MCA stoves in Phase I, the stove used most often was used to establish the intervention status. The benefit of ITT-style analysis is that it attenuates the bias from variations in outcomes due to possible non-random changes in stove use over time, providing a better estimate of the overall impact of the program under real-world conditions. For example, if an MCA stove user is unsatisfied with the stove and therefore supplements cooking or heating by using another stove, the attenuated impacts this household may experience should still be attributed to the MCA stove model. We examined the degree to which actual stove use reflects misallocation of intervention assignment and also conducted a compliance sub-analysis of key outcomes according to actual stove used. Apart from these sub-analyses, which are noted, all analyses are presented according to Phase I intervention status.

4.2 Household Characteristics

Annex 1 provides extensive results tables from the household survey, with key findings highlighted below. Several demographic characteristics were similar between treatment (MCA stove) and comparison (traditional stove) households. On average, each household had four members, with the head of household in mid-forties, who was likely to have completed at least a high school education (Table 11). Twenty-one percent of households were headed by females. Half of traditional stove owners lived in gers compared to 40% of MCA stove owners. The majority of stove tenders in both groups was female, had completed a high school education at a minimum, and did not work for income outside of the home. The balance of household characteristics related to propensity score matching is shown in Table 13.

Table 11. Household sample characteristics

	Traditional			MCA (treated)		
Variable description	***n***	**mean**	**SD**	***n***	**mean**	**SD**
Ger dwelling	201	50%	0.50	856	40%	0.49
Number of rooms in dwelling	201	1.62	1.00	856	1.50	0.90
Percent of HH members working	200	41%	0.25	847	42%	0.26
Wealth asset score	201	3.64	0.54	856	3.70	0.45
Number of people in HH	201	3.92	1.51	856	3.89	1.56
HH has children < 5 years old	201	38%	0.49	856	35%	0.48
HH has elderly > 60 years	201	22%	0.41	856	22%	0.42
Head of HH is married or has non-married partner	201	74%	0.44	856	74%	0.44
Head of HH age	201	44.65	15.13	851	46.27	14.11
Female-headed household	201	20%	0.40	855	21%	0.41
Head of HH is educated beyond high school	201	25%	0.43	856	33%	0.47
Head of HH did not complete high school	198	22%	0.42	851	20%	0.40
Age of main stove tender	198	41.53	16.91	845	44.19	15.29
Male is involved in tending stove	199	31%	0.46	852	33%	0.47
HH in Bayangol District	201	14%	0.35	856	0%	0.03
HH in Bayanzurkh District	201	25%	0.44	856	19%	0.39
HH in Chingeltei District	201	13%	0.34	856	31%	0.46
HH in Khan Uul District	201	5%	0.22	856	3%	0.17
HH in Songino Kharkhan District	201	28%	0.45	856	32%	0.47

The evaluation also aimed to understand whether the stove subsidy program had differential impacts on males and females. This is relevant due to the greater number of female stove tenders, who make decisions about stove operation, are usually involved in fuel and stove purchase choices, and who may experience the project's impacts more acutely. Some characteristics were examined according to the gender of the household head, as female-headed households are typically disadvantaged socially and economically. Females were primarily responsible for tending the stove in 67% of households, with similar proportions using traditional and MCA stoves (69% traditional; 67% MCA stoves). As shown in Table 11, the gender of the stove tender was not significantly different between traditional and MCA groups. This remained true after matching (Table 13). Households with female stove tenders purchased Ulzii and Dul stoves in similar proportions (70% and 68%, respectively), but female stove tenders were less likely to tend Khas stoves (59%). Female-headed households comprised 21% of the study population, with no significant differences in intervention status or stove type utilized.

4.2.1 Household economic standing

Household income proved to be a difficult and potentially unreliable measure. To estimate the household's income in the survey, the respondent was asked to estimate the prior month's income for every household member, as well as the amount each person received from pensions or other monthly allowances from the government. In an attempt to better capture additional sources of income, a general question was added in Phase III about total remittances or other income not reported for individual household members. The calculated total household income was most likely a lower bound estimate of actual income due to many "don't know" responses for income of particular family members and common anecdotal reports from enumerators and other Mongolian collaborators that Mongolians frequently avoid reporting income from secondary jobs, which are common and can often comprise a large proportion of income.

Likewise, expenditures on food, bills, household items (not including fuel), and luxury goods as measured in Phases II and III were potentially unreliable. Enumerators were instructed to encourage respondents to make their best estimate, enlisting help from other household members as needed. Enumerators reported that most respondents were highly uncertain, if not entirely unaware, of expenditures in various categories. There were numerous cases of households reporting spending more than their total reported income. For example, in Phase II, 21% had expenditures more than 50% higher than reported income, and 15% reported spending 100% more than their reported income. This trend was similar in Phase III.

Savings and credit were not measured, so such discrepancies could be partly explained by the use of these financial instruments; however, these discrepancies, as well as anecdotal reports of substantial respondent difficulties with these questions, cast strong doubt on the validity of these measures. Principal component analysis (PCA) was used to estimate a proxy for wealth, that accounted for the ownership of land, additional homes, household appliances (refrigerator, washing machine), electronics (radio, television, computer), additional cooking devices, a bicycle, a vehicle, the volume of the main living space, and the size and quality of the dwelling, from a one-room ger to a six-room house (Vyas & Kumaranayake, 2006). This wealth asset index was more stable, and since it was composed from more easily measured and verified items, it was used as the primary proxy for household economic status. The asset score was mildly correlated with average monthly income (R^2 = 0.24), and with essential expenditures on food, bills, and transport (R^2 = 0.28). This continuous measure was then used to categorize households into wealth quintiles.

4.2.2 Stove ownership and use

The evaluation sample included 201 traditional stove owners and 856 MCA stove owners, comprised of 340 Ulzii, 180 Khas, and 336 Dul households. Traditional stoves were equally split between gers and houses, and while Ulzii and Dul had a nearly equal division between dwelling type, only 17 (9%) Khas stove owners lived in gers (Figure 28). This is not surprising, as these stoves are larger and marketed as most appropriate for larger houses.

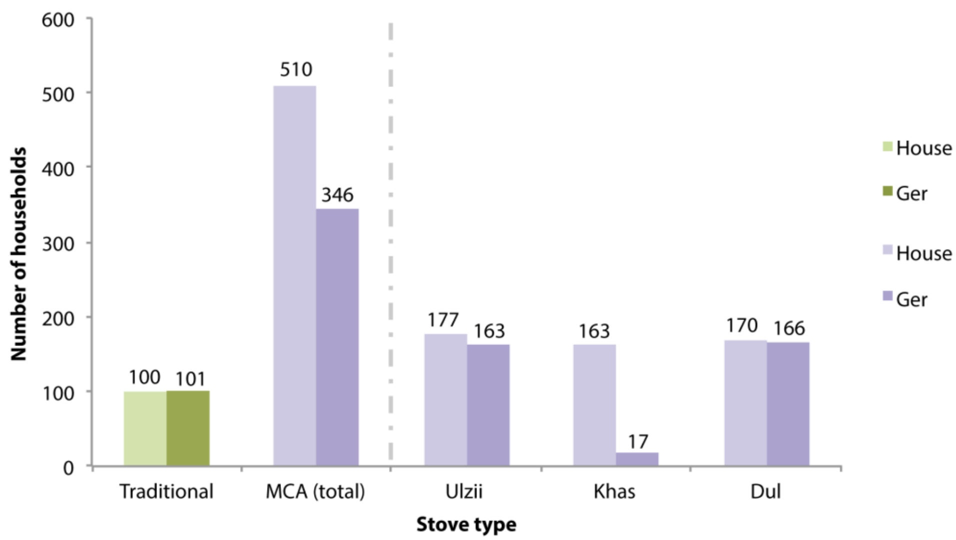


Figure 28. Stoves owned by sampled households, by stove type and dwelling.

Examining the overall sample, ownership of each type of stove remained largely constant throughout the winter; however, not everyone was using their stoves (Table 12). While 81% of all 1,057 households owned an MCA stove at Phase I, only 71% reported using it. This gap narrowed slightly in Phase II to seven percentage points. While a condition of purchasing a subsidized MCA stove was the removal of the home's traditional stove, 14% of MCA stove owners still owned a traditional stove in addition to their MCA stove, indicating the replacement was not completed or that these households had repurchased another traditional stove. However, the majority reported that they did not use their traditional stove concurrently with their MCA stove. By the end of the winter in Phase III, 4% of households reported owning more than one MCA stove, although only 1% reported using them concurrently (Figure 29).

Table 12. Observed stove ownership and use in sampled households

Variable description	*n*	Phase I		Phase II		Phase III	
		mean	SD	mean	SD	mean	SD
Has traditional stove	1057	33%	0.47	33%	0.47	33%	0.47
Uses traditional stove	1057	31%	0.46	29%	0.45	28%	0.45
Has MCA stove	1057	81%	0.39	80%	0.40	81%	0.39
Uses MCA stove	1057	71%	0.46	73%	0.44	73%	0.44
Has Ulzii stove	1057	33%	0.47	35%	0.48	34%	0.47
Uses Ulzii stove	1057	29%	0.45	31%	0.46	30%	0.46
Has Khas stove	1057	17%	0.38	17%	0.37	17%	0.37
Uses Khas stove	1057	15%	0.36	14%	0.35	14%	0.35
Has Dul stove	1057	32%	0.47	32%	0.47	33%	0.47
Uses Dul stove	1057	28%	0.45	29%	0.45	30%	0.46

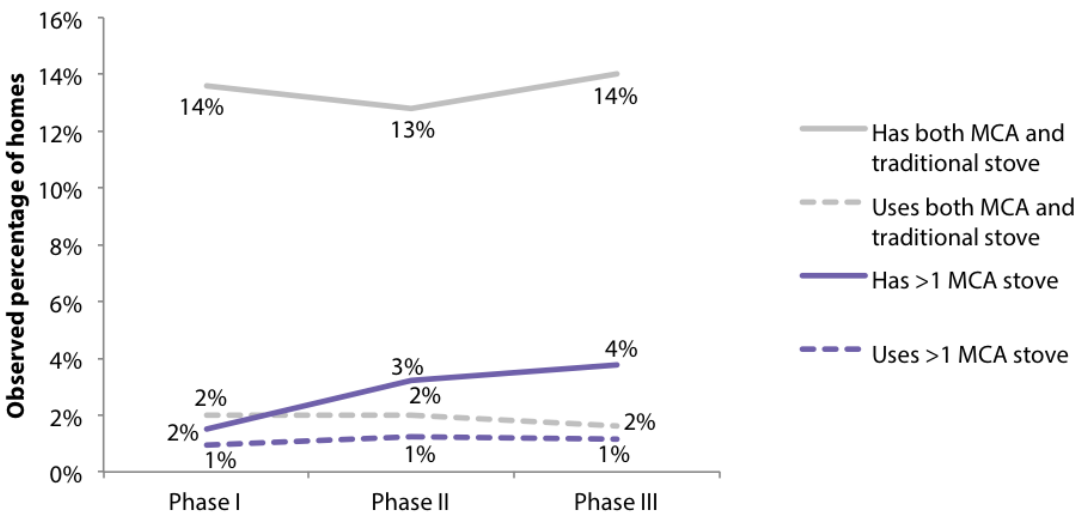


Figure 29. Ownership and use of multiple stoves over time.

Actual stove use, as reported over time, was compared to Phase I intervention assignment to assess the extent to which variance from initial stove ownership in Phase I may have influenced the overall impact (Figure 30). Among households assigned to the traditional stove (comparison) group in Phase I (red line), 11% began to use an MCA stove by Phase II. This climbed to 13% in Phase III. Among those assigned to the MCA group (blue line) at Phase I as a result of observed ownership of an MCA stove, only 88% reported *using* their MCA stove at Phase I. This level of use remained steady across all data collection phases. This 88% figure speaks to one of the indicators in the MCA-Mongolia Indicator Tracking Table (MMITT): percentage of subsidized stoves in participating homes (referencing those having an MCA stove in the home that actually utilize the MCA stove). With a goal of 90%, this represents 98% progress towards this target. See Annex 6 for more information. This suggests that there was some leakage of MCA stove effects to traditional stove owners. A separate compliance-adjusted analysis was also conducted to identify effects among true users who were compliant with operation instructions.

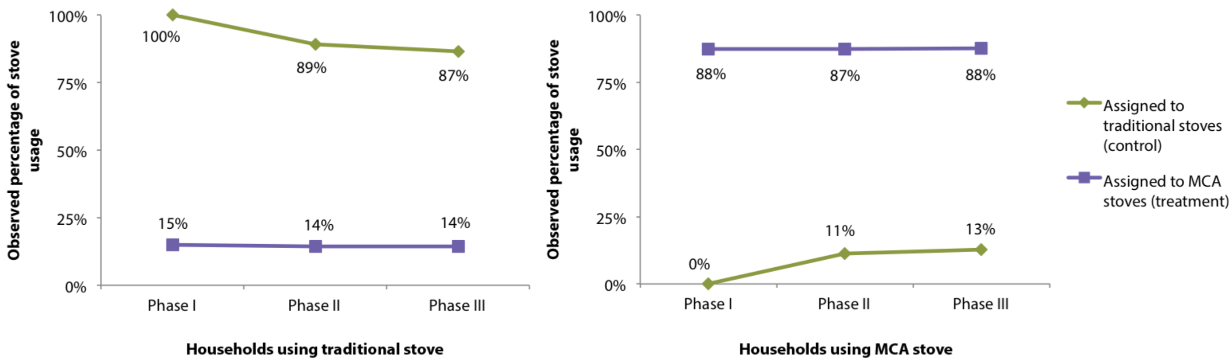


Figure 30. Comparison of Phase I intervention assignment to actual stove use over time.

4.2.3 Stove purpose

Stove use differed over time and between users of the various stove types (Figure 31). Given the cold temperatures and typical ger and house structure, it is not surprising that almost no stoves were used solely for cooking. Averaging across the three data collection phases, the majority (81%) of traditional stove owners used their stoves for both cooking and heating, ranging from 78% in Phase I to 85% in Phase II, with the remainder using their stoves for heating only. Only Dul stove owners had a similar pattern, with 71% to 84% in Phases I and II using their stoves for both heating and cooking. In contrast, less than half of Ulzii and Khas owners used their stove for both purposes in Phase I, although numbers climbed to a maximum average of 61% and 70%, respectively, in Phase II. Usage patterns for cooking and heating were quite similar, with no significant differences by gender of the stove tender.

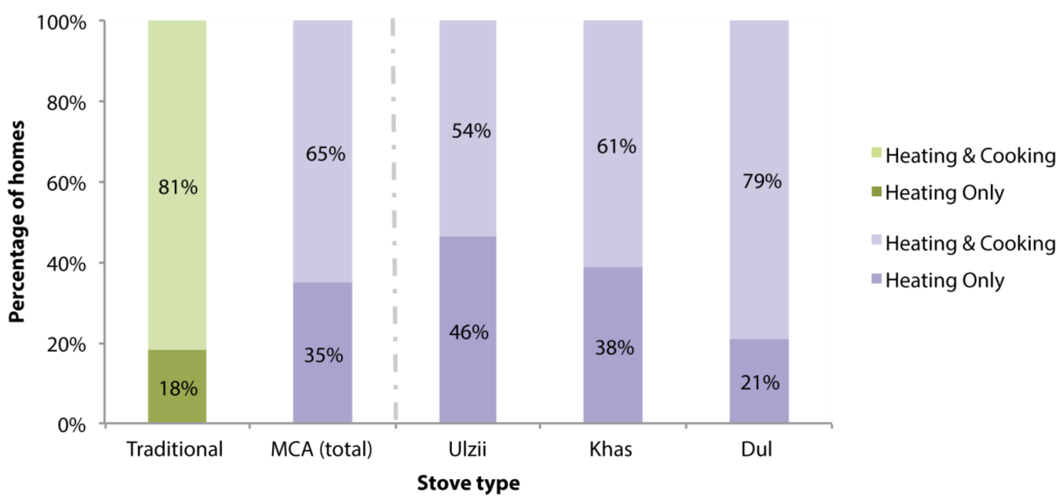


Figure 31. Use of stoves for cooking and heating by stove type

4.2.4 Heating wall use and adaptation

Heating walls, available in houses but not gers, are interior wall chimneys that increase the heating surface across the interior of the dwelling in order to retain heat longer and facilitate more gradual warming of the home, reducing the variation in heat output over the burn cycle of the coal. Heating walls were far more prevalent among traditional stove owners (80%) compared to MCA owners (58%) (Figure 32). Among MCA stove types, Dul stoves were most commonly connected to a heating wall (72%) compared to approximately half of Ulzii and Khas stoves. This pattern is linked to the finding that more Dul stove owners who had previously had a heating wall for their traditional stove were able to connect it to their new Dul stove (77%), with approximately half of Ulzii and Khas stove owners connecting their MCA stoves to their old heating wall. Related to this trend, overall, 44% modified their MCA stoves, with the primary adaptation being the connection of the stove to a heating wall; heating wall use increased from early to mid to late winter. Khas stove owners were most likely to modify MCA stoves (68%).

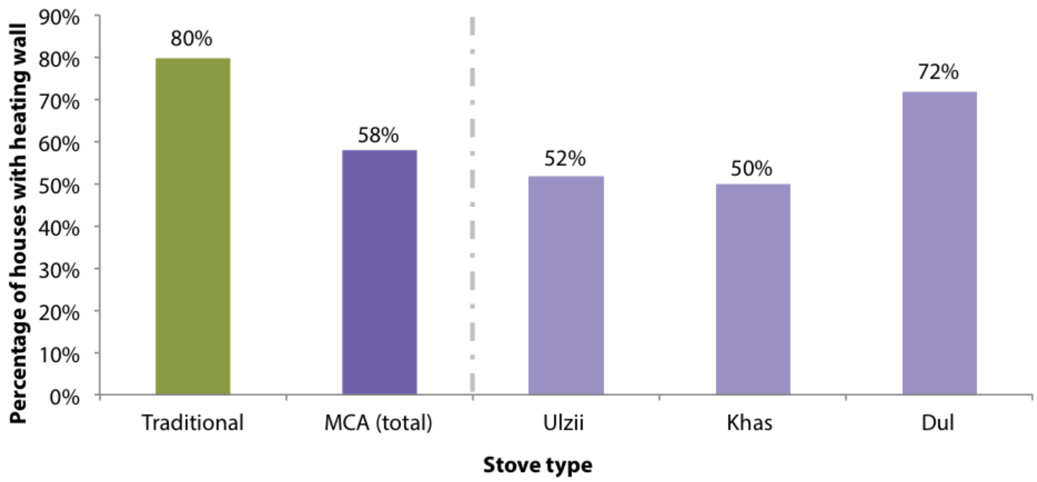
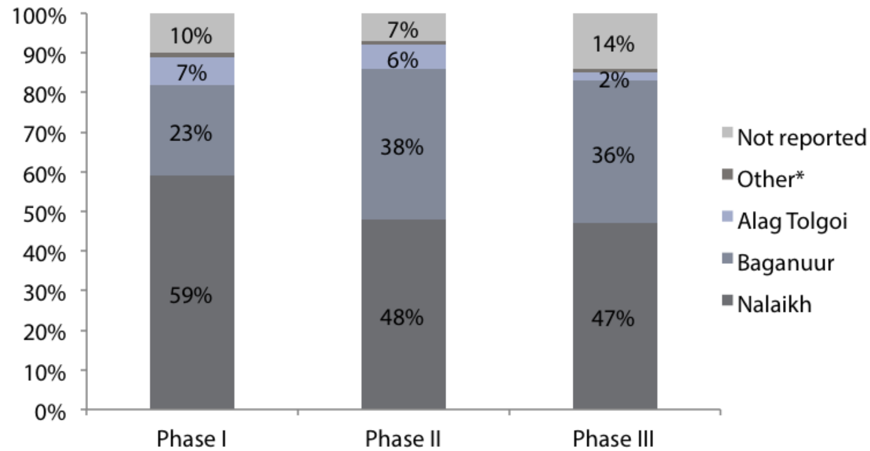


Figure 32. Connections to heating walls by stove type, among houses.

4.2.5 Fuel types used

Nearly all households reported using coal as the predominant stove fuel, with wood kindling. Nalaikh and Baganuur coal types were most common, with a few using Alag Tolgoi, and 1% using other types (Figure 33). No significant differences were observed in the type of coal used by male versus female stove tenders, or between male or female-headed households. Nalaikh coal is considered to be of the highest quality, with higher calorific value and lower emissions, while Baganuur coal is of lower quality. During the evaluation, the Mongolian Government began to subsidize Baganuur coal in the ger districts. This policy may partially explain general increases in Baganuur coal use over time. Whether this or another factor influenced coal choice, the trends in coal types used differed between MCA and traditional stove owners over time, as discussed in Section 5.4.4.



"Other" fuel types include shariin gol, shivee ovoo, egg and stick briquettes, semi-coke coal, and sawdust powder and briquettes. All combined were used by 1% of households at each phase.

Figure 33. Fuel usage by type and phase.

4.2.6 MCA stove satisfaction and demand

MCA stove owners reported superior performance of MCA stoves compared to traditional stoves in most categories (Figure 34). Among MCA stove owners surveyed, nearly all felt the MCA stove had better appearance than traditional stoves, and was easier to maintain in terms of ash removal and chimney cleaning. The majority (94%) believed their MCA stove polluted less; however, because households could not objectively verify pollution reductions, this may be more reflective of the reach of stove marketing messages. 87% believed their stove maintained heat longer than a traditional stove, and 82% believed it uses less fuel. This is in contrast to more objective measurements of fuel consumption (Section 5.2) and may therefore be more a reflection of expectation based on stove advertisements.

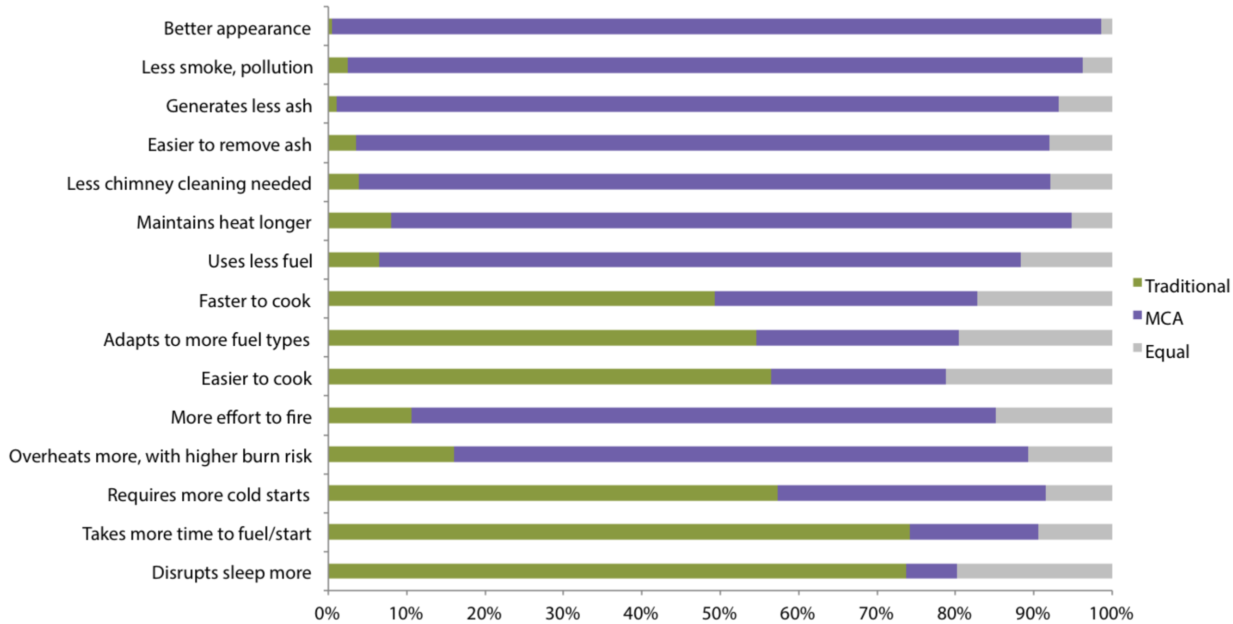


Figure 34. Comparisons of MCA to traditional stoves: MCA stove users.

MCA stove owners felt that traditional stoves were better in several categories. Many (56%) felt traditional stoves were easier to use for cooking, and 74% felt they were easier to light, although the same percentage of MCA stove owners reported traditional stoves as taking more time to fuel or start. Traditional stoves were also thought to be more adaptable to different fuel types and pose less burn risk due to overheating.

Gender did not appear to play a substantial role in stove tenders' comparative assessments, as women and men rated MCA stoves within three percentage points in nearly all categories (Figure 35).

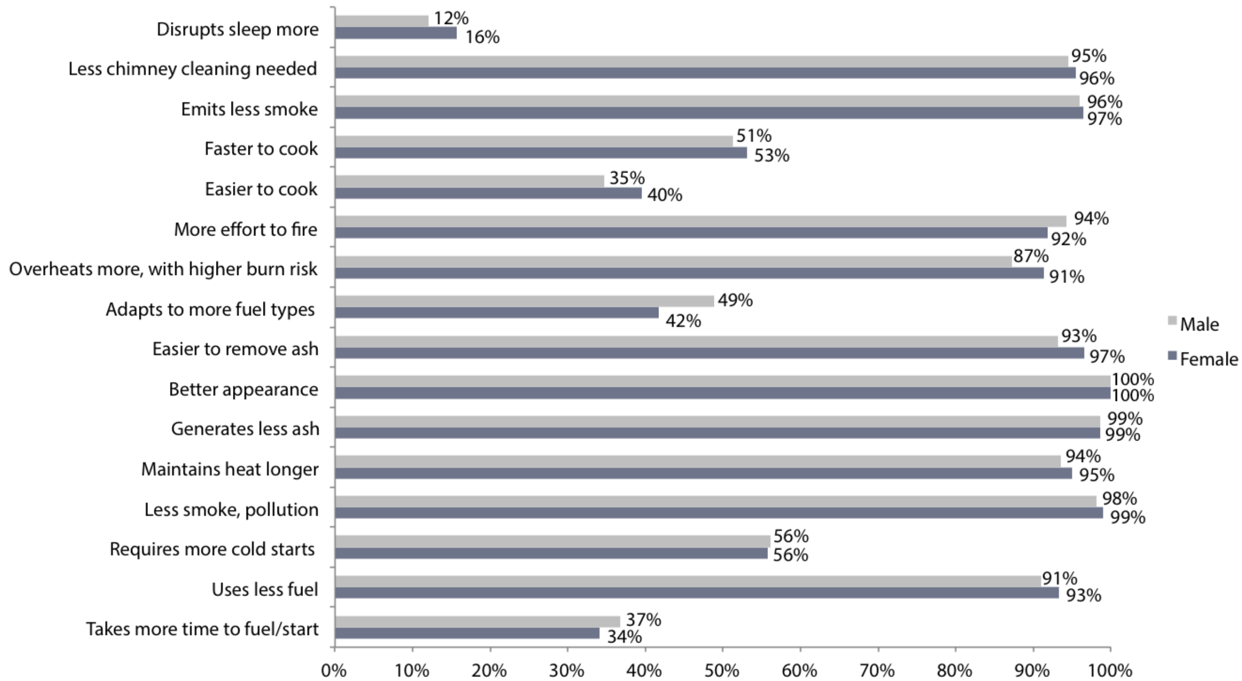


Figure 35. Comparisons of MCA to traditional stoves: female and male MCA stove tenders.

Demand for energy-efficient stoves was high, with 78% of traditional stove owners stating they wanted to acquire MCA stoves. The most common reasons reported were to save on fuel expenses, reduce air pollution, and to have a stove that keeps the home warm for a long time (Figure 36). This could reflect the success of the marketing campaign and positive word-of-mouth testimony by MCA stove users. Sentiments were similar between male and female heads of household; the largest gender difference in drivers of demand was that female-headed households were slightly more interested in the advertised fuel savings, perhaps due to being in a financially more vulnerable position. A comparison based on wealth yielded similar responses. The distribution of reported reasons for MCA stove demand had the same rank order among those in the poorest 40% of the population and those with greater wealth, and mirrored the rank order shown in Figure 36.

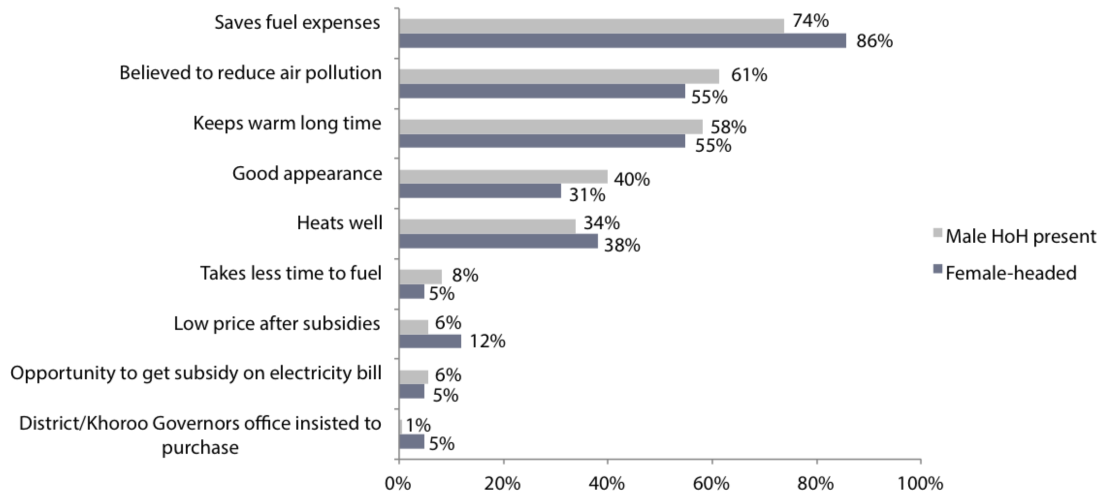


Figure 36. Reasons for wanting to acquire MCA stove: traditional stove owners by household head gender.

While reasons for wanting an MCA stove were similar across stove tender age categories, the characteristic with the widest range was the appeal of fuel savings. This was of value to 90% of tenders age 31-40, but only 55% of tenders age 41-50 and to 79% of tenders in age groups below 31 and above 50.

While reasons given for wanting to purchase an MCA stove were quite similar for both genders, among those who did *not* wish to purchase an MCA stove (44 female and 25 male stove tenders), a larger proportion of female tenders cited difficulty with cooking as a primary reason (Figure 37). The most common reason cited by male tenders, in far larger proportion than by females, was a doubt that the stoves would reduce smoke and air pollution as advertised.

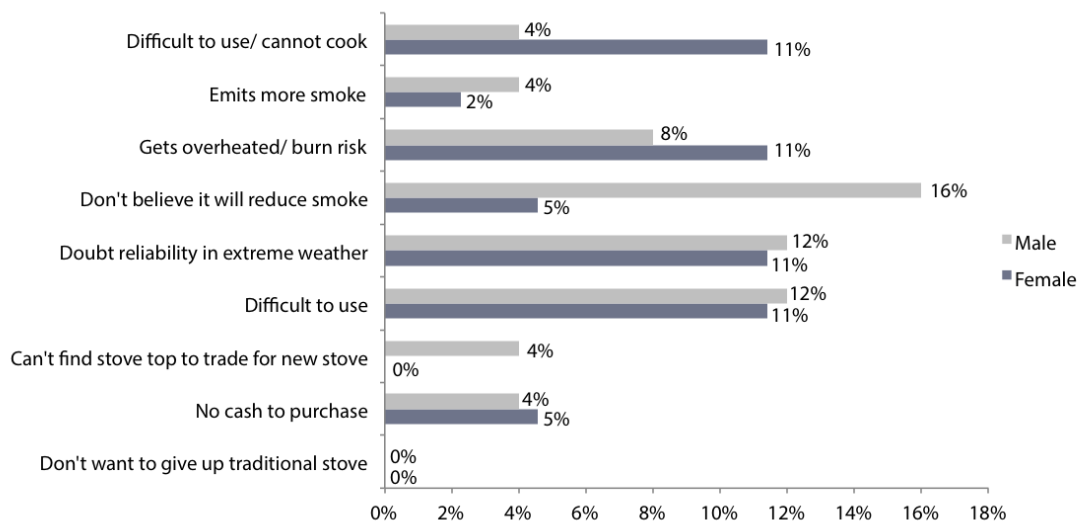


Figure 37. Self-reported reasons for not wanting MCA stove: traditional stove owners, stratified by gender of stove tender.

5 MATCHED IMPACT ANALYSIS RESULTS

5.1 Propensity Score Estimation

In order to identify traditional stove owners comparable to MCA stove owners, household characteristics thought *a priori* to be potential predictors of the ability or willingness to purchase an MCA stove were considered. These were first compared between both intervention groups to assess relative balance and association with participation in the intervention. Factors that were may influence access to the MCA stoves or influence the household's perceptions of the economic and air quality benefits of these stoves were selected. For example, the district of residence may influence the perceived need for air quality improvements, as air quality can differ based on dwelling location. Having a smoker in the household might be related to health effects of air quality. The poverty status of a household could either increase the perceived need for reduced fuel expenditures or reflect marginalization or lack of access to or comfort with banks to purchase the stoves. Households purchasing coal by the truck may be more likely to have larger cash reserves that could also be used to purchase a stove. The physical size and front door insulation of a household may be associated with benefits of a more energy-efficient stove. Age and education of the household head or stove tender may affect awareness of stove marketing or willingness to try new products. All variables included in calculating the propensity score are shown in Table 13. Other variables were considered but not included in the model due to a lack of variation in the parameter values, missing values, or data inconsistencies.

Before creating the matching model, the selected matching variables were compared between traditional and MCA stove owners using logit regression (Table 13, "unmatched") to develop a model for stove adoption. Significant predictors of MCA stove adoption included living in Bayangol or Chingeltei District (as expected, since Bayangol's raw coal ban prevented residents from obtaining an MCA stove, and because stove sales were highest in Chingeltei), number of rooms in the home, age of the stove tender, and wealth asset score. MCA stove owners, on average, had fewer rooms in their home, a slightly older stove tender, and were slightly wealthier than traditional stove owners. Based on this model, a propensity score was estimated using the *pscore2* command in Stata, for each household based on their values for the matching variables.

Separate propensity scores were estimated and applied for each data analysis subset, including the following:

1. Overall MCA stoves of any type versus traditional stoves
2. Ulzii versus traditional stoves
3. Khas versus traditional stoves
4. Dul versus traditional stoves
5. Overall MCA stoves versus traditional stoves within the SUM data subset

Table 13. Balance on household characteristics before and after matching

	Unmatched							Matched				
	Traditional			MCA (treated)				Traditional	MCA (treated)		SE	
Variable description*	***n***	**mean**	**SD**	***n***	**mean**	**SD**	***p*****	**mean**	**mean**	**diff.**	**(diff.)**	***p*****
HH in Bayangol District	201	14%	0.35	856	0%	0.03	**<0.001**	0%	0%	0%	0.03	0.500
HH in Bayanzurkh District	201	25%	0.44	856	19%	0.39	0.530	21%	20%	-1%	0.04	0.389
HH in Chingeltei District	201	13%	0.34	856	31%	0.46	**0.003**	25%	26%	2%	0.03	0.307
HH in Khan Uul District	201	5%	0.22	856	3%	0.17	0.494	3%	3%	0%	0.02	0.485
HH in Songino Kharkhan District	201	28%	0.45	856	32%	0.47	0.195	36%	36%	0%	0.04	0.486
Ger dwelling	201	50%	0.50	856	40%	0.49	0.517	41%	42%	2%	0.05	0.355
Log (natural) volume of main room in dwelling	201	17.82	0.57	856	17.89	0.55	0.732	17.89	17.88	-0.01	0.05	0.425
Number of doors (layers at main door)	201	1.13	0.34	856	1.12	0.33	0.889	1.11	1.13	0.02	0.03	0.311
Number of rooms in dwelling	201	1.62	1.00	856	1.50	0.90	**<0.001**	1.58	1.53	-0.06	0.09	0.276
Number of people in HH	201	3.92	1.51	856	3.89	1.56	0.913	3.85	3.93	0.08	0.14	0.286
HH has children < 5 years old	201	38%	0.49	856	35%	0.48	0.731	39%	36%	-3%	0.05	0.282
HH has elderly > 60 years	201	22%	0.41	856	22%	0.42	0.121	19%	22%	2%	0.04	0.283
Head of HH is married or has non-married partner	201	74%	0.44	856	74%	0.44	0.837	76%	76%	-1%	0.04	0.433
Head of HH age	201	44.65	15.13	851	46.27	14.11	0.306	44.94	45.75	0.81	1.39	0.280
Head of HH is male	201	80%	0.40	855	79%	0.41	0.429	81%	80%	-1%	0.04	0.382
Head of HH is educated beyond high school	201	25%	0.43	856	33%	0.47	0.123	32%	31%	-2%	0.04	0.341
Head of HH did not complete high school	198	22%	0.42	851	20%	0.40	0.896	21%	21%	-1%	0.04	0.443
Age of main stove tender	198	41.53	16.91	845	44.19	15.29	**0.052**	42.52	43.49	0.97	1.57	0.267
Male is involved in tending stove	199	31%	0.46	852	33%	0.47	0.151	33%	32%	-1%	0.04	0.393
Main stove tender smokes	201	29%	0.45	856	27%	0.44	0.170	26%	27%	1%	0.04	0.416
Percent of HH members working	200	41%	0.25	847	42%	0.26	0.902	42%	42%	0%	0.02	0.444
Total person-hours spent in HH during non-work day	200	81.46	36.17	853	80.11	36.33	0.508	79.00	80.75	1.76	3.41	0.304
HH buys coal by the truck	201	33%	0.47	856	37%	0.48	0.923	37%	37%	1%	0.05	0.455
Wealth asset score	201	3.64	0.54	856	3.70	0.45	**0.003**	3.72	3.69	-0.02	0.05	0.323

**All variables listed comprise the propensity score for overall traditional versus MCA stove comparisons*
*** Bold font indicates significant difference between groups*

Several algorithms and sensitivity analyses were performed to obtain an optimal matching method, as described in Annex 4. In the final kernel density model 57 observations were "off support", meaning these observations were dropped from the matched analysis since suitable matches for these observations could not be identified within the matching criteria. As shown in Table 13, the matching successfully balanced the intervention and comparison groups, such that none of the household characteristics were significantly different between groups. However, as with all PSM approaches, the degree to which unmeasured sources of bias affect the comparability of groups is unknown.

Alternative propensity score estimations for matching of particular MCA stove types to traditional stoves followed the same procedure. There were slight variations in the final list of variables included in each model by stove type. In the model for Khas stoves, the variable reflecting whether the household had children under five was excluded from the model to ensure balance. In the model for Dul stoves, the variables coding the district as Chingeltei and the parameter indicating the number of rooms within a house were not included to achieve covariate balance. Balance was achieved in all models, and propensity score density graphs are shown in Figure 38-39.

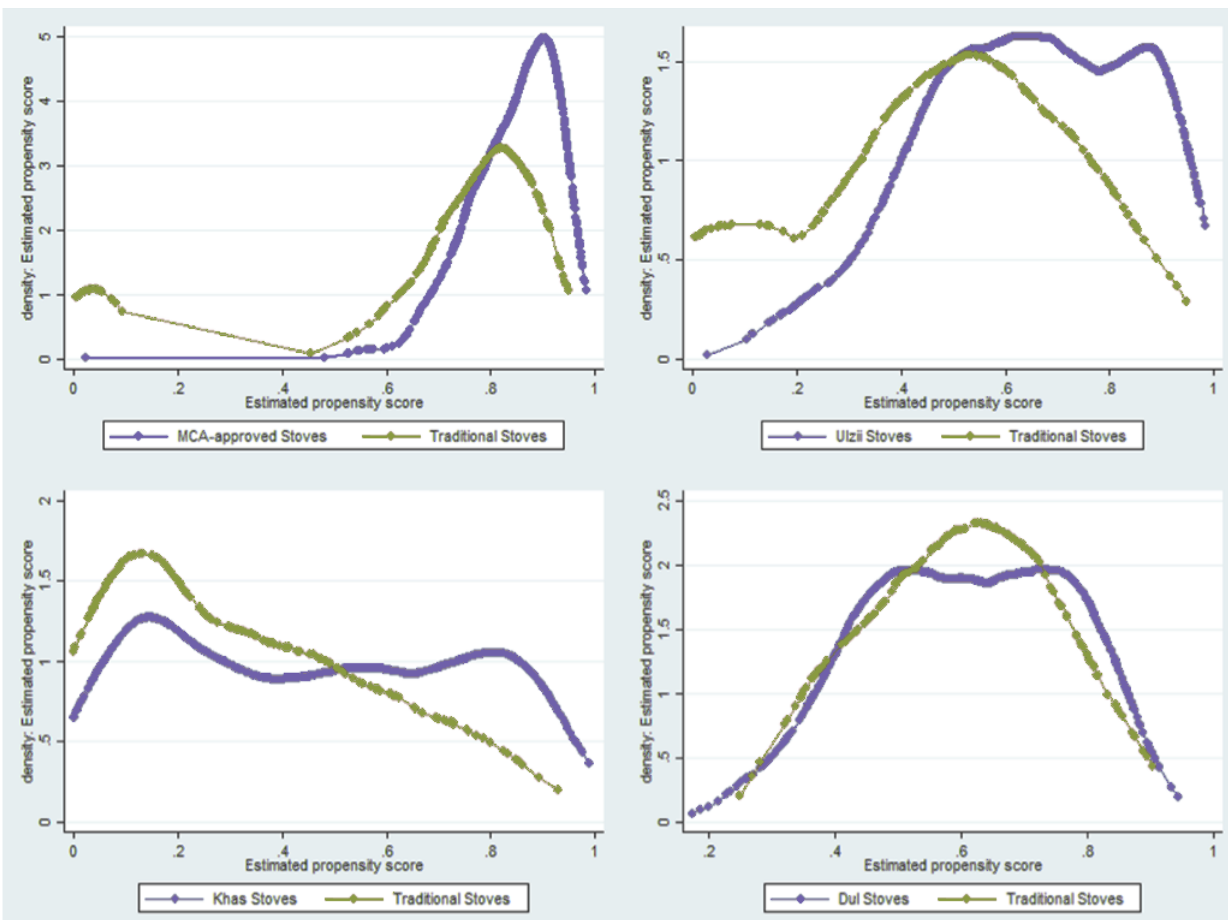


Figure 38. Density of propensity scores for matching: overall and by stove type.

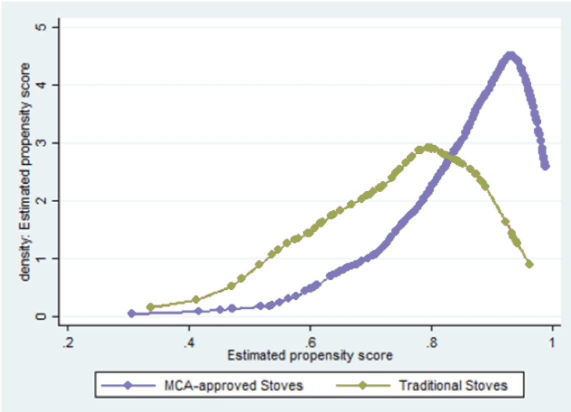


Figure 39. Density of propensity scores for overall matching in SUM data subset.

5.2 Fueling Events and Consumption

Annex 1 presents the comprehensive results tables for fueling and coal consumption outcomes, and the main results are highlighted below. Table 14 shows the overall fueling events and coal consumption data. Figure 40 presents the difference in fueling behavior for MCA stove versus traditional stove owners. The graph shows that when outside temperatures were coldest, in Phase II of data collection (January-February), the number of daily fueling events greatly increased in each group. Overall, MCA stove owners consistently reported significantly fewer fueling events during the prior 24 hours in all three phases, in both gers and houses (Figure 41a). Conversely, MCA stove owners added significantly more coal to their stoves per fueling event (Figure 41b). Overall, this group used 0.72 kg more coal, on average, than traditional stove users at each fueling. This trend was consistent across the three phases. Due to the competing trends in these two factors, total coal consumption reported for the prior 24 hours was not significantly different between traditional and MCA stove users, though small, non-significant reductions were observed (Figure 41c).

Table 14. Fueling events and coal consumption, overall and by phase

Variable description	Subset	Dwelling	*n**	Traditional mean	MCA (treated) mean	diff.	*p***
Daily fueling events	Winter average	Overall	959	2.68	2.34	-0.33	**<0.001**
		Ger	379	2.89	2.46	-0.43	**0.002**
		House	538	2.54	2.29	-0.25	**0.022**
	Phase I	Overall	933	2.30	2.03	-0.27	**0.009**
		Ger	369	2.56	2.17	-0.39	**0.014**
		House	523	2.14	1.95	-0.18	**0.083**
	Phase II	Overall	934	3.58	3.00	-0.57	**<0.001**
		Ger	368	3.86	3.09	-0.77	**0.001**
		House	525	3.40	2.98	-0.42	**0.031**
	Phase III	Overall	928	2.21	2.02	-0.19	**0.040**
		Ger	363	2.36	2.13	-0.24	**0.064**
		House	523	2.11	1.98	-0.13	0.193
Kg coal added per fueling event	Winter average	Overall	959	5.17	5.89	0.72	**0.001**
		Ger	379	4.03	4.66	0.63	**0.004**
		House	538	5.95	6.77	0.83	**0.006**
	Phase I	Overall	933	4.43	4.94	0.51	**0.033**
		Ger	369	3.59	3.88	0.28	0.220
		House	523	5.06	5.77	0.71	**0.026**
	Phase II	Overall	934	6.01	7.05	1.04	**0.001**
		Ger	368	4.77	5.60	0.83	**0.007**
		House	525	6.84	8.05	1.20	**0.008**
	Phase III	Overall	928	5.06	5.65	0.59	**0.019**
		Ger	363	3.75	4.40	0.66	**0.017**
		House	523	5.94	6.53	0.59	**0.065**
Total daily kg coal used	Winter average	Overall	959	13.53	13.36	-0.17	0.395
		Ger	379	11.57	11.06	-0.52	0.252
		House	538	14.87	15.18	0.31	0.372
	Phase I	Overall	933	10.04	9.46	-0.58	0.219
		Ger	369	8.75	7.94	-0.81	0.205
		House	523	10.99	10.74	-0.25	0.409
	Phase II	Overall	934	19.98	20.06	0.08	0.471
		Ger	368	17.83	16.31	-1.52	0.159
		House	525	21.41	22.86	1.45	0.182
	Phase III	Overall	928	10.77	10.70	-0.08	0.457
		Ger	363	8.64	8.75	0.12	0.443
		House	523	12.21	12.25	0.04	0.484

** Effective sample size available after matching*
*** Bold font indicates significant difference between groups*

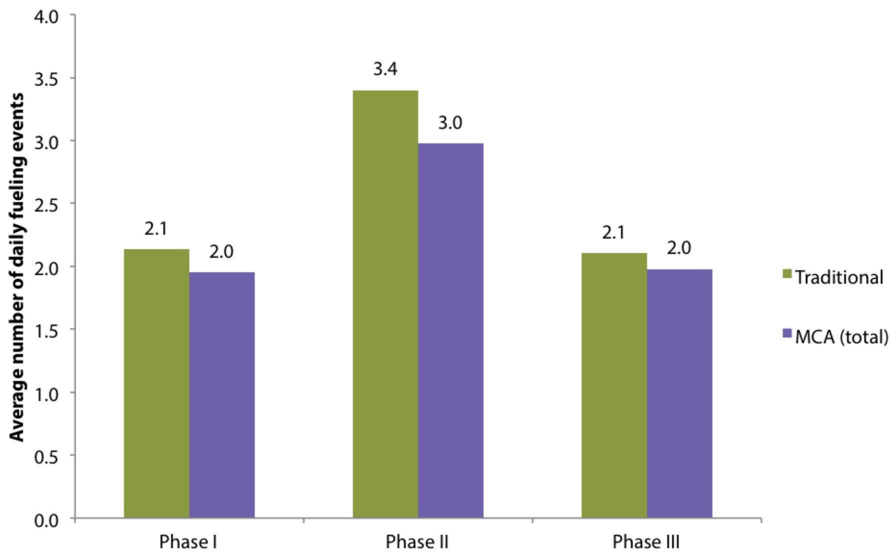


Figure 40. Fueling events per day, by phase.

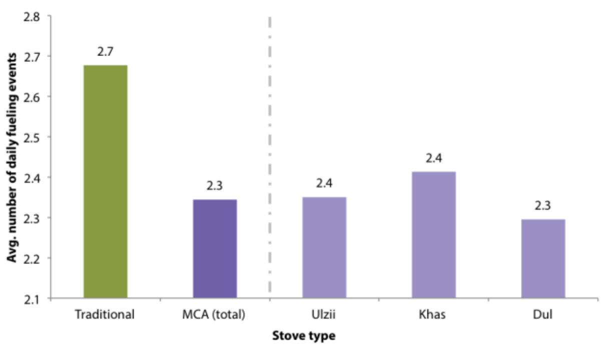


Figure 41a. Average daily fueling events, by stove type.

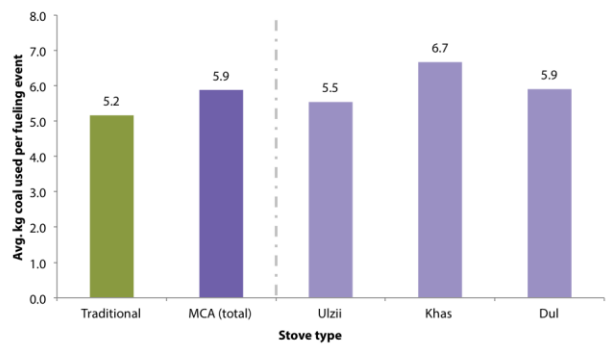


Figure 41b. Average quantity of coal used per fueling event, by stove type.

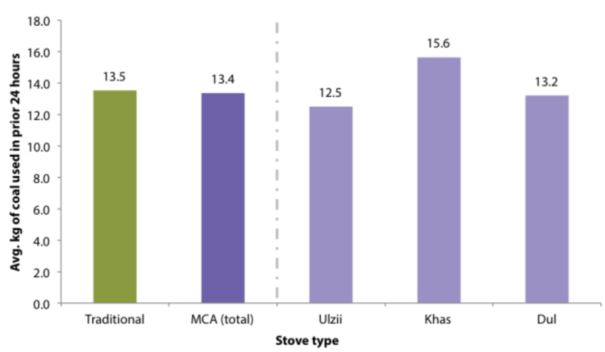


Figure 41c. Average daily quantity of coal used, by stove type.

Average daily coal use differed by dwelling type. Households living in houses with heating walls used the most coal (Figure 42). None of the differences in coal use between MCA and traditional stove owners by dwelling type or phase were significant.

These patterns were observed for each of the three MCA stove types. Complete tables by stove type are included in Annex 1. Dul and Ulzii stove owners had significantly fewer fueling events in all three phases. Khas owners generally reported fewer events in Phase I and II and slightly more in Phase III; however, not all findings were significant, perhaps due to the small sample size in the ger subgroup. Examining winter averages, owners of each of the three MCA stove types used significantly more coal per event than traditional stove owners, in both houses and gers. This result may relate in part to the larger size of the fueling chamber in the MCA stoves, with Khas stoves having the largest fueling chamber. The greatest difference was 2.3 additional kilograms of coal used in Phase II by Khas stove tenders in gers, compared to traditional stove owners. Differences in total daily coal usage for the winter, by stove, were also not significant.

From the winter average results, the percent difference in raw coal consumption for MCA stove owners compared to traditional stove owners—one of the indicators in the MMITT—was calculated to be 1.2% (although this difference was not significant), implying that approximately 8% of the MCC target – set at 15% - had been met (see Annex 6).

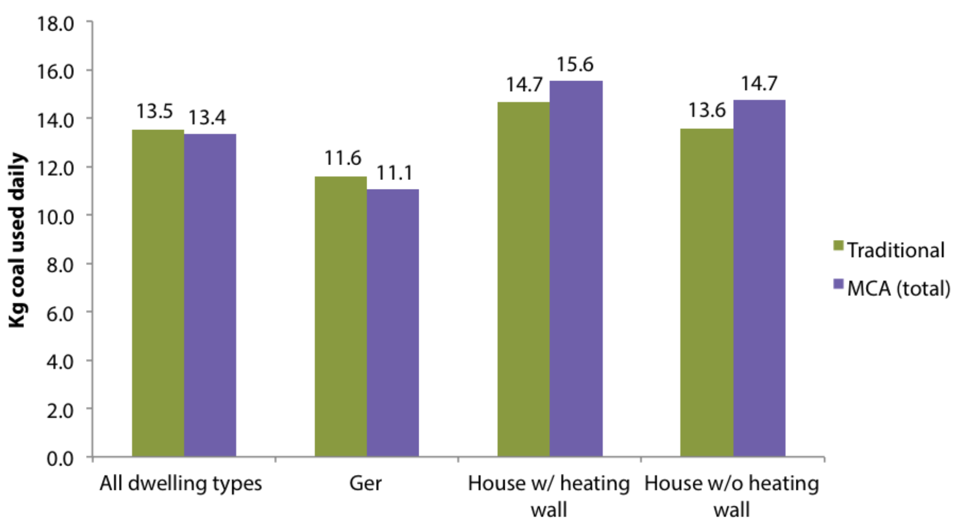


Figure 42. Average daily quantity of coal used, by dwelling type.

5.2.1 Cold starts and warm refuelings

MCA stove owners performed more warm refuelings than cold starts, on average, in each of the data collection phases, with some households performing only warm refuelings (Figure 43). This is contrary to stove operation instructions, in which users are instructed to perform only cold starts and no warm refuelings. Compliance with cold starts was lowest in the coldest data collection period (Phase II), when average daily cold starts dropped to 0.51 and warm refuels reached 2.5. Across stove types, Ulzii stove users performed slightly more cold starts on average than Khas and Dul owners, but warm refuelings were similar across MCA stove types (Figure 44-45). The influence of low compliance with operation instructions on fuel consumption is explored below.

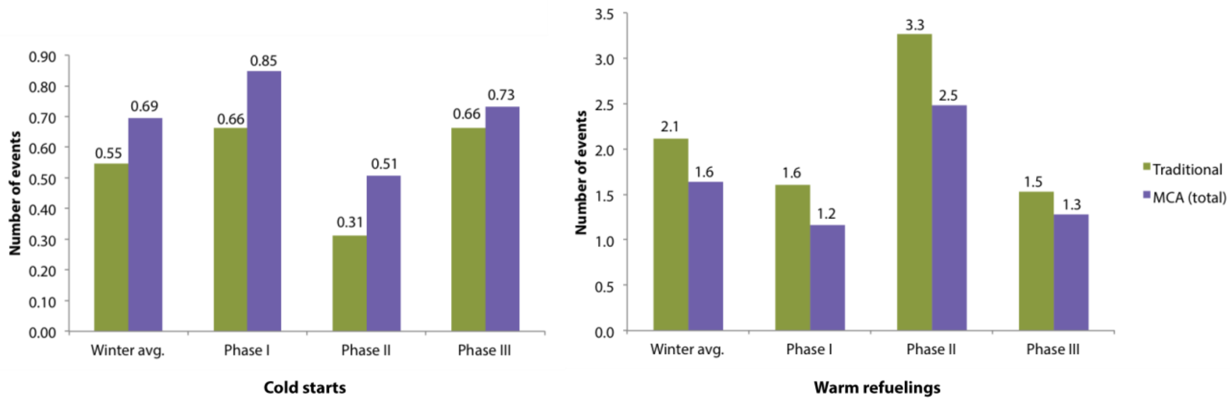


Figure 43. Average daily cold starts and warm refuelings, by phase.

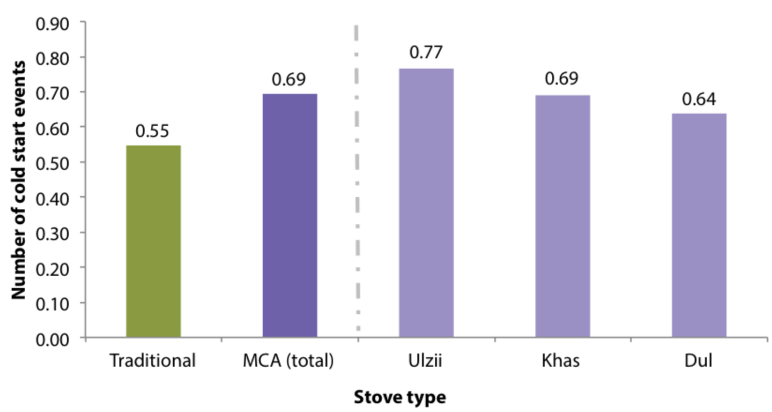


Figure 44. Average daily cold starts, by stove type.

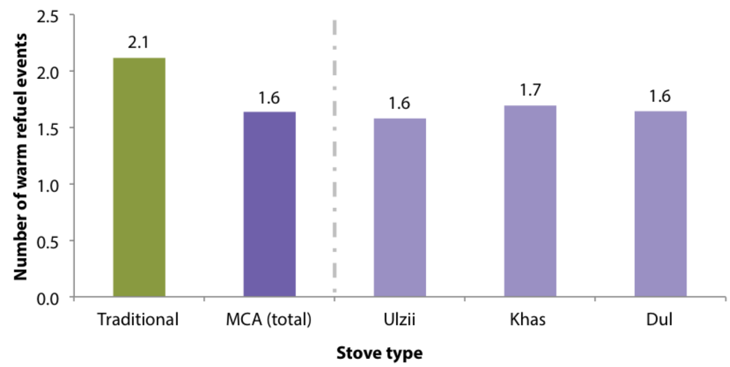


Figure 45. Average daily warm refuelings, by stove type

5.2.2 Coal use by dwelling size

Next, coal consumption was examined after taking into account the size of the dwelling and the presence of a heating wall, both of which may influence this outcome. There was no statistically significant difference in the quantity of coal used per cubic meter (m^3) of area in the main room of the home overall (Figure 46), by data collection phase, or by dwelling type. This suggests that differences in the size of the dwelling are not likely to affect coal consumption findings.

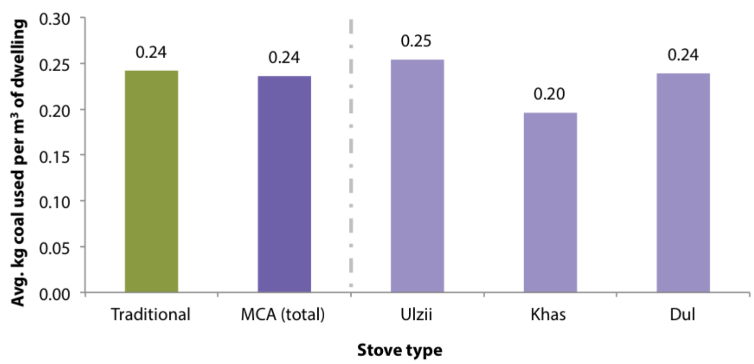


Figure 46. Daily coal used per m^3 volume of main room, by stove type.

5.2.3 Coal use by heating wall presence

Table 15 shows that among homes using heating walls, those with MCA stoves had significantly fewer fueling events, while no difference was observed among homes without a heating wall. On the other hand, MCA stove users used 1.16 kg more coal than traditional stove users per fueling event, which held true for both homes with and without the heating wall (although the difference was only statistically significant for the heating wall sub-group, likely due to the larger sample size). Overall, no significant differences in total daily coal consumption were observed, since these two differences work in opposite directions. In addition, accounting for the volume of the heating space negated the trend, such that no statistically significant difference in coal used per cubic m in the main space of the house was observed between traditional and MCA stove users with or without the heating wall. This might suggest that heating wall users had slightly larger homes.

Table 15. Fueling events, coal quantity, costs, by heating wall usage: houses

Variable description	Heating wall use	n*	Traditional mean	MCA (treated) mean	diff.	SE	p**
Daily fueling events	Used	344	2.54	2.21	-0.34	0.14	**0.010**
	Did not use	185	2.35	2.43	0.08	0.29	0.395
Kg coal added per fueling event	Used	344	5.92	7.07	1.16	0.38	**0.001**
	Did not use	185	5.60	6.36	0.77	0.66	0.124
Total daily kg coal used	Used	344	14.68	15.56	0.88	1.08	0.208
	Did not use	185	13.55	14.74	1.19	2.51	0.319
Avg. daily kg coal used, per cubic meter volume of main room in dwelling	Used	344	0.17	0.17	0.01	0.01	0.272
	Did not use	185	0.19	0.21	0.02	0.02	0.187

** Effective sample size available after matching*
*** Bold font indicates significant difference between groups*

5.3 Fuel Expenditures

Consistent with the finding that there was no significant overall difference detected in daily coal consumption, no significant difference was observed in the expenditures on fuel between MCA and traditional stove owners (Figure 47, Table 16). The percent reduction in median fuel costs, one of the indicators in the (MMITT) and defined as the difference in median fuel costs between households with project stoves and without project stoves, was calculated to be 7% (although this difference was not significant), implying that approximately 47% of the target – set at 15% - had been met (see Annex 6).

Overall, MCA stove owners spent MNT 1,055 less on coal each month than traditional stove owners, or an estimated 6,333 less across six months of winter, but this difference was not significant. After accounting for expenses for wood, coal, and other fuels (such as briquettes or semi-coking coal), MCA stoves did not appear to have significant impact on total fuel costs. There were also no significant differences in coal or fuel expenditures for any of the specific MCA stove types compared to traditional stoves (not shown).

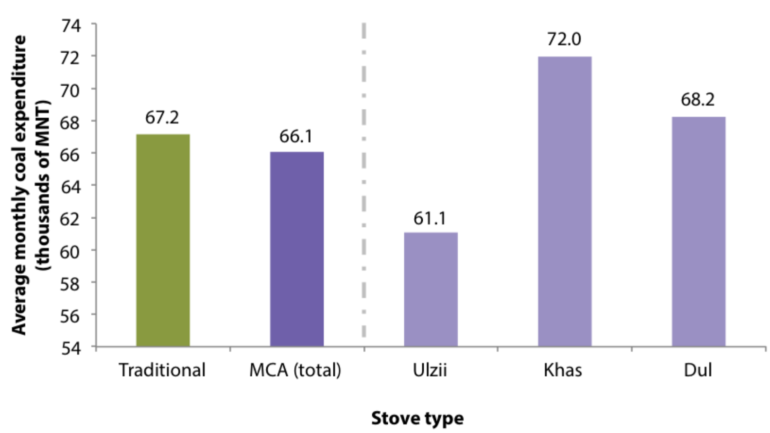


Figure 47. Average monthly coal expenditure, by stove type.

Table 16. Fuel expenditures (MNT), overall and stratified by poverty status

Variable description	Subset	*n**	Traditional mean	MCA (treated) mean	diff.	SE	*p***
Expenditure on coal throughout winter	Overall	857	402,694	396,361	-6,333	21,200	0.383
	Poorest 40%	324	322,080	365,186	43,106	26,472	**0.052**
Average monthly expenditure on coal	Overall	857	67,116	66,060	-1,055	3,533	0.383
	Poorest 40%	324	53,680	60,864	7,184	4,412	**0.052**
Expenditure on any type of fuel throughout winter	Overall	794	519,772	489,218	-30,555	28,124	0.139
	Poorest 40%	283	471,303	457,654	-13,649	46,930	0.386
Average monthly expenditure on any type of fuel	Overall	794	86,629	81,536	-5,092	4,687	0.139
	Poorest 40%	283	78,551	76,276	-2,275	7,822	0.386

** Effective sample size available after matching*
*** Bold font indicates significant difference between groups*

The impacts on fuel expenditures were also examined for the poorest 40% of households in our sample, identified using the wealth asset score. Poorer households with an MCA stove spent MNT 7,184 more on coal each month, and MNT 43,106 more throughout the winter. These results were marginally significant at p~0.05. But this trend reversed when all fuel types were considered together, with no statistically significant differences in fuel expenditures for the poorest 40%. These results may suggest that poorer households use more alternative fuel sources or have differential access to coal subsidies.

Similar to poor households, female-headed households with MCA stoves also spent more on coal than female-headed households with traditional stoves—a reversal of the overall trend of non-significant reductions in MCA stove coal expenses (Table 17). Among female-headed households, MCA stove owners spent MNT 10,614 more on coal monthly than their traditional stove owner counterparts (significant at p=0.056) whereas differences for male-headed households were not significant. This trend held for all types of fuel. This is in spite of female-headed households as a whole spending less money on fuel than male-headed households; the reason for these surprising differences is unclear. The reported types of coal typically used, which have different prices, were not significantly different by gender of the household head. It may be possible that female-headed households had less access to government subsidized coal; however, this evaluation was not able to verify this, and it is unlikely that coal subsidy access would explain differences between stove types. Further qualitative investigation to understand differences in purchasing behavior or expenditure management and decisions would be beneficial.

Table 17. Fuel expenditures (MNT), by gender of household head

Variable description	Subset	*n**	Traditional mean	MCA (treated) mean	diff.	SE	*p***
Expenditure on coal throughout winter	Female	155	309,450	373,133	63,683	39,910	**0.056**
	Male	696	422,321	401,128	-21,193	24,196	0.191
Average monthly expenditure on coal	Female	155	51,575	62,189	10,614	6,652	**0.056**
	Male	696	70,387	66,855	-3,532	4,033	0.191
Expenditure on any type of fuel throughout winter	Female	145	433,198	458,107	24,908	55,780	0.328
	Male	643	538,373	495,397	-42,976	31,960	**0.090**
Average monthly expenditure on any type of fuel	Female	145	72,200	76,351	4,151	9,297	0.328
	Male	643	89,729	82,566	-7,163	5,327	**0.090**

**Effective sample size available after matching*
*** Bold font indicates significant difference between groups*

In order to determine whether the stove program had differential impacts on households by gender, key outcomes were stratified by the gender of the main stove tender (Table 18). Regardless of intervention status, female stove tenders with both MCA and traditional stoves used slightly more coal than male stove tenders and performed more fueling events with less fuel per event. Female tenders as a whole spent slightly less money on coal than male tenders. Differences between traditional and MCA stove owners were comparable for male and female stove tenders, with few substantial differences. Both male and female MCA stove tenders performed fewer fueling events with more coal per event, compared to traditional stove owners of the same gender. No significant differences in total daily coal consumption were observed within either gender group.

One striking difference was the large and somewhat statistically significant reduction in coal expenditures for male stove tenders with MCA stoves compared to traditional stove owners, whereas no statistically significant differences were observed for female stove tenders.

Table 18. Fueling and coal consumption, stratified by gender of stove tender

Variable description	Sex of main	*n**	Traditional	MCA	diff.	SE	*p***
Daily fueling events	Female	643	2.82	2.43	-0.40	0.13	**0.001**
	Male	301	2.40	2.18	-0.22	0.13	**0.042**
Kg coal added per fueling event	Female	643	5.08	5.74	0.66	0.25	**0.004**
	Male	301	5.33	6.21	0.88	0.51	**0.044**
Total daily kg coal used	Female	643	14.01	13.59	-0.41	0.78	0.298
	Male	301	12.64	12.91	0.28	1.20	0.409
Expenditure on coal across winter	Female	580	374,587	393,969	19,382	24,035	0.210
	Male	263	465,517	404,094	-61,423	42,913	**0.077**
Average monthly coal expenditure	Female	580	62,431	65,661	3230	4,006	0.210
	Male	263	77,586	67,349	-10,237	7,152	**0.077**
Number of cold starts yesterday	Female	643	0.58	0.70	0.12	0.06	**0.019**
	Male	301	0.47	0.69	0.22	0.08	**0.005**
Number of warm refuelings yesterday	Female	643	2.24	1.72	-0.52	0.15	**<0.001**
	Male	301	1.89	1.47	-0.42	0.14	**0.001**

**Effective sample size available after matching*
*** Bold font indicates significant difference between groups*

5.4 Additional Exploration of Fueling Behavior and Consumption

5.4.1 Stove use monitor fueling event validation

Stove use monitors provided additional data to validate the reporting of fueling events within the household survey. Stove SUM data were obtained from 402 households (169 gers, 233 houses) from October 21, 2012 to January 4, 2013 (the interim between Phase I and II surveys), and from 421 households (179 gers, 242 houses) between January 13th, 2013 and March 22, 2103 (the interim between Phase II and III surveys). The sample was distributed as shown in Table 19.

In order to limit comparisons only to time intervals when stoves were in use, days were dropped from the analysis if they showed consistently low temperatures, indicating the stove could not have been in use during that day (e.g., if the family was staying outside the home during that time). Specifically, if over a 24-hour period the stove monitor never measured a temperature higher than 0°C, it was assumed that household members were not present for that given day. The SUM database was imported into a software program created by Social Impact to automate detection of a new fueling event at each low temperature "trough." Once events were marked, data were imported to Stata for additional cleaning and designation of event types. Fueling events were marked as cold start events if the starting temperature was below 10 °C before a sharp temperature rise exceeding a minimum 20 degree change. All other fueling events were considered warm refuelings. Limitations of these assumptions are discussed below.

Table 19. SUM sample by stove type

	Traditional	Ulzii	Khas	Dul	Total
Phase I-II interim	87	139	57	119	**402**
Phase II-III interim	83	143	63	132	**421**
Total	**170**	**282**	**120**	**251**	**823**

Matched comparisons between traditional and MCA stoves reveal no significant differences in the average number of daily fueling events measured in either time period and in overall average, although trends show slightly fewer fueling events for MCA stoves (Table 20). MCA stoves recorded significantly more daily cold starts (0.07 more on average), and non-significant reductions in warm refuelings. The SUMs results correspond to general findings in the household survey, including the observation that overall, households fuel their stoves between 2 and 3 times daily, on average. These results also confirm that many stove tenders do not appear to perform cold starts on their MCA stove, thereby contributing to averages below 1. Likewise, SUMs confirm that many MCA stove owners appear to be conducting warm refuelings. In the data obtained by SUMs, this behavior was observed at nearly the same rate for MCA stove owners as for traditional stove owners. Each stove type recorded significantly more cold starts. Dul stoves, in contrast to the other two models, had 0.19 fewer fueling events overall and 0.25 fewer warm refuelings. All results for Dul stoves were statistically significant. SUM-based results for each stove type are included in Annex 1.

Fueling events reported for each phase in the household survey (Table 20) may differ from the data recorded by the SUMs, as the latter provide interim data over the course of more than 50 days. Nonetheless, a comparison of the two data sources provides relatively parallel results. The average number of fueling events in the first and second SUM data collection fall between those reported in each household survey phase. The main difference in the SUM results is the attenuated magnitude of difference between traditional and MCA stoves.

SUMs may be considered more reliable than self-reported data, as households may have difficulty recalling all fueling events or Hawthorne bias may be present, with MCA stove owners underreporting fueling events to accommodate perceived expectations. On the other hand, the SUMs fueling event estimation software most likely overestimated the number of actual fueling events due to its high sensitivity in determining fueling events based on troughs and peaks in temperature changes. Stove temperature may fluctuate not only as a result of lighting or fueling the stove but also due to the breakdown of burning coal in the combustion chamber, opening of the stove door, use for cooking, and other reasons. These perturbations in stove temperature at times triggered a fueling event to be recorded by the software. To smooth out this "noise" in the data, a fueling event was further defined to include only the instances of at least a 5 °C increase in temperature between the trough and the peak temperature of a given "fueling event." Upon random inspection of several graphed daily SUM observations, we found this algorithm performed relatively well in identifying what appeared to be actual fueling events. However, we also observed some cases, in addition to the conservative limitations for which we corrected, in which the program may have both over- and underestimated fueling events. It appears that the program primarily overestimated these types of fueling events due to its overall sensitivity in identifying fuel events. This over-sensitivity would bias the number of fueling events upwards for all households, but at a constant rate regardless of housing type or stove type. This upward bias does not impact the analysis of outcomes since it is similar across all households.

Table 20. Fueling events recorded by stove use monitors (SUMs)

			Traditional	MCA (treated)			
Variable description	**Subset**	***n****	**mean**	**mean**	**diff.**	**SE**	***p****
Average number of daily fueling events	Overall avg.	325	2.72	2.70	-0.03	0.14	0.427
	Phase I-II interim	325	2.75	2.66	-0.09	0.14	0.267
	Phase II-III interim	340	2.75	2.73	-0.02	0.14	0.451
Average daily cold starts	Overall avg.	325	0.14	0.21	0.07	0.04	**0.044**
	Phase I-II interim	325	0.12	0.20	0.08	0.04	**0.017**
	Phase II-III interim	340	0.18	0.26	0.08	0.05	**0.062**
Average warm refuelings	Overall avg.	325	2.58	2.49	-0.10	0.14	0.248
	Phase I-II interim	325	2.63	2.46	-0.17	0.15	0.120
	Phase II-III interim	340	2.57	2.48	-0.09	0.15	0.269

**Effective sample size available after matching*
*** Bold font indicates significant difference between groups*

Another limitation was the difficulty in distinguishing cold starts from warm refueling events using SUMs. Since the only data available through the SUMs was temperature over time, any fueling event with a starting temperature below 10 °C, with a subsequent minimum 20 °C increase was considered to be a cold start. However, if a stove tender immediately relit the stove after all fuel had been consumed, it is possible that the starting stove temperature would be higher than 10 °C. In such cases, cold starts would have been underestimated and warm refuelings overestimated. We explored an alternative 15 °C temperature threshold to define the beginning of a cold start, which did not substantially alter the results. Under these revised assumptions, traditional stove owners performed a 0.29 cold starts daily per day, on average, compared to .42 for MCA stove owners. This represents a significant 0.12 increase in daily cold starts for MCA stoves (p=0.015). Likewise, the average daily warm refuelings across the winter under these assumptions were 2.43 and 2.28 for traditional and MCA stove owners, respectively. This 0.15 decrease was not significant (p=0.152). These findings suggest that the differences are relatively robust to the method through which cold and warm starts are calculated, as well as threshold selection. Based on the rate of increase in average daily cold starts when the threshold is shifted from 10 °C to 15 °C, the finding that MCA stove tenders perform fewer than one cold start daily is robust, even if a threshold of 15 °C is used to mark cold starts. Although it is possible to test the sensitivity of results of temperature threshold selection, uncertainties in interpreting cold starts from the very limited SUMs data cannot be overcome. Nonetheless, the consistent comparative trends between traditional and MCA stoves further support the notion that limits in cold start and warm refueling event estimation do not differ by stove type.

Table 21. Indoor temperatures by phase

Variable description	Subset	*n**	Traditional mean (°C)	MCA (treated) mean (°C)	diff.	SE	*p***
Average daily room temperature	Phase I-II interim	293	15.92	16.37	0.45	0.73	0.270
	Phase II-III interim	277	15.15	17.01	1.86	0.96	**0.026**
Average overnight room temperature	Phase I-II interim	288	16.74	16.98	0.23	0.73	0.375
	Phase II-III interim	271	15.70	17.55	1.84	0.97	**0.029**

**Effective sample size available after matching*
*** Bold font indicates significant difference between groups*

5.4.2 Indoor temperature and heating efficiency

Stove use monitors were placed on walls for a sub-sample of 396 households[17]. These SUMs recorded room temperature data concurrent with stove SUMs placed in the same homes. Temperature observations for certain days were dropped if the stove was not operated that day, according to the same procedure described above. Average daily room temperatures were calculated for each day and then averaged across each SUM data collection period. The results show that MCA stove owners kept their homes warmer than traditional stove owners, with temperatures of 0.45 °C to 1.86 °C higher, on average, in each period; however, only the differences between phases 2 and 3 were significant (Table 21). When constrained to overnight readings between 6 p.m. to 6 a.m., when most household members are likely to be home and the dwelling requires consistent heating, MCA stove owners still maintained warmer temperatures, with a significant, 1.84 °C warmer temperature in later winter.

5.4.3 Compliance-adjusted analysis

The impact of energy-efficient stove models on fuel consumption and emissions may not reach optimal levels if users are not compliant with special operating instructions. All MCA stove owners reported receiving instructions about the modified lighting and fueling procedure (Table 22). These instructions were designed to convey that kindling should be lit from the top of the coal pile and that all embers are to be extinguished prior to relighting (i.e., perform only cold starts and no warm refueling). In the open-ended question about the lighting procedure used, 63% of MCA stove owners reported using the correct procedure in all three phases, suggesting, at a minimum, correct knowledge of the appropriate lighting procedures. Observing behavior to confirm actual procedures followed was not possible. However, the 24-hour fueling event recall indicates that warm refuelings were common among MCA stove users, as only 5% of MCA

[17] There were 396 wall SUMs from the Phase I period and 374 from the Phase II period.

stove owners reported no warm refueling events in all three phases. There was temporal variation, as well, with 41% reporting no warm refueling in Phase I, 14% in Phase II, and 36% in Phase III. Using compliance criteria of both correct reported lighting procedures and no reported warm refuelings, full compliance with instruction across all three phases dropped to only 4% (Figure 48). Patterns were similar for all three MCA stove types. The reduced compliance in Phase II, which corresponds to the coldest time of winter, may suggest that households were not comfortable waiting for their stoves to completely burn out before relighting them.

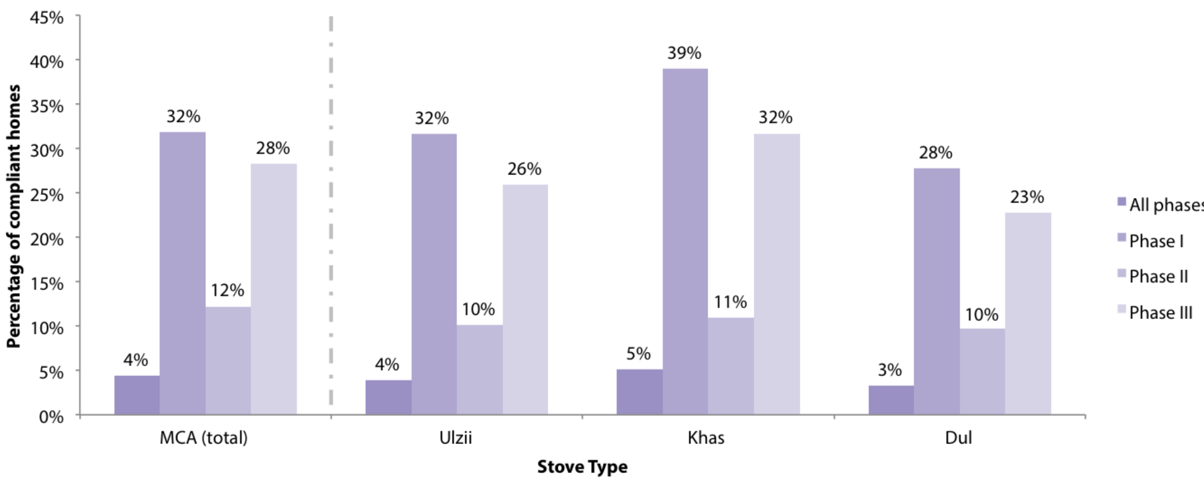


Figure 48. MCA stove owners' compliance with both top-light and no warm refueling instructions, by phase.

Table 22. Compliance with MCA stove usage instructions

Variable description	Subset	MCA (treated)			Ulzii			Khas			Dul		
		n	mean	SD	*n*	mean	SD	*n*	mean	SD	*n*	mean	SD
MCA stove owner received lighting instructions any time during winter	Overall	829	100%	0.07	328	100%	0.06	174	100%	0.00	327	99%	0.10
Report lighting fire from top of coal (correct procedure for improved stove) throughout winter	Overall	856	63%	0.48	516	60%	0.49	180	74%	0.44	336	53%	0.50
Report lighting fire from top of coal (correct procedure for improved stove)	Phase I	856	75%	0.44	516	73%	0.45	180	83%	0.38	336	67%	0.47
	Phase II	856	77%	0.42	516	75%	0.44	180	81%	0.40	336	71%	0.45
	Phase III	856	76%	0.43	516	74%	0.44	180	82%	0.39	336	71%	0.46
Number of cold starts yesterday	Overall avg.	854	0.70	0.54	340	0.76	0.58	180	0.70	0.52	334	0.63	0.52
	Phase I	828	0.86	0.82	326	0.91	0.83	174	0.83	0.76	328	0.83	0.83
	Phase II	833	0.50	0.77	333	0.59	0.82	175	0.52	0.75	325	0.41	0.72
	Phase III	827	0.74	0.80	326	0.81	0.88	178	0.73	0.73	323	0.66	0.74
Number of warm refuelings yesterday	Overall avg.	854	1.62	1.10	340	1.60	1.16	180	1.66	1.19	334	1.63	0.98
	Phase I	828	1.14	1.25	326	1.08	1.24	174	1.18	1.34	328	1.17	1.22
	Phase II	833	2.48	1.77	333	2.47	1.95	175	2.56	1.89	325	2.46	1.50
	Phase III	827	1.27	1.32	326	1.25	1.39	178	1.31	1.43	323	1.28	1.19
No warm refuelings reported yesterday throughout winter	Overall	841	5%	0.22	507	5%	0.21	176	6%	0.23	331	4%	0.20
No warm refuelings reported yesterday	Phase I	825	41%	0.49	499	40%	0.49	172	44%	0.50	327	39%	0.49
	Phase II	833	14%	0.35	500	12%	0.33	175	12%	0.33	325	13%	0.33
	Phase III	826	36%	0.48	500	34%	0.47	177	37%	0.49	323	32%	0.47
Both no warm refuelings yesterday & report lighting from top of coal for main stove throughout winter	Overall	845	4%	0.21	509	4%	0.19	176	5%	0.22	333	3%	0.18
Both no warm refuelings yesterday & report lighting from top of coal for main stove	Phase I	830	32%	0.47	503	32%	0.47	172	39%	0.49	331	28%	0.45
	Phase II	839	12%	0.33	504	10%	0.30	175	11%	0.31	329	10%	0.30
	Phase III	829	28%	0.45	502	26%	0.44	177	32%	0.47	325	23%	0.42

We explored the gender differences in stove use patterns using t-tests to compare compliance with top-light starting procedures and lack of warm refuelings between male and female stove tenders using an MCA stove. There were no significant differences by gender between those who reported no warm refuelings the prior day, and those who reported correct top-light starting procedures. However, female stove tenders were more likely to practice warm refueling: performing, on average, 0.17 more warm refuelings than male tenders in Phase I ($p = 0.06$) and 0.43 more in Phase 2 ($p < 0.001$).

Economically disadvantaged households comprising the poorest two wealth quintiles were especially non-compliant, with only 2% reporting no prior day warm refuelings at any of three data collection periods compared to 7% in the wealthier 60% of the population (significant at $p = 0.006$). Compliance with both cold start and top-light instructions throughout the winter was only reported by 2% of the poorest versus 6% (significant at $p = 0.012$). This may reflect a lower quality of home construction, which would reduce insulation efficiency. Measures of compliance did not differ significantly between male and female stove tenders.

Table 23. Fueling and coal consumption comparing compliant† MCA stove users to traditional stove users

Variable description	Subset	*n**	Traditional mean	MCA (treated) mean	diff.	SE	*p***
Daily fueling events	Phase I	544	2.14	1.46	-0.68	0.09	**<0.001**
	Phase II	385	3.28	1.88	-1.41	0.15	**<0.001**
	Phase III	502	2.14	1.39	-0.74	0.08	**<0.001**
Kg coal added per fueling event	Phase I	544	4.44	5.61	1.17	0.27	**<0.001**
	Phase II	385	6.34	8.58	2.24	0.41	**<0.001**
	Phase III	502	5.25	6.48	1.23	0.30	**<0.001**
Total daily kg coal used	Phase I	544	9.41	7.85	-1.56	0.62	**0.006**
	Phase II	385	19.42	16.01	-3.40	1.39	**0.007**
	Phase III	502	10.65	8.77	-1.89	0.62	**0.001**
Avg. daily kg coal used, per cubic meter volume of main room in dwelling	Phase I	544	0.16	0.13	-0.03	0.01	**0.003**
	Phase II	366	0.33	0.26	-0.07	0.03	**0.012**
	Phase III	476	0.18	0.15	-0.03	0.02	**0.018**

** Effective sample size available after matching*
*** Bold font indicates significant difference between groups*
† Compliant households are those with observed use of MCA stove, no reported refueling events during prior day, and correct lighting procedure reported

Key fuel and coal consumption variables were examined in a subset of households that used MCA stoves according to instruction (i.e., no warm refuelings in the prior day and correct lighting procedure). Due to very low compliance with usage instructions across all three data collection phases, compliance-adjusted analysis was performed for each phase separately. Reported use of an MCA stove as the main stove during that phase was also used to designate the intervention instead of Phase I intervention assignment. Matched comparisons with traditional stoves are presented in Table 23. As expected, compliant MCA stove users had significantly fewer fueling events, given that a requirement for this group was to have reported only cold starts. In the coldest part of winter (Phase II), these households reported 1.4 fewer fueling events than traditional stove users. Average quantities of coal added per fueling event remained significantly higher for the MCA group, with even greater differences compared to traditional stove users than observed in the overall group. A net reduction in daily coal consumption was thus observed among MCA compliant households. These households saved 1.56 kg (17% reduction), 3.4 kg (18% reduction), and 1.89 kg (18% reduction) in Phases I-III, respectively. All results were highly statistically significant. Significant reductions were also observed after adjustment for volume of the heating space.

These three snapshots of fueling behavior cannot fully capture daily temperature fluctuations throughout the winter. However, we did estimate the potential coal savings for the winter, by assuming that fuel savings observed in each data collection phase would represent approximately two months (~60 days) of the six-month winter. Based on these projections, MCA stove users who comply with lighting and refueling instructions might use approximately 411 fewer kg of coal throughout the winter, representing a 17% reduction in coal consumption.

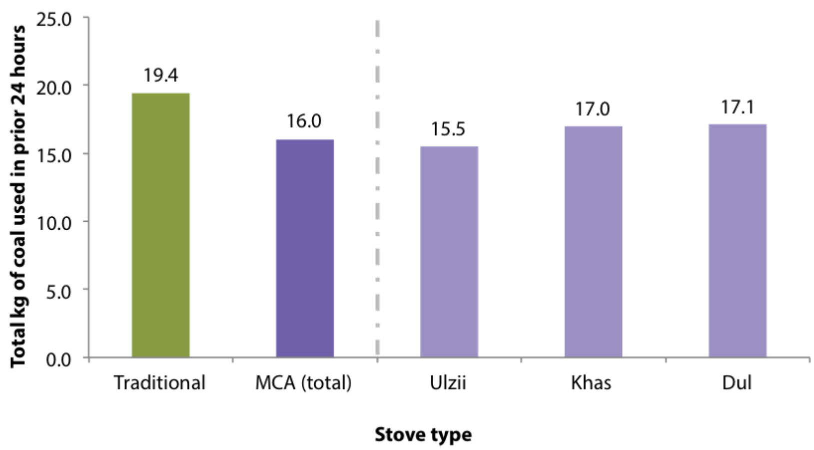


Figure 49. Total daily coal consumption (Phase II): users compliant with instructions, by stove type.

Similar trends were observed for compliant users of each MCA stove type. Despite a reduction in power due to lower sample sizes, most results remained highly significant. The greatest reductions in coal consumption were observed in Phase II, and are presented in Figure 49. The total daily coal consumption among Ulzii stove users compared to traditional stove users ranged from 2.37 to 4.05 fewer kg of coal across different data collection phases. This would amount to 570kg for the duration of the winter, or 24% coal savings. For compliant Khas users, coal savings would be approximately 163kg over the winter, on average, or 7% less that for traditional stoves, although these results were not significant. Similarly, reductions for compliant Dul stove users were only significant in Phase III; however, in our sample, this group was estimated to have saved 320kg of coal throughout the winter, a 13% reduction compared to traditional stoves. These results for compliant users are similar to those reported in laboratory tests in which Ulzii stoves reduced coal consumption by 26%, Khas by 11%, and Dul by 19%. Given that our compliance measure was based on self-reports, it is possible that compliance is over reported, with some households reporting correct operation but not practicing it. Increasing compliance with correct operating procedures for stove use would unlock further reductions in fuel consumption.

5.4.4 Comparison of coal types used

Matched comparisons between owners of traditional and MCA stoves revealed nearly opposite trends in the coal types used. While significantly more MCA stove owners reported using Nalaikh coal in Phase I compared to traditional stove owners, this trend reversed in Phases II and III, with more MCA stove owners used Baganuur coal than traditional stove owners (a marginally significant difference), as shown in Figure 50.

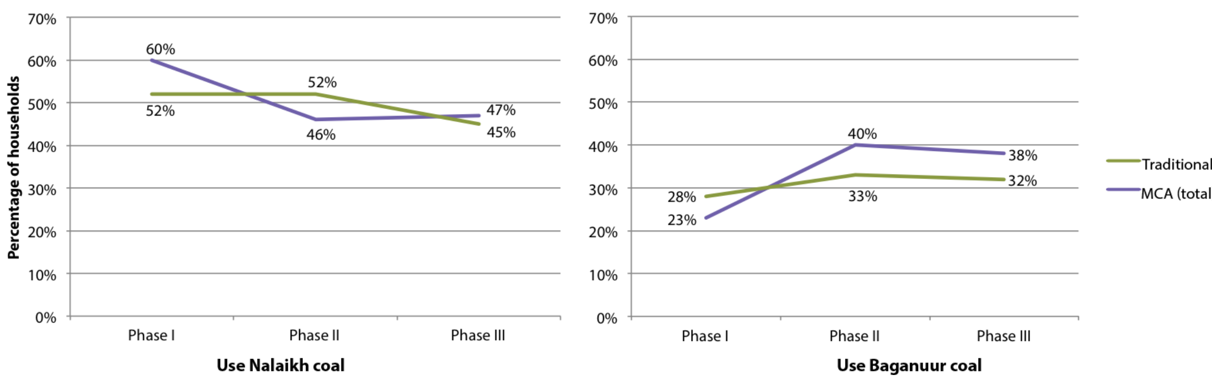


Figure 50. Changes in use of Nalaikh and Baganuur coal, by phase.

Table 24. Coal consumption, expenditures, and fueling events: households using only Nalaikh or only Baganuur coal

	Variable description	Subset	*n**	Traditional mean	MCA (treated) mean	diff.	SE	*p***
Use of Nalaikh coal only	Daily fueling events	Phase I	486	2.34	2.01	-0.33	0.15	**0.017**
		Phase II	353	3.27	3.00	-0.27	0.23	0.122
		Phase III	380	2.15	2.03	-0.12	0.14	0.192
	Kg coal added per fueling event	Phase I	486	4.72	5.02	0.30	0.32	0.170
		Phase II	353	6.35	7.30	0.96	0.62	**0.061**
		Phase III	380	4.67	5.65	0.98	0.44	**0.013**
	Total daily kg coal used	Phase I	486	11.24	9.61	-1.63	0.99	**0.050**
		Phase II	353	19.28	20.53	1.24	1.61	0.220
		Phase III	380	9.81	10.69	0.88	0.96	0.180
	Expenditure (MNT) on coal during 2-month period represented by data collection phase	Phase I	486	180,169	167,251	-12,917	15,082	0.196
		Phase II	343	198,572	195,887	-2,684	15,946	0.433
		Phase III	377	89,758	103,195	13,437	10,966	0.111
	Daily cold starts	Phase I	486	0.60	0.90	0.30	0.10	**0.002**
		Phase II	353	0.35	0.53	0.18	0.11	**0.054**
		Phase III	380	0.86	0.72	-0.14	0.12	0.112
	Daily warm refuelings	Phase I	486	1.73	1.10	-0.63	0.18	**<0.001**
		Phase II	353	2.92	2.46	-0.46	0.26	**0.039**
		Phase III	380	1.29	1.30	0.01	0.18	0.468
Use of Baganuur coal only	Daily fueling events	Phase I	186	2.57	2.09	-0.47	0.25	**0.029**
		Phase II	269	3.93	3.03	-0.90	0.33	**0.004**
		Phase III	296	2.27	2.03	-0.24	0.19	0.107
	Kg coal added per fueling event	Phase I	186	4.35	5.05	0.70	0.69	0.155
		Phase II	269	5.09	6.68	1.59	0.46	**<0.001**
		Phase III	296	5.00	5.48	0.48	0.52	0.183
	Total daily kg coal used	Phase I	186	10.76	10.16	-0.59	1.94	0.380
		Phase II	269	19.52	19.27	-0.25	2.38	0.458
		Phase III	296	10.91	10.46	-0.46	1.37	0.370
	Expenditure (MNT) on coal during 2-month period represented by data collection phase	Phase I	190	192,004	175,937	-16,067	29,843	0.295
		Phase II	265	154,271	149,888	-4,384	18,250	0.405
		Phase III	299	94,553	99,634	5,081	10,246	0.310
	Daily cold starts	Phase I	186	0.57	0.75	0.18	0.17	0.142
		Phase II	269	0.31	0.38	0.08	0.12	0.260
		Phase III	296	0.60	0.72	0.13	0.13	0.158
	Daily warm refuelings	Phase I	186	1.99	1.34	-0.65	0.28	**0.010**
		Phase II	269	3.63	2.63	-1.00	0.36	**0.003**
		Phase III	296	1.67	1.30	-0.37	0.23	**0.052**

** Effective sample size available after matching*
*** Bold font indicates significant difference between groups*

Government subsidies of Baganuur coal in the ger district might have encouraged higher coal use due to its increased affordability. Since Baganuur coal has a lower calorific value than Nalaikh coal, a large quantity would be required to provide the same amount of heat, thereby affecting coal quantities used throughout the winter. Any imbalance in coal types between groups may have influenced the coal consumption. As evidenced by the variety of coal types reported in each phase, many households were using multiple types of coal throughout the winter, making it difficult to isolate those only using one type of coal. In addition, those who purchased a truckload of one type of coal in Phase I might still have been using it in Phase III even if only recent sack purchases of another coal type were reported in the Phase III survey. We identified households that, according to household survey data, were using only one type of coal at a given time and assessed coal consumption within these subsets (Table 24). In the subset of Nalaikh coal users, MCA stove owners had fewer fueling events and less coal added per event than traditional stove owners (some of these differences were significant). Nalaikh coal users in Phase I had marginally significant 1.63 kg lower daily coal use compared to traditional users, but the differences in other phases were not significant. Similar results were observed for users of Baganuur coal, with lower daily coal usage in all three phases (non-significant). While it may be tempting to interpret these sub-group results as suggesting that coal type may not have a substantial impact, it is important to reiterate that these analyses are quite limited by the lack of precision in household data, which does not allow for reliable estimation of the type of coal utilized.

5.5 Effect Modification by Additional Energy Efficiency Products

While this evaluation was not designed or powered to directly measure the impact of MCA-subsidized ger insulation layers or front-door vestibules on fuel consumption, the degree to which these features modify the observed effect of stoves is explored descriptively. Among respondents residing in gers, 19 traditional stove owners and 134 MCA stove owners had felt insulation layers from MCA in Phase I (Table 25). Extra felt insulation was slightly more common in gers with Ulzii stoves. Overall, 19% of traditional stove owners and 24% of MCA stove owners had more than two felt insulation layers. MCA-subsidized vestibules were less common, with 2% of traditional and 7% of MCA households owning one. In Phase I, 52% of households with traditional stoves owned a vestibule of any kind, compared to 62% of households with MCA stoves. Ownership of these items did not change drastically over the winter heating season. Given that the majority of vestibules and insulation owned by households is not from MCA, in this section we consider the impact of additional felt insulation layer and vestibules in general, regardless of the source.

Table 25. Ownership of additional energy efficiency products

Variable description	Subset	Traditional			MCA (treated)			Ulzii			Khas			Dul		
		n	mean	SD	*n*	mean	SD	*n*	mean	SD	*n*	mean	SD	*n*	mean	SD
Has MCA insulation layers (among gers only)	Phase I	100	19%	0.39	343	39%	0.49	161	44%	0.50	17	35%	0.49	165	36%	0.5
	Phase II	100	19%	0.39	341	40%	0.49	159	43%	0.50	18	33%	0.49	164	38%	0.5
	Phase III	99	19%	0.40	339	40%	0.49	158	44%	0.50	18	33%	0.49	163	38%	0.5
Has >2 felt insulation layers (among gers only)	Overall	101	19%	0.39	350	24%	0.43	164	24%	0.43	20	25%	0.44	166	24%	0.43
Has MCA vestibule	Phase I	201	2%	0.14	856	7%	0.25	340	8%	0.27	180	3%	0.18	336	7%	0.3
	Phase II	191	2%	0.13	817	6%	0.24	325	8%	0.27	169	2%	0.15	323	7%	0.25
	Phase III	185	2%	0.13	782	6%	0.24	311	8%	0.27	160	3%	0.16	311	7%	0.25
Has vestibule (any kind)	Phase I	201	52%	0.50	856	62%	0.49	340	60%	0.49	180	69%	0.46	336	60%	0.5
	Phase II	201	52%	0.50	856	62%	0.49	340	61%	0.49	180	67%	0.47	336	59%	0.5
	Phase III	201	54%	0.50	856	63%	0.48	340	62%	0.49	180	69%	0.46	336	62%	0.5

Gers with both an MCA stove and three or more layers of felt insulation had better fuel use outcomes than MCA stove owners with less insulation and fewer fueling events over the winter than gers with two or fewer insulation layers (Table 26). Comparing traditional to MCA stove owners, those with more insulation had greater reductions in the number of daily fueling events than those with less insulation (0.72 fewer events compared to 0.35 fewer). Households residing in dwellings with three or more insulation layers experienced a marginally significant 2.23 kg reduction in daily coal used, whereas those with less insulation had only a non-significant marginal difference. This suggests that improvements in insulation might increase the impact of an energy-efficient stove on fuel consumption.

Comparing households that used a vestibule throughout the winter to those who did not use a vestibule, the same overall trends in fueling events and daily coal consumption emerge in both groups (Table 27). Differences in the total daily coal consumption reductions among those with and without vestibules were not significant.

Table 26. Fueling behavior and coal consumption in gers, stratified by insulation

Variable description	Insulation layers	*n**	Traditional	MCA (treated)	diff.	SE	*p***
Daily fueling events	3 or more	84	2.95	2.23	-0.72	0.32	**0.013**
	2 or fewer	296	2.88	2.52	-0.35	0.17	**0.019**
Kg coal added per fueling event	3 or more	84	4.28	4.72	0.44	0.62	0.243
	2 or fewer	296	3.97	4.67	0.70	0.26	**0.003**
Total daily kg coal used	3 or more	84	12.35	10.12	-2.23	1.67	**0.093**
	2 or fewer	296	11.42	11.38	-0.04	0.86	0.482
Avg. daily kg coal used, per cubic meter volume of main room in dwelling	3 or more	84	0.33	0.28	-0.05	0.08	0.283
	2 or fewer	296	0.35	0.32	-0.03	0.04	0.206
Expenditure (MNT) on coal throughout winter	3 or more	74	357,358	342,453	-14,905	55,290	0.394
	2 or fewer	264	337,991	373,431	35,441	28,104	0.104
Average monthly expenditure (MNT) on coal	3 or more	74	59,560	57,076	-2,484	9,215	0.394
	2 or fewer	264	56,332	62,239	5,907	4,684	0.104

** Effective sample size available after matching*
*** Bold font indicates significant difference between groups*

Table 27. Fueling behavior and coal consumption, stratified by vestibule use

Variable description	Use of vestibule	*n**	Traditional	MCA (treated)	diff.	SE	*p***
Daily fueling events	Yes	489	2.64	2.28	-0.36	0.14	**0.007**
	No	263	2.81	2.30	-0.51	0.15	**<0.001**
Kg coal added per fueling event	Yes	489	5.52	6.30	0.78	0.31	**0.006**
	No	263	4.28	5.44	1.17	0.43	**0.003**
Total daily kg coal used	Yes	489	14.20	13.96	-0.24	0.98	0.404
	No	263	12.03	11.95	-0.08	1.05	0.470
Avg. daily kg coal used, per cubic meter volume of main room in dwelling	Yes	489	0.21	0.22	0.01	0.02	0.328
	No	263	0.30	0.26	-0.04	0.04	0.170
Expenditure (MNT) on coal throughout winter	Yes	437	412,051	390,863	-21,188	32,161	0.255
	No	234	386,747	387,989	1,242	30,668	0.484
Average monthly expenditure (MNT) on coal	Yes	437	68,675	65,144	-3,531	5,360	0.255
	No	234	64,458	64,665	207	5,111	0.484

** Effective sample size available after matching*
*** Bold font indicates significant difference between groups*

5.6 Economic Impacts

The economic analysis considers two major benefit streams from the activity: health and fuel cost savings. Although the MCC cost benefit analysis for this program anticipated an increase in income (reduction in cost) from fuel cost savings as a result of expected reductions in fuel use and from savings related to improvements in respiratory health, it was not expected that these impacts would be directly measurable as a change in total household income within the Compact period. Rather, savings would likely be spent on other goods or services. Households' non-fuel expenditures were therefore examined. The majority of health and productivity gains from improvements in ambient air quality (as a result of reduced $PM_{2.5}$ and CO emissions) would have accrued to all UB residents regardless of stove type owned, as discussed in Section 7, thereby making fuel expense reductions the most likely source of potential household economic impacts.

As discussed previously, the reliability of both income and expenditure measurements was severely compromised by underreporting and respondent difficulty and reluctance in answering these questions. Nevertheless, reported expenditures were analyzed to assess suggestive evidence of differences, as presented in Table 28. The results show no evidence of differences between traditional and MCA stove households in non-fuel household expenditures, with the exception of spending on food in Phase II. This suggests that MCA stove ownership did not impact near-term income availability, which is not surprising in light of the lack of difference in fuel consumption.

Table 28. Non-fuel expenditures

Variable description	Subset††	*n**	Traditional mean	MCA (treated) mean	diff.	SE	*p***
Regular monthly food expenses	Phase II	800	200,951	232,033	31081	14,872	**0.018**
	Phase III	814	176,072	193,069	16997	15,529	0.137
Essential monthly expenses†	Phase II	923	446,991	443,422	-3569	39,525	0.464
	Phase III	917	393,912	415,605	21693	34,843	0.267
Small discretionary monthly expenses‡	Phase II	927	543,523	504,972	-38551	69,060	0.288
	Phase III	931	426,712	406,873	-19840	51,660	0.351
Major item expenses in past year (homes, vehicles)	Phase II	499	2,308,000	2,418,000	109371	709,940	0.439
	Phase III	781	1,601,000	1,621,000	20352	399,169	0.480
Discretionary expenses in past month and year (small and major)	Phase II	927	1,777,000	1,860,000	83205	400,299	0.418
	Phase III	931	1,833,000	1,769,000	-63744	357,155	0.429
All expenses	Phase II	927	2,222,000	2,302,000	79456	413,842	0.424
	Phase III	931	2,224,000	2,179,000	-44709	365,598	0.451

** Effective sample size after matching*
*** Bold font indicates significant difference between groups*
† Food, rent, utilities, mobile phone service, transport
‡ Alcohol, tobacco, gifts, money transfers, other domestic goods, kitchen or electric appliances
†† Expenditure data were not available in Phase I

5.7 Health Symptoms and Expenditures

As stated previously, while various health symptoms were assessed for vulnerable household members as part of the household survey, this aspect of the study was intended only to provide suggestive data on symptoms that could be associated with air pollution. The symptoms of interest were respiratory (e.g., phlegm, cough, short breath, wheezing, and cold); cardiovascular (e.g., chest tightness and rapid heartbeat); and dermal (e.g., eczema, dry or sore throat, eye irritation). Data for households with children under five years old or the elderly (older than 60 years) who reported these symptoms are shown in Table 29. There were no significant differences between traditional stove and MCA stove owners in these characteristics. It is important to note that no statistically significant or causal associations can be inferred from this household data. Instead, aggregate health impacts of the program were calculated using dose-response curves and WHO methodology for burden of disease estimates using modeling output of the reductions in ambient $PM_{2.5}$. These results are reported in Section 7.

Across all three survey phases, 53% of household members reporting the most respiratory illness symptoms were female, demonstrating relative equality with males in terms of health. The gender of those experiencing the most illness was not significantly different between households with MCA and traditional stoves: 54% and 53% females reported experiencing the most illness in traditional and MCA stove households, respectively (p=0.840).

In addition, self-reported expenditures related to the health symptoms that could be attributable to air pollution were collected in Phases II and III of the household survey. The respondent was asked about the total expenses for medication, if any, related to any household member of any age experiencing the above-mentioned symptoms. These results are presented in Table 29, as an average across all responding households, and for the subset of households that reported non-zero expenses in these categories. In both groups, and in both survey phases, the households with MCA stoves had higher health-related expenditures than households with traditional stoves. These differences are statistically significant. However, this result is counter-intuitive, since no statistically significant difference in the prevalence of these symptoms for vulnerable household members was observed between homes with MCA and traditional stoves. This implies that MCA-stove households may be spending more money on treating the same illnesses and symptoms, or that there may be unusual circumstances in the data. The underlying reported expense distributions for households with traditional stoves versus those with MCA stoves provides support to the latter hypotheses – the reported expenses for the MCA group are more skewed to the right, with a larger proportion of households reporting high expenses.

Table 29. Health symptoms and expenditures

Variable description	Subset	*n**	Traditional mean	MCA (treated) mean	diff.	SE	*p***
Any HH member <5 or >60 currently experiencing respiratory symptoms†	Phase I	518	52%	50%	-2%	0.06	0.378
	Phase II	547	38%	36%	-2%	0.06	0.400
	Phase III	560	31%	33%	2%	0.06	0.389
Any HH member <5 or >60 currently experiencing cardiovascular symptoms†	Phase I	518	18%	16%	-2%	0.05	0.337
	Phase II	546	11%	12%	1%	0.04	0.383
	Phase III	560	11%	11%	0%	0.04	0.480
Any HH member <5 or >60 currently experiencing dermal irritation symptoms†	Phase I	518	19%	20%	2%	0.05	0.381
	Phase II	546	18%	17%	-1%	0.05	0.411
	Phase III	559	15%	18%	3%	0.04	0.270
Total expenses (MNT) for medication related to above symptoms for any HH member in past 30 days (among those reporting any expenses)‡	Phase II	375	24,497	34,621	10,125	4,866	**0.019**
	Phase III	286	27,389	66,091	38,701	18,272	**0.017**
Total expenses (MNT) for medication related to above symptoms for any HH member in past 30 days‡	Phase II	961	9,985	13,524	3,539	2,298	**0.062**
	Phase III	961	8,416	20,721	12,304	5,742	**0.016**

** Effective sample size available after matching*
*** Bold font indicates significant difference between groups*
† Respiratory symptoms include phlegm, cough, short breath, wheezing, and cold; cardiovascular includes chest tightness, rapid heartbeat; dermal includes eczema, dry or sore throat, eye irritation
‡ Not available in Phase I

For instance, in Phase I, only 1.5% of households with traditional stoves reported health spending of at least MNT 100,000 in the last month, compared to 2.9% of households with MCA stoves. A similar pattern emerges in Phase III data, although both groups spent more in this time period: 2.5% of households with traditional stoves spent MNT 100,000 or more, compared to 3.9% of MCA stove households. While the highest amount spent by a household with a traditional stove was MNT 300,000, two households in the MCA group spent over 1 million MNT (i.e., 2 million and 3 million), and 18 households reached or exceeded MNT 300,000, which was the maximum expenditure by a comparison household with a traditional stove. Households with MCA stoves appear to be more likely to have high family spending on health, thus raising the average spending for the group.

It is unclear whether the self-reported health expenditures are accurately measured. As with other expenditure questions, enumerators reported that respondents had difficulty remembering how much they had spent on medications, and even more trouble attributing expenditures to certain symptoms. It is possible that households reported total health expenses since they could not separate their spending by symptom or type, so the self-reported expenditure values may be systematically biased up. In addition, the differences in spending between the traditional and the MCA stove groups cannot necessarily be attributed to the stove use, and instead may be caused by other household member or dwelling characteristics. This is further supported by the lack of significant differences in health outcomes for the two groups. Ultimately, since accurate and detailed health and spending data are not available for these households, it is difficult to discern the drivers of these results, and definitive conclusions cannot be drawn.

6 AIR QUALITY RESULTS

6.1 Emissions and Indoor Air Quality Results

6.1.1 Overall emissions results

Table 30 shows the emission components observed for MCA stoves versus traditional stoves during the 2012-2013 winter heating season, weighted by the proportions of stove types disseminated in Ulaanbaatar. The overall differences between MCA and traditional stoves indicate MCA stoves yielded a highly significant 65% reduction in nighttime $PM_{2.5}$ emissions per kg coal, from 6.5 to 2.3g $PM_{2.5}$/kg of coal. According to the MMITT targets, this 65% reduction represents 76% completion of the expected 86% $PM_{2.5}$ reduction (see Annex 6).In addition, a 16% reduction in CO emissions per kg of coal was observed for MCA stoves compared to traditional stoves, indicating improvement in combustion. Matching of homes by propensity scores did not significantly change the overall results, but did decrease power since some observations had to be excluded from matched analysis due to insufficient area of support. Further, given that emissions observations represent physical measurements of air quality parameters for individual stoves, the benefits of matching are quite limited, so unmatched results were utilized for the analysis.

Since the 24-hour recall methods of the household survey did not show significant reductions in fuel consumption between MCA and traditional stoves, similar overall reductions (69%) were observed for average $PM_{2.5}$ emissions per day. While stove use, including whether the stove is lit in compliance with instructions, certainly affects emissions, direct observation of lighting procedures was not performed during emissions measurements in order not to bias the fueling and lighting behavior of the stove tenders.

Table 30. Emissions from MCA vs. traditional stoves (weighted estimates)

	Traditional			MCA (treated)				
Variable description	***n***	**mean**	**SD**	***n***	**mean**	**SD**	**% diff.**	***p****
Nighttime $PM_{2.5}$ (g $PM_{2.5}$/kg coal)	95	6.5	7.0	98	2.3	4.3	-65%	**<0.01**
Nighttime $PM_{2.5}$ (g $PM_{2.5}$/day)	95	101.6	148.3	97	31.8	71.5	-69%	**<0.01**
Nighttime CO_2 (g CO_2/kg coal)	98	1938.3	203.1	98	1919.3	148.5	-1%	0.46
Nighttime CO (g CO/kg coal)	95	71.8	32.4	98	60.4	32.4	-16%	**0.01**

** Bold font indicates significant difference between groups*

6.1.2 Emissions stratified by stove type

Table 31 and Table 32 show the emission reductions observed for MCA stoves in the 2012-2013 winter heating season, stratified by stove and dwelling type. A similar pattern of $PM_{2.5}$ reductions emerged in both houses and gers, with highly significant reductions for the Ulzii stove in houses (74%, from 6.3 to 1.7 $gPM_{2.5}$/kg coal) and gers (83%, from 6.8 to 1.2 $gPM_{2.5}$/kg coal). No significant reductions were observed for Dul and Khas stoves compared to traditional stoves. In general, emissions per kilogram of fuel were higher in gers than in houses, but the overall emissions per day were higher from houses, since greater fuel consumption is required to heat larger spaces. However, the emissions per kilogram of fuel were higher from gers, possibly reflecting differences in stove performance when a heating wall was present (see Section 6.1.3). Sensitivity analyses using natural log transformations and comparison of medians showed similar reduction patterns.

Ulzii stoves have smaller capacity than Khas or Dul stoves, which may account for the lower levels of emissions. Median house sizes for homes using the Ulzii stoves were 70 m^2, compared to 85 m^2 for Khas, 78 m^2 for Dul, and 93 m^2 for homes with traditional stoves. Median ger sizes were 37 m^2 for Ulzii, 41 m^2 for Dul and 39 m^2 for gers with traditional stoves.

Table 31. Overall and nighttime emissions by stove type: gers

Variable description	Stove type	*n*	mean	SD	% diff.	*p**
Nighttime $PM_{2.5}$ (g substance/kg coal)	Traditional	20	6.8	7.6		
	Ulzii	26	1.2	1.8	-83%	**<0.01**
	Dul	16	4.2	5.1	-38%	0.23
Nighttime $PM_{2.5}$ (g emission/day)	Traditional	20	100.3	139.2		
	Ulzii	26	14.5	22.1	-86%	**0.01**
	Dul	15	54.8	63.5	-45%	0.21
Nighttime CO (g substance/kg coal)	Traditional	20	76.6	30.3		
	Ulzii	26	67.1	32.5	-12%	0.31
	Dul	16	65.0	26.6	-15%	0.23
Nighttime CO_2 (g substance/kg coal)	Traditional	21	1952.5	217.3		
	Ulzii	26	1902.3	136.9	-3%	0.36
	Dul	16	1904.4	179.2	-2%	0.47

** Bold font indicates significant difference between groups*

Table 32. Overall and nighttime emissions by stove type: houses

Variable description	Stove type	*n*	mean	SD	% diff.	*p**
Nighttime $PM_{2.5}$ (g substance/kg coal)	Traditional	19	6.3	6.0		
	Ulzii	22	1.7	2.5	-74%	**0.01**
	Khas	23	3.4	7.8	-46%	0.18
	Dul	14	4.4	4.9	-31%	0.32
Nighttime $PM_{2.5}$ (g emission/day)	Traditional	19	110.1	163.6		
	Ulzii	22	21.8	35.0	-80%	**0.03**
	Khas	23	63.0	152.0	-43%	0.34
	Dul	14	58.8	61.5	-47%	0.22
Nighttime CO (g substance/kg coal)	Traditional	19	61.7	34.3		
	Ulzii	22	52.9	41.2	-14%	0.46
	Khas	23	46.1	26.3	-25%	0.11
	Dul	14	55.7	32.5	-10%	0.62
Nighttime CO_2 (g substance/kg coal)	Traditional	19	1910.7	175.4		
	Ulzii	22	1953.3	140.1	2%	0.40
	Khas	23	1940.0	134.5	2%	0.55
	Dul	14	1954.7	168.8	2%	0.47

** Bold font indicates significant difference between groups*

6.1.3 Emissions stratified by heating wall

Comparison of homes with and without heating walls is complex, since homes with traditional stoves are more likely to have heating walls (Figure 32). Analysis of emissions from houses with heating walls (Table 33) shows significant reductions in $PM_{2.5}$ for all MCA stove types, with 70%, 59%, and 60% reductions for Ulzii, Khas, and Dul stoves, respectively, as compared to traditional stoves. In houses without heating walls, there were substantial, non-significant reductions for MCA stoves compared to traditional Table 34. The pattern of $PM_{2.5}$ and CO emissions reductions observed for Ulzii stoves was similar to that for the MCA stoves in aggregate (Table 30), although the $PM_{2.5}$ emissions reductions for Ulzii stoves were the greatest of all MCA stove models.

For houses with no heating walls, there were not enough traditional homes in the sample to make robust direct comparisons, as the vast majority of homes with traditional stoves have a heating wall. In general, however, the overall emissions from Khas and Dul stoves were higher in this subgroup, compared to homes with heating walls. The emissions of $PM_{2.5}$ and CO from the Ulzii and Dul stoves were similar to emissions from these stoves in gers (which do not have heating walls). One influencing factor may be that residents of houses may modify existing heating walls to accommodate the height of the new stove, which would decrease stove performance; emissions may also be higher when a straight chimney is used. While particle losses would be expected with use of a heating wall due to impaction and wall effects, similar losses would not be expected for gases like CO. Thus, these differences likely reflect differences in stove performance, possibly as a result of greater airflow.

Table 33. Emissions by stove type: houses with a heating wall

Variable description	Stove type	*n*	mean	SD	% diff.	*p**
Nighttime $PM_{2.5}$ (g $PM_{2.5}$/kg coal)	Traditional	16	6.0	5.8		
	Ulzii	13	1.8	3.0	-70%	**0.02**
	Khas	14	2.4	2.4	-59%	**0.04**
	Dul	7	2.4	2.3	-60%	**0.05**
Nighttime CO (g CO/kg coal)	Traditional	16	59.7	32.6		
	Ulzii	13	55.9	42.4	-6%	0.80
	Khas	14	51.3	26.4	-14%	0.45
	Dul	7	48.5	32.3	-19%	0.46
Nighttime CO_2 (g CO_2/kg coal)	Traditional	16	1873.1	160.1		
	Ulzii	13	1993.6	122.3	6%	**0.03**
	Khas	14	1942.1	147.4	4%	0.23
	Dul	7	1902.9	174.2	2%	0.71

** Bold font indicates significant difference between groups*

Table 34. Emissions by stove type: houses without a heating wall

Variable description	Stove type	*n*	mean	SD	% diff.	*p**
Nighttime $PM_{2.5}$ (g $PM_{2.5}$/kg coal)	Traditional	3	7.9	8.5		
	Ulzii	9	1.4	1.7	-82%	0.32
	Khas	9	4.8	12.4	-39%	0.66
	Dul	6	4.7	4.6	-40%	0.60
Nighttime CO (g CO/kg coal)	Traditional	3	72.4	49.4		
	Ulzii	9	48.5	41.4	-33%	0.50
	Khas	9	37.9	25.6	-48%	0.35
	Dul	6	69.4	31.7	-4%	0.93
Nighttime CO_2 (g CO_2/kg coal)	Traditional	3	2111.5	113.3		
	Ulzii	9	1895.2	150.5	-10%	**0.05**
	Khas	9	1936.7	120.1	-8%	**0.09**
	Dul	6	2035.4	152.1	-4%	0.43

** Bold font indicates significant difference between groups*

6.1.4 Indoor household $PM_{2.5}$ and CO concentrations

Indoor measurements of $PM_{2.5}$ and CO concentrations were conducted to ensure the safety of MCA stoves compared to traditional stoves, since exposure to high indoor concentrations of $PM_{2.5}$, and especially CO, could pose health risks. The use of MCA stoves was not associated with statistically significant differences in indoor emissions, with the exception of the Khas stove in houses, for which highly significant reductions in indoor CO emissions were observed. It is important to note that the evaluation was not powered to test for statistically significant changes in indoor air quality since a much larger sample size would have been required (see sample size Table 5). No significant differences in indoor concentrations of $PM_{2.5}$ were observed; however, this may be due to the confounding effect of tobacco smoking inside the home, which was reported by approximately 65% of dwellings. Within the small subgroup of households that did not report the presence of a smoker (Table 35 for gers and Table 36 for houses below), marginally significant reductions were observed in indoor CO levels in houses but not in gers, while differences in $PM_{2.5}$ concentration were inconsistent, unsurprising given the very small sample size. The results, however, suggest that the MCA stoves do not increase CO concentrations within the homes, and thus do not pose an increased health risk.

Table 35. Nighttime indoor concentrations of $PM_{2.5}$ and CO: gers

		Stove type	*n*	mean	SD	% diff.	*p**
Within full sample	$PM_{2.5}$ mg/m³	Traditional	34	0.17	0.12		
		Ulzii	34	0.16	0.08	-6%	0.60
		Dul	22	0.13	0.09	-24%	0.14
	CO ppm	Traditional	31	3.13	2.81		
		Ulzii	30	2.82	2.38	-10%	0.65
		Dul	23	2.77	1.97	-12%	0.58
Within gers with no smoking reported	$PM_{2.5}$ mg/m³	Traditional	8	0.14	0.08		
		Ulzii	15	0.14	0.08	0%	0.98
		Dul	13	0.11	0.08	-21%	0.34
	CO ppm	Traditional	7	2.26	2.23		
		Ulzii	13	3.86	2.59	71%	0.17
		Dul	12	2.84	1.53	26%	0.55

** Bold font indicates significant difference between groups*

Two indicators from the MCA-Mongolia Indicator Tracking Table (MMITT) related to indoor air quality were also estimated: average short-term indoor $PM_{2.5}$ concentrations and CO concentrations in project households (gers and houses combined). $PM_{2.5}$ concentrations were estimated to be 0.16mg/m³, on average, both for project households (for all MCA stoves, weighed by stove type) and households with traditional stoves, so no difference between the project and traditional stoves was detected. The CO concentrations were estimated to be 3.6 ppm, on average, in project households, compared to 4.5 ppm in households with traditional stoves, although these differences were also not significant. As described above, the data used to calculate these indicators are substantially confounded by smoking; thus the indicators derived from the indoor emissions measurements likely do not fully reflect the performance of the stove, which may yield substantial gains in indoor air quality. Some gains in indoor air quality are captured by the indoor CO concentration indicator, which suggests that CO emissions from project stoves are lower. CO can be viewed as a more reliable estimate of the reductions in indoor air pollution, since CO emissions from cigarettes are relatively small compared to the particulate matter, thus, while the $PM_{2.5}$ is confounded strongly, the CO concentration measure is much less so.

Table 36. Nighttime indoor concentrations of $PM_{2.5}$ and CO: houses

		Stove type	*n*	mean	SD	% diff.	*p**
Within full sample	$PM_{2.5}$ mg/m^3	Traditional	26	0.14	0.06		
		Ulzii	30	0.16	0.09	14%	0.54
		Khas	33	0.18	0.13	29%	0.15
		Dul	18	0.17	0.09	21%	0.35
	CO ppm	Traditional	29	6.91	4.39		
		Ulzii	29	6.40	12.35	-7%	0.84
		Khas	31	3.55	2.63	-49%	**<0.01**
		Dul	18	5.96	6.40	-14%	0.59
Within houses with no smoking reported	$PM_{2.5}$ mg/m^3	Traditional	9	0.13	0.06		
		Ulzii	12	0.16	0.10	23%	0.40
		Khas	15	0.12	0.06	-8%	0.70
		Dul	7	0.17	0.07	31%	0.30
	CO ppm	Traditional	13	7.27	4.54		
		Ulzii	12	4.46	3.13	-39%	**0.08**
		Khas	14	3.70	2.95	-49%	**0.03**
		Dul	7	4.39	2.71	-40%	**0.09**

** Bold font indicates significant difference between groups*

6.1.5 Limitations of emissions and indoor air quality data

6.1.5.1 Dwelling size

Some differences were observed in the volume of dwellings by stove type. The median volume of houses with traditional stoves was larger than those with the MCA stoves. The median volume of the gers with traditional stoves and MCA stoves was similar, although gers with Ulzii stoves tended to be slightly smaller that average, while the gers with Dul stoves were slightly larger. The volume of the dwelling is unlikely to have a large impact on the combustion efficiency of the stove directly, unless the stove is overloaded. Since emissions were expressed in per kg coal used, and fuel consumption in the household survey did not indicate large differences between traditional and MCA stoves, the impact of this factor is thought to be limited.

6.1.5.2 Time and temperature biases

We also examined whether the timing of data collection may have been non-randomly distributed between subgroups and could have biased results. Table 37 shows the distribution of emissions measurements over time during the 2012-2013 winter heating season. The measurements of traditional, Ulzii, and Dul stoves were approximately evenly distributed over the heating season. A somewhat higher proportion of measurements of Ulzii stoves took place in the cold period in January and February, although the absolute numbers of measurements in each phase of the heating season are fairly similarly distributed between the groups. The slightly higher proportion in the colder temperature season for the Ulzii would tend to inflate fuel consumption, but overall there should not be a significant bias in measurements due to seasonal conditions. More measurements of the Khas stoves were taken in the early and late phases of the heating season compared to the other stoves. While this may be reflected in fuel consumption patterns, the effect on combustion conditions inside the stove are hard to ascertain, especially given large variability in emissions between homes over the heating season. Overall, there does not appear to be a reason to suspect large biases in the data related to the timing of the emissions measurements.

Table 37. Winter 2012-2013 sampling distribution over time, by stove type

	Nov–Dec		Jan–Feb		Mar–Apr		Total	
Stove type	***n***	**%**	***n***	**%**	***n***	**%**	***n***	**%**
Traditional	2	5%	24	60%	14	35%	40	**100%**
Ulzii	2	4%	35	73%	11	23%	48	**100%**
Khas	5	22%	11	48%	7	30%	23	**100%**
Dul	2	7%	16	55%	11	38%	29	**100%**
Total	**11**	**8%**	**86**	**61%**	**43**	**31%**	**140**	**100%**

6.1.5.3 Measurement of coal consumption

Coal consumption estimates were derived from the measurements taken by the emissions team, weighing of coal to be used during the evening of the emissions sampling visit, and the 24-hour recall of morning fueling events on the day prior to the most recent household survey. While measurement was improved by requiring both visual demonstration of coal amount by the respondent and weighing by the enumerator, this method remained vulnerable to recall bias, and the application of household survey data that were not concurrent with emissions sampling could have added inaccuracies. Furthermore, the type of coal used by the households was not documented during emissions measurement visits, but was obtained from the household survey. Since the calorific values of different coal types in Ulaanbaatar vary substantially, the type of coal can greatly affect the performance of heating stoves. As reported above, there was substantial variation in the types of coal used, both between homes and within homes over time, often varying across survey phases. Initial laboratory assessments of stove emissions were based on the use of one lot of purchased Nalaikh coal; however, participants in this evaluation often used both Nalaikh and Baganuur coal and other coal types at different times throughout the winter, or concurrently. It is recommended that future studies use a more detailed survey of fuel consumption during emissions measurements, which would involve documentation and direct weighing of each separate fuel type present in the home over a period of several days. Finally, the moisture content of coal used in homes can vary substantially as coal is often left outside the home open to the elements. Since the moisture content can greatly impact emissions and fuel consumption, greater control of the moisture through drying of raw coal combined with better storage could significantly reduce emissions.

6.2 Ambient Air Quality Results

6.2.1 Ambient air quality modeling

Figure 51 shows the spatial distribution of residential heating stove contributions to ground-level ambient $PM_{2.5}$ mass concentrations for the 2012-2013 heating season, as modeled under the base case counterfactual assumption that all stoves are of the traditional design. There are strong concentration gradients across UB, and PM levels are greatest (up to ~135 $\mu g/m^3$) in the high population density ger districts because emissions are at ground level and the generally light winds and shallow mixing layer heights suppress the dilution of the emissions. Figure 52 shows the spatial distribution of modeled residential heating stove contributions to ground-level ambient $PM_{2.5}$ mass concentrations for the 2012-2013 heating season with implementation of the MCA stove subsidy program (Figure 51 and Figure 52 have the same color scales). Concentrations from heating stoves are lower across the city with maximum impact of ~100 $\mu g/m^3$. Figure 53 shows the reduction in ambient $PM_{2.5}$ mass concentrations for the 2012-2013 heating season that arises from the replacement of traditional stoves with MCA stove models (the intervention). Maximum reductions are about 50 $\mu g/m^3$ and occur in the areas with the highest levels of stove distribution. In particular, the concentration hot spots have been dramatically reduced compared to the hypothetical scenario in which all stoves are traditional, and concentrations across the city are more uniform after the implementation of the MCA stove program.

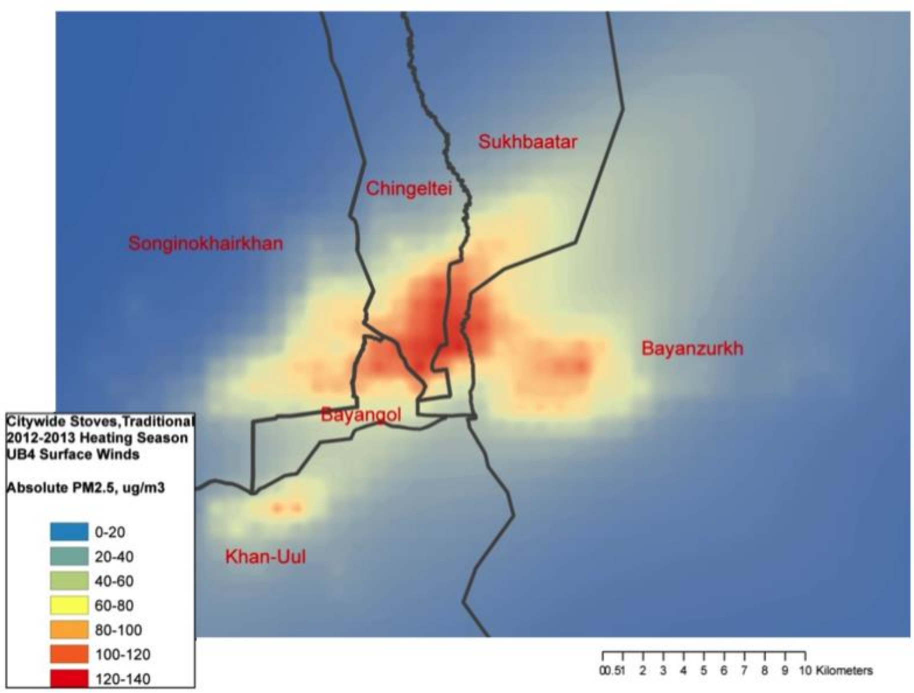


Figure 51. Modeled 2012-2013 heating season (October - March) average ambient $PM_{2.5}$ mass concentrations from residential stove emissions assuming all stoves are traditional (base case).

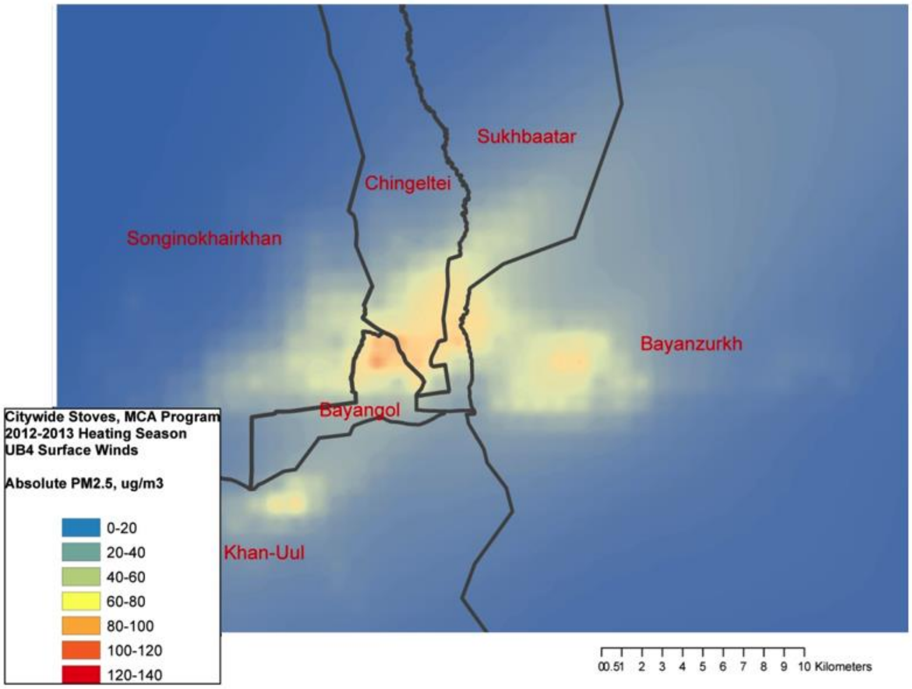


Figure 52. Modeled 2012-2013 heating season (October -March) average ambient $PM_{2.5}$ mass concentrations from residential stove emissions including implementation of the MCA stoves program.

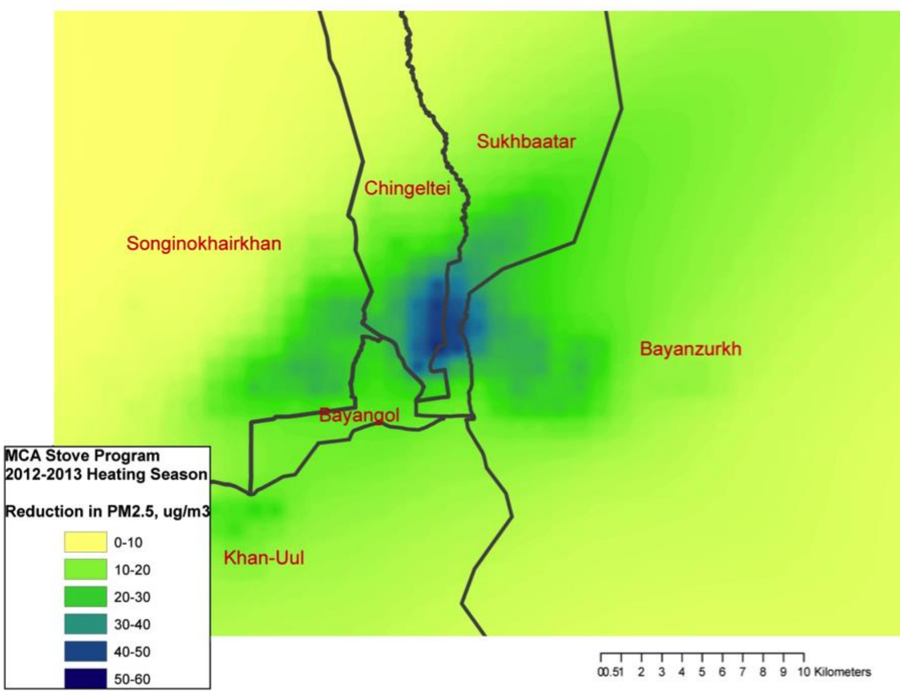


Figure 53. Modeled 2012-2013 heating season (October -March) average reductions in ambient $PM_{2.5}$ mass concentration resulting from the MCA stove subsidy program.

Population-weighted changes in air quality across UB were calculated from these modeling results. The MCA stove program intervention was estimated to reduce the average ambient $PM_{2.5}$ concentration by ~20 $\mu g/m^3$ in the heating season, weighted by the population, compared to the counterfactual of all households in UB using traditional stoves. This is likely a conservative estimate of the reductions for reasons described in Annex 5. Population-weighted ambient $PM_{2.5}$ contributions attributable to residential heating stoves were 30% lower for the intervention compared to the base case. A sensitivity study was conducted using surface winds data collected at NAMHEM station #7 (UB7) (Figure 24). The reduction in population-weighted ambient $PM_{2.5}$ concentration was consistent with the original analysis to within 15% and the ambient $PM_{2.5}$ contribution attributable to residential heating stoves was again 30%.

Two indicators from the MCA-Mongolia Indicator Tracking Table (MMITT) that related to ambient air quality were also estimated: the percent difference in $PM_{2.5}$ emissions and the absolute difference in total ambient $PM_{2.5}$ contributions from MCA stoves versus traditional stoves. The first indicator captures the percent reduction in $PM_{2.5}$ emissions that project stoves make to ambient concentration in Ulaanbaatar. The $PM_{2.5}$ emissions capture only household contributions during the heating season (October to March). The percent difference in $PM_{2.5}$ emissions from total, citywide, residential heating stoves, was estimated to be -28%. It is important to note that this percentage differs from the 30% reduction value presented above, because the latter corresponds to population-weighted ambient $PM_{2.5}$ concentrations from residential heating stoves, whereas this indicator is for emissions, and thus there is no population weighting. The second indicator, the absolute difference in total ambient $PM_{2.5}$ contributions from MCA stoves versus traditional stoves, was estimated to be -1,150 tons per heating season (from October to March).[18] All MMITT indicators and the calculated values are presented in Annex 6.

6.2.2 Ambient air quality measurements

An ambient $PM_{2.5}$ sampling and chemical speciation [19] study was conducted in winter/spring 2013 to collect data for the air quality modeling and provide additional insights into $PM_{2.5}$ emission sources and spatiotemporal patterns. This project was conducted by Ecography and Ecoworld – two Mongolian companies based in UB – under contract from MCA. 24-hour integrated sampling from noon to noon (next day) local time was implemented at four sites. Sampling was conducted simultaneously at the four sites (Figure 54) on alternate days or every third day. For each sampling event, two parallel samples were collected using identical hardware and operating conditions but different filter media. The initial plan was to collect on Teflon filters for gravimetric[20],

[18] For these two indicators it the calculations were based on the stove sales data at the time the analysis was initiated (97,192 MCA stoves), although the final sales volume was a bit higher.

[19] "Chemical speciation" refers to the analysis of PM samples to determine its chemical composition. The analysis typically includes total carbon resolved into elemental carbon (EC) and organic carbon (OC) fractions with the EC being soot-like; major ions including but not limited to sulfate, nitrate and ammonium; and trace elements.

[20] "Gravimetric analysis" is used to determine the total mass concentration of PM. It involves weighing the filter before and after sample collection to determine the

trace elements, and ion analysis and to collect onto quartz filters for carbon analysis. However, the desired sampling flow rate could not be maintained for the Teflon filters due to the excessive mass loadings of particles onto the filter as a consequence of the high PM pollution conditions in the UB wintertime. This issue led to all Teflon filter samples collected during the first three weeks of the study (December 16, 2012 through January 19, 2013) being invalidated and only carbon data are available for this period. Starting with the January 22, 2013 sampling event, two quartz filters were collected at each site and the sample analysis plan was modified to accommodate the gravimetric analysis, elemental analysis for air toxics metals (e.g., arsenic, lead, nickel) and ion analysis to also be conducted on quartz filters. There were 36 sampling events per site over the time period January 22 – April 22, 2013.

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mass of PM collected, and dividing by the total air volume passing through the filter.

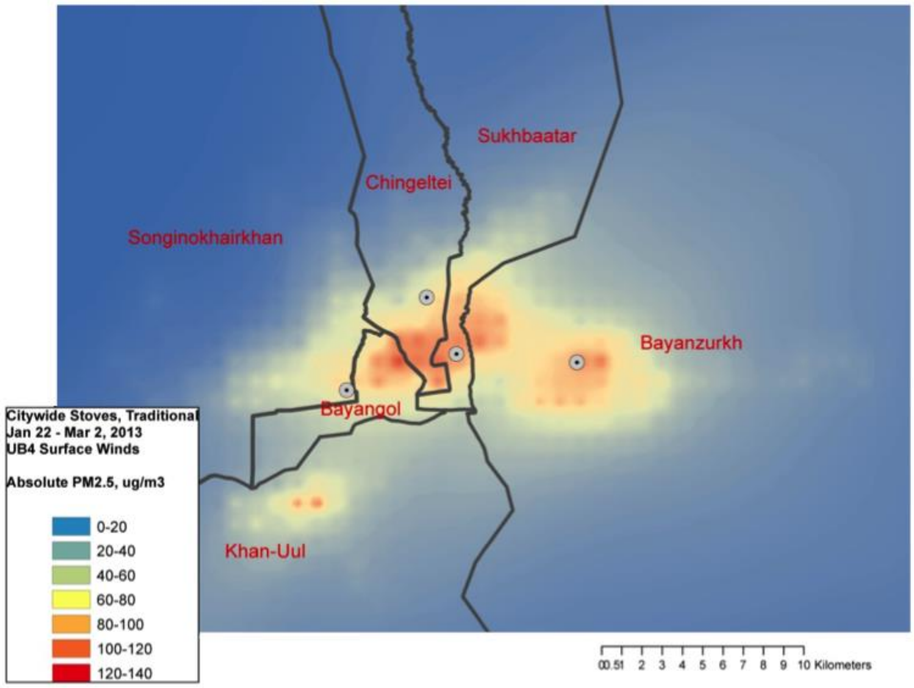

Figure 54. MCA Mongolia $PM_{2.5}$ speciation study sampling sites and modeled average ambient $PM_{2.5}$ mass concentrations from residential stove emissions including implementation of the MCA stoves program for the period January 1 – March 2, 2013.

Figure 55 shows the $PM_{2.5}$ mass concentration and composition averaged over the 19 sampling events from January 22 to March 2, 2013. Daily variations in $PM_{2.5}$ are well correlated between sites (r = 0.64-0.88) but there is high spatial variability with the mean Site 2 concentrations measuring 25-55% higher than the other three sites. However, the $PM_{2.5}$ composition is nearly identical across the four sites and is primarily organic matter (OM, 70-80%) and sulfate (SO_4^{2-}, 9-11%). Potassium ion (K^+) is only 0.15-0.25% and the very low ratio of K^+ to organic carbon (~0.003) suggests the contribution from wood smoke is relatively small. The high organic matter and sulfate mass fractions and low potassium mass fraction is consistent with low temperature and/or inefficient combustion of sulfur-bearing fossil fuels such as coal and oil. Relative contributions from power plants, HOBs, residential heating stoves, and motor vehicles cannot be distinguished from this data set. However, the very high correlation between $PM_{2.5}$ mass and arsenic across the entire data study (r = 0.91) does suggest the dominant source is coal combustion and not vehicles.

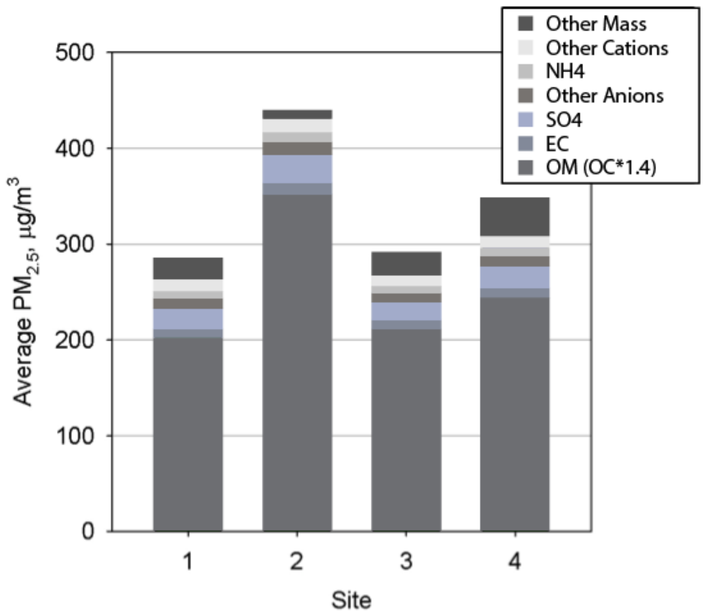

Figure 55. $PM_{2.5}$ average mass and species concentrations, January 22 – March 2, 2013.
(*Note: 19 24-hour average samples for each site, organic matter (OM) is assumed to be 1.4 times the measured organic carbon (OC) concentration.)*

6.2.3 Ambient air quality modeling and measurements comparison

Figure 55 also shows the modeled $PM_{2.5}$ concentration field averaged over all days (not just the sampling days) for January 22 – March 2, 2013. Modeled concentrations including the intervention are 85-90 $\mu g/m^3$ at Sites 1-3 and 115 $\mu g/m^3$ at Site 4. These modeled concentrations are only 20% to 33% of the measured concentrations. The model also does not capture the extent of spatial variability exhibited by the measurements. Emissions from other sources can explain some of these differences but, as detailed in Annex 5, the model is likely to significantly underestimate the $PM_{2.5}$ ambient concentrations attributable to heating stoves.

6.2.4 Air quality modeling summary

Air quality modeling suggests the MCA stove subsidy program has reduced the ambient $PM_{2.5}$ concentrations over UB by 30% compared to the counterfactual of all households using traditional stoves. Average reductions of up to ~50 $\mu g/m^3$ $PM_{2.5}$ for the heating season at the location of maximum impact (~20 $\mu g/m^3$ when weighted by population across UB) were estimated, with the largest reductions occurring in those areas that initially experienced the largest impacts from heating stove emissions (i.e., the PM hot spots that were the areas targeted in the MCA product rollout strategy). The modeled impacts of the intervention include not only lower $PM_{2.5}$ contributions attributable to heating stoves but also a homogenization of the spatial variability of impacts.

6.2.5 Air quality analysis limitations

Emissions measurement and ambient modeling both have limitations, many of which have been noted above. Although household emissions measurements were performed using methodology well accepted in the academic literature on this topic, the results still likely underestimate the true PM emissions as a result of downstream vapor condensation as the flue emissions cool after release into the atmosphere. In the extreme cold conditions such as those during the UB winter, the effects of this are likely to be pronounced, as the difference between the flue gas temperature (even after dilution with room air), and the ambient temperature are large and may cause a considerable mass of flue vapors to become particles, or to condense onto already formed particles, analogous to the visible fog that forms when one exhales on a cold day. The extent to which this additional PM mass reverts back to a vapor in a warmer environment – whether penetrating into a dwelling, being sampled by outdoor air quality monitors that are physically housed inside warm shelters, or remaining in the ambient air when temperatures increase after sunrise – remains unclear. Thus, although these effects are well known around the world, it is very difficult to quantify this bias, and more work is necessary to evaluate the impact of these dynamic processes on actual – and monitored – ambient air quality levels.

There is some variation in the reliability of air quality modeling results. The estimated percentage change in population-weighted ambient $PM_{2.5}$ concentration attributable to the intervention should be reliable, but estimated absolute change in concentration is likely underestimated. This arises from a modeling bias that cancels out in the comparison of the intervention to the base case. A more sophisticated air quality model must be used to better estimate the absolute contribution of domestic stove emissions to ambient $PM_{2.5}$ levels in UB. This modeling would require more refined meteorological data as inputs. Furthermore, robust estimates of domestic stove contributions to the overall air quality burden in UB, taking into consideration the contributions of other emission sources such as power plants, motor vehicles, and heat only boilers, would require the more sophisticated modeling approach. Additional limitations are described in Annex 5.

7 ESTIMATED HEALTH IMPACTS

The population-weighted annual average integrated $PM_{2.5}$ exposures and the related health burdens were modeled by L.D. Hill (University of California, Berkeley), using methods designed for a health burden assessment commissioned by the Mongolian Ministry of Environment and Green Development (MEGD, 2014). As described above, this analysis used assumptions and data inputs from a variety of sources to model the anticipated health impacts that would result from the measured $PM_{2.5}$ reductions from MCA stoves. Health impacts presented in this section were not measured directly from individuals or health facilities. The model was estimated for 2012 under a scenario with the MCA stove program and the counterfactual scenario with all traditional stoves. All other sources and parameters remained constant for both scenarios. The population-weighted annual average exposures to $PM_{2.5}$ were estimated using the measured wintertime heating season indoor concentrations and modeled wintertime heating season outdoor concentrations, combined with seasonal time activity patterns, estimated non-heating season concentrations, and environmental tobacco exposures. The calculations utilized the data collected as part of this impact evaluation (emissions and indoor air concentrations), as well as updated information from the 2012 census (population and number of dwellings). In addition, to adjust for underestimates of the number of dwellings in the census data when multiple dwellings are present at the same address, the dwelling numbers have been multiplied by a factor of 1.2 for ambient $PM_{2.5}$ modeling. This adjustment was based on the JICA review of data for various khoroos, and the discrepancies observed in the stove sales lists. In addition to household stoves, heat-only boilers, vehicles, and power plants were included as sources for modeling of ambient $PM_{2.5}$ concentrations in order to estimate health impacts. The modeled ambient $PM_{2.5}$ concentrations were scaled to the ambient $PM_{2.5}$ concentrations measured in an MCC-funded speciation study conducted by Ecography/Ecoworld, using a scaling factor of 2.8 applied to all emissions sources, except power plants. More detail on the methodology is provided in another report (MEGD, 2014). The analysis of premature mortality and morbidity related to $PM_{2.5}$ exposures utilizes the results of the Comparative Risk Assessments of the Global Burden of Disease Project (Burnett et al., 2014; Lim et al., 2012; Smith et al., 2014), which quantify $PM_{2.5}$ dose-response functions for five primary diseases: lung cancer, acute lower respiratory infection (ALRI) (ages 0-4 years), chronic obstructive pulmonary disease, ischemic heart disease, and stroke. Burden assessments for these five diseases rely on estimates of the Population Attributable Fraction, background disease rates provided by the Mongolian Ministry of Health, and a modified version of the HAPIT tool (Pillarisetti, Hanning, & Smith, 2014). Health estimates are calculated against a counterfactual annual $PM_{2.5}$ exposure of 12.0 $\mu g/m^3$, the current WHO air quality guideline to prevent health impacts in populations. More refined estimates of indoor particulate matter concentrations, exposures, smoking prevalence, and dose response curves from the 2012 Global Burden of Disease allow greater precision in appraisals of disease burdens and prevalence, and the health impacts of the MCA stove subsidy program.

The MCA stove program led to an estimated 11.5% reduction in population-weighted annual average exposures to $PM_{2.5}$ in Ulaanbaatar for 2012, which in turn implies a 9% reduction in the incidence of air pollution-related lung cancers (2.2% reduction in overall incidence), an 8.3% reduction in the incidence of air pollution-related chronic obstructive pulmonary disease (1.7% reduction in overall incidence), an 8.1% reduction in the incidence of air pollution-related ALRI in children between 0-4 years old (3.2% reduction in overall incidence), a 4.9% reduction in the incidence of air pollution-related ischemic heart disease (1.0% reduction in overall incidence), and a 2% reduction in the incidence of air pollution-related strokes (0.9% reduction in overall incidence). Overall, this would imply 47 avoided deaths and 1,643 DALYs, which under the ERR assumptions of the MCA project would be associated with a productivity gain of 3.9 million USD for the 2012-2013 heating season. It is important to note that these calculations focus only on one year of impacts (2012-13), and the overall impacts of the stove program should be assessed over the functional lifetime of the MCA stoves.

8 SUMMARY AND DISCUSSION

This evaluation assesses MCA stove usage and performance under real-world conditions of observed use, as compared to traditional stoves. Propensity score matching methodology was used to develop a counterfactual in the absence of a baseline, and allow estimation of intervention impacts, applying econometric techniques to minimize selection bias, to the extent possible, of households purchasing MCA stoves. PSM takes into account the characteristics that could potentially differ between MCA and traditional stove users. Matching results suggest the PSM was able to effectively control for selection bias; however, as with any quasi-experimental evaluation design, unmeasured sources of bias may remain and could affect the validity of the results. The study approach was designed to measure the overall impact of the intervention under real-world rather than ideal conditions. Our findings therefore capture variations in stove usage and ownership over time, shedding light on how households actually use their stoves and the impacts achieved by this intervention. In this section, we summarize and discuss the main results regarding emissions, fuel consumption, and health effects.

8.1 Air Pollution

MCA stoves produced significantly lower $PM_{2.5}$ and CO emissions compared to traditional stoves under actual stove use conditions in Ulaanbaatar. These reductions were calculated from household emissions measurements, which were then weighted by the MCA stove distribution in UB to produce aggregate estimates. Ulzii stoves had significant $PM_{2.5}$ reductions of 74% in houses and 83% in gers. Smaller reductions were observed in Khas stoves in houses (46% reduction) and Dul stoves in houses and gers (reductions of 31% and 38%, respectively) compared to traditional stoves, although these results were not significant, potentially due to low sample sizes. Moreover, there was no evidence that the use of MCA stoves increased health risk by producing higher concentrations of indoor CO compared to traditional stoves.

Using models of Ulaanbaatar's geographic and climatic conditions, air quality modeling was used to calculate the reductions in pollutants under current conditions with a hypothetical counterfactual of all households using traditional stoves. Ambient $PM_{2.5}$ concentrations in UB attributable to heating stoves were reduced by an estimated 30% as a result of MCA stove adoption, with largest reductions in highly polluted areas that were more heavily targeted by the program. Ambient $PM_{2.5}$ was reduced by up to 50 $\mu g/m^3$ at the location of maximum impact and ~20 $\mu g/m^3$, when weighted by population across the city, over the course of the 2012-2013 heating season.

8.2 Subgroup Analysis by MCA Stove Type

Three different MCA stove types were evaluated as part of this study: Ulzii, Khas and Dul. Differences in emissions and coal consumption were observed between the three stove models, as expected since the stoves have different structural designs and indications for use. Khas stoves are used almost exclusively in houses, since they are large in size and were advertised as appropriate for larger houses. The homes of households choosing Khas stoves tended to be the largest, on average; homes of households using Dul stoves were slightly smaller; and those of households using Ulzii stoves were the smallest. Dwelling size and type account for some differences in overall average coal consumption and fueling behavior.

As shown in Figure 31, a significantly higher number of Dul stove owners (18-25% more) reported using their stoves for both cooking and heating, compared to Ulzii and Khas owners. 31% of Dul stove users believed their stove was easier to cook with than a traditional stove, compared to only 16% and 19% of Ulzii and Khas users, respectively (Annex 1, Table 2). The use of a stove for cooking is associated with an increase in the number of fueling events, which could translate into increased fuel use and emissions, as well.[21]

Heating walls, utilized to help retain heat within the dwelling and available only in houses, were used by 20-22% more Dul stove users in houses compared to those who owned Ulzii or Khas stoves (Figure 32). This significant difference could be explained by the greater ease of connecting a heating wall to Dul stoves; in addition, Ulzii stove users were instructed to remove the heating wall. Table 15 demonstrates that households with heating walls had higher average coal consumption; a result that may help account for some of the different consumption trends between MCA stove types.

This significant variation in use patterns by stove type sheds light on the disparities observed between the performances of each MCA stove type relative to traditional stoves. These findings also highlight the role of user behavior and preferences in driving the observed results, as this evaluation focuses on stove performance with typical use. Interpretation of differences found between stove types must be grounded in the broader context of usage and consumer preference.

8.3 Satisfaction and Demand

Demand for MCA stoves remains strong, as MCA stove users reported high levels of satisfaction with their stove. The majority of MCA stove owners believed that their stoves had a better appearance, reduced coal consumption, reduced air pollution, and maintained heat longer than traditional stoves. Measures of satisfaction and demand were generally the same between male and female-headed households and between male and female stove tenders. While emissions results confirmed some of these perceptions, fuel consumption measurements did not provide empirical evidence for these beliefs. Areas of dissatisfaction with MCA stoves included difficulty cooking, higher burn risk, and the substantial effort required to start a fire. Bolstering the demand for MCA stoves, the majority of traditional stove users

[21] Since the project team was aware that any stove would be more efficient in heating mode only and that an increasing number of ger district residents were using a separate cooking device (at a minimum for convenience), during program design the project team considered including a cooking device as part of a bundled package for purchase, to incentivize separation of heating and cooking (e.g., buying the two together would bring greater subsidy than the sum of the two), but this was ultimately not implemented because the project team did not have the capacity or time to also perform the product review process on cooking devices.

reported that they would prefer an MCA stove, related to the expectations that MCA stoves would reduce fuel consumption and air pollution and maintain heat longer.

8.4 Coal Consumption

No significant differences in coal consumption were identified between MCA and traditional stoves, as measured by total daily coal use. Users of MCA-supported energy-efficient stoves, on average, performed 0.33 fewer fueling events ($p < 0.001$) per day, but used 0.72 kg more coal ($p = 0.001$) at each fueling. Due to these competing effects, no significant differences in total daily coal quantity used were observed between MCA and traditional stoves during the 2012-2013 heating season. These results were consistent across the winter months, stove types, dwelling types, presence of heating wall, and after adjustment for the volume of the heating space. Previous laboratory tests indicated that MCA stoves could reduce coal use by 11-26%, depending on the stove model. This evaluation suggests that under real stove use conditions, given the fueling behavior actually practiced by stove users, these upper limits of reductions in coal used are not being achieved by the households. Several potential explanations for this finding were explored, including compliance with usage instructions, the role of insulation, the role of indoor temperatures, data quality, and coal subsidies.

8.4.1 Low compliance with operation instructions

The lack of reductions in fuel consumption for those using MCA stoves is likely related to low compliance with MCA stove operation instructions. In addition, lack of compliance can significantly degrade performance with respect to reducing emissions. Compliance with recommended usage procedures was defined as practicing only cold starts, no warm refueling, and lighting from the top. Within most households, compliance was very low, with only 4% reporting correct use in all three data collection phases. MCA stove owners reported 1.64 warm refuelings and 0.69 cold starts per day, on average, implying that many households were only conducting warm refuelings. A sharp drop in compliance was observed in the coldest part of the winter.

The finding of significant reductions in emissions in spite of this low compliance suggests that emission reductions might be even greater if compliance was optimal. Although emissions results reflect the greater number of Ulzii stoves distributed, which had greater emissions reductions than the other stove types, laboratory tests performed by the SEET laboratory showed substantially greater emissions reductions than observed in homes with the Ulzii stove using Nalaikh coal. An additional consideration in explaining this seeming discrepancy is that it is not well understood how many coals or embers are required in the warm refueling process to change the stove function to increase emissions, and by what magnitude. Any refueling at which the respondent indicated coal or embers were still in the stove was considered a warm refueling; however, the specific amount of embers or coal present was not assessed. It is possible that if a minimal amount of burning embers remained in the stove at the time of a refueling, its impact on emissions might have also been minimal. In addition, MCA stove owners may not have followed instructions for adjusting their stove air intake, which would have also affected emissions and coal usage. While this was observed anecdotally, this study did not systematically evaluate air intake adjustments, so this cannot be confirmed as a partial explanation for the results. As stated by the manufacturers and according to laboratory tests, failure to use the stove according to instructions is expected to negatively impact fuel efficiency benefits of the stove. When fuel consumption was compared between fully compliant MCA stove users and traditional users, MCA stove users had highly significant 17% reductions in daily coal consumption ($p < 0.01$). Likewise, when results were disaggregated by MCA stove type, users reporting correct stove operation were found to have achieved high levels of coal reduction, approaching those estimated in laboratory tests. These results provide compelling evidence of the key role that low user compliance with cold starts and top lighting procedures played in the lack of overall impact on coal consumption.

8.4.2 Compliance: stove use and presence of insulation

Delving deeper into the reasons for low compliance, two main factors emerge. First, compliance may be especially challenging when a household is using the stove to cook, as one may need to refuel an already burning stove to enable cooking at the desired time. In addition, if homes are not well insulated it may not be comfortable for the residents to wait for the stove to fully extinguish before relighting when outdoor temperatures are extremely cold, as is often the case in UB. Our data suggest that the effect of insulation may be substantial: MCA stove owners in gers with three or more layers of felt insulation used 2.23 kg of coal less than traditional stove owners with the same level of insulation ($p = 0.093$) (Table 26). On the other hand, those with two or fewer layers used approximately the same quantity of coal as traditional stove owners. These results suggest that bundling interventions of stove purchase with higher insulation may be effective in encouraging compliance with cold start instructions and help to achieve intended fuel reduction benefits. Such an approach may result in greater equity and increased benefits for the poorest UB residents.

8.4.3 Improvements in comfort

A related explanation for the lack of fuel savings with MCA stoves stems from the differences in indoor temperatures observed for the two groups. According to the SUMs data, MCA stove owners kept their homes 1.86° C warmer, on average, compared to traditional stove owners – an interesting result since both groups were using approximately the same quantities of coal. This may have been intentional, representing a conscious choice by MCA stove owning households to keep their home a little warmer for greater comfort, without the need to use more coal. MCA stove owners may also have been choosing to fill their stoves to capacity each time they refueled, thus achieving higher indoor temperatures. Increased heat output could be the result of improved combustion performance of the MCA stoves, which would have resulted in more heat emitted per kg of coal. This effect may have occurred without a reduction in the burn rate of coal (kg/hour), which would have been required for significant fuel savings. In other words, MCA stoves could be burning hotter but not longer.

These results suggest that MCA stove owners might be able to maintain the same temperatures as traditional stove owners with less coal, but they either choose to maintain a more comfortable home temperature or are not aware that they have not changed their coal use habits after switching to an MCA stove. This is a widely discussed phenomenon in energy efficiency policy known as the *rebound effect* in which people often reduce net energy efficiency improvements by compensating with inefficiencies in other areas, either subconsciously or intentionally (Nadel, 2012). For example, it has been shown that purchasers of hybrid vehicles who experience greater fuel economy will often drive longer distances, thereby reducing the overall economic and environmental gains. Such behavior suggests that consumers may shift expected economic benefits to lifestyle improvements that are of value to them.

8.4.4 Data quality and comparison to pilot

An important factor that affects the interpretation of the evaluation results is the quality of the collected data, since obtaining accurate measurements of fuel consumption and the number of fueling events are challenging tasks. While the recall method used in this study is expected to have had limited accuracy, we were able to strengthen recall estimates by utilizing enumerator-assisted direct weighing of "demonstration buckets/bags" of coal for each fueling event performed by the households surveyed. However, it is possible that respondents had incomplete recall of the number of fueling events or grew tired of the tedious event-by-event questions and may have excluded some events or reported the same quantity for subsequent events to avoid re-weighing and shorten the survey time. Alternatively, enumerators may not have fully encouraged thorough responses within the recall questionnaire. However, the impact of these possible threats to validity of the estimate was likely quite limited, since data triangulation using temperature data from the stove use monitors supports the reporting of fueling events from the household survey. Checks using SUM data were conducted to estimate the number and types of fueling events reported, and the deviations from the household survey were found to be minimal.

The results from the January data collection period are also similar to findings from the pilot evaluation conducted at the same time of year in the previous year, with fewer fueling events observed for MCA stoves compared to traditional stoves in both time frames. Specifically, in January 2013, 3.6 versus 3 average daily fueling events were observed for traditional and MCA stoves, respectively, compared to 4 (traditional stoves) and 3 (MCA stoves) during the pilot phase (January-February 2012), when ambient temperatures were slightly lower.[22] Although the total number of fueling events was similar between the 2013 data collection and the pilot data collection a year earlier, the full 2012-2013 evaluation did not replicate the 13% reduction in total daily coal consumption found during the pilot for MCA stoves compared to traditional. While the precise cause of this discrepancy remains unclear, several possible explanations are possible. One potential explanation is that compliance with MCA stove use instructions was much higher in the pilot, with more households reporting correct lighting procedure more often: no more than one warm refueling and more than two cold starts for MCA stove owners, on average. We see a reverse trend in the full dataset, with more households using the stove incorrectly: with an average of 2.5 warm refuelings and 0.5

[22] Historical temperature data accessible at: http://weatherspark.com/history/34116/2012/Ulan-Bator-Ulaanbaatar-Mongolia

cold starts daily during the same cold time period. However, it is possible that compliance with correct use procedures had been overestimated in the pilot, as the pilot questionnaire was structured to allow respondents to self-categorize their prior day fueling events into cold starts and warm refuelings. Misunderstandings about the strict definition of a warm refueling could have led to more events incorrectly categorized as cold starts during the pilot. In the present evaluation, this bias was mitigated by eliminating self-categorization: respondents listed all fueling events in order, and for each they were to state whether there were embers or coal remaining in the stove. A fueling that was associated with either one of these states was categorized as a warm refueling for the purposes of the analysis.

8.4.5 Coal subsidies

Another factor that may have contributed to unusually high coal use within the study period was the ready availability of more affordable Baganuur coal, which was subsidized by the government in the middle of the 2012-2013 heating season. While MCA stove performance was evaluated in the laboratory using Nalaikh coal, Baganuur coal has a significantly lower calorific value, implying that more Baganuur coal would be required to achieve the same temperature. Although each MCA stove model has a fixed combustion chamber, and respondents were instructed to fill the chamber when they refuel the stove, the temperature and burn duration could vary with coal type used. Recent laboratory tests using Baganuur coal suggest that this type of coal is associated with significantly worse emissions performance of the stoves (Pemberton-Pigott, 2013), which may have also influenced the results of the impact evaluation. Since many households used a variety of different coal types during the heating season, at different times, it is difficult to isolate the impact of coal type used as a factor in stove performance. To study these impacts further, more controlled evaluation of the performance of MCA stove models used with various coal types is recommended. In particular, the possible impact on ambient air quality due to changes in use patterns of certain coal types to fuel household stoves should be evaluated directly to estimate environmental effects of large-scale subsidies to prevent unintended program consequences.

8.5 Health

Given the reduction in population-weighted annual average exposures to $PM_{2.5}$ in Ulaanbaatar for 2012 due to the MCA stove sales, this is expected to have resulted in substantial reductions in incidence of air pollution-related illnesses including lung cancer (9% reduction), chronic obstructive pulmonary disease (8.3% reduction), acute lower respiratory infection in children age 0-4 years (8.1% reduction), ischemic heart disease (4.9% reduction) and stroke (2% reduction) during 2012. The corresponding reduction of 47 deaths and 1,643 DALYs would, under the ERR assumptions of the MCA project, result in 3.9 million USD in productivity gains for the 2012-2013 heating season. These estimates focus only on one year of impacts when the stoves were implemented (2012-13), and the overall impacts of the stove program should be assessed over the functional lifetime of the MCA stoves. Estimates of population-weighted annual average exposure to $PM_{2.5}$ are largely based on indoor concentrations of $PM_{2.5}$. Since the reductions in indoor concentrations of $PM_{2.5}$ as a result of MCA stoves were considerably smaller than the reduction in emissions, a greater health impact could be achieved by focusing on stoves that also reduce indoor air concentrations in addition to the reductions in emissions to the ambient environment.

8.6 Limitations

It is important to note that the findings presented in this study are limited to the winter 2012-2013 heating season, and variation in results depending on temperature and meteorological trends is to be expected. In addition, the ambient modeling results have been estimated specifically for UB's unique climatic, geographic, and meteorological conditions and do not attempt to predict impacts that may occur in other contexts.

The ongoing pollution reduction initiatives in UB may influence perceptions of the value and need for energy-efficient stoves, whether positively or negatively, as alternative products become available on the market and as visible air pollution levels change. In addition, government initiatives to encourage relocation of ger district residents to apartments connected to the central heating system, if successful and able to outpace migration into the ger districts, could reduce demand for residential stoves in the future.

Since this study focused on the most widely used coal types - Nalaikh and Baganuur - the findings of this evaluation may not be valid when other types of coal are used to fuel the stoves. Emissions and coal use are dependent on both the stove and fuel type used, and the results of this evaluation would not apply if use of other coal types becomes more common in Ulaanbataar (e.g., as a result of changes in production or cost). For example, at the time of writing, the Nalaikh coal mine had recently been closed for safety and depletion reasons, and the possibility of providing additional support to another mine to improve capacity to supply UB was being considered (Minister Oyun, 2013). Efforts have also been made to make semi-coking coal available. It is essential that future studies assess both stove types and fuel types in concert, combining data from the laboratory and from homes to assess the variability of emissions, fuel consumption, and usability, which may impact the assessment of the costs and benefits of the different stove-coal combinations.

9 NEXT STEPS

9.1 Future work

While this evaluation was able to provide compelling evidence about the impacts of the EEP stove subsidy program, much more research remains to be done, and our study's findings suggest some fruitful areas of further inquiry.

First, future interventions could consider bundling stoves with other products that would improve emissions reductions and fuel savings, such as insulation efficiency products or cooking devices to facilitate cold start compliance. While ger insulation was available for subsidized purchase through this project, bundling was not highly incentivized. In addition, future work should also evaluate the performance of MCA stoves fueled using different coal types. Coal varieties used in winter 2012-2013 differed greatly. This evaluation did not capture enough specific data to assess directly the influence of coal type on stove performance. Each coal type has unique calorific value and emissions potential. Emissions levels are affected by both the stove and the coal type used; therefore, it is important to assess the efficiency impact of various types of coal and other fuels, especially those that may be considered for marketing or subsidy in the future.

Further research could measure fueling behavior in more detail and with greater precision. Though SUMs-triangulated data supports the accuracy of recall of fueling events by respondents, user recall methods have clear limitations and may be subject to bias in reporting. Future studies could use a more detailed survey of fuel consumption with documentation and direct weighing of each fuel type present in the home over a period of several days. In addition, the use of SUMs was found to be highly valuable to help estimate fueling behavior and is recommended for future studies.

Future studies should further explore gender differences in stove usage and project impacts, beyond what was measured in this evaluation. Most previous literature on gender impacts related to stoves is based on cookstove projects in other regions. These findings may not be fully applicable in Mongolia, where stoves are primarily for heating and where there is greater gender equity than in many African or Asian countries.[23] This evaluation was unable to answer all questions related to male and female stove tenders preferences and behavior related tocooking with MCA stoves versus other appliances, or whether and how they perceive their time availability to have changed as a result of their MCA stove purchase. While this evaluation shows few gender differences in stove preferences and use, the surprising differences in fuel expenditures within female-headed and poor households deserve further study. Qualitative methods in particular would provide valuable complementary information to this evaluation.

[23] Source: http://datatopics.worldbank.org/gender/country/mongolia

Additional research is necessary to better quantify assumptions used in estimating the impact of stoves on air quality. While stove emission testing in this impact evaluation was conducted using best-practice methods, measurement difficulties can arise since additional PM is formed when the stove chimney exhaust mixes with the cold outdoor air. Heating stove emissions estimates from this study and previous studies do not adjust for this additional PM load, which is particularly relevant given the extreme cold conditions in Ulaanbaatar. This emissions component should be quantified to better understand heating stove contributions to air quality in Ulaanbaatar and the impact of MCA stove adoption.

Future studies should also seek better measures of household income and expenditures, to allow better estimation of income effects. Reported household income as measured in our study was likely unreliable and underreported. Expenditures on food and household goods from the prior month proved highly difficult for respondents to estimate, particularly around the time of Lunar New Year celebrations when household expenses were atypical. A wealth score constructed from questions about asset ownership was found to be the most reliable, though imperfect, measure of household wealth, but could not be used to estimate income effects.

Finally, and with greatest urgency, barriers to compliance with cold start procedures should be studied and addressed to achieve optimal fuel savings from MCA stove adoption. While all MCA stove owners reported receiving stove operation instructions and were probably aware that they should utilize only cold starts with MCA stoves, compliance appears challenging in UB's extreme cold conditions. Waiting for stove to be fully extinguished prior to refueling may be highly uncomfortable, especially in poorly insulated homes, and it may be unrealistic to expect to achieve complete compliance on this front. Compliance with instructions may also be challenging if the stove is being used to cook, requiring the refueling of an already burning stove to allow cooking at the desired time (especially since cooking is commonly done by adding wood, instead of coal). Qualitative research, including interviews with both high and low compliers, may help understand how compliers have adjusted to the new procedures and to assess barriers to compliance, which may illuminate strategies to improve future interventions, use training, information outreach, or stove design.

9.2 Dissemination

The final impact evaluation report will first be circulated to key stakeholders for review and correction of factual inaccuracies if they exist. This group includes representatives from MCC, MCA Mongolia, stove manufacturers, subsidy transfer agents (banks), Mongolian government officials, and the UB City air quality office. Upon finalization, it will be made public on the MCC website, and MCC will be able to circulate it widely to Mongolian, US, and other international stakeholders (implementers, academics, government agencies, and non-government organizations) with an interest in stoves, air quality in Mongolia, and this project activity, specifically. The dissemination of the report to stakeholders in Mongolia will provide relevant and timely information to inform related programs, policies, and other activities that could benefit from lessons learned as part of this evaluation. Social Impact has already presented the preliminary results of this IE to Mongolian stakeholders in September 2013 and plans to continue reaching out to disseminate the results and answer any questions with regard to this IE.

Beyond this report, the authors will submit papers for publication in peer-reviewed and open source journals, to share both methodology and results of this IE with the global academic and practitioner communities. In addition, presentations at relevant conferences may be sought to continue dissemination of these findings in the coming years.

10 CONCLUSION

In summary, this evaluation finds that the stove subsidy activity of the EEP has achieved substantial benefits for the population of UB, most notably through improvements in environmental and health outcomes, as measured by air quality and modeled health impact evaluation. We find that dwellings using MCA stoves have significantly lower emissions of pollutants, with a 65% reduction in $PM_{2.5}$ and 16% reduction in CO emissions compared to traditional stoves. The program is thus estimated to have resulted in substantial improvements in ambient air quality over UB, reducing $PM_{2.5}$ concentrations attributable to heating stoves by 30% overall. These environmental gains can be linked to substantial reductions in the incidence of air pollution-related disease in Ulaanbaatar.

At the household level, MCA stove users have reported high demand for MCA stoves, and a positive perception of the benefits conferred by the stoves. Specifically, MCA stoves were perceived to save fuel and maintain heat longer. While our study finds that in dwellings with MCA stoves higher indoor temperatures are being achieved holding the amount of fuel constant, we do not observe a significant reduction in fuel consumption under typical use conditions. While MCA stove owners were found to have fewer fueling events, they used more coal per event, and the vast majority of households did not use MCA stoves according to instructions (i.e., for maximum stove efficiency, the stove should be lit from the top using only cold starts). Therefore, on average, MCA stove users did not experience reductions in fuel consumption compared to traditional stove users. However, the subgroup of MCA stove users who followed stove use directions for peak efficiency used 17% less coal per day, on average, a finding consistent with previously conducted lab tests. Insulation also played an important role for stove efficiency, as MCA stove owners in well insulated gers (i.e., three or more layers of felt) used significantly less coal each day than traditional stove owners with the same level of insulation.

In summary, we recommend that the drivers of stove user behavior be examined in more depth in future research to better understand the barriers preventing households from achieving peak fuel consumption efficiency that MCA stoves are capable of producing. Some reasons for the relatively low observed fuel consumption efficiency that were explored in this study included: the potential difficulties in using the stove for cooking while following correct cold start procedures; choosing to maintain a more comfortable environment in the home by enjoying a higher indoor temperature produced by the MCA stove; difficulty in adjusting to new habits in lighting the stove and managing fuel consumption; and the impact of insulation. However, the relative importance of these factors remains unclear and merits further inquiry, which could inform and facilitate interventions that would unlock cost savings associated with the higher efficiency MCA stoves.

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12 SUMMARY OF ANNEXES

Annexes are included in a separate document and include:

- Household data tables
- Household survey instrument (Phase III version)
    - English
    - Mongolian
- Household survey data quality monitoring
- Propensity score matching technical approach
- Limitations to ambient air quality modeling
- Summary of performance on output and outcome indicators from MCA-Mongolia Indicator Tracking Table (ITT)