

# Strategies for Reducing Particulate Emissions from Space Heating in the Ger District of Ulaanbaatar, Mongolia

Authors

Maithili Iyer, Henrik Wallman, and Ashok Gadgil

**Environmental Energy Technologies Division  
Lawrence Berkeley National Laboratory**

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Any errors or omissions in the document are the responsibility of the authors.

## Executive Summary

Many international organizations have funded studies of the air pollution problem in Ulaanbaatar with the result that both the extent of the problem and the sources of air pollution are well characterized; for example, the World Bank report<sup>1</sup> includes data from ambient air and source measurements. According to this report the 2007 coal consumption in Ulaanbaatar was 3.6 million metric tons for power generation, 500,000 tons for district heating (the term Heat-Only Boilers “HOB” is widely used in Mongolia to denote district heating) and 545,000 tons for home heating. In addition to coal, a substantial amount of wood is burned for home heating (413,000 tons according to report<sup>2</sup>). With such a large consumption of coal and wood in simple home heating stoves, many organizations have funded detailed studies of home heating stoves and possible stove improvements. For example, Asia Development Bank and the German Agency for Technical Cooperation (GTZ) have funded work to improve heating stove designs.

A natural target for the MCC project is the home heating sector that has been the focus of so many studies. However, there are certainly opportunities for source reduction in the HOB sector because these plants are also largely without adequate pollution control equipment (Japan International Cooperation Agency, JICA is in the process of characterizing this important pollution source). Augmenting HOB plants with pollution control equipment, or modernizing these plants completely would be a worthwhile goal for MCC. The difficulty here is that modern district heating plants require capital beyond the MCC budget constraints.

For effective use of allocated funds MCC has taken a market-based approach where subsidies are provided to consumers for products that reduce the pollution, particularly particulate matter, “PM” that comes from space heating. A subsidy program for a specific time period creates early adopters that lead the market transformation process. In order to sustain the transformation, legislated performance standards must be in place. Hence, the project focus is to promote commercially mature or almost mature products rather than funding R&D leading to such products. Subsidizing insulation and more energy efficient stoves are obvious choices. An area where the R&D component plays a big role is the so-called emission factor performance of the new stove designs, and this report is also a contribution to determining this important property of new stove designs. One of the constraints to implement a improved stoves program was the lack of reliable stove emissions data. The Project Implementation Unit (PIU) of the Millennium Challenge Account (MCA) set up a temporary testing laboratory in June 2010 to address this important aspect. (Other testing facilities were not available in time for the current heating season). The MCA testing laboratory consisted of an exchangeable stove in a ger equipped with flue gas analyzers for total particulate matter, “PM”, CO, NO<sub>x</sub> and SO<sub>2</sub>. The main objective of the work was the determination of the emission factors for PM and CO because these two pollutants are greatly affected by combustion conditions. The emission factor used in this work was defined as the amount of a particular pollutant emitted per unit fuel weight, typically in the unit g/kg coal. The thermal efficiency of the tested stoves was also determined.

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<sup>1</sup> World Bank 2009a.

<sup>2</sup> *ibid.*

The stove testing work shows that there are new stove designs that have a better efficiency and lower PM emissions than the traditional stoves currently in use. An overall stove efficiency of the order 75 % is feasible in comparison with the traditional stove at 58%. Such an efficiency improvement has the potential of reducing emissions by 30%. However, changes in use patterns such as an increased frequency of cold ignitions could reduce the emissions benefit from being directly proportional to the thermal efficiency. This is a consequence of the fact that cold ignitions produce “spikes” in the emission rate and that the heat output of heating stoves is most easily adjusted by varying the On/Off cycle. If high-efficiency stove manufacturers reduce stove capacity (kW output) in proportion to the increased efficiency, the frequency of ignitions remains unchanged. However, such scale down of stove dimensions is a demanding task for stove manufacturers but is not outside the realm of possibilities from a policy perspective.

The emission results from the laboratory tests show that a reduction of the PM emission factor by a factor of 2.5 appears feasible, i.e. the traditional stove emission factor of 7 g PM/kg coal would go down to 2.7 g PM/kg coal. Our simulation of the thermal performance of gers show that installation of 37 mm thick felt in walls and roof will reduce the heating demand by about 25%. Combining insulation with the installation of a vestibule raises the energy savings to 30%. The study also included a review of energy efficient homes promoted by UNDP as a potential measure for reducing emissions. The measure reduces the heating demand by about 70%.

With a combined approach of added insulation and a better stove it is possible to reduce PM emissions by 80% (the insulation and stove efficiency improvement gives a factor of 2, and the improved particulate burnout in the stove gives a factor of 2.5). From the perspective of having a significant impact through a large scale stove/insulation deployment program, our scenario analysis shows that a 10%, 30%, and 5% replacement of existing stock of eligible stoves, insulation, and detached homes over 2010-2013, may result in up to 32% reduction in PM emissions from stoves in the city by 2020. Even though the program ends in 2013, the scenario assumes continuation of efficiency gains due to a market transformation effect. While there may be uncertainties associated with market transformation impacts, the efficiency gains from the program could be solidified through a standards and labeling program for stoves and insulation. For a significantly deeper cut in emissions, the program may need to find stove designs that either reduce PM emissions even more drastically, or design a program that allows the residents to switch to cleaner burning fuels.

Other criteria pollutants (CO, SO<sub>2</sub>, NO<sub>x</sub>) may only go down by 50% due to the reduced fuel use. For SO<sub>2</sub> that can form secondary PM through condensation of sulfuric acid in the atmosphere, emission reduction by only 50% may be inadequate. An approach to SO<sub>2</sub> source emission reduction is a refined fuel consisting of coal-derived coke mixed with limestone in a briquette. The limestone serves to capture part of the SO<sub>2</sub> as calcium sulfate that becomes part of the ash. A potential difficulty with this approach is that it requires new fuel

production facilities that would take years to build and it may require subsidies for the refined briquette fuel market to be in place.

## **1. Introduction**

### **1.1. Overview**

Ulaanbaatar (UB) experiences very poor ambient air quality during the long winter months leading to significant health impacts on the population. The main contributors to air pollution are emissions from the combustion process associated with space heating in the Ger districts of the city. Coal is the dominant fuel used in the stoves used for heating purpose and the PM emissions from the combustion process affects the air quality. As population in the Ger area grows, so does the use of coal for heating and this worsens the problem of pollution. Several studies in the past have looked into the problem of air pollution in UB city and while there have been significant improvement in understanding of the problem and potential ways to address it, there has been little success in implementation and moving the residents into either using cleaner fuels or low-emission stoves. This study builds on earlier efforts to evaluate policy options and to develop a comprehensive program for reducing emissions in the city.

The Project Implementation Unit (PIU) of the Millennium Challenge Account (MCA) performed a set of tests on select stove models in a Ger in June 2010 under LBNL supervision. The current study utilizes results from these tests and findings from earlier studies in this area to perform consumer cost-benefit analysis and evaluate the cost-effectiveness of switching to a cleaner stove and the impact on the air quality at the city level from a large scale implementation of a stove/insulation program. This report provides preliminary recommendations on the next steps toward the design of lower emission alternatives in Ulaanbaatar.

The goal of this project was to come up with a reasonable set of solutions to address the growing air quality problem in the city of Ulaanbaatar (UB city) during the severe winter months of the year. The project focused on one of the largest sources of emissions during the winter months, i.e. heating in the Ger district. Earlier studies<sup>3</sup> have indicated that fossil fuel; mostly coal in UB city, (e.g., combustion to meet the residential heating and cooking demand, power generation, industrial processes, and motor vehicles) is the primary source of air pollution. In addition, the burning of biomass such as firewood, agricultural and animal waste contributes in the household sector for a large proportion of the pollution in some urban areas.

### **1.2. Project Scope and Approach**

The study focuses on three key measures for reducing emissions from the heating end-use in the Ger area – these include replacement of stoves with cleaner, lower emitting models;

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<sup>3</sup> The World Bank 2005, 2007, and 2009b reports

improving the insulation of the homes in the Ger area; and replacing the existing detached homes with energy efficient construction. Given the goal of this project, the project focused on two main tasks – a) Conducting a product review to identify appropriate stove designs that could deliver heating with improved efficiency while significantly reducing PM emissions; b) Perform economic analysis on the available/identified stoves/insulation to evaluate their cost-effectiveness from the consumer perspective; and assess their impact on the overall air quality of the city during heating season from a larger deployment program of these products.

This report estimates potential efficiency savings for a few important products. Thus, the estimated benefits represent only a part of the total that might be realized through a comprehensive program of efficiency improvement applied to a larger set of energy-using products. Our focus is to provide the most specific and technically accurate analysis available. For this reason, we do not consider likely opportunities where solid technical data is not yet available.

### **1.3. Report Organization**

This report is organized into six key sections. Section 2 discusses the background of the study with focus on literature review of past studies. These studies provide essential background on the Ger area residents and characterize the household, their energy use patterns, stove ownership and fuel use. Section 3 provides a methodological overview followed in the study that leads to an assessment of the existing technologies to address the air quality problem; and the size and scale of impact from pursuing a large clean stove deployment program. Section 4 of the report covers the fuel analysis data and technical analysis of stove test data. This section provides results in the form of stove thermal efficiency and emission factors. The section also covers heat demand analysis for different levels of Ger insulation. Outputs from this section are used in the following section on consumer impact analysis. Section 5 on consumer impact analysis evaluates considered technological options and various combinations through a cost-benefit analysis. This section deals with consumer life-cycle cost calculations and impact of health costs. Section 6 takes the cost-effective technological options from section 5 to the next level of analyzing it at the city level. This section provides city level impact of the high efficiency cases on emissions reduction and their financial implications. Finally, section 7 provides discussion of the results and recommendations.

## **2. Background**

According to the World Bank Report of 2007<sup>4</sup>, coal is the primary source of air pollution. In Mongolia, coal is used in combustion mostly for residential heating and cooking, power generation, industrial processes, and some transportation. Additionally, biomass burning such as firewood and agricultural and animal waste accounts for a large proportion of the pollution from the residential sector in urban areas. The pollutants include suspended particulate matter (SPM), sulfur dioxide (SO<sub>2</sub>), volatile organic compounds (VOCs), lead

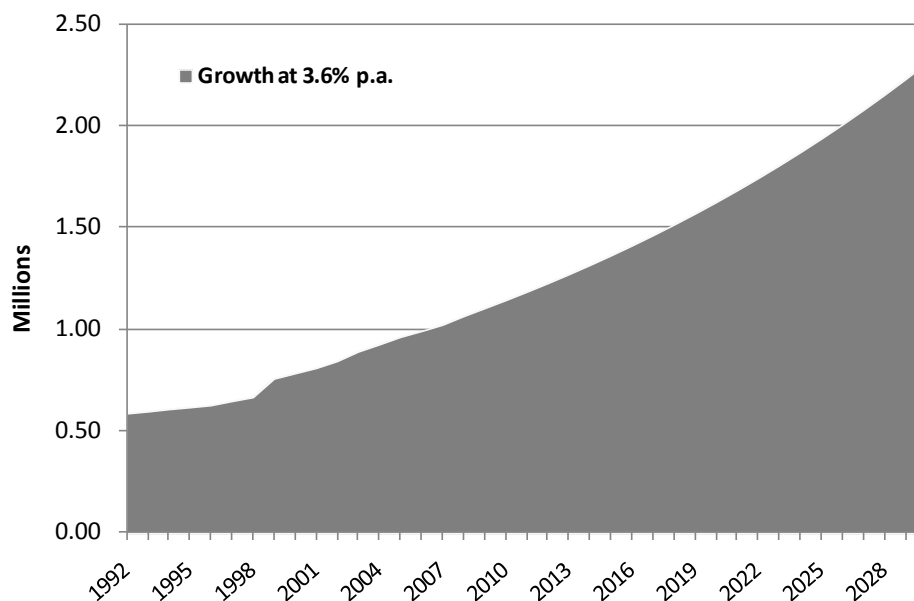
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<sup>4</sup> The World Bank 2007.



(Pb), carbon monoxide (CO), nitrogen oxides (NO<sub>x</sub>), ozone (O<sub>3</sub>), and, of course, carbon dioxide (CO<sub>2</sub>). Of all the pollutants listed above, it has been established through health impact studies that PM is one of the most critical pollutants responsible for the largest health and economic damages. Because of the impact of PM on human health, it has been a target pollutant for analysis and intervention in many studies.

According to the latest available census, the population of Ulaanbaatar as of 2009 is 1,106,719. The city can be divided into two main areas, the city center and the surrounding Ger area. The total population of the city comprises about 273,182 households, of which 156,453 reside in the Ger area<sup>5</sup>. A review of the historical growth in the number of households in UB city points to a steady rate of 4.6% over the period 1992-2009. The population of the city has been growing at the rate of 3.6% during the same period. This indicates an overall trend of decreasing household size in the city. The figure below shows the population growth in the city, which will be a key driver in emissions from the Ger area. We estimate the population to reach a conservative 1.6 million by 2020, if the current growth rate continues. The Statistical Yearbook of Ulaanbaatar, however, reports the population to reach 1.75 million. Other studies consider their assessment to be on the higher side. To be conservative, we assume the current growth rate over 2010-20, the period of analysis for this study.



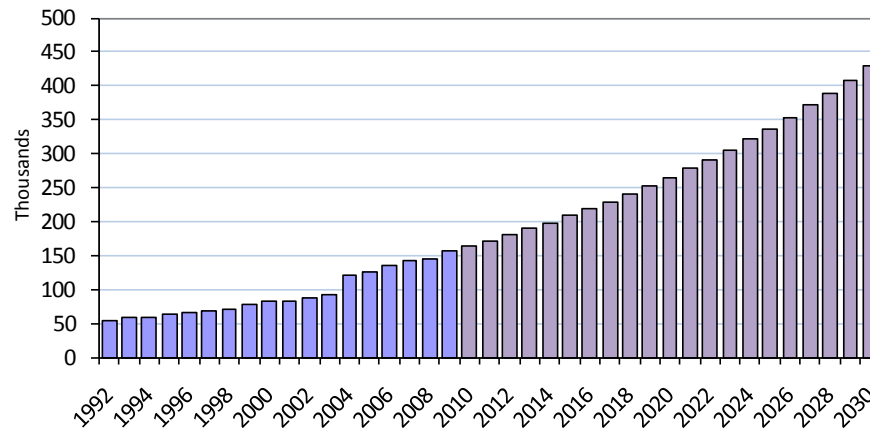
Source: Forecast based on Social and economic Data of UB, Ministry of Statistics

**Figure 1. Population Growth in Ulaanbaatar**

Based on the above forecast as well as data from the Ministry of Statistics on number of households in UB city and Ger area, we calculate the growth in the number of households in the Ger area. As shown in the figure below, the number of households in the Ger area will

<sup>5</sup> GOM 2009

increase from about 156 thousand in 2010 to over 265 thousand by 2020. This is a significant growth and will have serious implications for emissions from heating.



**Figure 2. Growth in Number of Ger Households**

Several studies have focused on Air quality in Ulaanbaatar ranging from those focusing on improving stove design, promoting improved stoves and cleaner fuels to those assessing perception of the Ger residents about existing and improved stoves. The report<sup>6</sup> published by the Asia Sustainable and Alternative Energy Program (ASTAE) characterizes the Ger area by providing information on the number, size and types of dwelling units; their energy use patterns; the stock and types of heating equipment in place; and the consumer perception of existing and improved heating stoves. The report’s findings are based on a survey of about a thousand households residing in the area, which was conducted in December 2007. The findings are significant in terms of increasing the understanding of energy use patterns of the Ger residents. Our study draws on the findings from that report quite extensively in the analysis.

## 2.1. Characteristics of households in Ger Areas

The Ger area typically has two types of dwelling units – a felt Ger or a one story detached houses. Households living in a ger or a small, one room type of detached house use a heating stove to heat their home directly. Households living in a larger house tend to use heating stoves with a heating wall. The largest and more modern separate/single home uses low pressure boilers. As per the ASTAE report and shown in the tables below, Gers make up about 43% of the dwelling type, while detached houses make up about 55% of the dwelling units. As shown in Table 2, 5-wall Ger is the most common type of Ger accounting for over

<sup>6</sup> The World Bank 2009b.

63% of the units. The table also shows some variation in the size of the floor area amongst the detached house type dwellings.

**Table 1 Number of Households by Dwelling Type in the Ger District**

	WB report	Census	
	<b>2007</b>	<b>2007</b>	
Ger	43607	61443	43.2%
Detatched House	55820	78651	55.3%
Ger+ Detatched hse	707	996	0.7%
Other	808	1138	0.8%
	<b>100942</b>	<b>142228</b>	

**Table 2 Type and Size of houses in the Ger District**

Ger			
	4 walls	5 walls	> 5 walls
	29.10%	63.60%	7.30%
Det House			
	No Ht Wall	Ht Wall	w/ LPB
	14%	70%	16%
Fspace (m2)	38.4	43	65

The study assumes the existing stock of stoves to roughly reflect the number of households in the Ger district. The existing stock of traditional stoves in 2009 is assumed to be about 182,000. This figure is based on the assumption that each residential unit has at least one space-heating appliance and the ASTAE survey finding of the proportion of traditional stoves in the Ger residential units. Our estimate of the stock is higher (142,000) than the ASTAE study estimate of 103,000 for the year 2007. However, since our assumption is based on the number of households as published in the census, we consider the difference to be justified.

The ASTAE report estimates that during 2003-2007, about 11,500 stoves have been added on average, each year. Our estimates based on new housing estimates that about 11080 new stoves are added each year during the same period. These additions are calculated purely on the basis of an increase in the number of households in the Ger area. Survey results point to there being a potential second-hand market. However, in the absence of any conclusive data on that, we do not consider such a market in our analysis. However, the used stove market appears to be even more informal than the market for new stoves.

## 2.2. Heating Stove Types, Ownership and Fuels

Studies have found that greater part of standalone stoves in use comprise a traditional, simple design that was originally optimized for easy transport and decentralized production in small workshops, and has the ability to burn all major fuels from raw coal to cattle dung. According to the ASTAE report, about 88% of the Ger households use traditional heating stoves made of sheet metal and/or cast iron. The other prevalent stove type popular among ger residents is the sawdust stove. These are estimated to constitute around 8% of the households. The remaining 4% are brick stoves. In the case of the detached houses in the Ger area, metal stoves make up about 65% of the households, 15% use brick stoves, 16% use Low Pressure Boilers (LPBs) and 4% use improved stoves. The following table shows the share of different types of stove/heating equipment in the Ger area.

**Table 3 Types of Stoves and their Share in the Ger Area**

<b>Traditional Stove</b>	
Metal/Cast Iron	74.9%
Brick Stove	8.9%
Sawdust Stove	3.8%
<i>Total</i>	<i>87.6%</i>
<b>Improved Stove</b>	
TT-03	1.2%
G2-2000	0.7%
EB-1	0.1%
BONA-2	0.1%
<i>Total</i>	<i>2.1%</i>
<b>Korean Stove</b>	1.2%
<b>Small LPB<sub>1</sub></b>	
Made Locally	7.2%
Imported	2.0%
<b>Total</b>	<b>100%</b>

Although the penetration of improved stoves among Ger residents is still low, ASTAE study concludes that a majority of the households is interested in changing to an improved stove model. A driving factor in the willingness to switch to an improved stove is a reduction in the heating bill and an expectation of better performance from improved stoves. Findings from the study seems to indicate that credible information communicated through credible channels will generate an interest in switching to new systems

The fuels available vary in type including sawdust, raw coal, dung, firewood, and semi-coke. They also vary in the form in which they are available and get used. Residents burn the fuel both raw as well as in the form of briquettes. Coal makes up 94.9% in share of all the fuels currently in use. Although there has been some concern among manufacturers and stove designers about the things that get used as fuel in the stove, typically classified as “anything that burns”, this typically makes up less than 0.3% of the share.

Stove studies are currently underway which focus on reducing emissions through modifications such as changing the air supply, the geometry of the combustion chamber and the heat storage capacity. Several prototypes have been tested as part of this project that will be discussed in some detail in Section 4.

### **3. Methodology Overview**

The study follows two approaches for addressing the twin goals of this project. The first objective of conducting a product review to identify potentially beneficial stove designs requires testing of the available stove models. The second objective is to identify those products or combination of products that are cost-effective to the consumer and also reduce emissions. The study combines a bottom-up engineering-economic analysis of specific technologies with a projection of the market evolution for considered products.

#### **3.1. Technology Cost-Efficiency Analysis**

Efficiency policies have a particularly important role to play when new equipment enters the stock, either in the form of replacements of existing stoves, or as the market expands. Cost-effective efficiency measures will save consumers money, but they also address other important issues, as in this case, lower particulate emissions, and resultant health benefits.

For considered product, we first characterize key parameters (including efficiency level). In the current study, the characteristics of the most common current product establish the baseline, for which we collect data on purchase price<sup>7</sup>, energy-use, and emissions characteristics. Efficiency improvements and their costs are estimated relative to this baseline. The technical data regarding emission factors and thermal efficiency of the stove performance comes from the analysis of the test results (discussed in the following Section).

We estimate the energy savings and additional purchase cost associated with specific technologies that enhance efficiency. The fundamental component of the purchase cost is the per-unit manufacturing cost. Typically, we would apply markups for manufacturers and distributors that result in the purchase price. However, in this study we do not have the necessary data to estimate the purchase price accurately. We therefore utilize prices provided by manufacturers for the specific products. At the time of promulgating a standard or certification, it may be appropriate to develop a cost-efficiency curve that will enable the regulators to maximize efficiency gains at a low cost.

#### **3.2. Market Projection**

The approach for estimating the sales of each product for each year in the 2010-2020 period involves the use of historical shipments data (for estimating replacement sales), lifetime function of the product and indicators or key drivers for any additional growth or new sales. In the absence of historical sales data, the study utilized historical data on population and the number of households residing in the Ger area and used it in combination of the saturation of

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<sup>7</sup> Here, we considered the manufacturer declared prices that include retail and distribution mark-ups.

the heating appliance in the households. In this study we assumed 100% saturation as a household would typically have one working stove at any given time.

### 3.3. Potential Impacts with Low Emissions Products

Taking typical product utilization and equipment lifetime into account, we calculate the Life-Cycle Cost (LCC) of owning and operating a product at alternative efficiency levels for a typical user. The LCC accounts for the energy costs paid by the consumer. The price of the fuel that is saved at the margin is based on current fuel prices. We freeze the fuel price at the current price while calculating the operating cost savings, as we did not have sufficient data to project future energy prices. We calculate LCC values using discount rates appropriate for the user.

Once we establish the cost-effectiveness of the considered products or product combinations, we rank order them from the perspective of maximum environmental benefit. For each product, we identify the efficiency level with the lowest LCC, which represents the most economically justifiable design for the consumer. Of course, policy makers will consider other factors besides consumer LCC in reaching their decisions about target efficiency levels, including impacts on manufacturers. In the current analysis, we pick one efficiency level for each considered product to evaluate the impact of a large scale deployment of that product on the overall emissions. For simplicity, we call it the Emissions Impact Analysis (EIA).

## 4. Air Pollution Caused by Stoves and Fuels

### 4.1. Fuel Data Analysis

The fuels used in this study were analyzed by the Stewart Group in Ulaanbaatar in accordance with standard coal analysis procedures. All three fuels are available to the public in UlaanBaatar. Key results are in Table 4 listed below

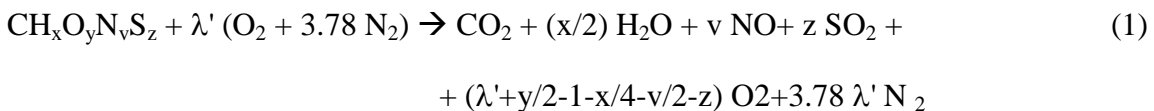
**Table 4 Fuel Data Analysis Results**

	<b>Nalaikh Coal (raw coal and coal briquette)</b>	<b>TN Coke Briquette</b>	<b>B28 Coke Briquette</b>
As received fuel analysis, wt%			
Organic matter	80.44	58.47	64.95
Ash	8.33	35.11	30.17
Water	11.22	6.42	4.88

Ultimate analysis of organic matter, wt%			
C	77.17	94.39	86.06
H	5.74	1.81	3.32
N	1.70	1.09	1.28
S	0.64	1.00	0.65
O	12.44	1.71	8.69
Calculated properties (maf basis)			
Lower Heating Value, MJ/kg coal	30.92	31.86	31.57
Stoichiometric air factor, kg air/kg coal	10.32	11.53	10.78

## 4.2. Stove Efficiency

In this work we reference the efficiency of a stove to the ideal case where the fuel is converted to fully oxidized products. In terms of chemical stoichiometry, the organic portion of the coal “CH<sub>x</sub>O<sub>y</sub>N<sub>v</sub>S<sub>z</sub>” which is referred to as the moisture and ash free (“maf”) coal is converted as follows,



where  $\lambda'$  is the air factor expressed as mol oxygen/mol maf coal.

An important special air factor is the “stoichiometric” air factor  $\lambda'_s$  that leaves no oxygen in the products but supplies exactly the amount of oxygen needed for complete oxidation. This stoichiometric air factor can be calculated based on the coal composition as

$$\lambda'_s = (2 + x/2 + 2z + v - y)/2 \text{ mol O}_2/\text{mol CH}_x\text{O}_y\text{N}_v\text{S}_z \quad (2)$$

It is more practical to express the air factor in terms of air instead of in terms of oxygen, coupled with mass units, viz.

$$\lambda'_{s, \text{air}} = (2 + x/2 + 2z + v - y)/2 (32 + 3.78 \cdot 28)/\text{MW}_{\text{coal}} \text{ kg air/kg maf coal} \quad (3)$$

In combustion engineering it is customary to express  $\lambda'_{\text{air}}$  as follows

$$\lambda'_{\text{air}} = \lambda \cdot \lambda'_{\text{s,air}} \quad (4)$$

where,  $\lambda$  is the excess air factor defining how much air is supplied to the reaction above the stoichiometric amount calculated from the combustion reaction. The excess air factor is conveniently determined experimentally from the measured  $O_2$  concentration ( $C_{O_2}$ ) in the flue gas by the following relationship

$$\lambda = 1 + \frac{C_{O_2}(\%)}{20.95 - C_{O_2}(\%)} \quad (5)$$

In practical cases where CO is a significant combustion product, a more accurate relationship for  $\lambda$  is to replace the numerator by  $[C_{O_2}(\%) - 1/2 C_{CO}(\%)]$  to account for carbon that has not been converted to the fully oxidized state  $CO_2$ , viz.

$$\lambda = 1 + \frac{C_{O_2}(\%) - \frac{1}{2} C_{CO}(\%)}{20.95 - C_{O_2}(\%)} \quad (6)$$

If coke or unburned coal is an important product the stoichiometric air factor should be adjusted by using the amount and maf coal stoichiometry of the fuel that is actually burned. There are also corrections that can be applied to high-moisture fuels by considering the moisture contribution to the measured  $H_2O(\%)$  concentration in the flue gas. However, for the coals used in this work, this correction was not applied. For high-moisture wood as the fuel, this correction should be applied.

In this work, the excess air factor of Eq (5) was used rather than an air factor corrected for both the CO and  $H_2O$  effect (coke was assumed to be a negligible product judging from the light grey color of the ash product). The CO and  $H_2O$  effect on the calculated flue gas rate have opposite signs making neglecting both of them a better approach than neglecting only one of the effects.

The flue gas flow rate can now be calculated from the coal burning rate  $r$  (kg maf coal/h) as follows

$$F_{\text{flue}} = (1 + \lambda \cdot \lambda'_{\text{s,air}}) r \quad (7)$$

The thermal efficiency  $\eta$  is defined as the ratio of heat rate delivered indoors and the maximum possible heat generation rate based on lower heating value of the coal,  $LHV_{\text{coal}}$ . The efficiency is reduced below 100% because of chemical enthalpy loss attributable to partially oxidized products, mostly CO, and because of flue gas convective heat loss. Accounting for the combined stack and chemical enthalpy loss, the efficiency is

$$\eta = \{r \cdot \Delta H_{\text{react}} - F_{\text{flue}} \cdot c_P \cdot (T_{\text{flue}} - T_{\text{indoor}})\} / (r \cdot LHV_{\text{coal}}), \text{ or using Eq(7) for } F_{\text{flue}}$$



$$\eta = \{\Delta H_{\text{react}} - (1+\lambda \cdot \lambda'_{\text{s,air}}) \cdot c_p \cdot (T_{\text{flue}} - T_{\text{indoor}})\} / \text{LHV}_{\text{coal}} \quad (8)$$

where  $F_{\text{flue}}$  is the flue gas rate and  $c_p$  is the flue gas heat capacity

When CO is the dominant un-oxidized component,  $\Delta H_{\text{react}}$  can be determined from the CO emission factor  $\text{EM}_{\text{CO}}$  (see below) in accordance with

$$\Delta H_{\text{react}} = \text{LHV}_{\text{coal}} - \text{EM}_{\text{CO}} \cdot 10.9 \cdot 10^{-3} \quad (\text{MJ/kg maf coal}) \quad (9)$$

where  $10.9 \cdot 10^{-3}$  is the heat of combustion of CO in MJ/g. Substitution of this expression into Eq (8) yields the final result for the efficiency results reported in the work

$$\eta = \{ \text{LHV}_{\text{coal}} - \text{EM}_{\text{CO}} \cdot 10.9 \text{ MJ/kg} - (1+\lambda \cdot \lambda'_{\text{s,air}}) \cdot c_p \cdot (T_{\text{flue}} - T_{\text{indoor}}) \} / \text{LHV}_{\text{coal}} \quad (10)$$

The average heat release  $Q_{\text{burn}}$  of the stove can be expressed as

$$Q_{\text{burn}} = \bar{r} \{ \text{LHV}_{\text{coal}} - \text{EM}_{\text{CO}} \cdot 10.9 \cdot 10^{-3} \} \quad (\text{kW}) \quad (11)$$

where  $\bar{r}$  is the average coal burning rate (the instantaneous rate  $r$  was not measured).

### 4.3. Stove Emission Factors

The PM emission factor is defined as

$$\text{EM}_{\text{PM}} = F_{\text{flue}} C_{\text{PM}} / (\rho_{\text{flue}} \cdot \bar{r}) \quad (12)$$

where  $C_{\text{PM}}$  is the measured average PM concentration in the flue gas (g/m<sup>3</sup>) and  $\rho_{\text{flue}}$  is the flue gas density. Substitution of the expression for  $F_{\text{flue}}$  from Eq(7) yields the practically useful relationship

$$\text{EM}_{\text{PM}} = (1+\lambda \cdot \lambda'_{\text{s,air}}) C_{\text{PM}} / \rho_{\text{flue}} \quad (\text{g PM/kg maf coal}) \quad (13)$$

An instantaneous emission factor could not be determined for PM because the flue gas PM concentration was not measured as a function of time. Gas emission factors on the other hand were available as instantaneous values calculated from the instantaneous gas concentrations  $C_{\text{CO}}$ ,  $C_{\text{SO}_2}$ ,  $C_{\text{NO}_x}$  as

$$\text{EM}_{\text{CO}} = (1+\lambda \cdot \lambda'_{\text{s,air}}) C_{\text{CO}} / \rho_{\text{flue}} \quad (\text{g CO/kg maf coal}) \quad (14)$$

$$\text{EM}_{\text{SO}_2} = (1+\lambda \cdot \lambda'_{\text{s,air}}) C_{\text{SO}_2} / \rho_{\text{flue}} \quad (\text{g SO}_2/\text{kg maf coal}) \quad (15)$$

$$\text{EM}_{\text{NO}_x} = (1+\lambda \cdot \lambda'_{\text{s,air}}) C_{\text{NO}_x} / \rho_{\text{flue}} \quad (\text{g NO}_x/\text{kg maf coal}) \quad (16)$$

Reported emission factors were averaged over the entire run.

#### 4.4. Experimental Procedure

Figure below shows the planned experimental test stand. In this test stand, two flue gas sample streams are extracted by sample pumps from the flue pipe and metered at the sample pumps. The flue-gas sample ports are located on opposite sides of the flue pipe at a height of 1 m above the stove. The approach to determining the coal burning rate is by recording the weight loss of the stove, and as a secondary approach, by measuring the flue gas rate which allows calculation of the burning rate. The planned setup also includes double particulate (PM) measurements: One branch shown on the left side of the flue pipe in Figure 3 uses a heated sample line leading to the hot filter holder containing a ceramic cup for trapping all the PM in the stream. The collected filter cake on the cup is determined gravimetrically which together with the metered volume of sample gas allows the PM concentration to be calculated. The second PM determination shown on the right side of the flue pipe in Figure 3 is an instantaneous reading from an optical instrument like the DustTrak. This type of instrument requires a diluted sample. The DustTrak also has the capability of providing particle size information of the PM.

Because of the tight schedule for characterizing stove performance in June 2010, experiments were performed in a test ger with only part of the instrumentation installed. This work was conducted by MCA EEP personnel under the supervision of LBNL. The flue gas rate measurement and the DustTrak were not available leaving the weight scale as the only burn rate measurement, and the gravimetric PM filter as the only PM measurement. Since the gravimetric PM measurement is an integral measurement several filter “yield” periods were tried on some stove tests but this approach was abandoned because of the complications of changing filters in the middle of a run. Hence, only a single filter measurement was performed for an entire run implying that PM was only determined as an average for the entire run. Averaging over the entire test was also applied to the fuel weight loss because any differences in the rate of weight loss were difficult to determine during the test.

A standard test procedure was defined as follows

1. Load the stove with 400 g of dry starter wood
2. Ignite the starter wood
3. Load 3 kg of test fuel
4. Adjust air registers as per manufacturer’s instructions
5. When the CO level has increased by a factor of two at the end of the burn, rake the ashes, and recharge the stove with a second 3 kg batch of test fuel
6. Allow the second the fuel batch to burn out

For a nominal burning rate of 1 kg/h, a test run in accordance with this procedure was expected to be of 6 h duration. In most tests however, the burning rate was much higher resulting in significantly shorter test runs (4 h total test time more typical). Because of the short duration of the test, the stove ignition event was a much larger contributor to average performance results than the typical winter use of stoves that often involves around the clock operation (with no ignitions from cold conditions in a 24 h period). Hence, the test results are conservative in nature; emissions in the field are expected to be lower than the lab test results

because the cold ignition events in the field are expected to be much less frequent than once per 6 h burn time. Quantification of the frequency of ignitions will come from the future field monitoring program.

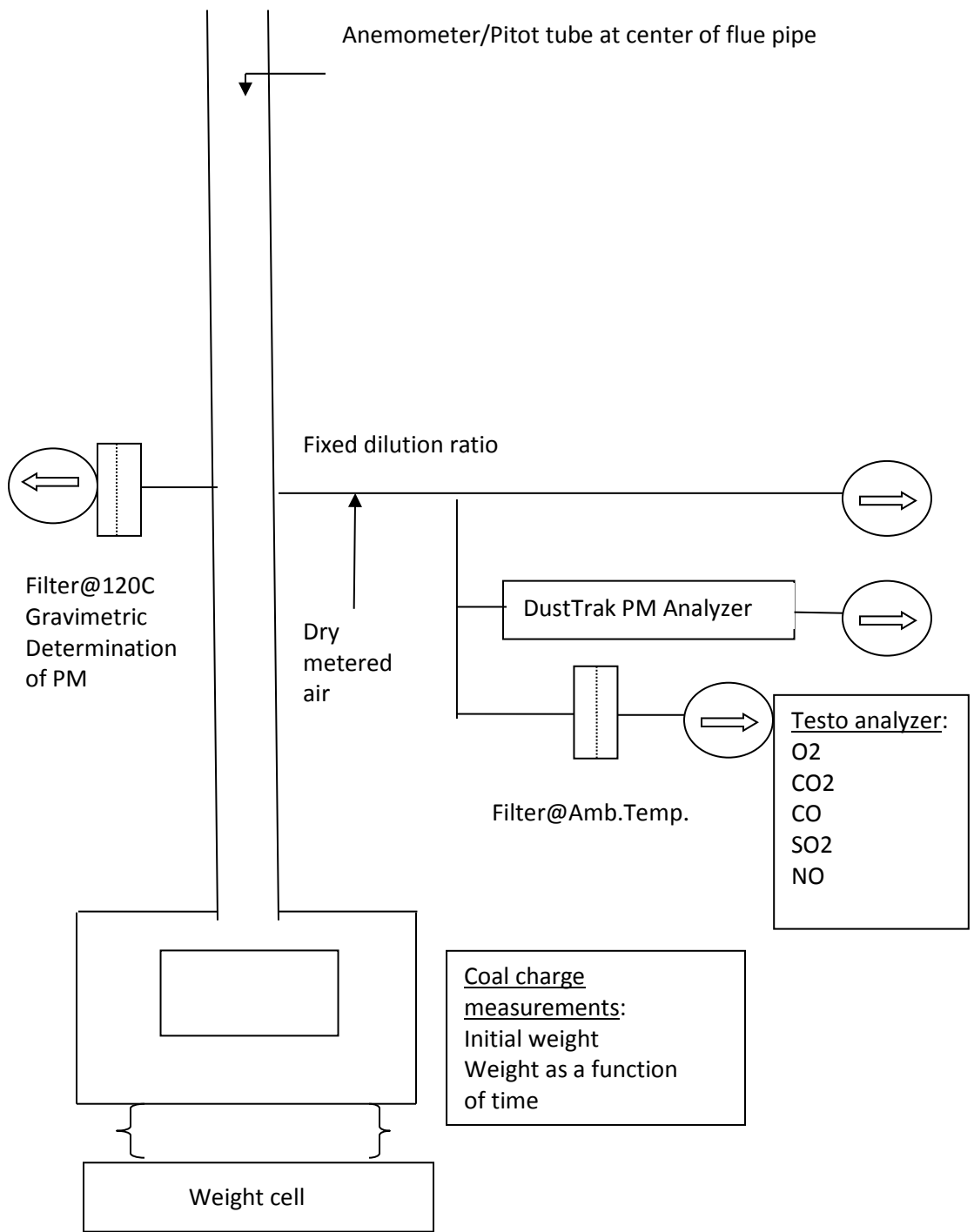
Refueling which was done only once in any one test is also a higher-than average emission event. The World Bank<sup>8</sup> reports the typical wintertime number as 7 refuelings per 24 h period, and a total daily use of coal as 23 kg. This means that the refueling frequency (once per 3 h) and refueling amount (3 kg) were fairly typical in the tests performed.

A set of test runs with a shorter test procedure (no refueling) was conducted early with several stoves including the ST-son stove (Physics Institute), the ASA, the Victoria, and the Nikko stoves. This test series narrowed the number of stoves to be compared to four main categories: Traditional, or stoves currently used in homes in Ulaanbaatar, Anard downdraft stove (two capacities), several models of GTZ developed stoves, and a Korean stove. This was by no means a comprehensive list of stove candidate but the tight MCA project schedule did not allow an extensive test program. Publicity played a role in the selection of the stoves; for example, the Anard stove had recently won a local competition for new stoves showing promise of improved emission performance.

Nalaikh coal was considered the standard fuel, and it was used in most of the experiments. However, stoves that showed favorable results with Nalaikh coal were also tested with several types of coke briquettes available in Ulaanbaatar. The objective here was to demonstrate that the stove also produced reasonable performance with a fuel different from the “design” condition because it is quite possible that the homeowner will use fuels different from the fuel specified by the stove manufacturer.

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<sup>8</sup> The World Bank 2005.



Experimental Test Stand

**Table 5 Test run results**

Stoves with Nalaikh Coal*	Q <sub>burn</sub> kW	Excess air factor $\lambda$	T <sub>flue gas</sub> C	Efficiency $\eta$ %	Chem. Loss % (incl in $\eta$ )	CO Emission g/kg maf coal	PM Emission g/kg maf coal	NOX Emission g/kg maf coal
Trad. Magsarjav (short run)	19	3.3	334	61	6	168	15	16
Common Stove	17 (?)	4.4	271	54	13	325	4.8	21
Trad. Magsarjav	7	4.2	328	60	3	88	10	3
Anard_small (short run)	10	4.0	290	50	16	465	4.9	19
Anard_small	9.6	5.1	176	57	18	510	4.3	15
Anard_small (rerun)	17(?)	3.3	228	64	3	93	1.7	12
Anard_small_mod (short run)	9.1	6.3	133	56	24	1190	19	36
Anard_large (short run)	16	3.2	217	74	6	172	4.6	11
Anard_large	16	4.0	239	64	10	282	3.4	11
Korean Stove	10	3.7	207	64	16	545	10	22
GT5 (short run)	NA	3.4	294	62	8	218	NA	14
GT6 (short run)	16	2.3	184	82	5	128	11	9
GT6	11	11 (!)	206	25	14	402	24	51
GT7	8	2.8	224	80	1	26	0.6	6

\*)Nalaikh coal analysis: Lower heating value 30.9 MJ/kg maf coal (“maf” stands for moisture and ash free). Ash and moisture amount to 19.55 wt% of as-received coal

Stove/Fuel	Q <sub>burn</sub> kW	Excess air factor $\lambda$	T <sub>flue gas</sub> C	Efficiency $\eta$ %	Chem. Loss % (incl in $\eta$ )	CO Emission g/kg maf coal	PM Emission g/kg maf coal	NOX Emission g/kg maf coal
Common Stove/TNCoke Briquette*	6.9	8.3	164	18	43	1592	6.7	21
Magsarjav/Coal Briquette**	NA	6.7	190	60	5	123	13	4
Magsarjav/B28Coke Briquette***	4.7	3.7	291	64	2	53	3.3	2

Anard_small/TNCoke Briquette	~2.7	17 (!)	84	~24	~57	~1640	~3.2	~2
GT7/TNCoke Briquette	2.9	6.0	146	48	26	748	21	14

\*) TN Coke Briquette: Lower heating value 31.9 MJ/kg maf Briquette. Ash and moisture amount to 41.53 wt% of as-received fuel Briquette

\*\*\*) assumed to have the same chemical properties as Nalaikh coal

\*\*\*) B28 Coke Briquette: Lower heating value 31.6 MJ/kg maf Briquette. Ash and moisture amount to 35.05 wt% of as-received fuel

## 4.5. Stove Results

Table 1 contains the key results from the runs with the standard test procedure. A question mark next to a result indicates that there is some conflict in the primary experimental data. However, the most likely result is presented. Error estimation for these results is very difficult to perform because of the limited number of data points. Small differences in fuel stack geometry are believed to be responsible for much of the poor reproducibility. Some tests were also performed under very unfavorable operating conditions; these points are marked by an exclamation mark next to the result (some tests, for example, were conducted with a very high level of excess air).

Two traditional stoves were tested in experiments identical to the experiments with the new stoves. One traditional stove called Magsarjav in Table 5 was an existing stove in a neighboring ger that was borrowed for these tests. The other called “common stove” was actually purchased at the Ulaanbaatar market place. When the three “baseline” run results are averaged the average efficiency is 58%, the average PM emission about 9 g/kg coal, and the average CO emission about 230 g/kg coal (all emission factors are reported on a moisture-ash-free “maf” coal basis). Also, the emission factors show great variability even for repeat runs on the same stove; Magsarjav for example shows PM emissions of 15 g/kg coal in one run and 10 g/kg coal in another almost identical run. Similarly, the CO emission is 170 g/kg coal in one run and 90 g/kg coal in the other.

Averaging the three runs using the Anard small stove yields an efficiency of 57%, PM of 4 g/kg coal, and CO of 360 g/kg coal. Here, the PM is significantly better than the baseline but the CO is significantly worse. Thermal efficiency is essentially the same as the baseline stove data.

The Anard small stove was also tested with a design modification of the air intake register that proved to have very unfavorable consequences for the emissions (called “Anard\_small\_mod” in Table 5). It was also tested with the TN coke briquette fuel with very unfavorable results for thermal efficiency and CO emission.

The Anard large-capacity stove that was tested in two runs show a higher a higher efficiency (69%), essentially the same CO (230 g/kg coal) and a lower PM (4 g/kg coal) in comparison with the baseline data.

The Korean stove is interesting only in terms of a relatively high thermal efficiency (64%).

The new GT7 stove design shows promise with respect to all three parameters (efficiency 80%, PM about 1 g/kg coal, and CO 30 g/kg coal). However, further testing of this new stove would be required before any commercial use is contemplated. The previous GTZ stove model (GT6) also has a high efficiency (82%) but poorer PM (11 g/kg maf coal) and CO (130 g/kg maf coal) values.

The Common and the Anard stoves showed very poor thermal efficiency with the TN briquette fuel, and the low efficiency was a result of high losses associated with poor burnout (high CO). The flue gas CO concentration in these runs was so high that any accidental release of flue gas into the home would constitute a safety hazard. This fuel was made from a

highly devolatilized coke in contrast to the other coke briquette called “B28 coke briquette” in Table 5 that had a higher content of volatile matter. Interestingly, the traditional Magsarjav stove performed as well with the B28 coke briquette as it did with Nalaikh coal. The TN briquette also degraded the performance of the GT7 stove (lower efficiency, and much higher PM and CO emissions)

When comparing the results in this study to published data the broad ranges of published data for the stove thermal efficiency and for the emission factors become apparent. For example, the UNDP Report<sup>9</sup> quotes the likely existing stove efficiency range as 30-80%. Similarly, the EBRD<sup>10</sup> has published emission factors for PM in the range 3-20 g/kg coal and CO emission factors in the range 80-260 g/kg coal for Nalaikh coal in traditional stoves. Unfortunately, many other reports dealing with emissions from coal stoves in Ulaanbaatar report only flue gas pollutant concentration in g/m<sup>3</sup>, but this measure is not useful because the emission rate in g/h also depends on the flue gas rate that varies from stove to stove, and also varies with the air intake adjustments for any one stove.

Sulfur dioxide, SO<sub>2</sub> is an undesirable pollutant but the SO<sub>2</sub> cell in the Testo analyzer used in the tests was malfunctioning leading to very uncertain results. However, even in the absence of experimental data, it is possible to estimate the SO<sub>2</sub> emission factor based on the coal analyses. The SO<sub>2</sub> emission factor is of about 13 g SO<sub>2</sub>/kg maf coal for Nalaikh coal and the B28 briquette, and about 20 g SO<sub>2</sub>/kg maf coal for the TN briquette (100% of the sulfur contained in the fuel is assumed to be converted to SO<sub>2</sub> and emitted with the flue gas). In the atmosphere the emitted SO<sub>2</sub> is partially converted to sulfuric acid that can condense on particulate matter and further worsen the environmental effects of PM.

#### **4.6. Ger Insulation Results**

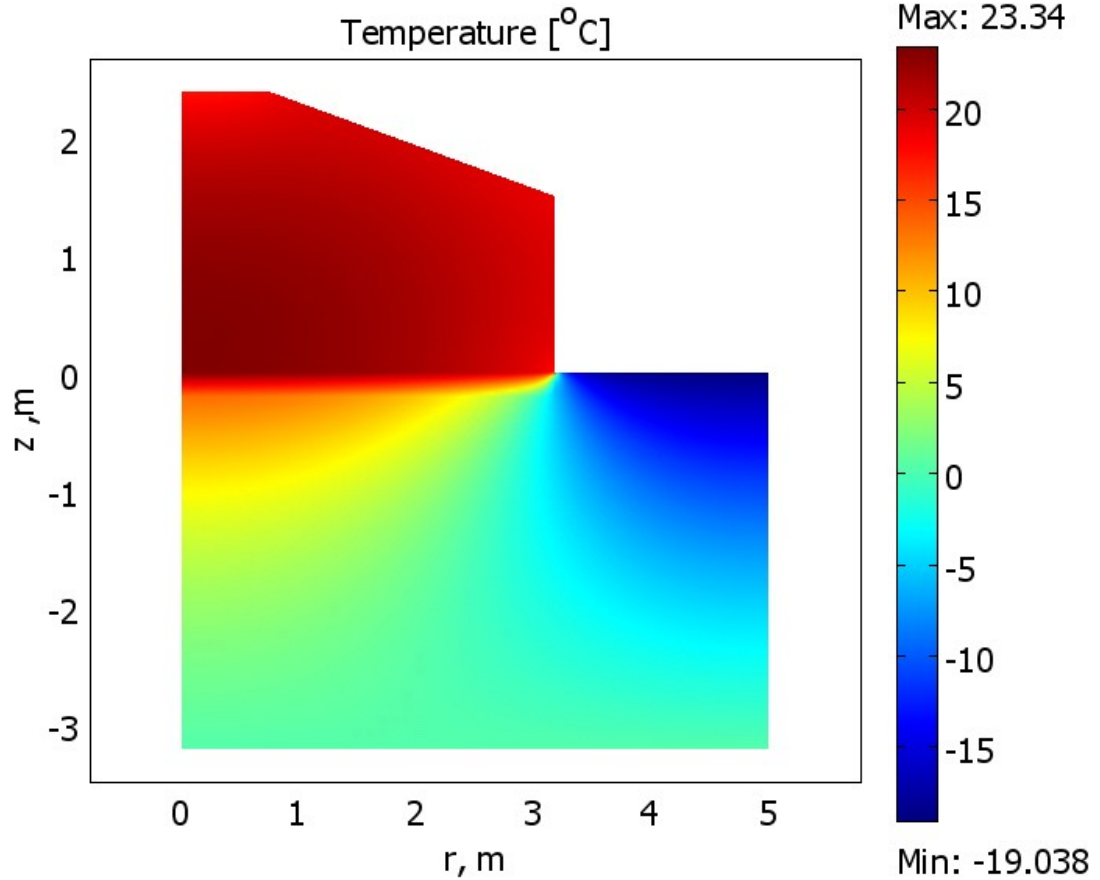
A Microsoft Excel-based building model (Courtesy of Mr. Crispin Pemberton-Pigott, Consultant to the Asian Development Bank in Mongolia) was used to determine the heating requirement for gers of three sizes. This building model is a standard single-zone building heat balance calculation with input for wall, roof, floor and ceiling materials as well as input for outdoor temperature data. In the model, the outdoor temperatures in Ulaanbaatar were allowed to change on an hourly basis, but instead of daily variations, monthly averages were used. The floor loss calculation required input of soil temperatures which was available down to a depth of 3.2 m. A conductive heat loss model was programmed using the Comsol Multiphysics program to ascertain that the temperature field at a soil depth of 3.2 m was unperturbed by the presence of the building. Figure 4 shows the temperature field under the ger with an assumed outdoor temperature of -20 C. All building calculations included the ground down to a depth of 3.2 m.

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<sup>9</sup> UNDP 2004.

<sup>10</sup> EBRD 2009.





**Figure 3 Temperature Field in the Ground Under Ger Floor (only half of the ger is shown because of symmetry). The outdoor temperature is -20 C.**

For the heat loss calculation, the indoor temperature was assumed to be constant at the standard indoor design temperature of 21 C.

Estimation of infiltration rates proved difficult because available studies have reported very broad distribution of so-called blower-door test results. Also, translating the blower-door results to real infiltration rates requires specification of wind conditions around the ger envelope. This type of modeling was considered to lie outside the scope of this work. Instead, an estimated average infiltration rate was estimated based on an assumed average pressure difference of 1 Pa between outdoors and indoors, and the reported average blower-door air exchange rate of about 21 ACH at 50 Pa taken from the UNDP study<sup>11</sup>. This resulted in 3 ACH for the gers. For the estimation of the effect of the added vestibule on the air exchange rate, a further assumption was made about the ger door: an air gap of 1 mm width was

<sup>11</sup> UNDP 2004.

assumed for the leakage area between the door and the door frame which resulted in the door accounting for about 11% of the air exchange rate in the large ger, 14% in the medium ger and about 19% in the small ger. With the installation of the vestibule, the door infiltration rate was assumed to drop to zero.

The assumed ger dimensions are shown in Table 6, and the results in Table 7. The base cases have 20 mm felt in walls and roof, while the remolded cases have either a single layer (30 mm), a double layer (37 mm), or a triple layer (44 mm) replacing the old 20 mm felt. The door has 13 mm felt in all cases. Infiltration is assumed to remain constant for all insulated cases. As Table 7 shows, the energy savings are substantial with improved insulation. The calculation also shows that the heat loss through the floor with a 25 mm thick plank floor and a 10 mm air gap above the soil is small (Table 8). A felt layer in the floor instead of the air gap would produce similar results. In this table the heat demand is seen to be dominated by conduction through the walls, conduction through the roof, and the convective heat loss associated with the air exchange.

The effect of added insulation on the air exchange rate was recently measured by the MCA team with the result that 3 ACH is a reasonable estimate for the insulated cases whereas the standard-insulation base case probably has about double the air exchange rate, or 6 ACH. This means that the estimates for energy savings in this report are conservative, and field data should prove even more favorable.

The ger model also shows that the maximum heating demand occurs at 7:00 am in January, and it is 5.2 kW even for the small 4-wall ger (with standard insulation). Since the outdoor temperature is -24 C at this time, the outdoor design temperature of -29 C calls for a proportionally larger heating capacity. Even with triple insulation, the indoor temperature would drop to -3 C with only a 2.2 kW heater at the design outdoor temperature. Water would freeze in the ger, and the conclusion is that a 2.2 kW heater is inadequate even for the smallest ger. Electric heating in a typical ger with only one 10 amp circuit at 220V is limited to 2.2 kW.

**Table 6 Ger dimensions**

	4-Wall Ger	5-Wall Ger	6-Wall Ger
Number of Lattices	4.0	5.0	6.0
Lattice Width (m)	4.2	3.9	3.6
Lattice Height (m)	1.5	1.5	1.5
Crown Diameter (m)	1.3	1.5	1.6
Door Width (m)	0.8	0.8	0.8
Roof Angle (deg)	19.0	20.0	22.0
Base Diameter (m)	5.3	6.2	6.8
Cone height (m)	0.9	1.1	1.4
Tip height (m)	0.2	0.3	0.3
Ceiling height (m)	0.7	0.9	1.1
Ground to crown (m)	2.2	2.4	2.6
Cone slant (m)	2.8	3.3	3.7
Ceiling slant (m)	2.1	2.5	2.8
Wall Surface Area (m <sup>2</sup> )	25.0	29.2	32.0
Ceiling Surface Area (m <sup>2</sup> )	19.1	26.1	32.0
Ground Surface Area (m <sup>2</sup> )	22.1	30.2	36.3
Door Surface Area (m <sup>2</sup> )	1.2	1.2	1.2
Volume (m <sup>3</sup> )	39.7	56.5	70.9

**Table 7 Annual heat demand**

Ger Type\Insulation Level	Annual Heating Demand, MJ
4-Wall Base Ger	72968
single layer replacement insulation	60892
double layer replacement insulation	55630
triple layer replacement insulation	51785
5-Wall Base Ger	97033
single layer replacement insulation	81858
double layer replacement insulation	75248
triple layer replacement insulation	70416
6-Wall Base Ger	116543
single layer replacement insulation	98977
double layer replacement insulation	91324
triple layer replacement insulation	85732
Add Vestibule to any ger type	Annual Energy Saving= 5000 MJ

**Table 8 Heat loss distribution in base cases (20 mm felt)**

	4-Wall Ger	5-Wall Ger	6-Wall Ger
Walls	34%	30%	27%
Roof	25%	26%	27%
Floor	6%	6%	6%
Door	2%	2%	2%
Infiltration	33%	36%	38%

#### **4.7. Comparison with international standards for combustion**

In the US, there are no emission standards for coal burning heating stoves. However, many localities impose a total ban on coal burning stoves through building codes.

For wood burning stoves equipped with a catalyst, the US EPA standard mandates that the particulate emission be below

$$3.55 \text{ (g/kg)} \cdot r + 4.98 \text{ g/h} \quad \text{where}$$

$r$  is the wood burning rate in kg/h in the range 0-2.98 kg/h

For burning rates above 2.82 kg/h and catalyst-equipped stoves, the allowable PM emission is 15 g/h. As an example, the emission limit is 8.53 g PM/h at a wood burning rate of 1 kg/h translating to a maximum allowable emission factor of 8.53 g PM/kg wood.

The emission limit for wood burning stoves without catalytic converters is slightly higher than the limits above.

## 5. Consumer Impact Analysis

In determining whether economic justification exists, we must determine that the benefits from moving to an improved stove, insulation and/or an energy efficient home exceed its burdens to the greatest extent possible. Key factors in this decision are:

- i) The total projected amount of energy savings likely to result directly in the policy case, and
- ii) the savings in operating costs throughout the estimated average life of the product in compared to any increase in the price of, or in the initial charges for or maintenance expenses of, the products which are likely to result from the policy case.

This study aims to evaluate the level of incentives necessary to achieve some level of penetration of improved stoves

### 5.1. Cost-benefit Analysis

#### 5.1.1. Cost of Conserved Emissions, Cost of Conserved Energy and Life Cycle Cost Analysis

To prioritize the stove/fuel/insulation combination, we analyzed 66 stove/insulation/fuel combination options in this study. The fuels studied included raw coal, TN briquette, Nalaikh briquette, coke briquette, electricity, and LPG. Since the key objective of the program is reduction of PM emissions, our main prioritizing criterion was total PM emissions from a specific combination. The test results did not provide the PM emissions by size, and therefore, the cost-benefit analysis had to treat them in aggregate. The 66 options analyzed in this study resulted in 54 options that reduced total PM emissions compared to the base case<sup>12</sup>. We use cost of conserved emissions (CCEm) as the basis to prioritize these 54 options.

#### *Cost of Conserved Emissions (CCEm)*

Emissions reduction from using a new technology has an indirect social benefit in the form of decreased health costs. These are offset, however, by the increased capital expenditure involved in purchasing low-emission equipment. To analyze the options from a programmatic perspective, we use the CCEm to prioritize the newer stove/fuel/insulation options based on the unit cost of emissions reduction. Here, we calculate the non-discounted CCEm as follows:

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<sup>12</sup> The base case here represents a traditional stove burning raw coal with no change in insulation.

$$CCEm = \frac{\Delta EC}{\sum_1^L \Delta Em_{PM}}$$

where

$CCEm$	=	Cost of Conserved Emissions
$\Delta EC$	=	Incremental Consumer Equipment Cost
$\Delta Em_{PM}$	=	Annual Total PM Emissions Reductions from the new technology
$L$	=	Equipment Lifetime

Calculation of CCEm values requires application of a present worth factor (PWF) to spread the initial incremental cost over the lifetime of the equipment. The PWF uses a discount rate to effectively amortize costs over time. We also call this the capital recovery factor;

$$CRF = \frac{dRate}{1 - (1 + dRate)^{-L}}$$

In this study we use a discount rate of 8% real.

Figure 5 shows a plot of the CCEm and total emissions. Only those combinations are worth considering that yield a total emissions level lower than the current baseline. The figure 1 shows the plot of 48 combinations for coal, LPG and electricity. Figure 6 shows the plot of 20 combinations for results from briquette analysis.

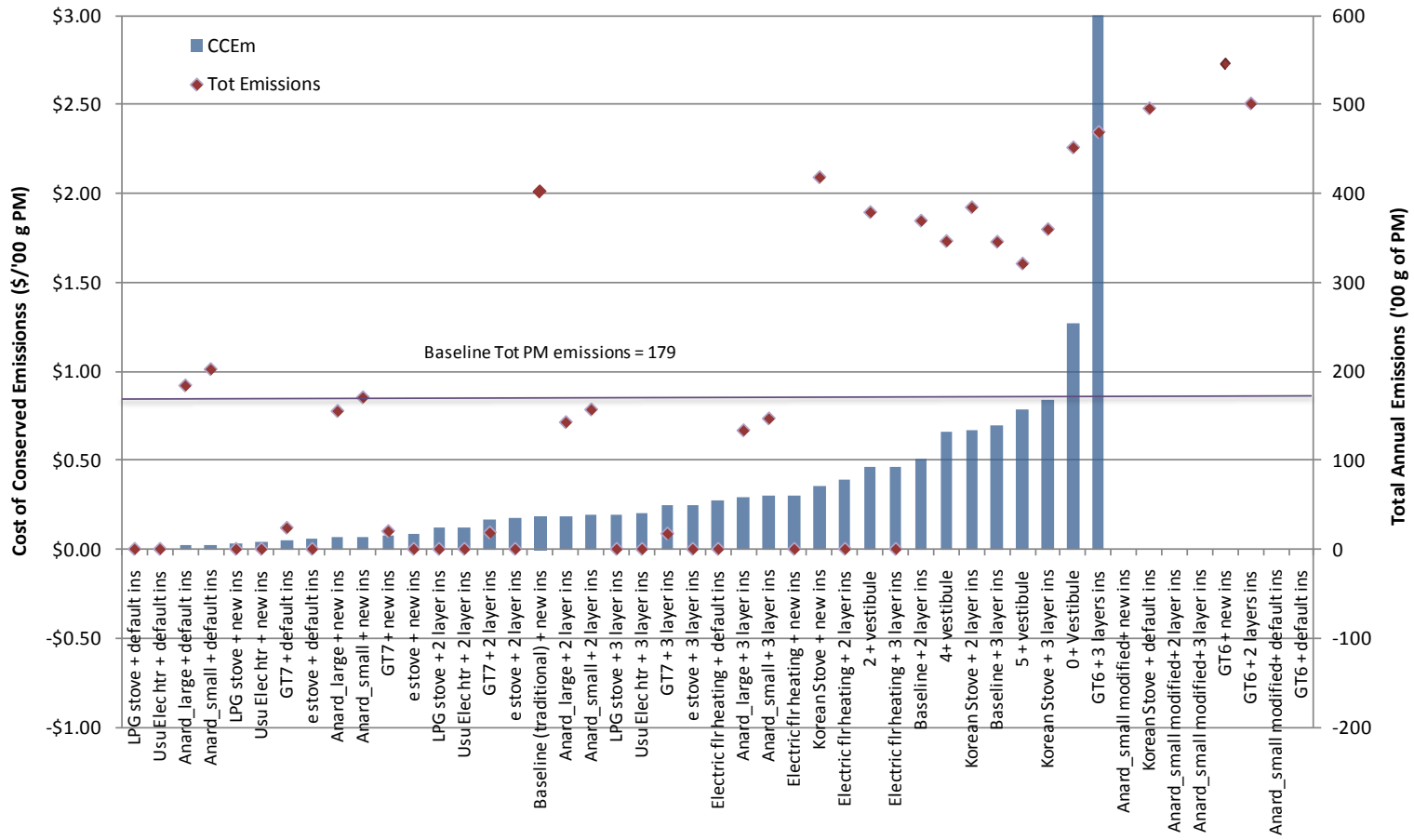


Figure 4 Cost of Conserved Emissions for Stove and Insulation Combinations

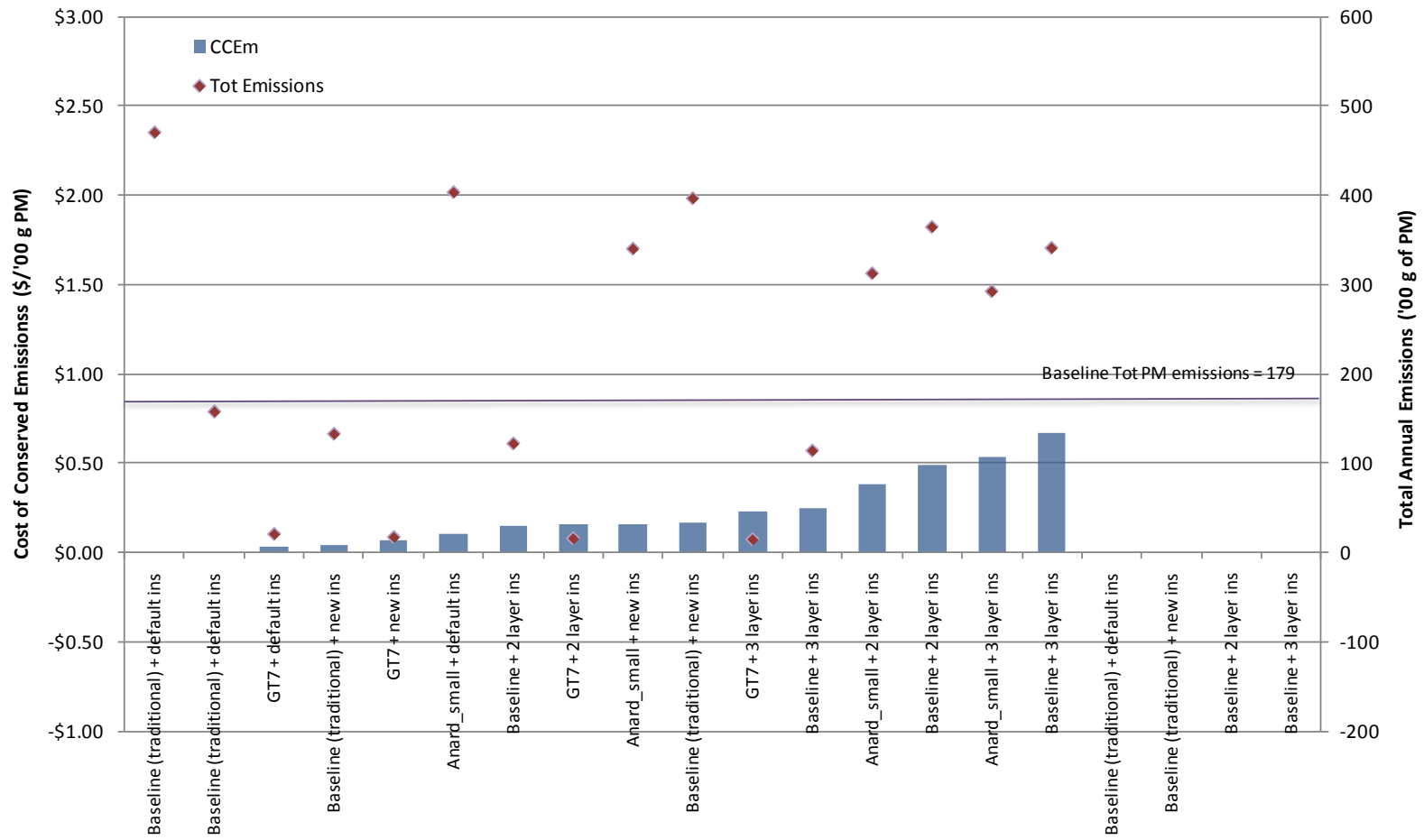


Figure 5 Cost of Conserved Emissions for Stove and Insulation Combinations for briquette



The briquette tests were conducted only on traditional, Anard\_small, and GT7 stoves. The analysis shows favorable results for certain combination of traditional stove and GT7 with options for insulation. Anard\_small shows a significant drop in thermal efficiency, which has an unfavorable impact on the resulting PM emissions.

Having narrowed down the options, we now evaluate the cost-effectiveness from the consumer's perspective. Consumer's perspective can be evaluated by using both the cost of conserved energy (CCE) as well as Life Cycle Cost (LCC). The former provides a reasonable metric that can be compared to the unit fuel price to the consumer. If the CCE is lower than the unit fuel price, it is generally a cost-effective option. However, CCE does not capture the increase in the operating costs associated with fuel switching that results in an increased LCC compared to the base case. This case is applicable in the case of LPG stoves and electric heating equipment. The Life Cycle Cost is the total consumer expense over the life of the equipment, including purchase expense and operating expense (including energy expenditures). To compute the LCC we discount<sup>13</sup> future operating expenses to the time of purchase and sum them over the lifetime of the equipment. The LCC provides a reasonable metric for us to compare the baseline stove/insulation combination with the new stove/insulation option. The considered option is cost-effective if the consumer experiences a positive LCC savings by switching to the new stove/insulation option.

### ***Life Cycle Cost (LCC)***

Life-cycle cost is the total customer expense over the life of an appliance, including purchase expense and operating costs (including energy expenditures). To accurately represent future expenditure accruing from the use of the equipment/appliance for the present, we discount future operating costs to the time of purchase, and sum them over the lifetime of the equipment. We thus define LCC by the following equation:

$$LCC = IC + \sum_{t=1}^L \frac{OC_t}{(1 + dRate)^t}$$

where:

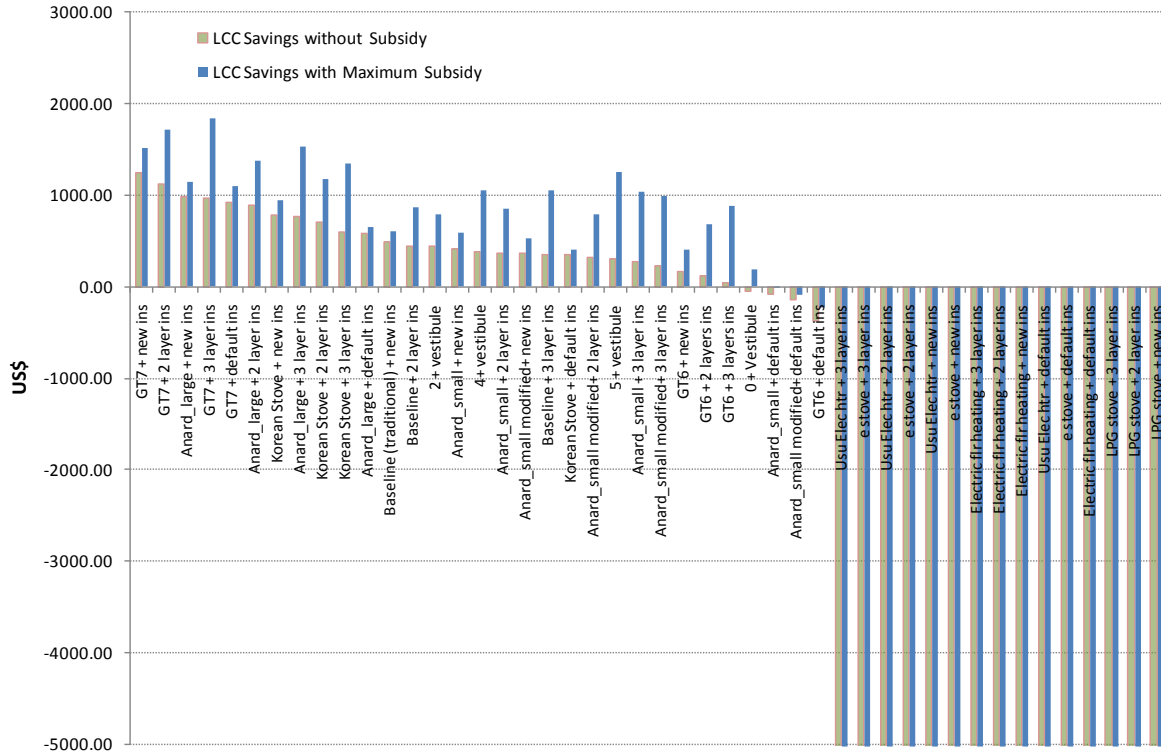
$LCC =$	Life-cycle cost in dollars,
$IC =$	Total installed cost in dollars,
$\sum =$	Sum over the lifetime, from year 1 to year L,
$L =$	Lifetime of appliance in years,
$OC =$	Operating cost in dollars,
$dRate =$	Discount rate, and
$t =$	Year for which operating cost is being determined.

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<sup>13</sup> Current analysis assumes an 8% real consumer discount rate

In this study we use a discount rate of 8% real.

Figure 7 below shows the LCC savings for the various combination of heating equipment and insulation with and without subsidy. The case with subsidy assumes a maximum subsidy aimed at price equalization. The figure illustrates that there are several options that are cost-effective (even without a subsidy) from the consumer perspective.



Note: Positive LCC Savings indicate that the options are cost-effective to the consumer

**Figure 6 Life-Cycle Cost Savings with and without Subsidy**

The table below presents a summary of 26 technology option combinations that yield a positive LCC savings with maximum subsidy. Most of these options are cost-effective and make economic sense for implementation for emissions reduction associated with space heating end-use even without subsidies. However, we consider cases with subsidy because consumers in general may not perceive benefits accrued over the life of the new stove/insulation.

**Table 9 Subsidy Levels for Stove and Insulation Combinations**

Stove + Insulation Model Combination	Thermal Eff of stove	Insulation Price	Equipment price	Total Installed Price	D Ins Price	D Eq Price	D Tot Price	Emissions	D emissions saved	New D LCC	CCEm \$/'00 kg PM	Max Subsidy per case	Max Subsidy per case	Subsidy level where LCC=0 (Min subsidy)
	%	\$	\$	\$	\$	\$	\$	PM	PM			\$	\$	
								gm/Kg	gm				Heating Eqpt Plus Refund for old stove where applicable ~ \$22.80	
<b>Base Case</b>	57.3%	\$211.05	\$45.72	\$256.77	\$0.00	\$0.00	\$0.00	7.0						
1 GT7 + 44 mm Insulation + electric cooktop	80.0%	\$914.20	\$213.65	\$1,127.85	\$703.15	\$167.93	\$871.08	0.5	45920	1849	\$0.25	\$167.93	\$703.15	\$0
2 GT7 + 37 mm Insulation + electric cooktop	80.0%	\$633.15	\$213.65	\$846.80	\$422.10	\$167.93	\$590.03	0.5	45802	1712	\$0.17	\$167.93	\$422.10	\$0
3 Anard_large + 44 mm Insulation	69.0%	\$914.20	\$109.73	\$1,023.93	\$703.15	\$64.01	\$767.16	3.3	34295	1530	\$0.29	\$64.01	\$703.15	\$0
4 GT7 + 30 mm Insulation + electric cooktop	80.0%	\$316.57	\$213.65	\$530.22	\$105.52	\$167.93	\$273.45	0.5	45640	1524	\$0.08	\$167.93	\$105.52	\$0
5 Anard_large + 37 mm Insulation	69.0%	\$633.15	\$109.73	\$742.88	\$422.10	\$64.01	\$486.11	3.3	33379	1371	\$0.19	\$64.01	\$422.10	\$0
6 Korean Stove + 44 mm insulation	64.0%	\$914.20	\$100.00	\$1,014.20	\$703.15	\$54.28	\$757.43	8.1	11658	1349	\$0.84	\$54.28	\$703.15	\$0
7 Vestibule + 44 mm insulation	57.3%	\$1,155.61	\$45.72	\$1,201.33	\$944.56	\$0.00	\$944.56	7.0	15525	1253	\$0.79	\$0.00	\$944.56	\$0
8 Korean Stove + 37 mm insulation	64.0%	\$633.15	\$100.00	\$733.15	\$422.10	\$54.28	\$476.38	8.1	9188	1178	\$0.67	\$54.28	\$422.10	\$0
9 Anard_large + 30 mm insulation	69.0%	\$316.57	\$109.73	\$426.30	\$105.52	\$64.01	\$169.53	3.3	32125	1154	\$0.07	\$64.01	\$105.52	\$0
10 GT7 + electric cooktop	80.0%	\$211.05	\$213.65	\$424.70	\$0.00	\$167.93	\$167.93	0.5	45267	1094	\$0.05	\$167.93	NA	\$0
11 44 mm insulation	57.3%	\$914.20	\$45.72	\$959.92	\$703.15	\$0.00	\$703.15	7.0	13070	1055	\$0.70	NA	\$703.15	\$0
12 Vestibule + 37 mm insulation	57.0%	\$874.55	\$45.72	\$920.27	\$663.50	\$0.00	\$663.50	7.0	13001	1049	\$0.66	NF	NF	
13 Anard_small + 44 mm insulation	57.0%	\$914.20	\$106.07	\$1,020.27	\$703.15	\$60.35	\$763.51	3.0	32965	1043	\$0.30	NA	\$703.15	\$0
14 Anard_small modified+ 44 mm insulation	56.0%	\$914.20	\$106.07	\$1,020.27	\$703.15	\$60.35	\$763.51	15.5	-30502	993	NF	\$60.35	\$703.15	\$0
15 Korean Stove + 30 mm insulation	64.0%	\$316.57	\$100.00	\$416.57	\$105.52	\$54.28	\$159.80	8.1	5810	944	\$0.36	\$54.28	\$105.52	\$0
16 GT6 + 44 mm insulation	54.0%	\$914.20	\$180.00	\$1,094.20	\$703.15	\$134.28	\$837.43	9.0	727	887	\$14.91	\$134.28	\$703.15	\$0
17 37 mm insulation	57.3%	\$633.15	\$45.72	\$678.87	\$422.10	\$0.00	\$422.10	7.0	10697	863	\$0.51	NA	\$422.10	\$0
18 Anard_small + 37 mm insulation	57.0%	\$633.15	\$106.07	\$739.22	\$422.10	\$60.35	\$482.45	3.0	31958	850	\$0.20	\$60.35	\$422.10	\$0
19 Anard_small modified+ 37 mm insulation	56.0%	\$633.15	\$106.07	\$739.22	\$422.10	\$60.35	\$482.45	15.5	-35865	797	NF	NF	NF	
20 Vestibule + 30 mm insulation	57.0%	\$557.98	\$45.72	\$603.70	\$346.93	\$0.00	\$346.93	7.0	9741	786	\$0.46	NF	NF	
21 GT6 + 37 mm insulation	54.0%	\$633.15	\$180.00	\$813.15	\$422.10	\$134.28	\$556.38	9.0	-2492	684	NF	\$134.28	\$422.10	\$0
22 Anard_large	69.0%	\$211.05	\$109.73	\$320.78	\$0.00	\$64.01	\$64.01	3.3	29248	655	\$0.03	\$64.01	NA	\$0
23 30 mm insulation	57.3%	\$316.57	\$45.72	\$362.29	\$105.52	\$0.00	\$105.52	7.0	7452	601	\$0.18	NA	\$105.52	\$0
24 Anard_small + 30 mm insulation	57.0%	\$316.57	\$106.07	\$422.64	\$105.52	\$60.35	\$165.88	3.0	30580	587	\$0.07	NF	NF	
25 Anard_small modified+ 30 mm insulation	56.0%	\$316.57	\$106.07	\$422.64	\$105.52	\$60.35	\$165.88	15.5	-43201	529	NF	NF	NF	
26 Vestibule	57.3%	\$452.45	\$45.72	\$498.17	\$241.40	\$0.00	\$241.40	7.0	2455	198	\$1.27	NA	\$241.40	\$43
NF	Not Feasible, does not lower emissions													
NA	Not Applicable													
	Unbundled option													

The suggested maximum for subsidy levels for options includes the full incremental cost of the new stove/insulation combination plus a refund on the existing stove/insulation to account for an early replacement by the consumer<sup>14</sup>. Although, the options are cost-effective even without a subsidy, consumers find an increase in the first cost daunting and will likely be disinclined to switching to new heating equipment or new insulation purely on the basis operating cost savings over the life of the equipment/insulation. Since this would be an early replacement program of the stoves/insulation, we recommend that in addition to offering a subsidy on the incremental cost, a refund on the old stove/insulation be made. The refund amount could be based on the amortized value of the remaining life of the equipment, with up to a maximum of 50% of the base cost.

## 5.2. Health Impact Considerations

Technically, health costs due to respiratory ailments should get factored into the cost-benefit analysis driving consumer decision making. The table below shows an estimate of the implicit burden of health related costs on a household due to respiratory ailments. This estimate is calculated for the entire population of the city of Ulaanbaatar and then normalized to a household level. This burden is estimated at \$187.89 per household per year. However, implicit burden is not a direct expense that a consumer can easily put a value on. According to the Guttikunda report<sup>15</sup> on air pollution sources, stove use in Gers account for only 25% of all PM emissions. At this point we cannot find a proportional correlation between reduction in emissions and reduction in health cost<sup>16</sup>. In this analysis, we assume a best case scenario, where reduction of particulates due to improved stoves will be the entire health cost of \$187.89.

Let us assume a scenario where the entire Ger population of Ulaanbaatar switches to LPG stoves from heating. Switching to an LPG stove<sup>17</sup> increases the operating cost of a household by \$275.19 compared to the base case of using traditional stoves. For a consumer to make a reasonable cost-effective decision, the operating cost differential will have to be lower than \$187.89. Thus, replacement with LPG stove option in this scenario is not viable in the absence of a fuel subsidy to offset the increase in operating costs.

The above scenario assumes the following:

1. The entire population switches to LPG stoves
2. There is a direct health benefit from a reduction in particulate emissions
3. The consumers experience the health cost directly in their cash flow.

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<sup>14</sup> Here the consumer is expected to replace the existing stove or go for new insulation, even though there useful life remaining on these stoves/insulation. The refund assumes a 50% remaining life for the existing stove/insulation.

<sup>15</sup> Guttikunda 2007. Urban Air Pollution Analysis for Ulaanbaatar.

<sup>16</sup> Many factors affect reduction in health costs, including ambient levels of PM, and marginal benefits from PM reduction.

<sup>17</sup> This case includes 3 layers of insulation and considers electric cooking. This case is used as an illustrative example of all combinations of LPG and Electric stoves. This case has the least increase in operating cost for the consumers.

**Table 9 Assessment of Health Cost Burden**

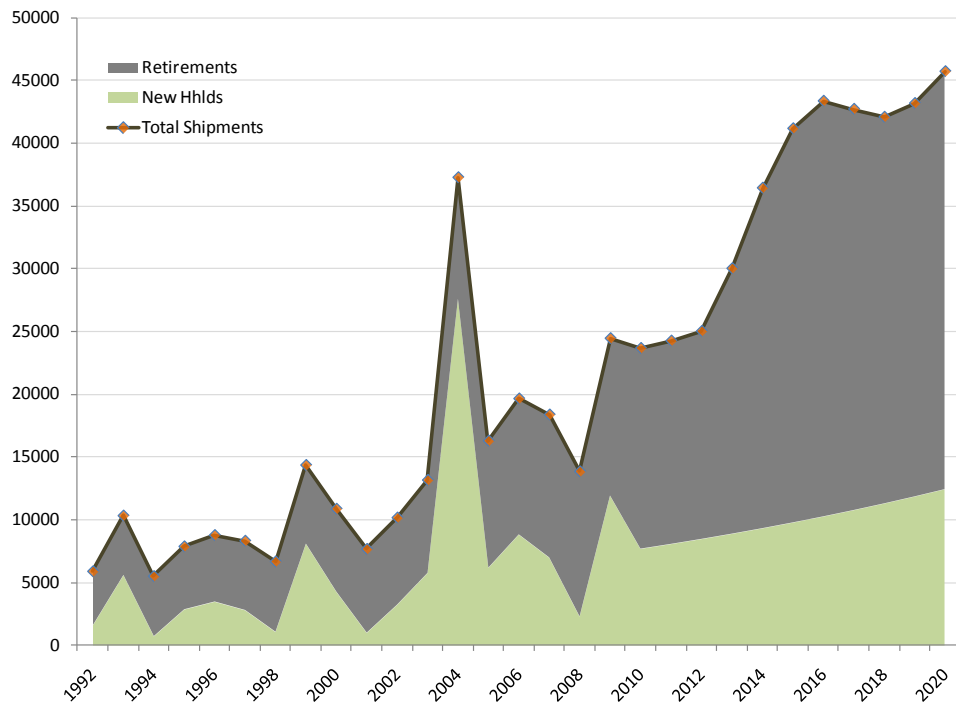
<b>Health Cost Burden Estimates</b>	
Treatment cost per respiratory case (US\$/illness)	\$76.74
Percent of population treated each year	3.8%
Treatment Cost for UB City per year	\$3,342,718
Normalized Treatment Cost per Household	\$11.87
Disability Adjusted Life Years (DALYs)/100,000 population	2105.59
Productivity Loss for UB City per year	\$49,574,448
Implicit burden from productivity loss per household	\$176.02
<b>Total implicit burden on a household from respiratory illness (including treatment cost)</b>	<b>\$187.89</b>
<b>Source:</b> Assumptions regarding treatment costs and DALYs are based on MCC's ERR Model	

## 6. City Level Impact of High Efficiency Case

To evaluate how a large scale deployment program of stoves and/or insulation would impact the city level emissions, we develop a shipments forecast for the city and its consequent impact on PM emissions.

### 6.1. Shipments Forecast

The base case shipments forecast forms the backbone of the Emissions Impact Analysis by providing an estimate of the annual sales and in-service stock of products for the forecast period. These are projections of product shipments in future years in the absence of the policy or other efficiency measures. The shipments or unit sales are modeled and takes into account growth in ownership, and replacements. The model assumes that a new unit is shipped every time an old one is replaced or as a share of new construction or in this case, influx of population from other parts of the country. The model is developed to simulate how existing and future purchase decisions are incorporated into the existing stock of aging products that are gradually replaced. Since the study did not have access to historical sales data or new construction for future, we used historical population data on the number of households in the Ger area as proxy for the new construction. The following figure shows the shipments forecast over the period 2010-20.



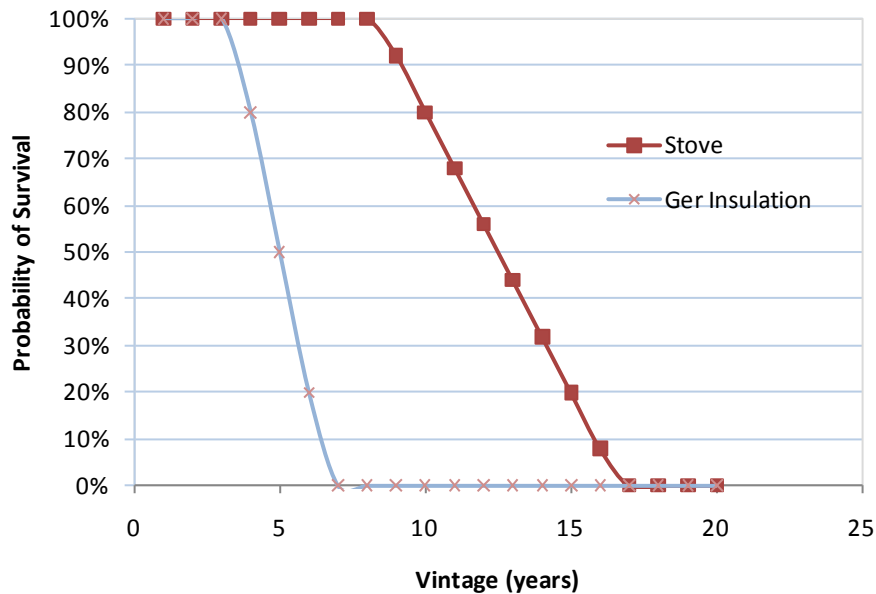
**Figure 7 Shipments Forecast of Stoves in the Ger Area**

### 6.1.1. Stock Forecast

The total stock and vintage of stoves or insulation in any given year is needed in order to calculate energy consumption and savings at the city level. The stock is calculated using a straightforward accounting method that takes each year's sales as input. For each year, some fraction of the cohort installed in previous years remains, according to a survival function. For the purposes of this analysis, the survival function is a simple curve based on the average lifetime.

Figure below shows the survival function for coal-burning stoves and insulation. According to this function none of the stoves are retired before 10 years ( $2/3$  of the mean lifetime of 12.5 years<sup>18</sup>), and all of them are replaced by 16 years ( $4/3$  of the mean lifetime). Between these limits, the probability of retirement is a straight line.

<sup>18</sup> Average life of 12.5 is based on discussions with experts and past studies.



**Figure 8 Survival Function of Ger Insulation and Stoves**

The Base Case provides a reference against which we measure the potential impacts of the High-Efficiency Case. The Base Case employed assumes no improvements in the baseline efficiency, and no change in the (inflation adjusted) retail price of the baseline units.

For the Policy Case or the High-Efficiency Case, we assume an early replacement program of stoves, insulation, and/or energy efficient homes. We consider two scenarios:

- 1) Early Replacement + ramp-up Scenario – In this scenario, the early replacement program is operational during 2010-2013 and thereafter, the market transforms gradually to a 100% market shift (i.e. all sales) to the efficient product by the year 2020;
- 2) Early Replacement + Standard Scenario – In this scenario, we assume the case where the early replacement program is operational during 2010-2013 and thereafter in 2014, efficiency standard kicks in that will shift the entire market to the efficient product. This assumption corresponds to achievement of the full cost-effective potential of efficiency improvement.

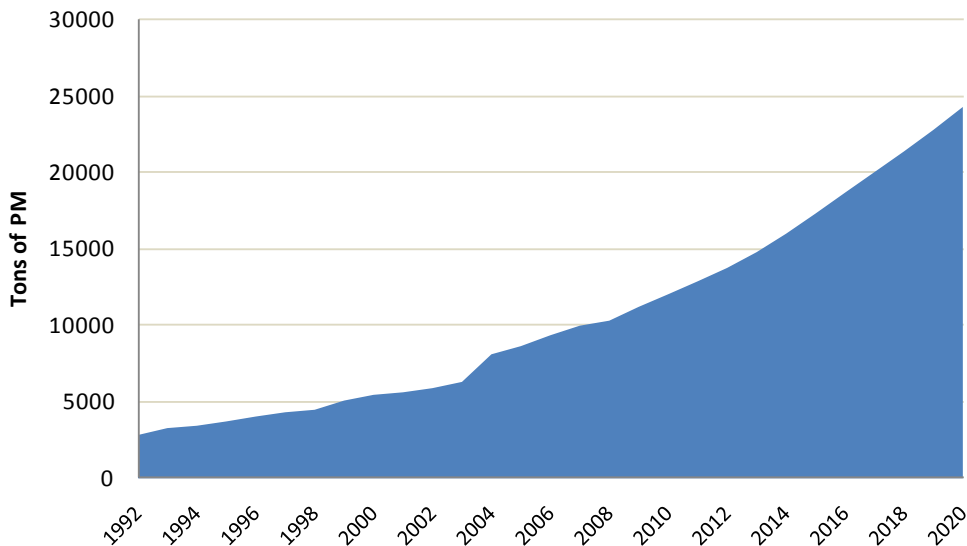
A lack of data on historical trends in efficiency makes it difficult to assess to what extent efficiency of the considered products may improve in Mongolia due to market forces.

Only a fraction of the sales (as determined by the program) is affected by the policy during 2010-20 in Scenario 1. We assume a replacement factor of 10%, 30%, and 5% of the eligible stock of stoves, insulation, and detached homes in this analysis. All sales of products during 2014-20 are affected by the policy in Scenario 2, and savings are estimated from these

products only. Sales that occur after 2020 do not affect overall savings; however, there are savings due to units that remain in the stock after this time. We do not include the energy and cost savings until the last unit shipped in 2020 is retired from the stock.

## 6.2. Base Case Forecast

Based on the shipments forecast, we estimate PM emissions in the base case that is in the absence of any program on efficiency improvement. The following figure presents the total emissions from stoves in the Ger area.



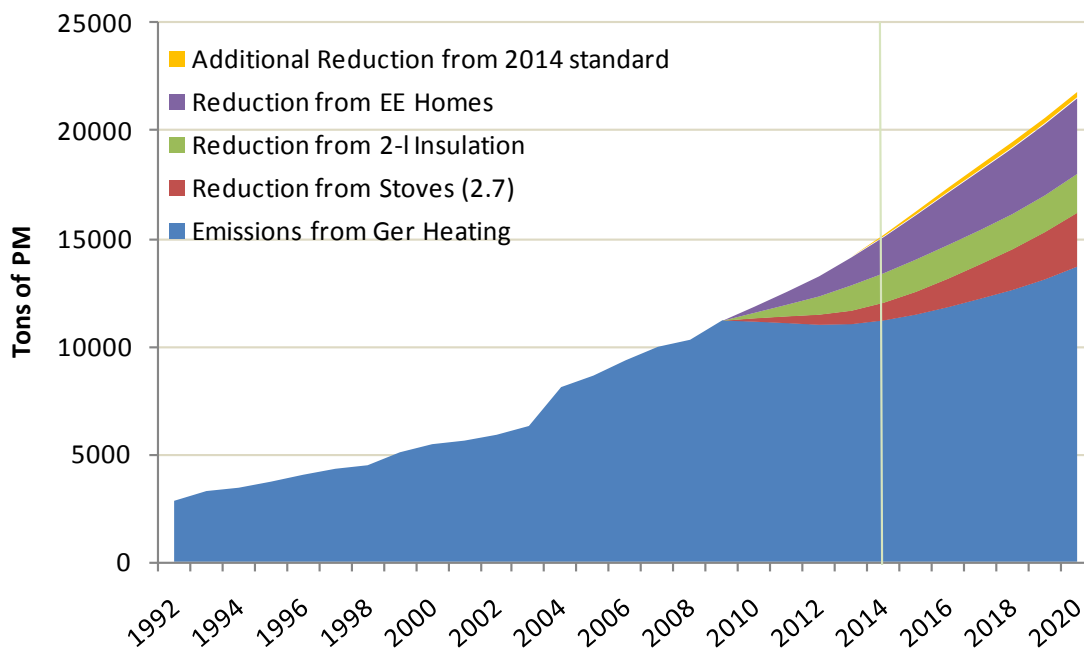
**Figure 9 Estimated PM Emissions from Stoves in the Ger Area – BAU**

## 6.3. Emissions Reduction Scenarios

The figure below illustrates emissions reduction potential for the assumed early replacement factor for the two scenarios defined earlier. For a 10%, 30%, and 5% replacement of existing stock of eligible stoves, insulation, and detached homes over 2010-2013, the city is able to reduce the total PM emissions by 25% over the base case in Scenario 1 by 2014 and 32% by 2020. These emissions reductions have associated reductions in CO<sub>2</sub> and SO<sub>2</sub> emissions. The reduction in CO<sub>2</sub> and SO<sub>2</sub> emissions amounts to about 40% compared to the base case by the year 2020. We see a larger impact on CO<sub>2</sub> and SO<sub>2</sub> emissions than on PM emissions due to the fact that the stock averages of PM factor for the insulation and EE Homes cases are lower after stove replacement, thus lowering the PM reductions. Scenario 2 of early replacement with Standards coming into effect in 2014 provides only a marginal increase in emission reductions. This is due to the optimistic assumption we make in favor of market transformation after the replacement program withdraws. In the event that the market does not transform fully or as quickly, the benefits from standards would ensure the savings



shown below. Furthermore, more aggressive emissions reduction targets are achievable from a higher replacement rate for EE homes, and less so from increasing replacements of stoves and insulation, under the current efficiency improvement levels. This is primarily due to the fact that we see the most significant improvement in efficiency from EE homes. If the program finds a stove that drove down the PM emissions further, it would be easier to accomplish deeper cuts in emissions from an aggressive stoves program. MCC's current implementation plan considers a 1% replacement of eligible stoves. Unlike the 10% replacement case, this scenario will obviously lower the overall emissions and will achieve a 20% reduction by 2014 and 27% by 2020 while maintaining the earlier insulation and EE Homes replacement.



Reductions based on 10%, 30%, and 5% replacement of existing stock of stoves, insulation, and Detached Homes over 2010-13

**Figure 10 Estimated Reduction in Emissions from Various Measures**

## 7. Conclusions, Recommendations and Discussion of Opportunities

From the perspective of having a significant impact through a large scale stove/insulation deployment program, our scenario analysis shows that a 10%, 30%, and 5% replacement of existing stock of eligible stoves, insulation, and detached homes over 2010-2013, may result in up to 32% reduction in PM emissions from stoves in the city by 2020. These reductions are achieved if either the market transforms itself into shifting entirely to more efficient

stoves by 2020, or if the government enacts a regulation on the performance efficiency of the stoves sold in the market by 2014. For a significantly deeper cut in emissions, the program may need to find stove designs that either reduce PM emissions even more drastically, or design a program that allows the residents to switch to cleaner burning fuels.

Our simple stove test procedure conducted on two traditional stoves showed that these traditional stoves had an average thermal efficiency of 58%. This result agrees well with the efficiency range of 30-80% reported in the literature for traditional stoves in Ulaanbaatar. The new stove designs tested showed efficiencies in the range 60-80%. Hence, there is potential for a significantly increased thermal efficiency in the field if the old stove stock were to be replaced by more efficient models. We also found that the new stove designs performed better in terms of PM emissions; traditional stoves showed PM emissions in the range 4-12 g/kg coal whereas the new designs yielded 1.5-4 g PM/kg coal. However, reduction of CO emissions with the new stove designs was modest. The results from the testing will be verified through field testing.

The experimental testing to date is limited to a very simple test procedure involving a single cold ignition and a single refueling. The planned field testing will provide data on how the stoves are used in the field, and this information can be incorporated in a more rigorous lab testing procedure. . For example, it is important to determine the frequency of cold ignitions because of the large contribution of these events to the total emissions. Cold ignition and refueling events reflecting field application can then be incorporated in the laboratory test procedure in order to improve the applicability of laboratory-determined emission factors to the field use of stoves.

To date the lab test procedure of stoves has been modeled after actual stove use in the field, and from this perspective it is desirable to make the test be of longer duration with several refueling. However, such long-duration tests may be impractical from a stove certification point of view especially if repeated long-duration tests show poor reproducibility. Instead, it may be desirable to have certification test conditions be limited to the more-or-less steady period of the test procedure conceivably like the EPA-mandated test procedure for wood stoves in the US. Such a testing approach is likely to have better reproducibility than the field-use mimicking approach typically used in this work.

The recent completion of the ADB-sponsored stove testing laboratory allows emission tests to be carried out on new or modified stove designs. With the capability of this lab it will be possible to determine emission factors not only with a fixed burn protocol but with variable protocols that mimic different field use patterns. Information from field use may also improve the burn protocol used in “standard” tests. Such information will be very useful to stove manufacturers who aim to improve their products. One example of a potential future development is the separation of the cooking function from the heating stoves that would lead to a different use pattern for the heating stove by, for example, reducing the frequency of cold ignitions.

Separating heating and cooking functions also potentially opens the heating end-use to alternate fuels such as electricity and LPG. The current barriers to these two alternatives include transmission and distribution infrastructure. In the case of Ulaanbaatar, a practical constraint for electric cooking appliances is the same as for electric heating namely the 10 amp current limit of the typical ger circuit. An alternative approach would be to improve the electrical grid so at least cooking with electricity becomes possible. Such a plan may also be expanded to allow electric heating which is an environmentally better solution as long as the coal-fired power plants have modern pollution control equipment or are renewably generated. However, fuel tariffs put both electricity and LPG at a comparative disadvantage with coal. Any policy to promote alternative fuels will need to address this issue.

Other potential fuels for Ulaanbaatar could include synthetic gas and liquid derived from domestic coal. Any gas option would require a gas pipeline network since gas cannot be transported in pressurized containers from a practical point of view (a very small amount of gas can be transported in a container of manageable weight). Coal derived fuels would have very favorable emission factors because the synthetic fuels are refined relative to the coal feedstock. However, coal refining plants require huge capital investments, and in the case of synthetic natural gas, a huge additional investment in gas pipelines.

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