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Utilizing Solar Energy to Reduce Air Pollution in Ulaanbaatar

A Master's Thesis submitted for the degree of
"Master of Science"

supervised by
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Affidavit

I, **ENKHCHIMEG MUNKHGEREL**, hereby declare

1. that I am the sole author of the present Master's Thesis, "UTILIZING SOLAR ENERGY TO REDUCE AIR POLLUTION IN ULAANBAATAR", 63 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
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Abstract

Ulaanbaatar, the capital city of Mongolia, is among the top 5 cities with worst air quality in the world. Particulate matter pollution is extreme during winter with $PM_{2.5}$ and PM_{10} reaching 436 μg/m^3 and 1100 μg/m^3, respectively. One of the major air pollution sources is suburban traditional housing areas called "ger districts". Households of ger districts consume approximately 850,000 tons of coal per year primarily for heating purposes, emitting tons of pollutants into the atmosphere. This thesis presents possibilities of utilizing solar energy to reduce air pollution from ger districts. Solar heating systems are inexpensive and simple. With combination of conventional heating systems it can provide reliable and stable energy and reduce fossil fuel consumption. The emission coefficient, calculated and measured by the City Air Quality Department was used to determine current total emissions and potential emission reductions from ger districts. The thesis concludes that solar heating systems have potential to reduce total coal consumption in ger districts by a factor of two and would reduce the overall emissions of PM_{10} by 6%, SO_2 by 12%, NO_X by 5% and CO by 23%.

Keywords: air pollution, particulate matter, solar energy, flat-plate solar collectors, evacuated solar collectors, "ger districts".

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Last but not least, I wish to express my deep appreciation to my boyfriend Tulga, who has been my best friend and companion during this two years of my studies. The support, encouragement, and patience you showed me is invaluable.

List of abbreviations

ADB	Asian Development Bank
CAQD	City Air Quality Department
CHP	Combined Heat and Power
DAF	Dry Ash-Free
DDS	Drain-Down System
DT	Differential Thermostat
ETC	Evacuated Tube Collector
FPC	Flat-Plate Collector
GTZ	German Technical Cooperation Agency
HOBs	Heat-Only Boilers
IRENA	International Renewable Energy Agency
NAMEM	National Agency of Meteorology and Environment Monitoring
NAQS	National Air Quality Standard
SDU	Statistics Department of Ulaanbaatar
TEOMs	Tapered Element Oscillating Microbalances
UNDP	United Nations Development Program
WHO	World Health Organization

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1 Introduction

Ulaanbaatar, the capital city of Mongolia, was established in 1639, and settled permanently at its current location in 1776. Prior to 1776, the city had changed its location several times in accordance with the nomadic traditions of the people. However, the real industrialization and construction of the city begun only in 1945 with financial and technical support from the Soviet Union. Since then the city has become the cultural and economic center of Mongolia, concentrating higher education schools, hospitals, roads and train rails. This in turn has attracted majority of the population to Ulaanbaatar in search for job opportunities, adequate health services, and better education. As a result, the city which was initially planned for 400-500 thousand inhabitants, now has become a home for 1.4 million people (CIA World Fact Book 2015). The steadily growing population has stretched the capacity of the city and has caused several social and environmental issues, such as air and soil pollution, housing shortage, inadequate healthcare and education, and immense traffic.

Numerous studies, conducted by the government and international agencies on the air quality of Ulaanbaatar city, concluded that the air pollution there has reached disastrous and harmful levels, with particulate matters surpassing the World Health Organization (WHO) guidelines by 10 to 20 times. This puts the city among the top 5 cities with the worst air qualities in the world (Guttikunda et al. 2013). While Beijing's air pollution issue has made headlines internationally, Ulaanbaatar's air quality is worse than in Beijing. Ulaanbaatar's current PM_{10} level is approximate to Beijing's and Delhi's level in the late 1990s (Allen et al. 2011).

Air pollution is one of the major environment related issues that threaten human health. According to a study by Allen et al. (2011), nearly 10% of Ulaanbaatar's total mortality is caused by air pollution annually. These 1,000 to 1,500 deaths per year do not include mortality of infants and young children. Children are particularly vulnerable to poor air quality due to immature respiratory organ systems. According to the Ulaanbaatar's Public Health Institute, incidents of birth defects have increased considerably over the past decade. Moreover, it was found that miscarriage increases by a factor of four during winter, when the emission levels peak in Ulaanbaatar (The UB Post 2016).

Main sources of air pollution in Ulaanbaatar city are: coal power plants, ger districts, heat-only boilers (HOB), vehicles and soil. Ger districts or ger areas apply to areas of the city, where people live in gers, traditional Mongolian dwellings, or small brick houses, that are not connected to the district heating systems. According to a 2013 report by the City Air Quality Department, 32% of coal combustion based emission comes from ger areas, which makes it the second biggest source of particulate pollution. Approximately 60% of Ulaanbaatar's population, i.e. about 190,000 households, reside in ger districts and each household in average consumes 5 tons of coal and 1.5 tons wood annually, primarily for space heating purposes in winter. Because majority of these areas consist of low-income households, they burn low quality, raw coal, which contribute to the severity of air pollution in the city.

Air pollution is beyond the control of individuals and requires action by public authorities at the national level. Since ger districts account for a significant share of air pollution in Ulaanbaatar, the government aims to reduce emissions from the households in ger areas by introducing heat efficient clean stoves, promoting high quality clean coals, reducing electricity price for ger districts and funding construction of low-cost apartments, which are affordable for households in ger areas. Between 2011 and 2013, 124,000 households were distributed heat efficient stoves (City Air Quality Department 2013). The intention of a heat efficient clean stove is to retain the heat for a longer period of time, so the amount of coal burned can be reduced. Another policy initiated by the government is restricting supply of low-quality raw coal and promoting washed coal and smokeless briquettes. Washed coal generates more heat, emits less pollutants, and produces twice less ash. However, it is more expensive. Furthermore, this year, the government has decided to provide free electricity for ger districts at night to promote electric heaters. Over 146,000 households were included in the discounted rate from the 1st of January to the 1st of April. The project has cost the government two million USD. Some officials are critical of the decision, arguing that it would induce residents to waste energy. Another solution for air pollution, generated by ger districts, is to eliminate these districts. Although it is the most desirable long-term solution, it's not an easy one. Ger districts cover 218 km^2 of the city while apartments account for only 58 km^2 (Engel 2015). Around 60% of Ulaanbaatar's total population live in ger areas. The government has initiated two major housing projects called “40,000 homes” and “100,000 homes” aiming to relocate ger district households to apartments. These projects are directed towards constructing low-cost apartments throughout the country, with the majority in Ulaanbaatar city; and providing below market interest rate and long term house loans to low- and middle-income households. As a result, by 2012 the construction sector has increased by 25%. For instance, between 2000 and 2011, 53,000 buildings for accommodation purposes were built within the city. Unfortunately, apartment prices have also soured. In 2005, the average price of an apartment was $ 170-250 per 1 m^2. By 2013, the price has increased by a factor of 4 to 4.7 and has reached $ 800-1000 per 1 m^2 (Engel 2015). Despite all these initiatives and actions taken by the government, the air quality in Ulaanbaatar has not been improving. Thus, air pollution still remains as one of the most troublesome and challenging issues for the residents of the city.

In this thesis I discuss possibilities to utilize solar heating systems in Ulaanbaatar to reduce air pollution generated by ger districts. Sun is the infinite source of most of our energy supplies on Earth. Solar energy is clean and sustainable. It causes fewer health hazards to humans and has less burden on the environment. Its use entails much lower greenhouse gas emissions as well as emissions of other pollutants compared to fossil fuels. There are number of technologies that use the sun's power for space heating purposes. Each case is unique and requires a specific technology that is suitable for the location and the climate. Thus, the sun's radiation, geographical and climate characteristics of the location is important in identifying the suitable technology for a specific site.

Ulaanbaatar is located in a valley slightly east of the center of Mongolia at about 1,350 meters above the mean sea level. Due to its high elevation and relatively high latitude Ulaanbaatar is the coldest capital city in the world, with an average temperature of - 0.4 Celsius degrees. Nevertheless, the city has significant solar energy potential. The average solar radiation received by the city is approximately 1,550 kWh/m^2 (Solargis.com 2017). The average duration of annual sunshine hours in the city is 2,790. Moreover, with a new vision of achieving sustainable development, the government of Mongolia has set ambitious goals to increase the share of renewable energy to 20% by 2023 and to 30% by 2030. Within this vision, the government has initiated and supported various programs to exploit the sun's energy. For instance, 100,000 small photovoltaic cells have been successfully provided to the nomadic households in rural areas to generate electricity for small electrical appliances such as radios, TVs and cellphone chargers. Also, the nation's first large-scale solar power plant, with a capacity of 10 MW, has started its operations in January. Thus, with substantial solar radiation potential and the national goals to increase renewables, Ulaanbaatar has great possibilities to utilize solar heating systems and improve its air quality.

As mentioned before, there are many methods to use solar energy in space heating. The simplest one is passive solar heating, which maximizes the capture of sunlight with the help of the design of buildings. Another method is active solar heating, which usually involves solar collectors. The solar collectors, which are usually mounted on the roofs of buildings, absorb solar energy and heat air or water that runs through it. The heated air/water is then drawn through ducts into the building transferring heat from the collectors. These systems are suitable for regions with long cold winters, abundant solar radiation and many sunny days (Thorpe 2013). Also, the system is usually used in combination with other heating systems such as electric heaters, stoves or boilers. Hence, the solar air heating systems are very suitable for suburban ger districts in Ulaanbaatar. In these households the system can be used in conjunction with the existing stoves, replacing 20 to 50% of traditional heating. Moreover, once installed, the system does not require fuels and there is no maintenance cost for 30 years. This would make the system very attractive to the low-income ger district households.

The purpose of this thesis is to find out by how much the air pollution in Ulaanbaatar can be reduced by introducing solar thermal energy technologies in ger districts. To find the answer to my research question, first, I will determine the amount of relevant emissions attributed to one ton of coal and wood combustion in ger districts. Second, I will find out by how much the coal and wood consumption can be reduced in households with solar thermal technologies. Finally, I will determine how much tons of emissions will be saved each year by replacing fossil fuels with the power of sun.

2 Air pollution in Ulaanbaatar city

2.1 Pollution levels and patterns

The air quality monitoring system in Ulaanbaatar has improved significantly in recent years. There are 10 government monitoring sites in the city at the moment. Four of them are utilized with monitoring devices that use tapered element oscillating microbalances (TEOMs), which were supplied by the German Technical Cooperation Agency (GTZ) in 2008 (Figure 1). These four sites have a capacity to monitor continuously emission levels of carbon monoxide (CO), ozone (O_3), sulfur dioxide (SO_2), nitrogen oxides (NO_x), particulate matter 2.5 ($PM_{2.5}$) and particulate matter 10 (PM_{10}). The National Agency of Meteorology and Environment Monitoring and the City Air Quality Department measure routinely emission levels of major pollutants in the city.

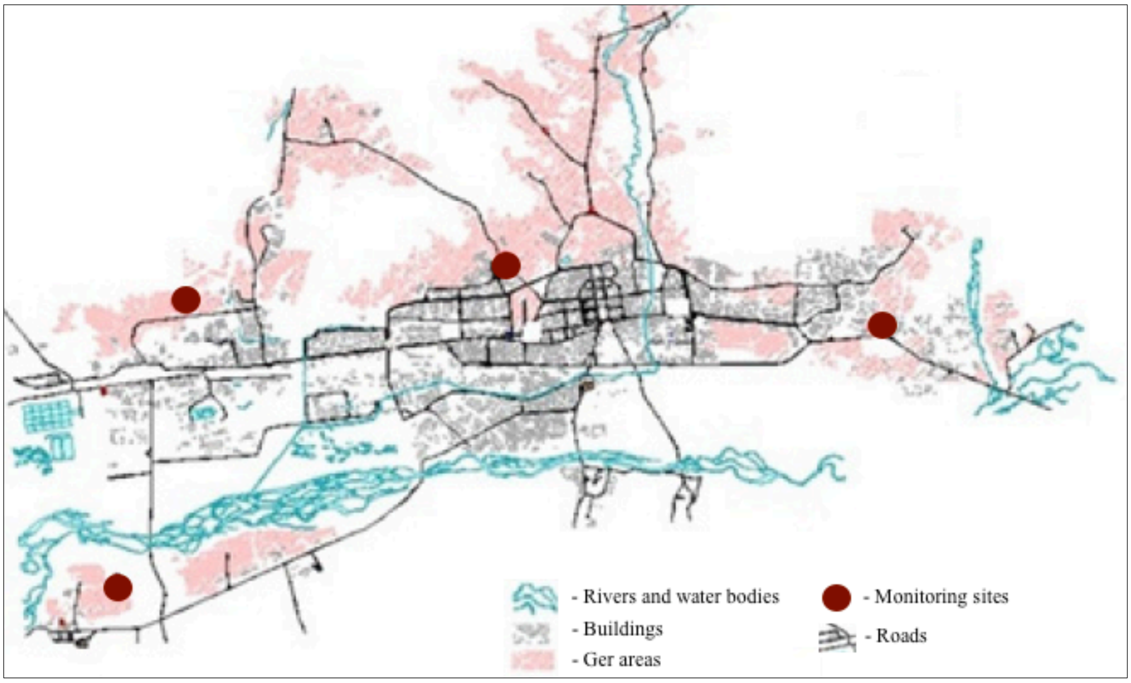

Figure 1: Tapered element oscillating microbalances (TEOMs) air pollution monitoring sites in Ulaanbaatar. *Source:* City Air Quality Department 2013, 27.

There are number of air pollution sources in Ulaanbaatar: the city's three coal-fired power plants, ger districts, heat-only boilers, vehicles and airborne soil originating from crustal matter. From these sources, low-income traditional housing districts account for 32% of coal combustion caused pollution (City Air Quality Department, 2013). Approximately 190,000 households live in ger districts and each household in average burns 5 tons of coal and 1.5 tons of wood annually for heating and cooking purposes. Thus far, previous studies have shown that high concentrations of PM and SO_2 are consistent with patterns of coal and wood combustion in ger districts. Since the purpose of this thesis is to find out by how much the air pollution from ger districts can be reduced by utilizing solar air heaters, I will focus on concentration levels and patterns of $PM_{2.5}$, PM_{10} and SO_2, majority of which result from combustion of coal.

2.1.1 Particulate matter 2.5 ($PM_{2.5}$)

$PM_{2.5}$ consists of liquid or solid particles with less than 2.5 micrometers in diameter and can damage respiratory organs when inhaled. Most $PM_{2.5}$ results from combustion activities. Allen et al. (2011) used emission data of $PM_{2.5/10}$ and SO_2 from June 1, 2009 to May 31, 2010 from the above mentioned four sites, concentrating on the site that was located in the center of the city, to characterize diurnal and seasonal patterns in pollution concentrations. The results of their study indicate that concentrations are highest in winter. During the months from December to February, when the temperature quite often drops to -30 to -40 degrees Celsius, the 24-hour mean concentration of $PM_{2.5}$ has reached 147.8±61.2 $\mu g/m^3$ (Figure 2). This is almost 6 times higher than the WHO air quality guidelines of 25 $\mu g/m^3$ (WHO 2006). Whereas in summer the mean 24-hour $MP_{2.5}$ concentration was 22.8±9.0 $\mu g/m^3$. Nonetheless the annual average concentrations of $PM_{2.5}$ was 75.1 $\mu g/m^3$, which is also significantly high compared to the WHO guideline of 10 $\mu g/m^3$ (Allen et al. 2011).

Although the WHO has chosen 10 $\mu g/m^3$ to be the annual mean guideline value for $PM_{2.5}$, it encourages more stringent guidelines where it is possible. In fact, adverse health effects have been observed at $PM_{2.5}$ concentrations of 3-5 $\mu g/m^3$ in the United States and Western Europe (WHO 2006). The guidelines are set based more on capabilities and health priorities of the countries. Moreover, as susceptibility and exposure varies widely among individuals, the guidelines promoted by the WHO are not capable of protecting each and every person. Thus, having $PM_{2.5}$ concentrations that are 6-7 times higher than the WHO guidelines in the city where the half of the country's population reside is not desirable.

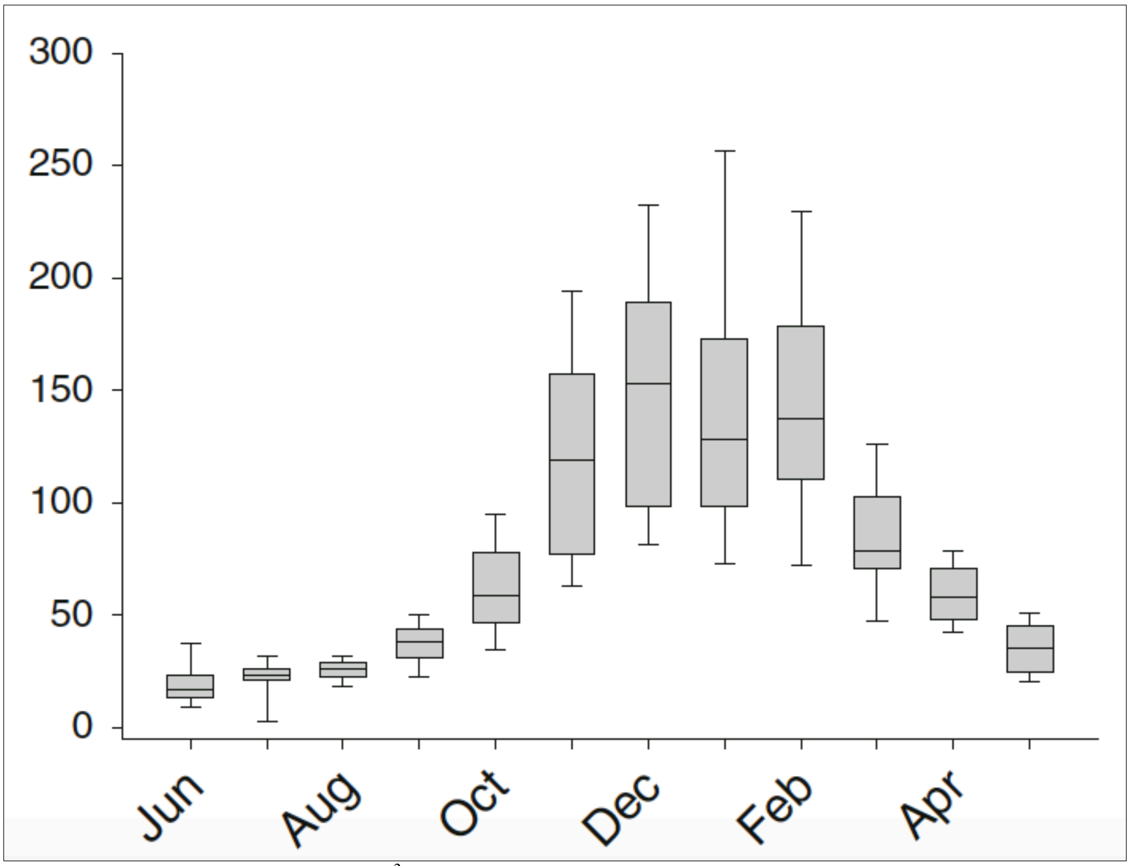

Figure 2: $PM_{2.5}$ concentration (μg/m^3) in 2008-2009. *Source:* Allen et al. 2011, 142.

Davy et al. (2011) analyzed particulate matter data from 2004 to 2008 and concluded that both $PM_{2.5}$ and PM_{10} concentrations can reach extreme levels exceeding 200 μg/m^3 at times. They also found that while particulate matter pollution was dominated by PM_{10}, high $PM_{2.5}$ concentrations were observed during winter often exceeding 100 μg/m^3. The City Air Quality Department's analysis also indicate that $PM_{2.5}$ concentrations are highest during winter. For instance, in October 2014 the 24-hour mean concentrations of $PM_{2.5}$ were measured 62 times and 48% of them were above the National Air Quality Standard, which is 50 μg/m^3 for $PM_{2.5}$ 24-hour mean. The concentrations have increased in the following months. In November from 59 values 76%, in December from 60 values 92%, in January from 59 values 97% of the concentration data was above the National Air Quality Standard. When the 2014 monthly average concentrations of $PM_{2.5}$ were compared to the National Air Quality Standard, in October the concentrations were by 1.1 times, in November by 1.8 times, in December by 2.9 times and in January by 3.1 times higher than 50 μg/m^3 (Figure 3). In winter 2015, the highest 24-hour mean value of 436 μg/m^3 was recorded in the city center, and in winter 2016 the highest value recorded was 546 μg/m^3, also in the center of the city (The National Agency of Meteorology and Environment Monitoring 2016). This is 8.7 and 11 times higher than the National Air Quality Standard respectively.

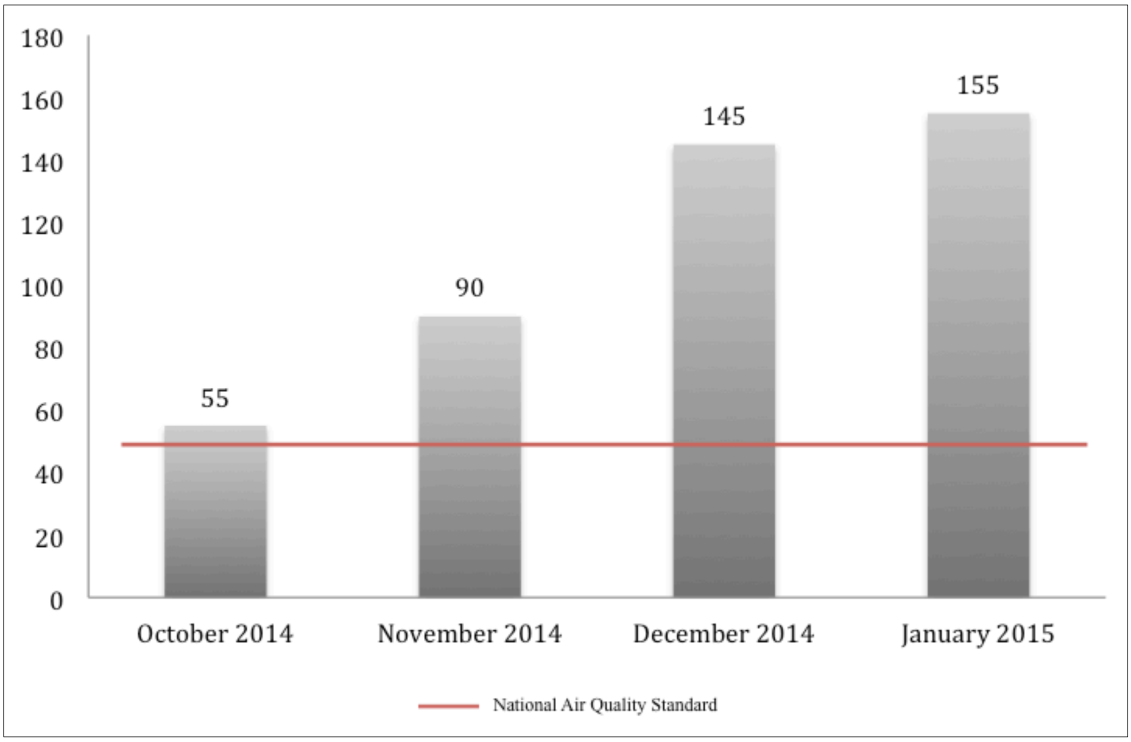

Figure 3: $PM_{2.5}$ concentration (μg/m^3) in 2014-2015. *Source:* Data from the National Agency of Meteorology and Environment Monitoring 2016, 3.

Besides seasonal variation, Allen et al. (2011) observed diurnal differences in the $PM_{2.5}$ concentration. Pollution levels peaked in the morning and in the evening at different hours in summer and winter. As shown in Figure 4, $PM_{2.5}$ concentration peaked in the morning between 08:00 and 10:00 o'clock, both in summer and winter. However, the evening peak hours are not the same in summer and winter. In the summer, the concentrations were highest during 20:00 and 23:00, while in winter the peak occurred approximately between 22:00 and 02:00 and continued a little longer than in summer. This variation is possibly caused by more coal burning in the ger districts in the morning and the evening compared to the hours of the afternoon, when the majority of the inhabitants are at work and school. Moreover, diurnal variations are highly correlated with the intensity and depth of temperature inversion in winter. For instance, Batmunkh et al. (2013) observed high concentrations in the morning and low in the evening in January 2008 when the intensity of temperature inversion was twice as high in the morning than in the evening. The concentration fluctuated between 24.4 μg/m^3 and 211.1 μg/m^3.

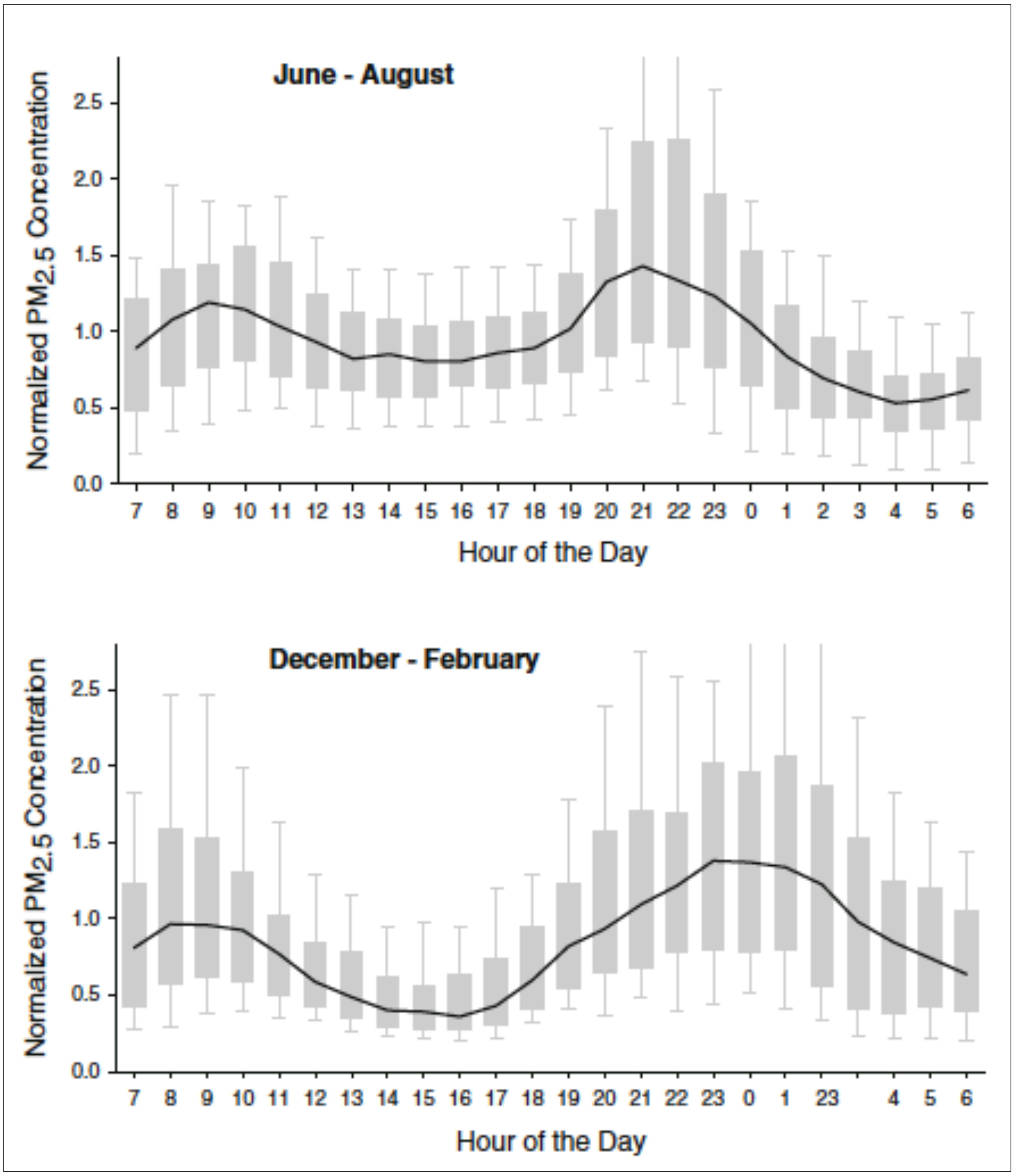

Figure 4: Diurnal variation of $PM_{2.5}$ concentration during summer and winter 2008-2009. *Source:* Allen et al. 2011, 143.

To sum up, the annual average $PM_{2.5}$ concentrations are considerably high in Ulaanbaatar. This is because of the extremely high concentration levels during winter, reaching 150 µg/m^3 in the center of the city and even higher levels in the suburban ger areas. The concentration levels also vary during the hours of the day, the most concentrations occurring in the morning and in the evening. In winter, the peaks occur later in the day and last longer than in summer. These high levels of $PM_{2.5}$ pollution threaten health and well-being of the population. Because of their very small size these particles can penetrate deep into lungs and damage respiratory systems. Since, Ulaanbaatar shelters half of the country's population, high concentrations of $PM_{2.5}$ represent a major threat to the public health and a greater challenge to the government. The high concentrations of $PM_{2.5}$ are mainly caused by coal combustion in the city's power plants and ger districts. Also, cold temperatures and inversion hinder the dispersion of emissions and contribute to the accumulation of pollutants. These explain the seasonal and diurnal variations in the concentration levels. The sources of the air pollution will be discussed more in detail in the Part 2.2 of this thesis.

2.1.2 Particulate matter 10 (PM_{10})

PM_{10} consist of particles less than 10 micrometers in diameter, which can penetrate into lungs and cause serious health issues. Most PM_{10} pollution is dust and soot. Air particulate matter pollution in Ulaanbaatar is dominated by PM_{10}. During the four years of sampling from 2004 to 2008, Davy et al. (2011) recorded some shocking concentrations of 1,100 $\mu g/m^3$. Although the authors assume that there might have been some uncertainty in the samples at such extreme levels due to the potential filter clogging, later data from the National Agency of Meteorology and Environment Monitoring also indicate incidents when the concentration levels reached 1,100 $\mu g/m^3$ in suburban districts. This is 22 times higher than the WHO guideline for PM_{10} 24-hour mean, and 11 times higher than the National Air Quality Standard.

According to the WHO, for each 10 $\mu g/m^3$ increase in the daily concentration of PM_{10}, mortality increased by around 0.5% in both developed and developing countries. Consequently, the WHO recommends immediate mitigation actions if the concentrations reach 150 $\mu g/m^3$ (WHO 2006). However, in Ulaanbaatar the concentrations quite often exceed 300 $\mu g/m^3$ (Davy et al. 2011). This translates to roughly 12% increase in daily mortality. The annual average PM_{10} concentration in central Ulaanbaatar is 165 $\mu g/m^3$, which is more than the concentration levels in Mexico city and Buenos Aires (Allen et al. 2011). WHO guideline for annual mean PM_{10} concentration is 20 $\mu g/m^3$ and the Mongolian National Air Quality Standard for annual mean concentration is 50 $\mu g/m^3$.

Seasonal and diurnal patterns of PM_{10} concentration more or less resemble patterns of $PM_{2.5}$, i.e. concentrations are highest during winter and the diurnal peaks occur in the morning and in the evening. According to the National Agency of Meteorology and Environment Monitoring (2016), the 24-hour mean of PM_{10} concentration in October 2014 has exceeded the National Air Quality Standard in 83% of the measurements. In

November and December it has exceeded in 89%, in January 2015 in 75% of the measurements. Also, the average 24-hour mean concentrations of PM_{10} in October were by 1.7 times, in November and December by 2.3 times, and in January by 2.6 times higher than the National Air Quality standard, which is 100 μg/m^3 (Figure 5). In 2015, the highest 24-hour mean concentration of 1,101 μg/m^3 was recorded in January in the eastern suburban ger areas of the city.

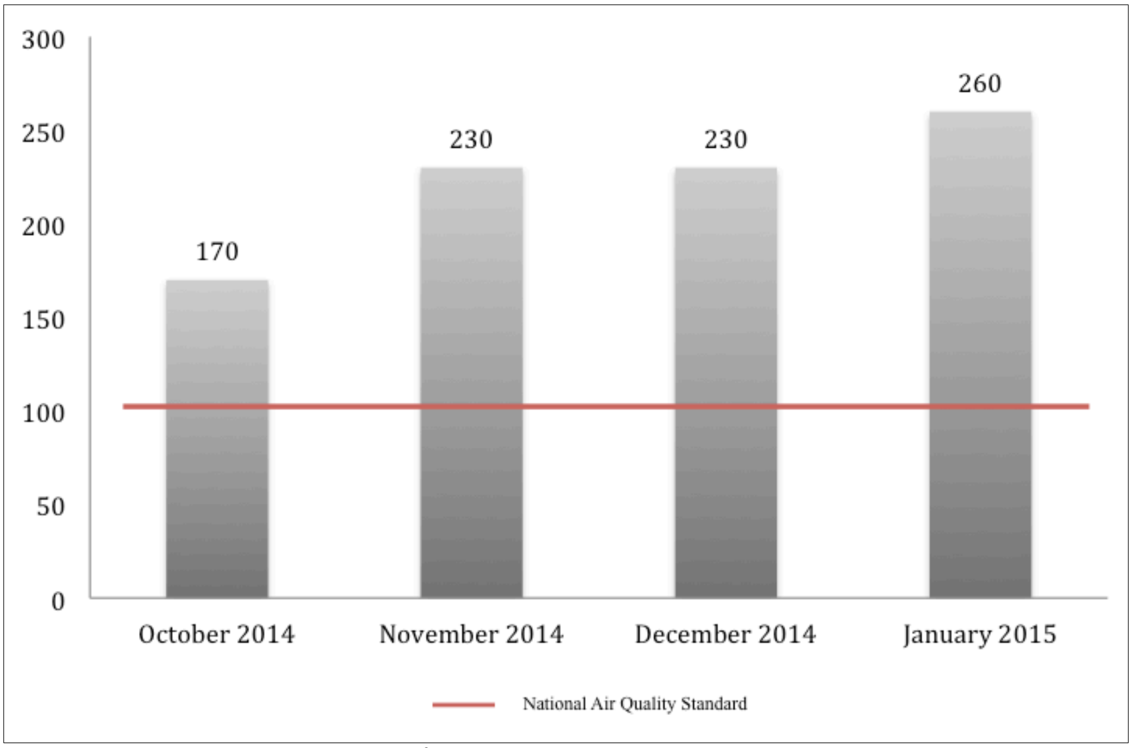

Figure 5: PM_{10} concentration (μg/m^3) in 2014-2015. *Source:* Data from the National Agency of Meteorology and Environment Monitoring 2016, 2.

Compared to the $PM_{2.5}$ concentrations, the PM_{10} concentrations tend to be high in spring and autumn as well (Figure 6). This is because spring and autumn are extremely dry and windy in Mongolia, as most of the precipitation falls in summer. Consequently, crustal matter contributes to the PM_{10} concentrations during these seasons, with coal ash contributing in winter.

In addition to the seasonal variation, clear diurnal variations were also observed in the data accumulated between 2014 and 2015 by Sonomdagva, Batdelger and Chuluunpurev (2016). For instance, the PM_{10} concentrations varied between 179.1 μg/m^3 and 32.49 μg/m^3 in the eastern part of the city, while in the southern part of the city concentration varied between 41.23 μg/m^3 and 18.17 μg/m^3. The peaks usually occurred twice a day: in the morning and in the evening. The lowest concentrations are observed in the afternoons (Figure 7).

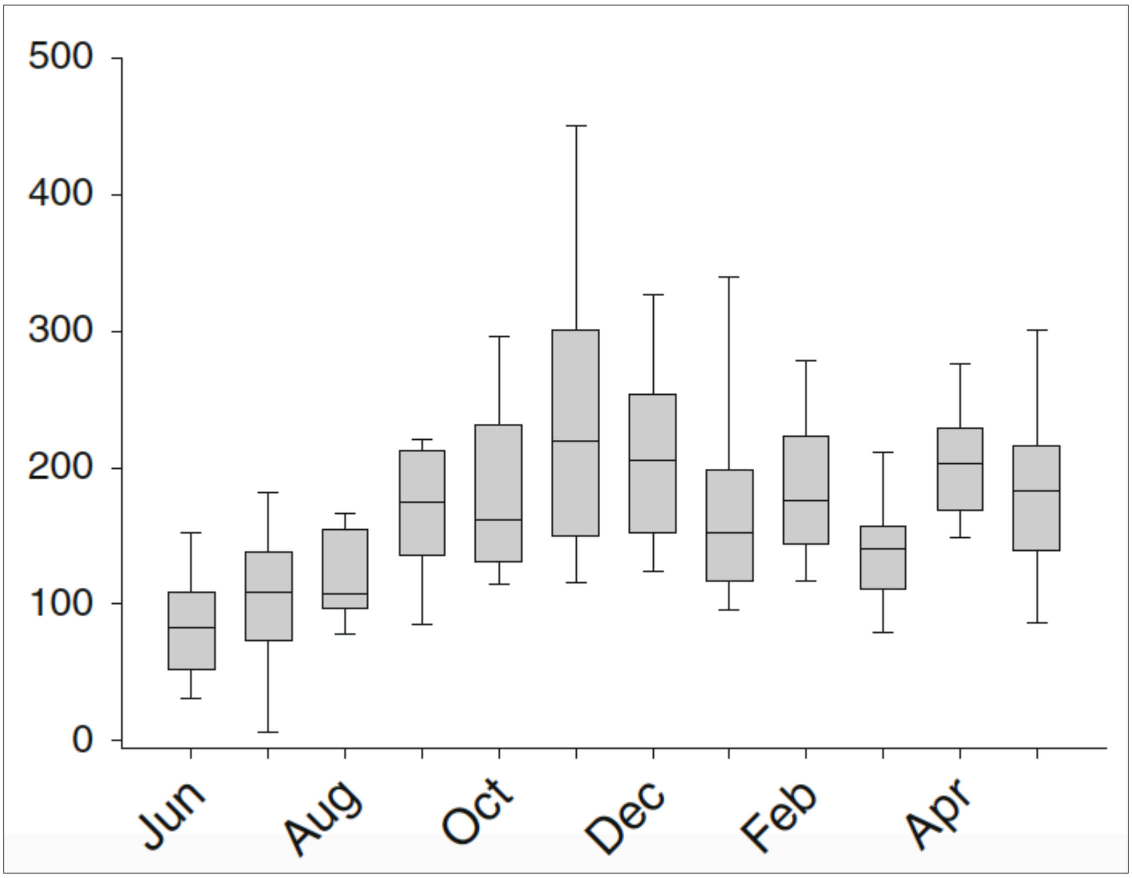

Figure 6: PM_{10} concentration (μg/m^3) in 2008-2009. *Source:* Allen et al. 2011, 142.

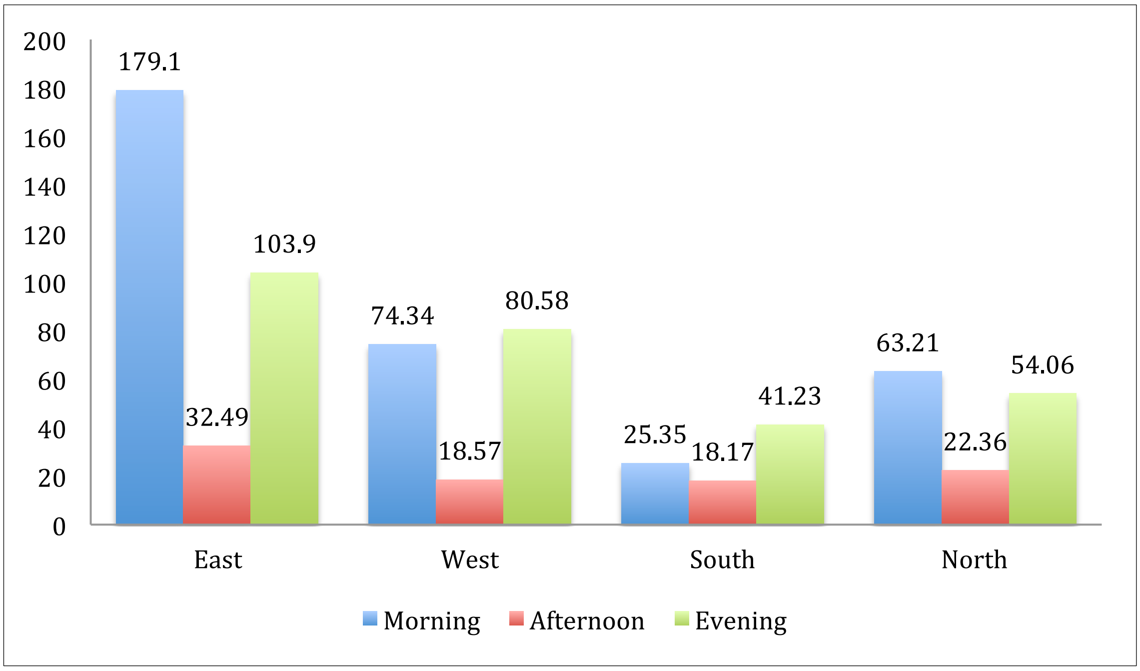

Figure 7: Diurnal variation of PM_{10} concentration in the 4 parts of the city in 2014. *Source:* Sonomdagva, Batdelger, and Chuluunpurev 2016, 828.

In brief, coarse particulate matter concentrations in Ulaanbaatar is extremely high with 24-hour mean reaching 1,100 μg/m^3 and exceeding 300 μg/m^3 for many days. There is a seasonal variation with concentrations peaking in winter, and a diurnal variation with peaks occurring in the morning and in the evening. The PM_{10} concentrations also tend to be high in the spring and autumn, when the weather is dry and windy. Concentration variations are strongly correlated with coal combustion patterns of ger district households, as well as weather and temperature inversion conditions in the city.

2.1.3 Sulfur dioxide (SO_2)

SO_2 is a colorless gas that mainly result from coal combustion. During combustion, elemental sulfur in coal reacts with oxygen and forms SO_2. Short-time exposure to this gas can cause respiratory ailments, breathing difficulty and premature death. Moreover, SO_2 can participate in formation of PM pollution, which is also harmful to human health. Besides adverse health effects, SO_2 damages environment by forming sulfur trioxide (SO_3) and sulfuric acid (H_2SO_4), which then settle back to Earth as acid deposition.

Starting 1996, SO_2 concentrations have been continuously measured and recorded by the National Agency of Meteorology and Environment Monitoring throughout Mongolia. A very interesting study by Luvsan et al. (2012) showed that annual average SO_2 concentration has increased from 6.04 $\mu g/m^3$ to 21.48 $\mu g/m^3$ in Ulaanbaatar from 1996 to 2009 (Figure 8). Since the population of the city has doubled during this period of time, the authors believe that immense increase in SO_2 concentrations were significantly contributed by the rapid increase in population number. Also, in this 13-year analysis, the highest concentrations were recorded in winter, during December and February. The highest and lowest concentrations in the city varied between 26.01 $\mu g/m^3$ in December and 3.61 $\mu g/m^3$ in July.

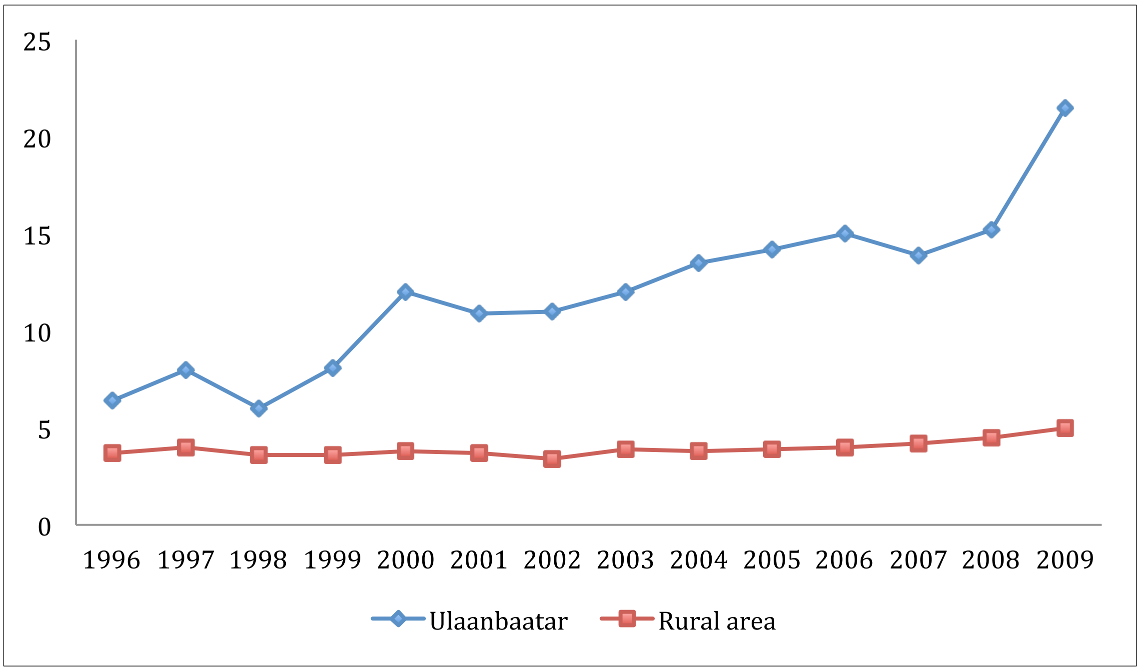

Figure 8: Annual average SO_2 concentrations (µg/m^3) in Ulaanbaatar and rural areas from 1996 to 2009. *Source:* Luvsan et al. 2012, 546.

Recent measurements by the National Agency of Meteorology and Environment Monitoring (2017), however, indicate higher SO_2 concentrations during winter compared to Luvsan et al., values exceeding 80 µg/m^3 in January 2014 and reaching 70 µg/m^3 in January 2015 (Figure 9). The Agency measured concentrations 220 times in October 2015, and 17% of them exceeded the National Air Quality Standard. However, in November the concentrations increased dramatically and 85% of 186 values were above the standard. In December, 90% of the measurements, in January and February 2016, 95% and 92% of the measurements were above the National Air Quality Standard, respectively. The Mongolian National Air Quality Standard for 24-hour mean concentration of SO_2 is 20 µg/m^3, which is equal to WHO guideline for this gas. As for the diurnal variations of the SO_2 levels, peaks normally occur in the morning approximately between 07:00 and 09:00, and at night from 21:00 to 00:00 o'clock.

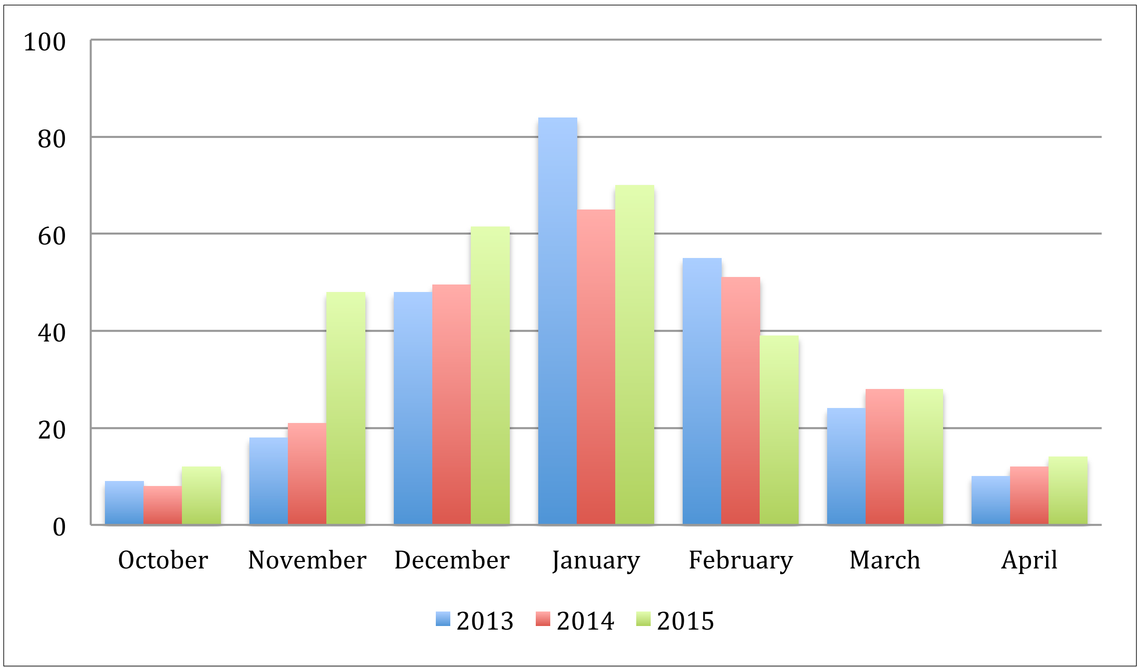

Figure 9: Seasonal variation of SO_2 concentrations (μg/m^3). *Source:* National Agency of Meteorology and Environment Monitoring 2017, 4.

In 2015, the highest 24-hour mean concentration of 309 μg/m^3 was observed in winter in the eastern suburban ger district called "100 ail". This is 15 times higher than the National and the WHO guidelines. Although there is still significant uncertainty to the SO_2 direct health effects, studies in a number of cities throughout the world found a correlation between SO_2 concentrations and daily mortality rate. For instance, in 12 Canadian cities with an average concentration of 5 μg/m^3 and the highest average concentration of 10 μg/m^3, considerable association between SO_2 levels and daily mortality was observed. Same association was studied in more than 100 metropolitan areas in the United States, with mean SO_2 concentration of 18 μg/m^3 and the highest mean concentration of 85 μg/m^3. Thus, the population of Ulaanbaatar is constantly exposed to extremely dangerous levels of SO_2.

2.1.4 Conclusion

Extremely high concentrations of particulate matter pollution places Ulaanbaatar among the most polluted cities in the world. In 2015, 24-hour mean concentrations of PM_{10} and $PM_{2.5}$ reached 1,100 μg/m^3 and 436 μg/m^3, respectively. The SO_2 concentrations were also very high, peaking to 309 μg/m^3. There are distinct seasonal variations for these pollutants, concentrations reaching extremely high levels and constantly exceeding the National Air Quality Standards during winter (Figure 10). In addition to seasonal variations, concentration levels also vary diurnally, peaks occurring in the morning between 07:00 and 10:00, in the evening between 21:00 and 02:00.

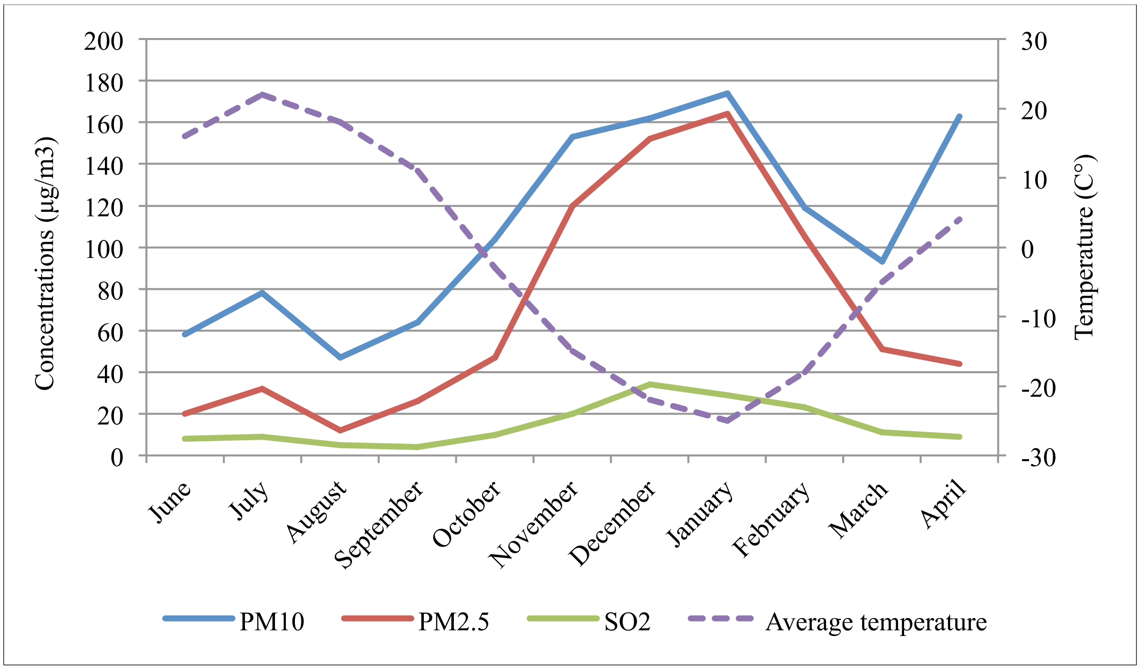

Figure 10: PM_{10}, $PM_{2.5}$, and SO_2 concentrations and average temperature in Ulaanbaatar from June 2016 to April 2017. *Source:* Data from Air Quality Department, available from: http://agaar.mn/index and https://www.worldweatheronline.com/ulaanbaatar-weather-averages/ulaanbaatar/mn.aspx

Since, ger districts account for 32% of air pollution in Ulaanbaatar, the seasonal and diurnal patterns of these pollutants are consistent with coal combustion behavior in ger districts. The ger district households burn coal to heat their homes. This means that coal is burned in these areas mainly during winter and in the coldest hours of the day, which is in the morning and in the evening. In addition to the characteristics of the emission sources, meteorological conditions during winter contribute to the pollution concentration in Ulaanbaatar. The city is located in a river valley and surrounded by mountains. Consequently, it frequently experiences thick inversion layer of 629-809 meters during the cold seasons (Batmunkh et al. 2013). Strong inversion intensity and thickness generally observed in the morning, corresponding to high concentration of air pollution in Ulaanbaatar.

Air pollution poses a significant threat to public health in Ulaanbaatar. Study by Allen et al. (2011) attribute 10% of the city's overall mortality, excluding mortality of infants and young children, to the air pollution. According to the Ulaanbaatar's Public Health Institute, incidents of birth defects and miscarriage have increased considerably in winter (UB Post 2016). Moreover, in recent years patients suffering from respiratory diseases doubled and incidents of developing any kind of allergy has increased. The

World Bank claims that Mongolia spends $420 million annually on air pollution induced diseases and health problems (Branigan 2013).

2.2 Sources of air pollution

Up to now, previous studies have identified number of sources of air pollution in Ulaanbaatar. The key contributors to ambient air pollution are power plants, ger districts, heat-only boilers, vehicles and dust. From these, the city's power plants account for the significant part of SO_2 and PM_{10} pollution, followed by the ger districts. Soil originated from crustal matter also contributes considerably to the PM_{10} pollution (Figure 11). Much of the research on air pollution in Ulaanbaatar focus on particulate matter emissions and identify ger districts as the major source of particulate pollution. For instance, the City Air Quality Department (2013) attributes 60% of $PM_{2.5}$ emissions to the ger districts. Similarly, Davy et al. (2011) suggest that fine particulate matter pollution is dominated by the combustion of coal for domestic heating purposes. Guttikunda et al. (2013) name the coal and wood combustion in households as the "single largest source of particulate pollution in Ulaanbaatar". However, as shown in Figure 11, data from the City Air Quality Department indicates the power plants as the largest emitter of PM_{10}, as well as other pollutants.

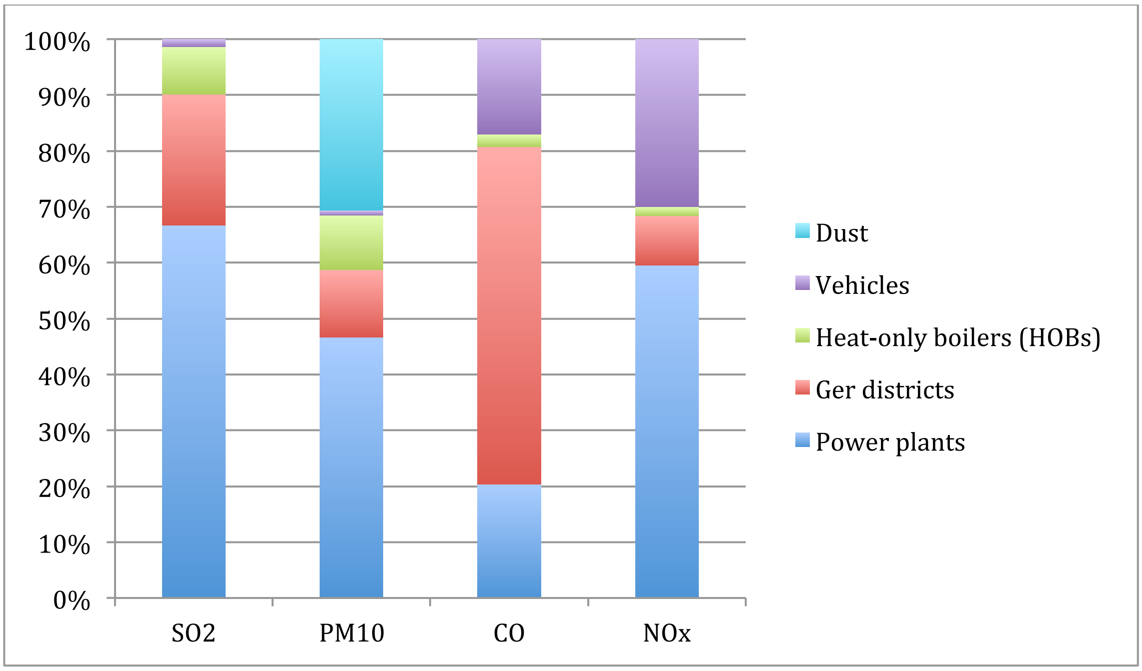

Figure 11: Contribution of emission sources in Ulaanbaatar. *Source:* Data from the City Air Quality Department 2013, 10.

2.2.1 Power plants

The three largest coal-fired Combined Heat and Power (CHP) Plants were originally built at the outskirt of Ulaanbaatar between 1960s and 1970s. However, as the city grew bigger, the power plants were engulfed in it and became the major source of air pollution in the city (Figure 12). Today the plants are the main suppliers of district heating and suffice 80% of energy needs in Ulaanbaatar. They consume approximately 3 to 4 million tons of coal per year (Table 1), operating at a higher load during winter, and emit 16 kilotons of PM_{10}, 19.6 kilotons of SO_2, 15.5 kilotons of NO_X, and 136.6 kilotons of CO (Table 3).

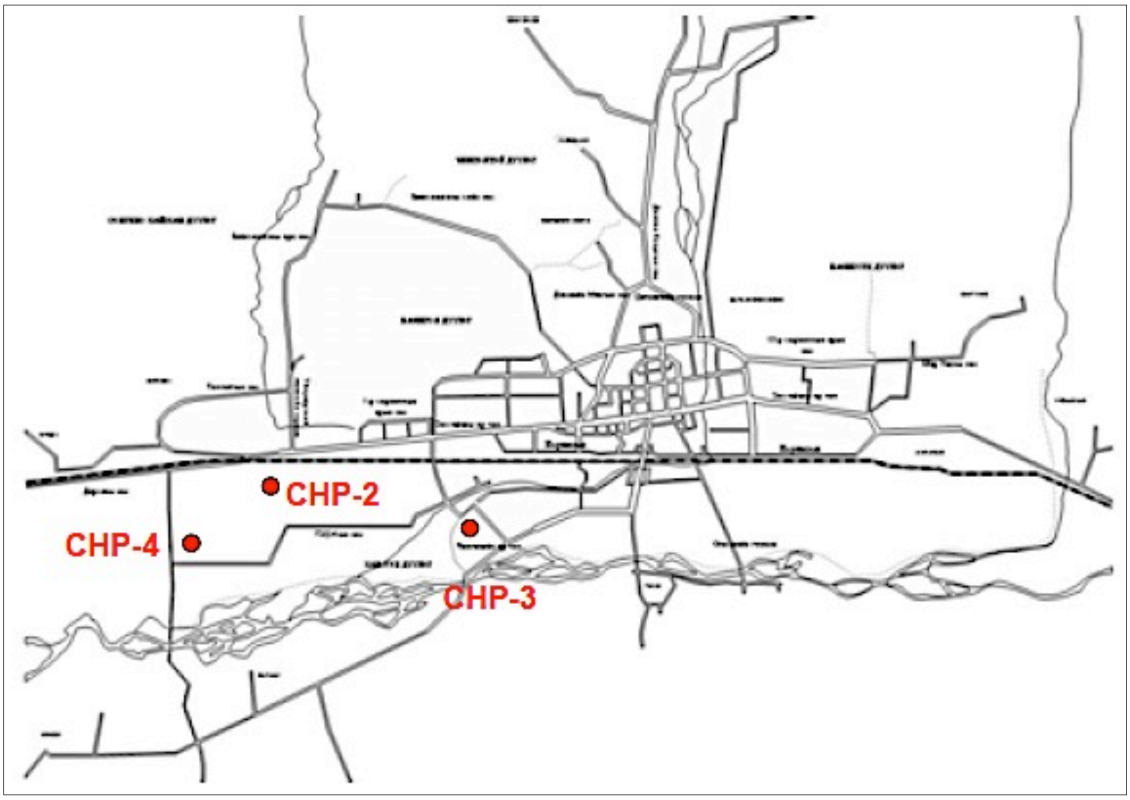

Figure 12: Combined Heat and Power (CHP) Plants locations in Ulaanbaatar. *Source:* Guttikunda 2007, 39.

Table 1: Annual coal consumption (t/y) of power plants in Ulaanbaatar (base year: 2011). *Source:* City Air Quality Department 2013, 47.

Power plants	Coal consumption (ton/year)
CHP-2	190 210
CHP-3	1 035 953
CHP-4	2 879 677
Total	**4 105 840**

Table 2: Power plants emission coefficient (kg/t). *Source:* Data from the City Air Quality Department 2013, 47.

Power plants	Emission coefficient (kg/ton)			
	PM_{10}	SO_2	NO_X	CO
CHP-2	14.95	3.30	0.97	41.00
CHP-3	7.54	12.20	3.98	124.37
CHP-4	1.89	2.20	3.90	0.00

Table 3: Annual power plants emissions (t/y). *Source:* Calculated by the author (Emissions = Annual coal consumption × Emission coefficient).

Power Plants	Emissions (ton/year)			
	PM_{10}	SO_2	NO_X	CO
CHP-2	2 843.64	627.69	184.50	7 798.61
CHP-3	7 811.09	1 2638.63	4 123.09	128 841.47
CHP-4	5 442.59	6 335.29	11 230.74	0.00
Total	**16 097.31**	**19 601.61**	**15 538.34**	**136 640.08**

The power plants 2 and 3 clean their flue gas with wet scrubbers, power plant 4 operates an electrostatic precipitator. However, according to the report by Guttikunda (2007), pollution control technologies in the power plants have low efficiencies. Moreover, the fly ash or sludge from the scrubbers and electrostatic precipitator are collected and disposed into ash ponds near the plants. The ponds are not covered and not treated. Consequently, the ash erodes and rises back into the atmosphere, further contributing to the air pollution.

2.2.2 Ger districts

Another major source of air pollution in Ulaanbaatar are undeniably the low-income traditional housing areas, which are called “ger districts”. Ger is a traditional Mongolian yurt, made of wooden frame and several layers of wool felts. It is a very cheap construction that can be dismantled and moved around to different locations. Although the areas are traditionally called ger districts, only half of the households actually live in traditional gers. Today, the ger districts comprise of various types of housings, including gers and one-story small houses built with various materials such as wood, bricks, concrete and cement blocks (Figure 13). Also, the word “districts” in this case does not mean actual administrative subdivision. Ulaanbaatar is divided into 9 districts, and each district is a mix of modern residential buildings and so called ger districts. Since this housing areas are not connected to the district heating systems, their residents burn coal and wood for space heating purposes in winter, creating severe air pollution problems for the whole city.

Figure 13: Ger districts in Ulaanbaatar. Source: http://grandpoohbah.blogspot.co.at/2013/12/ulaanbaatar-ger-district.html.

Ulaanbaatar's total population as of 2015 is 1.4 million (CIA World Factbook). Due to continuous immigration from neighboring provinces, the city's population is growing steadily with a 5% growth rate (Guttikunda 2007; City Air Quality Department 2013). About 60% of the total population, i.e. approximately 190,000 households, reside in ger districts (Figure 14). From these 190,000 households, 54.5% reside in small houses and 44.3% live in traditional gers (City Air Quality Department 2013). However, the number of households does not directly correspond to the number of stoves in ger districts. This is because some households have two stoves in their houses, or some households have two or more gers and houses. According to Guttikunda (2007), the total number of stoves is at least 30% more than the total number of households in the ger areas. In 2011, the ger districts were estimated to have 201,400 stoves (City Air Quality Department 2013). Nonetheless, the consumption of coal and wood is usually attributed to the households but not to the stoves.

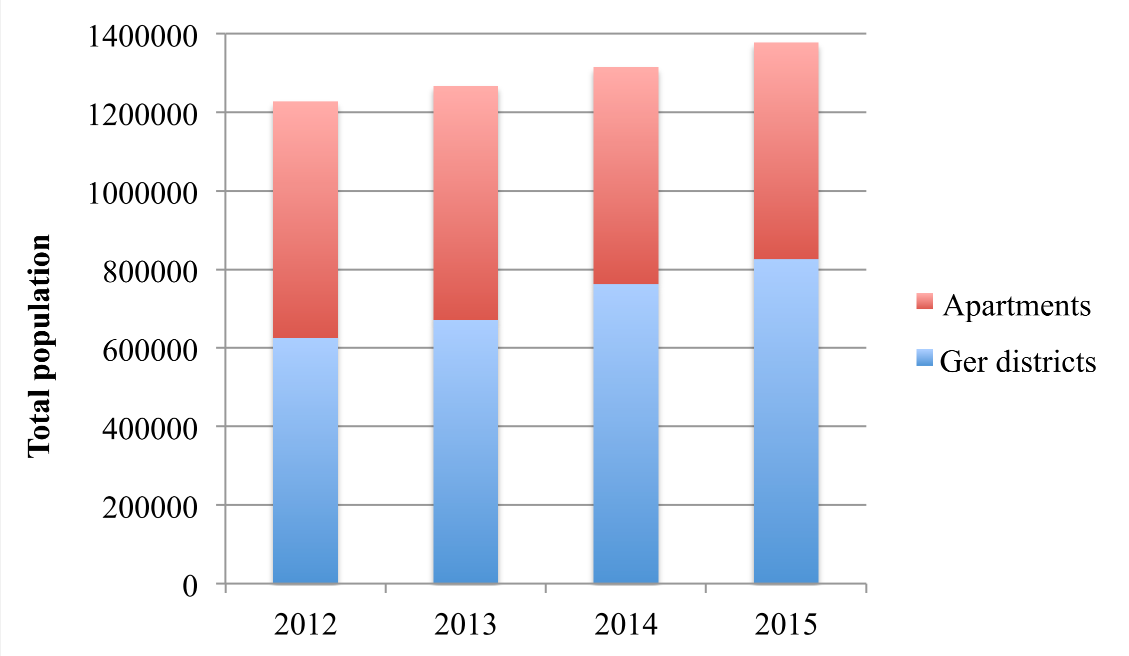

Figure 14: Share of the population living in ger districts and apartment buildings. *Source:* Statistics Department of Ulaanbaatar, available from: http://www.ubstat.mn/Upload/Reports/niisleliin_khun_amiin_oron_suutsnii_khangamj_2012_ulaanbaatar_2013-04.pdf

Traditionally, residents of ger district use coal and fuel wood for heating needs. But the lowest income households also consume unconventional fuels such as rubber from old tires and bricks dipped in coal tar. Lack of adequate data on the usage of these materials adds to the uncertainty of emission levels from ger districts. It is estimated that each household consumes 3 to 5 tons of coal and 1.5 tons of fuel wood per year, and all the households in ger districts in total consume approximately 850,000 tons of coal and 285,000 tons of firewood annually (Table 5). Most of the coal is consumed during winter, while wood is mostly used in summer and in late spring (Figure 15). Consequently, each year ger districts emit significant amount of pollutants into the atmosphere (Table 6), making it the second biggest air pollution source in Ulaanbaatar.

Table 4: Ger district emission coefficient (kg/t). *Source:* Data from the City Air Quality Department 2013, 54.

Fuel	Emission coefficient (kg/ton)			
	PM_{10}	SO_2	NO_X	CO
Coal	3.3	7.5	2.4	173.34
Wood	3.82	0.008	1.2	69.2

Table 5: Annual fuel consumption (t/y) of ger districts in Ulaanbaatar (base year: 2011). *Source:* Data from the City Air Quality Department 2013, 54.

Fuel	Fuel consumption (ton/year)	
	One household	Total households
Coal	3-5	850 000
Wood	1.5	285 000

Table 6: Annual ger district emissions (t/y). *Source:* Calculated by the author (Emissions = Annual fuel consumption × Emission coefficient).

Fuel	Emissions (ton/year)			
	PM_{10}	SO_2	NO_X	CO
Coal	2 805	6 375	2 040	147 339
Wood	1 088	2	342	19 722
Total	**3 893**	**6 377**	**2 382**	**167 061**

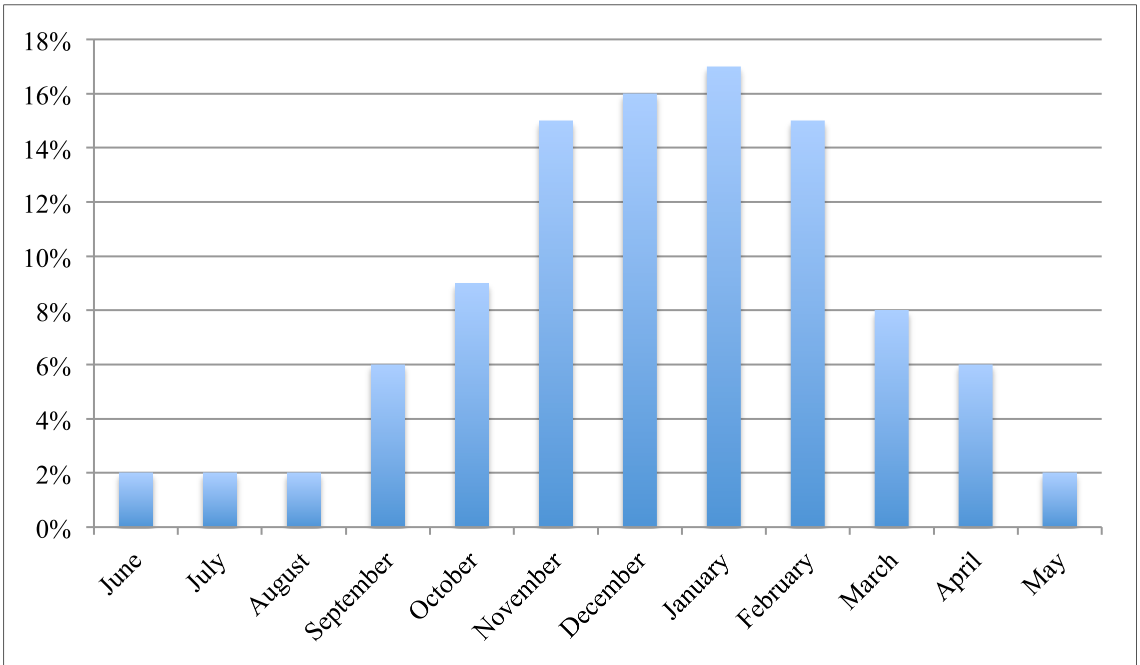

Figure 15: Ger household annual coal consumption cycle. *Source:* Data from Guttikunda 2007, 34.

The coal mainly comes from two major coal mines: Nalaikh and Baganuur mine, which are located 45 km and 130 km from Ulaanbaatar. Baganuur mine coal is the cheapest available coal in Ulaanbaatar. But customers claim that it has high ash content and low calorific value. On the contrary, coal from Nalaikh mine is more expensive, but customers believe it to have high calorific value and low ash content. However, the elemental analysis of coal from these two mines by the City Air Pollution Reduction Agency indicate the contrary (Table 4). The coal price fluctuates depending on the temperature. The colder it gets, the higher the price will go. In 2016, one ton of coal cost between 26.0 to 34.0 Euros.

Table 7: Elemental analysis of coal from two main coal suppliers in Ulaanbaatar. *Source:* City Air Pollution Reduction Agency, http://aprd.ub.gov.mn/medee/bolovsruulsan-tulsh/172-2013-06-05-07-00-26.html.

	Elemental Analysis							
	Heat value H_u (MJ/kg)	**Water W^r (%)**	**Ash A^r (%)**	**Sulfur S^r (%)**	**Carbon C^{daf} (%)**	**Hydrogen H^{daf} (%)**	**Nitrogen N^{daf} (%)**	**Oxygen O^{daf} (%)**
Nalaikh mine	14.65	22	24	0.7	63.98	4.63	2.78	27.3
Baganuur mine	14.72	33	12	0.9	72.3	4.55	0.91	21.67

2.2.3 Heat-only boilers (HOBs)

Unlike combined heat and power (CHP) plants, which produce heat and electricity, heat-only boiler (HOB) stations produce only thermal energy. Thus, they are used in small towns and isolated areas, where extension of district heating systems is not feasible. In Ulaanbaatar, there are 108 such stations operating 215 HOBs with a capacity of higher than 500 kW (City Air Quality Department 2013). In addition to these large HOBs, there are 1000 small HOBs with capacity of less than 500 kW (Figure 16). Over 95% of the boilers are used in state or municipal properties, and less than 5% are owned privately. Boilers ranging from 100 kW to 500 kW are installed in schools, small hospitals, small administrative and office buildings, and small residential buildings with up to 200 flats. Boilers with a capacity ranging from 500 kW to 30 MW are used in larger administrative and hospital buildings, and for medium to large size district heating (Nexant 2004).

These HOBs are another major source of air pollution in Ulaanbaatar, consuming approximately 170 kilotons of coal per year and emitting 3,3 kilotons of PM_{10}, 1,3 kilotons of SO_2, 0,3 kilotons of NO_X and 11,1 kilotons of CO per year (Table 8 and 10). Over 80% of the HOBs are manufactured either in Mongolia or are Russian-made models and operate with low efficiency of around 40%. Most of the auxiliary equipment are aged and in poor operating condition. Also, it is estimated that about 70% of them utilize pollution technologies (Guttikunda 2007).

Use of HOBs in Ulaanbaatar has been increasing due to the rapid growth of population. Because of the limited capability of the district heating systems to extend to the every corner of the ever growing city, a number of new HOB stations was constructed in the city center as an alternative to the district heating system. Also, the connections and capabilities of the existing boilers were increased extensively.

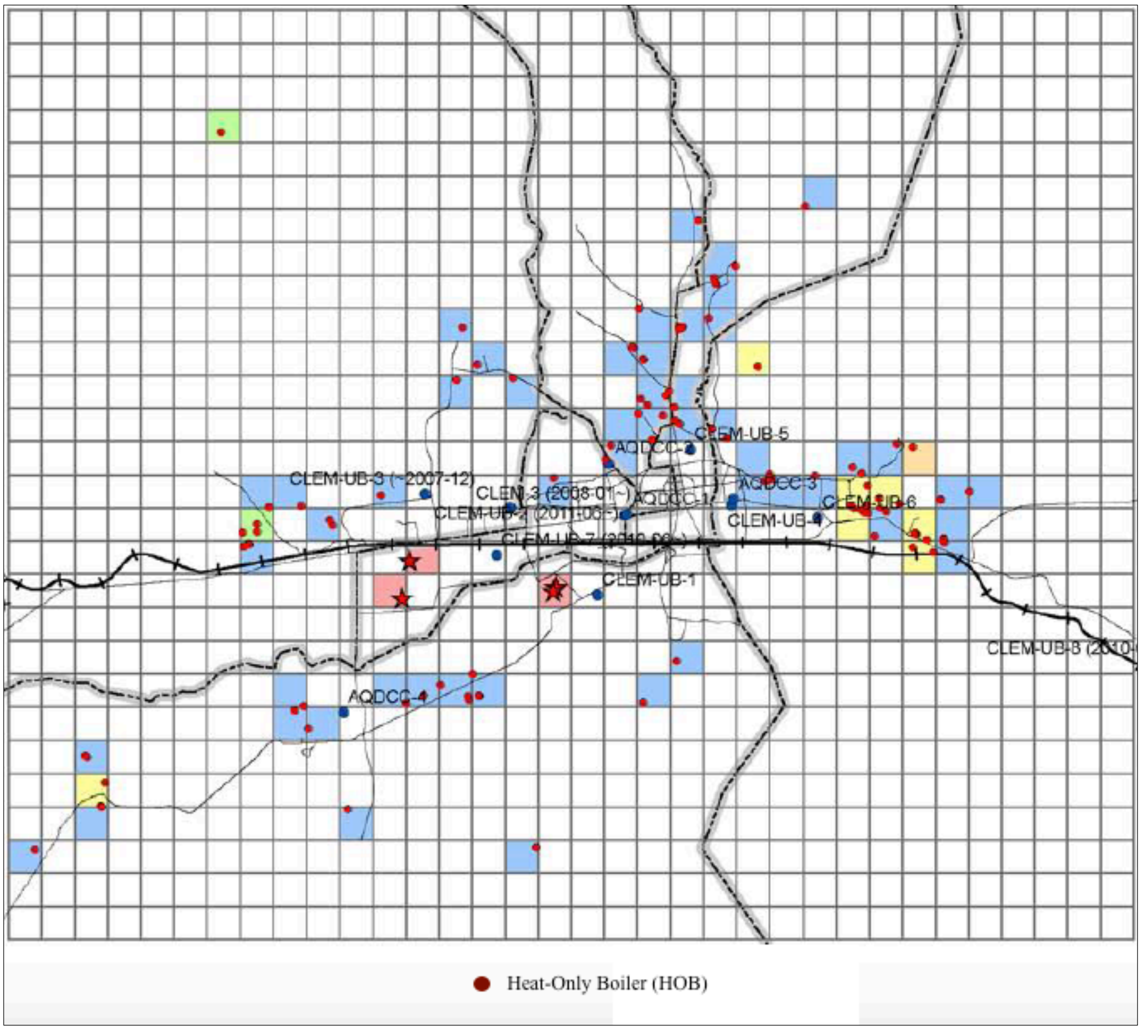

Figure 16: Spread of HOBs in Ulaanbaatar. *Source:* City Air Quality Department 2013, 50.

Table 8: Number of and annual coal consumption (t/y) of HOBs in Ulaanbaatar. *Source:* City Air Quality Department 2013, 49-51.

	Large HOBs (>500 kW)	Small HOBs (<500 kW)	Total HOBs
Number	215	1 000	1 215
Annual coal consumption (ton/year)	150 000	19 857	169 857

Table 9: Emission coefficient (kg/t) of HOBs in Ulaanbaatar. *Source:* City Air Quality Department 2013, 49-51.

	Emission coefficient (kg/ton)			
	PM_{10}	SO_2	NO_X	CO
Large HOBs	21.37	6.96	1.69	71.48
Small HOBs	6.6	15.8	5.2	23.38

Table 10: Annual emissions (kg/t) of HOBs in Ulaanbaatar. *Source:* City Air Quality Department 2013, 49-51.

	Emissions (ton/year)			
	PM_{10}	SO_2	NO_X	CO
Large HOBs	3 206	1 044	254	10 722
Small HOBs	131	314	103	464
Total HOBs	**3 337**	**1 358**	**357**	**11 186**

2.2.4 Vehicles

In 2014, there were 297,000 vehicles registered in Ulaanbaatar. This is 68% of total vehicles in the country. In recent years the number of vehicles in the city has been increasing rapidly with a 12% growth rate, creating worst traffic problems and related pollution (Statistics Department of Ulaanbaatar, 2014). Majority of the vehicles are gasoline operated. Although, the use of electric and gas cars have been increasing, they still count for a very small portion of the overall vehicles number (Table 11). Moreover, 70% of vehicles in Ulaanbaatar have been in use for 10 or more years. According to Guttikunda (2007), 80% of vehicles do not fulfill fuel consumption and emission standards. Consequently, the city's growing number of vehicles emit 6,7 kilotons of NO_X and 42 kilotons of CO per year (Table 12).

Table 11: Number of vehicles in Ulaanbaatar by fuel type. *Source:* Statistics Department of Ulaanbaatar, available from: http://www.ubstat.mn/Report.

	2013	2014
Gasoline	143 296	160 868
Diesel	82 580	87 931
Electric	22 093	37 172
Gas	9 529	11 037
Total	**257 498**	**297 008**

Table 12: Annual emissions (t/y) of vehicles in Ulaanbaatar. *Source:* City Air Quality Department 2013, 57.

Emissions (ton/year)			
PM_{10}	SO_2	NO_X	CO
265	270	6 786	42 478

2.2.5 Dust and soil from crustal matter

Dust is a non-point air pollution source, which significantly contributes to PM_{10} pollution in Ulaanbaatar. Dust and soil mainly come from unpaved roads, agricultural croplands and construction sites. Also, ger areas are unpaved and there is pretty much no vegetation there, except some grass during summer. Ger districts cover 218 km^2 in the city, while apartment buildings cover 58 km^2 (Engel 2015). The problem of dust is very common in the dry months of spring and summer. Spring is also a beginning of mass construction works in the city. In the last 2 decades with economic boom and population growth, the construction sector has increased by 25% and Ulaanbaatar has experienced development of immense amounts of apartments, offices, houses, shopping malls and entertainment centers. This in turn disturbs the ground and leads the topsoil to wear away.

In addition to the dust originating from within the city itself, a study by Allen et al. (2011) found a considerable amount of dust in the air masses arriving to Ulaanbaatar from west and northwest. The authors suggest that the dust is most likely transported from Desert Betpaqdala to the northwest of Ulaanbaatar, Taklamakan Desert in China to the west of Mongolia, and Gobi Desert in the south part of Mongolia.

2.2.6 Conclusion

Besides, traditional air pollution sources such as power plants and traffic, the Mongolian people's nomadic style yurts have become a notorious source of air pollution in Ulaanbaatar. Excessive use of coal in ger districts results in extremely high concentrations of PM and SO_2 in winter, making the ger districts the second largest source of air pollution in the city. However, it is generally believed by the public that ger districts emissions surpass the emissions from the power plants, even though the data from the City Air Quality Department indicates otherwise (Table 13). Nevertheless, it is important to consider difficulties and uncertainties in allocating exact amount of emissions to the sources, particularly in ger districts. As mentioned before, in low income households there is an extensive use of unconventional fuels such as old tires and bricks. Inadequate data and research on the usage of these materials adds to the uncertainty of emission levels from ger districts. Thus, there need to be a more comprehensive and detailed research on the fuel consumption and stove performance in ger districts. Moreover the fact, that high concentrations of pollutions are usually observed in ger areas, is suggestive. The highest levels of SO_2 and PM_{10} are commonly recorded in the north-eastern suburban ger districts of the city. Furthermore, the government's efforts mostly concentrating on reducing air pollution from ger districts is another indication that these households account for larger portion of air pollution. Nonetheless, in my thesis I will be using emissions and emission coefficient data, calculated and measured by the City Air Quality Department.

Table 13: Annual emissions (t/y) of the main sources.

	Emissions (ton/year)			
	PM_{10}	**SO_2**	**NO_X**	**CO**
Power plants	16 097	19 601	15 538	136 640
Ger districts	3 893	6 377	2 382	167 061
Industrial boilers	3 337	1 358	357	11 186
Vehicles	265	270	6 786	42 478
Dust	9 266	0	0	0
Total	**32 858**	**27 606**	**25 063**	**357 365**

2.3 Government initiatives and measures against air pollution

Air pollution is beyond the control of individuals and requires action by public authorities at the national level. In recent years, the government has been initiating and implementing a number of projects to reduce air pollution in Ulaanbaatar, with majority of them aiming at ger districts. These include introducing heat efficient clean stoves, promoting high quality clean coals, reducing electricity price for ger districts and funding construction of low-cost apartments.

Between 2011 and 2013, 124,637 efficient stoves were sold to 66% of households in ger districts at a 85-93% discounted price (City Air Quality Department 2013). The project was financed from the Mongolian Millennium Challenge Fund, “Clean Air” Government Special Fund and soft loan from the World Bank. The laboratory analysis showed that these heat efficient stoves retained their heat twice longer and emitted 94% less $PM_{2.5}$, and 86% less CO in comparison to the traditional stoves. However, real measurements from the 135 randomly chosen households with traditional and heat efficient stoves yielded much lower results compared to the laboratory results. The efficient stoves emitted 63% less $PM_{2.5}$ and 16% less CO. Moreover, the results varied significantly depending on the type of stoves and houses. The considerable gap between the laboratory results and the real measurements are mainly due to coal consumption behavior of the households. For instance, it is a common practice to use mix of different coals and fuel in ger districts.

Another policy initiated by the government is restricting supply of low-quality raw coal and promoting supply of processed fuel such as refined coal and saw dust briquettes in Ulaanbaatar’s ger areas. Currently, Mongolia is producing three types of processed fuel: saw dust briquettes, coking coal briquettes and coking coal. These fuels have high calorific value and produce much less polluting elements compared to raw coal. For instance, saw dust briquettes have 2-5 times less ash content and no sulfur content compared to raw coal (Table 14). Accordingly, their emission levels are lower (Table 15). However, processed fuels are twice as expensive as raw coal. The government has been subsidizing the price of processed fuels to bring it at the same level as raw coal (Table 16). But saw dust briquettes burn down faster than raw coal. Consequently, the consumption of saw dust briquettes is 1.5 times higher than raw coal, making it expensive despite the subsidies. Another issue with the processed fuels is that because of their high heat value, they basically not suitable for the stove types that are presently owned by the majority of the ger districts. Its high heat value damages the stoves in the long run. Thus, despite low emission levels and generous government subsidies, the use of processed fuels still remains low.

Table 14: Elemental analysis comparison of saw dust briquettes and raw coal from the two main coal mines in Ulaanbaatar. *Source:* City Air Quality Department 2013, 93.

		Elemental Analysis			
		Calorific value H_u (kcal/kg)	Water W^r (%)	Ash A^r (%)	Sulfur S^r (%)
Saw dust briquettes		4 500	10	5	-
Raw coal	**Nalaikh mine coal**	3 496	22	24	0.7
	Baganuur mine coal	3 513	33	12	0.9

Table 15: Emission coefficient comparison of saw dust briquette and raw coal from Nalaikh coal mine. *Source:* City Air Quality Department 2013, 95.

	Emission coefficients (kg/ton)			
	PM	SO_2	NO_X	CO
Saw dust briquettes	1	0.42	0.35	32
Nalaikh raw coal	4.4	1.2	1.1	58

Table 16: Prices of fuels and government subsidy. *Source:* City Air Quality Department 2013, 102.

	Prices of fuels (Euro/ton)			
	Raw coal	Saw dust briquette	Coking coal briquette	Coking coal
Initial price	34	57	65	57
Government subsidy	-	23	35	27
Subsidized price	34	34	30	30

Since long the public authorities have been subsidizing electricity price for ger district in order to promote electric heaters. This year they have gone one more step further and have decided to provide free electricity for ger districts at night. Over 146,000 households were included in the discounted rate from the 1st of January to the 1st of

April, 2017. The project has cost the government two million USD. Some officials are critical of the decision, arguing that it would induce residents to waste energy. Minister of Energy said: "Nighttime electricity tariff discount for ger districts may affect the energy system negatively. Residents should understand that there are limited recourses of energy and they should try to limit their energy consumption". Despite the considerable subsidies on electricity prices, the share of households that use electric heaters still remain low. An estimated number of 1,924 households in ger districts are using electric heaters (City Air Quality Department).

Another major government policy aimed at reducing air pollution caused by ger districts is resettlement of these households into apartment buildings. The government has initiated two major construction projects called "40,000 homes" and "100,000 homes" in order to relocate ger district residents to flats. These projects are directed towards constructing low-cost apartments throughout the country, with the majority of it in Ulaanbaatar city and allowing low- and middle-income households to buy these apartments with long-term house loans at below market interest rate. In order to build low-cost apartment buildings, the government is responsible for constructing and providing infrastructure and utility systems, such as heat, water, and sewage, to the areas, where the apartments are planned to be built. Once the area is connected to the infrastructure and utility systems, construction companies come in and start the construction work.

Presently, 20 companies are building apartments at 17 locations. These locations also include land, that is currently covered by ger districts. Usually, areas that are closely located to the existing infrastructure and utility network are chosen for the construction sites. Relocating and relieving land from these households is the main and most common problem faced by the construction companies, which slows down the progress of the projects. Households that reside in those areas, where the new apartments are planned to be built, are asked to move to different locations, and in return they will receive a new flat for free in two to three years. People are reluctant to move for many different reasons. Some people want bigger apartments than they are offered, some people want money in exchange for their lands, some people don't want to move. In ger districts, the households own their land and surround it by a fence. Generally, the area within a fence is 0.07 hectare, a size of land entitled to every Mongolian citizen by law. The problem is, in many occasions several households are sharing one fence. When these households are asked to vacate their land they are offered only one apartment in exchange of their land. In these cases, the constructing companies negotiate with these citizens. If they cannot come to an agreement, the government will pressure the households to vacate their land, for instance by cutting off their electricity. Thus, the housing projects are progressing slowly. Nonetheless, between 2000 and 2012 the construction sector has increased by 25% and 53,000 residential buildings were built in Ulaanbaatar.

Unfortunately, meanwhile the apartment prices have rocketed in Ulaanbaatar. In 2005, the average price of a flat was \$170-250 per 1 m^2. By 2013, the price reached \$800-1000 per 1 m^2 (Engel 2015). This disturbed the initial idea of providing low-cost apartments with low interest rate loans. It has become more and more difficult to get the soft loan as the prices of apartments ascended. Thus far, various government efforts to reduce air pollution from ger districts have not been entirely successful.

One very small but interesting project, that is relevant to the topic of this thesis, has been implemented in Ulaanbaatar. Water-based solar collector systems were installed in number of public service buildings and 21 households for space heating purposes (Figure 17). The sun's energy is collected on flat-plate solar collectors. Water runs through pipes that pass through collectors, transferring the heat from the collectors to the buildings. The system is aided with an auxiliary electrical source. The buildings that were included in the project are: a district governor building, a district hospital, a city police post, and 21 ger district households with house areas ranging from 45 to 128 m^2. This is the first example of renewable energy being utilized in reducing air pollution in ger districts. Share of renewable energy is expected to increase in the near future, as Mongolia has set goals to supply 30% of the total installed power-generation from renewable sources by 2030. Thus, seeking solutions that involve cleaner energy sources is might be a better choice in the long run, rather than shifting air pollution from ger districts to other sources such as power plants and HOBs.

Figure 17: Solar air collectors with water-based delivery systems installed on buildings in Ulaanbaatar's ger districts. *Source:* City Air Quality Department 2013.

3 Solar energy technologies and possible applications in ger districts of Ulaanbaatar

Sun is basically the principal source of all energy forms on Earth. We use solar energy both directly in the form of solar radiation and indirectly in the form of biomass, fossil fuels, water and wind power. In the process of photosynthesis, plants store the sun's energy in the form of chemical energy. Humans have been using wood and other biomass as fuel for centuries. Then, when the plants die and are preserved in sediments for thousands of years they form fossil fuels, the most widely used energy source today. Solar energy also drives wind patterns and hydrological cycle. Because of the Earth's axis tilt, different parts of the planet receive different amounts of radiation. This results in extreme differences of temperature and pressure in various locations, consequently creating conditions for wind formation and ocean currents.

Although harnessing solar power is thought to be a novel phenomenon and solar energy is constantly referred to as a "new" renewable energy, in reality it is the most ancient form of energy used by the humanity. For instance, people have been designing their homes in a way that could maximize the direct use of solar power for lighting and heating. And active solar technologies that collect solar power dates back to 1767 (Withgott and Brennan 2011). However, by then the advantages of coal have been realized and soon it replaced the traditional energies such as wood, wind, water and sun. Since the industrial revolution fossil fuels have become our society's dominant source of energy, despite growing concerns about its adverse environmental effects and its limited recourses. But after the 1970s oil crisis and rise of environmental movements, countries have realized the prospect of running out of fossil fuels and its hazardous impacts on our ecosystems and the global climate. Accordingly governments have started to search for alternatives to fossil fuels and investments in sustainable energy sources such as solar power have increased. However, as oil prices stabilized, governments' support for solar energy has declined. Nonetheless, worldwide use of solar energy has grown by 31% since 1971. Solar energy has been especially attractive for developing countries for it could provide electricity to remote isolated areas that are not connected to the grids. For instance, in Mongolia photovoltaic cells are providing electricity to the nomadic families, who move constantly to different locations, roaming for pasture.

Sun’s energy is inexhaustible and it is more than enough for all our energy needs. Moreover, solar technologies are quite, safe, require little maintenance, can be decentralized, and do not use fuel. Most importantly, it does not pollute the air and emit no greenhouse gases. However, solar technology still remains expensive in comparison to fossil fuel use, even though the costs have been declining and efficiencies have been improving. For instance, in 1950s solar technologies cost $ 600 per watt and had an efficiency of 6%. Today, PV cells have up to 20% efficiency and are becoming less expensive.

There are various ways in which we can harness solar energy. The simplest method is passive solar heating. Passive solar heating means maximizing the capture of sunlight with the help of the design of buildings. Super-insulated or passive-house design requires less energy for space heating and consumes less fossil fuel. Also, the roofs, floors and walls of these houses are built with materials that absorb and store heat (Figure 18). Another way to harness solar energy is active solar methods. The most common active solar technology is solar collectors on rooftops. These technologies are usually made of dark-colored, heat-absorbing metals and covered with glass. Water or air run through these collectors. The collectors absorb solar energy and heat the air/water. Then the ducts deliver hot water/air into the buildings or its water tank. Usually these technologies are quite simple and used for small-scale domestic heating. Probably the most widely known solar technology are photovoltaic (PV) cells. It is the most direct way to produce electricity from the sun. PV cells are made of two silicon layers: one of which is boron-enriched, the other one is phosphorus-enriched. When the sun light hits these silicon layers, electrons from the silicon atoms get loose and move from the boron-enriched layer to the phosphorus-enriched layer. The wire that connects these two layers enables electrons to flow back to the original layer. This flow of electrons through wires creates electrical current or direct current, which can be converted into alternating current and used as electricity. PV cells are not the only solar technology that creates electricity. Utilities that concentrate solar power from wide area also can generate electricity. For instance, a parabolic trough concentrate sunlight and heat liquid in horizontal tubes. The heated liquid then creates steam and turn turbines, generating electricity as in conventional power plants.

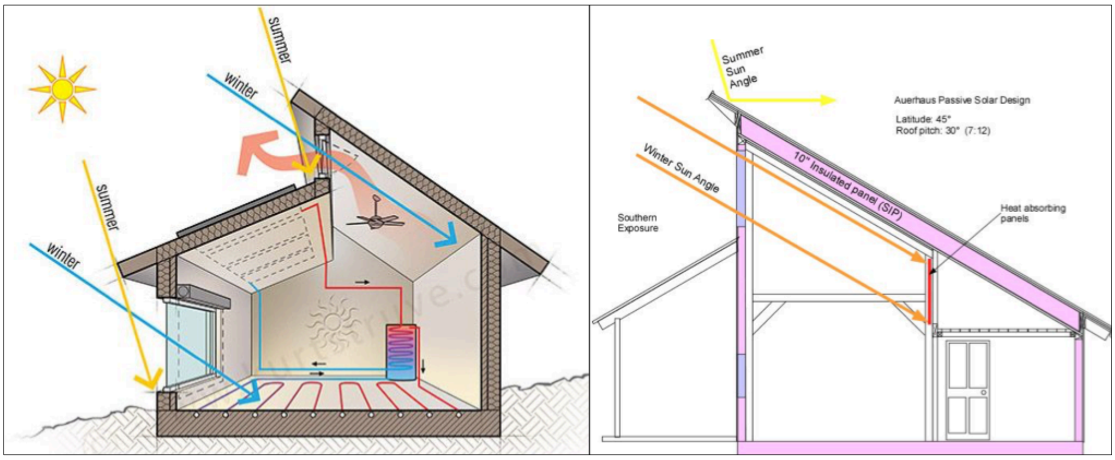

Figure 18: Passive house designs.

The purpose of my thesis is to find out whether air pollution in Ulaanbaatar's ger districts can be reduced by using solar energy. As discussed in Part 2.2, ger districts burn coal to heat their houses, emitting massive amount of air pollutants each year. Thus, I will analyze solar technologies that generate thermal heat and that would minimize the total fossil fuel consumption in these households.

3.1 Active solar space heating systems

As mentioned above, there are two solar space heating methods: active and passive. Active systems use solar collectors to heat a medium, which is most commonly water or air; storage units to store the heat; and fans to transfer the heat to the building or storage. This system can be used in combination with a conventional auxiliary heating source. The auxiliary heating source can generate heat when there is no sunshine or when the storage unit is not loaded. Also, when the heat produced by the collectors or storage cannot meet the heating demand of the building, auxiliary systems can work simultaneously to cover the building load. Thus, in combination with conventional heating systems, solar heating equipment can provide reliable and stable energy. It is technically possible to construct a solar heating system that can alone satisfy all the heating demands of a building. However, it would be too big most of the time.

3.1.1 Solar collectors

A solar collector, which is the main element of any solar system, is a kind of heat exchanger that transforms solar radiation into heat and transfers that heat to a transport medium. There are bountiful types of collectors varying in design and application. In general, they can be grouped into two types: concentrating and non-concentrating. Concentrating solar collectors have curved surfaces which concentrate the sun's energy to a smaller area, increasing the radiation flux. These collectors are suitable for high-temperature steam raising and electricity generation. Non-concentrating collectors have the same area for receiving and absorbing solar radiation, which makes it more suitable for low-temperature applications, such as water or space heating. Hence, in this thesis I will examine types of non-concentrating solar collectors.

There are two main types of non-concentrating solar collectors: flat-plate collectors and evacuated tube collectors.

3.1.1.1 Flat-plate collectors

Flat-plate collectors are made of many different materials and in many different designs. They are commonly used to heat mediums such as water, air, or water mixed with antifreeze additive. A typical flat-plate collector consists of glazing, absorber plate, flow tubes, header tubes, insulation and casing (Figure 19). The sunlight passes through the transparent glazing and hit the absorber plate. The absorber plate absorbs large portion of the energy and transfers it to the medium in the flow tubes. The both ends of the flow tubes are connected to the header tubes, which are larger in diameter and serve as inlet and outlet of the medium. The casing surrounds all the components and protects them from dust, moisture and other damages.

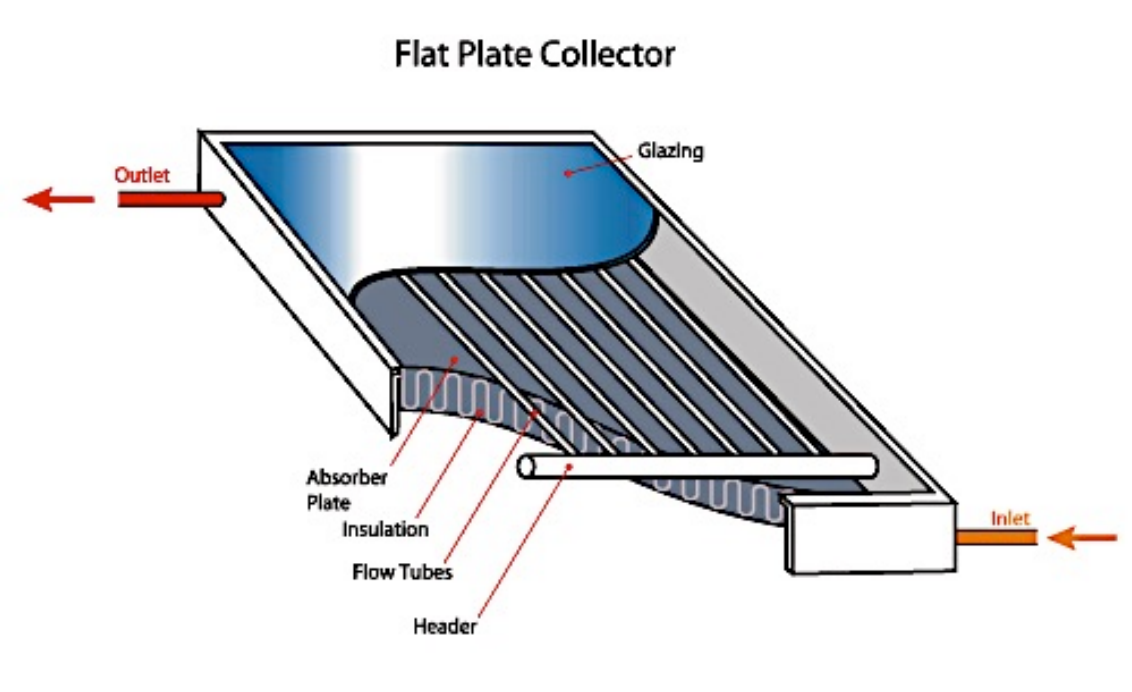

Figure 19: A typical flat-plate collector. *Source:* Solar Advice, available from: https://solaradvice.co.za/flat-plate-solar-water-heating/

The glazing is usually made from glass, and sometimes from plastic. The space between the glazing and the absorber plate is between 15 and 40 mm. Its purpose is to reduce convection losses from the absorber plate by maintaining static air layer between the absorber plate and glazing. Glass also minimizes radiation losses from the absorber plate, because it is transparent to shortwave radiation but almost opaque to longwave radiation, which is emitted by the absorber plate. Glass with low iron content is more suitable for glazing material, since it has relatively high transmittance for shortwave radiation and essentially zero transmittance for longwave radiation. Plastics also have high shortwave transmittance. But most of them also tend to have high longwave transmittance. Besides, only few varieties of plastic can withstand high temperatures for long time without deterioration. However, compared to glass they are thin, light, flexible and are not broken by hails or stones. Usually the solar collectors are single glazed. But sometimes there is an additional second glazing layer. The more elaborate the glazing, the less the convection and radiation losses would be. The effect of dust on transmittance is not significant. The cleaning effect of an occasional rainfall is enough to keep the transmission at its maximum value (Kalogirou 2009).

The absorber plate should absorb as much solar radiation as possible, convert it to heat and transfer the heat to the medium. The absorptivity of the plate depends on the color and nature of the coating and on the incident angle. The cheapest coating alternative is black matte paint. However, performance of this kind of absorber plate is low. Another more efficient alternative is a selective surface, which has a high shortwave absorptivity and a low longwave emittance. A typical selective surface consists of two layers: a thin upper layer with a high shortwave absorptivity but transparent to longwave thermal radiation; and a lower layer with a high reflectance and low emittance for longwave radiation. Many materials for absorber plate have been tried with success including aluminum, copper and stainless steel. Because the absorber plate transfers the collected energy to the medium it must be made of materials with high thermal conductivity. The absorber plate must be well insulated from beneath and from sides to reduce conduction losses. The insulation is made from fiberglass or mineral fiber mat that does not evaporate at high temperatures.

The flow tubes can be fastened to the absorber plate or they can be integral part of the plate. Figure 20(a) is an example of a bonded plate design, where the tubes are integral part of the plate. In figures 20(b) and 20(c) are shown the designs, where tubes are fastened to the plate. The main issue is finding a good fastening method at low cost. Examples of fastening methods include mechanical pressure, thermal cement, brazing, clips and clamps. Soft solder cannot be used to fasten the tubes to the plate, as high plate temperature could melt the solder. As for the material for the tubes, copper is most widely used because of its resistance to corrosion.

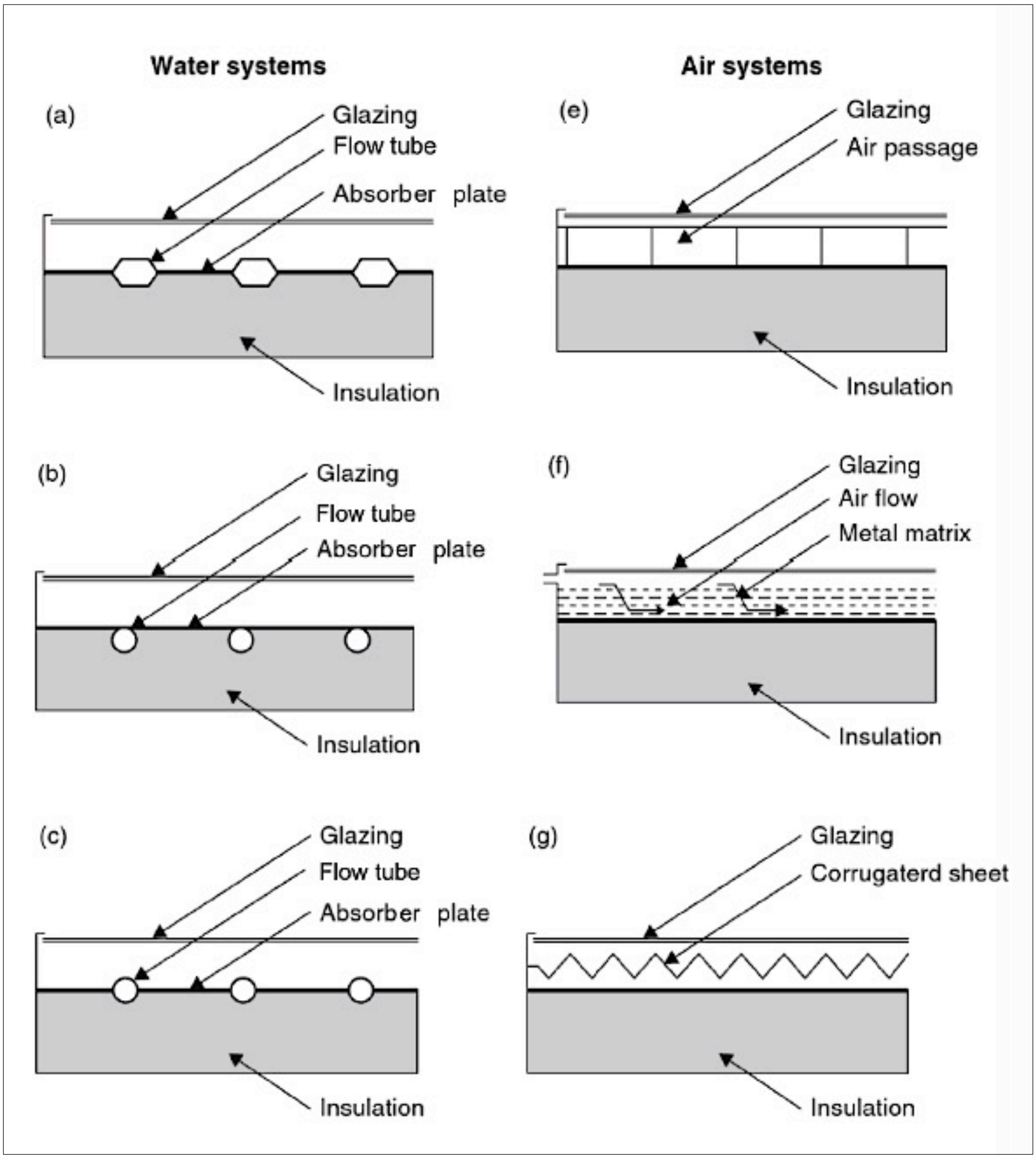

Figure 20: Various designs of flat-plate solar collectors for water and air. *Source:* Kalogirou 2009, 128.

With flat-plate collectors that use air or other gas as transport medium, some type of extended surface is needed to counteract the low heat transfer coefficient between the air and the absorber plate. These could include metal or fabric matrices, thin corrugated metal sheets and porous absorbers (Figure 20(e-g)). With air systems it is important to have a large contact area between the air and the absorber plate.

The flat-plate collectors are inexpensive to manufacture; do not require fuel; are fixed in a permanent position throughout the entire year, or possibly adjusted just once a year; and can last up to 20 or more years with little or no maintenance (Boyle 2012). The optimal tilt angle is equal to the latitude of the location plus 10° for space heating application, and plus 5° for water heating application (Kalogirou 2009). The solar collector should be facing the equator. Thus, in the Northern Hemisphere it should be directed towards south, and in the Southern Hemisphere it should be facing north. It does not have to be installed to a precise tilt or orientation for adequate performance. For instance, a collector installed at an angle 30° off the required direction still collected 86.6% power (Ehrlich 2013). This means that location and orientation of existing buildings should not be a limiting factor in supporting solar collectors.

3.1.1.2 Evacuated tube collectors

Evacuated tube collectors can operate at higher temperatures than flat-plate collectors. They consist of a heat exchanger and evacuated tubes, which are filled with absorber plate and heat pipe (Figure 21). The evacuated tubes act as a glazing in the flat-plate collectors. They prevent convective and radiation heat losses from the absorber plate. The absorber plates absorb solar radiation, convert it to thermal energy and transfer it to the heat pipe, which is attached to the absorber plate. The heat pipe, which is sealed and made of copper, contains small amount of fluid, usually methanol. The fluid boils and evaporates as the sun heats the equipment. The vapor rises to the tip of the heat pipe, which is connected to the heat exchanger. There it condenses and returns to the solar collector and the cycle is repeated (Figure 22). Water flows through the heat exchanger (i.e. the manifold) and collects the heat from the heat pipe tips. The heated water can be used for various applications.

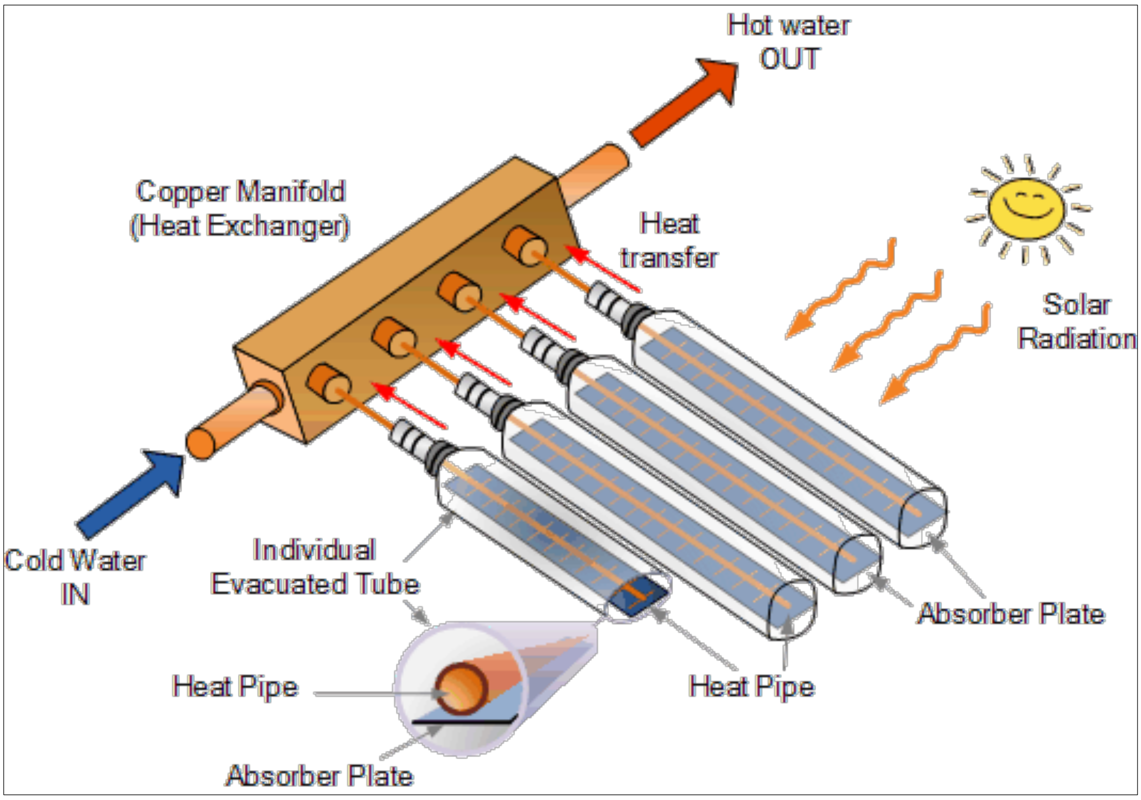

Figure 21: Evacuated tube collector. *Source:* Alternative Energy Tutorials, available from: http://www.alternative-energy-tutorials.com/solar-hot-water/evacuated-tube-collector.html

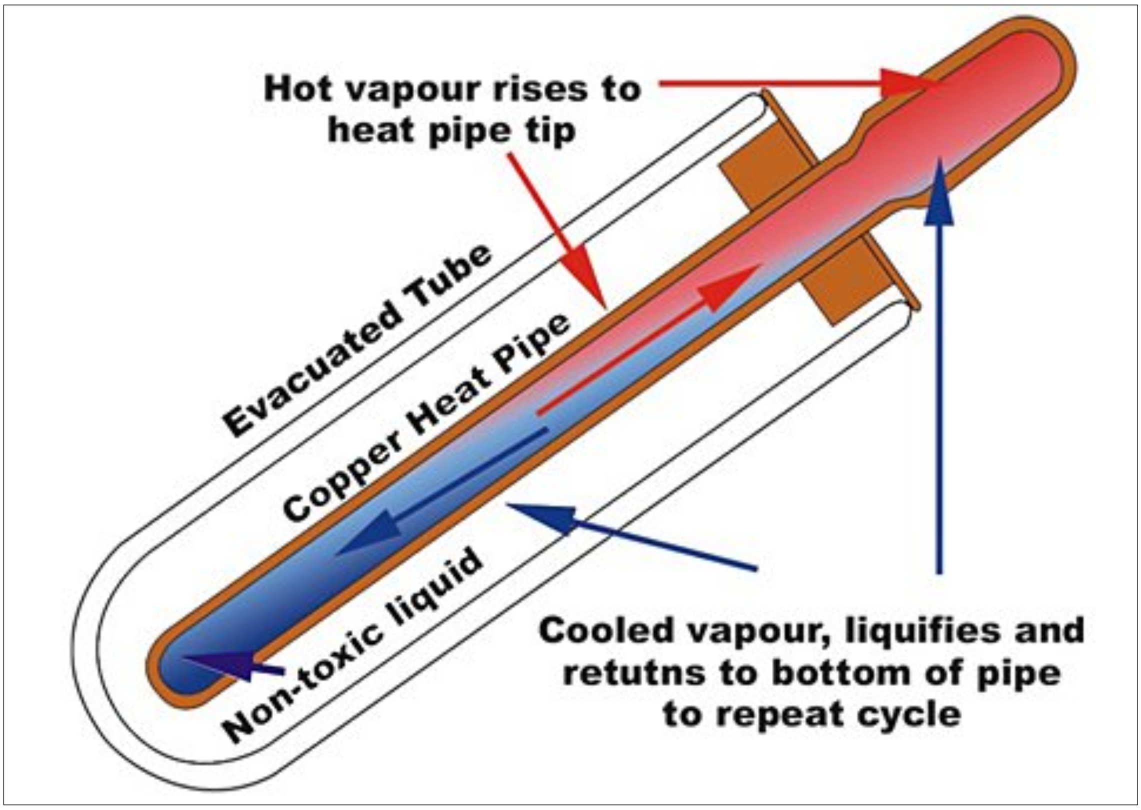

Figure 22: Evaporating-condensing cycle in the heat pipe of an evacuated tube collector. *Source:* China Senior Supplier, available from: http://www.chinaseniorsupplier.com/Energy/Solar_Energy_Products/1592425113/Pressurized_vacuum_tube_solar_collector_instal_on_the_wall.html

Evacuated tube collectors are generally more expensive than flat-plate collectors, but they perform better in cold conditions. Kalogirou (2009) explains: "because no evaporation or condensation above the phase-change temperature is possible, the heat pipe offers protection from freezing and overheating". Besides, cost can be reduced by reducing the number of tubes and using reflectors behind the tubes to increase the radiation absorbed by the tubes (Figure 23). A reflector increases absorptivity of each tube by 25% for normal incidence. Since, evacuated tube collectors also perform very good at low incidence angle, such system increases energy collection over a full day by 10%.

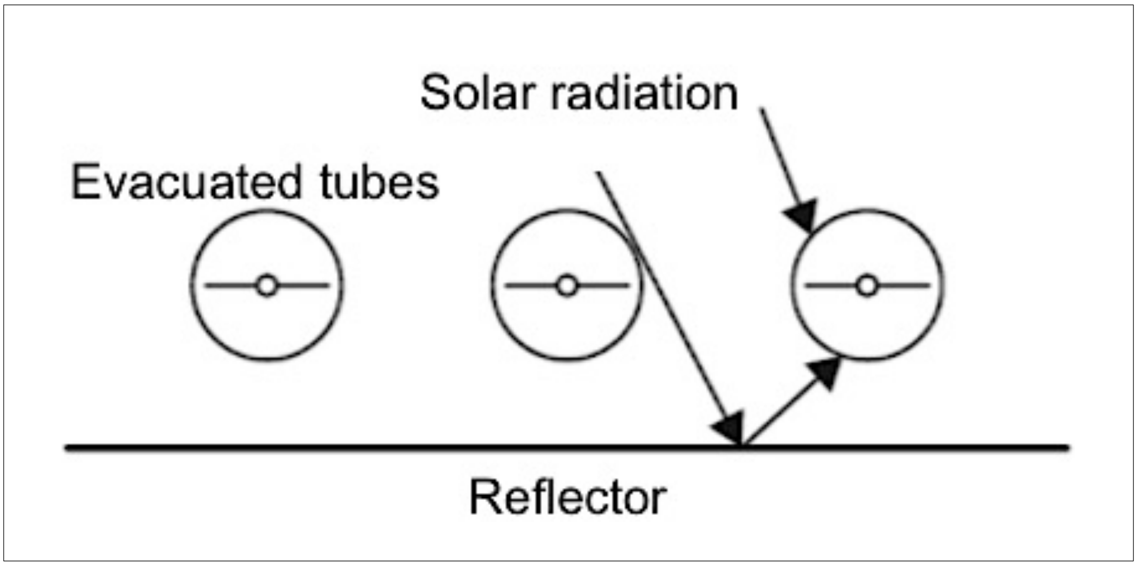

Figure 23: Evacuated tube collectors with reflector. *Source:* Kalogirou 2009, 134.

3.1.2 Solar collectors with air-based delivery system

We have discussed the two most common solar collectors: the flat-plate collectors and the evacuated tube collectors. The flat-plate collectors can use both air and water as its heat transfer medium. In this part we are going to look at the air-based delivery system. During daytime, when the sun is shining, the collectors heat the air and the system delivers the hot air to the storage. The heat for the building is then acquired from the storage. Usually it is not efficient to add and subtract heat from the storage simultaneously. When the heat supplied by the solar collector or storage is not enough to meet the demand, conventional heating source can help the system to meet the building load. Also, the system can be bypassed as whole and the heat can be supplied by the conventional source alone, when there is no sunshine and the storage is depleted.

The advantage of the air-based system is that it does not have to be protected from freezing or boiling and the medium fluid does not degrade, which is the case with water medium systems. Additionally, air is not corrosive, plentiful and free. The weakness of the system is that the ducts, fans, and storage require more space than the equipment of water-based system. Also, air leaks are difficult to detect.

Storage is very important because it has significant influence on the performance, stability and cost of the system. The most common storage material that is used with air-based collectors is gravel. It is cheap and bountiful. A typical design of gravel or pebble thermal storage bed consists of a container made of concrete, masonry or wood filled with gravel. The size of rocks depending on the airflow, storage shape, and desired pressure can range from 35 to 100 mm in diameter. Airflow must be in one direction, either horizontal or vertical. The size of the gravel bed depends on the output of the solar collector. For domestic space heating system, the storage size typically ranges from 0.15 to 0.3 m^3 per square meter of collector area.

Figure 24 shows a basic scheme of solar air heating system with a pebble storage. With the help of dampers, the system can be operated in various modes. For instance, when the sun is shining, but heat is not needed in the house, then the solar energy is delivered to the storage. On the other hand, when heat is required and solar energy is available, the solar energy bypasses the storage and is delivered directly to the building to supply the load. When there is no solar energy and the storage is depleted, auxiliary source takes over. In a case when the storage is fully loaded and the building does not require heat, and the solar collectors are producing heat, then the solar energy is simply discarded.

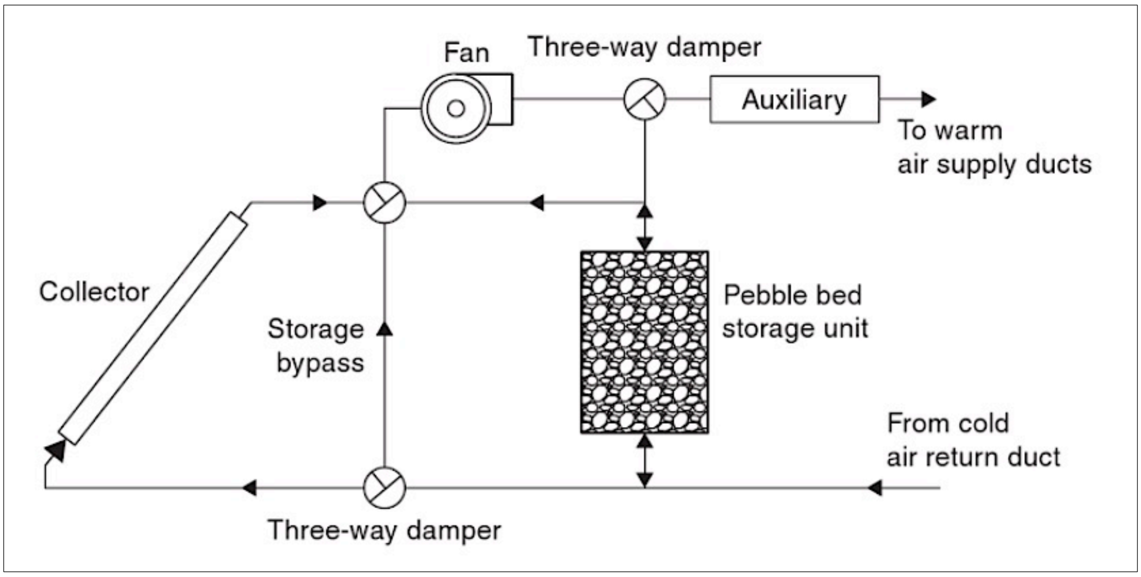

Figure 24: Basic solar air heating system with pebble bed storage. *Source:* Kalogirou 2009, 351.

Solar air heater is a very suitable system for small houses in ger districts of Ulaanbaatar. It is inexpensive, simple, and can be used in combination with the traditional stoves in ger households. Also, the system can be manufactured domestically, since it is not complex and does not require rare and scarce materials. In addition there is no need to protect the system from freezing. The collectors can be mounted on the roofs of houses as well as on traditional gers. About 90% of the houses in these areas are one-storied. Thus there is no risk of houses overshadowing the collectors. Finally, Ulaanbaatar receives plenty of sunshine, usually above 270 sunny days a year, most of them in winter.

3.1.3 Solar collectors with water-based delivery system

Solar water heat system is basically similar with the air heat system described above. Only the transport medium here is usually water and the storage unit is a water tank. Both flat-plate collectors and evacuated tube collectors can use water as delivery medium. The collector works with a differential temperature controller. A temperature controller is important for a proper function of the system. The temperature control system should be able to handle all the different operating modes of the system, such as available solar energy, but no demand; depleted storage and no available solar energy; use of auxiliary heating system; and it is also responsible for activating freeze protection systems in case of low temperatures and power failures. The differential temperature controller or differential thermostat measures and compares the temperature of the collector and the storage. When the temperature of the collector is higher than the tank's the controller switches on the pump. When the collector's temperature is lower than the temperature of the storage by 2-5°C, the pumps are turned off. The solar water heat system is more suitable for warmer climates. To use it in climates where freezing is possible, antifreeze system must be in place. The typical freeze protection system is based on draining the collector water out with an automatic discharge valve. The storage tank is usually made of copper, galvanized metal or concrete. The size of the tank depends on the solar collector's area. Typically, per square meter of collector area 40 to 80 liter of water is required. Water systems usually have single storage tank, but two or more storage design is also possible.

There are two main types of solar water heaters: direct circulation systems and indirect circulation systems. In the direct circulation system, the water is circulated from storage to the solar collector. The heated water is returned back to the storage tank until it is needed (Figure 25). The storage tank is usually equipped with an auxiliary boiler, in case solar energy is not available or inadequate. The system however should not be used in areas with hard or acidic water, because it can corrode or clog the collectors. There are two freeze protection methods for this system: recirculating warm water from the storage tank and drain-down system, which drains water out from the exterior piping isolating the collectors. The recirculating antifreeze method should be used in locations with few freezing days. Because it uses the warm water from the storage tank, applying this method frequently would result in greater heat loss. With the drain-down antifreeze system, the location of the solar collectors and external piping must be carefully sloped to drain all the water.

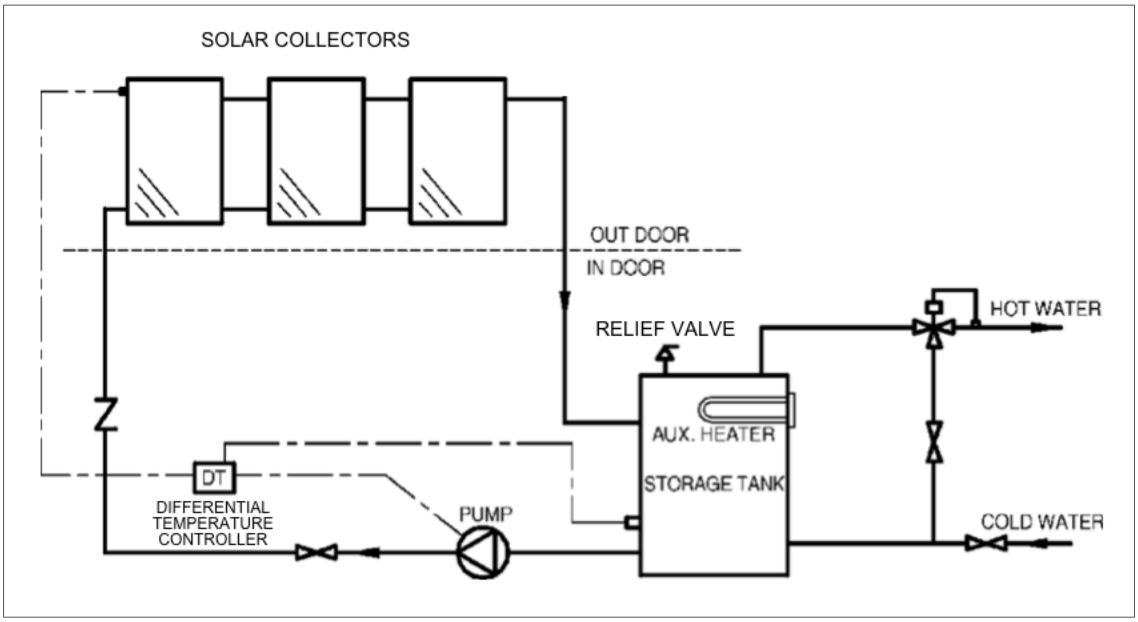

Figure 25: Direct circulation system. *Source:* Kalogirou 2009, 265.

In the indirect circulation system, the water is circulated in a closed collector loop. The heat absorbed by the collectors is transferred to the storage tank through a heat exchanger (Figure 26). In the closed collector loop the water is usually mixed with ethylene glycol as an antifreeze solution. Also, other fluids such as oils and refrigerants can be used.

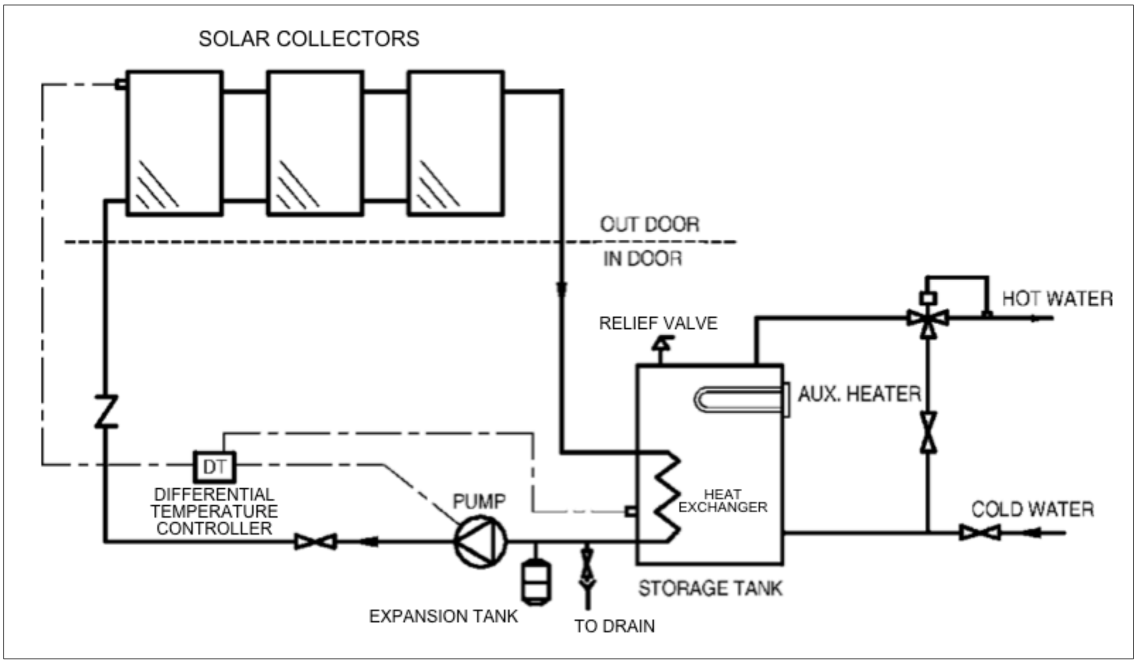

Figure 26: Indirect circulation system. *Source:* Kalogirou 2009, 267.

A basic water system is shown in Figure 25. It consists of a solar collector, water tank, auxiliary boiler, controller and pump. Solar collectors absorb the sun radiation and transfer the energy to the water. The temperature controller switches on a pump to circulate water through pipes to the collector and to the tank. The hot water in the tank is then used for various applications. An auxiliary boiler is present to heat water when solar energy is not adequate for the load or not available.

Solar water heat system can be more suitable for bigger houses in ger districts. As mentioned before, about 90% of the ger district houses are small and one-story. However, the remaining 10% are larger houses with two or more stories. Because of the larger size these houses often use heat-only boilers (HOBs) to supply the heat demand of the building, where the traditional stoves are not capable to meet the load. And HOBs are the third largest air polluters in Ulaanbaatar. Thus, use of solar water heaters in combination with conventional heating appliances can contribute in reduction of air pollution from the ger districts. In fact, such systems have been recently installed in 21 residential houses and in number of public service buildings as part of an air pollution reduction project in Ulaanbaatar.

3.2 Passive solar space heating systems

Passive solar space heating methods have been used by humans from ancient times. In Rome, for instance, large glass sheets were used in communal meeting places and baths. Passive systems maximize solar energy collection, heat storage capacity, and its distribution with the help of architectural design of the building and make minimal use of mechanical equipment. All buildings are to some extend passive. Sun warms a building during day and it releases its heat at night. However, passive solar heating can be enhanced by special designs, insulation, window placement and thermal storage walls. A typical passive system can supply up to one-third of a building's heating demand (Goswami 2015).

Special design known as "passivhaus design" involves good insulation, responsive heating system, southward orientation and no overshadowing by other buildings. Passive houses that were built in England in the late 1970s used only half as much gas for heating compared to conventional buildings. The construction cost 2.5% more, but the payback time was only four years (Boyle 2012).

New buildings can be designed and constructed in this way. However, thermal performance of old buildings can be improved significantly by improving insulation. For instance, when in Germany some buildings that were built in the 1950s were insulated, the thermal energy consumption fell by factor of seven. Insulation is a very important factor in reducing thermal load. According to Boyle (2012), insulation can save 9000 kWh per year in fossil fuel heating. Insulation of 200 mm or greater thickness has a potential to reduce heating load almost to zero in some cases.

The window is an element of passive systems. Sun's energy enters through window and is absorbed and distributed within the habitable space. This is called a direct gain system. The important thing to consider is, whether the window is providing net gain, in other words, whether the incoming flow of heat through the window is higher than the outgoing. This depends on the internal and ambient temperature, the solar radiation, the transmittance characteristics of the glass, orientation and shading of the window, the glazing of the window: single or double. For instance, in cold climates a single-glazed window is a heat loser, while a double-glazed window balances the gain and loss, resulting in zero net gain. Thus, for cold climates too many or too large windows might result in thermal loss, rather than gain. In addition, the distance between buildings must be planned carefully in order to avoid overshadowing the windows.

Another important purpose of the window is daylighting. Daylighting is illumination of building interiors with sunlight. Daylighting can have major influence on energy saving. For instance, in the UK in 2010, domestic lighting accounted for only 2.6% of the domestic energy use (Boyle 2012). However, in office buildings lighting can account for up to 30% of energy use. This is because, residential buildings are better designed to use natural light.

While solar radiation can contribute to the building load directly through the windows, it can also contribute indirectly through the construction materials, also known as thermal mass. Thermal mass absorbs the heat, stores it and releases it later into the building. To store the heat effectively, the thermal mass must have high density, thermal capacity, and conductivity. Materials with low density, thermal capacity and conductivity have low storage capacity, regardless of the thickness. Common construction materials such as bricks have 10-hour heat storage capacity, concrete has 8-hour capacity, and wood has 20-hour storage capacity due to high water content (Kalogirou 2009). Orientation of the thermal mass is important. Since north facing surface receives little radiation, it does not need high storage capacity. Southern surfaces can operate with an 8-hour storage capacity materials. In this way the heat from midday will be delayed until the late evening hours. Glazing of south-facing walls reduces losses of heat radiating back from the wall and increases the collection efficiency of the wall during the day. Effective use of thermal mass can contribute considerably to the heating load of the building and reduce the building’s energy consumption.

In brief, effective incorporation and harmonious combination of passive solar heating systems can reduce the thermal heat load of the building that needs to be supplied by a conventional heating system.

3.3 Utilizing solar energy to reduce air pollution in ger districts of Ulaanbaatar

Since a wide variety of solar thermal energy technologies is available on the market, a number of different solar heating systems can be utilized in ger districts, that would suit heat demand of various types of houses. Solar collectors also offer number of price choices. For instance, flat-plate collectors range from 150 to 600 Euros per square meter. Evacuated tube collectors are more expensive at 500 to 1200 Euros per square meter collector surface.

Solar collectors can take over some portion of heating load in ger districts, thus reducing fuel consumption in traditional heating appliances such as stoves and HOBs. The efficiency of the collectors basically depends on the solar irradiance of the location and the temperature difference between ambient air and inlet fluid. Consequently, higher irradiance and lower temperature difference results in higher efficiency of collectors (Figure 27). However, efficiency varies considerably for different types of collector designs and materials used for glazing, absorber plate, and storage.

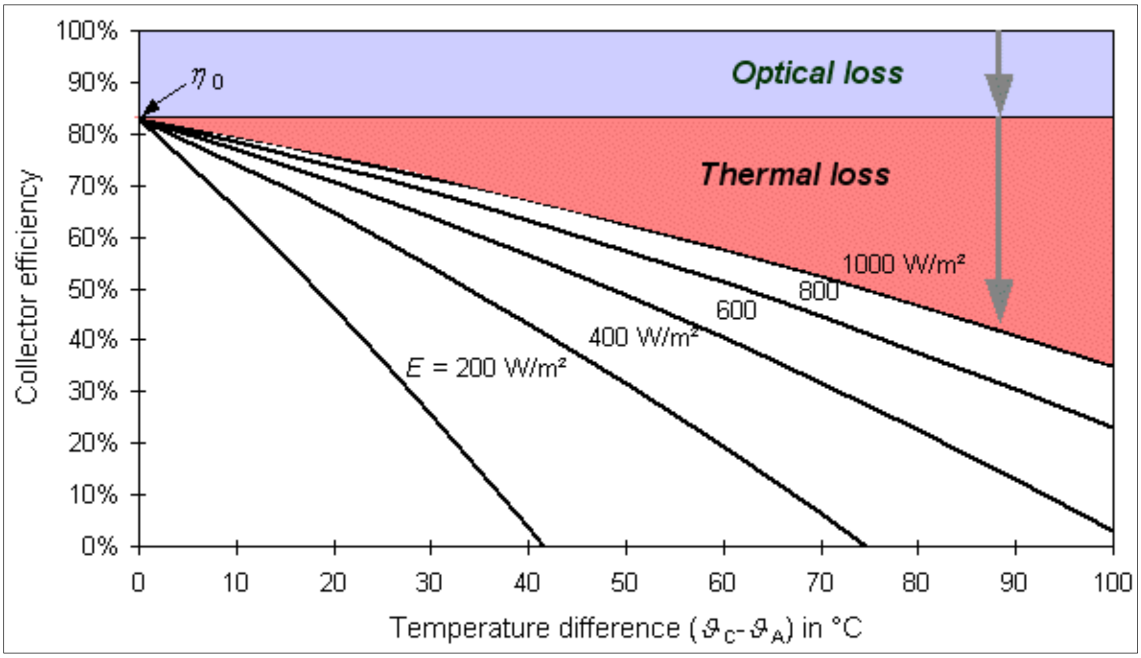

Figure 27: Collector efficiency curves. *Source:* Erneuerbare Energien und Klimaschutz, available from: https://www.volker-quaschning.de/articles/fundamentals4/index.php

As for the solar irradiance, Mongolia has from 270 to 300 sunny days annually and from 2,250 to 3,300 hours of sunshine a year. The daily average solar radiation range from 3.4 to 5.4 kWh/m^2 (IRENA 2016). The southern part of the country receives the most solar radiation. Gobi desert in the south of Mongolia is ranked as the third desert on the world with high solar energy potential (Figure 28). Ulaanbaatar, located in north central Mongolia, receives a fairly good and reliable solar radiation, ranging from 1,278 to 2,685 Wh/m^2 during the months of winter, and from 4708 to 6045 in the months of summer (Table 17). Thus, the radiation during winter and the colder months of spring and autumn, when the houses demand large amount of energy for heating, is adequate to operate solar collectors in Ulaanbaatar. However, temperature is very low during winter.

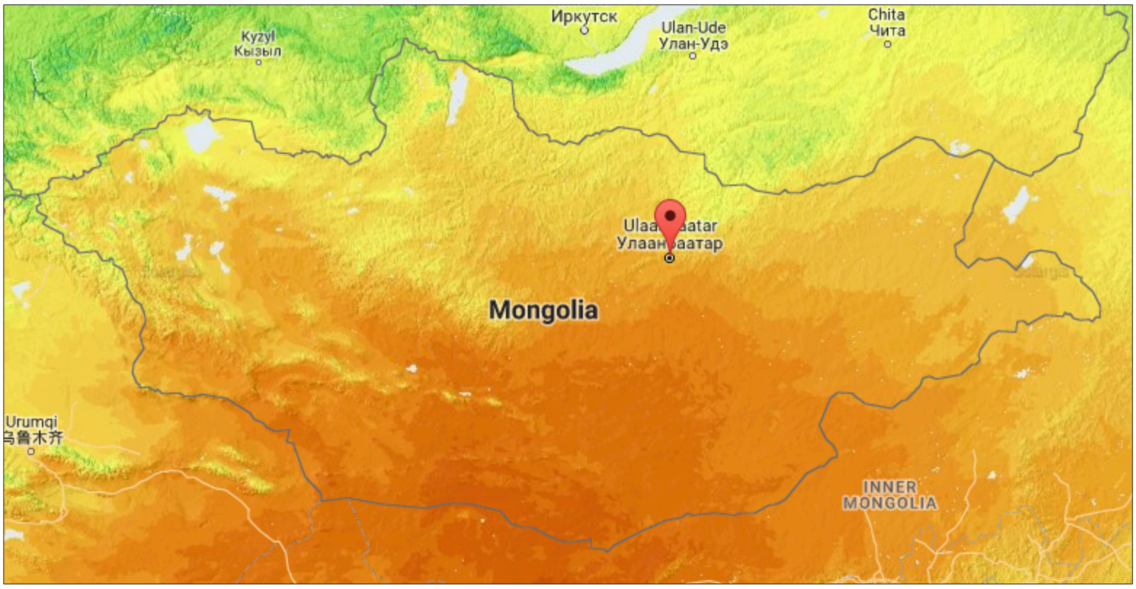

Figure 28: Solar radiation map of Mongolia. *Source:* Solargis.com, available from: https://solargis.info/imaps/#loc=47.910819,106.903839&c=47.906677,107.032928&z=5

Table 17: Solar radiation, radiation duration and average temperature in Ulaanbaatar. *Source:* https://www.ctc-n.org/resources/rural-electrification-renewable-energy-utilization-mongolia

Daily (Wh/m^2) and annual (kWh/m^2) solar radiation in Ulaanbaatar												
Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
1557	2685	4075	5024	6000	6045	5259	4708	4012	2890	1884	1278	1383
Daily and annual solar radiation duration (hour) in Ulaanbaatar												
Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
176.1	204.8	265.2	262.5	299.3	269.0	249.3	258.3	245.7	227.5	177.4	156.4	2791
Average temperature (C°) in Ulaanbaatar												
Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
-25	-18	-5	4	8	16	22	18	11	-3	-15	-22	-0.4

3.3.1 Possible application of flat-plate solar air collectors in ger districts

From the previously discussed solar thermal energy systems, flat-plate collectors with air-based medium system are a suitable alternative for majority of the ger district houses. First, flat-plate collectors with air system are the cheapest solar thermal energy system available, ranging from 150 to 500 Euros per square meter. Since the large percentage of the ger district households have low-income, the cost of the system makes it attractive. However, even 150 Euros is very expensive for most of the households and promotion of these systems in ger district would need investment and support from the government. Second, the construction is very simple and does not require expensive and scarce materials. Thus, it is possible to be manufactured in Mongolia by specialized companies or even by individuals. Third, from 190,000 households living in ger districts, 54% reside in small houses and 44% reside in traditional gers. Usually the area of the houses and gers is very small, mostly comprising of two rooms and ranging from 25 to 60 m^2. Thus, the heating load is not much and can be supplied by flat-plate air collectors in combination with the existing stoves or other conventional heating systems. Furthermore, ger district households buy their drinking and utility water from nearby wells. This limitation to water supply makes the air system more attractive in these cases. Also, when water is used as delivery medium, additional antifreeze system is required, which increases the overall cost of the system. However, air based system does not require antifreeze systems. Due to its high elevation and relatively high latitude Ulaanbaatar is the coldest capital city in the world. Thus, the climate is a subject to frequent freezing temperatures.

Efficiency of solar air collector in general is a fraction of usable thermal energy compared to the received solar energy. There are many methods and formulas to calculate collector efficiency. For instance, Ehrlich (2013), first determines the energy balance equation, where incoming power equals outgoing power and formulates the equation:

$$GA = eGA + \rho GA + \Delta T/R \text{ (Figure 29)}$$

Where GA is the input (i.e. incident solar power per unit area), eGA is the power carried away by the fluid (since this power is the useful output of the collector it equals efficiency (e) multiplied by the inflow (GA)), ρ is the reflected fraction of input (GA), and $\Delta T/R$ represents the thermal power loss from the collector, where ΔT is the temperature difference between the ambient air and the collector, R is thermal resistance. From this equation he derives the efficiency of the collector:

$$e=(1-\rho)-\Delta T/RGA$$

Thus, a specific efficiency for a specific type of collector, for a specific ambient temperature and radiation can be calculated using various formulas as discussed above. In general, flat-plate air collectors with storage can reach efficiencies as high as 80% and temperatures as high as 115°C. El-Sebaii et al. (2007) found that double glazed flat-plate collector with limestone and gravel heat storing media can have efficiencies up to 80%. Similarly, Esakkimuthu et al. (2013) and Saxena et al. (2013) observed efficiencies from 60% to 73% with single glazed flat-plate collectors using desert sand and granular carbon powder as storage material. In all these studies efficiency of collectors where increased significantly with the use of storage unit. For instance, in a survey by Saxena et al. (2013) found that efficiency of a collector improved from 43% to 73%, when there was a storage unit incorporated into the system.

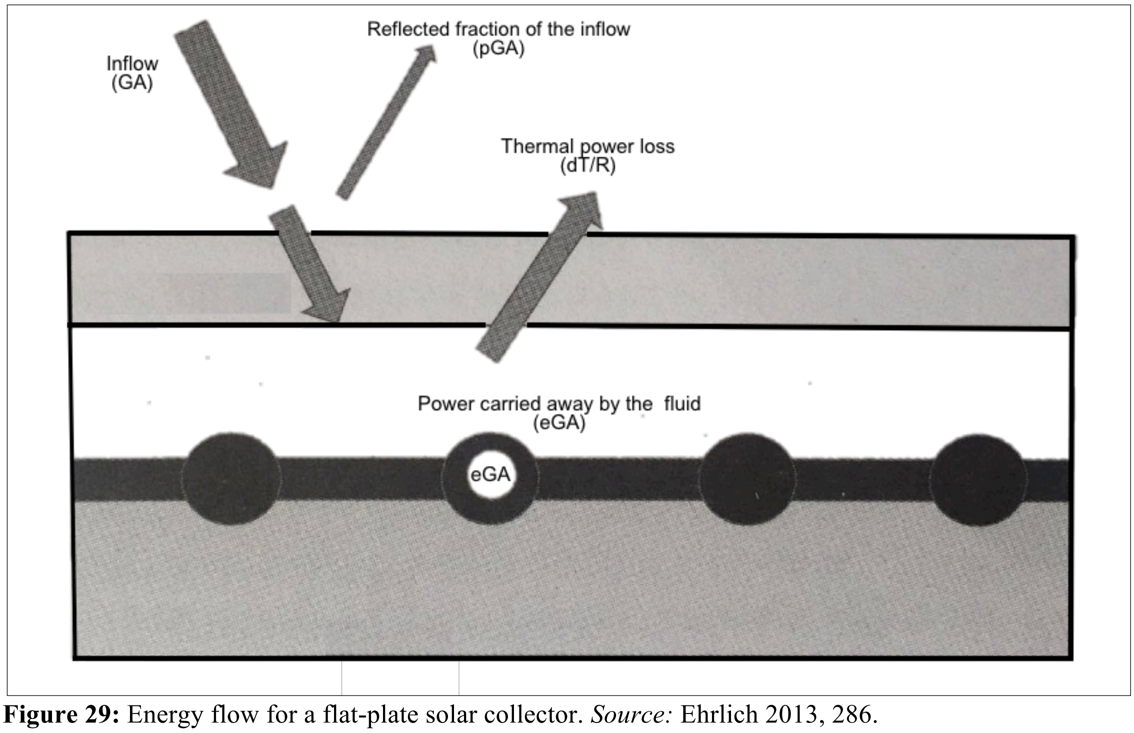

Figure 29: Energy flow for a flat-plate solar collector. *Source:* Ehrlich 2013, 286.

According to the efficiency curves derived for different types of solar collectors by Kalogirou (2009), in Ulaanbaatar, where the solar radiation during winter is higher than 1000 Wh/m^2 (Table 17), efficiency of flat-plate collectors can reach up to 50% and 60% and temperatures differences of 30°C to 40°C (Figure 30). Consequently, flat-plate solar air heaters could supply up to 50-60% of the heating demand in ger district households in Ulaanbaatar during winter. The percentage could increase in the early months of spring and august when the radiation increases and the temperature difference decreases. In these months substantial heating is still required in ger households.

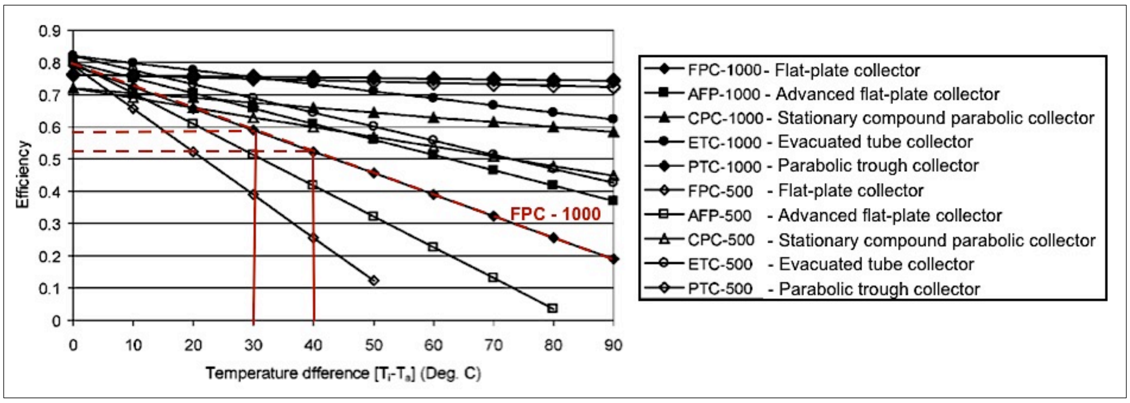

Figure 30: Comparison of efficiency of various collectors at two irradiance levels: 500 and 1000W/m^2. *Source:* Kalogirou 2009, 224.

If 50% of the heating demand could be supplied by solar energy, fuel consumption in a ger district household would decrease twofold. Each household in ger district in average consumes 5 tons of coal and 1.5 tons of wood per year. There are 190,000 households in ger areas of Ulaanbaatar and they in total consume approximately 850,000-950,000 tons of coal and 285,000 tons of wood per year. Solar air heaters have potential to reduce total coal consumption to 400,000-500,000 tons per year. This would translate to 2.1 kilotons less PM_{10}, 3.5 kilotons less SO_2, 1.3 kilotons less NO_X, and 92.1 kilotons less CO emissions per year from ger districts. This reduction of coal and wood consumption in ger districts of Ulaanbaatar would reduce the city's overall emissions of PM_{10} by 6%, SO_2 by 12%, NO_X by 5% and CO by 23% (Table 18).

Table 18: Ger district household annual emission comparison between heating systems aided by the solar energy and systems that are not. *Source:* Calculated by the author.

	Annual emissions (tons/year)			
	PM_{10}	**SO_2**	**NO_X**	**CO**
Without solar energy	3 893	6 377	2 382	167 061
With solar energy	1 946	3 188	1 191	83 530
Overall emission reduction in Ulaanbaatar	6%	12%	5%	23%

Besides reducing the city's air pollution level, solar energy is a cost efficient heating alternative for ger district households. One ton of coal costs between 26 and 34 Euros in Ulaanbaatar. The price tends to increase when the temperature gets lower. In average both ger district houses and gers consume 5 tons of coal per year. Correspondingly, each household spends approximately 130-170 Euros per year on fuel. This accounts for over 50% of average ger district household income (ADB 2008). Thus, households with a solar air heat system would save each year approximately 65-85 Euros on fuel. In addition, the system requires little or no maintenance and usually lasts for 20-30 years.

3.3.2 Possible application of water-based solar heat systems in ger districts

Water-based solar heating systems can work both with flat-plate and evacuated tube collectors. Evacuated tube collectors are more expensive than flat-plate collectors, but they perform better in cold climates compared to the flat-plate collectors. The vacuum reduces convection and conduction losses, resulting in higher temperatures. Also, due to their form, the tube collectors have higher efficiency at low incident angels. Thus, due to its high temperature and better efficiency, evacuated tube collectors could be a suitable alternative for heating small public properties such as small district hospitals, administrative and municipal offices, as well as small flats and houses which are not connected to the district heating and use traditional stoves or heat-only boilers (HOBs) for heating and hot water supply.

HOBs are the third largest air pollution source in Ulaanbaatar. An estimated number of 1,215 HOBs are operating in Ulaanbaatar. Majority of them are installed in state in municipal properties such as schools, hospitals, police posts and administrative buildings. They consume 169,857 tons of coal each year and emit tons of pollutants into the atmosphere. Recently, the number of HOBs has been increasing in Ulaanbaatar due to the population growth and the inability of the district heating to expand.

Thus, evacuated solar collector could replace or supplement the existing HOBs in such properties to reduce the consumption of coal. However, the heat transport medium in this type of collector is usually water. And when water is used as transfer medium in cold climates where freezing occurs frequently, a reliable antifreeze system should be in place. In fact, such collectors are being used in number of chosen properties in Ulaanbaatar as a part of air pollution reduction initiative. The properties include a district administration building, a district hospital, a police post, and 21 ger district households, ranging from 45 to 128 m^2. The system is supported with an auxiliary electric boiler. In recent years, the government of Mongolia has been actively supporting utilization of renewable energies. As a country with abundant recourses of coal, the energy sector has been solely dominated by coal. However, taking into consideration the environmental concerns and insecurity of relying on one source of energy, Mongolia has decided to shift its dependence on coal and pursue sustainable energy future. Thus, it is a good opportunity to take advantage of the government's growing interest in renewable energy technology and utilize it in reducing air pollution in Ulaanbaatar.

Efficiency of evacuated tube collector is calculated on the same principles as the flat-plate collectors. That is by calculating how much of the received solar energy is transferred to usable thermal energy. As there are less thermal losses with tube collector compared to the flat-plate collector, efficiency is also higher. In Ulaanbaatar, winter solar radiation is higher than 1000 Wh/m^2 and the ambient temperature can drop as low as -30°C. Under these conditions, evacuated collectors can have efficiency up to 70%.

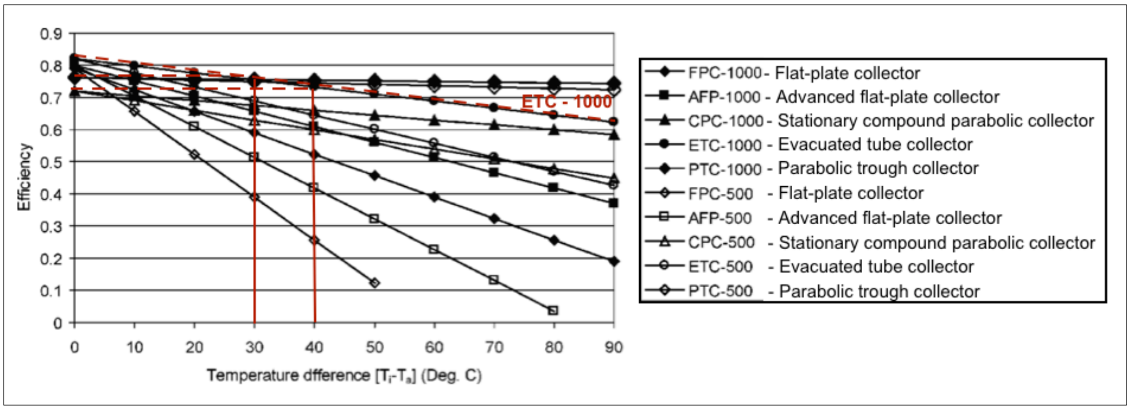

Figure 31: Comparison of efficiency of various collectors at two irradiance levels: 500 and 1000W/m^2. *Source:* Kalogirou 2009, 224.

If the 1000 small HOBs in Ulaanbaatar were to be replaced or supplemented with evacuated tube collectors, up to 70% of the heating demand could be supplied by solar energy. This would mean possibility of coal consumption reduction up to 70% by the small HOBs. The current 1000 small HOBs consume 19,857 tons of coal annually. Solar heating system would have a potential to reduce the coal consumption by 70% saving 13,900 tons each year. This would translate into 92 tons less PM_{10}, 220 tons less SO_2, and 325 tons less CO (Table 19). However, as shown in the table 19, the coal consumption reduction in small HOBs does not have much influence on the overall emission levels. This is because large portion of HOBs emissions are produced by the large HOBs with a capacity of higher than 500 kW. The 215 large HOBs consume 150,000 tons of coal per year, while 1000 small HOBs consume only 19,857 tons of coal per year.

Table 19: Small HOBs annual emission comparison between heating systems aided by the solar energy and systems that are not. *Source:* Calculated by the author.

	Annual emissions (tons/year)			
	PM_{10}	SO_2	NO_X	CO
Without solar energy	130	313	103	463
With solar energy	38	93	31	138
Overall emission reduction in Ulaanbaatar	0%	1%	1%	0%

The large HOBs that provide district heating in some parts of the city also can be supported by solar energy. District solar space heating systems have been in operation since the 1970s. This system collects solar energy from larger fields and stores it in large underground storage tanks. However, it cannot operate alone to supply all of the districts thermal energy needs throughout a year. Nonetheless they can contribute significantly (Thorpe 2013). Thus, utilizing solar energy in district heating also might have considerable potential to reduce air pollution in Ulaanbaatar, where large HOBs account for considerable portion of the emissions. However, in my thesis I will concentrate on utilizing small-scale solar heating technologies that is most suitable for individual households in ger districts. Analyzing large scale solar heat systems and their potential to reduce air pollution can be another interesting research topic in this area.

3.3.3 Possible application of passive solar heating system in ger distrcits

As discussed in the Part 3.2, effective incorporation of passive solar heating system into the design of the building can reduce energy consumption of the building. In Ulaanbaatar, about 60% of the total population, i.e. approximately 190,000 households, reside in ger districts. From these 190,000 households, 55% reside in small houses and 44% live in traditional gers (City Air Quality Department 2013).

Mongolian traditional ger or yurt is comprised of wooden circular frame covered with wool felt (Figure 32). There are different size ranges of ger. Typical size is 25 square meters. According to the World Bank (2013), 65% of the ger in Ulaanbaatar has double or more felt layers, and 30% of the gers has only one layer of felt cover. Almost all the gers (i.e. 98%) cover the wheel, a circular frame opening at the top of the ger, with glass. Majority of the ger has wooden floors. Usually larger gers that were built for permanent residence purposes have thick insulated floors, while smaller temporary gers have thin wooden floors. About 10% of gers have concrete floors. Also, one-third of the gers have small hallways built to the ger’s door to reduce heat losses from the door.

Wool felt cover is a type of insulation for gers. Wool is a highly insulating clothing material due to its ability to trap air. Thermal insulation basically means reduction of heat transfer between objects. Thus to reduce heat transfer a low thermal conductivity material is used. Air has low thermal conductivity if it can be trapped. Thus, it is advisable to have two or more layers of wool cover for gers to reduce thermal losses. The government should initiate projects to provide ger covers at reduced prices to low income households residing in gers. The United Nations Development Program (UNDP) provided 400 gers in Ulaanbaatar with highly insulated ger covers, and found out that the households fuel consumption was reduced by a factor of three (ADB 2008).

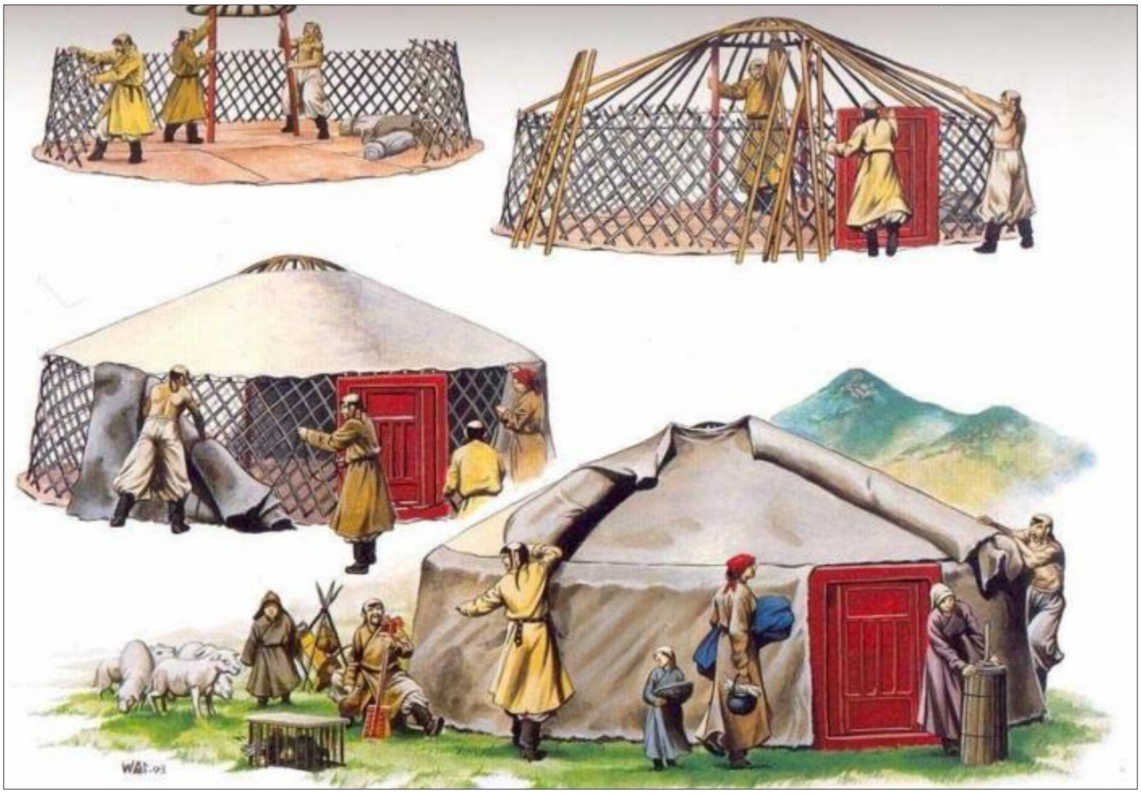

Figure 32: Construction of Mongolian traditional ger.

As there are no windows and no thermal walls on gers, direct and indirect solar gain is very low for gers. Thus, the heating in ger is solely supplied by the stoves installed in the center. Also, as there is little thermal mass in ger construction to absorb and store the energy, the temperature rises and falls very quickly in it. Thus, inhabitants fuel their stoves until late in the night and start early in the morning. Concrete floors could serve as thermal storage and might reduce the hours of continuous coal combustion in gers. Moreover, the color of ger is usually white or light grey, which is the color of the wool felt. However, some gers have an outer thin white layer for aesthetic reasons. But white is a color that reflects solar energy. It will reduce the absorption of incoming radiation by gers and possible direct or indirect solar gains. Thus, maybe a new design and color for ger covers, preferably darker color, might foster utilization of passive solar energy in gers.

About 55% of ger district households (i.e. 190,000) live in small individual houses, typically 24-32 m^2. The houses are made of various different materials: 47% of the houses are made from wood and bricks; 33% from wood and clay; 6% from concrete; 14% from mix of different materials (City Air Quality Department 2013). Majority of the houses are small one-story buildings. Two or more story buildings comprise only 10%. Each house is surrounded by a fence up to 700 m^2. In some cases, one such a fence is shared by two or more households. The quality of the houses in general is very poor, not complying to engineering and construction standards and requirements. About 90% of the houses are informally constructed by individuals without any architectural plan or design.

Figure 33: Ger district in Ulaanbaatar. *Source:* http://www.eurasianet.org/node/62619

Usually in Mongolia, both houses and gers face the south. Small houses in general have up to three small windows, most placed on the southern walls. Overshadowing of the windows occur rarely, since the houses are located at some distance from each other. Thus, almost all the houses are to some extend passive. However, due to poor quality construction and insulation, the houses are very inefficient in thermal energy. According to the Asian Development Bank (2008), energy consumption of households in ger districts, both living in gers and small houses, could be halved by proper insulation. For instance, there are 25,000 gers with only one layer of insulation. If these gers were to be insulated it would save 62,500 tons of coal per year. This translates to 206 tons of PM_{10}, 470 tons of SO_2, and 10833 tons of CO.

4 Conclusion

In recent years, air pollution has become one of the most pressing issues in Ulaanbaatar, concentrations of PM_{10} and $PM_{2.5}$ reaching 1100 μg/m^3 and 436 μg/m^3, respectively. This is 22 and 17 times higher than the WHO guidelines. The key contributors to the air pollution are ger districts, power plants and heat-only boilers. In this thesis I analyzed application of various solar energy technologies in ger districts to reduce air pollution levels.

About 190,000 households reside in sub-urban ger districts of Ulaanbaatar and consume 850,000 tons of coal per year, mainly for heating purposes. Consequently, these households annually emit 3,893 tons of PM_{10}, 6,377 tons of SO_2, and 167,061 tons of CO into the atmosphere (Part 2.2.2 Table 6). Since, Mongolia receives abundant solar radiation ranging from 1278 kW/h in winter to 6040 kW/h in summer, solar energy could provide a sustainable and cost efficient heating for these households.

There is a wide variety of solar space heating systems available today. Flat-plate solar air collector could be a suitable alternative for ger district households mainly due to its low price. In combination with the existing heating system, flat-plate collectors can provide reliable and adequate thermal energy to meet the heating load of houses and gers both. The efficiency of flat-plate collector vary depending on the design and materials used, and the available solar radiation of the location. Nonetheless, some designs with storage can reach efficiencies as high as 80% and temperatures as high temperatures as 115°C.

Solar air heaters have potential to reduce total coal consumption to 400,000-500,000 tons per year. This would translate to 2.1 kilotons less PM_{10}, 3.5 kilotons less SO_2, 1.3 kilotons less NO_X, and 92.1 kilotons less CO emissions per year from ger districts. This reduction of coal and wood consumption in ger districts of Ulaanbaatar would reduce the city's overall emissions of PM_{10} by 6%, SO_2 by 12%, NO_X by 5% and CO by 23% (Part 3.3.1 Table 18).

Evacuated tube collector is a possible alternative for replacing or supplementing small heat-only boilers (HOBs) in Ulaanbaatar. However, the coal consumption reduction in small HOBs does not have much influence on the overall emission levels. This is because large portion of HOBs emissions are produced by the large HOBs with a capacity of higher than 500 kW. The 215 large HOBs consume 150,000 tons of coal per year, while 1000 small HOBs consume only 19,857 tons of coal per year. Thus, replacing large HOBs with large scale solar energy systems could have considerable effect on air pollution reduction efforts.

All in all, effective incorporation of various solar heating systems in ger districts has a significant potential in reducing air pollution in Ulaanbaatar. Besides, the government of Mongolia has set goals to increase share of renewable energies to 30% by 2030. Thus, it is a suitable time to promote and develop solar energy systems in the country.

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