Future $PM_{2.5}$ exposures & health impacts in Ulaanbaatar under alternative policy pathways and

Demonstration of double compression household heat pumps in winter 2017-18

Presentation by Prof Kirk R. Smith, UC Berkeley

Prepared by the

Research Teams of Kirk R. Smith and Xudong Wang (Tsinghua) with Mongolian Researchers

At the UNDP, Ulaanbaatar, Mongolia

November 17, 2017

Report of the Project:

Impact of Urban Air Pollution on Public Health

For the Ministry of Environment and Green Development, Ulaanbaatar

An International Collaboration

University of California, Berkeley

University of California, Irvine

Washington University in St. Louis

Mongolia National University of Medical Sciences

National Institutes of Health

Desert Research Institute

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RESEARCH ARTICLE

Health assessment of future $PM_{2.5}$ exposures from indoor, outdoor, and secondhand tobacco smoke concentrations under alternative policy pathways in Ulaanbaatar, Mongolia

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Abstract

Introduction

Winter air pollution in Ulaanbaatar, Mongolia is among the worst in the world. The health impacts of policy decisions affecting air pollution exposures in Ulaanbaatar were modeled and evaluated under business as usual and two more-strict alternative emissions pathways through 2024. Previous studies have relied on either outdoor or indoor concentrations to assesses the health risks of air pollution, but the burden is really a function of total exposure. This study combined projections of indoor and outdoor concentrations of $PM_{2.5}$ with population time-activity estimates to develop trajectories of total age-specific $PM_{2.5}$ exposure for the Ulaanbaatar population. Indoor $PM_{2.5}$ contributions from secondhand tobacco smoke (SHS) were estimated in order to fill out total exposures, and changes in population and background disease were modeled. The health impacts were derived using integrated exposure-response curves from the Global Burden of Disease Study.

Hill et al 2017, PLOSOne

Study objectives

- Develop 3 emissions policy pathways for Ulaanbaatar (UB), 2014-2024
    1. Business as usual, or BAU: no major changes from 2013 emissions trends
    2. Pathway 1: moderate emissions reductions
    3. Pathway 2: major but feasible emissions reductions
- Estimate demographics and background disease values, 2014-2024
    - Diseases considered: stroke, lung cancer, ischemic heart disease, chronic obstructive pulmonary disease, and acute lower respiratory illness in children
- Estimate UB-wide $PM_{2.5}$ exposures under each pathway
- Convert exposures into estimates of health effects

Findings from Hill et al 2017

Summary of key baseline and pathway features

2014	2024		
Baseline	Business as Usual (BAU)	Pathway 1	Pathway 2
• "Clean indoor" heat in apartments • assumes no indoor emissions • Some heat-only boilers (HOB) • Houses & ger heat with "improved" MCA stove or similar (e.g. low pressure boiler, [LPB]) • 4 combined heat & power plants (CHP) • Nearly 100% growth in traffic from 2010 values	• Not much change from home heating schema of 2014 • Add 1 CHP, meets US standards (NSPS) • 2.5% traffic growth per year from 2014, Euro III emissions standards	• "Clean indoor" heat in many houses, all apartments • 50% HOB retired, others retrofitted • New "Future Tech" improved coal stove in many houses, all ger • LPB still in some houses • 4 CHP retrofitted • Add 1 CHP at US NSPS • Same traffic growth as BAU, Euro V standards	• **"Clean indoor" heat in all homes** • All HOB retired • 3 original CHP retrofitted • Add 1 CHP at US NSPS • 1 CHP replaced by renewables and/or imports • 50% reduction in traffic emissions from Pathway 1

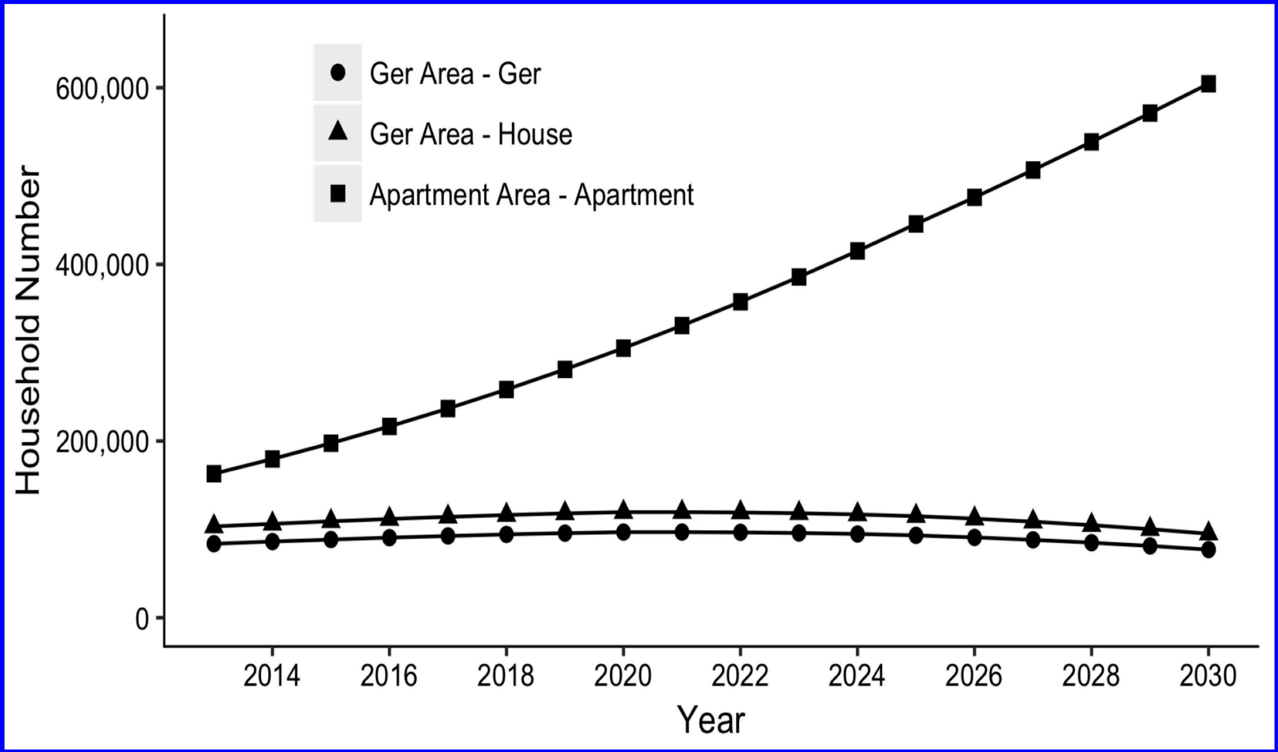
Adapted from Table 1, Hill et al 2017. Summary of the assumptions made for emissions sources, by category.

Estimates of demographic and disease trends

Findings from Hill et al 2017

Anticipate major growth in total population and household number

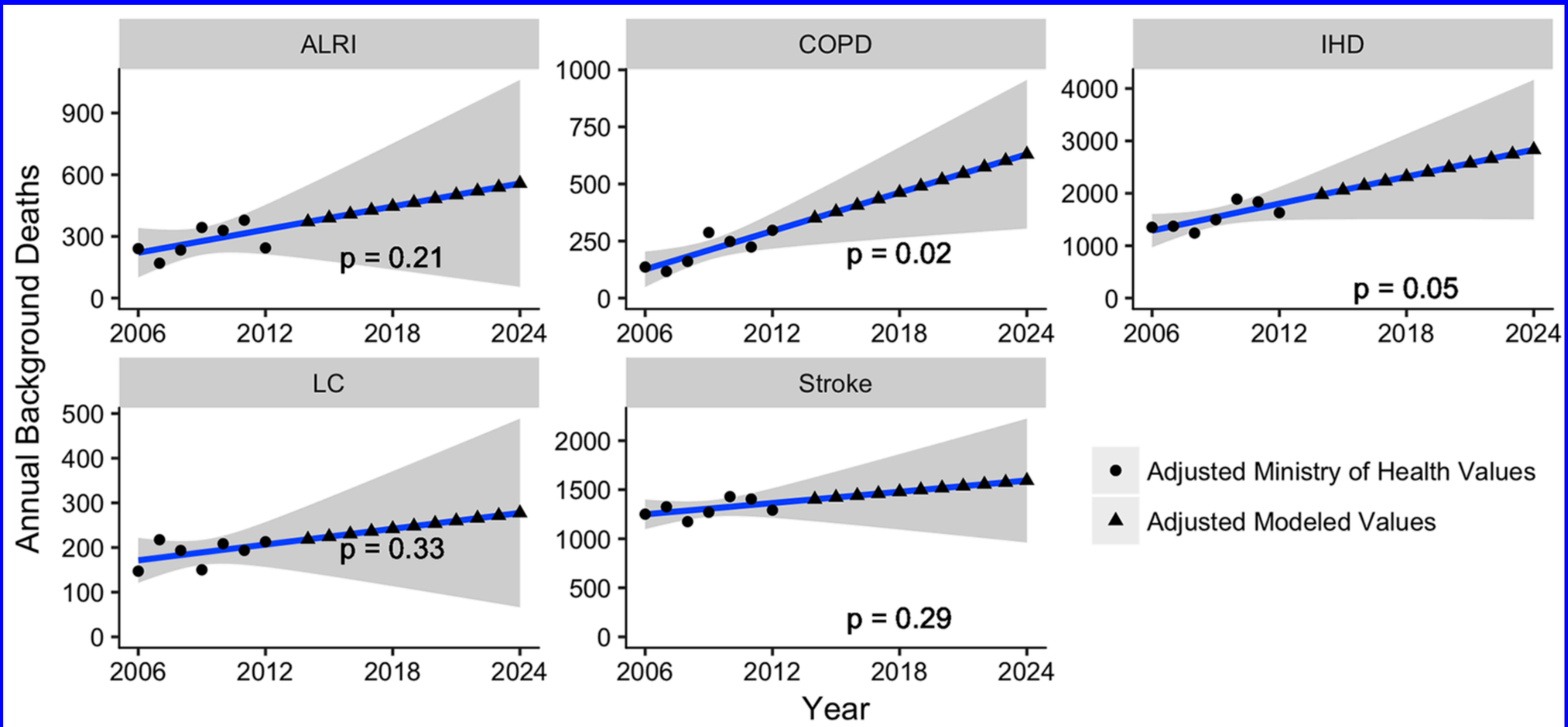
Expect increase in % population living in Apartments



see manuscript for methods, data sources, assumptions

Findings from Hill et al 2017

Projected annual background mortality for 5 diseases



see manuscript for methods, data sources, assumptions

Findings from Hill et al 2017

Key aspects of the exposure assessment

Findings from Hill et al 2017

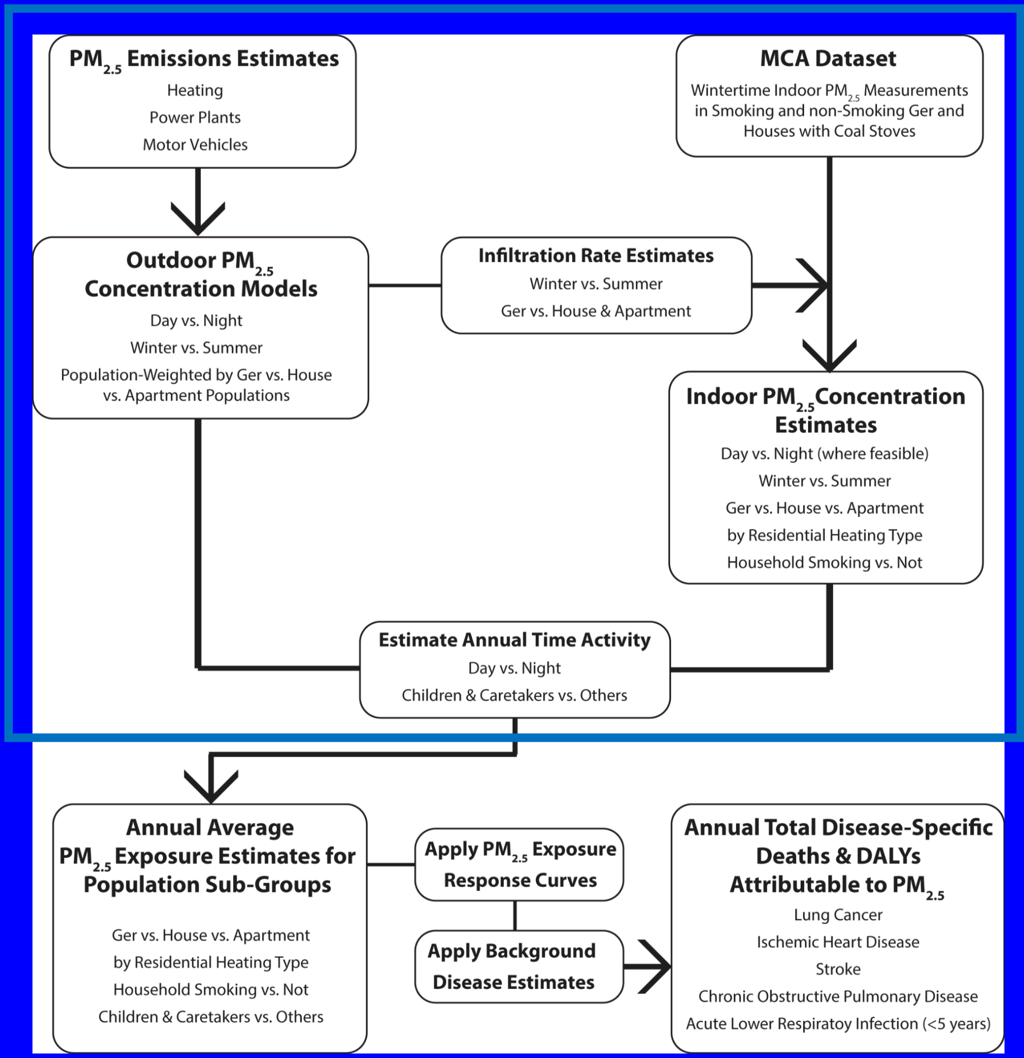
Total exposure approach

Combined:

- Modeled outdoor concentrations
- Indoor concentrations estimated by:
  - Home type
  - Home heating type
  - Presence of tobacco smoke (SHS)
- Estimated time activity values

Produced estimates of seasonal and annual average $PM_{2.5}$ exposures in UB

Fig 1, Hill et al 2017. High-level flow chart of the general exposure and disease analysis approach.



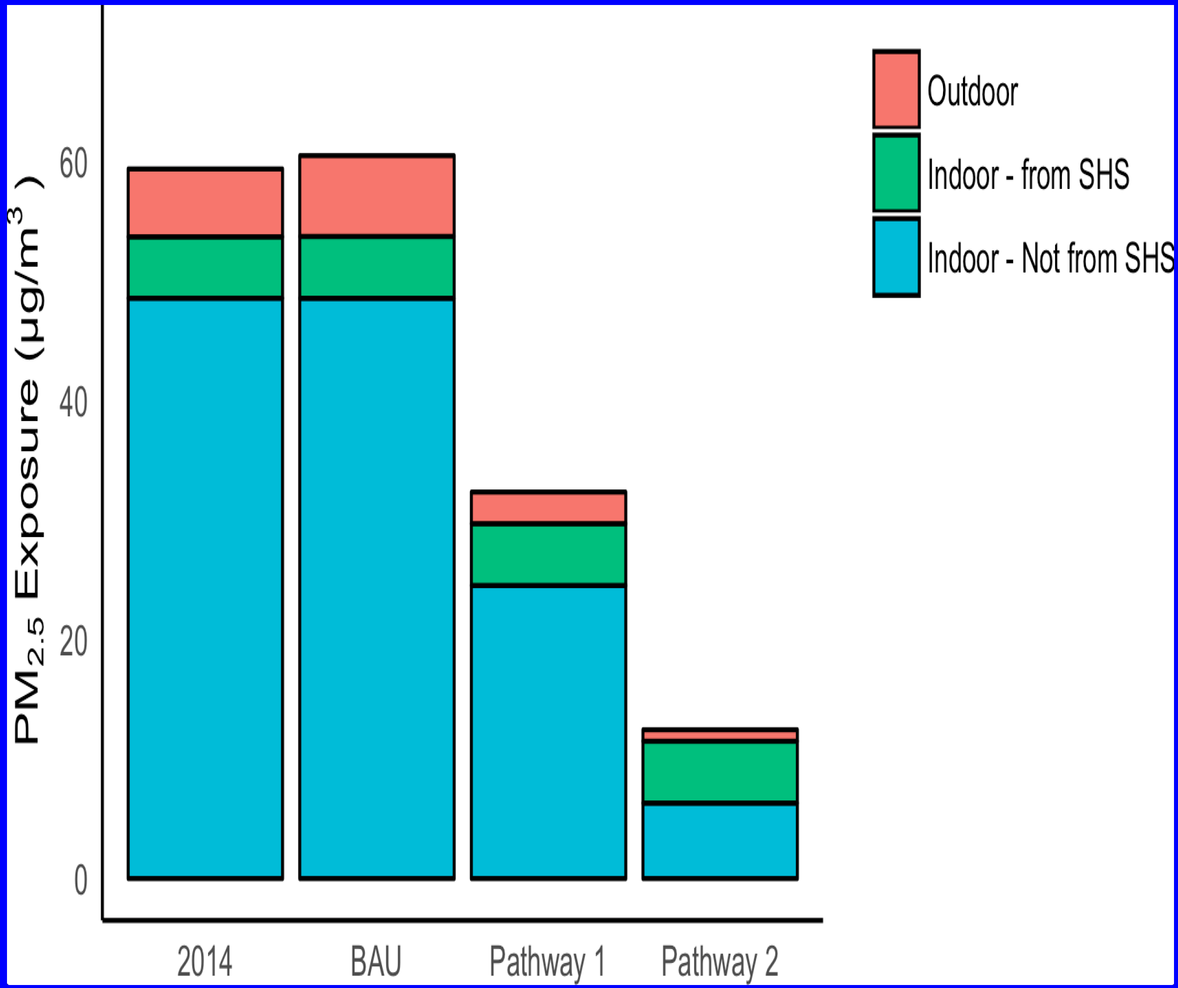
Findings from Hill et al 2017

Annual average $PM_{2.5}$ exposures in UB

2014: 59 µg/m^3

2024:

- BAU: 60 µg/m^3
- Pathway 1: 32 µg/m^3
- Pathway 2: 12 µg/m^3



Findings from Hill et al 2017

Summary of $PM_{2.5}$- attributable health impact estimates

Findings from Hill et al 2017

Metrics

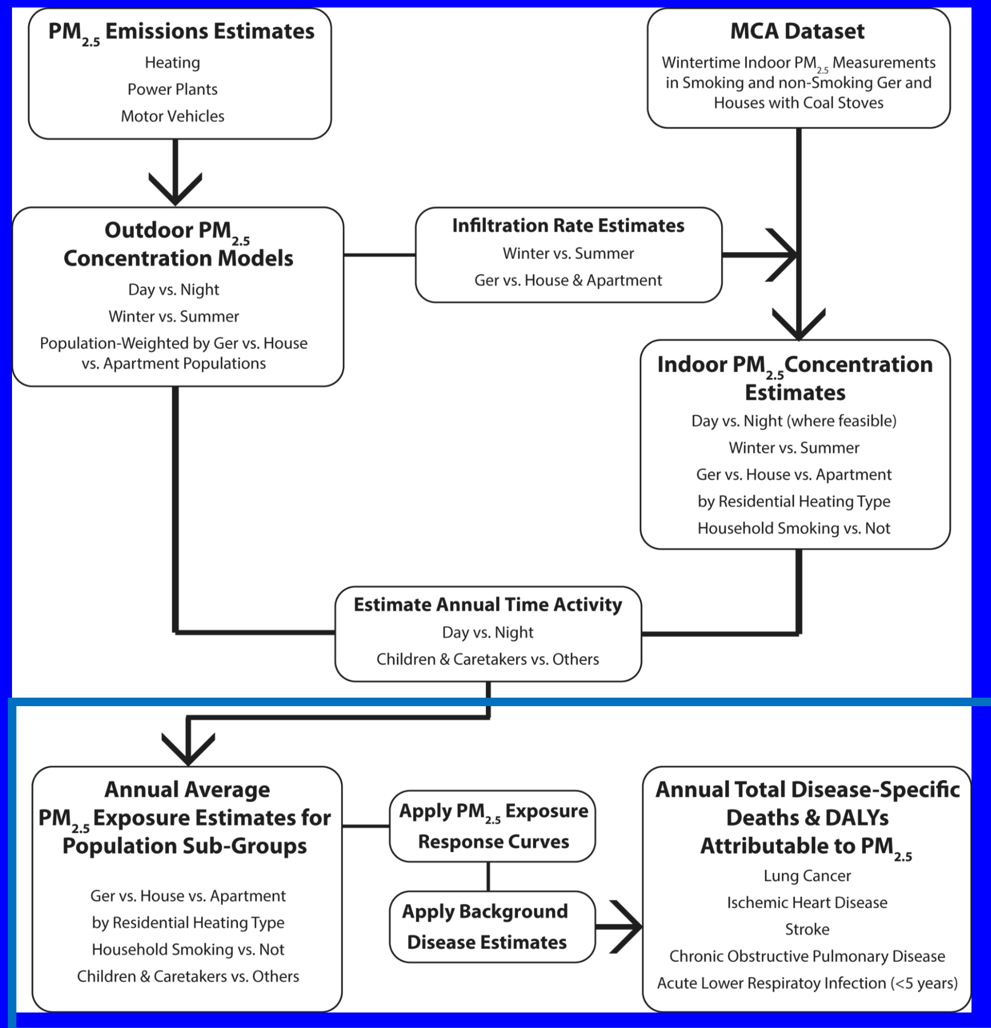
- Premature deaths due to air pollution caused diseases

- Disability Adjusted Life Years lost – DALYs
  - This metric is adjusted to account for the age of death and the severity of the illness even if not fatal
  - Important when adding together child and adult outcomes

$PM_{2.5}$ attributable deaths and DALYs estimated from:

- Annual avg. UB exposure estimates
- $PM_{2.5}$ exposure-response curves used in the 2010 Global Burden of Disease study (Burnett et al 2014, Lim et al 2012)
  - Counterfactual (i.e. relative risk = 1) of **12.0 µg/m³**
- Projected demographics and background total mortality for 5 diseases
- Disease-specific Death/DALY ratios for Mongolia in 2010 (Lim et al 2012)

Fig 1, Hill et al 2017. High-level flow chart of the general exposure and disease analysis approach.



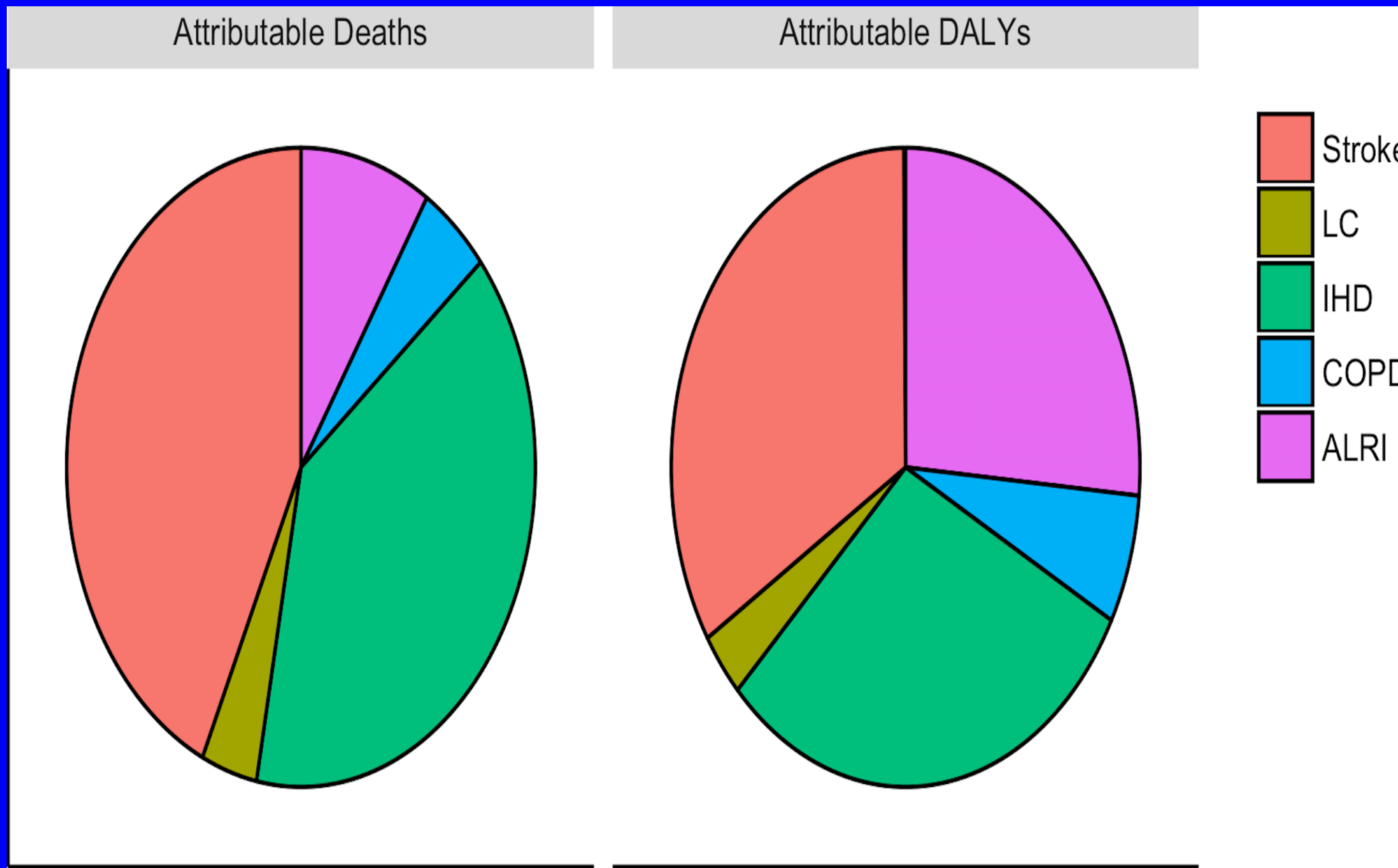
Findings from Hill et al 2017

Estimated $PM_{2.5}$ health impacts

At baseline, 2014
- 1,400 deaths
- 40,000 DALYs

Deaths accrued, 2014 -24
- BAU: 18,000
- Pathway 1: 14,000
- Pathway 2: 9,800

DALYs accrued, 2014-24
- BAU: 530,000
- Pathway 1: 420,000
- Pathway 2: 290,000

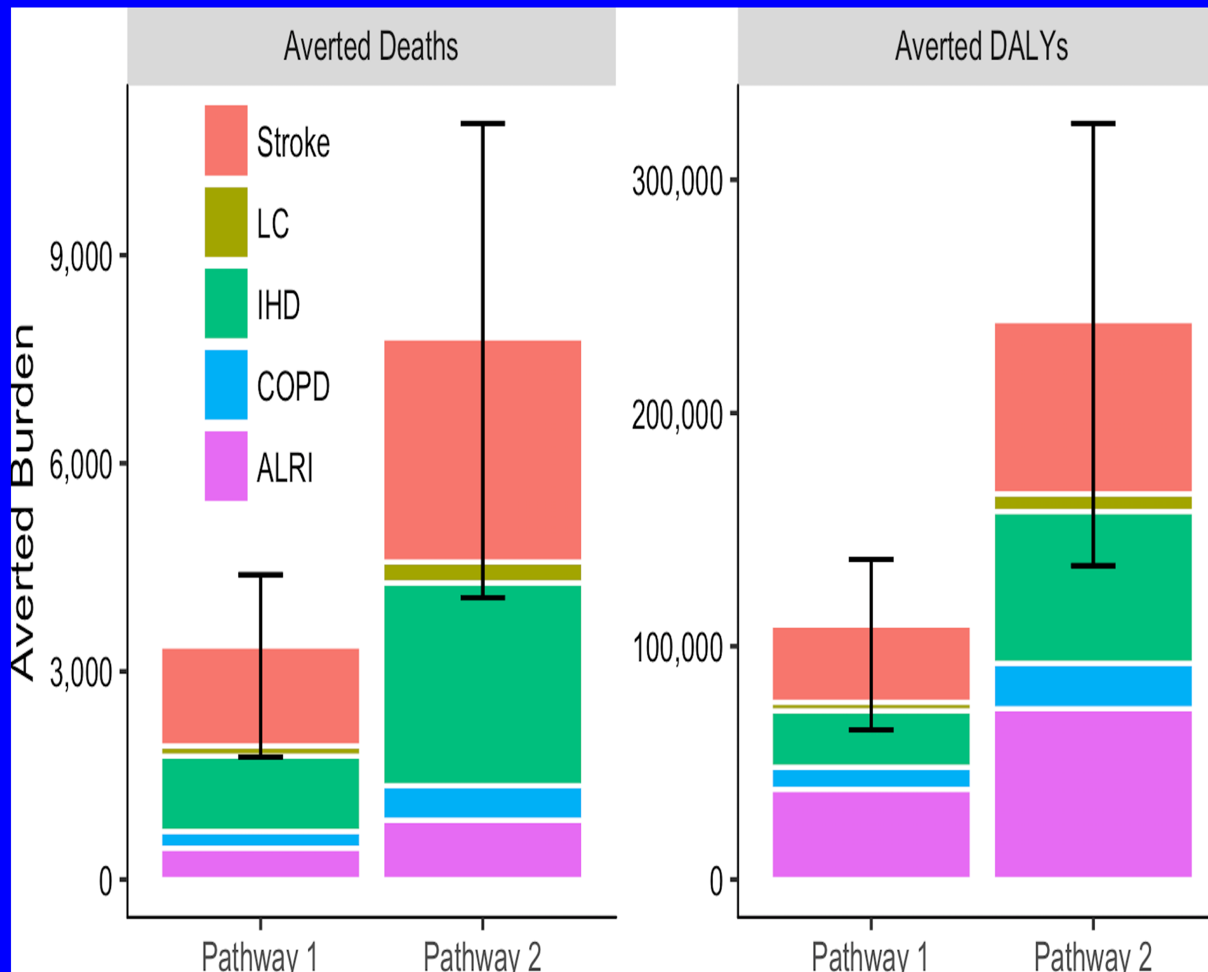


Findings from Hill et al 2017

Pathways 1 & 2 avert thousands of deaths and many more DALYS otherwise accrued under BAU

Child disease (ALRI) accounts for many of the averted DALYs

<u>Substantially more burden averted by Pathway 2 than Pathway 1</u>

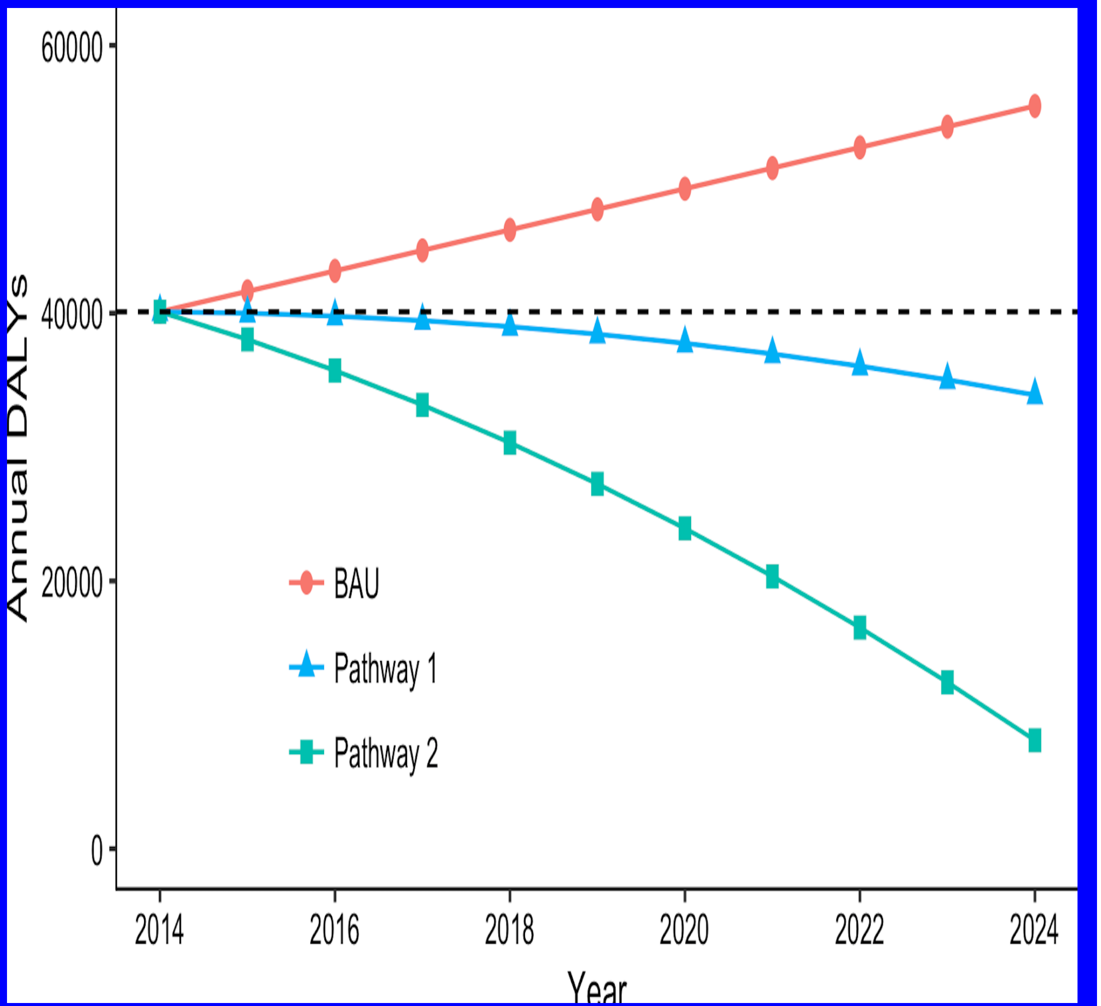


Findings from Hill et al 2017

Total DALYs from $PM_{2.5}$ increase by 2024

- Due in part to population growth

Large reductions in *total* annual DALYs from $PM_{2.5}$ are achieved under the major emissions reduction policy pathway



Findings from Hill et al 2017

Caveats

- Does not include every source of pollution ; only the major ones
- Tobacco smoke, which begins to be important late in the period, may come down as anti-tobacco policies are implemented
- Not all air pollution health effects included, only the five in the Global Burden of Disease studies
- There is growing evidence of other effects, however, including
  - Other cancers
  - Adverse pregnancy outcomes
  - TB, adult pneumonia, and flu
  - Diabetes
  - Etc.

2014	2024		
Baseline	Business as Usual (BAU)	Pathway 1	Pathway 2
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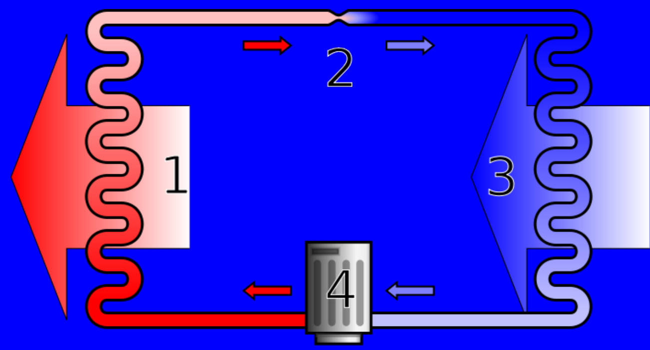
What might be done?

- Better coal stoves: Not clean enough, not reliable enough
- LPG: Requires imports
- Natural Gas: Also requires imports plus pipelines
- Synthetic NG or LPG from coal? Requires synfuel industry
- Electric heating: Most households electrified, but conventional heaters too inefficient

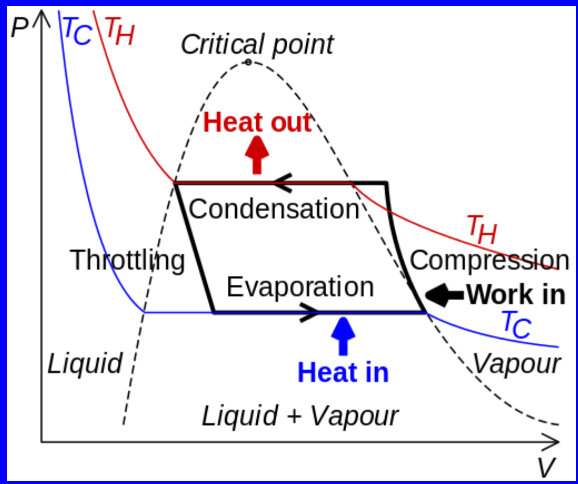
Heat pumps

- A **heat pump** is a device that **transfers** heat energy from a source of heat to a destination called a "heat sink".
- Heat pumps are designed to move thermal energy in the opposite direction of spontaneous heat transfer by absorbing heat from a cold space and releasing it to a warmer one.



A simple stylized diagram of a heat pump's vapor-compression refrigeration cycle: 1) condenser, 2) expansion valve,
3) evaporator, 4) compressor.

Hypothetical pressure-volume diagram for a typical refrigeration cycle



$$COP = \frac{Q}{W} \leq \frac{T_H}{T_H - T_C}$$

$\boldsymbol{Q}$ is the amount of heat delivered to a hot reservoir at temperature $\boldsymbol{T_H}$.
$\boldsymbol{W}$ is the energy consumption of heat pump (work input).
$\boldsymbol{T_H}$ and $\boldsymbol{T_C}$ are the temperature of hot and cold reservoir, respectively.

Heat Pumps, cont.

- Heat pumps draw heat from the cooler external air **(air source heat pump**) or from the ground (ground source heat pump).
- Although air conditioners and freezers are familiar examples of heat pumps, the term "heat pump" is more general and applies to many HVAC (heating, ventilating, and air conditioning) devices used for **space heating**.

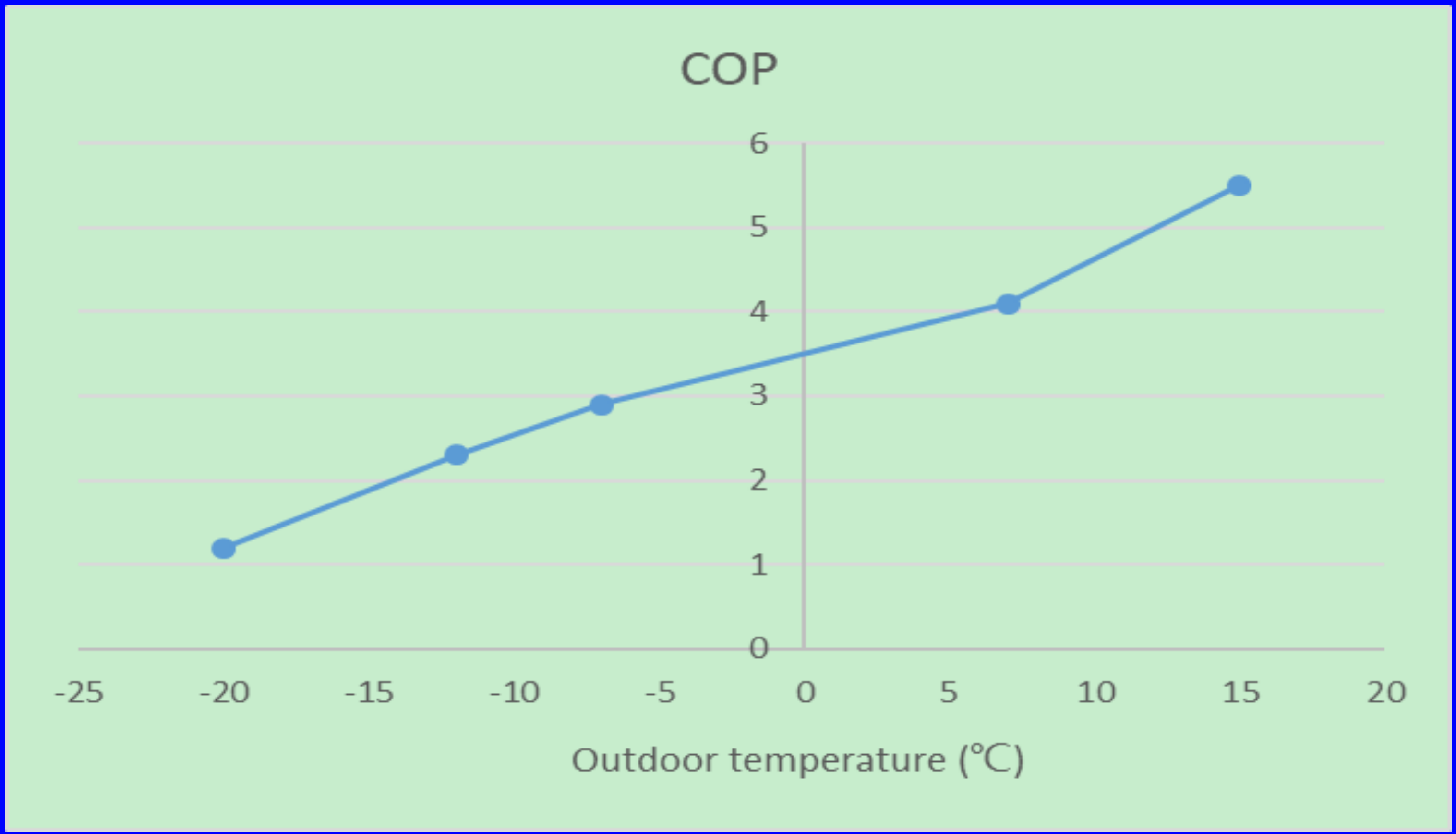
Coefficient of Performance (COP)

- A heat pump uses a small amount of external power to accomplish the work of transferring energy from the heat source to the heat sink.
- The term **coefficient of performance (COP)** is used to describe the ratio of useful heat movement per work input.

COP, cont.

- **The COP for heat pumps range from 3 to 5** for air source heat pumps, that means heat pumps are three to five times more effective at heating than simple electrical resistance heaters using the same amount of electricity.
- Due to refrigeration cycle efficiency limits, the **COP will decrease as the outdoor-to-indoor temperature difference increases** (outside temperature gets colder).

COP: Normal Heat Pump



Problems of conventional heat pumps in cold areas

Heating capacity is insufficient in cold ambient conditions

As the outside air temperature drops, the buildings heating load increases but the heat pumps efficiency decreases.

Low reliability in cold ambient conditions

As the ambient temperature decreases, the suction pressure decreases, which is likely to increase the compression ratio and rapidly increase the discharge temperature. The high discharge temperature may lead to the decomposition of refrigerants and the carbonization of lubricant oils.

Low thermal comfort in heating season

A traditional wall-mounted air source heat pump blows warm air from upper sideways, which causes the warm air to accumulate in and be constrained to the top of the room. Temperature stratification occurs in the vertical direction, which reduces comfort (for instance, owing to cold feet).

Improvement by changing compressor

Traditional single stage compressor (one cylinder)

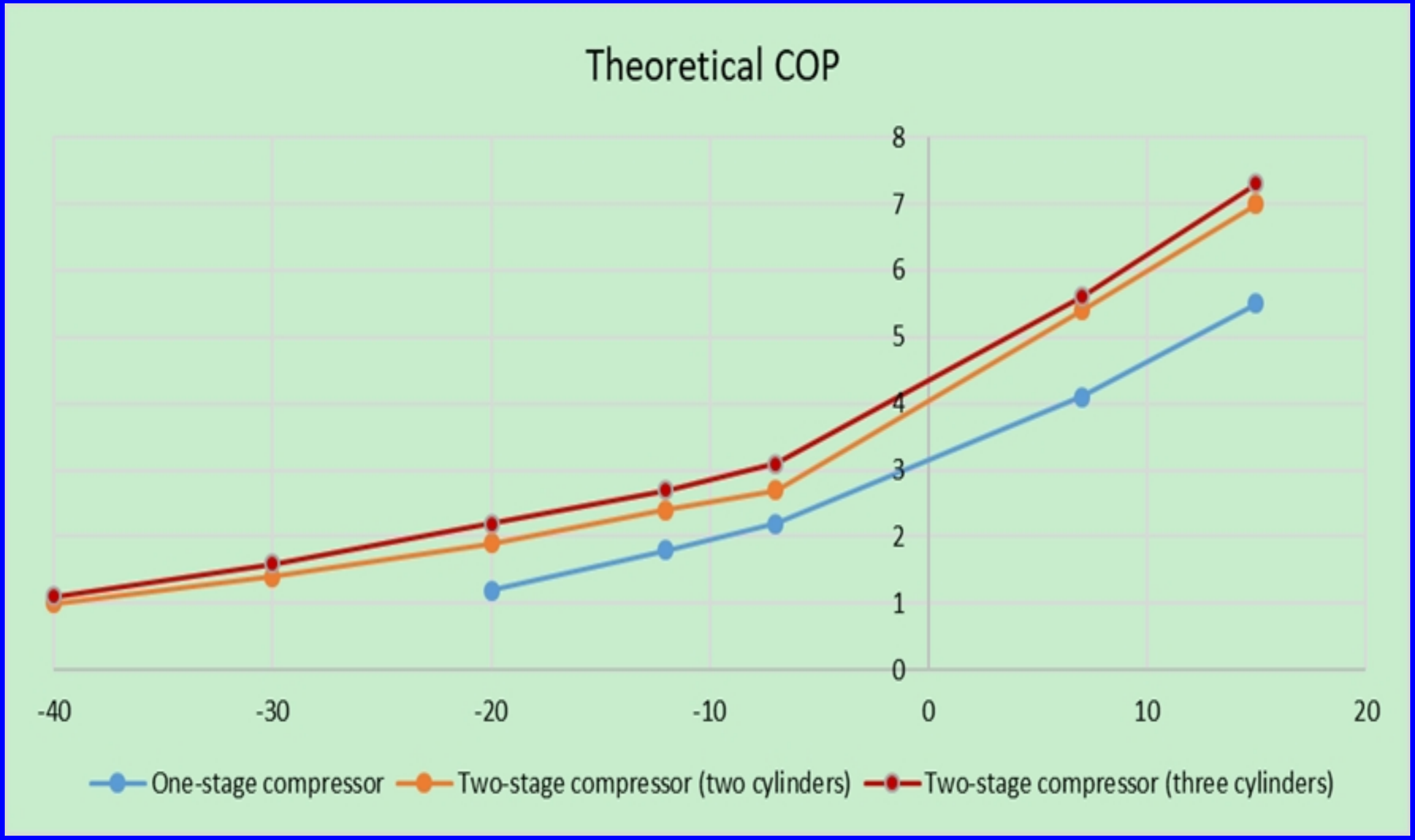
Improved double stage enthalpy-added compressor

(Two cylinders)

(Three cylinders)

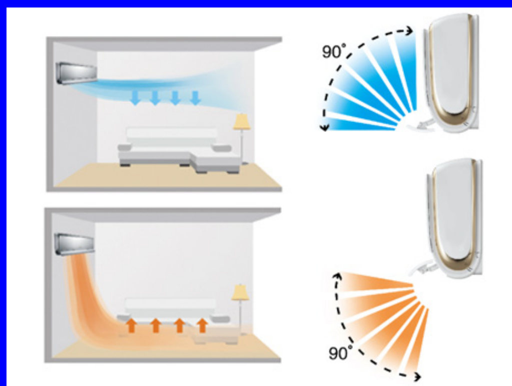
- Enhanced capacity in cold ambient Improved conditions
- COP is up to 2.0+ at the outdoor temperature of -20℃
- Can running normally at the outdoor temperature of -35℃
- Includes automatic defrost
- Working fluid is R-32 , Difluoromethane, also called HF C-32.

Benefits of Double Compression



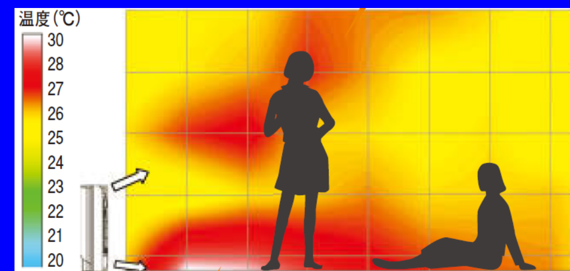
Improvements of thermal comfort

Generation 1



Motional air distribution technology
Big air guide louver allows 180°up&down swing and 130°left&right swing. Air distribution is much wider, with cooling from top to bottom and **heating from bottom to top**.

Generation 2



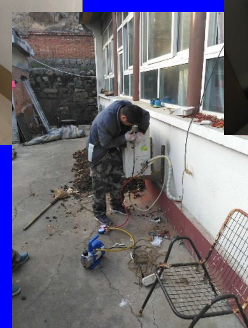
2 air supply outlets Warm air can be transported to human body (upper) and **feet** at the same time.

Case studies in the Beijing Area

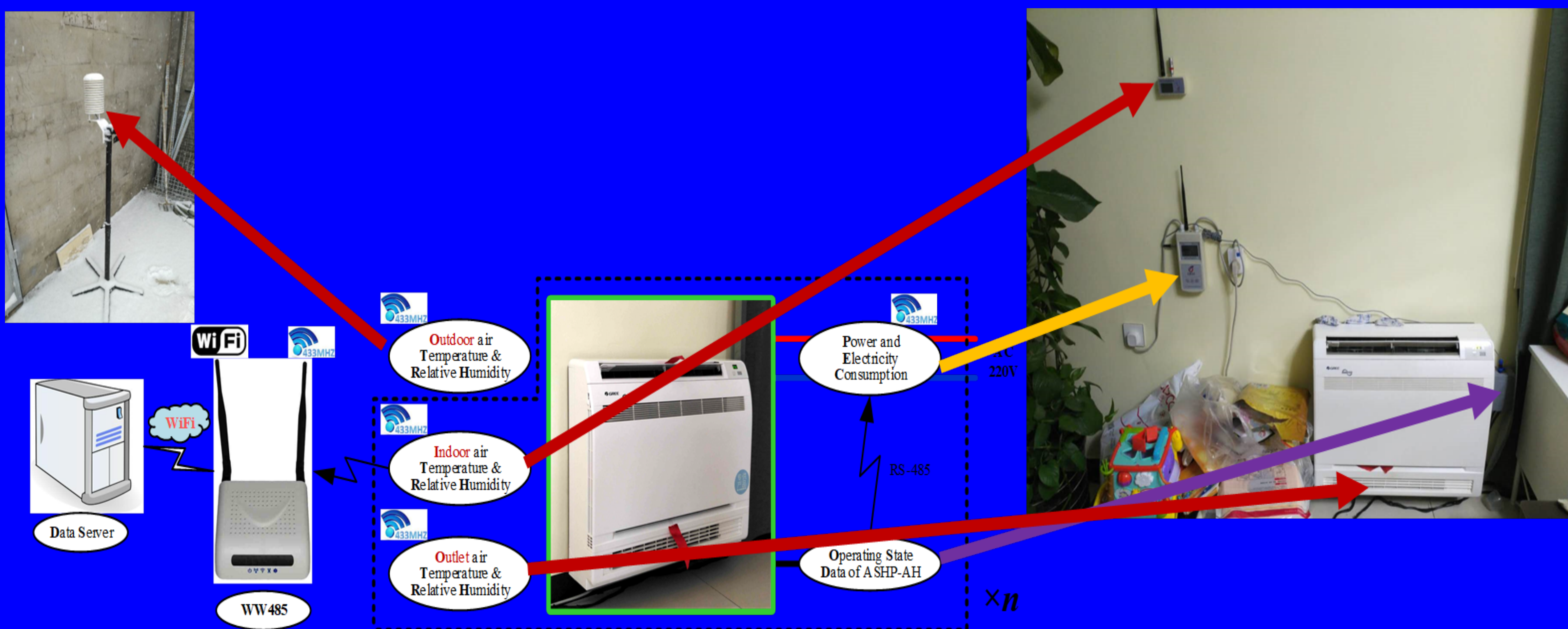
Installation



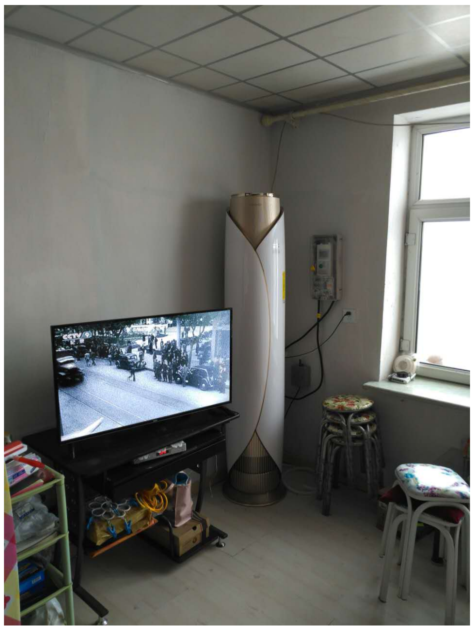





Monitoring system

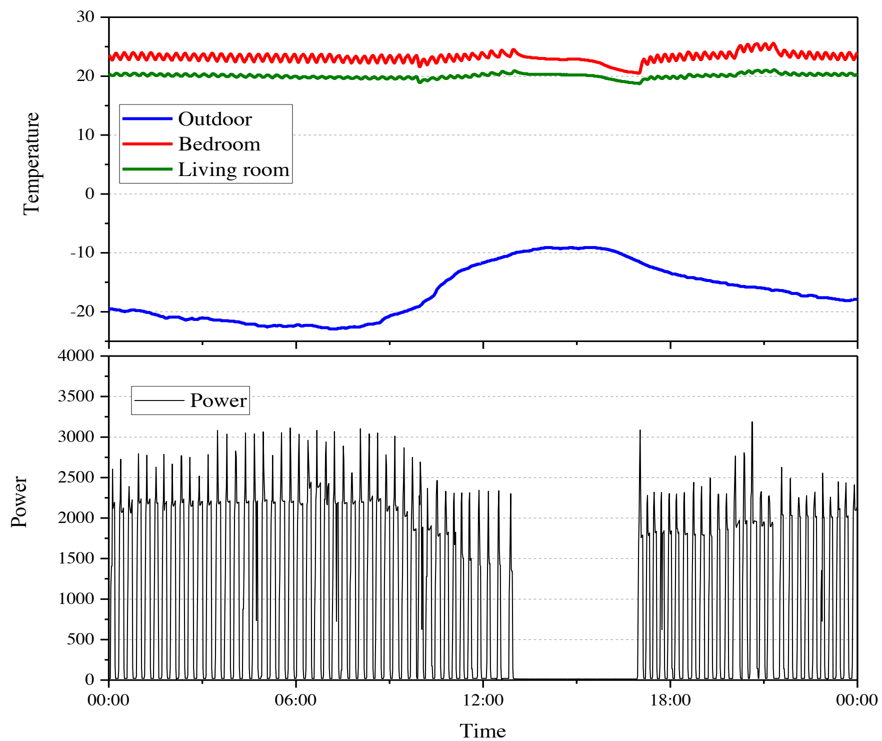


Test and analysis: extreme cold day in Heilongjiang province



A 65.1m² rural house in Qiqihar city, Heilongjiang province

JAN 24, 2017 (**extreme cold day --!**)



Temperature (MIN/MAX/AVG):

- Outdoor: **-22.9/-9.1/-16.7℃**
- Bedroom: **20.5/25.6/23.2℃**
- Living room:**18.7/21.1/20.0℃**

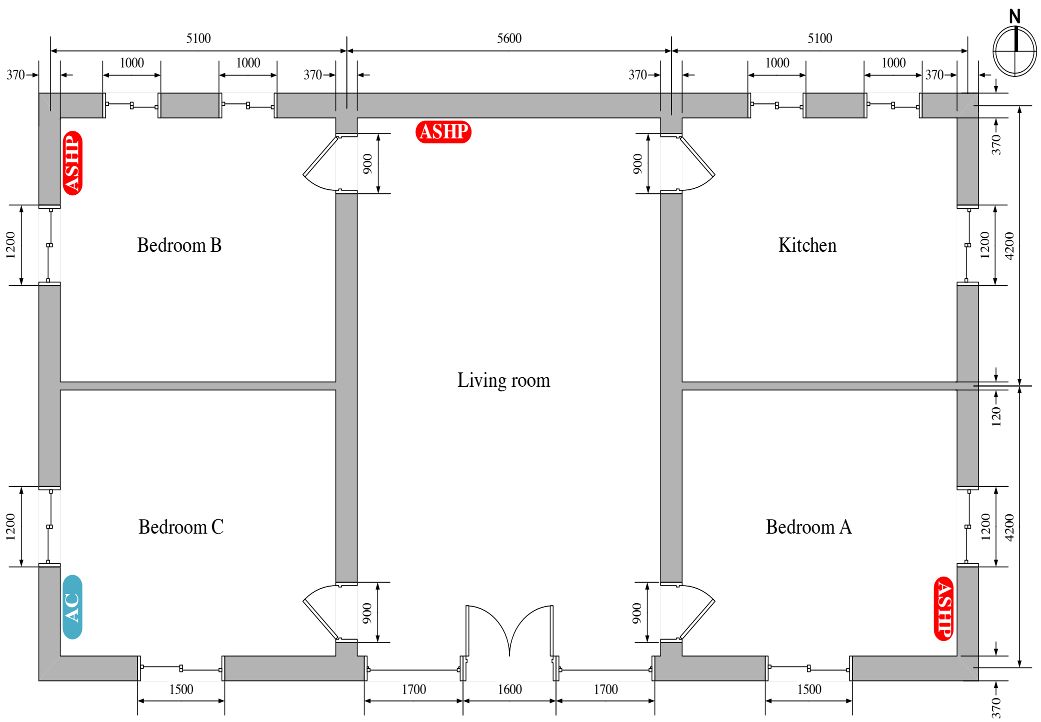
Power (MIN/MAX/AVG):

- **4.4/3186.5/943.1W**

Energy consumption:

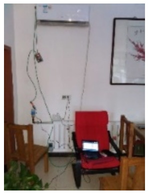
- **22.6kWh**

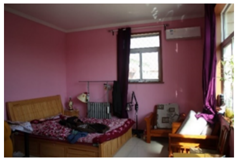
Test and analysis: heating season in Beijing

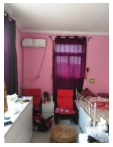


ASHP×3

Floor area: 142m^2
Height: 3.0m
Walls: 370mm solid brick wall & east, north, west with 70 mm exterior adhesive polystyrene granule layer
Roof: 100 mm plaster concrete + 120mm interior polystyrene granule package
Floor: ceramic tiles
Design heating load index per unit floor area: 59.6 W/m^2







Test and analysis: heating season in Beijing

Time: December 9, 2015 to April 3, 2016 (**117days**)

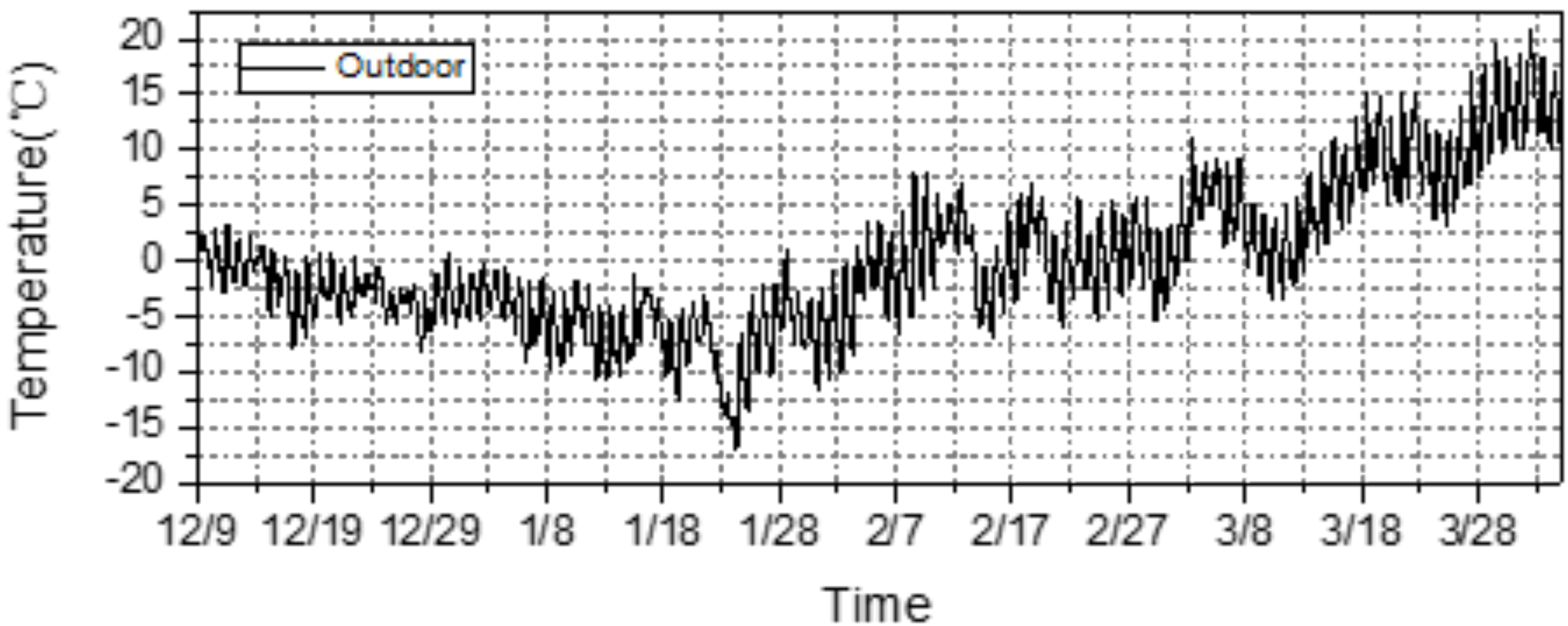
Temperature	MIN/℃	MAX/℃	AVG/℃
Bedroom A	13.4	25.4	**20.5**
Bedroom B	12.8	25.6	**19.4**
Bedroom C	9.3	27.4	**20.5**
Living room	10.3	24.3	**17.7**

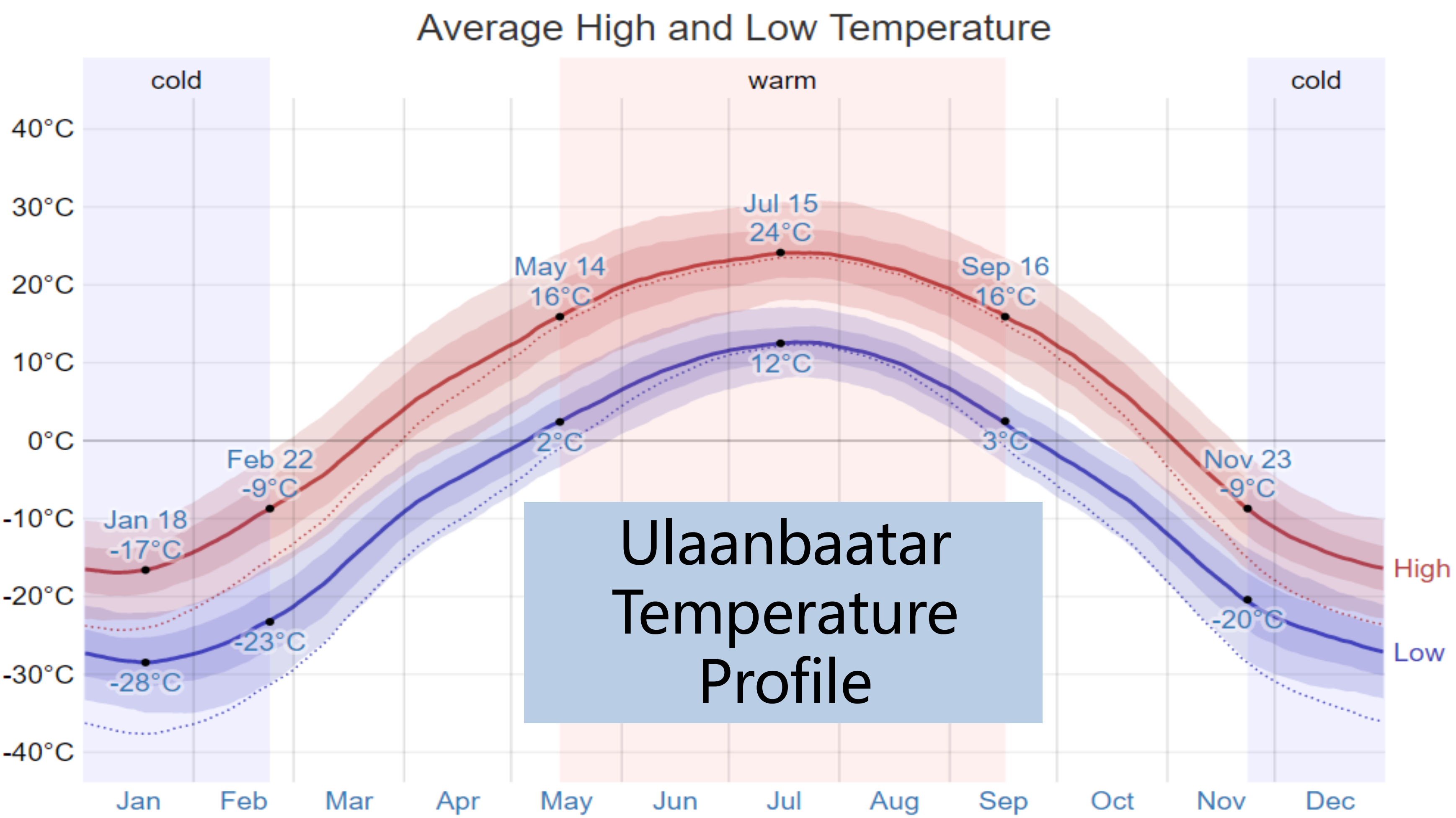
	Run time/days	Avg. run time per day/hours	Power consumption/kWh		
			Flat	Valley	Total
Bedroom A	94	11.56	289.56	370.40	659.96
Bedroom B	99	9.09	262.50	452.10	714.60
Bedroom C	60	2.77	37.20	15.60	52.80
Living room	66	9.64	312.90	125.90	438.80
TOTAL	-	-	**902.16**	**964.00**	**1866.16**

Floor area /m^2	Power consumption of HS* /kWh	Power consumption of HS* per unit floor area/(kWh/m^2)	Bills** /CNY	Bill** per unit floor area /(CNY/m^2)
142	2612.10	18.40	748.06	5.27

*HS: 120 days **Based on the electricity price in Beijing

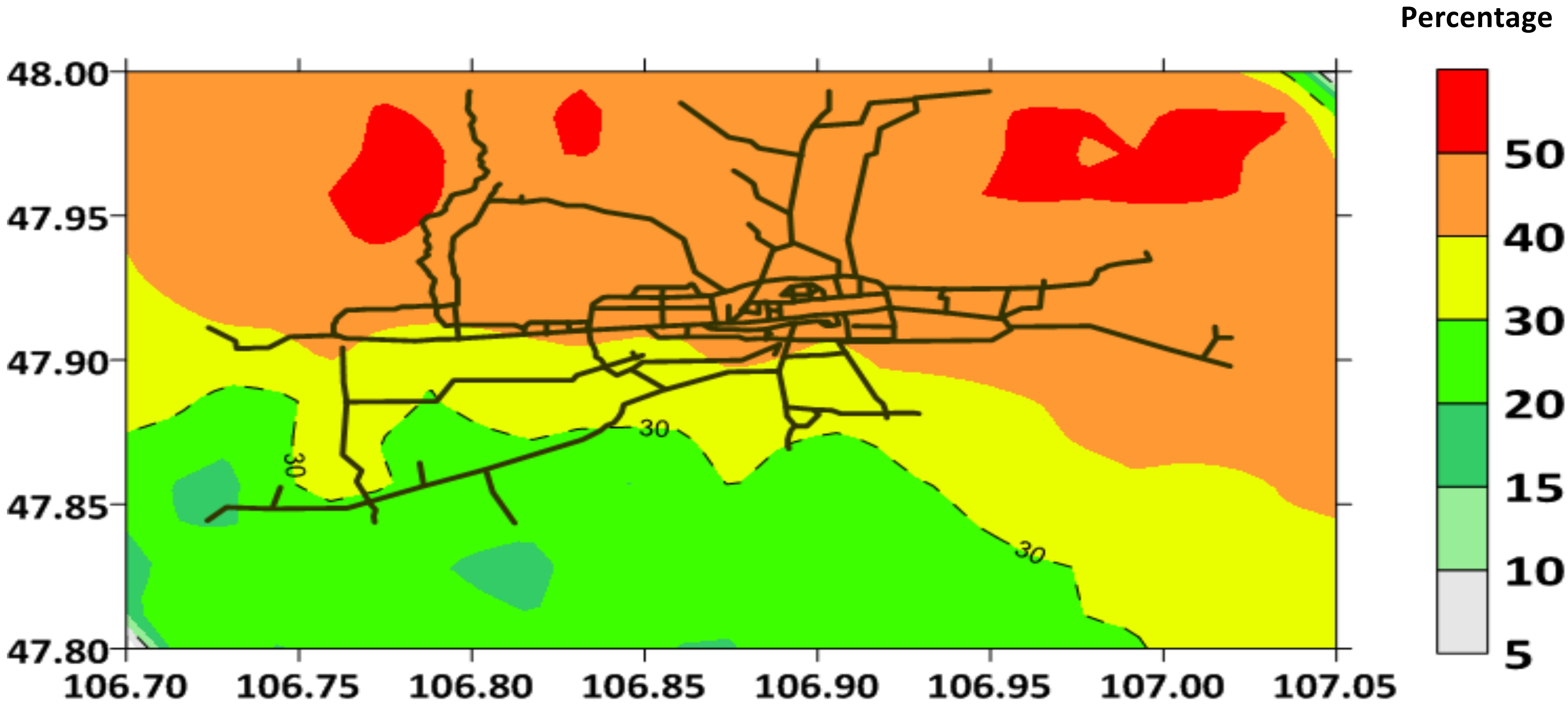
Temperature Profile in China





The daily average high (red line) and low (blue line) temperature, with 25th to 75th and 10th to 90th percentile bands. The thin dotted lines are the corresponding average perceived temperatures.

Modelled Stove Contributions
Winter Months: Ulaanbaatar



Guttikunda, 2014

What we need to show

- Cost of heating will be a function of electricity cost and capital cost of the pumps with installation (plus lifetime, maintenance, etc)
- Electricity demand will be a function of outside temperature, inside temperature, and household characteristics such as insulation and ventilation
- The pumps will work at all temperatures, but will have a COP close to 1 at the lowest levels in UB, i.e. -35 deg C
- Question is the total electricity demand over the heating season given the distribution of usage with the distribution of outside temperature, i.e. COP

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The impact of household cooking and heating with solid fuels on ambient $PM_{2.5}$ in peri-urban Beijing

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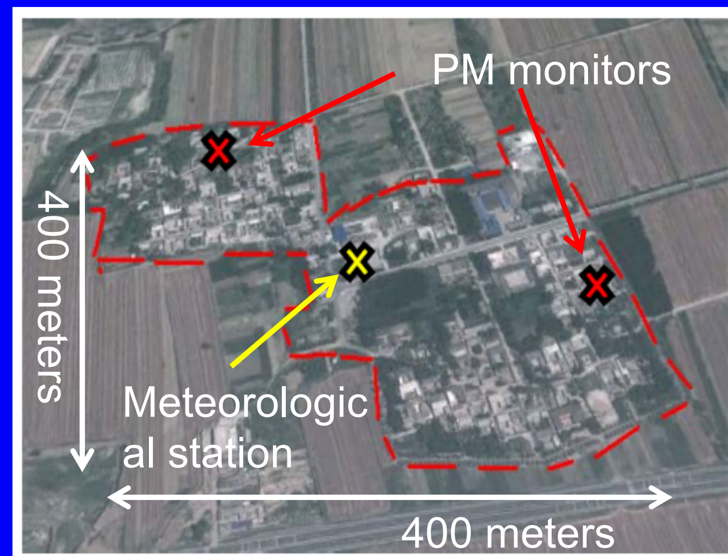
Ambient Air Pollution in a Peri-urban Village in Beijing

Sample site: Erhezhuang (EHZ) Village



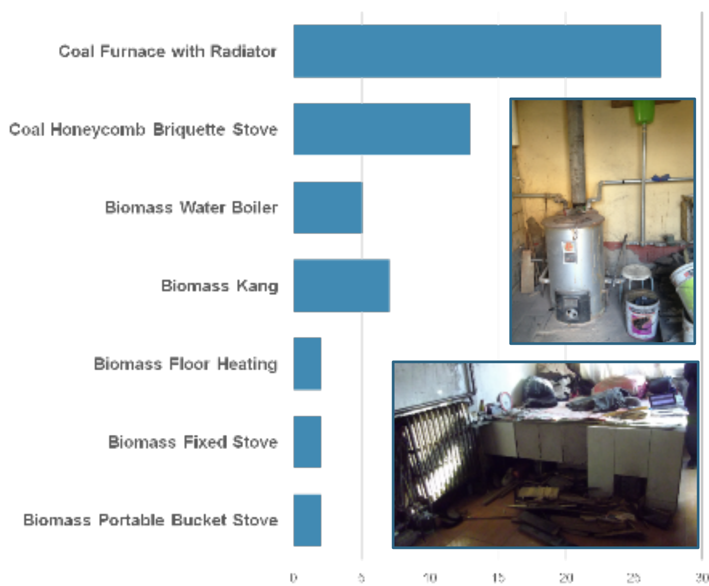
- We conducted surveys on fuel use and monitored solid fuel heating and cooking devices using SUMS in recruited households from January 9th to March 10th, 2013.
- Ambient $PM_{2.5}$ concentrations were measured, and a meteorological station was installed at the village center from January 9th to March 10th 2013.

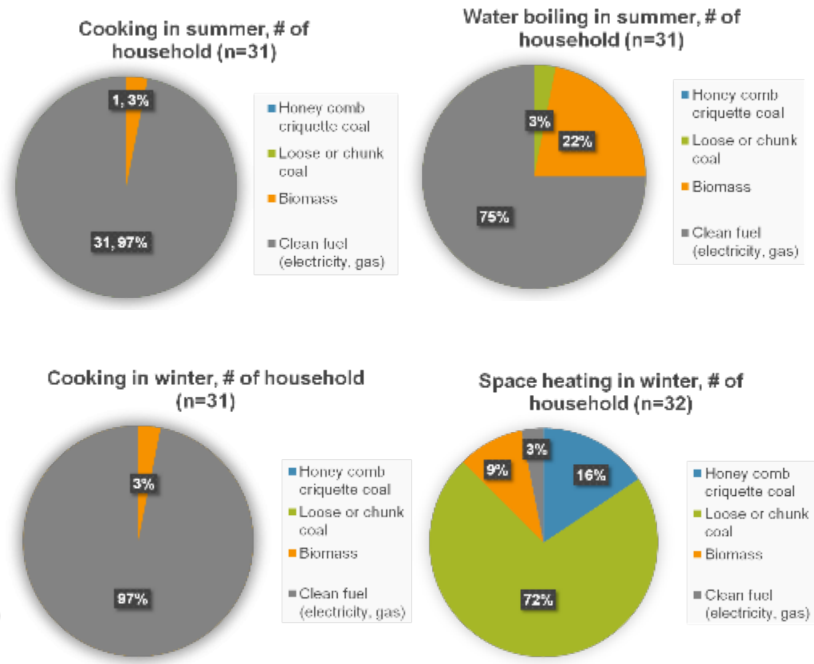
Energy Use Patterns in EHZ village

- Most of household adopted clean fuel to cook, but still using large amount of solid fuel for space heating in winter.
- The average biomass for cooking, biomass for space heating and coal for space heating per household is 87 kg/year, 102 kg/year and 3,000kg/year, respectively.
- In winter heating season, 92% of the primary $PM_{2.5}$ emission from household solid fuel use are from coal combustion for space heating.

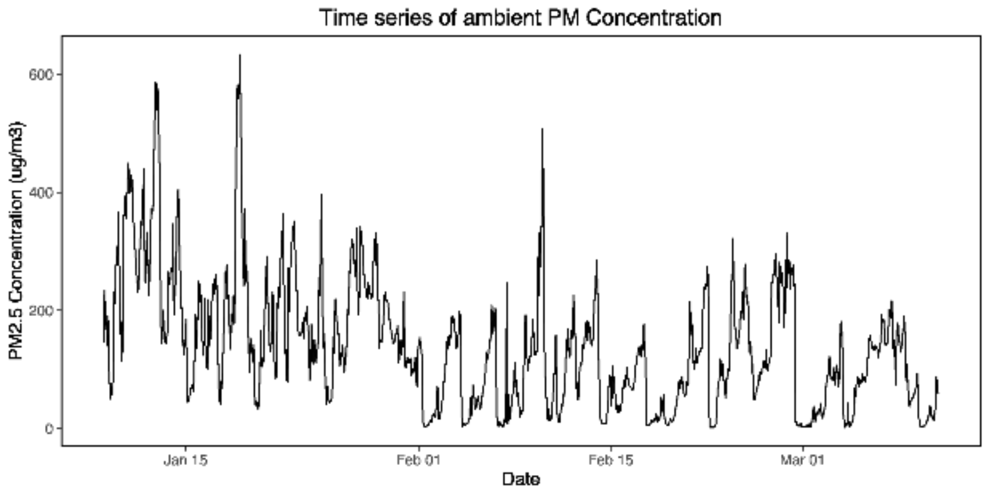
Primary Fuel for household tasks in summer and winter

# of Households with Devices (n = 33)

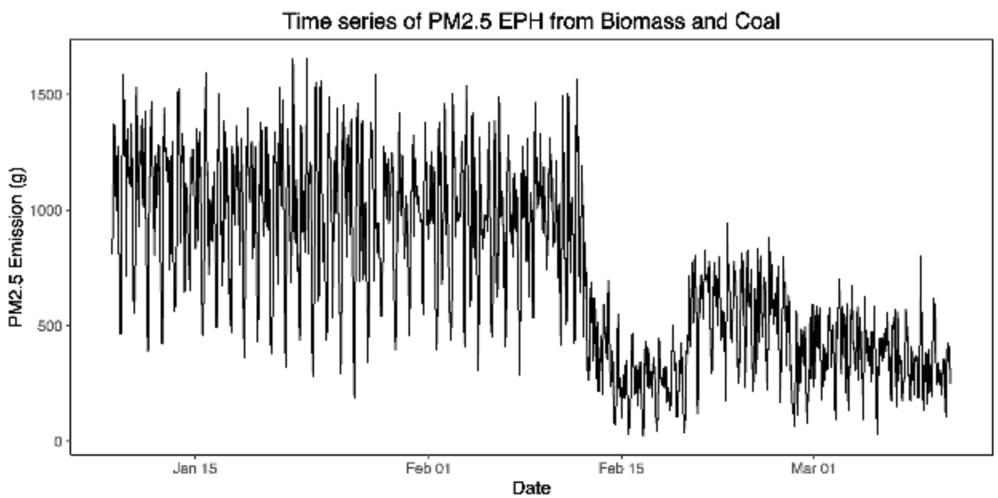




Contribution of Space Heating to Ambient Air Pollution



Time Series Modeling:
During Jan. 9th to Mar. 10th, 2013, the average ambient $PM_{2.5}$ concentration is 139±107 μg/m^3 (mean ± standard deviation), and average primary $PM_{2.5}$ EPH from household biomass and coal is 735.5±381 g/hour at study site.

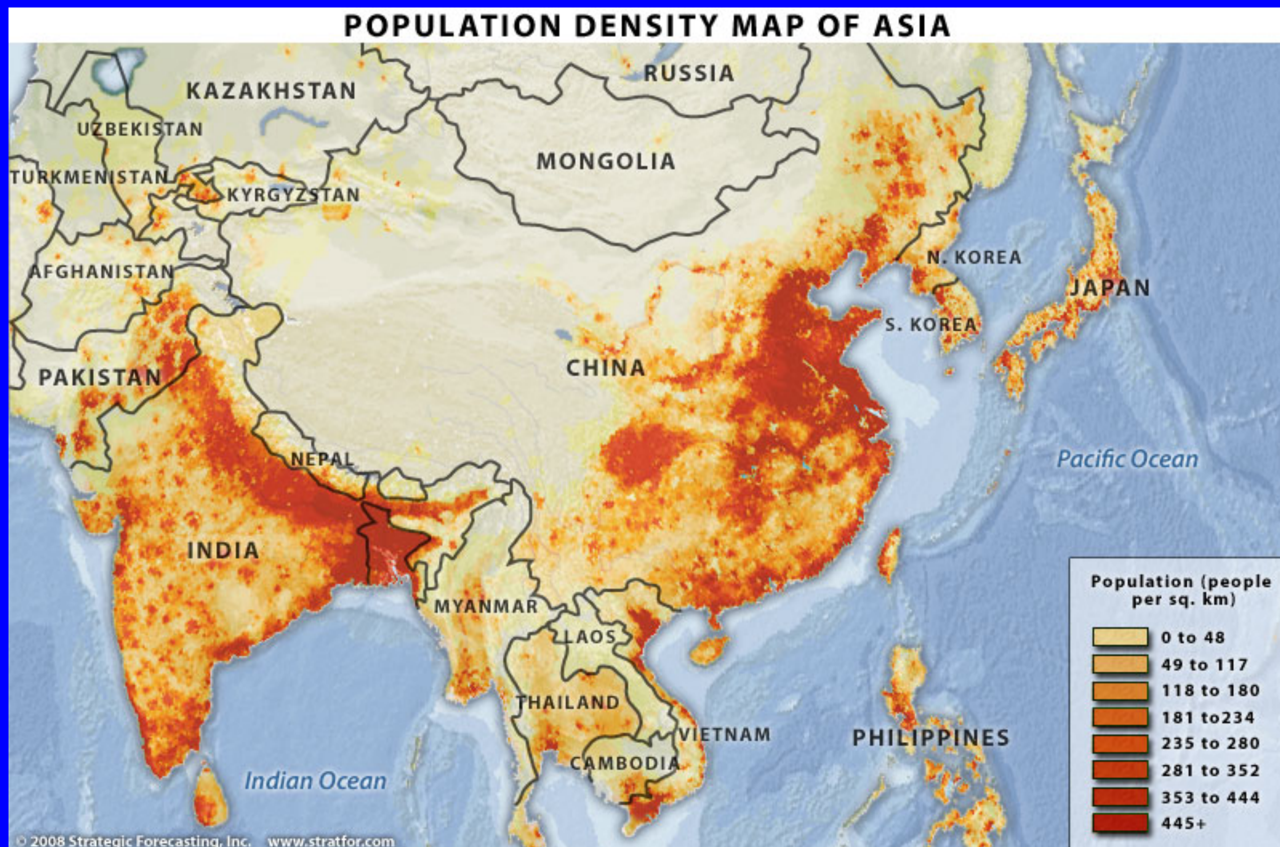


During the heating season, 39% of hourly averaged ambient $PM_{2.5}$ was associated with household space heating emissions.

The Mongolia of Not So Long Ago

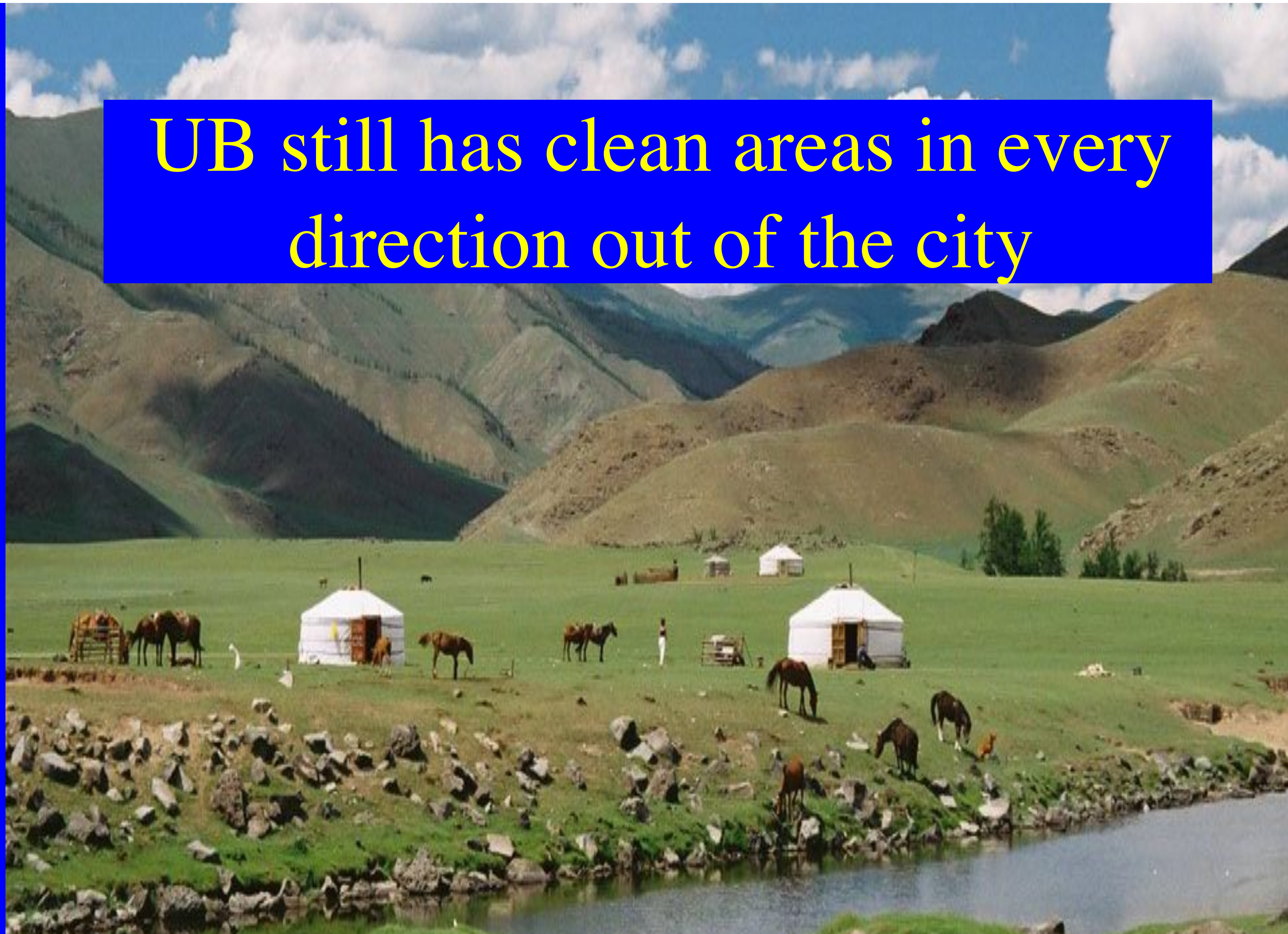
This is half of Mongolia today

The coldest capital city in the world, and heats with coal in a valley with air inversions. Thus, in the winter



Mongolia is the least densely populated country in the world

UB still has clean areas in every direction out of the city



Unlike Beijing, Delhi, Hong Kong, and nearly all other polluted cities in Asia, therefore

Ulaanbaatar

holds its destiny in

its own hands.

Acknowledgments

- For Air Pollution Policy Study
  - Mongolia Ministry of Environment and Green Development
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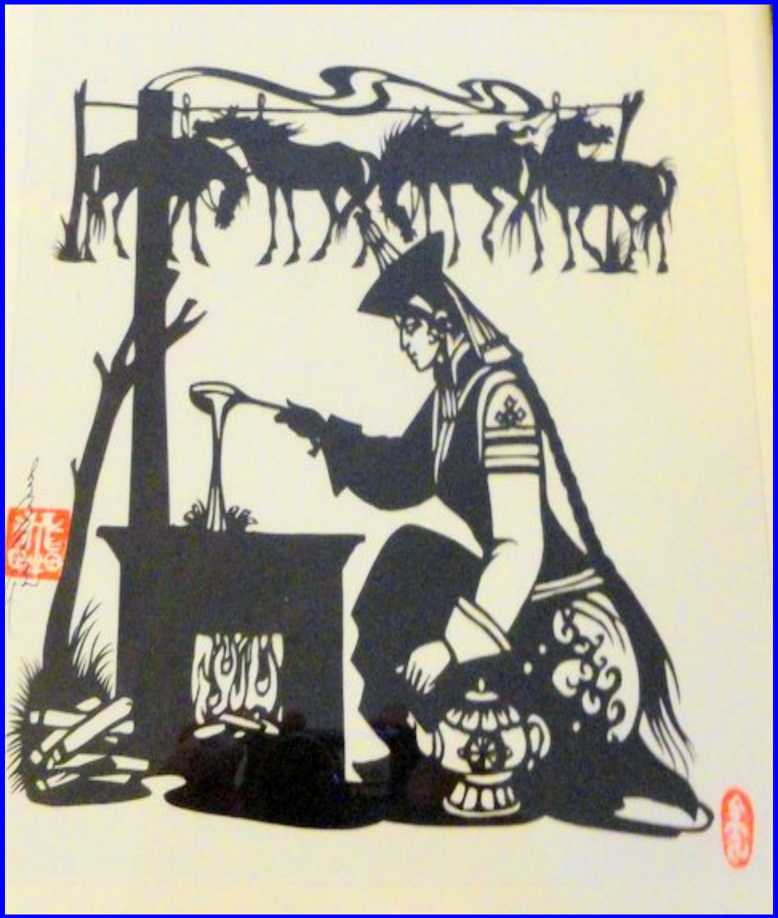
  - Collaborative Clean Air Policy Centre, New Delhi
  - Building Science Department, Tsinghua University
  - GREE Corporation, Beijing
  - UNDP

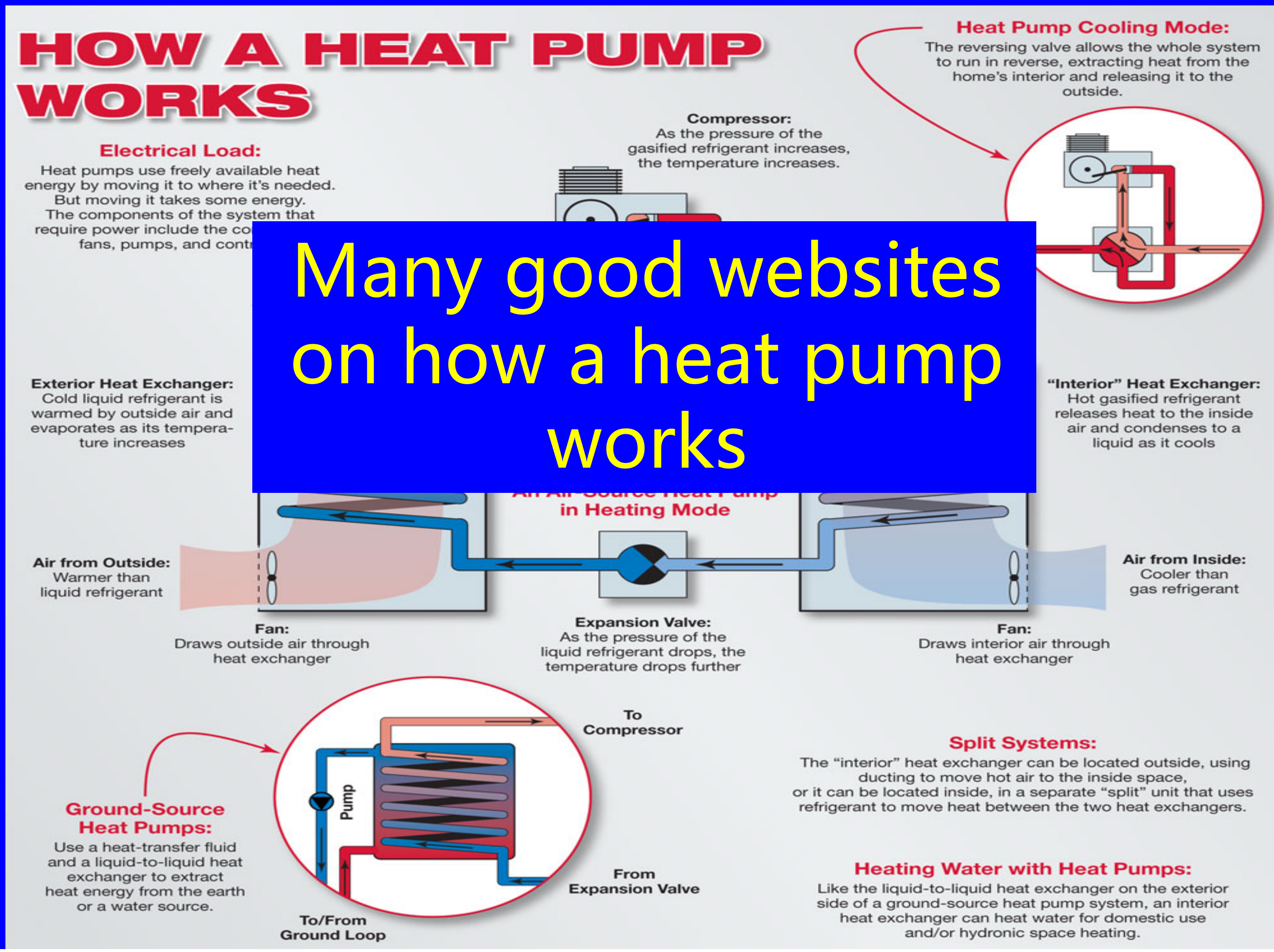
Findings from Hill et al 2017

Thank you

Publications on website: Just Google "Kirk R. Smith



Many good websites on how a heat pump works



Good videos also

https://www.youtube.com/watch?v=14MmsNPtn6U

https://www.youtube.com/watch?v=g39nM7GbSJA