The 8th IEA-Tsinghua Joint Workshop

清華大學 Tsinghua University

Fossil-free distributed heating: Technology advancement and large scale applications

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October 27, 2022

Outline

- Background and problems
- Breakthrough in air source heat pumps
- Innovation in solar PV heating with storage
- Summary and conclusion

Background

- Solid fuels are still widely used for household heating in rural China and many other developing countries.

Raw coal

Ball-shaped coal

Honey coal

TOTAL coal: (120.3 million tons/year)

Branches

Firewood

Straw

TOTAL biomass: (82.8 million tons/year)

Background

Over-dependence on coal has created a number of problems.

– Low efficiency

– Poor comfort

- Higher CO, PM2.5 exposure

– Respiratory disease: COPD, asthma, etc

– Lower lung function (FVC)

– High bold pressure

– Cardiovascular diseases

– Greater health, economic and environmental burden

Background

A few options for non-centralized clean heating (worldwide issue):

- **Natural gas heating**
  (cost, availability, infrastructure, safety, CO2 emission)
- **Processed biomass + clean heating stoves**
  (resource, processing, pollution control & monitoring)
- **Solar thermal heating**
  (initial cost, auxiliary heat source, anti-freezing)
- **Low ambient temperature air source heat pump**
- **Solar PV heating with thermal storage**

Air source heat pump

- A **heat pump** is a device that **transfers** heat from a source of heat to a destination.

- **The coefficient of performance (COP) for heat pumps range from 2 to 4** for household air source heat pump units.

- Due to nature of thermodynamic cycle and heat transfer process, the **heat pump does not work favorably as the indoor-to-outdoor temperature difference increases** (i.e., when outside temperature gets colder).

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 both the heat pumps efficiency and capacity 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 thermal comfort (for instance, cold feet).

Air source heat pump

Technology innovation: Double stage enthalpy-added compressor

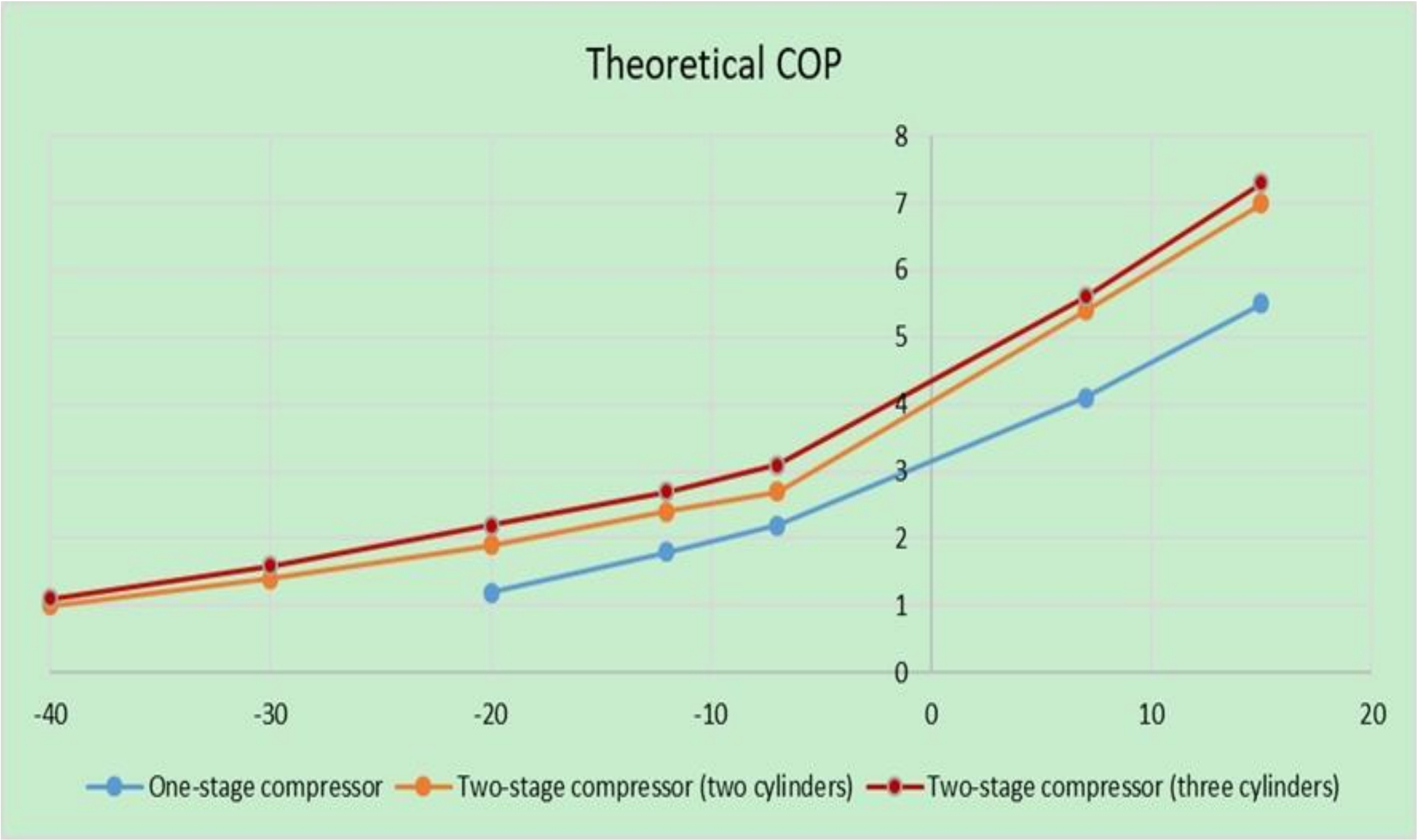
Traditional single stage compressor (one cylinder)

(Two cylinders)

(Three cylinders)

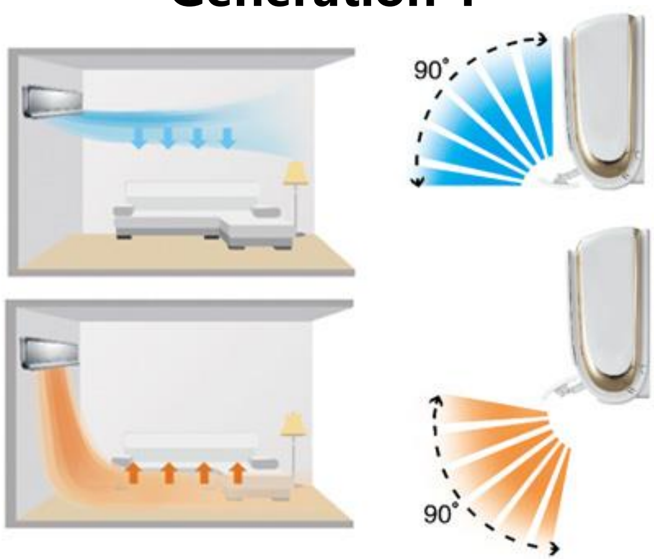
- **Enhance capacity in cold ambient conditions**
- **COP is up to 2.0+ at the outdoor temperature of -20°C**
- **Can run normally at the outdoor temperature of -35°C**

Benefits of double compression



Improvements of thermal comfort

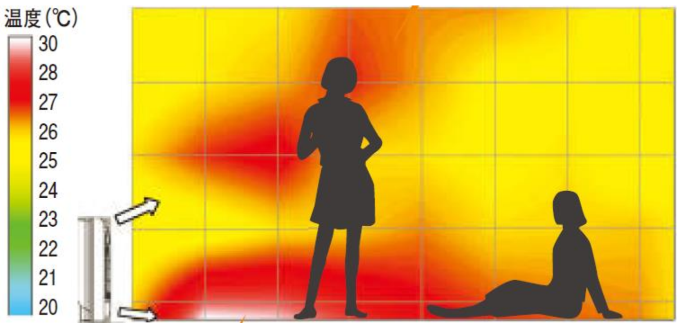
Generation 1



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.

Operations with occupant control behavior

Objective: meet individual user's behavior, comfort, and energy-saving demand

1. Easily adjustable indoor temperatures → individual comfort requirements
2. Rooms not all occupied at all times → allow partial space, partial time control
3. Easy to operate and maintain → "user friendly"
4. Be viewed high on "energy ladder" →."good feeling" in social status
5. Affordable initial and operating cost → key for market penetration

Air source heat pump

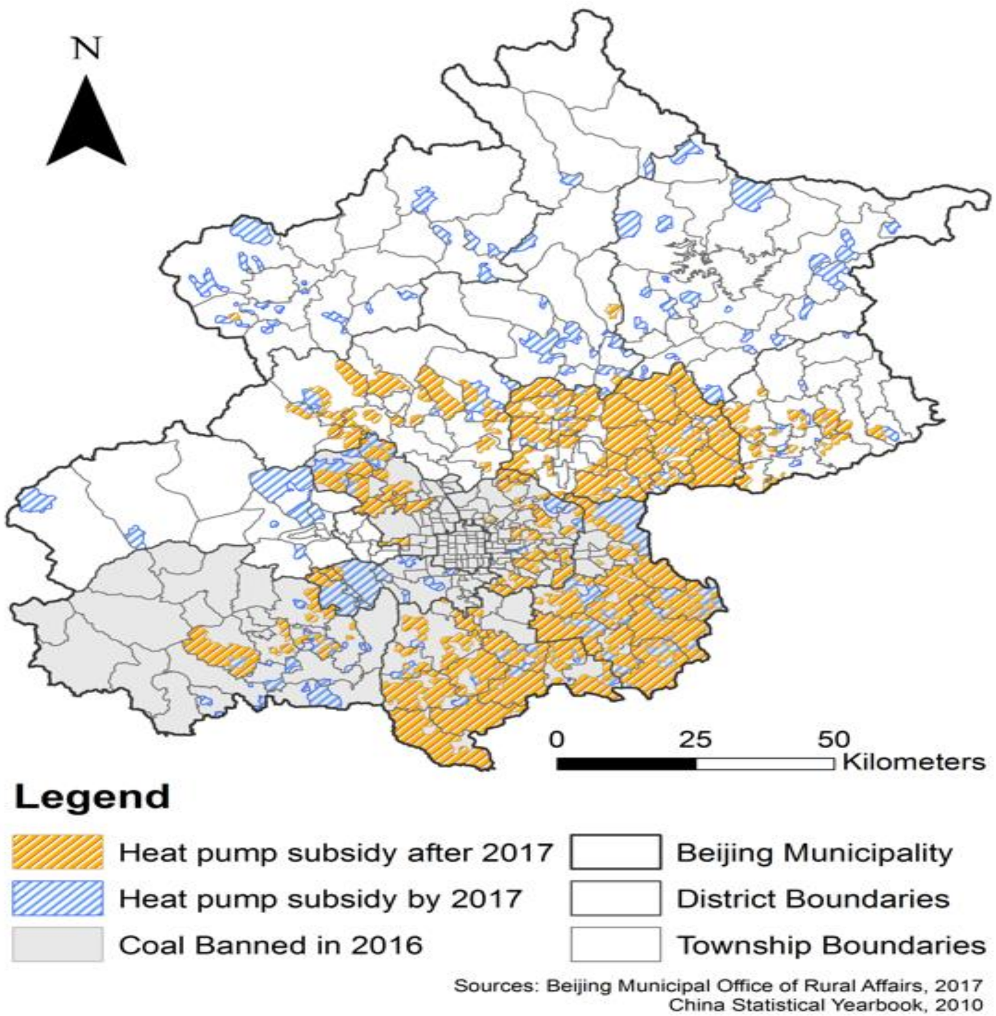
Tsinghua University

Operations with occupant control behavior

Use patterns	Rooms	Room area(m^2)	Average running time per day (hours)	Average indoor temperature when running ℃ (F)	Energy consumption of heating season per unit area(kWh/m^2)
USED EVERYDAY & CONTINUOUS OPERATION	Master Bedroom in Household 1#	14	23.2	18.2 (64.8)	36
USED EVERYDAY & INTERMITANT OPERATION	Bedroom A in Household 2#	22	9.4	19.7 (67.5)	37
USED IRREGULARLY	Living & Dining in Household 1#	27	2.1	21.0 (70)	11

Based on detailed tests in real households in Beijing
Heating season: from Nov. 15th to next Mar. 15th (120 days).

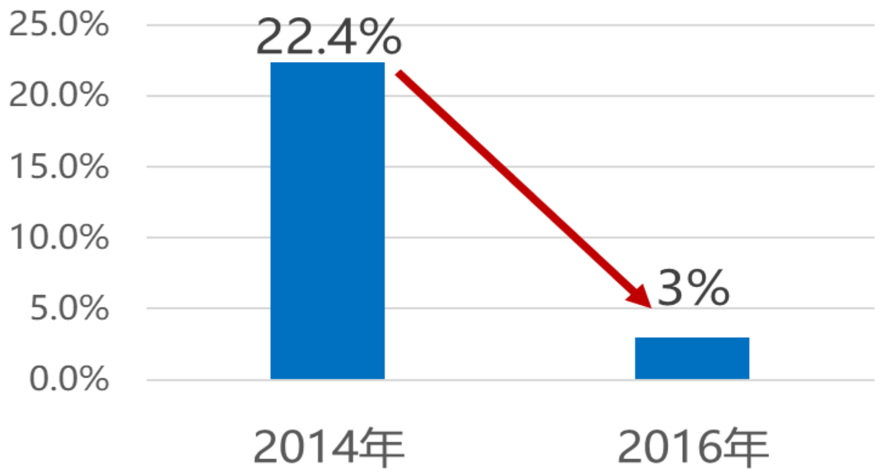
Rural household energy transitions in Beijing: Coal to clean energy



Air source heat pump

Coal to clean energy: Environmental benefit in Beijing

- More than 1 million small coal boilers removed
- Over 300 million ton scattered coal was reduced, 12 k-ton PM2.5, 8.60 m-ton CO_2, 4.6 k-ton SO_2, 7.6 k-ton NO_x

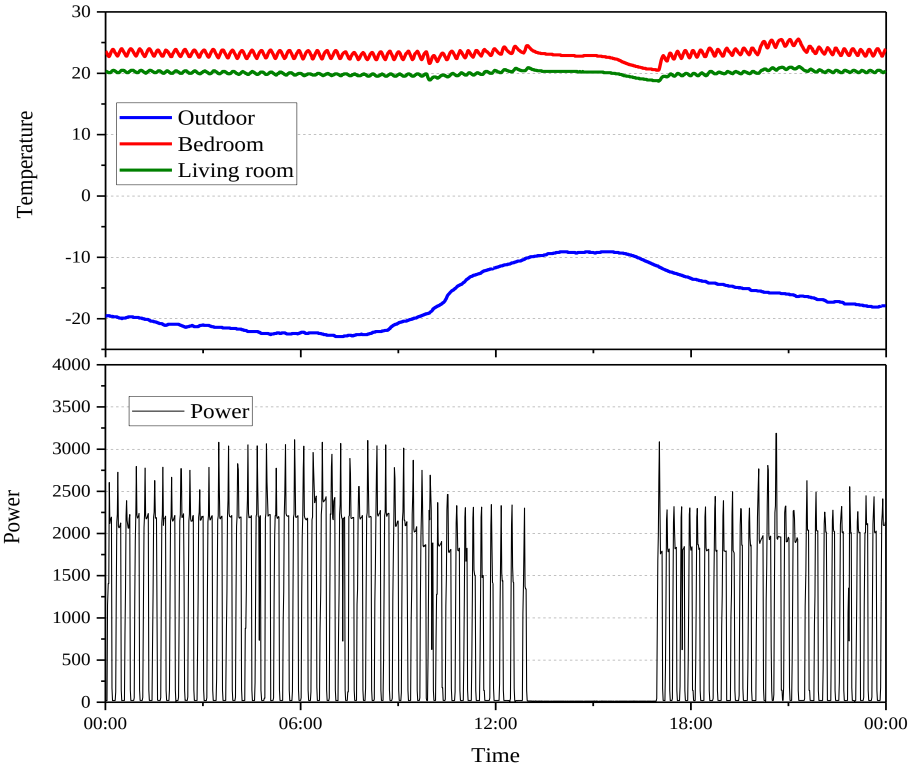


Air source heat pump

Test and analysis: extremely cold climate (Heilongjiang province)

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

A 65.1m^2 rural house in Qiqihar city, Heilongjiang province



Temperature (MIN/MAX/AVG):

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

Power (MIN/MAX/AVG):

- **4.4/3186.5/943.1W**

Energy consumption:

- **22.6kWh/day**

Air source heat pump

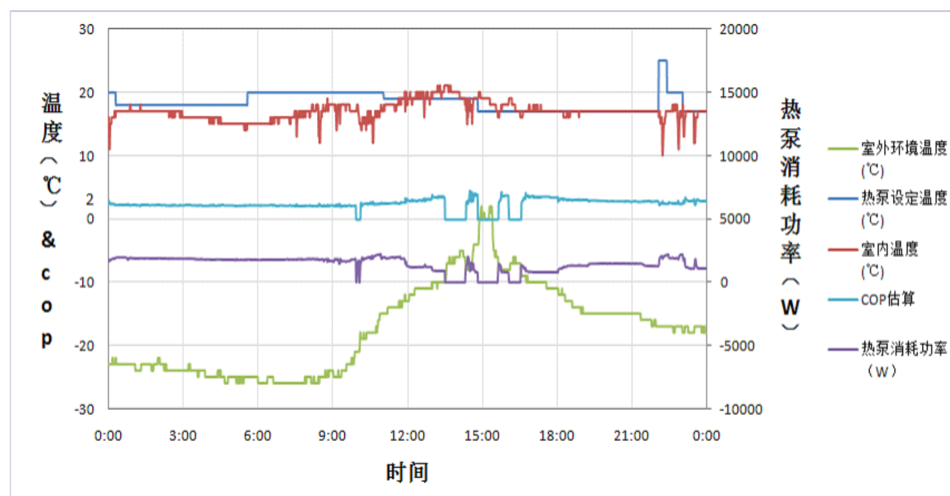
Heat pump heating in Gerrs, Mongolia

1 Time： 2018.02.02——2018. 03.05

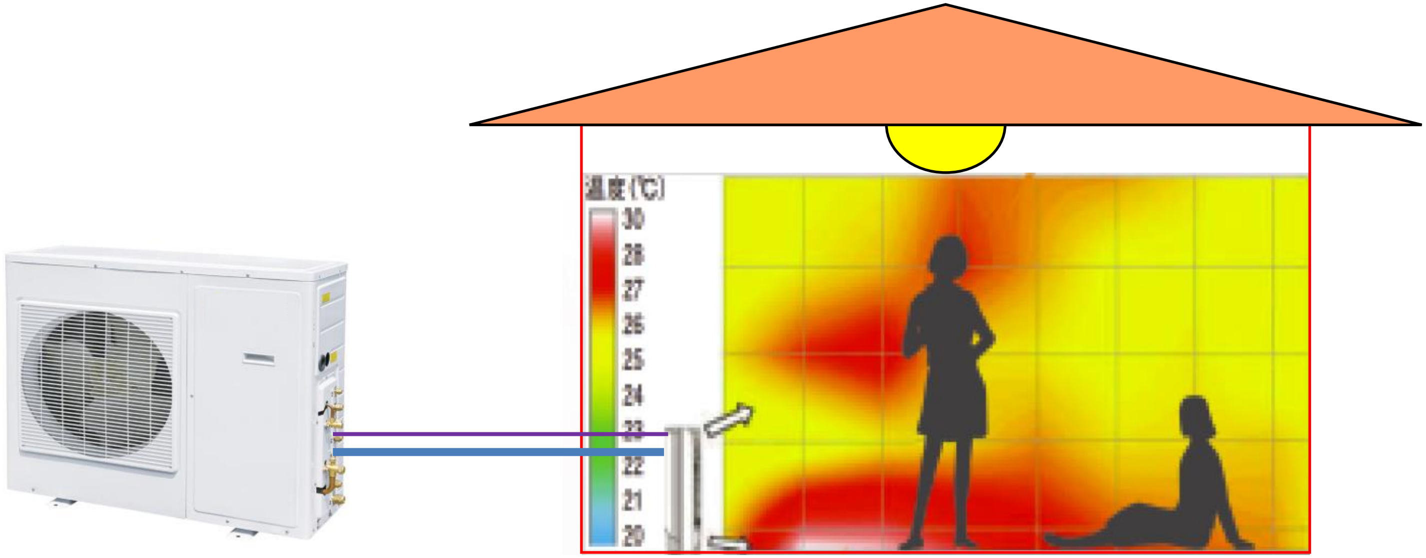
2 Outdoor temperature range :-6℃ ~ -28℃；

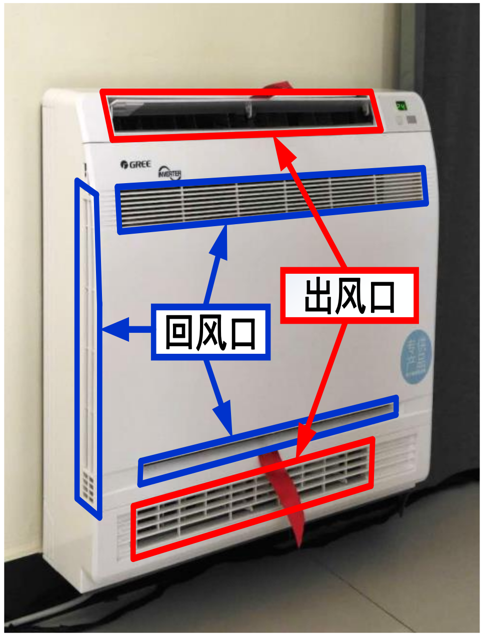
3 Indoor temperature setting： 18℃ ~ 28℃，

4.Actual indoor temperature： 16℃ ~ 29℃。



Air source heat pump





- **Low cost:** ~4500CNY/unit
- **High COP:** ≥3.0 in Beijing
- **Low operating cost:**

  15-40 kWh/m^2•winter

  8-20 CNY/m^2•winter

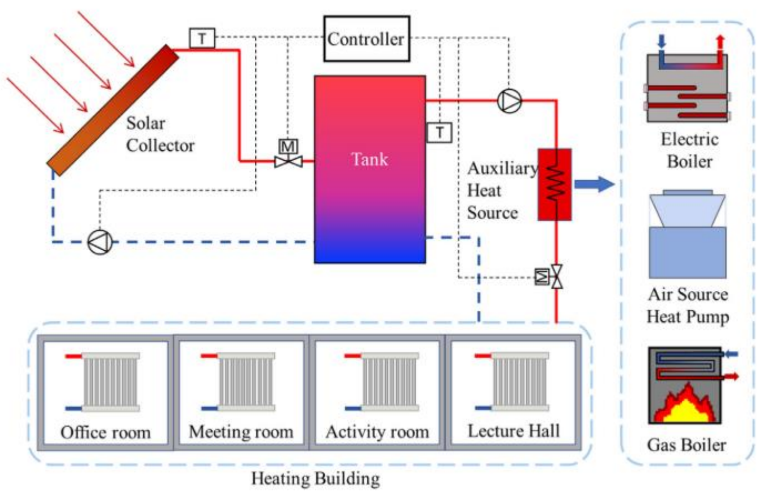
- First technical standard developed
- Market penetration: >1 million units/year

Why PV heating?

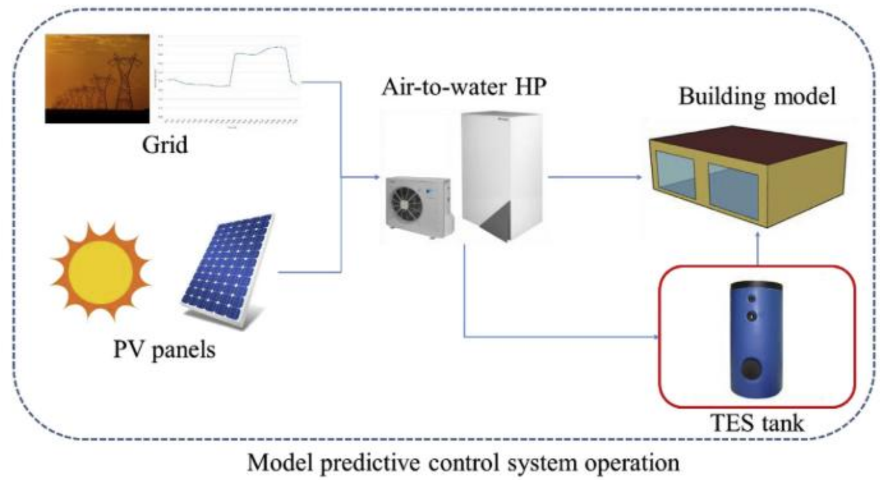
Compared to solar thermal heating system:

1, PV heating system has higher year-round usage. In the non-heating season, it can still generate electricity (sell to the grid or self-consumed).

2, PV heating system is simpler in structure and occupies less space.



Solar thermal heating system

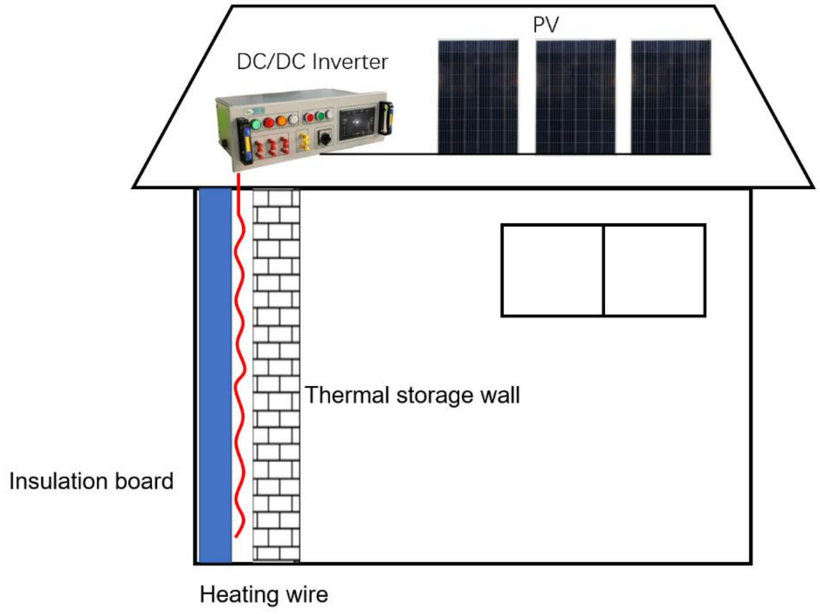


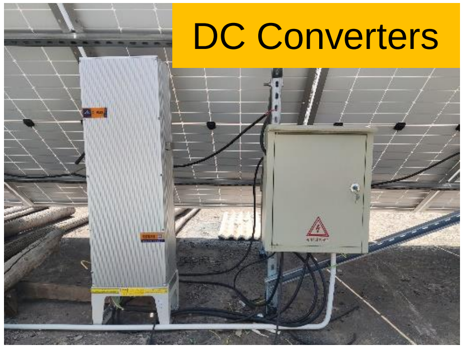
PV heating system

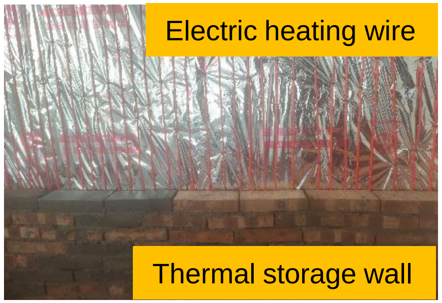
1, Chel, A.; Tiwari, G. N., Stand-alone photovoltaic (PV) integrated with earth to air heat exchanger (EAHE) for space heating/cooling of adobe house in New Delhi (India). Energy Conversion and Management 2010, 51 (3), 393-409.
2, Tarragona, J.; Fernández, C.; de Gracia, A., Model predictive control applied to a heating system with PV panels and thermal energy storage. Energy 2020, 197.

PV heating System Design

The system has to overcome three obstacles:
1, To avoid overheating in the afternoon on sunny days;
2, To ensure relatively stable temperature at night and on cloudy days;
3, To avoid abandoning PV energy and expensive batteries as storage.



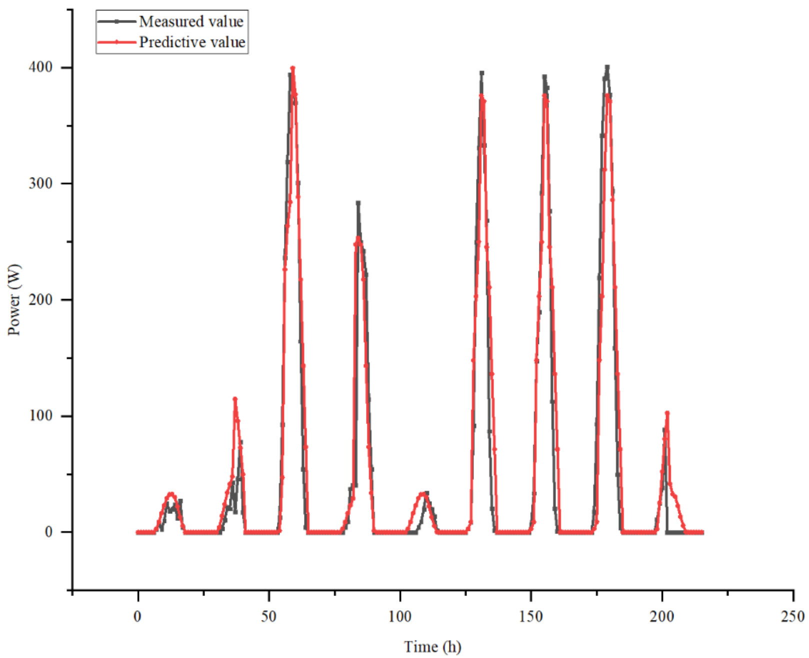




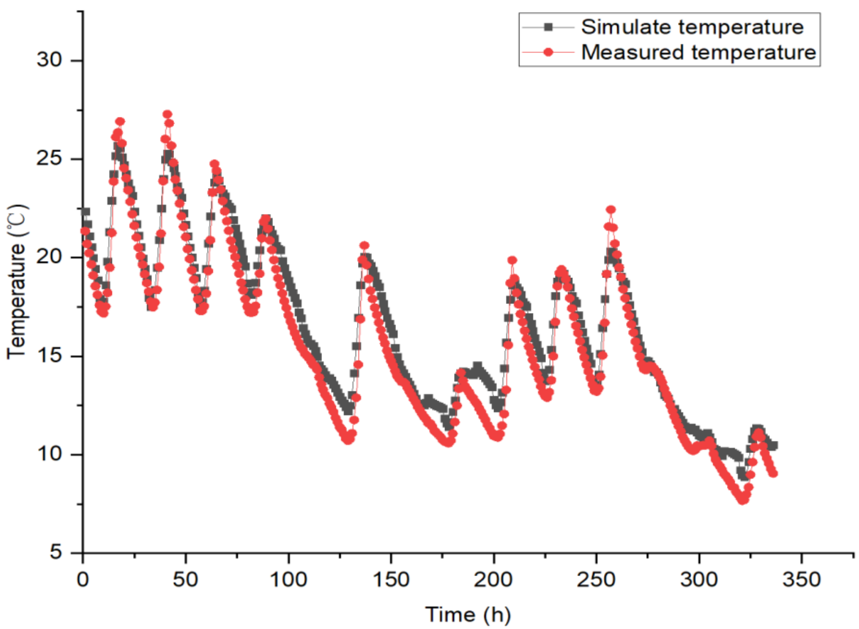
Solution: cheap energy storage together with smart control
The wall's heat storage function regulates the heat flow to the room by the electric heating wire, while the heat stored in the wall can be released at night and on cloudy days.
The wall can also be an insulation layer to reduce heating loss to the outside.

PV heating System Design

This system has a simple structure, **but requires complex model calculations and optimization.** We simulated the building thermal load and combined it with the PV power prediction model to obtain the optimal PV capacity and energy storage capacity of the system.



Photovoltaic Power Forecasting Model Accuracy Verification

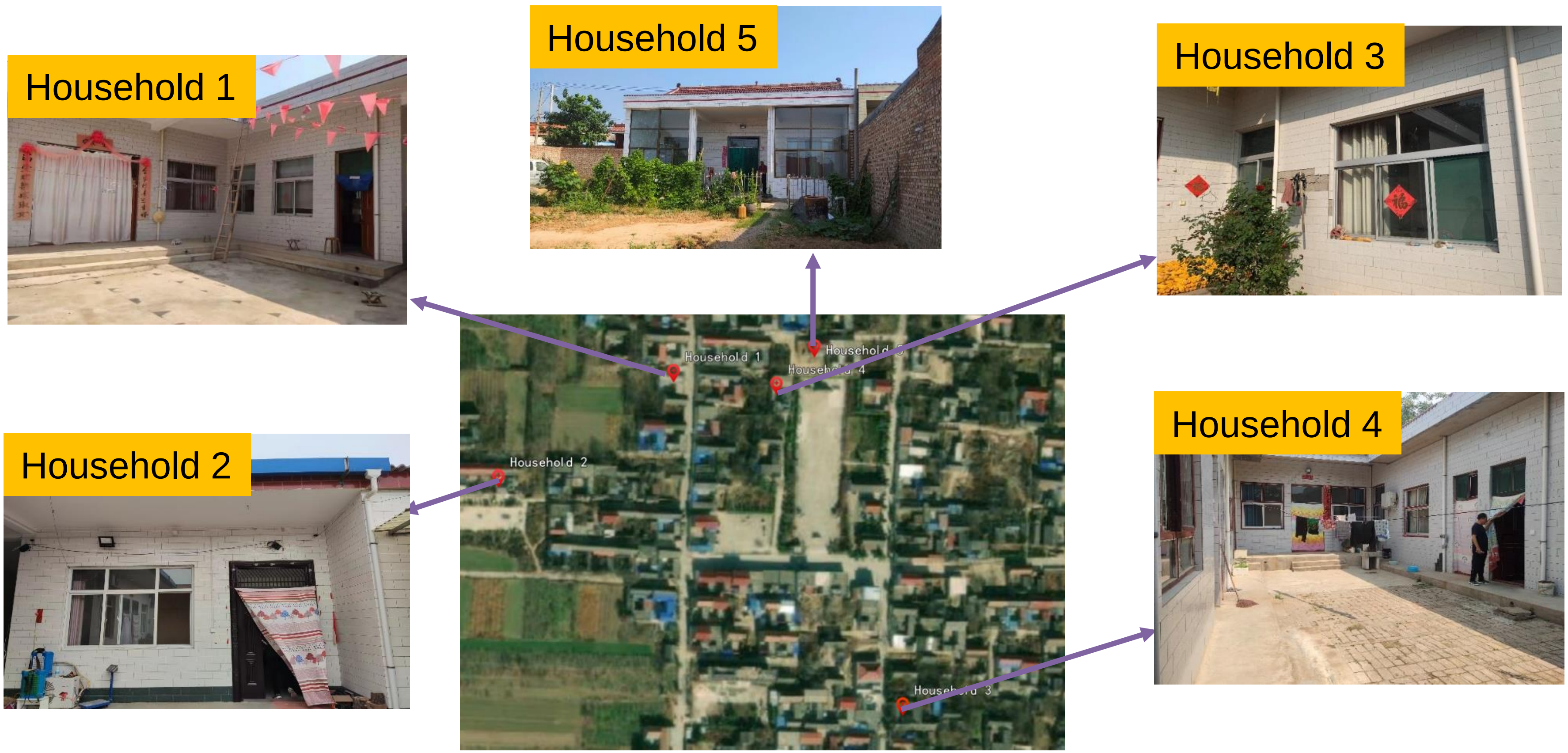


Validation of room temperature prediction model

According to the simulation results, the optimal ratio of system PV panel area, heat storage wall area and heating area is approx. 2:1:1 under the local climate conditions（Ruicheng, Shanxi）.

Demonstration Project

We selected five farm houses in Richeng County, Shanxi Province to establish a demonstration project of the PV heating system and tested the effect of the whole heating season.



The five households vary in occupancy, age, and heating area, and represent several types of rural households in the village.

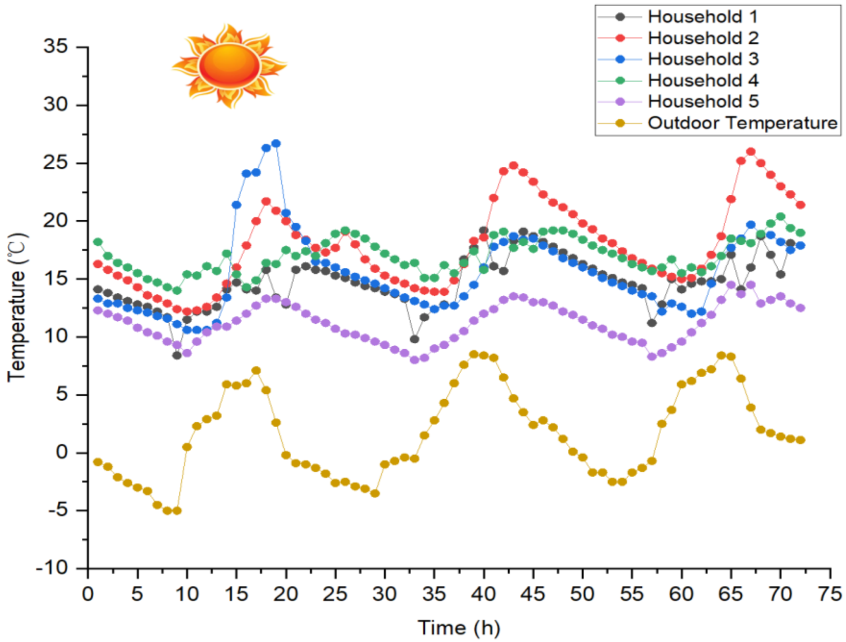
Demonstration Project

For comparison, we designed different area ratios to compare the differences in heating effects. Among them, Households 1 and 2 are in compliance with the desired conditions and Households 3-5 with some variations.

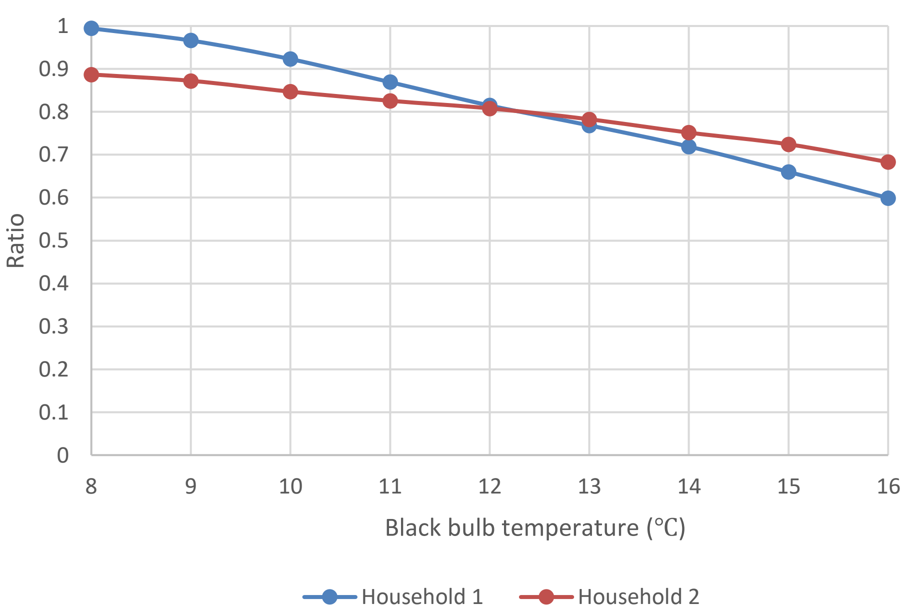
Number	Heating area/㎡	Permanent population	Age	Original heating method	Profession	PV panel capacity/W	Heat storage wall area/㎡	The ratio of PV panel area to heating area	The ratio of Heat storage wall area to heating area
Household 1	11	1	80	Coal stove, Kang	Famer	5340	11.2	2.2	1.0
Household 2	12	2	50	Electric heater	Village cadre	6230	13.0	2.2	1.0
Household 3	23	3	20	Electric heater	College Student	8900	18.2	2.0	0.9（Lack of energy storage capacity）
Household 4	15	2	45	Coal-fired boiler with radiator	Famer/worker	6230	7.0	1.9（Lack of PV capacity）	0.5（Lack of energy storage capacity）
Household 5	16	1	45	Coal-fired boiler with radiator	Famer/worker	6230	19.7	1.5（Lack of PV capacity）	1.1

Heating effect analysis

- During the heating season, the average indoor temperatures of the five households were 17.9℃, 18.0℃, 13.1℃, 14.3℃, and13.3℃.
- When the weather changed from sunny to cloudy, the indoor temperature decreased from 15.6 ℃ to 14.7 ℃ for household 1 and from 17.7 ℃ to 16.7 ℃ for household 2.
- The indoor black-bulb temperature of Households 1 and 2 can maintain above 16 ℃ more than 60% of the time throughout the heating season.
- Compared to Household 1 and Household 2, the indoor temperatures of other households are slightly lower due to configuration of PV capacity or heat storage capacity.



Indoor temperature of households on continuous sunny days



Proportion of hours of indoor black ball temperature in households

Summary and conclusions

- Innovative split-type, low ambient temperature air source heat pump has been developed and commercialized for individual heating in "all weather" winter conditions around the globe.
- A novel solar PV heating with thermal storage has been proposed and tested for a whole winter, which can provide desired indoor heating in winter and electricity in other seasons.
- Results indicate that both technologies can
  - Avoid the use of fossil fuels such as coal and natural gas;
  - Meet various and individual thermal comfort needs;
  - Have significant energy saving potential (up to a factor of 3);
  - Be cheaper in operating cost compared to fossil-burning stoves.
- Further studies on performances in more sophisticated conditions and interaction with power grid is under way.

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