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BETTER AIR QUALITY Conference

Manila 2023 Nov.

Environmental and Health Benefits of Clean Heating and Cooking in Rural China

中国农村居民清洁取暖与炊事 方案及成本效益分析

S. Tao, G.F. Shen, H.F. Cheng et al.,

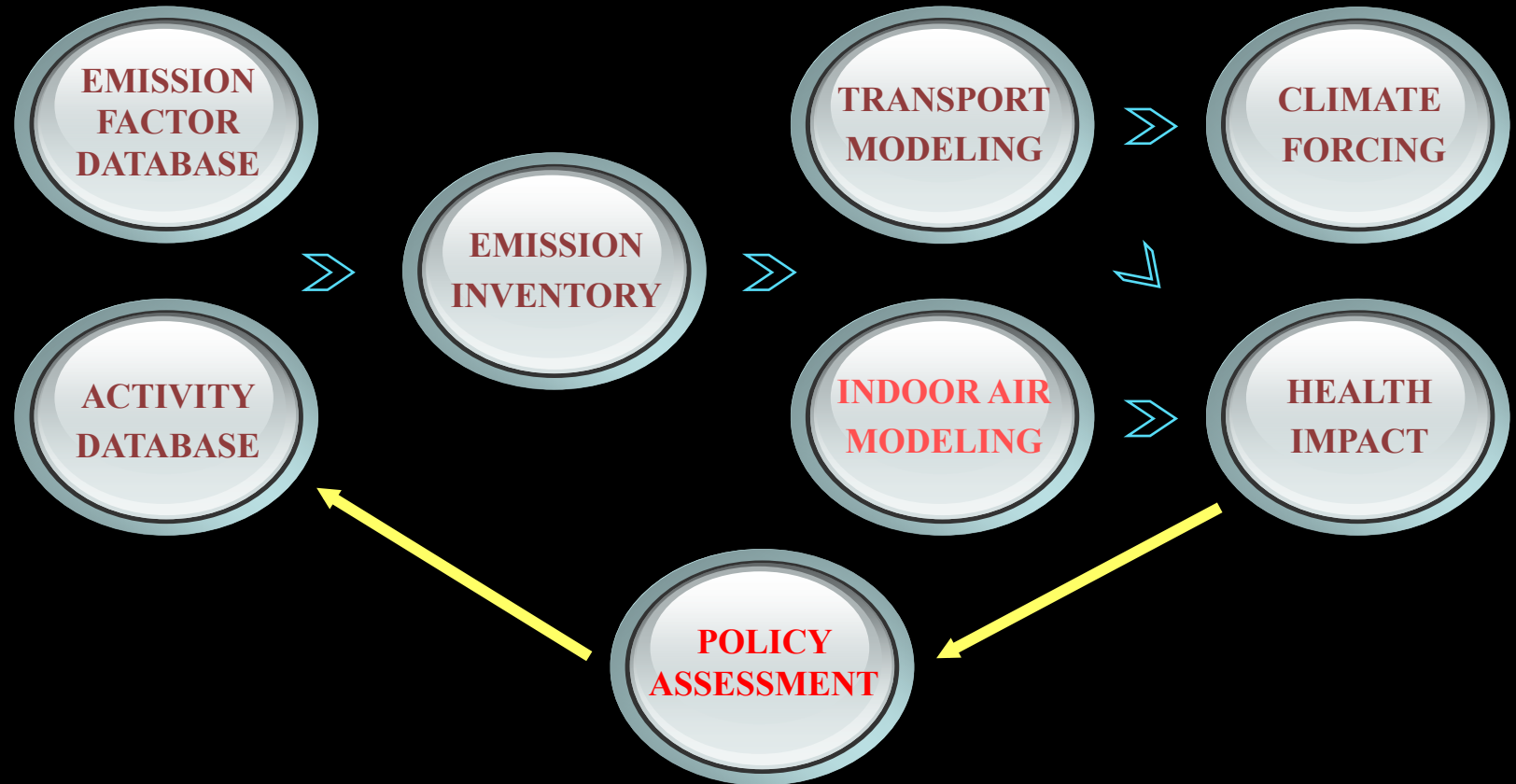
陶澍 沈国锋 程和发等

Peking University, Southern University of Science & Technology

北京大学、南方科技大学



- From emission inventory compilation to decision supporting 从清单构建到决策支持



From PKU inventories to GEMS PKU清单的全面更新

Pollutants

CO₂, CO, SO₂, NO_x, PM_{2.5}, PM₁₀, TSP, BC_{char}, BC_{soot}, OC, BrC, Hg, PAHs, et

Sources

Six sectors, five fuel types, and 147 detailed categories

Coverage

Global from 1960 to 2019

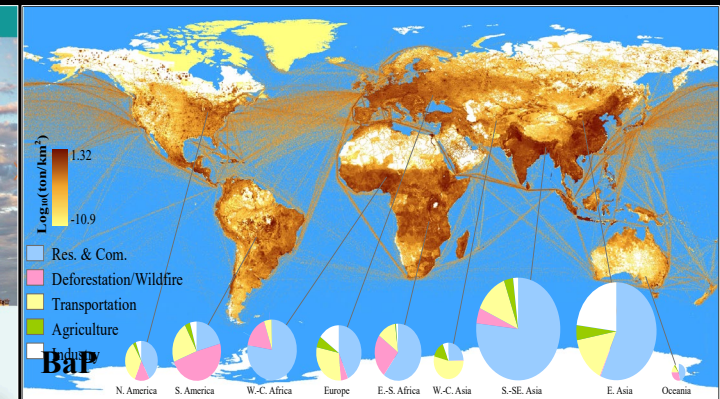
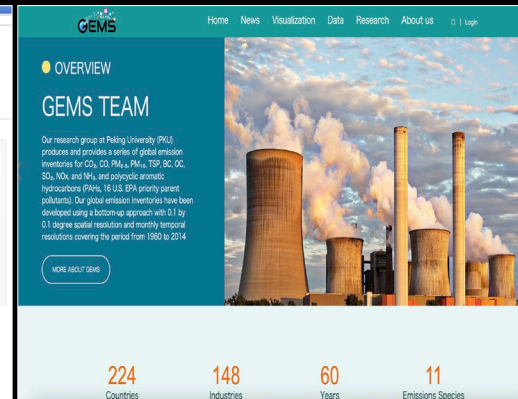
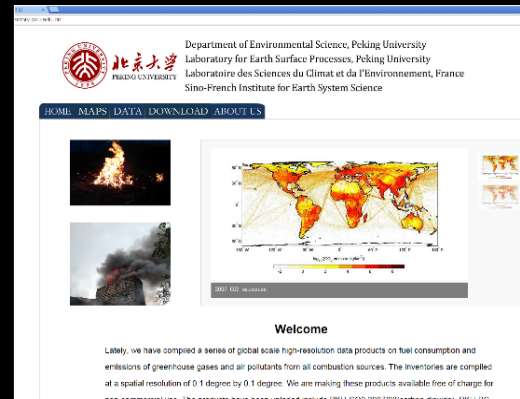
Resolutions

0.1°×0.1°, monthly/daily

Major updating 主要更新

First-hand surveys, field observations, remote-sensing data, and the literature

Chen et al., ES&T 2013
Wang et al., ACP 2013
Huang et al., ES&T 2014
Wang et al., PNAS 2014
Huang et al., AE 2015
Shen et al., AE 2015
Zhong et al., ERL2016
Meng et al., ES&T 2017
Huang et al., ES&T 2017
Zhong et al., ES&T 2020
Xu et al., ES&T 2022
Li et al., submitted



■ Air pollution in China 中国的空气污染

Air quality has been improved since 2014

A long way to go to meet the national standard / WHO guideline

■ Residential emissions 生活源排放的重要性

Residential solid fuels

Contribute substantially to both ambient and indoor air pollution

Meng et al., ES&T, 2021



炉灶	描述	典型炉灶	能源	典型燃料
开放炉灶	简易灶		生物质、煤、畜粪	
↓ 阶段1	传统炉灶		生物质、煤、畜粪	
↓ 阶段2	节能炉灶		生物质、煤、蜂窝煤	
↓ 阶段3	清洁炉灶		成型生物质、成型煤	
↓ 阶段4	燃气灶		液化石油气、管道天然气、沼气	
电炉	电炉、电饭锅、电磁炉等		电	

- **Data gap and high uncertainty** 数据缺口和不确定性

Free biomass fuels were not well accounted, most likely overestimated

Stacked energy use increases challenges household energy statistics

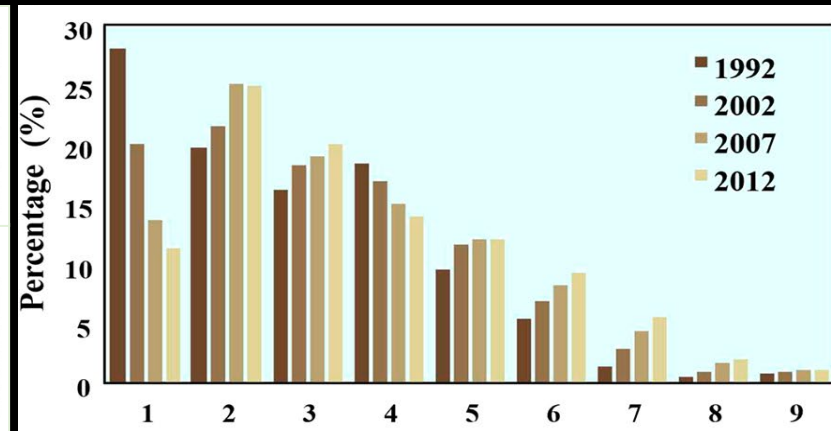
- **Household energy survey and fuel-use weighting** 生活能源调查和称重

Questionnaires >90,000 from two campaigns (1992-2012, 2017)

Fuel-use weighting ~4340 Household days

Emission tests ~ 3000 tests

Tao et al., Nature Energy 2018; Shen et al., Nat. Sci. Rev. 2022



▪ Solid fuels 固体燃料

Coal and biomass fuels contribute almost equally

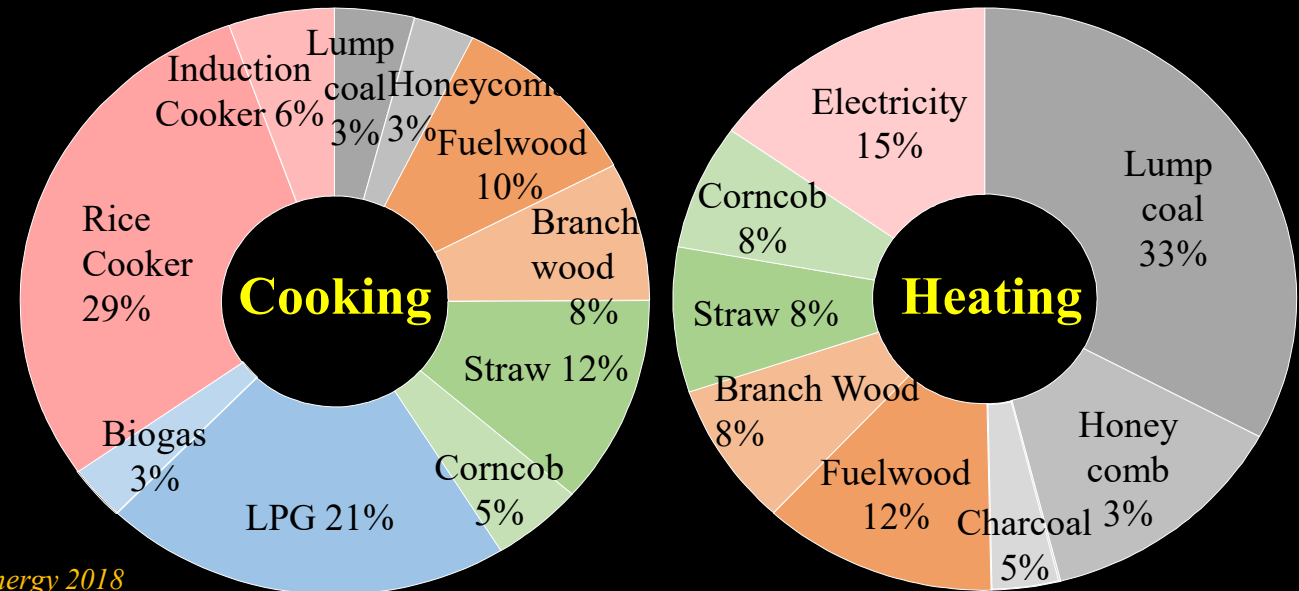
Cooking **92%** in 1992, **41%** in 2012, **24%** in 2021 driven by living condition improvement

Heating **98%** in 1992, **85%** in 2012, **73%** in 2021 in middle China with short heating period

intervention in North China Plain

▪ Clean energy 清洁燃料

Relative clean at user end



Contributions along the process chain 民用能源沿过程链的贡献

Energy use → emissions → air PM_{2.5} → exposure → premature deaths

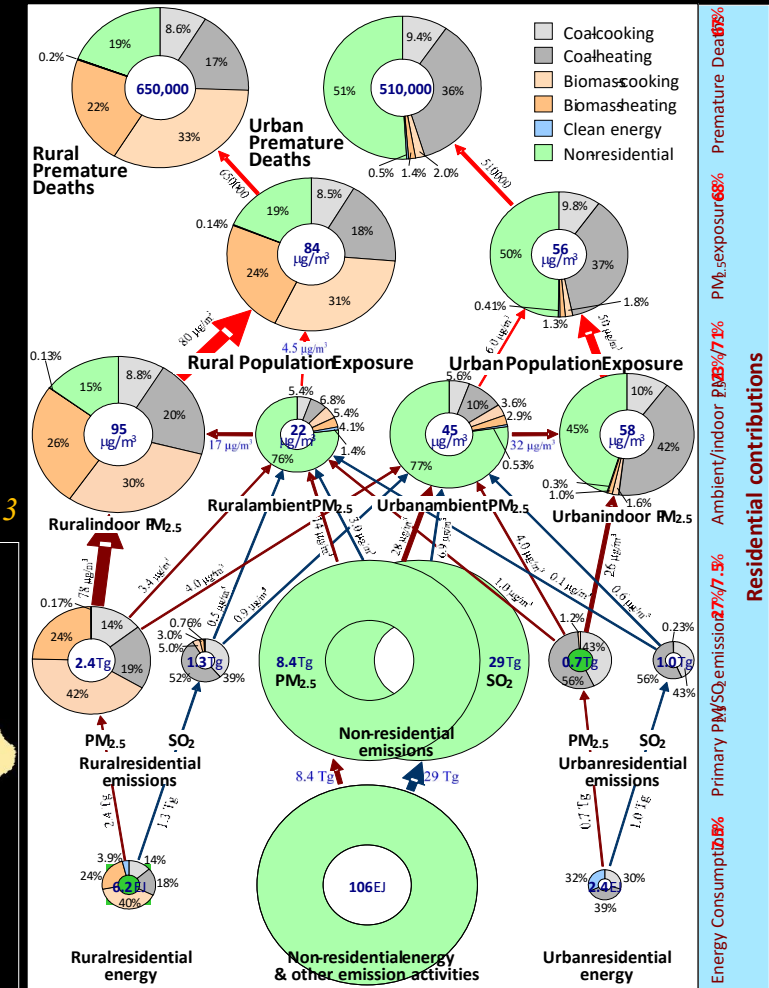
Energy use **7%**; emissions ~**20%**, ambient air ~**20%**

Indoor air, exposure, and premature deaths >**66%**

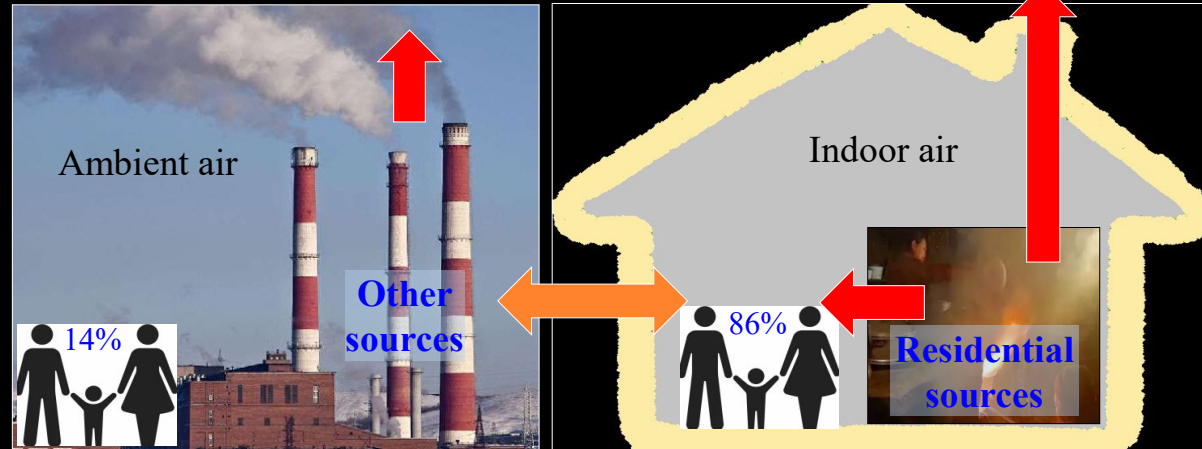
Indoor exposure 室内暴露

Contributes predominantly to population exposure

Yun et al., Sci. Adv. 2020



Duan et al., 2013



Health benefits in clean transition 自发转型的健康收益

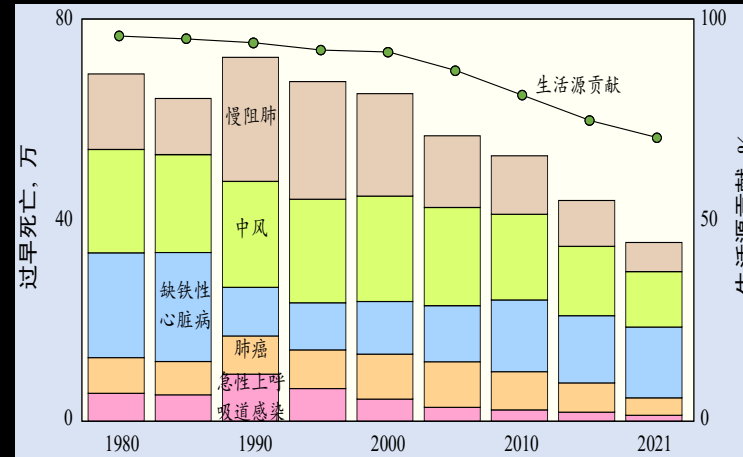
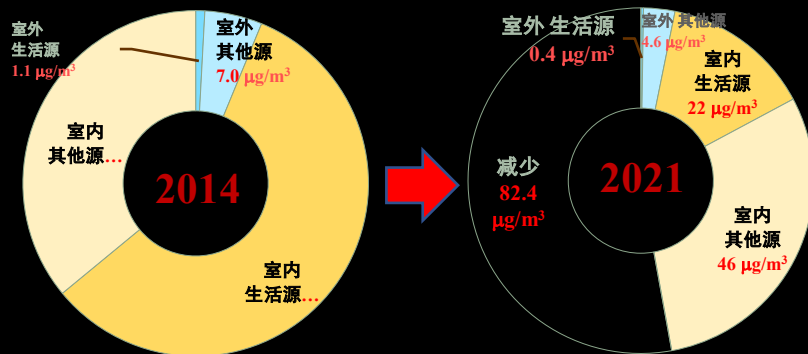
Attributable for **700,000** and **400,000** premature deaths in 1980 and 2021

Relative contributions declined from 96% to 70% during that period

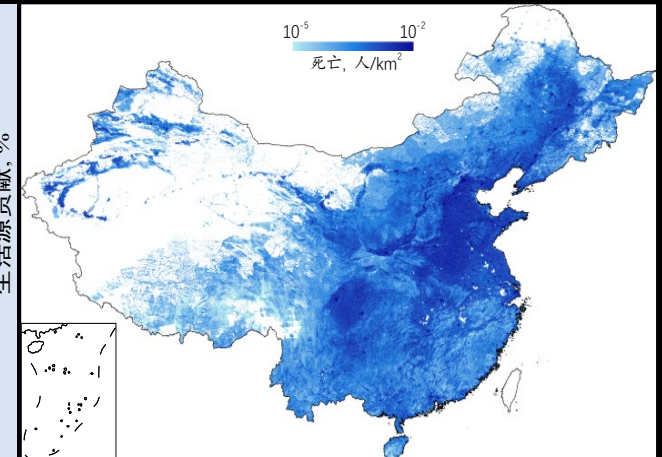
Clean heating campaign 清洁取暖行动计划

The campaign in North China Plain led to a reduction in exposure from **135** $\mu\text{g}/\text{m}^3$ to **78** $\mu\text{g}/\text{m}^3$

Meng et al., PNAS 2019



Shen et al., Nature Comm, 2019



■ Cooking energy 清洁炊事能源

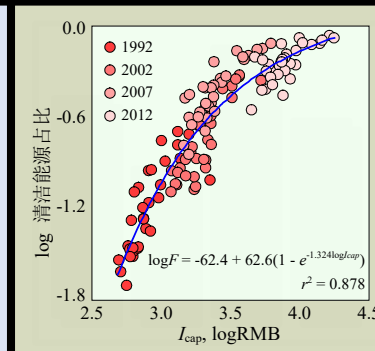
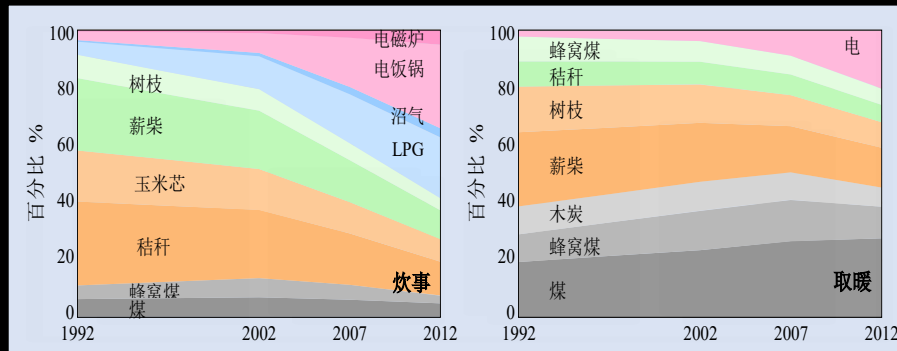
Electricity

rice cooker, induction cooker, electric oven, microwave oven, ...

Liquefied petroleum gas, LPG

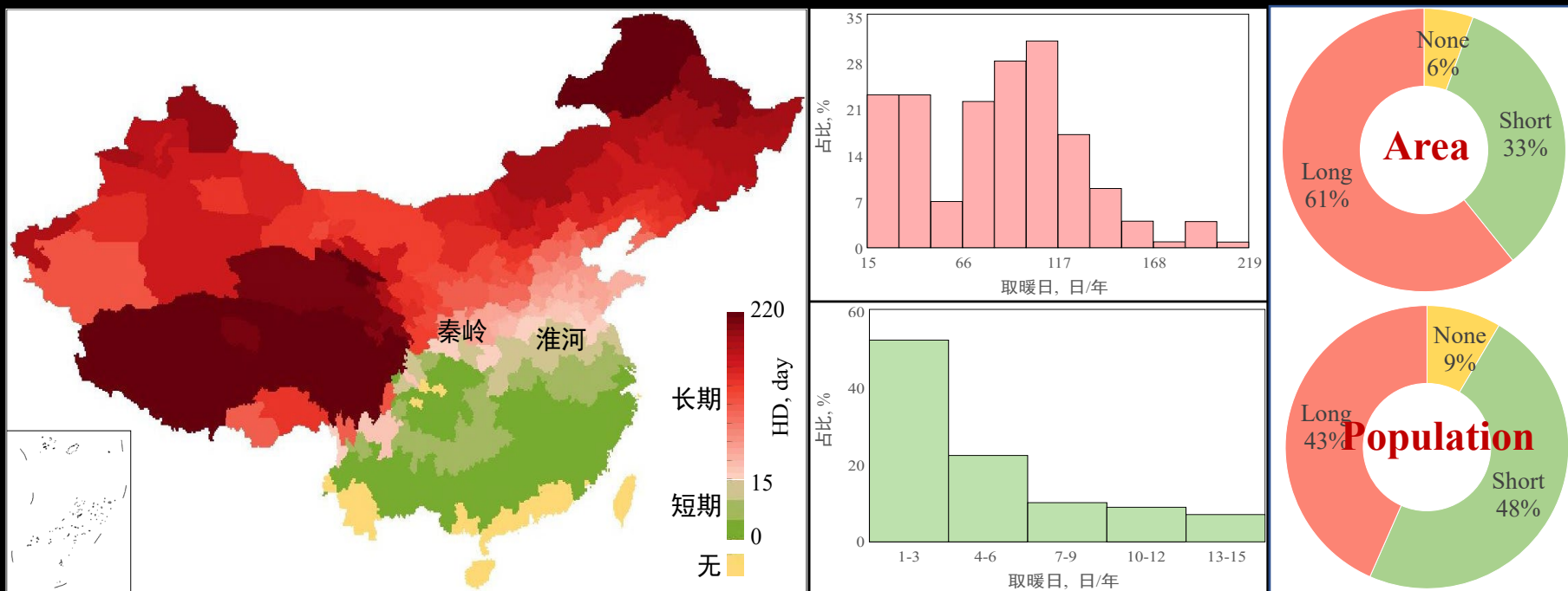
■ Intervention 干预

To accelerate the transition for remained **22%** households in less developed areas



■ Heating zoning 取暖分区

- Long-term HD > 15 days **43%** population and 61% area most between half to three months
- Short-term HD 1-15 days **48%** population and 33% area most less than 3 days
- No heating HD = 0 **9%** population and 6% area



■ Heating demand 取暖需求

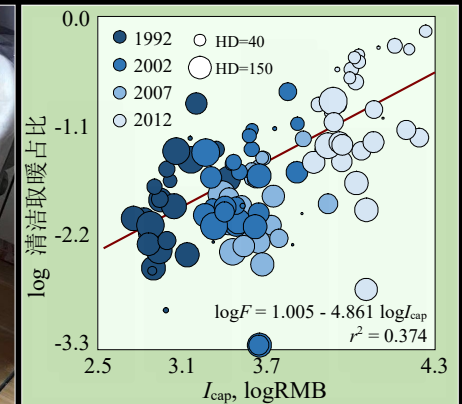
HD < 15 days with low HDD most in middle China

No heating traditionally increased heating demand as living conditions improved

■ Heating 取暖方式

Cannot to heat the entire house due to poor airtightness

Convenient and inexpensive to use electric heaters or convection heaters limited space and time



■ Heating demand 取暖需求

HD > 15 days with high HDD north, northeast, and west

■ Traditional heating 取暖方式

Permanent heating facilities required stoves, heating bed, heating wall ... with low thermal efficiencies

Solid fuels coal, fuelwood, animal dung ... with high emissions

■ Clean heating 清洁取暖方式

Electricity air source heat pump, electric heaters, and convection heaters

Natural gas gas heater



- **Where clean heating is too expensive** 不能负担电取暖地区

Areas with low population density or income

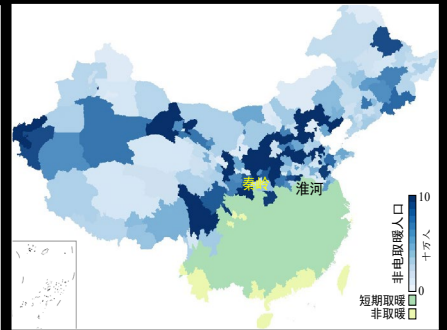
- **Alternatives** 替代选择

Pressed biomass fuels or coal briquettes + clean stoves 8,000 households in Yantai

Emissions: air pollutants and carbon incomplete combustion products, NO_x, ultrafine PM, CO₂

- **Other measures** 辅助手段

Building insulation, ventilation, air purification ... to reduce emissions/exposure



■ Clean cooking costs

Electricity

600 RMB for electric cookers, 1,000 RMB/year for electricity

LPG

300 RMB for gas container/range, 1,200 RMB/year for LPG

Intervention

To provide 44 million rural households with equipment at discount prices

■ Clean heating costs

Infrastructure cost 基建成本

Equipment cost 户用设备成本

Operational cost 运行成本

Electricity/gas, coal



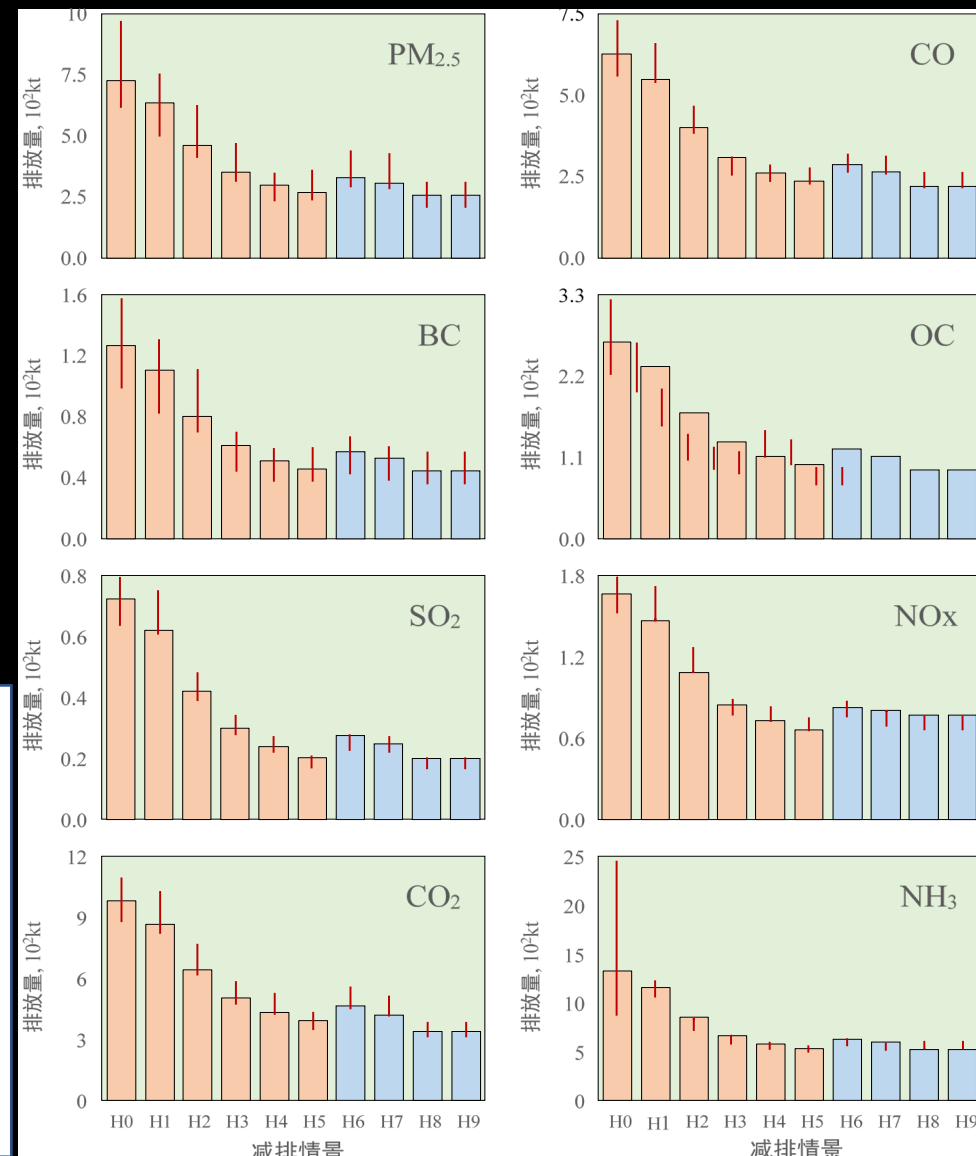
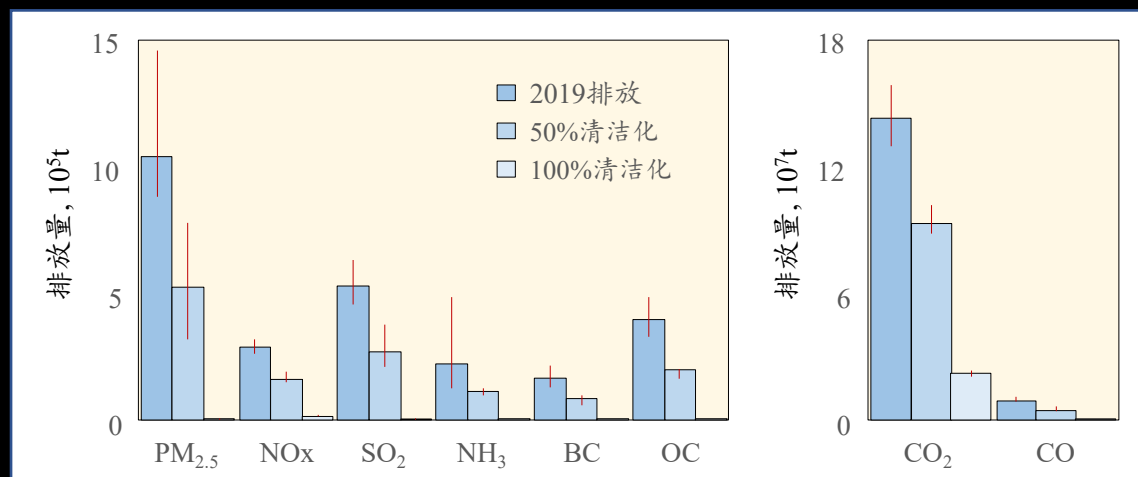
- **Clean heating 清洁取暖减排**

Nonlinear response from H0 to H1

- **Clean cooking 清洁炊事减排**

Almost proportional to clean heating rate

Exceptions: CO₂, NO_x, ultrafine particles



■ Contributions to ambient air PM_{2.5} 对室外大气PM_{2.5}的影响

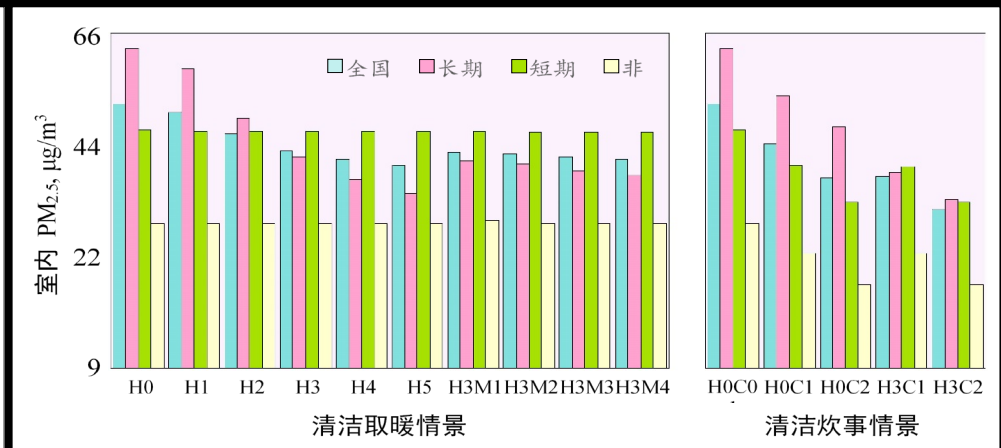
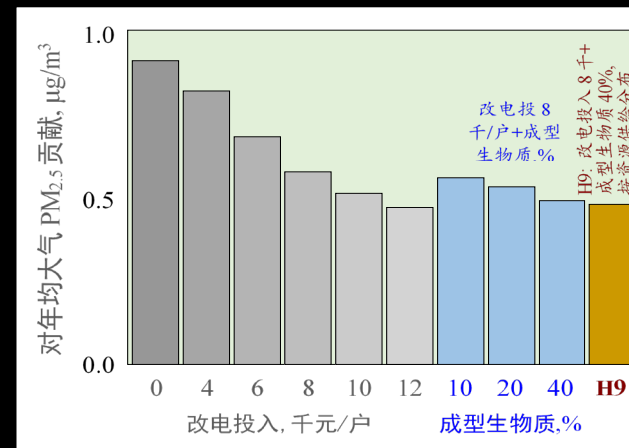
Significant reduction by electricity heating from 0.91 μg/m³ (H0) to 0.57 μg/m³ (H3)

Significant reduction by clean cooking from 1.09 μg/m³ (H0) to 0.66 μg/m³ (50%)

Combined effect from 2.00 μg/m³ (H0) to 1.23 μg/m³ (H3-50%)

■ Contributions to indoor air PM_{2.5} 对室内空气PM_{2.5}的影响

Similar to that to ambient air for all long, short, and no heating zones



- Population exposure 降低人群暴露

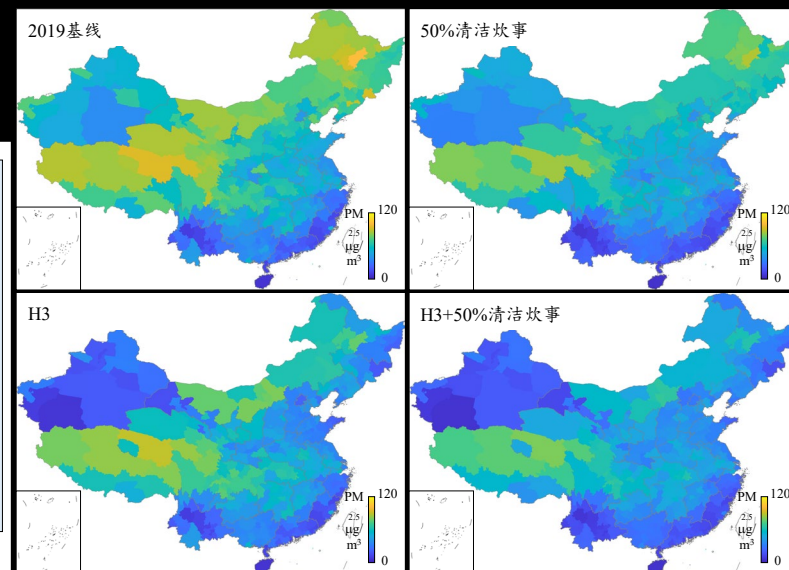
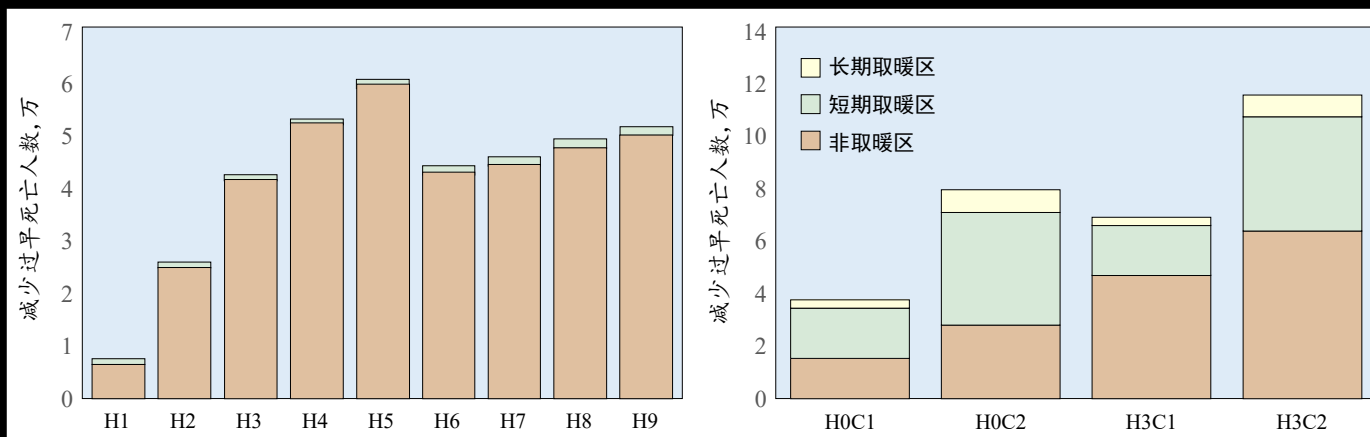
Similar to that on indoor air adults spend 86% time indoor

- Avoided premature deaths annually 减少过早死亡

Clean heating (H3) **42,000**

Clean cooking (100%) **79,000**

Clean heating (H3) + cooking (100%) **114,000**



- **Total cost for clean heating and cooking** 清洁取暖和炊事总投入

H3 clean heating scenario + 100% clean cooking **162 billion RMB, 0.13% GDP**

- **Monetized health benefit** 货币化的健康效应

Based on a **value of a statistical life** from the literature, VSL additional benefits

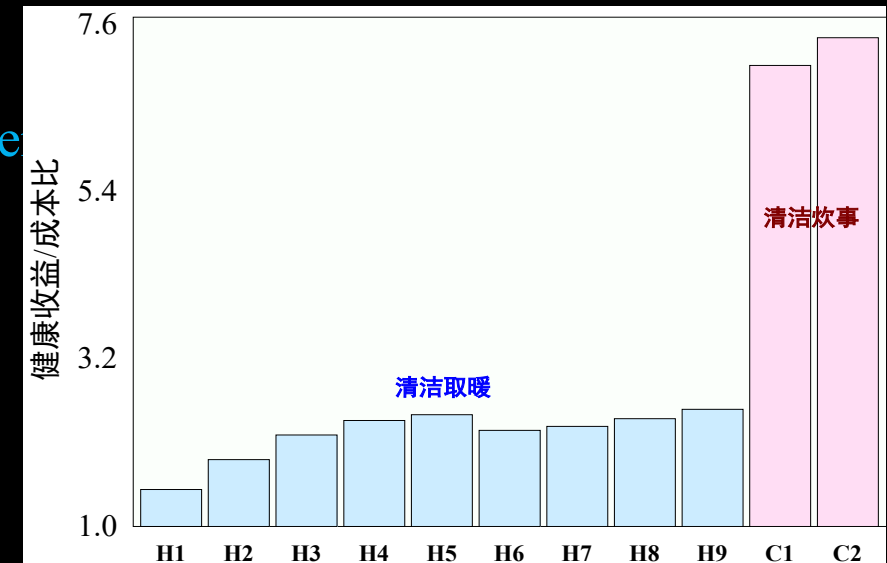
- **Cost-benefit analysis**

VSL/Cost all above 1

Clean cooking is more effective no infrastructure investment

high uncertainty

VSL, modeling ...



■ Clean cooking 清洁炊事

Electricity and liquified natural gas are highly beneficial

推行电和液化石油气

■ Clean heating 清洁取暖

Electricity using air source heat pump is recommended if affordable

成本许可时使用气源热泵

Nature gas is not preferred due to cost, safety, and security reasons

天然气昂贵, 不安全且缺乏保障

Pressed biomass fuels can be promoted as an alternative

不适合用电, 考虑压块生物质等

■ Supplementary measures 辅助手段

Ventilation, building insulation, air purification ...

通风、建筑保温和空气净化等



谢谢



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Coal to gas/electricity in 2+26 散煤替代

Initial objective – reduce wintertime haze, 60% clean heating in rural areas

Adjusted by depreciation rate and inflation

Significant health benefits 显著的健康效益

Ambient PM_{2.5}: 12 to 5 $\mu\text{g}/\text{m}^3$; Indoor PM_{2.5}: 209 to 89 $\mu\text{g}/\text{m}^3$;

Exposure levels were reduced by about 60%

Meng et al., PNAS 2018

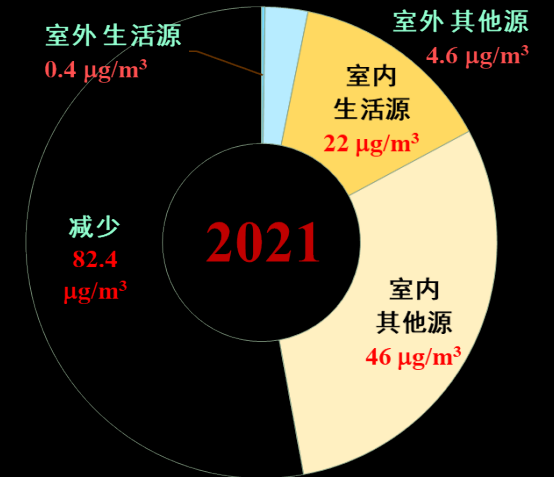
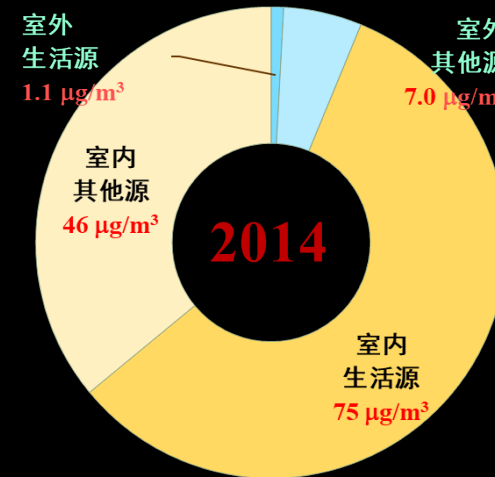


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文件

发改能源〔2017〕2100号

关于印发北方地区冬季清洁取暖规划
(2017-2021年)的通知

为深入贯彻党的十九大精神，落实习近平总书记在中央财经领导小组第14次会议上的重要指示，以习近平新时代中国特色社会主义思想为指导，按照党中央、国务院决策部署，发展改革委、能源局、财政部、环境保护部、住房和城乡建设部、国资委、质检总局、银监会、证监会、军委后勤保障部制定了《北方地区



Annualized cost for 2+26 年化成本

The sum of the initial investment, operational cost, maintenance cost, and avoided cost

Adjusted by depreciation rate and inflation

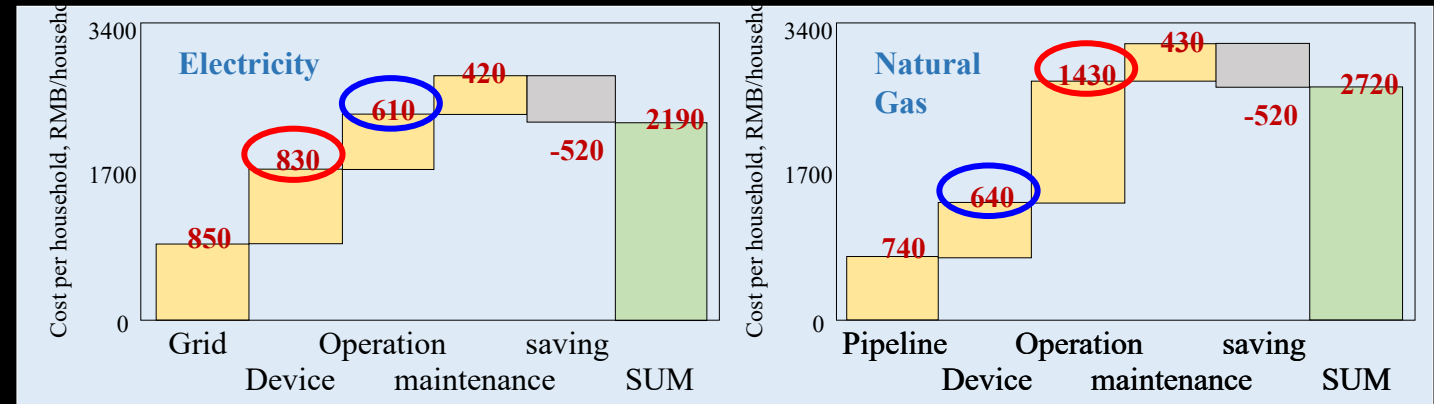
Comparison 电/气对比

Electricity **2,190** RMB/household vs. Natural gas **2,720** RMB/household

Initial investment electricity > natural gas

Operational cost gas > expensive

Other costs similar



■ Clean heating campaign in North China Plain 2+26地区的清洁取暖行动

Natural gas or electricity **56% or 44%**

Less developed areas tended to choose natural gas **2,720 vs. 2,190 RMB/household**

lower initial investment, but heavier financial burden in long-term

■ Additional pros and cons 其它利弊

Operational safety

Energy security

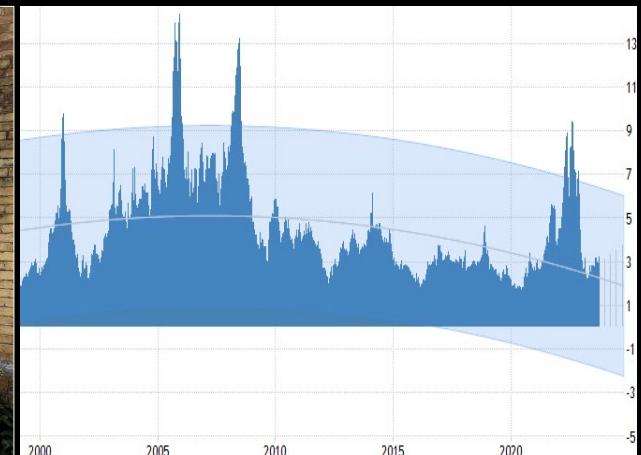
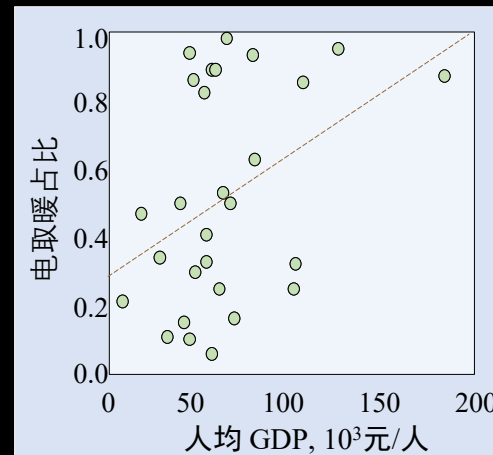
Emissions of CO₂, NO_x, and PM

Suitability for Chinese dish preparation

■ Conclusion 关键结论

Natural gas is not recommended

Meng et al., ES&T 2023



Intervention pilot programs “美丽中国” 先导专项

Clean coals, biomass pellets, etc., ~ 2200 Homes

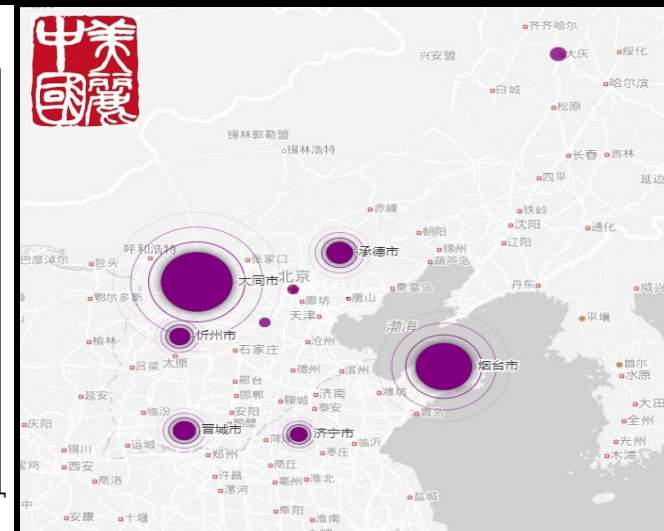
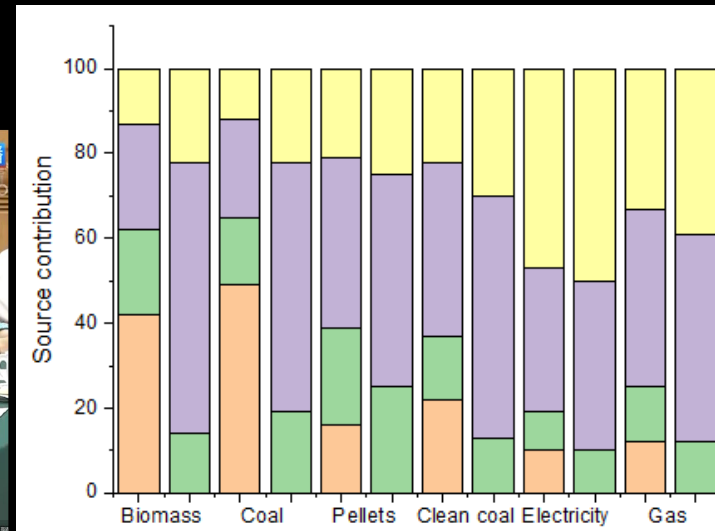
Field measurements on pollutant emissions; indoor air quality;

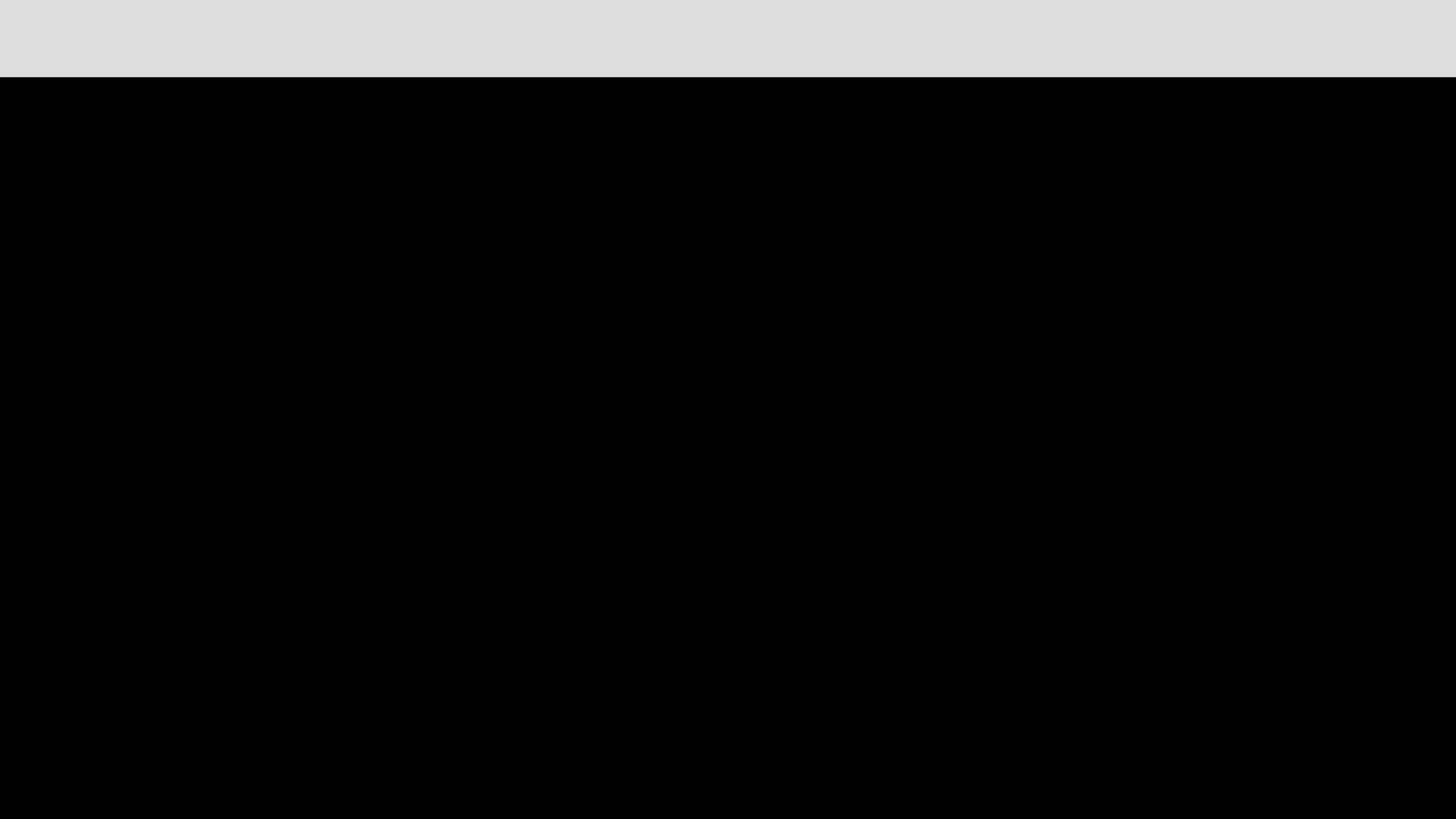
Policy recommendations in building BEAUTIFUEL AND HEALTH CHINA

Indoor air quality improvement

Gas/electricity for cooking; Ventilation

Subside and equality issues





■ Clean heating campaign in North China Plain 2+26地区的清洁取暖行动

Urban population increased from 1980 - 2014 by **148%** from 1980 to 2000

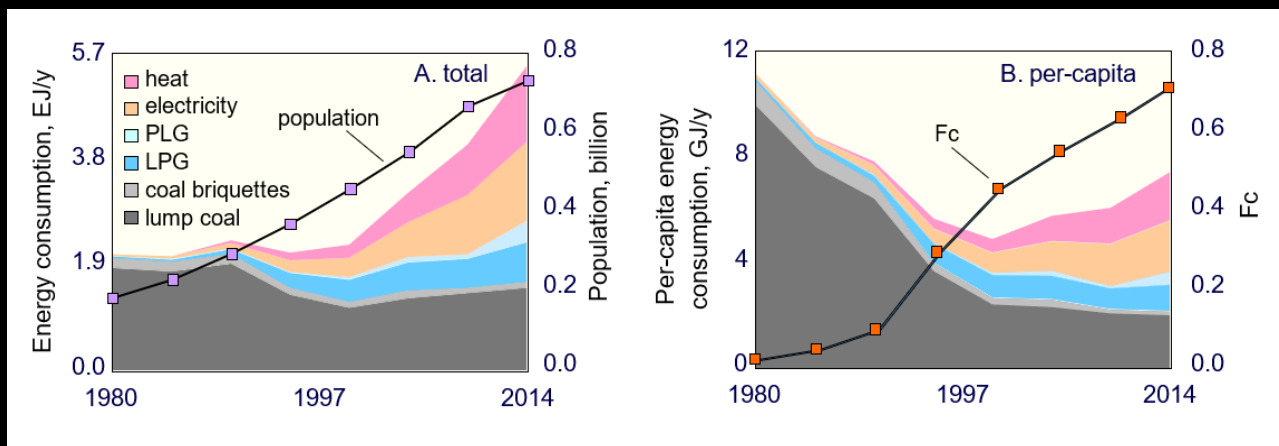
Energy use increased especially after 2000 **10%** in TJ; Clean energy **2%** to **71%**

Most air pollutant emissions declined obviously

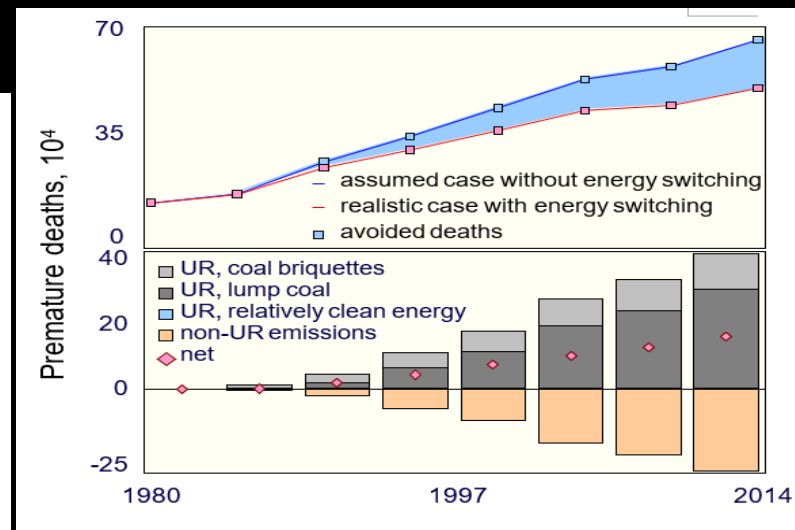
■ Health benefits

~ **2.0 million** premature deaths avoided over the 30 years

Indoor air quality improvement contributed largely

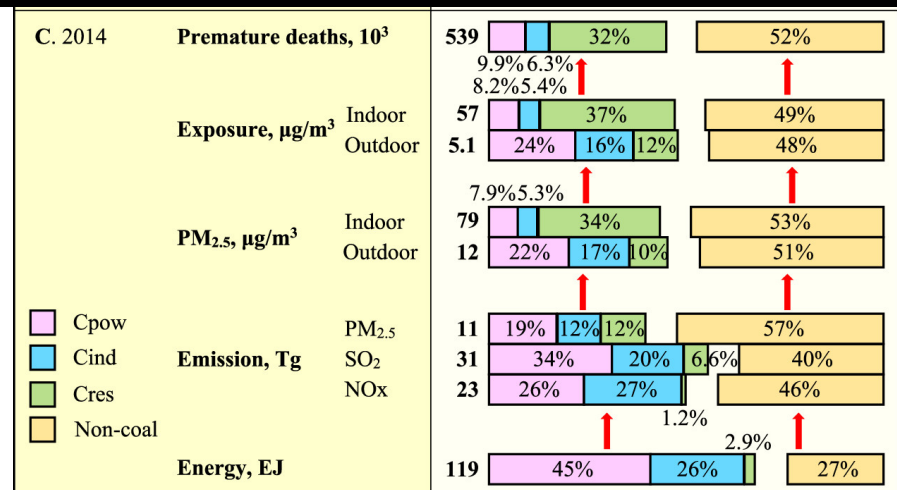
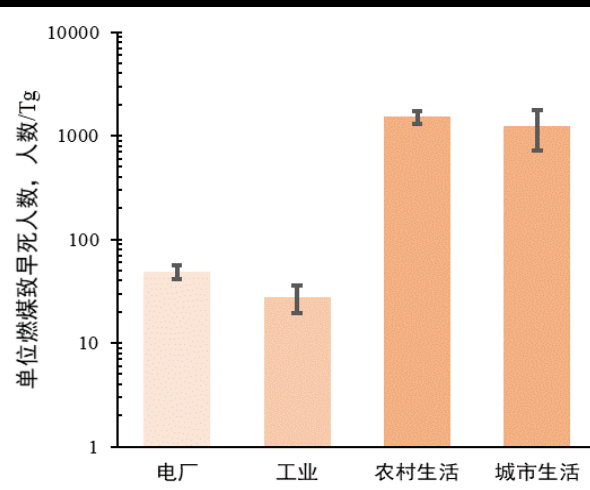
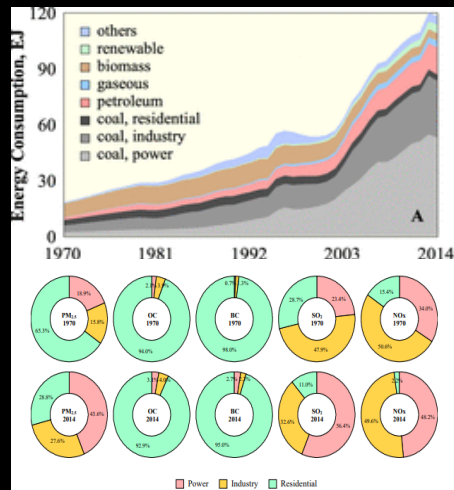


Zhang et al., *One Earth* 2021



- Coal consumption** Total coals: **0.35 to 3.47 Pg**; Residential use: **0.13 to 0.15 Pg**
- Emissions** Different in sectors by pollutants; Residential shares are generally declining
- Health impacts** 50% due to coal use, of which residential sector contributed 34%
 ~ **40 times** as “deaths per Tg coals” in the residential sector compared to others

Yun et al., ES&T 2021



- **Exposure as a non-linear function of residential and non-residential emission reduction**

Outdoor $PM_{2.5}$: a heavy emphasis on nonresidential emissions;

Co-reduce coal and biomass emissions;

more emphasis on heating (1.48:1) and rural areas (2.4:1) can lead to better results

- **A simple theoretical analysis**

Perpendicular to the contoured isoclines

Further details in technologies and cost-benefits analysis

