

Original Article



Research on the Emission Reduction Benefits of Clean Heating Projects in a City in Northwestern China Based on Carbon Emission Index Accounting

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Abstract:

Clean heating is a crucial technological pathway for improving air quality and achieving China's "dual carbon" goals. To quantify the carbon reduction benefits of clean heating, this study develops a comparative carbon emission analysis model based on distinct baseline scenarios: urban centralized heating and rural decentralized coal heating. An innovation has established the "unit area carbon reduction" indicator, which enables the direct calculation of emission reductions from a given implementation area, offering a practical assessment tool for regions with similar climatic and building characteristics. In a case study of a city in Northwest China, the model was applied to clean heating projects, revealing significant annual CO₂ reductions of 810,300 tons for urban areas and 584,000 tons for rural areas. These findings provide a systematic and quantitative scientific basis for the performance evaluation of clean heating projects, thereby offering support for the achievement of the "dual carbon" goals.

Keywords: Clean heating, Carbon emission reduction, Benchmark model, Performance evaluation

Introduction

At the general debate of the 75th United Nations General Assembly held on September 22, 2020, President Xi Jinping proposed that China strive to peak carbon dioxide emissions before 2030 and achieve carbon neutrality before 2060 [1]. In October 2021, the State Council issued the "Action Plan for Carbon Peaking Before 2030" [2], proposing to include urban and rural construction carbon peaking actions as one of the ten major carbon peaking actions. It also actively promotes clean heating in cold and severe cold regions, advancing combined heat and power centralized heating, accelerating the large-scale application of industrial waste heat for heating, and steadily carrying out nuclear energy heating demonstrations. Additionally, it called for the promotion of clean and low-carbon heating methods such as heat pumps, biomass energy, geothermal energy, and solar energy, based on

local conditions. These documents became important guidelines for the application of clean heating project demonstration cities, with carbon emission indicators becoming a key component in measuring the performance targets of these projects.

Against the backdrop of global warming and climate change, governments and international organizations worldwide face the urgent challenge of addressing greenhouse gas (GHG) emissions. Carbon accounting has become a crucial tool for monitoring and reducing emissions, enabling the accurate quantification of emissions and supporting effective management and emission reduction efforts. The Intergovernmental Panel on Climate Change (IPCC) has provided carbon emission accounting guidelines for five sectors (energy, industry, agriculture, land use change, and waste management) [3]. In 2014, the

International Council for Local Environmental Action (ICLEI), the World Resources Institute (WRI), and the C40 Cities Climate Leadership Coalition developed the Global Protocol for Community-Scale Greenhouse Gas Emission Inventories (GPC), a simplified framework that allows local governments to adapt methods based on available data, promoting globally comparable urban carbon emission accounting methods [4]. The choice of methods for calculating urban-level carbon emissions depends on emission sources, data availability, and accounting objectives. Common methods include the emission factor method, mass balance method, and direct measurement method. Among these, the emission factor method is the most widely used, particularly for estimating emissions from energy consumption and industrial processes [5,6]. Regarding heating energy consumption and carbon reduction in northern regions, the literature [7] constructed a bottom-up statistical empirical model to predict residential heating energy demand in rural China by 2050, using IPCC-recommended carbon emission factors to calculate carbon emissions from residential heating in northern rural China. These research findings provide technical references for governments to implement carbon reduction strategies.

To address air pollution in the Beijing-Tianjin-Hebei region, China launched the "Clean Heating Urban Construction Project" in 2017, with five batches implemented to date. In the early stages, the project primarily focused on controlling scattered coal use, with performance evaluations emphasizing the reduction of scattered coal consumption in target areas. Since 2021, clean heating projects have become a key technological pathway for cities to achieve the "dual carbon goals," and their carbon reduction contributions have been prioritized in government performance assessments. However, the electricity used in these projects isn't entirely clean. Combined heat

and power (CHP) systems, ultra-low emission retrofits for coal-fired boilers, and biomass/gas heating projects still emit carbon dioxide. There remains a lack of targeted quantitative methods to analyze how these projects contribute to urban carbon reduction. The year 2025 marks the performance evaluation phase for the fifth batch of clean heating projects. This initiative aims to provide quantified carbon reduction analysis methods for each technology type in participating cities, establish calculation indicators for post-implementation carbon reductions, and offer scientific guidance for evaluating clean heating projects in a city in Northwest China.

research technique

Under the dual carbon strategy, clean heating should prioritize improving people's livelihoods and achieving energy conservation and carbon reduction. Carbon emissions are closely related to both the carbon emission factors of technology types and the equipment used. This study employs a comparative analysis approach to establish a benchmark model for technology evaluation. By comparing clean heating technologies with the benchmark model, we derive a method for calculating the overall carbon reduction of clean heating projects. The research methodology is as follows:

- (1) Based on the implementation plan of a heating project summarized in a city in Northwest China, compile the implementation area of clean heating projects with the same technical approach; according to the corresponding project type (urban or rural buildings), adopt different heat consumption calculation indicators to determine the annual heat consumption of such projects.
- (2) The comprehensive efficiency of the adopted technology (including combustion efficiency and transportation efficiency) is considered and converted into the calorific value of the required fuel.
- (3) Calculate the annual carbon emissions of the

technology based on the carbon emission index per unit heat value of the fuel.

(4) Establish benchmark calculation models and clean heating retrofit models for each technical project, respectively, derive carbon emissions under both models, and calculate the carbon reduction achieved by implementing this project in the city through the difference between the two models.

Carbon Emission Factors of Key Technology Types

The carbon dioxide emission factors of clean heating technologies are closely related to building energy consumption and energy types, with significant variations across different energy sources. Typically, energy consumption is

converted to standard coal consumption for calculation purposes. Natural gas and briquette emissions are determined according to the national standard "Building Carbon Emission Calculation Standard" (GB/T51366-2019) [8]. For the Northwest Regional Power Grid, the average CO₂ emission factor in 2023 was 0.6423 kgCO₂/kWh. Based on a 2023 study by Yan Kun *et al.* from Shenyang Jianzhu University [9], the CO₂ emission factor for coal-fired combined heat and power (CHP) units is 0.054 tCO₂/GJ, equivalent to 0.1944 kgCO₂/kWh (heat); while coal-fired thermal power has a factor of 0.109 tCO₂/GJ, corresponding to 0.3924 kgCO₂/kWh (heat). Emission factors calculated for different heat sources are shown in Table 1:

Table 1 Carbon Emission Factors for Different Energy Forms

order number	Heat source type	CO ₂ emission factor
1	Ningxia Power Grid (2023)	0.6423 kg CO ₂ /kWh (electricity)
2	coal-fired cogeneration	0.1944 kg CO ₂ /kWh (heat)
3	natural gas	0.1999 kg CO ₂ /kWh (heat)
4	burning of loose coal (coal briquette)	0.3992 kg CO ₂ /kWh (heat)
5	centralized coal-fired heating	0.3924 kg CO ₂ /kWh (heat)
6	photovoltaic power generation	0 kgCO ₂ /kWh (electricity)

Setting of key parameters of main technology

Equipment efficiency and pipeline losses are major factors affecting carbon emissions from heat sources. Therefore, we consider the thermal efficiency (or COP) of different heat sources, with each type of equipment's thermal efficiency following either design standards or individual product specifications.

(1) The thermal efficiency of gas boiler-based centralized heating is calculated at 92% according to the industry standard "Energy Efficiency Design Standard for Residential Buildings in Severe Cold Regions" (JGJ26-2019) [10].

(2) For centralized heating systems using water-source heat pumps, the coefficient of performance (COP) is 4.0 as specified in the national standard

"Water (Ground) Source Heat Pump Units" (GB/T 19409-2013) [11]. For household air-source heat pumps, the performance coefficient (HSPF) is determined by the standard "Low Ambient Temperature Air Source Heat Pump (Chilled Water) Units-Part 2: Household and Similar Applications" (GB/T 25127.2-2020) [12]. In cold climate regions, the HSPF limit values are 2.8 for floor heating, 2.6 for fan coil units, and 2.3 for radiators, with the HSPF value being the midpoint of 2.5.

(3) For air-source heat pump combined with photovoltaic heating systems, the heat pump's HSPF (Heat Supply Factor) is set at 2.5, powered by photovoltaic panels, and produces zero CO₂ emissions.

(4) For household gas wall-hung boilers, the

Ningxia Hui Autonomous Region mandates compliance with the national standard GB 20665-2015 (Energy Efficiency Limit Values and Grades for Household Gas Quick Water Heaters and Gas Heating Water Boilers) [13], requiring a minimum grade of 2 with a thermal efficiency of 0.85.

(5) For the ultra-low emission retrofitting project of regional coal-fired boilers, the boiler efficiency shall be 88% after retrofitting; for combined heat and power (CHP) projects, the boiler thermal efficiency shall be 90%.

(6) Solar PV + heat pump heating system: The solar power generation has a 50% reliability rate, with surplus electricity supplied by the municipal grid.

(7) The solar thermal heating system has a 50% solar energy reliability rate, with air-source heat pumps serving as auxiliary heat sources at night.

Analysis of emission reduction benefits of clean heating project in a city in northwest China

The clean heating project in a city in north-west China comprises urban and rural components. Due to the significant differences in heating load characteristics between urban and rural buildings, and the distinct heating methods used — centralised heating in cities versus scattered coal stoves in rural areas — there are substantial variations in the calculation benchmarks for carbon emissions. This division enables a detailed analysis of the benefits of reducing emissions across different technical solutions.

Carbon Emission Reduction Benefit of Urban Area Project

The urban area employs the following technical solutions: combined heat and power (CHP), centralised gas heating, and air and water source heat pumps. Prior to implementing clean heating, the baseline model for a city in northwestern China was configured as follows:

Assuming that all urban heating sources are centralised coal-fired boiler rooms in residential complexes, the building heat consumption index is calculated according to the local Ningxia standard, 'Energy Efficiency Design Standard for Residential Buildings' (DB60/521-2013) [14]. For a city in north-west China, the building heat consumption index is 15.0 W/m², with an actual heating season of 151 days. This results in a cumulative heat consumption of 54.36 kWh/m² per unit area during the heating season.

(2) The boiler operation efficiency is 0.78, and the outdoor pipeline transmission efficiency is 0.91.

The efficiency values of various technologies in the comparative model for clean heating projects implemented in urban areas are presented in Section 1.2. When the distributed heating mode is adopted, the listed projects avoid heat loss from pipeline transportation compared to centralised heating. For centralised heating projects involving large-temperature-difference retrofitting, the average water temperature is lower, resulting in increased transportation efficiency. The outdoor heat pipeline network achieves a transportation efficiency of 0.94.

Table 2 shows the energy consumption of different clean heating projects in an urban area in northwestern China.

Table 2 Energy Consumption of Projects with Different Technologies in Urban Areas of a City in Northwest China

Technology type	area of structure (10,000 sqm)	Building terminal energy consumption (10,000 kWh)	Benchmark heat source energy consumption (10,000 kWh)	Clean heating model heat source energy consumption (10,000 kWh)
air source heat pump	57	3098.5	4365.3	1239.4

				(Electricity)
Water Source Heat Pump	106.29	5777.9	8140.2	1444.5 (Electricity)
Solar Photovoltaic + Air Source Heat Pump	321	17449.6	24583.8	3489.9 (Electricity)
Combined heat and power (large temperature difference)	2981	162047.2	228299.7	191545.1 (Heat)
centralized gas heating	1060	57621.6	81180.1	68826.6 (Heat)
subtotal	4525.3	245994.8	346569.1	--

The carbon emissions of each clean heating project were calculated using carbon emission factors based on primary technical types, with the

baseline model employing thermal carbon emission factors for coal-fired centralized heating. The results are presented in Table 3.

Table 3 Carbon Emission of Different Types of Projects in Urban Area of a City in Northwest China

Technology type	Carbon emissions of the baseline model (10,000 tons of CO ₂)	Clean heating carbon emissions (10,000 tCO ₂)	carbon emission reduction (tCO ₂)	Emission reduction per unit area (kgCO ₂ /m ²)
air source heat pump	1.71	0.80	0.92	16.09
Water Source Heat Pump	3.19	0.93	2.27	21.32
Solar Photovoltaic + Air Source Heat Pump	9.65	2.24	7.41	23.07
Combined heat and power (large temperature difference)	89.58	37.24	52.35	17.56
centralized gas heating	31.86	13.76	18.10	17.07
subtotal	135.99	54.96	81.03	--

Using computational analysis and a centralised coal-fired boiler heating system as a baseline, we calculated the carbon reduction metrics per unit area for various thermal solutions employing electricity, combined heat and power (CHP) and natural gas. The photovoltaic-heat pump hybrid system demonstrated the greatest emission reduction benefits, followed by water-source heat pumps. In a northwestern Chinese city, the planned clean heating area of 45.25 million square metres is projected to achieve a reduction of 810,300 tonnes of CO₂ upon implementation.

However, given the maximum carbon dioxide emission quota for power grids, the emission reduction may fall below that of coal-fired CHP and gas-fired heating when the system's energy efficiency ratio is low. This paper presents the

emission reduction per unit area for various technologies in a city in northwestern China. During project performance evaluation, aggregating the implementation areas of the relevant technologies enables emission reductions to be calculated.

Economic Benefits of Carbon Emission Reduction in Rural Project

In a rural area of a city in north-west China, the main technical solutions are combined heat and power (CHP) systems (centralised in villages along the heat network), centralised gas heating, and decentralised clean energy heating (air-source heat pumps, solar photovoltaic systems combined with air-source heat pumps and gas wall-hung boilers). The baseline model information for clean heating in this rural region is as follows:

(1) Based on field research in rural areas, the average annual coal consumption for heating per household is estimated at 2.2–3.0 tons of briquettes (with an estimated value of 2.5 tons). Assuming an average heating area of 100 m² per household and 60% combustion efficiency for rural coal stoves, the annual heating energy consumption for rural residential buildings is calculated to be 15 kg of briquettes per m² per year. Assuming a calorific value of 23,848 kJ/kg for briquettes, the cumulative heating energy consumption per unit area during the heating

season is 99.37 kWh/m².

(2) The benchmark model uses a coal-fired stove for heating and burns briquettes with a boiler combustion efficiency of 60%.

For clean heating projects implemented in rural areas, the comparative model presents the efficiency values of various technologies as shown in Section 1.2. Table 4 illustrates the energy consumption of different technologies in rural areas of a city in north-west China.

Table 4 Energy Consumption of Different Technology Types in Rural Areas of a City in Northwest China

Technology type	area of structure (10,000 sqm)	building terminal energy consumption (10,000 kWh)	Benchmark model heat source energy consumption (10,000 kWh)	Clean heating model heat source energy consumption (10,000 kWh)
heat and power cogeneration	410.0	40741.7	67902.8	48158.0 (Hot)
centralized gas heating	13.0	1291.8	2153.0	1543.0 (Hot)
Ultra-low emission retrofit of coal-fired boiler	60.0	5962.2	9937.0	7445.3 (Hot)
Gas wall-mounted boiler	59.0	5862.8	9771.4	7002.9 (Heat)
air source heat pump	600.8	59698.5	99497.5	23879.4 (Electricity)
Solar Thermal Utilization + Heat Pump	129.0	12818.7	21364.6	2563.7 (Electricity)
Photovoltaic power generation system + heat pump	100.0	9937.0	16561.7	1987.4 (Electric)
subtotal	1371.8	136312.8	227188.0	--

The carbon emissions of each clean heating project were calculated using emission factors for major technical types, with the baseline model

employing thermal carbon emission factors for briquette combustion. The results are presented in Table 5.

Table 5 Carbon Emission of Different Types of Rural Projects in a City in Northwest China

Technology type	Carbon emissions of the baseline model (10,000 tons of CO ₂)	Clean heating model carbon emissions (10,000 tCO ₂)	carbon emission reduction (tCO ₂)	Emission reduction per unit area (kgCO ₂ /m ²)
heat and power cogeneration	27.11	9.36	17.74	43.28
centralized gas heating	0.86	0.31	0.55	42.39
Ultra-low Emission of Coal-fired Boiler	3.97	2.92	1.05	17.42

Gas wall-mounted boiler	3.90	1.40	2.50	42.39
air source heat pump	39.72	15.34	24.38	40.58
Solar Thermal Utilization + Heat Pump	8.53	1.65	6.88	53.35
Photovoltaic power generation system + heat pump	6.61	1.28	5.33	53.35
subtotal	90.7	32.3	58.4	--

We calculate the carbon reduction per unit area for various thermal solutions employing electricity, combined heat and power (CHP), and gas, using decentralised coal-fired heating in rural areas as a baseline. Photovoltaic (PV) + heat pump technology demonstrates the most significant benefits in terms of emission reduction. As both the PV and solar thermal systems in this study operate at 50% reliability, their carbon reduction metrics are consistent. The PV + heat pump system achieves greater emission reductions as the proportion of PV generation increases.

When we compare the carbon emission reduction outcomes of the same technology in rural and urban areas, rural regions demonstrate significantly higher efficiency due to their lower baseline emissions. Carbon emissions from scattered coal combustion far exceed those from centralised heating systems, making rural areas substantially more effective at reducing emissions than urban areas. In a city in north-west China, rural clean heating coverage reached 13.718 million square metres, resulting in a reduction of 584,000 tonnes of CO₂ post-implementation. Using the same urban approach, performance evaluations of rural clean heating projects in this city use statistical coverage data and calculated per-unit-area emission reduction metrics to accurately determine project-specific emission reductions.

Conclusion

The implementation of clean winter heating projects serves as a crucial technical approach to improve air quality in a city in Northwest China. This study establishes a comparative analysis

model for heating-related carbon emissions, using urban centralized heating and rural decentralized coal-fired heating as baseline benchmarks across urban and rural dimensions. By evaluating the energy efficiency characteristics of each clean heating technology, the carbon emission differences from the baseline models are calculated to serve as the basis for assessing emission reduction effectiveness. Through aggregating the computational results of various technologies, the study quantifies the overall contribution of clean heating initiatives to the city's carbon emission reduction efforts.

This paper presents a method for evaluating carbon emission reductions in urban clean heating projects. By calculating emission reduction metrics per unit area for each technology, the results enable the direct quantification of carbon reductions in regions with identical climate and building conditions when the implementation areas are known. The findings provide a scientifically validated, quantitative approach to assessing the performance of clean heating initiatives.

According to the calculations and analysis, the implementation of the clean heating project in a city in north-west China will result in an annual reduction of 810,300 tons of carbon dioxide in urban areas and 584,000 tons in rural areas. The total annual reduction in carbon emissions from heating in the city after implementation of the project will be 1,394,000 tons.

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