Energy Conversion and Management 279 (2023) 116764

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Integrated assessment on the implementation of sustainable heat technologies in the built environment in Harbin, China

Tianrun Yang [*], Wen Liu, Gert Jan Kramer

Copernicus Institute of Sustainable Development, Utrecht University, Princetonlaan 8a, 3584 CB Utrecht, the Netherlands

ARTICLE INFO

Keywords:
Seasonal thermal energy storage
Heat pump
Biomass
Levelized cost of heat
Integrated assessment

ABSTRACT

Heating in built environments is an essential factor regarding energy consumption and CO_2 emissions. Thus, the application of sustainable heating technologies is vital for reducing CO_2 emissions. The literature indicates the requirement for a comprehensive assessment of the technical, economic, and environmental performances of various sustainable heating technologies and their implementation feasibility at the local level. Accordingly, this study presents a quantitative assessment relative to Harbin, a typical northern city with a coal-dominated heating system. Seven sustainable heating technologies were examined using current policy and future renewable scenarios. The results indicate that the examined heating technologies are technically feasible. Biomass heating saves costs and emissions (CO_2 avoidance costs of 24–47 €/t), although fuel availability and storage management limit its implementation. Solar heating is a promising technology with reduced costs and low CO_2 emissions (CO_2 avoidance costs can decline by 50% from 2020 to 2050). However, its current resident acceptance is relatively low as lengthy investigations and periods for underground construction are required. Electric heating is preferable in terms of implementation feasibility; however, its economic competitiveness and environmental impact depend heavily on electricity prices and grid cleanliness (CO_2 avoidance costs of 120–463 €/t). This study contributes to the existing literature on sustainable heat transition in China by providing informative local circumstances in Harbin and presenting assumption-making methods in detail when local data is not transparent. The integrated assessment provides solid evidence to facilitate decision-making in the clean heating transition in northern cities of China. The methods are applicable to other countries with similar heat-supply structures and climate conditions.

1. Introduction

As the world's largest energy consumer, contributing approximately 30% of global CO_2 emissions, China has promised a peak in CO_2 emissions by 2030 and to achieve carbon neutrality before 2060 [1]. Heating is an important factor in energy consumption and is a significant CO_2 emitter in China's building sector [2]. In 2020, urban heating in the northern area consumed 214 million tons of coal equivalent and emitted 550 million tons of CO_2, accounting for 26% and 33% of national energy consumption and CO_2 emissions in the built environment, respectively [3]. Therefore, decarbonizing residential heating is essential to achieving China's carbon neutrality target.

To alleviate environmental pollution and carbon emissions caused by coal-dominated heating, China issued the *Clean Winter Heating Plan in Northern China (2017–2021)*, clarifying the definition of clean heating for the first time [4]. Clean heating, in the plan, refers to using natural gas, electricity, geothermal, biomass, solar energy, industrial waste heat, clean coal (ultra-low emission), and nuclear energy to achieve low-emission and low-energy-consumption heating methods through highly efficient heating systems. These technologies largely align with the focus of alternative heating methods emerging in developed countries and regions [5]. The implementation of this plan requires local authorities to comprehensively evaluate and select suitable sustainable heating technologies (SHTs) based on local conditions.

The clean heating transition is essential to an effective response to climate change. Itten et al. [6] discussed the transition to sustainable heating systems (e.g., district heating systems, heat pumps, and solar thermal systems, in combination with thermal insulation) with a focus on developing, implementing, and testing incentives that target home/building owners to make investments. Yuan et al. [7] analyzed the trade-off problem between excess industrial heat and heat pumps in district heating systems under a 100% renewable energy scenario for 2050 for Aalborg. López-Bernabé et al. [8] introduced energy-efficiency policies

---

* Corresponding author.
E-mail address: t.yang1@uu.nl (T. Yang).

https://doi.org/10.1016/j.enconman.2023.116764
Received 31 October 2022; Received in revised form 25 January 2023; Accepted 29 January 2023

Nomenclature

Symbols

E	energy (kWh)
I	investment cost (€)
m	mass (kg)
n	lifetime (year)
r	discount rate
t	time (year)

Greek symbols

ΔCO_2	CO_2 emission reduction (kg)
η	efficiency
μ	CO_2 emission factor (kg/kWh)

Abbreviations

ASHP	air source heat pump
BB	biomass boiler
CAC	CO_2 avoidance cost
COP	coefficient of performance
EB	electric boiler
GSHP	ground source heat pump
HP	heat pump
LCOH	levelized cost of heat
MCM	Monte Carlo method
NGB	natural gas boiler
O&M	operation and maintenance
SAGSHP	solar-assisted ground source heat pump
SF	solar fraction
SHT	sustainable heating technology
STES	seasonal thermal energy storage
TMY	typical meteorological year

Subscripts

bore	borehole
CS	conventional system
el	electricity
sys	system
th	thermal

for decarbonizing residential heating in Spain, analyzing the role of perceptions from different stakeholders in the heating transition process. Molar-Cruz et al. [9] proposed the cost-optimal coordinated deployment of geothermal heating plants with heat transport and distribution networks to simultaneously supply geothermal heat to multiple urban areas. Those studies either focused on one solution or discussed the transition from policies and public participation perspectives.

Previous studies have focused on decarbonizing China's heating systems. Xiong et al. [10] formulated a development strategy for district heating in China, indicating reductions of 60% and 15% in the energy consumption for residential heating and heating costs, respectively. Zhang et al. [11] proposed four district heating pathways combining renovations of heating sources and buildings in the Inner Mongolia autonomous region, reducing coal consumption by 41%. However, these studies ignored the fluctuations in fuel and electricity prices influenced by the improvement of the power structure. Zhang et al. [12] analyzed how Beijing could develop a low-carbon heating sector in 2030 by deploying natural gas boilers (NGBs) and heat pumps (HPs) in the EnergyPLAN model. They found that gas heating fails to continuously reduce direct CO_2 emissions; however, HPs can be advantageous in terms of carbon emissions and benefits to the power grid. Zhang et al. [13] discussed three heating system scenarios in Beijing dominated by gas heating, HPs, and solar-thermal power plants. Yuan et al. [14] found that integrating large-scale HPs in the Beijing–Tianjin–Hebei region could result in 10% energy savings and 9% CO_2 emission reduction.

The primary focus of existing studies has been the strategical development of an energy system on a country, province, or city scale. Several SHTs were integrated into the heating strategies; however, the overall performance of such technologies and their implementation feasibility at the local level remains unknown. Moreover, the influence of fuel and electricity price dynamics on economic performance has not been examined extensively. Thus, there is a requirement for a comprehensive quantitative assessment of the technical, economic, and environmental performances of SHTs and their feasibility at the local level.

Harbin, the northernmost capital city in China, endures severely cold winters with a half-year heating season. District heating supplies 95% of the heat demand in the built environment in Harbin, of which 96% is supplied by coal-fired cogeneration plants and boilers [15]. The annual heat supply for residential heating is 189.7 PJ, which equals 20.2 GJ per capita and 576.4 MJ/m^2 [16]. Following the national plan, Harbin published the *Clean Winter Heating Implementation Plan in Harbin (2019–2021),* which promotes natural gas, biomass, electricity, ground source heat pumps (GSHPs), and industrial waste heat usage in district heating systems [15]. Harbin is a representative city with a high demand for heating, a coal-dominant district heating system, and an ambition to implement clean heating transition. Therefore, it was selected as a case study to implement the proposed methodological steps and gain insight into the performance of SHTs. It also serves as a showcase for investigating the feasibility of implementing the multiple technologies.

Previous experimental and numerical studies have investigated the performance of some SHTs in Harbin and primarily focused on technical performance; economic competitiveness and environmental impact have hardly been evaluated. In addition, the feasibility of implementing certain technologies at the local level has not yet been examined. The assessment in this study was based on a local residential community in Harbin. Several SHTs are evaluated regarding technical, economic, environmental, and implementation feasibility involving current policy and future renewable scenarios. As Harbin City is adopted for representation, the results can facilitate a policymaker's decision-making in the clean heating transition field.

This study aimed to answer the following research question: What are the technical, economic, and environmental performances of various SHTs and their implementation feasibility at the local level regarding the current policy and future renewable scenarios? The main contributions of this study are summarized as follows: 1) The knowledge gap in the existing literature is filled through analyses of the techno-economic-environmental performance of the seven SHTs and their implementation feasibility in a community where coal is predominantly used as the heat supply. 2) The methods embody electricity price forecasting in future sustainable heating system scenarios. Electricity price can significantly impact the economic comparativeness of electricity-dominated heating technologies; however, it has rarely been examined in previous studies. 3) The research can assist the formulation of clean heating transition policies, and the methods are generic and applicable to other northern cities in China and countries with similar climatic conditions. The rest of the paper is organized as follows. Section 2 comprehensively details the methods, including heating system modeling and simulation, scenario development, assessment indicators, and uncertainty analysis. Section 3 provides the results of the techno-economic-environmental, implementation feasibility, and uncertainty analyses. The discussion and conclusions are presented in Sections 4 and 5, respectively.

2. Methods

A four-step method was proposed to fulfill the research objectives of this study (Fig. 1). The technical, economic, and environmental performances as well as implementation feasibility of different SHTs were investigated considering the case of a community in Harbin besides the current policy and future renewable scenarios. Because some SHTs are electricity-dominant, a power structure for future renewable scenarios based on government policies, reports, and renewable energy potentials was developed. Two perspectives on electricity price prediction have been proposed to address the uncertainty of China's electricity marketization. In addition, the Monte Carlo method (MCM) was applied to address the uncertainty of economic performance in future scenarios.

2.1. Hourly dynamic heating load simulation

The selected community, located in the northwest area of Harbin City, consists of eight eleven-floor residential buildings, with eight family apartments on each floor. Each apartment includes one kitchen, dining room, living room, restroom, balcony, and two bedrooms, with the total area of 75 m^2 and housing three or four residents. A three-dimensional model of the building was developed in Sketchup [17] and then imported into TRNBuild for further parameter settings. The layout of two adjacent apartments and the developed building model are illustrated in the Supplementary materials. The thermal characteristics of the building envelopes were set according to architectural design instructions, and personnel occupancy, lighting, and equipment utilization rates were set according to the Chinese design standard for residential buildings [18], as summarized in Table 1. The heating load profile of the community was acquired by simulating the building model in TRNSYS using local typical meteorological year (TMY) weather data with the indoor cut-off temperature of 18 °C [18]. The hourly and cumulative heating loads are presented in Fig. 2. Note that only space heating was considered, and domestic hot water was excluded because these two systems are typically separate in China.

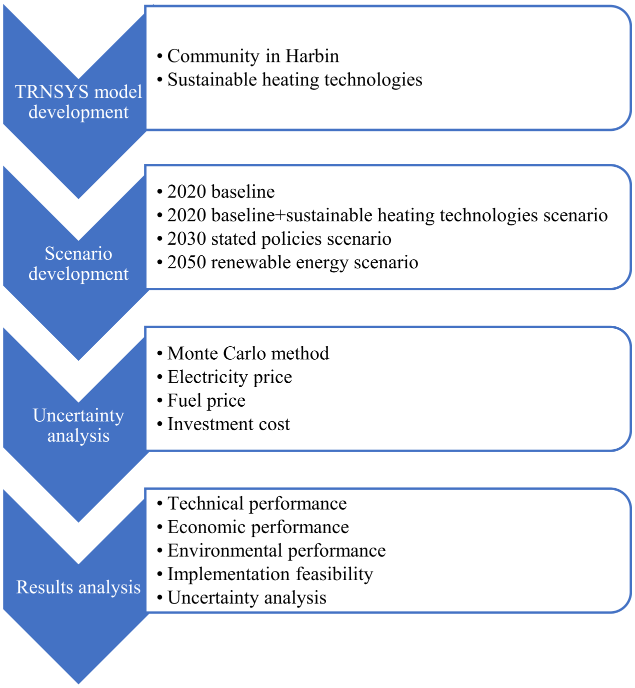

Fig. 1. Flowchart of the methods employed in this study.

Table 1
Building design characteristics of the selected community in Harbin.

	Unit	Value
$U_{exterior\ wall}$	$W/(m^2{\cdot}K)$	0.244
$U_{adjacent\ wall}$	$W/(m^2{\cdot}K)$	0.358
U_{roof}	$W/(m^2{\cdot}K)$	0.124
U_{floor}	$W/(m^2{\cdot}K)$	0.184
U_{window}	$W/(m^2{\cdot}K)$	1.1
$g_{glazing}$		0.62
Air change of infiltration	1/h	0.5
Personnel density	m^{-2}	0.05
Lighting power density	W/m^2	5
Equipment power density	W/m^2	3.8

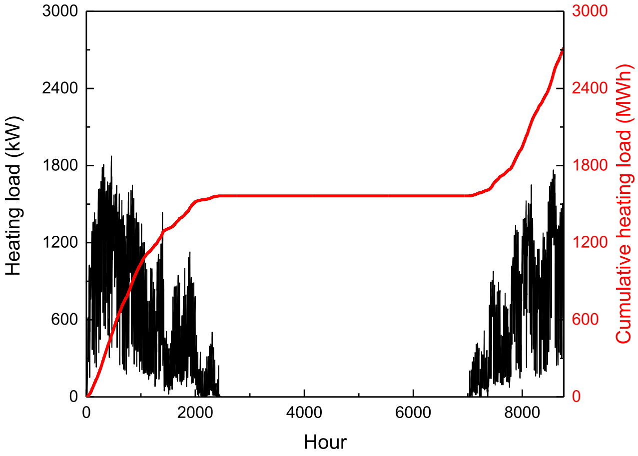

Fig. 2. Heating load profiles considering the selected community.

2.2. Simulation details for sustainable heating technologies

Previous studies have investigated the performance of SHTs in Harbin. Zhang et al. [19] experimentally tested the heating temperature, coefficient of performance (COP), and frost characteristics of an air-source heat pump (ASHP) on cold days. Low COPs were observed owing to the large difference between indoor and outdoor air temperatures. Other experimental and simulation studies have also indicated that ASHP applications in Harbin are limited by their relatively poor performance [20,21]. Similarly, GSHP applications in Harbin can cause a soil thermal imbalance with severe cold accumulation, leading to a decline in heating performance and heating deficiency [22,23]. Thus, the hybrid GSHP system should be integrated with other technologies to maintain an effective long-term operation. Solar-assisted ground source heat pumps (SAGSHPs) can decrease cold accumulation in soil and ensure the COP stability of the HP unit by storing solar energy in the soil [24]. In addition to HP systems, seasonal thermal energy storage (STES) has been recognized as an effective method for clean heating in northern China owing to its low energy consumption and emissions [25]. Several numerical studies have tested the performance of STES applications in Harbin and demonstrated a positive application prospect [26,27].

Heilongjiang province has the largest forest region and the highest crop yield per capita in China, promoting biomass heating applications in Harbin [28]. Wang et al. [29] integrated biomass gasification into the cooling, heating, and power systems of a hotel in Harbin and effectively reduced CO_2 emissions. Many studies in Harbin have focused on improving the performance of biomass boilers (BBs) to facilitate their applications [30,31]. Additionally, benefitting from the abundant renewable electricity resources and "coal-to-gas" policy, electric and gas heating has become a substitute for coal-based heating in Harbin [32]. Several studies have further discussed the possibility of integrating electric boilers (EBs) and NGBs for heating purposes [33,34].

According to Harbin's local renewable energy resources and national and local clean heating plans, seven SHTs were selected for analysis in this study, including:

- Natural gas boiler (NGB)
- Biomass boiler (BB)
- Electric boiler (EB)
- STES with an NGB as the auxiliary heating device (STES+NGB)
- STES with a BB as the auxiliary heating device (STES+BB)
- STES with an EB as the auxiliary heating device (STES+EB)
- Solar-assisted ground source heat pump (SAGSHP).

These technologies are further categorized into boiler, STES, and SAGSHP systems. A schematic of the boiler system is presented in Fig. 3. The boiler is set as open when there is a heating load during the heating season. A variable-speed pump is used to maintain the difference between the supply and return temperatures.

The STES system constitutes a solar loop, short-term storage loop, borehole storage loop, and load loop, as shown in Fig. 4. The system comprises evacuated tube solar collectors totaling 5000 m^2 and 98 boreholes with a spacing of 4 m and depth of 100 m. The area of solar collectors depends on the maximum installation area in the community, with the aim of increasing the solar thermal energy penetration. The borehole number was set according to multi-optimization, considering the economic and environmental impacts. The borehole depth was determined according to Harbin’s groundwater level (110–150 m) [35]. The tilt angle and azimuth of the solar collectors were set to 54° and 4°, respectively, optimized using GenOpt [36], with maximum solar thermal energy penetration as the objective. The ground was preheated to 25 °C before the operation to expedite the startup process [25]. The thermal energy collected by the solar collectors is first transferred to the short-term storage tank and then charged into the borehole. When a heating load occurs, the stored thermal energy is discharged from the borehole to users through the tank. An auxiliary boiler was used to heat the supply water when it failed to meet the setpoint supply temperature.

The SAGSHP system comprises a solar loop, borehole storage loop, and load loop, as illustrated in Fig. 5. The solar collector and borehole configurations are similar to those of the STES system. Two HPs were utilized to provide heating services to users, among which GSHP 2 only worked when GSHP 1 reached 90% capacity. A water tank was employed as the heat source in the HPs when the temperature in the water tank was 10 °C higher than that in the borehole. Otherwise, ground was used as the heat source.

A five-year simulation of the systems was conducted from July 1 to June 30, with the timestep of 0.125 h. The heating season was set from October 20 to April 20, according to *Harbin City Heating Measures* [37]. The supply and return temperatures for heating were set to 40 and 35 °C, respectively, in accordance with the radiant heating system in the *Design Code for Heating Ventilation and Air Conditioning of Civil Buildings* [38]. The 4th Generation district heating also suggests that lower distribution temperatures can decrease grid losses and increase efficiencies [39]. The TMY weather profile in Harbin and heating load profile generated from the building simulation were applied to these models. The TRNSYS types, functions of these components, and a summary of the main equipment parameters are provided in the Supplementary materials.

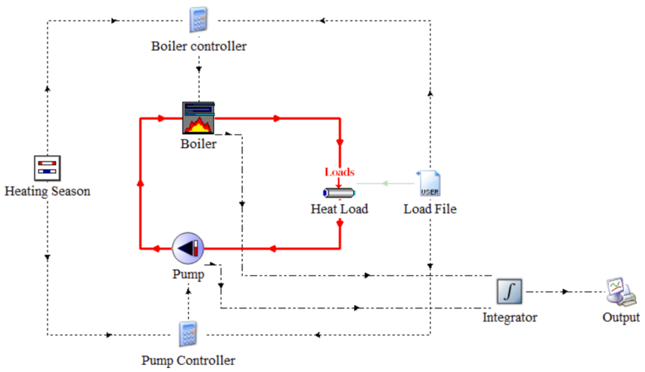

Fig. 3. Boiler system diagram.

2.3. Heating supply scenario

The year 2020 was selected as the base year because it was the latest year with complete data. The heating system in Harbin in 2020 was regarded as the reference case for comparison with various SHTs under different scenarios.

Three scenarios were developed to analyze the economic feasibility and environmental impacts of the current policy and future renewable scenarios. As some SHTs are electricity-dominant, a higher renewable energy portion of the power generation system may significantly influence the economic performance of these heating options through the electricity cost and the environmental performance via the power grid CO_2 emission factor. China’s power grid was grouped into six relatively independent regional power grids, and Harbin was affiliated with the northeast power grid (Liaoning, Jilin, Heilongjiang, and East Inner Mongolia). However, owing to statistical data availability, Inner Mongolia is considered to be a single sub-region of the north power grid [40]. In this study, the power grid boundary was set for the other three provinces.

2020 baseline + (2020 B+) scenario: The 2020 baseline+ scenario was designed based on the 2020 baseline, and the original heating system was replaced with the examined SHTs. The power generation mix was obtained from [41].

2030 stated policy (2030 SP) scenario: The current energy strategy involves increasing the proportion of renewable energy in the energy system, and renewable power plants are expected to develop rapidly. Since 2020, provincial governments have gradually released the 14th Five-year Plan and the 2035 Long-range Objectives. The power generation mix of the 2030 SP scenario was based on the projected power generation or installed capacity in 2030. The utilization hours of recent years were used to predict the power generation accompanied by the projected installed capacity.

2050 renewable energy (2050 RE) scenario: The 2050 RE scenario was promoted to eliminate dependence on fossil fuels to evaluate the selected SHTs in a 100% renewable energy system. The power generation mix was simulated using EnergyPLAN [42] according to the renewable energy potential and projected electricity demand (illustrated in the Supplementary materials). Notably, among the seven SHTs, two related to NGBs were not applicable to this scenario. The power generation mixes for the three scenarios are depicted in Fig. 6.

2.4. Techno-economic-environmental assessment

The performance of SHTs in different scenarios was evaluated using several technical, economic, and environmental indicators.

2.4.1. Technical performance

Indicators considered in the technical performance analysis include the solar fraction (SF), storage efficiency (η_{bore}), COP, and system efficiency (η_{sys}). SF indicates the proportion of the heating load met by solar thermal energy and can be expressed as:

$$SF = \frac{\text{solar heat to load}}{\text{total heat to load}} \tag{1}$$

The performance of a borehole in the STES systems was evaluated based on the storage efficiency, indicating the efficiency of the borehole given by:

$$\eta_{bore} = \frac{\text{heat discharged from borehole}}{\text{heat charged into borehole}} \tag{2}$$

The performance of an HP is usually evaluated by the COP, which

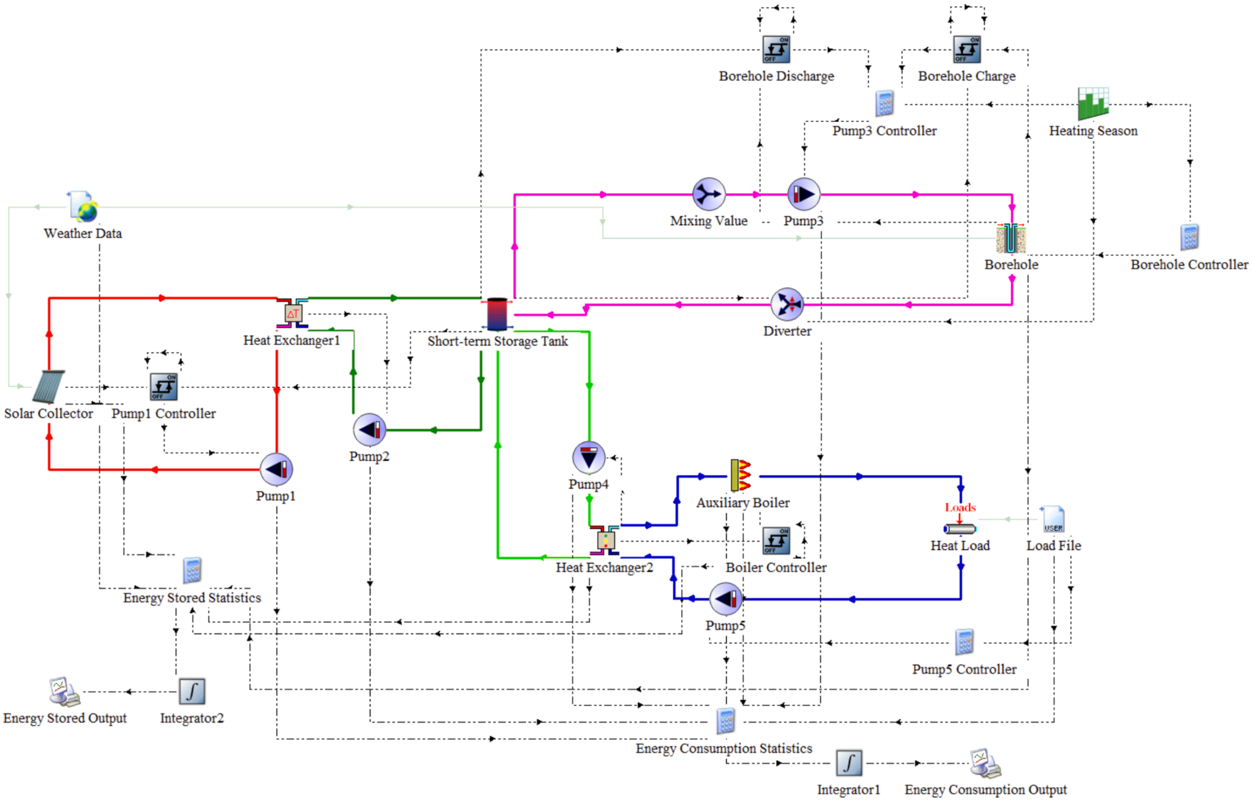

Fig. 4. Diagram of the STES system.

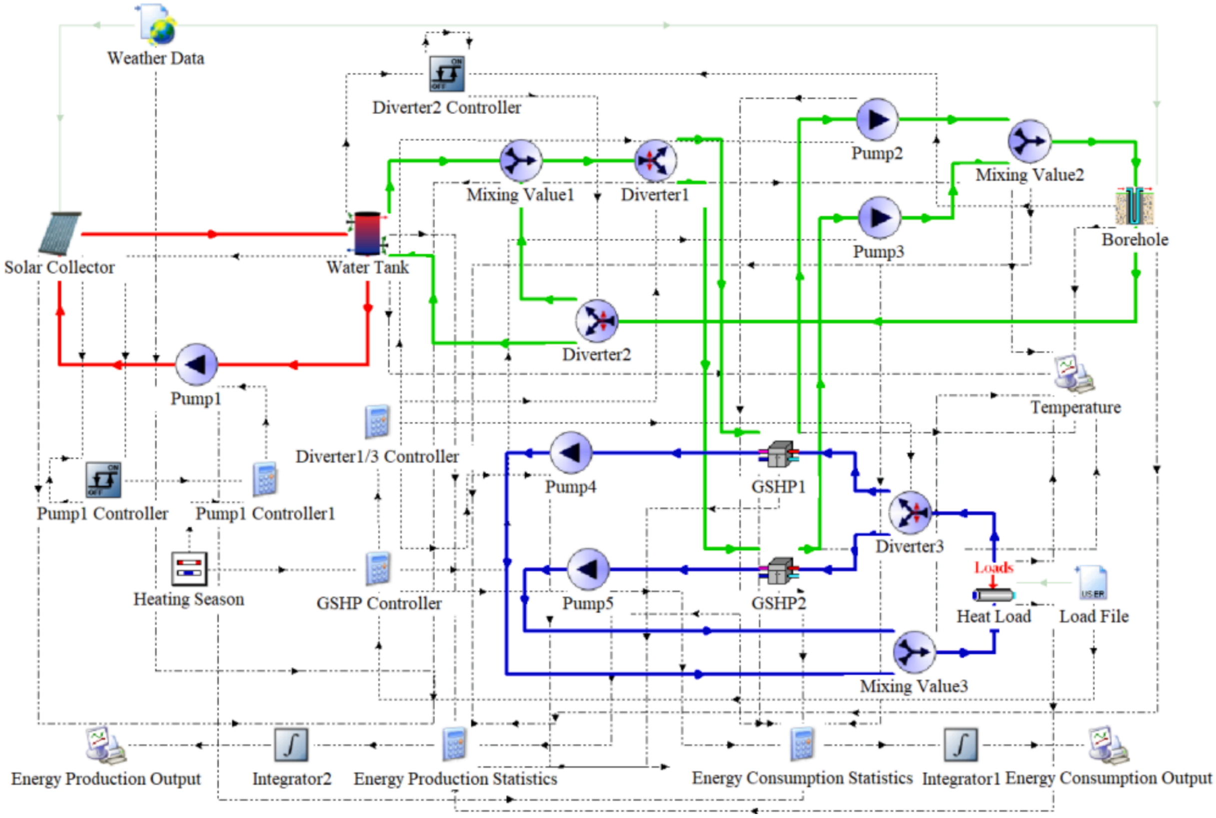

Fig. 5. Diagram of the SAGSHP system.

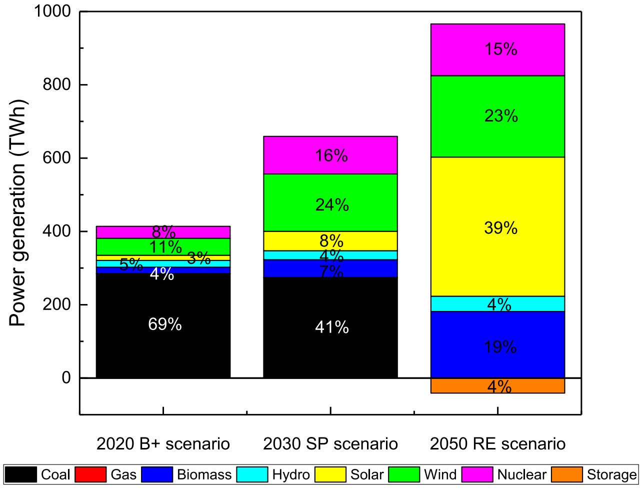

Fig. 6. Power generation mixes in the three scenarios.

expresses the ratio of the amount of heat produced to the electricity consumed by the compressor. The COP of the HP unit and system can be calculated using:

$$\mathrm{COP_{HP}} = \frac{\text{heat production of heat pump}}{\text{electricity consumption of heat pump}} \tag{3}$$

$$\mathrm{COP_{sys}} = \frac{\text{heat production of system}}{\text{electricity consumption of system}} \tag{4}$$

The system efficiency is expressed as the ratio of the heat output to the energy input of the system:

$$\eta_{sys} = \frac{\text{total heat production}}{\text{total energy consumption}} \tag{5}$$

2.4.2. Economic performance

The levelized cost of heat (LCOH) was calculated to assess the economic performance, and can be determined using:

$$\mathrm{LCOH} = \frac{I + \sum_{t=1}^{n} \frac{O\&M}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_{th}}{(1+r)^t}} \tag{6}$$

where I is the initial investment, n denotes the lifetime, t represents time, O&M indicates the annual operation and maintenance cost, r is the discount rate, and E_{th} is the annual heat production.

In this study, the lifetime of the heating system was set to 25 years. The discount rate is 5%, which is approximately equivalent to the long-term housing loan interest rate [43]. The main equipment unit prices of a system in the 2020 B+ scenario were sourced from China's leading wholesale trade platform [44] and several studies performed in China [45–49]. The solar collector and borehole storage costs were expected to reduce by 8% and 10% in the 2030 SP scenario and by 18% and 17% in the 2050 RE scenario, respectively, while other equipment costs were relatively constant [50,51]. Table 2 summarizes the investment costs of the main equipment in the three scenarios. The cost of the conventional heating system at the baseline was acquired from a heating supplier in Harbin.

The annual fixed O&M cost was set at 0.75% of the total investment costs [52], while the variable O&M cost was calculated based on the annual electricity and fuel consumption of the heating system. The electricity price in 2020 B+ was taken from [53], and those in the 2030 SP and 2050 RE scenarios were calculated based on the projected power generation mix from the policy and technical innovation perspectives (presented in the Supplementary materials). The fuel prices in the 2020 B+ scenario were sourced from [44,54] and those in the 2030 SP and 2050 RE scenarios were derived from [55–58]. The electricity and fuel prices for the three scenarios are presented in Table 3.

2.4.3. Environmental performance

The environmental performances of the SHTs were evaluated based on the corresponding CO_2 emission reduction and CO_2 equivalent emission factor of the overall system. The mass of CO_2 emitted while consuming energy was calculated as follows:

$$m_{CO_2} = \mu^{E}_{CO_2} \bullet E \tag{7}$$

where $\mu^{E}{}_{CO2}$ denotes the CO_2 emission factor and E represents the energy consumption.

The CO_2 emission reduction was determined by comparing the CO_2 emissions of an SHT system with that of the conventional system, as:

$$\Delta \mathrm{CO_2} = m^{\mathrm{CS}}_{\mathrm{CO_2}} - m^{\mathrm{SHT}}_{\mathrm{CO_2}} \tag{8}$$

where $m^{CS}{}_{CO2}$ and $m^{SHT}{}_{CO2}$ represent the CO_2 emissions of the conventional heating system of the baseline and SHT, respectively, which can be calculated from:

$$m^{\mathrm{CS}}_{\mathrm{CO_2}} = \mu^{\mathrm{th}}_{\mathrm{CO_2}} \bullet E_{\mathrm{th}} \tag{9}$$

$$m^{\mathrm{SHT}}_{\mathrm{CO_2}} = \mu^{\mathrm{el}}_{\mathrm{CO_2}} \bullet E_{\mathrm{el}} + \mu^{\mathrm{th}}_{\mathrm{CO_2}} \bullet E_{\mathrm{th}} \tag{10}$$

where $\mu^{th}{}_{CO2}$ and $\mu^{el}{}_{CO2}$ denote the CO_2 emission factors of heating and electricity production, respectively, and E_{th} and E_{el} indicate heat production and electricity consumption, respectively. The total heat production and fuel consumption in the 2020 baseline were obtained from [59]. Accordingly, the CO_2 emission factor of a heating system was calculated using the CO_2 emission factors of various fuels (presented in the Supplementary materials). The grid CO_2 emission factors in the 2020 B+ and 2030 SP scenarios were 0.56 and 0.32 kg/kWh, respectively (details in the Supplementary materials). The CO_2 emission factor for natural gas heating was 0.20 kg/kWh [60].

The CO_2 equivalent emission factor indicates the emission level of an overall system during the heat-producing process, expressed as:

$$\mu_{\mathrm{CO_2}} = \frac{m_{\mathrm{CO_2}}}{E_{\mathrm{th}}} \tag{11}$$

The CO_2 avoidance cost (CAC) was employed to evaluate the

Table 2

Investment costs of the main equipment in the three scenarios.

Equipment	Unit	2020 B+	2030 SP	2050 RE
Solar collector	€/m^2	122	112	100
Short-term storage tank	€/m^3	94	94	94
Borehole	€/unit	2400	2160	1992
NGB	€/unit	18,429	18,429	18,429
BB	€/unit	21,734	21,734	21,734
EB	€/unit	27,350	27,350	27,350
HP	€/unit	58,974	58,974	58,974
Pump	€/unit	512	512	512
Pipeline	€/m	108	108	108

Table 3

Electricity and fuel prices in the three scenarios.

	Unit	2020 B+	2030 SP	2050 RE
Electricity	€-ct/kWh	9.3	10.5 (from a policy perspective) 9.7 (from a technical innovation perspective)	8.5
Natural gas	€-ct/kWh	4.5	5.0	–
Biomass	€-ct/kWh	3.0	3.3	3.9

marginal costs of CO_2 emission reduction for SHTs compared with the conventional system, and is given by:

$$\mathrm{CAC} = \frac{\mathrm{LCOH_{SHT}} - \mathrm{LCOH_{CS}}}{\Delta \mathrm{CO_2}} \tag{12}$$

2.5. Implementation feasibility assessment

In addition to the techno-economic-environmental evaluation, the feasibility of implementing the SHTs was assessed. The perspectives considered in the assessment included interaction with the rest of the energy system, infrastructure requirements, investigation and construction period, fuel availability, affordability, application prospects, public acceptance, and government support. Based on the literature and government document reviews, a half-quantitative assessment was conducted to identify the positive or negative impact of these factors on technology implementation at the local level.

2.6. Uncertainty analysis

The MCM was adopted for analysis of the economic uncertainty in future scenarios. This method involves a mathematical model to propagate probability distributions and applies it to cases where the output result relies on different input variables [61,62]. MCM simulations were performed using @RISK [63], generating arbitrary values for selected variables and deriving the results using the designed mathematical model, including LCOH and CAC, in the 2030 SP and 2050 RE scenarios. The selected variables included the costs of electricity, fuel, and investment. The electricity prices in the 2030 SP and 2050 RE scenarios were projected based on the power generation mixes and the LCOE of power generation technologies. A triangular distribution was applied to the LCOE of the power generation technologies derived from different sources. Normal distribution was used to address the uncertainties in transmission and distribution prices and government funds and supplements. For fuel prices, the historical prices of natural gas and wood fuel from 2001 to 2021 were collected [64,65]. The trends in the data points were combined with knowledge of the underlying quantities to determine the distribution type [66]. The coefficient of variation of the historical data was applied to the distribution of selected variables. The uncertainty of the investment cost was addressed using a normal distribution within a certain range.

Table 4 summarizes the ranges and probability distribution parameters of the input variables. For normal and lognormal distributions, A and B represent the mean and standard deviation, respectively. For the ExtValueMin distribution, A is the location parameter and B is the shape parameter. For a triangular distribution, A is the minimum value, B is the most likely value, and C is the maximum value. The MCM simulation was performed 100,000 times.

3. Results

This section summarizes the findings from techno-economic-environmental performance analysis, implementation feasibility assessment, and uncertainty analysis.

3.1. Technical performance

The representative energy flows, SFs, and storage efficiencies of the STES system are displayed in Fig. 7. In the first year of operation, little heat was discharged from the borehole because the borehole was under the startup process. The collected solar energy was directly transferred to the load through a short-term storage tank. The collected solar energy decreased over time because more thermal energy was required in the early years to heat the borehole. Decreasing and increasing trends were observed in the energy flows charged into the borehole and discharged from the borehole, respectively, indicating that the ground gradually reached a thermal balance during the operation. As more thermal energy is stored in the borehole, the portion of the load met by solar thermal energy increases, and that met by the boiler decreases accordingly. The total energy to load was constant because the same load profile was applied annually. The SF and storage efficiency increased over time from 47% to 77% and from 0 to 44%, respectively, and the growth trend gradually plateaued. As the borehole gradually reached a thermal balance, the indicators gradually stabilized.

Fig. 8 (a) exhibits the unit and system COPs of the SAGSHP system. The unit and system COPs increase by 11% and 7%, respectively, during the five years of operation. Unlike a normal GSHP applied in cold regions whose COP would gradually decrease over the years [22,67], the

Table 4
Ranges and probability distribution parameters of the input variables.

	Unit	Distribution	5% level	95% level	A	B	C
2030 SP scenario							
LCOE of coal power generation	€-ct/kWh	Triangular	5.70	6.56	5.50	6.13	6.76
LCOE of gas power generation	€-ct/kWh	Triangular	7.89	9.72	7.47	8.80	10.14
LCOE of biomass power generation	€-ct/kWh	Triangular	5.70	8.73	5.07	6.84	9.50
LCOE of hydropower generation	€-ct/kWh	Triangular	2.94	3.20	2.88	3.07	3.27
LCOE of solar power generation	€-ct/kWh	Triangular	1.82	2.36	1.69	2.09	2.49
LCOE of wind power generation	€-ct/kWh	Triangular	3.30	3.71	3.21	3.51	3.80
LCOE of nuclear power generation	€-ct/kWh	Triangular	4.94	5.40	4.83	5.22	5.49
Transmission and distribution price	€-ct/kWh	Normal	3.68	4.34	4.01	0.20	
Government funds and supplements	€-ct/kWh	Normal	0.29	0.35	0.32	0.02	
Gas price	€-ct/kWh	Lognormal	3.51	11.69	6.59	2.69	
Biomass price	€-ct/kWh	ExtValueMin	2.09	3.68	3.48	0.39	
Solar collector price	€/m^2	Normal	103.01	121.47	112.24	5.61	
Borehole price	€/unit	Normal	1982	2338	2160	108	
2050 RE scenario							
LCOE of biomass power generation	€-ct/kWh	Triangular	5.70	8.73	5.07	6.84	9.50
LCOE of hydropower generation	€-ct/kWh	Triangular	2.94	3.20	2.88	3.07	3.27
LCOE of solar power generation	€-ct/kWh	Triangular	1.25	1.26	1.24	1.26	1.27
LCOE of wind power generation	€-ct/kWh	Triangular	2.52	3.22	2.36	2.87	3.38
LCOE of nuclear power generation	€-ct/kWh	Triangular	4.91	5.25	4.83	5.08	5.33
Transmission and distribution price	€-ct/kWh	Normal	3.68	4.34	4.01	0.20	
Government funds and supplements	€-ct/kWh	Normal	0.29	0.35	0.32	0.02	
Biomass price	€-ct/kWh	ExtValueMin	2.50	4.41	4.17	0.47	
Solar collector price	€/m^2	Normal	91.81	108.27	100.04	5.00	
Borehole price	€/unit	Normal	1828.2	2155.8	1992	99.6	

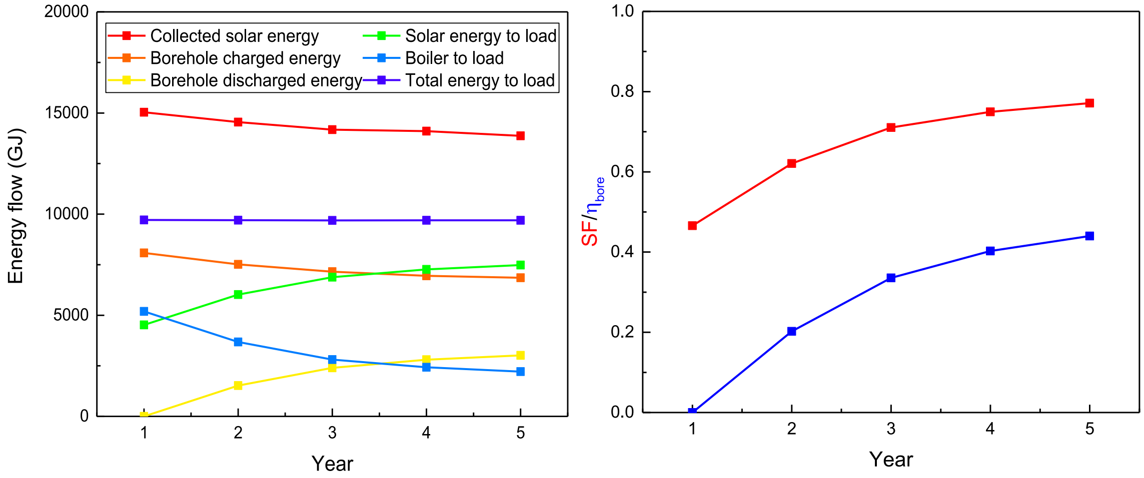

Fig. 7. Energy flow, SF, and storage efficiency results for the STES systems.

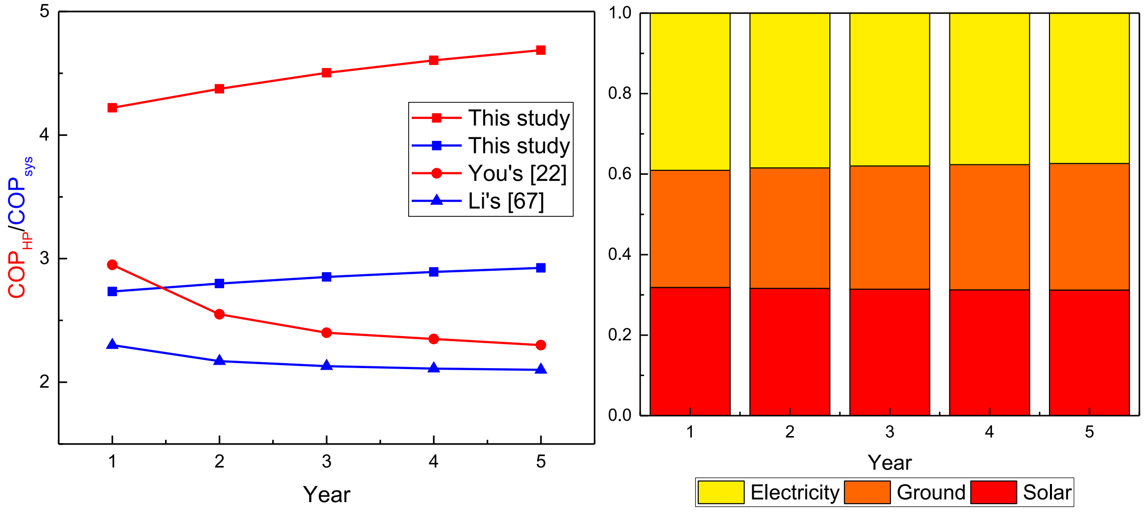

Fig. 8. (a) Unit and system COPs and (b) heat sources of the SAGSHP system.

average borehole temperature of the SAGSHP system rises slightly during operation with the collected solar heat, leading to a higher COP. The results are similar to those of previous studies on SAGSHP applications in cold regions [68,69]. The heat sources of the SAGSHP system are presented in Fig. 8 (b). Stored solar heat in the tank and heat in the ground account for 62% of total heat demand, which helps reduce the electricity usage. During the operation, the share of electricity usage in the heat sources slightly decreases because the solar input helps slowly increase the ground temperature.

The system efficiencies of the boiler, STES, and SAGSHP systems are compared in Fig. 9. The efficiencies of the boiler systems illustrate the heat production associated with the fuel and electricity consumption. In contrast, the efficiencies of the STES and SAGSHP systems present heat production related to fuel and electricity consumption and the collected solar thermal energy. The efficiencies of the STES systems are relatively low because of the seasonal storage of solar heat. In the SAGSHP system, the collected solar energy is directly used as the heat source for the heat pump, leading to a higher system efficiency than that of the STES system.

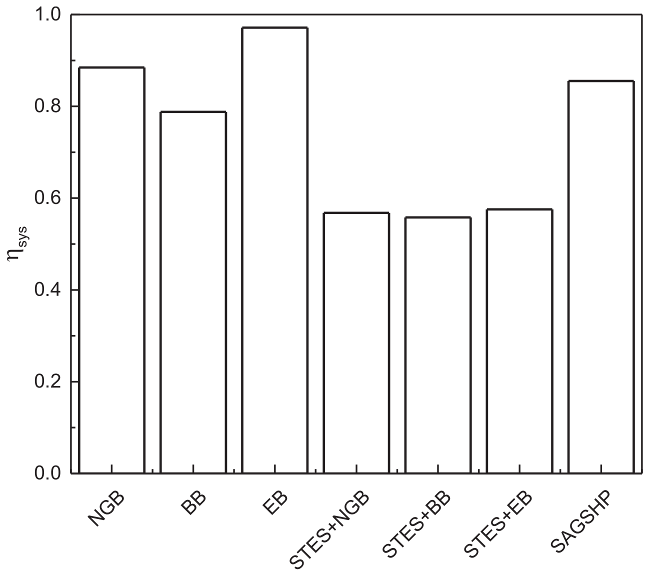

Fig. 9. Efficiencies of the boiler, STES, and SAGSHP systems.

3.2. Economic performance

Fig. 10 (a) shows the LCOHs of the various SHTs in the designed scenarios and the heating system at the 2020 baseline. The LCOH

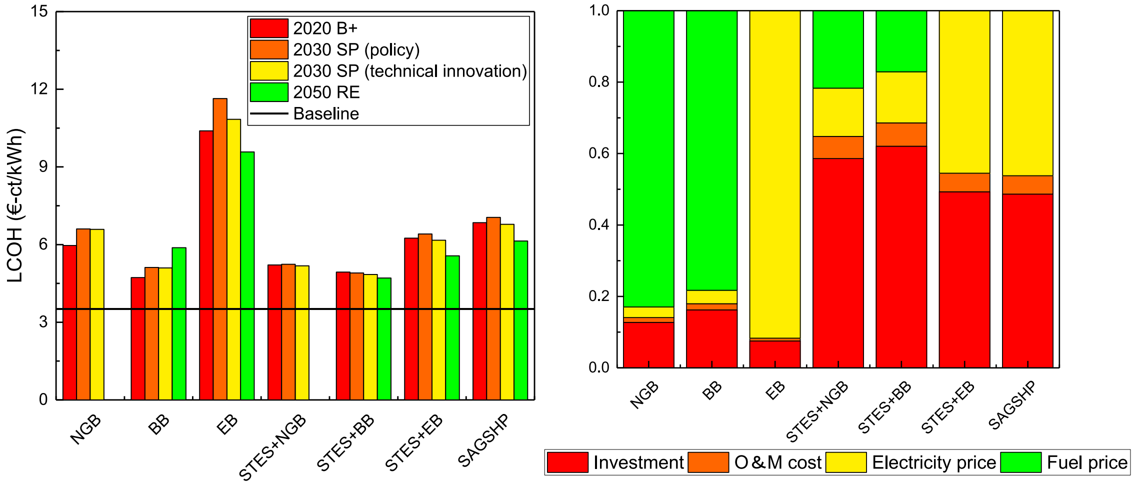

Fig. 10. (a) LCOHs and (b) LCOH configurations of the SHTs in the designed scenarios.

configurations of the various SHTs in the 2020 B+ scenario are depicted in Fig. 10 (b). All SHTs in each scenario exhibit higher LCOHs than the baseline. The EB system presents the highest LCOH because the cost of electricity consumption was much higher than that of gas and biomass. Similarly, the STES+EB system produced the highest LCOH among the three STES systems. The LCOHs of the STES and SAGSHP systems decrease from the 2020 B+ scenario to the 2050 RE scenario because their investment costs, accounting for 50%–60% of the LCOH calculation, are projected to decrease. Unlike the other options, the LCOH of the BB system in the 2050 RE scenario is higher than those in the 2020 B+ and 2030 SP scenarios because the biomass price is predicted to increase, accounting for the highest proportion of its LCOH calculation. The LCOHs of the EB, STES+EB, and SAGSHP systems indicate more significant differences (3%–7%) than the other options (less than 1%) between the policy and technical innovation perspectives in the 2030 SP scenario because the electricity price is a larger influential factor in their LCOH calculation. The BB system indicated the lowest LCOH in the 2020 B+ scenario, while that of the STES+BB system was the lowest in the other scenarios.

3.3. *Environmental performance*

The CO_2 equivalent emission factors of the various SHTs in the designed scenarios and the heating system in the 2020 baseline are displayed in Fig. 11. Evidently, the SHTs demonstrate significant potential to reduce CO_2 emissions, except for the EB system in the 2020 B+ scenario. This indicates that replacing the current heating system with the EB system fails to reduce CO_2 emissions when considering the power generation mix. A similar finding was reported in [70] that the environmental benefits of electric heating primarily depend on the power structure, and the application scale of electric heating should be coordinated with the power structure. In addition, with a gradually cleaner power generation mix, the CO_2 equivalent emission factors of the SHTs showed a decreasing trend from the 2020 B+ scenario to the 2030 SP scenario and reached zero in the 2050 scenario. The extent of the decline between the 2020 B+ and 2030 SP scenarios of different heating options depends on their electricity-dominant level. The BB system exhibited the most significant potential for reducing CO_2 emissions in the designed scenarios.

Fig. 12 presents the CACs of the SHTs in the designed scenarios. Owing to higher LCOH and lower CO_2 emission reduction, the EB system exhibits the highest CAC among the examined heating technologies and fails to reduce CO_2 emissions in the 2020 B+ scenario. Although the EB system demonstrates the potential to reduce CO_2 emissions with a cleaner power generation mix in the 2030 SP and 2050 RE scenarios, it is

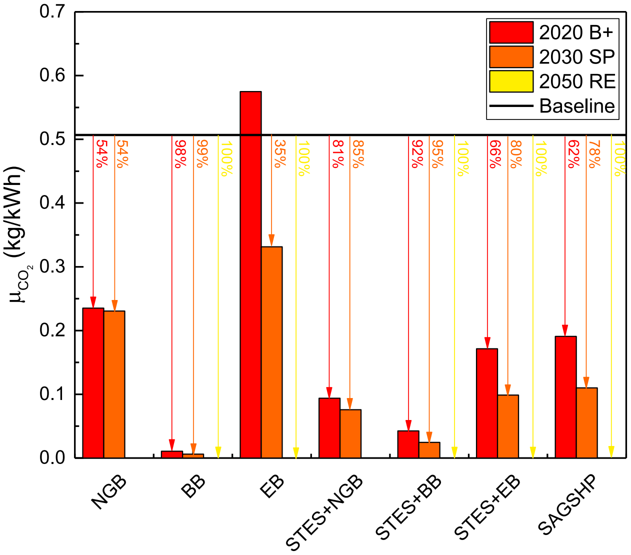

Fig. 11. CO_2 equivalent emission factors of the SHTs in the designed scenarios.

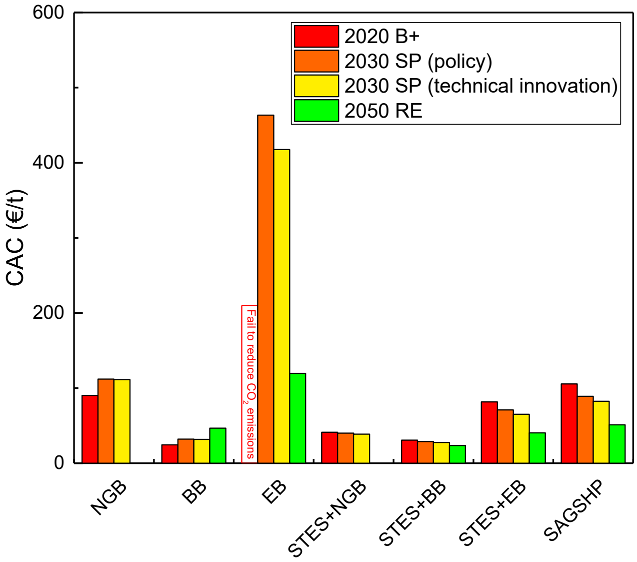

Fig. 12. CAC results for the SHTs in the designed scenarios.

still limited by the high cost. Meanwhile, the NGB and BB systems exhibit no significant differences in their LCOHs; however, the BB system benefits from higher CO_2 emission reduction; therefore, it has a lower CAC. The CACs of the STES and SAGSHP systems exhibit a declining tendency from the 2020 B+ scenario to the 2050 RE scenario because their investment costs are projected to reduce, and they can greatly reduce CO_2 emissions. Generally, the BB system has the lowest CAC in the 2020 B+ scenario, while the STES+BB system has the lowest CAC in the other scenarios.

3.4. Implementation feasibility

The results of the feasibility assessment are summarized in Table 5. From a policy incentive perspective, Harbin has announced that it provides subsidies of 15.7, 5.2, and 47.2 k€/t based on the tonnage of newly built boilers for those who use NGBs, BBs, and EBs to replace coal-fired boilers, and the subsidy of 4.7 €/m^2 for those who use solar heating and HPs [71]. In addition, the subsidy of 1.3 €-ct/m^3 is provided for natural gas usage, while the "coal-to-electricity" electricity price policy was formulated to extend the valley period time and reduce the valley period electricity price. In terms of the case community, these policies can bring a reduction of approximately 17%–19% in the LCOHs of the EB, STES+EB, and SAGSHP applications. The LCOHs of STES+NGB and STES+BB systems decreased by 13%, while those of NGBs and BBs decreased by less than 4%.

NGBs are highly accepted by the public and the most widely used heat-producing mode in urban areas to replace low-efficiency coal burning in China. The NGB system is relatively mature, and has strong industrial support and marketing possibilities [72]. However, in the long term, gas heating might be phased out by a fully renewable society. Large-scale STES systems with solar heating remain in an emerging stage. China's solar thermal industry (mainly domestic hot water systems) has a long history and has developed rapidly, accounting for 70% of global solar collector installations [73]. It is expected that STES with solar heating will have broad applications in Harbin, with abundant solar resources and favorable policies [74]. Electric heating is also a promoting option as grid cleanliness increases.

As for infrastructure requirement issues, a storage tank or pipeline needs to be built for NGB applications, and BB applications require a large storage space with a concern for fire hazards [75]. This also raises ash handling and management issues, requiring extra equipment [76]. Meanwhile, STES and SAGSHP require a relatively long investigation and construction period for underground construction compared with boiler applications.

Considering fuel availability, the natural gas production in Heilongjiang province in 2020 was 4.7 billion m^3, 40% of which was used for industry [59]. The rest could only meet 48% of the heat demand in Harbin. China has become the world's largest natural gas importer since 2018, with a much faster growth in gas consumption than production [77]. The extensive implementation of gas heating will increase China's import dependence as well as harm national energy security. Regarding biomass applications, Heilongjiang province has abundant biomass resources (129.2 TWh), of which 17.4% are located in Harbin [78]. The demand for heating in Harbin is 52.7 TWh, accounting for 41.8% of the total provincial district heating consumption [79]. Therefore, the local biomass resource can potentially sustain only 34% of the district heating demand in Harbin, which is insufficient. Biomass is also needed in the power and transport sectors to support low-carbon transitions.

From an affordability perspective, EBs have the highest LCOH, primarily because of its high electricity price. Electricity-dominant heating technologies, including EB, STES+EB, and SAGSHP, may negatively influence the power grid operation [80]. If EBs dominate the heat supply in the built environment in Harbin, electricity demand will increase by 54.2 TWh, which is more than twice the total electricity consumption in 2020. The increased load can pose a burden for constructing new electricity production units and extending the existing capacity of the electric grids.

In general, gas heating is an easy-to-implement option benefitting from the public acceptance and "coal-to-gas" policy. However, it poses a threat to national energy security and is not preferable for a fully renewable society in the long term. Biomass heating has significant potential to reduce CO_2 emissions; however, fuel availability and raw material management limit its wide implementation. Electric heating is becoming increasingly attractive as grid cleanliness increases, with significant support from the government. However, its LCOH is higher than that of other technologies owing to the high electricity prices. STES and SAGSHP are promising technologies with decreasing LCOH and increasing CO_2 emission reduction ability. The current resident acceptance in the local area is relatively low, but it holds a prospective future in large-scale applications with sufficient local resources and strong support from governments.

3.5. Uncertainty analysis

Considering that the analyses in the 2030 SP and 2050 RE scenarios were based on the projected costs of electricity, fuel, and investment, the MCM was employed to address uncertainties in the economic performance. Fig. 13 presents the MCM simulation results of the LCOHs of the SHTs in the designed scenarios. The LCOH for the NGB system has an extensive range because it is mainly determined by the gas price, and the lognormal distribution with a long tail on the right-hand side was applied to the gas price. Similarly, the LCOH of the BB system exhibits a long tail on the left-hand side because biomass price is a dominant factor, and it is associated with the ExtValueMin distribution. Within the two figures in the 2030 SP scenario, the SHTs present similar relative positions of the LCOH, while the LCOHs from the technical innovation perspective are lower because of lower electricity prices. However, in the 2050 RE scenario, the LCOHs of the STES and SAGSHP systems are more significantly reduced than those of the boiler systems because the solar and storage costs decrease, and the declining electricity price has a greater influence on the LCOH.

The MCM simulation results for the CACs of the SHTs in the designed scenarios are presented in Fig. 14. The relative positions are similar to those of the LCOHs. Note that the CACs of the NGB and BB systems might have negative values because they may be able to simultaneously reduce CO_2 emissions and have a lower LCOH than the baseline. In addition,

Table 5
Implementation feasibility of the SHTs.

	NGB	BB	EB	STES+NB	STES+BB	STES+EB	SAGSHP
Policy support	+	+	+++	++	++	+++	+++
Resident acceptance	+++	+	++	−−−	−−−	−−−	+
Application prospect	−	++	+++	+	+++	+++	+++
Infrastructure requirement	−	−−	N	−−−	−−−	−−−	−−−
Investigation and construction	N	N	N	−−−	−−−	−−−	−−−
Fuel availability	−−	−−	N	−	−	N	N
Affordability	−−	−	−−−	−	−	−−	−−
Impact on the power grid	N	N	−−−	−	−	−−	−−

(Note: + and – symbolize positive and negative impacts on implementation feasibility, respectively; N represents ignorable impact).

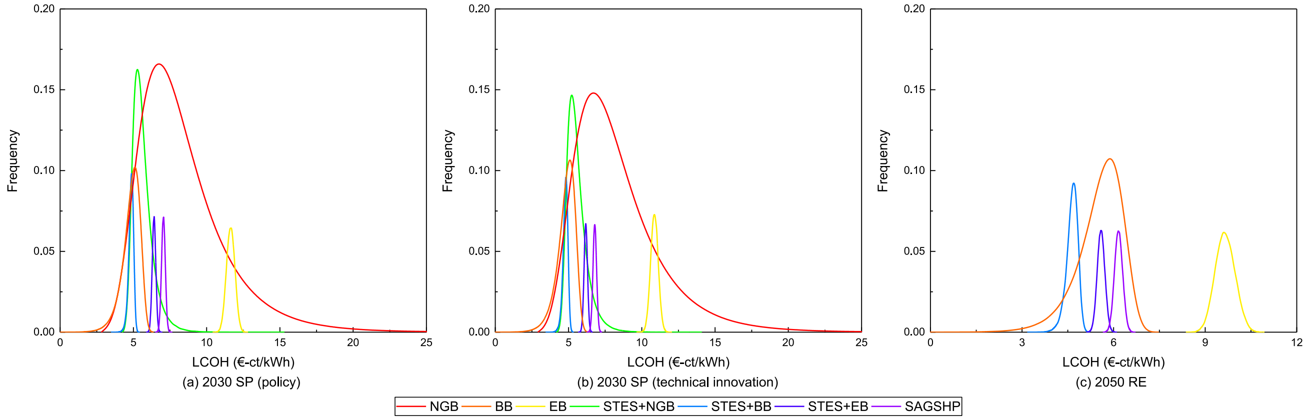

Fig. 13. MCM simulation results for the LCOHs of the SHTs in the designed scenarios.

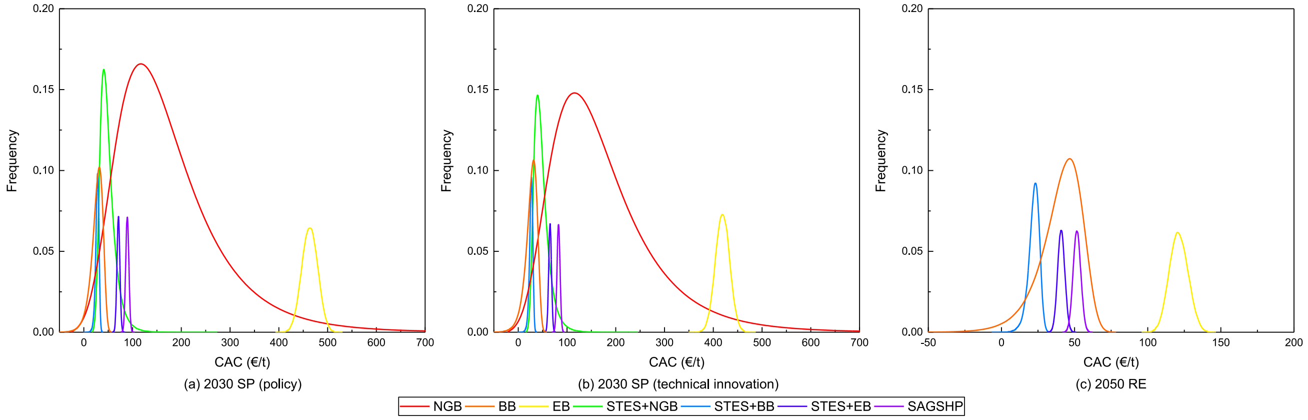

Fig. 14. MCM simulation results of the CACs of the SHTs in the designed scenarios.

considering the uncertainties of the electricity price, fuel price, and investment cost; the NGB, BB, STES+NGB, and STES+BB systems provide favorable options in the 2030 SP scenario. Whereas, the BB and STES+BB systems may be favorable options for the 2050 RE scenario.

4. Discussion

This study performed techno-economic-environmental analyses of seven SHTs and evaluated their implementation feasibility at the local level regarding the current policy and future renewable scenarios. The assessment was based on a case study community in a coal-dominated location. The results indicate that BB and STES+BB are attractive in terms of cost and CO_2 emission reduction. However, fuel availability is an issue in large-scale implementation. In addition, biomass heating faces storage and ash handling and management issues. Solar heating is a promising technology with decreasing LCOH and increasing CO_2 emission reduction ability. However, its current resident acceptance in China is relatively low, and usually requires a longer investigation and period for underground construction. Electric heating is preferable in terms of implementation feasibility; however, its economic competitiveness and environmental impact depend heavily on electricity prices and grid cleanliness. It can also pose a burden for constructing new electricity production units and extending the existing capacity of electric grids for large-scale implementations. In addition, replacing the current heating system with electric heating failed to reduce the CO_2 emissions. Based on the released policies and reports, it can reduce CO_2 emissions in the 2030 and 2050 scenarios; however, its LCOH is still much higher than those of the other SHTs owing to high electricity prices. Recent research has suggested that the synergistic development of electric heating and idle renewable energy generation could help reduce wind or solar power curtailment as well as increase the flexibility of the energy system [81]. Electric heating using renewable energy curtailment can significantly improve its economic competitiveness and emission-reduction ability.

For a long time, northern China has lacked the overall planning of heating supply in various energy forms, leading to an insufficient heat supply and demand balance and an unscientific heating layout. The clean heating transition is a systematic project. Local governments are required to coordinate the heat supply and demand balance, and comprehensively adopt various clean heating methods to reduce emissions in the heating field. Based on the local resource endowment and infrastructure, local governments should formulate appropriate clean heating strategies with scientific evaluation and full consideration of residents' consumption capacity. In addition, heat, natural gas, and electricity prices are all subject to the unified pricing of local governments, which lack market-oriented adjustment ability. Local governments should adopt supporting policies to reduce the cost of electric heating, including improving the peak-valley time-of-use price system, optimizing the tiered price policy for residential electricity consumption, and expanding market-based transactions. Moreover, the natural gas heating costs can be reduced by improving the tiered price system, implementing seasonal price differential policies, and using market-based trading mechanisms. The price of clean heating should be reasonably set within the range of residents' affordability, considering clean heating renovation and operating costs [4].

The Chinese government has implemented electricity market reforms twice since 2002; however, the pricing and operating mechanisms of the power sector remain under government control [82]. Previous studies on sustainable heating transition ignored electricity price fluctuations in future scenarios. As some SHTs are electricity-dominant, electricity prices can significantly influence the economic competitiveness of SHT applications. Appropriate methods are required to estimate the future electricity price when the pricing mechanism becomes market oriented [83]. This study proposed two methods for predicting electricity prices in future scenarios: one follows current policies, whereas the other involves facing a competitive pricing mechanism, which can provide a reference for future research.

This study was a local-specific case that comprehensively considered local circumstances in Harbin and made an effort to provide an informative and transparent presentation based on regional specificity. A case community in Harbin was selected and modeled to obtain a representative heating profile. The examined SHTs were based on a review of local clean heating plans and previous studies for Harbin. Three scenarios (current situation, stated policies, and future renewable scenarios) were developed. Local policies on energy system planning and local renewable energy potential were comprehensively considered. The feasibility assessment was carried out by thoroughly considering the current energy system situation, fuel availability, and incentives for promoting clean energy use issued by the local government. This study provided a comprehensive and transparent showcase of the clean heating transition at the local level. The integrated assessment method developed in this study comprehensively considered the technical, economic, environmental, and implementation feasibility perspectives regarding the current policy and future renewable scenarios. It can be used for case studies in other countries with similar climate conditions and an objective of clean heat transition. In the application, local-based SHTs, renewable energy potential, energy system planning, and implementation feasibility are suggested to be considered.

This study used EnergyPLAN to predict the power generation structure in 2050 to guarantee the grid supply and demand balance at an hourly level. The forecast is based on the local renewable energy potential and the projected electricity demand. Although the predicted power generation mix might not be unique, the results of this study are representative because the prediction was aimed at the maximum solar and wind energy penetration, as they were expected to be the cheapest power generation technologies in the next few decades [84].

For the environmental assessment, only the CO_2 emissions from fuel combustion were considered, ignoring fuel production and transportation processes. Biomass-related heating alternatives show great potential for CO_2 emission reduction because biomass is derived from renewable resources and is basically carbon-neutral in terms of growth and combustion [85]. However, the biogenic carbon neutrality principle is not applicable to life cycle analysis [86]. The results of this study were based on the assumption that biomass is carbon-neutral.

Moreover, this study only evaluated the techno-economic-environmental performances and implementation feasibility of the seven SHTs according to Harbin's local renewable energy resources, as well as national and local clean heating plans. Other options, including geothermal heating and industrial waste heat heating, can be assessed within the framework in future studies to provide comprehensive evidence to facilitate a policymaker's decision-making regarding clean heating transition.

5. Conclusions

The transition to clean heating plays an important role in realizing a peak in CO_2 emissions before 2030 and carbon neutrality before 2060 in China. A literature review demonstrates the requirement for a comprehensive and quantitative assessment of the performance of SHTs and their implementation feasibility at the local level. Accordingly, this study evaluated seven SHTs from technical, economic, and environmental perspectives and their implementation feasibility regarding the current policy and future renewable scenarios. The assessment was based on a community in Harbin, a typical city where fossil fuels dominate heating systems.

Consequently, the seven SHTs are applicable from a technical perspective, considering Harbin's climatic conditions and heat demand. Concerning economic and environmental performances, the BB system is a favorable option in the 2020 B+ scenario, with the CAC of 24 €/t. However, with the prediction of rising biomass price, the STES+BB system is advantageous in the 2030 SP and 2050 RE scenarios, with CACs of 28 and 24 €/t, respectively. Replacing the current heating system with electric heating failed to reduce CO_2 emissions. Based on the released policies and reports, CO_2 emissions can be reduced accordingly in the 2030 and 2050 scenarios. However, the corresponding CACs (over 400 €/t in 2030 and 120 €/t in 2050) remain much higher than those of other SHTs owing to high electricity prices. Considering the uncertainties in future scenarios, the MCM results indicate that the NGB, BB, STES+NGB, and STES+BB systems can all provide favorable options in the 2030 SP scenario. The BB and STES+BB systems may be favorable alternatives for the 2050 RE scenario. In addition, power structure is an important issue that should be considered when implementing electricity-dominant heating technologies.

Considering feasibility of implementation, gas heating has the highest public acceptance. However, it may threaten national energy security and is not preferable for a fully renewable society in the long term. Although Harbin could benefit from abundant forest and crop resources in Heilongjiang Province, fuel availability remains an issue for biomass heating. Electric heating is also a promoting option with a relatively high public acceptance and increased grid cleanliness. However, it exhibits a high LCOH, and requires additional power supply units as well as expansion of electric grids. Solar heating currently has relatively low residential acceptance, but broad application prospects with abundant solar resources and favorable policies.

This study contributes to the existing literature on sustainable heat transition in China by providing informative local circumstances in Harbin and presenting methods of assumption making in detail when local data is not transparent. Formulating appropriate clean heating strategies requires local governments to comprehensively adopt various SHTs based on local resource endowments and infrastructure, with scientific evaluation and full consideration of residents' consumption capacity. This study conducted an integrated assessment of SHTs considering the technical, economic, and environmental performances, besides implementation feasibility, providing solid evidence to facilitate the decision-making process in the clean heating transition in northern cities of China. Furthermore, these methods are applicable in other countries with similar energy mixes and climate conditions.

CRediT authorship contribution statement

Tianrun Yang: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Visualization. **Wen Liu:** Conceptualization, Investigation, Writing – review & editing, Supervision. **Gert Jan Kramer:** Conceptualization, Writing – review & editing, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The financial support from the China Scholarship Council (No. 201806220072) is gratefully acknowledged.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.

org/10.1016/j.enconman.2023.116764.

References

1. IEA. An energy sector roadmap to carbon neutrality in China. https://www.iea.org/reports/an-energy-sector-roadmap-to-carbon-neutrality-in-china; 2021.
[2] Ma M, Ma X, Cai W, Cai W. Carbon-dioxide mitigation in the residential building sector: a household scale-based assessment. Energy Convers Manag 2019;198:111915. https://doi.org/10.1016/j.enconman.2019.111915.
[3] Building Energy Research Center of Tsinghua University. Annual Report of China Building Energy Conservation 2022. Beijing, China: China Architecture & Building Press; 2022.
4. National Development and Reform Commission. Clean winter heating plan in northern China (2017–2021). https://www.ndrc.gov.cn/xxgk/zcfb/tz/201712/t20171220_962623.html;; 2017.
[5] Hou X, Zhong S, Zhao J. A critical review on decarbonizing heating in China: pathway exploration for technology with multi-sector applications. Energies 2022; 15(3):1183. https://doi.org/10.3390/en15031183.
[6] Itten A, Sherry-Brennan F, Hoppe T, Sundaram A, Devine-Wright P. Co-creation as a social process for unlocking sustainable heating transitions in Europe. Energy Res Soc Sci 2021;74:101956. https://doi.org/10.1016/j.erss.2021.101956.
[7] Yuan M, Thellufsen JZ, Sorknæs P, Lund H, Liang Y. District heating in 100% renewable energy systems: combining industrial excess heat and heat pumps. Energy Convers Manag 2021;244:114527. https://doi.org/10.1016/j.enconman.2021.114527.
[8] López-Bernabé E, Linares P, Galarraga I. Energy-efficiency policies for decarbonising residential heating in Spain: a fuzzy cognitive mapping approach. Energy Policy 2022;171:113211. https://doi.org/10.1016/j.enpol.2022.113211.
[9] Molar-Cruz A, Keim MF, Schifflechner C, Loewer M, Zosseder K, Drews M, et al. Techno-economic optimization of large-scale deep geothermal district heating systems with long-distance heat transport. Energy Convers Manag 2022;267:115906. https://doi.org/10.1016/j.enconman.2022.115906.
[10] Xiong W, Wang Y, Mathiesen BV, Lund H, Zhang X. Heat roadmap China: new heat strategy to reduce energy consumption towards 2030. Energy 2015;81:274–85. https://doi.org/10.1016/j.energy.2014.12.039.
[11] Zhang Y, Xia J, Fang H, Zuo H, Jiang Y. Roadmap towards clean heating in 2035: case study of inner Mongolia, China. Energy 2019;189:116152. https://doi.org/10.1016/j.energy.2019.116152.
[12] Zhang H, Zhou L, Huang X, Zhang X. Decarbonizing a large City's heating system using heat pumps: a case study of Beijing. Energy 2019;186:115820. https://doi.org/10.1016/j.energy.2019.07.150.
[13] Zhang H, Zhao X, Zhang R. Synergistic development of heating system decarbonization transition and large-scale renewable energy penetration: a case study of Beijing. Energy Convers Manag 2022;269:116142. https://doi.org/10.1016/j.enconman.2022.116142.
[14] Yuan M, Thellufsen JZ, Lund H, Liang Y. The first feasible step towards clean heating transition in urban agglomeration: a case study of Beijing-Tianjin-Hebei region. Energy Convers Manag 2020;223:113282. https://doi.org/10.1016/j.enconman.2020.113282.
15. Harbin Development and Reform Commission. Clean winter heating implementation plan in Harbin (2019–2021). http://www.harbin.gov.cn/art/2020/1/7/art_24978_863216.html;; 2019.
[16] Harbin Bureau of Statistics. Harbin Statistical Yearbook 2021. Beijing, China: China Statistics Press; 2022.
17. Trimble. Sketchup. https://www.sketchup.com/;; 2021 [accessed 8 April 2021].
[18] Ministry of Housing and Urban-Rural Development of the People's Republic of China. Design Standard for Energy Efficiency of Residential Buildings in Severe Cold and Cold Zones (JGJ 26–2018). Beijing: China Architecture & Building Press; 2018.
[19] Zhang Y, Ma Q, Li B, Fan X, Fu Z. Application of an air source heat pump (ASHP) for heating in Harbin, the coldest provincial capital of China. Energy Build 2017; 138:96–103. https://doi.org/10.1016/j.enbuild.2016.12.044.
[20] Dai B, Qi H, Dou W, Liu S, Zhong D, Yang H, et al. Life cycle energy, emissions and cost evaluation of CO_2 air source heat pump system to replace traditional heating methods for residential heating in China: system configurations. Energy Convers Manag 2020;218:112954. https://doi.org/10.1016/j.enconman.2020.112954.
[21] Su C, Madani H, Palm B. Heating solutions for residential buildings in China: current status and future outlook. Energy Convers Manag 2018;177:493–510. https://doi.org/10.1016/j.enconman.2018.10.005.
[22] You T, Yang H. Feasibility of ground source heat pump using spiral coil energy piles with seepage for hotels in cold regions. Energy Convers Manag 2020;205:112466. https://doi.org/10.1016/j.enconman.2020.112466.
[23] Wu W, You T, Wang B, Shi W, Li X. Evaluation of ground source absorption heat pumps combined with borehole free cooling. Energy Convers Manag 2014;79:334–43. https://doi.org/10.1016/j.enconman.2013.11.045.
[24] Wang X, Zheng M, Zhang W, Zhang S, Yang T. Experimental study of a solar-assisted ground-coupled heat pump system with solar seasonal thermal storage in severe cold areas. Energy Build 2010;42(11):2104–10. https://doi.org/10.1016/j.enbuild.2010.06.022.
[25] Yang T, Liu W, Kramer GJ, Sun Q. Seasonal thermal energy storage: a techno-economic literature review. Renew Sust Energ Rev 2021;139:110732. https://doi.org/10.1016/j.rser.2021.110732.
[26] Shah SK, Aye L, Rismanchi B. Simulated performance of a borehole-coupled heat pump seasonal solar thermal storage system for space heating in cold climate. Sol Energy 2020;202:365–85. https://doi.org/10.1016/j.solener.2020.03.111.
[27] Zou B. Simulation Study of Heating System of Trough Solar Collectors Combined with Gas Boiler [Dissertation]. Harbin: Harbin Institute of Technology; 2014.
[28] Yuan Y, Zhao J. Study on the supply capacity of crop residue as energy in rural areas of Heilongjiang province of China. Renew Sust Energ Rev 2014;38:526–36. https://doi.org/10.1016/j.rser.2014.06.009.
[29] Wang J-J, Xu Z-L, Jin H-G, Shi G-h, Fu C, Yang K. Design optimization and analysis of a biomass gasification based BCHP system: a case study in Harbin, China. Renew Energy 2014;71:572–83. https://doi.org/10.1016/j.renene.2014.06.016.
[30] Hua C. Control System Design of Biomass Boiler [Dissertation]. Harbin: Harbin Institute of Technology; 2019.
[31] Meng X. The Combustion Characteristics of Blend Biomass in a Fixed Bed Reactor [Dissertation]. Harbin: Harbin Institute of Technology; 2019.
[32] Xu J, Lv T, Hou X, Deng X, Liu F. Provincial allocation of renewable portfolio standard in China based on efficiency and fairness principles. Renew Energy 2021; 179:1233–45. https://doi.org/10.1016/j.renene.2021.07.101.
[33] Ma X, Li P. Comparative test and analysis of various clean energy supply heating modes in Harbin city. Low Temp Archit Technol 2020;42(10):138–41. https://doi.org/10.13905/j.cnki.dwjz.2020.10.033. (In Chinese).
[34] Wang J. Heat and Power Synergic Dispatch and Optimal Configuration of Clean Heat Sources for District Energy System [Dissertation]. Harbin: Harbin Institute of Technology; 2019.
[35] Jia Z, Bian J, Wang Y. Impacts of urban land use on the spatial distribution of groundwater pollution, Harbin City, Northeast China. J Contam Hydrol 2018;215:29–38. https://doi.org/10.1016/j.jconhyd.2018.06.005.
36. GenOpt. Generic optimization program. https://simulationresearch.lbl.gov/GO/;; 2022 [accessed 2 May 2022].
37. Harbin Municipal People's Government. Harbin city heating measures. http://www.harbin.gov.cn/art/2011/10/25/art_4444_60616.html;; 2011. accessed 30 April 2022.
[38] Ministry of Housing and Urban-Rural Development of the People's Republic of China. Design Code for Heating Ventilation and Air Conditioning of Civil Buildings (GB 50736–2012). Beijing: China Architecture & Building Press; 2012.
[39] Lund H, Werner S, Wiltshire R, Svendsen S, Thorsen JE, Hvelplund F, et al. 4th Generation District Heating (4GDH): integrating smart thermal grids into future sustainable energy systems. Energy 2014;68:1–11. https://doi.org/10.1016/j.energy.2014.02.089.
[40] Zhang Q, Chen W. Modeling China's interprovincial electricity transmission under low carbon transition. Appl Energy 2020;279:115571. https://doi.org/10.1016/j.apenergy.2020.115571.
[41] China Electricity Council. China Electricity Statistical Yearbook 2021. Beijing, China: China Statistics Press; 2021.
[42] Lund H, Thellufsen JZ, Østergaard PA, Sorknæs P, Skov IR, Mathiesen BV. EnergyPLAN – advanced analysis of smart energy systems. Smart Energy 2021;1:100007. https://doi.org/10.1016/j.segy.2021.100007.
43. The People's Bank of China. Benchmark interest rate for RMB loans of financial institutions. http://www.pbc.gov.cn/;; 2021 [accessed 8 April 2021].
44. Alibaba Group. Alibaba.com. https://www.alibaba.com/;; 2021. accessed 8 April 2021.
[45] Yang L, Qiao B, Xu W, Zhou Q. Analysis of the influence of borehole depth on energy efficiency and cost of ground source heat pump system. In: Proceedings of the 12th IEA Heat Pump Conference; 2017 May 15–18; Rotterdam, the Netherlands; 2017.
[46] Huang J, Fan J, Furbo S. Demonstration and optimization of a solar district heating system with ground source heat pumps. Sol Energy 2020;202:171–89. https://doi.org/10.1016/j.solener.2020.03.097.
[47] Chi H. Economic evaluation of ground source heat pump in a residential building. Energy Conserv 2014;33(04):33–7 (In Chinese).
[48] Yu L, Cheng J. Study on engineering design and cost performance of borehole heat exchangers. Math Probl Eng 2015;2015:870380. https://doi.org/10.1155/2015/870380.
[49] Luo J, Zhang Y, Rohn J. Analysis of thermal performance and drilling costs of borehole heat exchanger (BHE) in a river deposited area. Renew Energy 2020;151:392–402. https://doi.org/10.1016/j.renene.2019.11.019.
[50] Otanicar T, Taylor RA, Phelan PE. Prospects for solar cooling – an economic and environmental assessment. Sol Energy 2012;86(5):1287–99. https://doi.org/10.1016/j.solener.2012.01.020.
51. Teske S. Energy revolution: a sustainable pathway to a clean energy future for Europe. http://eu.greenpeace.org/downloads/energy/EU25scenario2050.pdf; 2005.
52. Mauthner F, Herkel S. Technology and demonstrators. Technical report subtask C - Part C1. http://task3.iea-shc.org/data/sites/1/publications/IEA-SHC-Task52-STC1-Classification-and-benchmarking-Report-2016-03-31.pdf;; 2016.
53. China Electricity Council. China electricity price system. http://cep.cec.org.cn/api/index.html;; 2021 [accessed 8 April 2021].
54. Harbin Development and Reform Commission. Notice on adjusting the sales price of pipeline natural gas for non-residential use. http://fgw.harbin.gov.cn/art/2020/3/15/art_24909_951074.html;; 2020. accessed 8 April 2021.
[55] Luo S, Hu W, Liu W, Xu X, Huang Q, Chen Z, et al. Transition pathways towards a deep decarbonization energy system—a case study in Sichuan, China. Appl Energy 2021;302:117507. https://doi.org/10.1016/j.apenergy.2021.117507.
[56] Hong L, Lund H, Mathiesen BV, Möller B. 2050 pathway to an active renewable energy scenario for Jiangsu province. Energy Policy 2013;53:267–78. https://doi.org/10.1016/j.enpol.2012.10.055.
[57] He G, Lin J, Sifuentes F, Liu X, Abhyankar N, Phadke A. Rapid cost decrease of renewables and storage accelerates the decarbonization of China's power system. Nat Commun 2020;11(1):2486. https://doi.org/10.1038/s41467-020-16184-x.

[58] Tan X, Li H, Guo J, Gu B, Zeng Y. Energy-saving and emission-reduction technology selection and CO_2 emission reduction potential of China's iron and steel industry under energy substitution policy. J Clean Prod 2019;222:823–34. https://doi.org/10.1016/j.jclepro.2019.03.133.

[59] National Bureau of Statistics of China. China Energy Statistical Yearbook 2021. Beijing, China: China Statistics Press; 2022.

60. National Center for Climate Change Strategy and International Cooperation (NCSC). Guidelines for compiling provincial greenhouse gas inventories. http://www.ncsc.org.cn/SY/tjkhybg/202003/t20200319_769763.shtml;; 2011 [accessed 8 April 2021].

[61] Jang D, Kim K, Kim K-H, Kang S. Techno-economic analysis and Monte Carlo simulation for green hydrogen production using offshore wind power plant. Energy Convers Manag 2022;263:115695. https://doi.org/10.1016/j.enconman.2022.115695.

[62] Sadeghi M, Kalantar M. Multi types DG expansion dynamic planning in distribution system under stochastic conditions using covariance matrix adaptation evolutionary strategy and Monte-Carlo simulation. Energy Convers Manag 2014;87:455–71. https://doi.org/10.1016/j.enconman.2014.07.010.

63. Palisade. @RISK. https://www.palisade.com/risk/;; 2022 [accessed 18 May 2022].

64. FRED Economic Data. Global price of LNG, Asia. https://fred.stlouisfed.org/series/PNGASJPUSDM;; 2022. accessed 18 May 2022.

65. ITC Trade Map. List of products imported by China. https://www.trademap.org/Product_SelCountry_TS.aspx?nvpm=1%7c156%7c%7c%7c%7c2711%7c%7c%7c4%7c1%7c1%7c1%7c2%7c1%7c1%7c3%7c1%7c1;; 2022 [accessed 18 May 2022].

[66] Heck N, Smith C, Hittinger E. A Monte Carlo approach to integrating uncertainty into the levelized cost of electricity. Electr J 2016;29(3):21–30. https://doi.org/10.1016/j.tej.2016.04.001.

[67] Li B, Han Z, Meng X, Zhang H. Study on the influence of the design method of the ground source heat pump system with considering groundwater seepage. Appl Therm Eng 2019;160:114016. https://doi.org/10.1016/j.applthermaleng.2019.114016.

[68] Wang E, Fung AS, Qi C, Leong WH. Performance prediction of a hybrid solar ground-source heat pump system. Energy Build 2012;47:600–11. https://doi.org/10.1016/j.enbuild.2011.12.035.

[69] Dai L, Li S, DuanMu L, Li X, Shang Y, Dong M. Experimental performance analysis of a solar assisted ground source heat pump system under different heating operation modes. Appl Therm Eng 2015;75:325–33. https://doi.org/10.1016/j.applthermaleng.2014.09.061.

[70] Wang W, Li F. Study on substitutable value of electric heating instead of coal heating in northern China under carbon constraints. J Clean Prod 2020;260:121155. https://doi.org/10.1016/j.jclepro.2020.121155.

71. Harbin Municipal People's Government. Measures for the administration of financial subsidy funds in Harbin for renovating coal-fired boilers and promoting clean energy use. http://www.harbin.gov.cn/art/2019/11/15/art_24408_812711.html;; 2019. accessed 4 July 2022.

[72] Zhang Z, Zhou Y, Zhao N, Li H, Tohniyaz B, Mperejekumana P, et al. Clean heating during winter season in northern China: a review. Renew Sust Energ Rev 2021;149:111339. https://doi.org/10.1016/j.rser.2021.111339.

[73] Zhou X, Xu Y, Zhang X, Xu D, Linghu Y, Guo H, et al. Large scale underground seasonal thermal energy storage in China. J Energy Stor 2021;33:102026. https://doi.org/10.1016/j.est.2020.102026.

[74] Huang J, Fan J, Furbo S. Feasibility study on solar district heating in China. Renew Sust Energ Rev 2019;108:53–64. https://doi.org/10.1016/j.rser.2019.03.014.

[75] Thomson H, Liddell C. The suitability of wood pellet heating for domestic households: a review of literature. Renew Sust Energ Rev 2015;42:1362–9. https://doi.org/10.1016/j.rser.2014.11.009.

[76] Munawar MA, Khoja AH, Naqvi SR, Mehran MT, Hassan M, Liaquat R, et al. Challenges and opportunities in biomass ash management and its utilization in novel applications. Renew Sust Energ Rev 2021;150:111451. https://doi.org/10.1016/j.rser.2021.111451.

[77] Liu G, Dong X, Kong Z, Jiang Q, Li J. The role of China in the East Asian natural gas premium. Energy Strat Rev 2021;33:100610. https://doi.org/10.1016/j.esr.2020.100610.

[78] Ma C, Zhang Y, Li T. GIS-based evaluation of solar and biomass perspectives – case study of China regions. J Clean Prod 2022;357:132013. https://doi.org/10.1016/j.jclepro.2022.132013.

[79] Heilongjiang Bureau of Statistics. Heilongjiang Statistical Yearbook 2021. Beijing, China: China Statistics Press; 2022.

[80] Chen Q, Xia M, Wang H, Liu W, Wang Z, Zhang X, et al. Evaluation indices set and decision-making method for regional "coal to electricity" optimal development mode. AIP Conf Proceed 2019;2154(1):020003. https://doi.org/10.1063/1.5125331.

[81] Pu L, Wang X, Tan Z, Wu J, Long C, Kong W. Feasible electricity price calculation and environmental benefits analysis of the regional nighttime wind power utilization in electric heating in Beijing. J Clean Prod 2019;212:1434–45. https://doi.org/10.1016/j.jclepro.2018.12.105.

[82] Peng X, Tao X. Cooperative game of electricity retailers in China's spot electricity market. Energy 2018;145:152–70. https://doi.org/10.1016/j.energy.2017.12.122.

83. The State Council of the People's Republic of China. Working guidance for carbon dioxide peaking and carbon neutrality in full and faithful implementation of the new development philosophy. http://www.gov.cn/zhengce/2021-10/24/content_5644613.htm;; 2021 [accessed 8 May 2022].

84. IEA. World energy outlook 2021. https://www.iea.org/reports/world-energy-outlook-2021; 2021.

[85] Wang C, Chang Y, Zhang L, Pang M, Hao Y. A life-cycle comparison of the energy, environmental and economic impacts of coal versus wood pellets for generating heat in China. Energy 2017;120:374–84. https://doi.org/10.1016/j.energy.2016.11.085.

[86] Mohamed U, Zhao Y-J, Yi Q, Shi L-J, Wei G-Q, Nimmo W. Evaluation of life cycle energy, economy and CO_2 emissions for biomass chemical looping gasification to power generation. Renew Energy 2021;176:366–87. https://doi.org/10.1016/j.renene.2021.05.067.