Carbon Neutrality

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The role of heat pump in heating decarbonization for China carbon neutrality

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Abstract

Heating decarbonization is a major challenge for China to meet its 2060 carbon neutral commitment, yet most existing studies on China's carbon neutrality focus on supply side (e.g., grid decarbonization, zero-carbon fuel) rather than demand side (e.g., heating and cooling in buildings and industry). In terms of end use energy consumption, heating and cooling accounts for 50% of the total energy consumption, and heat pumps would be an effective driver for heating decarbonization along with the decarbonization on power generation side. Previous study has discussed the underestimated role of the heat pump in achieving China's goal of carbon neutrality by 2060. In this paper, various investigation and assessments on heat pumps from research to applications are presented. The maximum decarbonization potential from heat pump in a carbon neutral China future could reach around 1532Mton and 670Mton for buildings and industrial heating respectively, which show nearly 2 billion tons CO_2 emission reduction, 20% current CO_2 emission in China. Moreover, a region-specific technology roadmap for heat pump development in China is suggested. With collaborated efforts from government incentive, technology R&D, and market regulation, heat pump could play a significant role in China's 2060 carbon neutrality.

Keywords: Carbon neutrality, Heat pump, Heating decarbonization, Techno-economic assessment, Technological roadmap, Building heating, Industrial heating

1 Introduction

Heating accounts for nearly 50% of the terminal energy demands [1], and heating decarbonization is essential for the 2060 carbon neutral commitment [2, 3], especially for industrial heating that is hard to be decarbonized [4]. Previous study has discussed the underestimated role of the heat pump in achieving China's goal of carbon neutrality by 2060 [5]. However, current China's heating is highly associated with coal-fired process, which is particularly carbon-intensive with a high CO_2 emission intensity over $400gCO_2 \cdot kWh^{-1}$ [6].

In terms of current supplier of heat, coal-based heating is a highly emission intensive thus must be eliminated in the near future [7]; compared to coal, natural gas is relatively cleaner, yet coal-to-natural-gas switch could bring additional risk of natural gas heating infrastructure lock-in, which would further hinder deep decarbonization to zero level, the instability of natural gas supply might be problem worldwide; solar heating is a cheap heating technology yet its variability and unpredictability could undermine its reliability. Although biomass is expected to play important role in future net-zero energy systems, yet biomass resource has limited supply and current biomass fuel is associated with PM2.5 emissions [8]. Electric heating could directly convert power to heat with wide-temperature range flexibly. However, considering the electricity is a secondary energy, heating by electrical resistance currently costs higher than fuel-based heating. By contrast, heat pumps provide an overall balance between energy efficiency, reliability, emission performance and economics; furthermore, the fact that electric heat pumps are driven by electricity will make them an

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even cleaner heating option with progressive power grid decarbonization. As the emission intensity of electricity goes lower, heat pump could provide heating with little or even no greenhouse gas emissions.

Current heat pumps could supply heat over 160 °C, which can cover almost all building heating demand (building space heating usually requires hot water below 80 °C or even lower, while residential hot water demand are usually below 50 °C), and 30%–50% of the industrial process heating demands (80 ~ 160 °C) currently [9]. In addition, it is expected that further technological advancement through multistage compression and cascade cycle could increase heat pump heating supply over 200 °C, and high-temperature heat pumps with temperature-lift over 100 °C (e.g., the temperature difference between heat source and heat sink could reach 100 °C) are now considered reasonable [10].

Despite the great opportunities discussed above, rapid rollout of heat pumps in both buildings and industry faces multiple challenges. Although it is widely acknowledged that heat pumps will be a silver bullet solution for heating decarbonization [11, 12], it is also clear that they will continue to compete against fossil fuel (furnaces, boilers) in the decades ahead, especially for high temperature heat supply. Notably, recent advances of large-temperature-lift heat pumps have made high-temperature heating for industrial heating possible [10, 13, 14]. On the other hand, insights from engineering solutions for climate change are clear that significant heating decarbonization progress must be made in coming decades to get China on track to reach a national CO_2 emission peak in 2030 and carbon neutrality by 2060 [15, 16]. Decisiveness and speed of heating market structural changes are of vital importance in such a transition [17, 18]: given the long lifespan of heating facilities (boilers, heat pumps etc.), there are only two or three heating system replacement cycles between now and 2060. An immediate discussion on substantial new actions to decarbonize heating is urgently needed for China to materialize its 2060 carbon neutral commitment.

2 Heat pumps' research and applications

As shown in Fig. 1, a heat pump is essentially a heating device based on reverse Carnot cycle, which can extract heat from low-temperature heat source and supply high-temperature heat to various end-users. The low-temperature heat can come from ambient air source, ground source or industrial waste heat, all of which are considered as "free", and the operating cost is the electricity consumption.

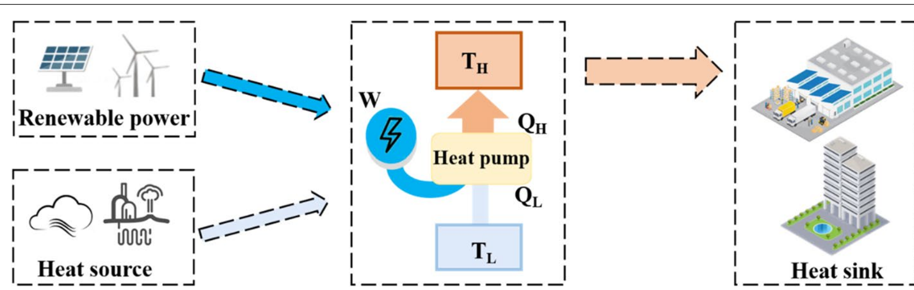


Fig. 1 Sketch of heat pump

Table 1 Performance Indicators and their explanations of the heat pump

Performance Indicator	Explanation
$Q_H = Q_L + W$	Q_H is the heat transferred to heat sink with high temperature (T_H), Q_L is the heat collected from heat source with low temperature (T_L), while W is electricity (for compression type) or heat (for absorption type) input.
$COP = \frac{Q_H}{W} = 1 + \frac{Q_L}{W} > 1$	The coefficient of performance (*COP*) is the ratio between heat supply to work. Higher COPs equate to higher efficiency, lower energy (power) consumption, thus lower operating costs. The COP is always over 1 in heat pumps, because it pumps "free" heat from heat source to heat sink.
$COP_{max} = \frac{T_H}{T_H - T_L}$	Maximum theoretical COP_{max} (Carnot COP) of heat pump operating between specific heat source T_L and heat sink temperature T_H.
$\varepsilon_{HP} = \frac{COP}{COP_{max}}$	Thermodynamic perfectness ε_{HP} is the ratio between heat pump COP and the maximum theoretical COP_{max}, which could never reach 100%.
$\Delta T_{lift} = T_H - T_L$	Temperature lift ΔT_{lift} is the temperature difference between the high-temperature heat sink and the low-temperature heat source.

Several typical indicators (Table 1) are usually used when it comes to heat pump performance benchmarking, including heat capacity (Q_H), coefficient of performance (COP), thermodynamic perfectness (ε_{HP}), temperature lift (ΔT_{lift}).

2.1 Building applications

For the building sector in China, about 50% of building energy consumption is used for heating [19], including water heating, space heating as well as some niche needs such as clothes drying [20] and dehumidification [21].

The buildings' heating contains multiple heating modes as shown in Fig. 2. As is summarized in Table 2 [22], the buildings' heating is usually with a relatively low temperature less than 80 °C,and the ambient air could serve as the heat source in most cases. The air source heat pump could reach a seasonal heating COP of 3.2 in Qingdao and 3.5 in Shanghai [23], and validated prototypes [24] with improved cycles [25–27] have achieved COP over 2.7 with the ambient temperature as low as -15 °C. Currently, there are more than 450 million units of air-conditioners in China [28, 29], which could be also regarded as spilt-type air-source heat pumps if they are used for heating in winter and cooling in summer. If there are accesses to other sources with higher temperature, such as geothermal [30], waste heat [31], the efficiency will be further improved. For example, geothermal heat pump could gained a higher seasonal COP about 4.32 in Qingdao and 4.79 in Shanghai [23], yet there are simply not enough space for underground wells in most highly urbanized China cities [32]. Therefore, air-source heat pump, in particular small-scale air source heat pump, has accumulated its advantage in China's heating market.

Table 2 Temperature range of buildings' heat demands

Heating mode	Temperature needed
Radiator heater	80 °C (inlet water temperature)
	60 °C (return water temperature)
Hot water	40 ~ 50 °C
Floor heating	35 °C–40 °C
Fan coil unit	35 ~ 45 °C

Moreover, through recovering waste heat from industrial process, large-scale heat pumps could achieve a better performance. As shown in Fig. 3, there are two validated cases based on waste heat recovery for district heating adopting absorption heat pump and compression heating pump. Figure 3 a shows the absorption heat pump absorbing heat from power station's waste heat (Heat source: ~35 °C with 0.24 MPa driven steam, Heat sink: 81.34 °C; Heating capacity:57 MW, COP:1.77) [33]. Figure 3 b shows a compression heat pump system recovering waste heat from a steel plant for district heating (Heat source: 32.5 °C waste water, Heat sink: 62.5 °C; Heating capacity:9.67 MW, COP:6.67) [34]. As the above two projects have utilized waste heat according to local

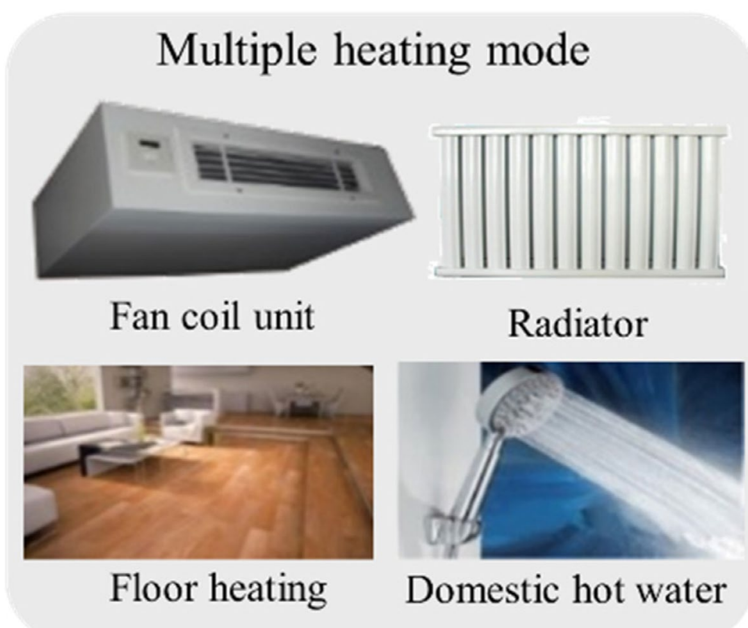


Fig. 2 Multiple buildings' heating modes

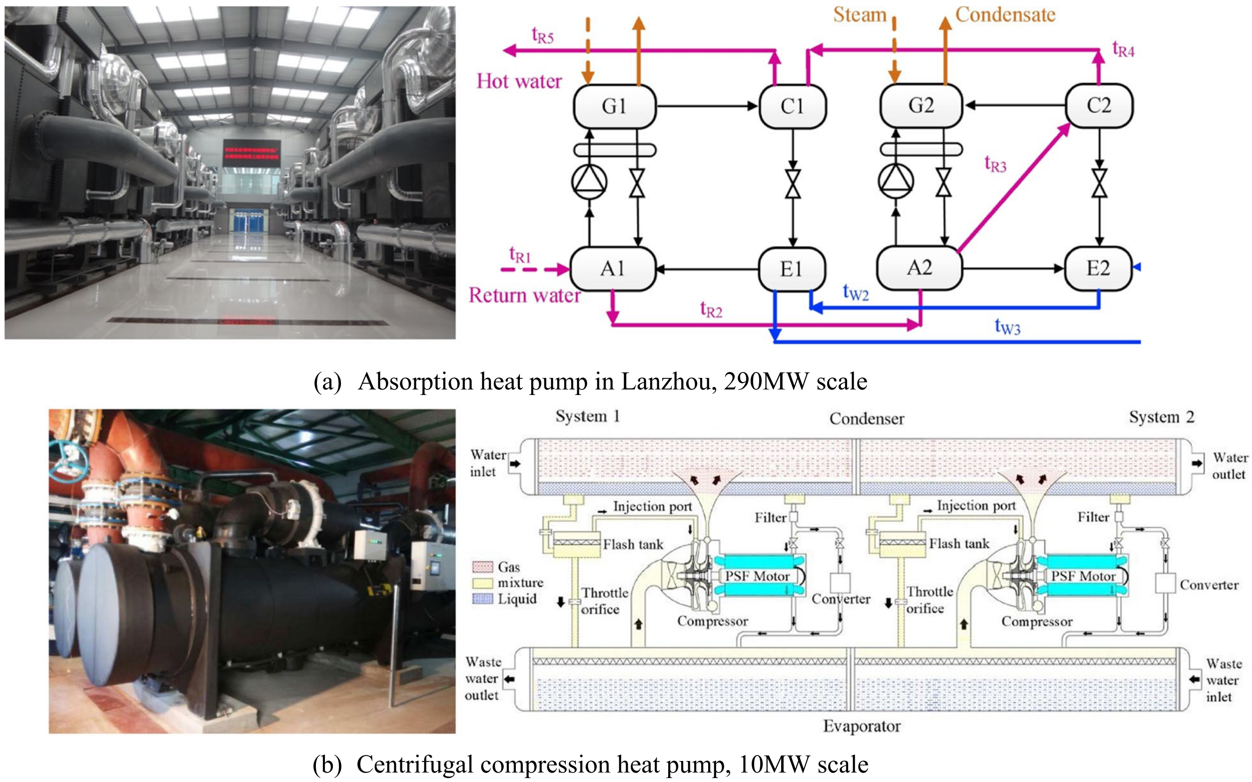


Fig. 3 Waste-heat-based heat pumps for district heating. **a** Absorption heat pump in Lanzhou, 290 MW scale. **b** Centrifugal compression heat pump, 10 MW scale

conditions and achieved high-efficiency by waste heat recovery, their investment payback periods are about 2–3 years.

Water heating remains an increasing residential energy demand in China, given the urbanization rate and relatively lower living standard compared to developed countries [35] (water heating accounts for about 30% of Japan's total residential energy consumption [36]). According to the national standards applicable for heat pump water heaters in Japan [37] and China [38], heat pump water heaters could gain a COP value of 3.2 to 3.7 under the nominal condition (based air-source with wet-bulb temperature of 15 °C for 55 °C hot water generation [38]) on and even reach 4.6 by excellent manufacturers [36].

Generally, most of current heat pump systems for buildings have a seasonal heating COP ranging between 3.0 and 4.5, further innovations could even increase the system COP to more than 6 [39], especially combined with waste heat recovery. For buildings' heating, thermal comfort is also important, and some pilot research on small temperature difference (STD) fan coil unit [40] and desiccant-coated heat pumps(DSHP) [41] would be beneficial. As shown in Fig. 4, STD fan coil unit is suggested in an air source heat pump heating system, whereas the heat transfer area is expanded and the water supply temperature could be reduced to less than 35 °C. In that case, the COP of the heating system could be further improved. The desiccant coated heat pump's heat exchangers are coated with solid desiccant, and thus the heat exchangers can independently handle sensible and latent loads at the same time. The DSHP is with an ultra-high COP value of more than 6.2 without sacrificing any comfort or compactness. Such technology could also be applied into automobile [42] and high speed trains [43].

2.2 Industrial applications

In China, heat accounts for about 50%–70% of industrial energy consumption, 30%–50% of which are in the range of 80 °C–160 °C [9]. As shown in Fig. 5, compared to buildings' heat demands, the industrial heat demands are often with relatively higher temperatures. Due to a higher temperature demand in industry, industrial heat pumps often adopt industrial waste heat as the heat source. Validated cases have shown the COP of 120 °C heat pump is

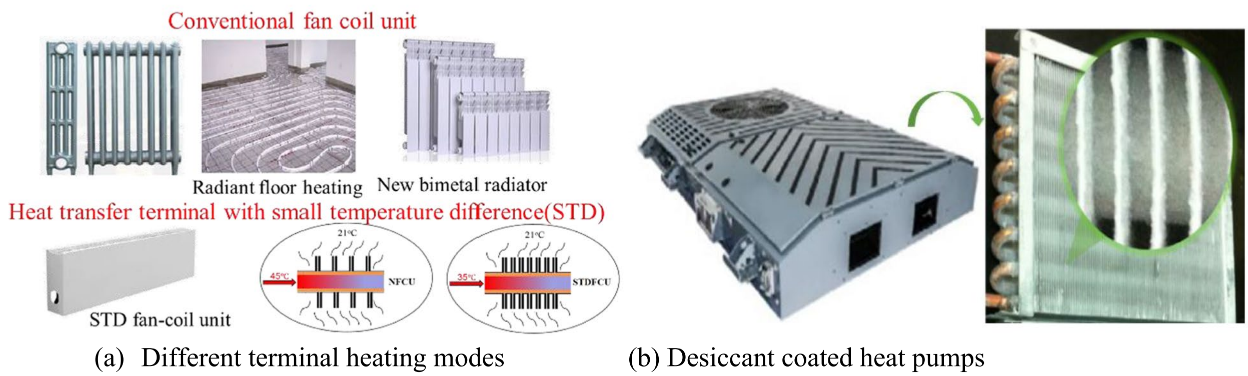


Fig. 4 Pilot research for thermal comfort and high efficiency heating and cooling. **a** Different terminal heating modes. **b** Desiccant coated heat pumps

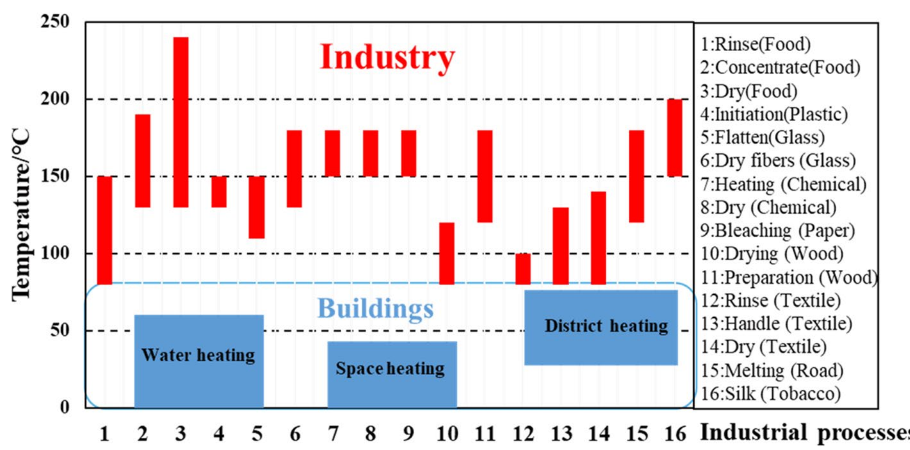


Fig. 5 The temperature range of heating demands in buildings and different industrial processes

larger than 4.0 with a temperature lift value over 40 °C [44]. Newly-developed refrigerants could enable heating temperature up to 168 °C [45], and combining with absorption heat pumps could further achieve heating temperature to 180 °C [46]. Concerning heating temperature up to 100 °C, the corresponding refrigerants could be hydrocarbon (e.g., R290 and R600, yet with a heating capacity restriction), carbon dioxide, and synthetic refrigerants (e.g., R1234ze(E) and R1233zd(E)), and the corresponding compressors and other devices are also with a wide range of options. For heating output temperature less than 100 °C, ammonia is with market-available large-scale compressors and validated application cases [47], and could be considered for large-scale applications. However, there is still a lack of available commercial compressors with large capacity and high efficiency, especially the centrifugal compressor is considered to be only one choice for megawatt scale currently. The current good option could be ammonia vapor compression heat pump hybrided with LiBr-water absorption heat transformer for large scale industrial heating, as both systems are matured. Since water/steam also play an important role in the ammonia-water absorption cycle, it could be possible to find good combination of ammonia-water based vapor compression and absorption hybrid cycles suitable for various applications [48, 49].

The above-mentioned heat pumps are with closed cycle, whereas the heat pump transfer heat in an indirect way through the heat exchanger (condenser). However, when considering the fair matching between heat pumps and certain industrial processes such as distillation, concentration and drying, that are widely integrated in petroleum pharmacy, and food industries [50], open cycle could be further adopted. Mechanical vapor compression/recompression [51] is a typical open cycle, an improved efficiency could be gained through recovering the latent heat from condensed steam [52]. For industrial heat pumps, another development trend would be large temperature lift. According to the statistical data, the amount of available heat sources increases dramatically when the heat source temperature decrease, while there is also increasing heat demands with higher temperature [53]. Therefore, a typical large temperature lift heat pump would be useful yet guaranteeing a high-efficiency is hard. Cascade cycles and multistage cycles are often adopted for large temperature lift, but the temperature lift value is hard to exceed 100 °C. As shown in Fig. 6, recent studies verified that air-source heat pump based water vapor compression system could generate 120 °C steam with COP over 130% at -18 °C ambient temperature, 210% at 35 °C ambient temperature [54]. With an average operating COP of 170%, the air-source heat pump boiler can directly satisfy the high temperature steam demand of small and medium-sized enterprises, and is an efficient driver for terminal electrification of high-temperature heating [13].

In many cases, industrial processes have heating demands across different temperature ranges [55], particular appling to industrial parks with various industry clusters [56]. In such cases, the benefits of coupling heat pump with other sources such as solar power would be flexible and efficient. In summary, industrial heat pumps based on different heat sources have already been applied in different cases, yet for the high temperature heating and large scale, high efficiency for compressors, improved cycle with less inverse loss and low-GWP refrigerants would be further investigated for much more competitive advantages in heating markets.

3 Data and methodology

3.1 Emission intensity assessment

3.1.1 China' heating sector GHG emission

Many processes have heating demands varing temperature, energy source and other aspects, evaluating emission intensity for heat consumption is a complicated problem. Herein we did some estimations based on the published references from authorities, and the average GHG emission intensity in China's heating sector is derived from the following data shown in Table 3 [6], around 378 gCO_2/kWh.

3.1.2 Emission intensity of heating facilities

The heating facilities are driven by power or fuel sources, and heating facilities' emission intensity $E_{Heating}$ is essential related with the input sources emission intensity, and could be calculated by the following equations:

$$E_{Heating} = \frac{E_{source}}{\eta} \tag{1}$$

Table 3 GHG emission intensities and market shares of different heating technologies in China

China *Heating type*	GHG direct *gCO_2/kWh*	GHG indirect *gCO_2/kWh*	Proportion (%) *2020*
Oil	356	100	9.91
Oil Advanced	310	87	0.33
Gas	269	62	11.4
Gas Advanced	224	52	1.24
Biomass	0	390	27.05
Biomass Advanced	0	69	2.28
Coal	472	30	12.96
District	472	30	12.95
Electric	717	0	5.74
Heat pump - Ground source	239	0	1.67
Heat pump - Air-Water	239	0	1.66
Heat pump - Air-Air	239	0	1.71
Solar Thermal	0	0	11.09

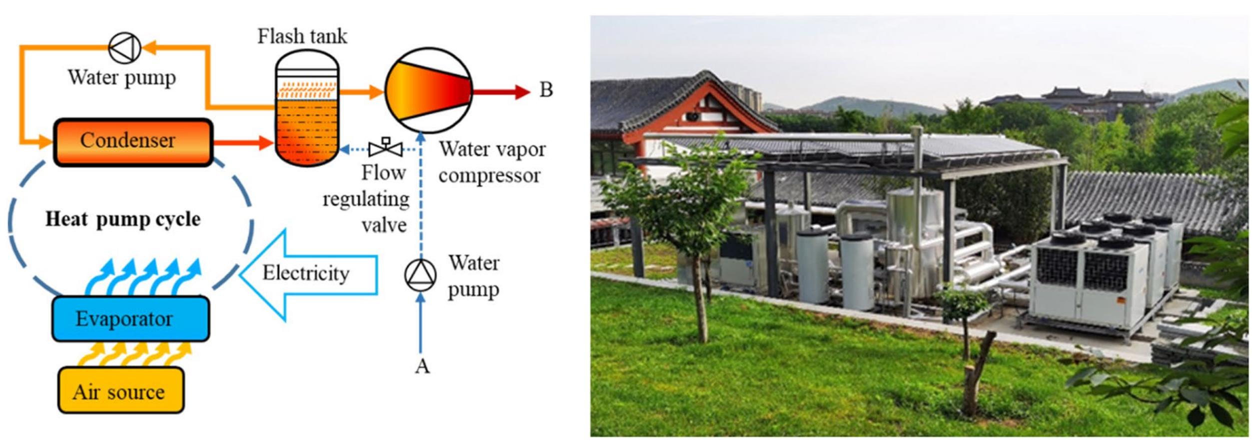


Fig. 6 Air source heat pump for steam generation [13]

Where E_{source} is the sources' emission intensity of heating facilities, and η is the heating efficiency of heat facilities. For example, the heating efficiency of heat pump is COP mostly around 2–5, and the heating efficiency electrical resistance heating and natural gas boiler could reach 95%.

3.2 Heat pumps' market share in China assessment

The buildings' heating contains multiple heating modes as shown in Fig. 2 and Table 3, the buildings' heating is usually with a relatively low temperature less than 80 °C, and the ambient air could serve as the heat source in most cases. According to the investigation, as for the primary energy consumption in China's building sector, about half was used to provide heating [19]. According to our investigation as shown in Fig. 5 and Table 4, many industrial processes are with temperature demand between 80 °C and 160 °C, which could be satisfied by current industrial heat pump technology.

As for heat proportion, according to the investigation [9], for China's industrial sector, 50% to 70% of energy is consumed in the form of thermal energy(heat),and 45% of the heat is with medium and low temperature (<250 °C). Meanwhile, taking EU industrial heating demand as an example, currently 45.80% of such process heating is within temperature below 200 °C, while 41.75%% is below 150 °C [57] as shown in Fig. 7. In terms of temperature match, the first part could be totally replaced by current industrial heat pump, while the heating demands between 150 and 200 °C is also expected to be replaced with the development of heat pump technology.

Conservatively, it is estimated that 60% of industrial energy consumption is consumed through heat, and 40% of this heat can be replaced by heat pump at temperatures below 150 °C. This alternative proportion by heat pump will further increase with the development of heat pump technology.

3.3 Decarbonization potential assessment

3.3.1 Prediction of the end-use energy consumption variation by sectors and time

As is shown in Table 5, according to data from ***National Grid Research Institute 2020*** [58], the terminal energy demand of industrial part is 2.110 billion tons of standard coal, that of construction part is 810 million tons of standard coal, that of transportation

Table 4 The heat demands in some industrial processes [9]

Industrial process	Use	Heat-carrying form	Temperature
Food	Rinse	Air	80-150 °C
	Concentrate	Steam	130–190 °C
	Drying	Steam (air)	130–240 °C
Plastic	Initiation	Steam	130–150 °C
	Rapid Separation	Steam	150 °C
	Extrusion	Steam	150 °C
	Drying	Steam (air)	180 °C
	Blend	Steam	150 °C
Glass	Flatten	Air	110–150 °C
	Dry fibers	Air	130–180 °C
Chemical industry	Heating dipping	Steam (air)	150–180 °C
	Drying	Steam (air)	150–180 °C
Paper-making	Kraft bleaching	Steam	150–180 °C
	Drying	Steam	150 °C
Woodworking	Drying in cellar	Air	80–120 °C
	Preparation of plywood	Steam	120–180 °C
	Hot-pressed fiberboard	Steam	200 °C
Synthetic rubber	Initiation	Steam	130 °C
	Monomer recovery	Steam	130 °C
	Drying	Steam (air)	130 °C
Textile industry	Rinse	Water	80–100 °C
	Handle	Steam	80–130 °C
	Drying	Steam (air)	80–140 °C
Road construction	Melting asphalt	Steam	120–180 °C
Tobacco industry	Silk making	Steam	150–200 °C

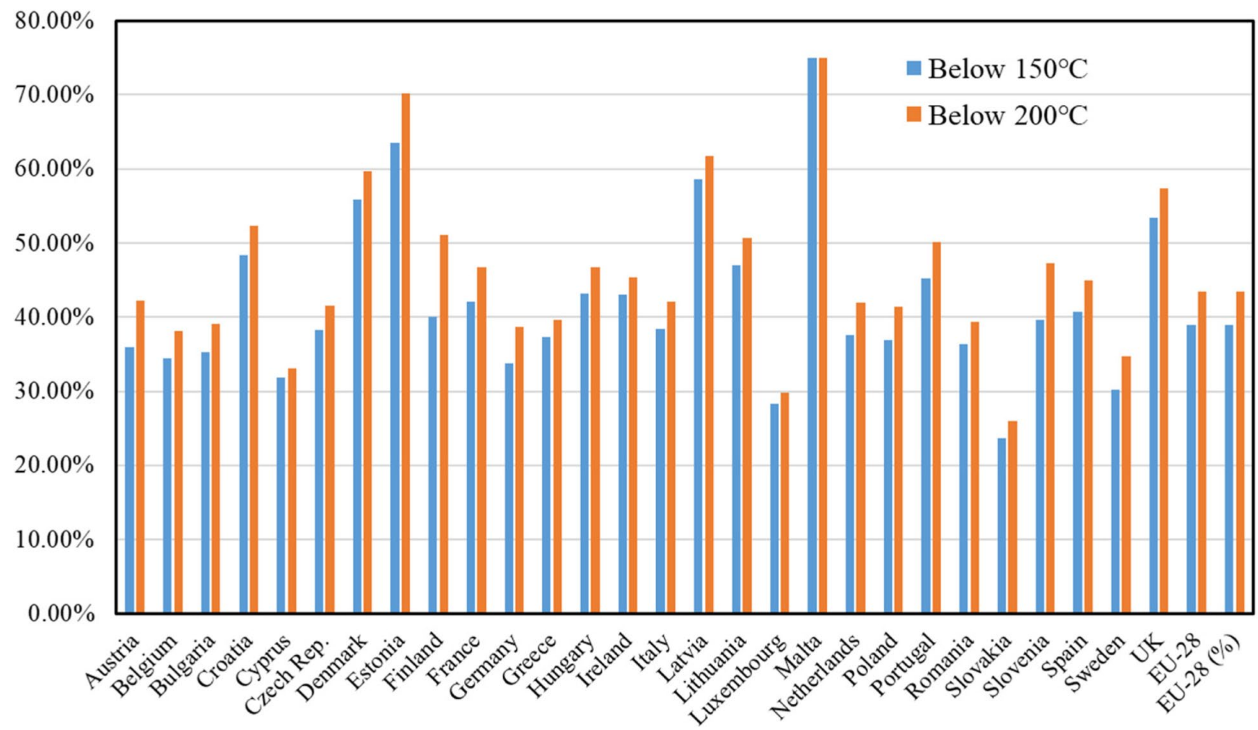


Fig. 7 Heating energy consumption fractions in EU industries divided by temperature [57]

Table 5 End-use energy demand by sector

End-use energy demand by sector	2020		2030		2040		2050		2060	
	Amount	Share	Amount	Share	Amount	Share	Amount	Share	Amount	Share
Industry	21.1	60%	19.3	49%	14.6	40%	12	36%	10.7	35%
Building	8.1	23%	11.3	28%	12.2	33%	11.6	34%	11.5	37%
Transportation	5	14%	7.9	20%	8.8	24%	9.2	27%	7.8	25%
Other	0.9	3%	1.2	3%	1.1	3%	1	3%	0.9	3%

Note: The energy unit is 10^9 tons of standard coal

part is 500 million tons of standard coal and that of other parts is 0.9 billion tons. The industrial sector's energy demand will reach 1.07 billion tons of standard coal in 2060; The buildings' sector will consume 1.15 billion tons of standard coal in 2060.

3.3.2 Basic assumptions on heat pump

- Targeted sectors: buildings' sector and industrial sector
- The COP of buildings' heat pump is set as 3.5, while industrial heat pump is set as 2.5.
- For buildings' sector: The heating energy consumption accounts for 50% of the end-use energy consumption, which could be completely supplied by heat pumps.
- For industrial sector: The heating energy consumption accounts for 60% of the end-use energy consumption, of which 40% could be supplied by heat pump

3.3.3 Heat pump decarbonization potential assessment

Previous study has indicated the huge CO2 emission offset brought by heat pumps [5], herein we provided the detailed methodology to quantify the heat pump-based heating decarbonization potential. The decarbonization potential of heat pumps is estimated by collating the end-use energy consumption projection in both buildings and industry, heating related energy use, heating energy that could be supplied by heat pumps. The detailed calculation procedure for heat pump

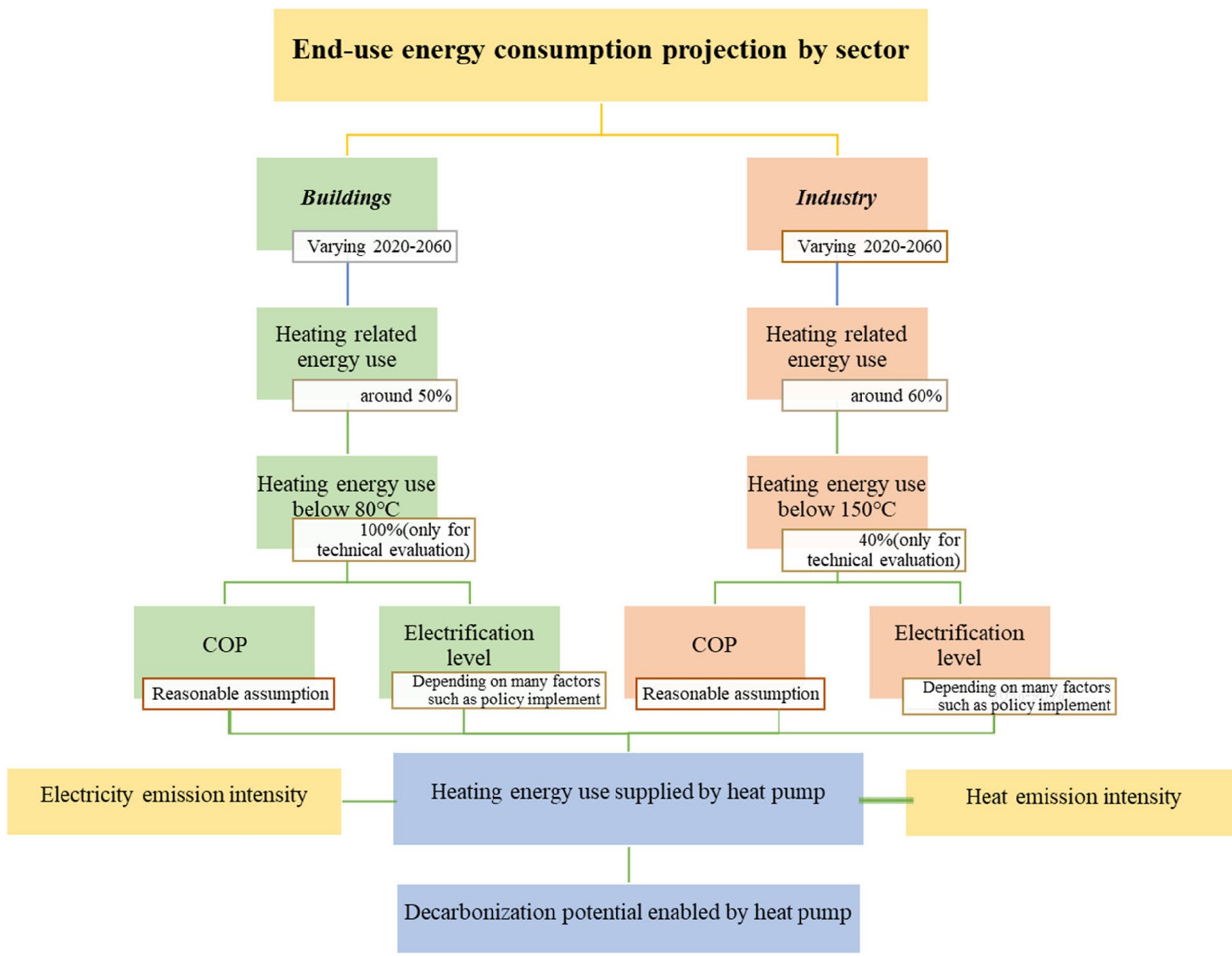


Fig. 8 Flow chart of the quantification of the heating decarbonization potential by heat pump

decarbonization potential consists of the following steps as shown in Fig. 8:

1. Projection of end-use energy consumption by sectors (residential commercial, transportation, industry) is based on the forecast from *China Energy & Electricity Outlook* [58];
2. 50% and 60% of final energy use in building and industrial sector is treated as heating related (refer to section 3.2 for detail);
3. In building sector, heating temperature below 80 °C is assumed within the working range of heat pump, which accounts for 100% of the total heating energy end use in buildings; in industrial sector, heating temperature below 150 °C is assumed within the working range of heat pump, which accounts for 40% of the total heating energy end use in industry.
4. For heating energy end use that is suitable for heat pump, three different scenarios with different heat pump penetration levels (e.g. percentage of heating energy end use that are actually supplied by heat pump) and COP of heat pump are assumed.
5. Based on the heating energy end use projection in step 3, plus the penetration level and COP of heat pump in step 4, total heating energy use supplied by heat pump can be obtained.
6. With emission intensity projection of electricity, the total emission induced by heat pump heating can be calculated. By further comparing such results with the emission of current heating emission intensity, the decarbonization potential of heat pump can be quantified.

3.4 LCOH assessment

The economics of heating facilities can be affected by many factors include the energy price and operating boundary conditions and could be evaluated by many factors such the payback period, IRR and NPV. The Levelized Cost of Heating (LCOH) has been proposed as a more direct indicator to benchmark the economic performance of heat suppliers [4] and be calculated as follows:

$$\mathrm{LCOH} = \frac{\text{Amortized Capital Cost}}{\text{Capacity Factor}} + \text{Cost of Energy} \times \frac{\text{Energy In}}{\text{Heat Out}} + \frac{\text{Other O\&M}}{\text{Heat Out}} \tag{2}$$

where the amortized capital cost represents the nameplate capacity of the heating facilities; the Capacity Factor represents percentage uptime; the Cost of Energy represents energy price such as natural gas price and electricity price; And the Energy In and Energy input represents such natural gas and electricity input and output amount; the Heat Out represents the heat supplied by heating facilities; the O&M represents the Operating and maintain cost.

The detailed assumptions for LCOH calculation are shown in Table 6. As mentioned in Section 2.1, the COP value of buildings' heat pump is calculated by eq. (3), with the average ambient temperature as the heat source's temperature [59].

$$COP_{Tsource\rightarrow Tsink} = a\cdot\left(\Delta T_{lift} + 2\cdot \mathrm{b}\right)^{c}\cdot\left(T_{sink} + \mathrm{b}\right)^{d}$$

$$-10^{\circ}\mathrm{C} \le T_{source} < 60^{\circ}\mathrm{C}, 25^{\circ}\mathrm{C} \le T_{sink} < 100^{\circ}\mathrm{C}, 10K \le \Delta T_{lift} \le 78K \tag{3}$$

where ΔT_{lift} represents temperature lift, T_{sink} is the outlet temperature, and the fitting parameters are as follows:

$a = 1.4480\cdot 10^{12}$, $b = 88.730$, $c = -4.9460$, $d = 0.0000$;

As mentioned in Section 2.2, the COP value of industrial heat pump is conservatively set as 2.5 that most waste heat based industrial heat pump could reach.

4 Assessment on heat pumps and other heating facilities

Although heat pumps could already supply heat to various scenarios with high-efficiency, they have to compete with other heating facilities, including natural gas, electrical resistance, etc. The comparison between heat pump and other heating facilities are with multiple aspects, including but not limited to environmental factors, economic factors.

4.1 CO_2 emission evaluation

The CO_2 emission of heat-pump-based-heating is mainly from its input power's CO_2 emission. Currently the CO_2 emission intensity of China's power generation is around 581 g·kWh^{-1} due to coal-dominant power generation mix. In such cases, as shown in Fig. 9a, the total CO_2 emission intensity of heat pump would be comparable to that of natural gas-based heating, when the COP is above 3. Such indicator could be relatively achieved by air source heat pumps in most climate zones in China.

Figure 9 b further shows the CO_2 emission intensity of heat pumps under current and future scenarios. With the proportion increasing of renewable power in China, it is estimated that the power sectors' average CO_2 emissions intensity will be reduced to 320 g·kWh^{-1} by 2030. In that case, the CO_2 emission of heat pumps will be less than that of natural-gas heating even with a COP less than 2. For scenarios where renewable electricity is used, due to the relatively lower CO_2 emission intensity less than 100 g·kWh^{-1}, even the electrical resistance heating will have a less CO_2 emission than natural gas heating, let alone heat pump-based heating.

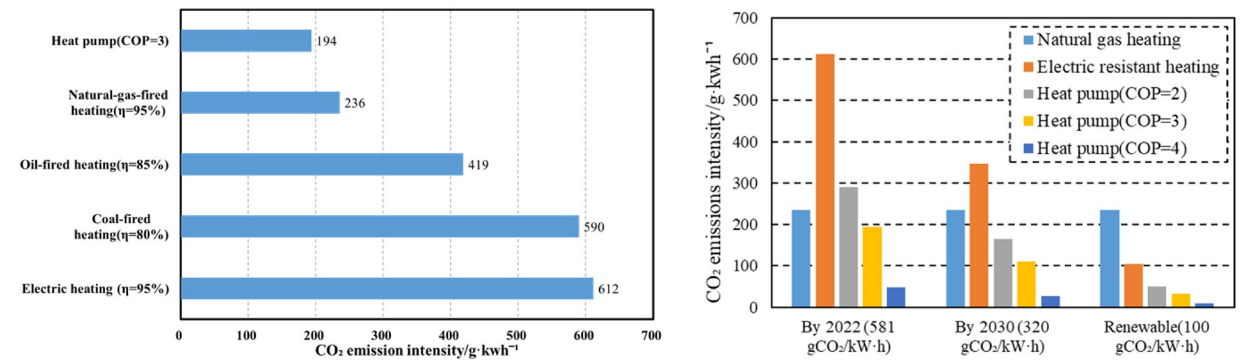
4.2 Heat pumps' decarbonization potential

Based on the previous analysis, with progressive decarbonization of power grid, heat pumps would be one of the optimal clean-heating-facilities. Therefore, it is expected a huge emission reduction potential from heat pump will be fully unleashed and we provided the detailed methodology. We defined the heat pumps' share in 2060 for industrial and buildings' sector respectively. It should be addressed the share herein is a relative proportion, for example, based on current technology

Table 6 The key assumptions for LCOH calculating

Parameters	Buildings' sector			Industrial sector		
Type	Heat pump	Natural gas	Electrical resistance	Heat pump	Natural gas	Electrical resistance
Capital cost CNY·kW^{-1}	971	261	162	1714	143	169
Annual operation hours	4000	4000	4000	6000	6000	6000
Lifetime years	15	15	15	15	15	15
Efficiency/COP	~3–4	95%	95%	2	95%	95%
Maintain cost factor	1.5%	1.5%	1.5%	1.5%	1.5%	1.5%

Note: The typical lifetime years, maintain cost factor, COP value are determined by some references [4, 59] and our investigation, while capital cost is based on our investigation on the market available products on average, while 20 kW heater for building sector with and 350 kW steam boiler for industrial sector. The calculation model does not consider financing or inflation, nor the degradation of collector efficiency or any residual value of the asset



(a) Different heating modes' CO_2 emission intensity based on current power structure (b) CO_2 emission of heat pumps under current and future scenarios

Fig. 9 CO_2 emission evaluation on heat pumps compared with other heating modes. **a** Different heating modes' CO_2 emission intensity based on current power structure. **b** CO_2 emission of heat pumps under current and future scenarios

level, heat pump could cover ~100% buildings' heating demands and ~40% industrial heating demands(there is a lack of accurate proportion of industrial heat demand by temperature level and herein 40% is adopted which would be reasonable in many research [9, 50, 60]), and these proportion that could be replaced by heat pumps are set as the maximum share.

By combining such statistics with the electricity grid emission projection as illustrated in method section (Heat pump decarbonization potential assessment), the decarbonization potential of heat pump is projected as shown in Fig. 8. As shown in Fig. 10, with an increasing share of heat pumps in buildings' and industrial sectors, the maximum decarbonization potential would reach ~2232 Mton, with GHG emission offset potential reaching ~1532 Mton and ~670 Mton for buildings and industry heating respectively (The industrial energy consumption is predicted to be less than buildings' energy consumption in 2060, and thus results in a less GHG emission reduction in 2060 for industrial sector). The overall mitigation potential is more than 20% of China's current CO_2 emission. Yet the current heat pumps' market share is around 5% for buildings sector [6] and even lower in industrial sector.

4.3 Economic evaluation

The economic factors have a more significant effect on the users' willingness-to-pay for the heating facilities [59, 61, 62], especially with poor economic conditions and cold climate conditions [63]. Herein, two typical

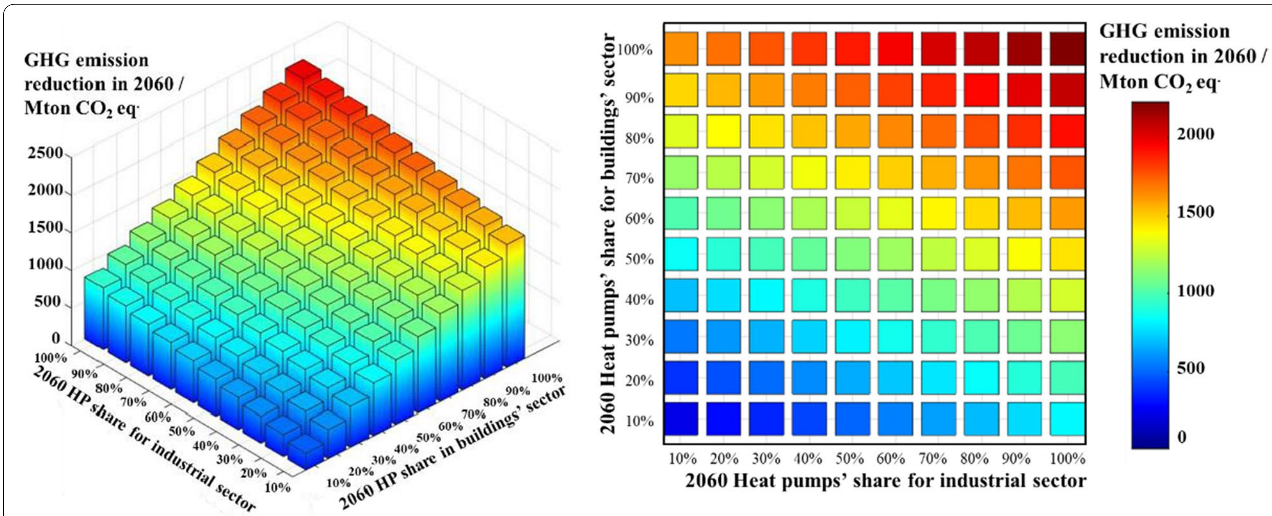


Fig. 10 Decarbonization potential of heat pump in 2060 with increasing share for industrial and buildings' sector

scenarios are set for buildings' sector and industrial sector. In order to benchmark such economic comparison, the Levelized Cost of Heating (LCOH) has been proposed as a useful indicator; In such context, an economic comparison between heat-pump-based heating and other typical heating modes (using natural gas and electrical resistance as proxy) as shown in Fig. 11.

For buildings' heating, herein a 20 kW heater is taken as a typical product. The LCOH presented in Fig. 11 a with ambient air as the heat source, and calculation is based on 15-year lifetime and 4000-hour annual operating time. The results show that the average LCOH of heat-pump-based-heating is around CNY 0.392·kWh^{-1}, whereas LCOH of natural-gas-based-heating is around CNY 0.396·kWh^{-1}, which shows the heat pump for residential heating has an overall economic advantage over natural gas in 20 provinces of China, and the rest provinces are mainly located in northeastern with relatively cheaper access to natural gas. Compared to electrical resistance heating, the LCOH values of heat pump are always lower as shown in Fig. 11 b.

For industrial heating, herein a 0.5ton·h^{-1} steam boiler(~ 350 kW) is taken as a typical product. The LCOH value is calculated on the basis of 15-year lifetime and 6000-hour annual operating time. The results in Fig. 11 c show that the LCOH of heat pump is lower than that of natural gas heating in 26 provinces of China, most of which are located in the country's southeastern region with relatively higher natural gas price and meanwhile with good industrial base. Compared to electrical resistance heating, the LCOH values of heat pump are always lower as shown in Fig. 11 d.

To summarize, heat pumps have obvious economic advantages when compared to electrical resistance heating due to higher efficiency, while heat pumps could be economic comparable to natural gas in most cases. For buildings' heating, heat pump has obtained overwhelming advantage over natural gas in most region of China. For industrial heating with relatively higher heating temperature and lower efficiency, the predominance area of heat pump is concentrated in the southeast region of China, which accounts for more than 70% of China's total industrial revenue.

5 Discussion and future prospects

Given the above discussions, it is generally defensible that heat pump would be a cleaner and cheaper heating solution compared to fossil fuel and electrical resistance

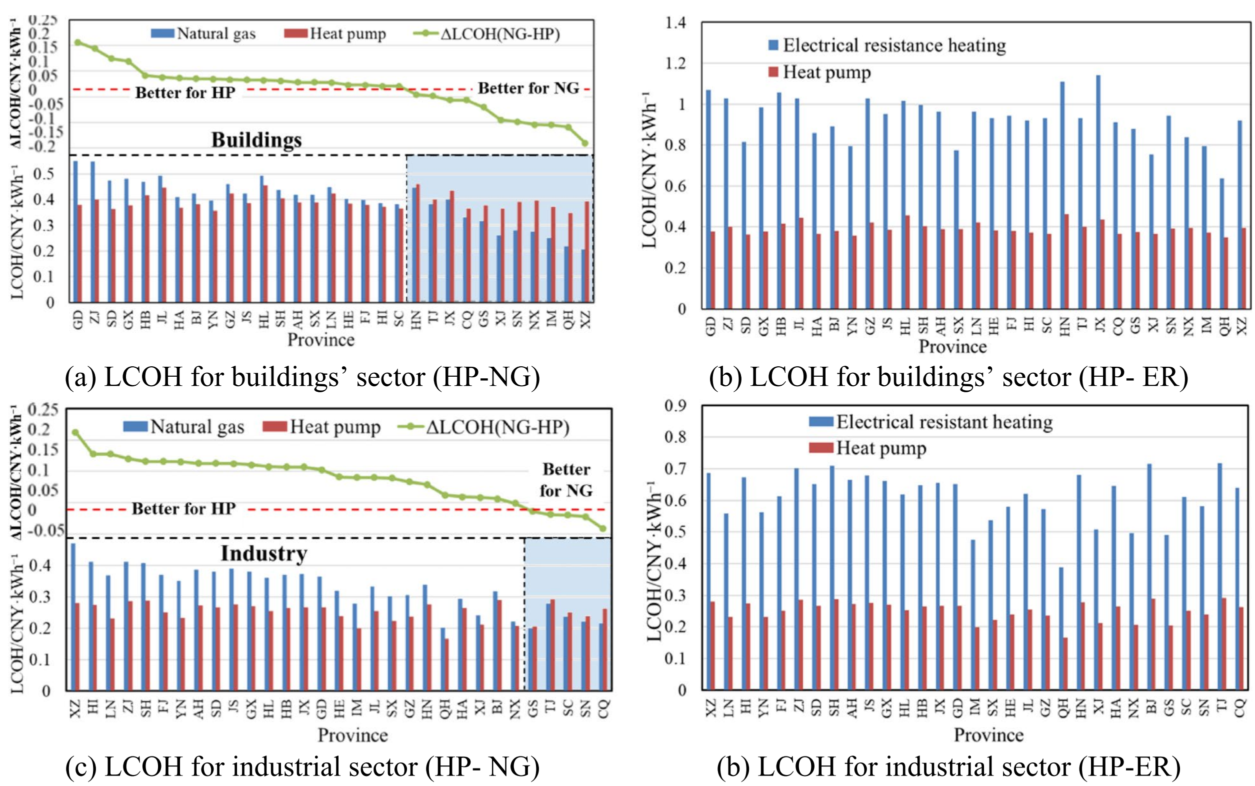


Fig. 11 Techno-economics comparison between heat pump (HP), electrical resistance heating (ER) and natural gas heating (NG) among different provinces in China's Mainland based on the current situation. **a** LCOH for buildings' sector (HP-NG). **b** LCOH for buildings' sector (HP- ER). **c** LCOH for industrial sector (HP- NG). **d** LCOH for industrial sector (HP-ER)

heating in a carbon constrained and renewable power dominated future. Based on the LCOH results from Fig. 12, switching fossil fuel heating to heat pump is already cost-effective in many regions and applications in China. The long-term benefits of electrification would be further amplified with improving heat pump energy performance and decreasing cost. Yet the bottlenecks restricting heat pump penetration in China should not be neglected: heat pump usually has a higher initial capital cost compared to fossil fuel counterpart and an average payback period over 5 years [62], which will bring uncertainty to both investors and customers. Residential heat pump in severe cold region such as northeastern China still has low energy efficiency, and the industrial heat pump with high-temperature heat supply is usually based on waste heat, making it inapproachable for distributed heating. The information conveyed by such analysis is clear: although coal-to-gas provide instant emission reduction, it will unnecessarily bring additional carbon lock-in through investing on new gas facilities, thus becoming obstacles for heat pump rollout in the future. In other words, there is little rationale to invest on new gas heating facilities in the China's carbon neutral transition pathway. The path lock-in effect from existing fossil fuel heating stakeholders, together with the relatively unfamiliarity of heat pump compared to existing fossil fuel facilities, should be considered in such transition as well.

Therefore, as suggested previously [5], a heat pump technology development roadmap to overcome such challenges is proposed in the study. As shown in Fig. 12, taking different regional features into considerations (including climate conditions, social and economic development, energy price etc.), in such technology roadmap, we consider the role of government, manufactures, users in promoting heat pump in near-term, middle-term and long-term. Hereafter, a detailed heat pump development roadmap highlighting the regional difference, policy approach, and scalability pathway in such a transition is suggested.

5.1 Regional difference

As a climate-sensitive technology, the energy performance of heat pump is location specific. For example, the south and southeast regions is with good industrial base, relatively warmer climate condition and relatively higher natural gas price. Such conditions would be better for heat pump-based heating, especially for some pilot heat pump projects such as air-source heat pump boilers [13].

Target Region (Province)		Eastern ,Southern, Southwest region (Yunnan, Guangdong)	Central, Northern region (Hebei, Hubei)	Northeast, Northwest region (Heilongjiang, Jilin, Xinjiang)
Feature	Weather	Mild zone Hot summer warm winter	Hot summer warm winter Hot summer cold winter	Cold and severe climate
	Energy price	High natural gas price Low electricity price	Middle natural gas price Middle electricity price	Low natural gas price High electricity price
	Industry	Industry cluster	Heavy industry	Light industry Dispersed-industry
	Population	Densely populated	Densely populated	Sparsely populated
Product	Building	Spilt air-source heat pump	Large-scale heat pump	Geothermal heat pump
	Industry	Waste-heat heat pump Air source heat pump	Waste-heat heat pump	Waste-heat heat pump Geothermal heat pump

	Near term	Middle term	Long term
Government	➢Restricting fossil-fuel heating expansion ➢Expand the public awareness of heat pump ➢Public funding for heat pump R&D	➢Subsiding heat pump installation ➢Focus on large temperature lift heat pump ➢Focus on low-GWP refrigerants	➢Gradually phasing out of subside ➢Focus on customer service business model ➢Focus on recycling of retired heat pump
Manufacture	➢Learning by doing through scale-up ➢Continuing compressor R&D ➢Temperature supply up t0 180°C	➢Focus on thermal comfort increase ➢Focus on novel thermodynamic cycle ➢Demand response potential from heat pump	➢Focus on small-scale heat pump ➢Temperature supply up to 200°C ➢Digital diagnosis and maintenance
End-user	➢Extensive rollout of air-source heat pump ➢Early demonstration of waste heat and geothermal heat pump in favorable condition	➢Large-scale rollout of geothermal heat pump ➢Integration with industrial parks ➢Low-GWP refrigerant replacement	➢Large temperature lift heat pump in cold ➢Comfortable and flexible heat pump ➢High market share of various types

Fig. 12 Technology roadmap for heat pump development in China 2060 carbon-neutrality. Shown in the box is a proposed technology roadmap for heat pump decarbonization. Government, Manufacturer, and users could work together to create a development roadmap for heat pump market penetration in near-term, middle-term, and long-term

Comparatively, increasing heat pump heating market share in north regions of China is more challenging: on one hand, there already exists fossil-fuel based central heating in many parts of north China, which creates barriers for heat pump penetration. In such cases, strategic use of existing fossil fuel heating capacity, together with heat pumps, as a so-called "dual-source system" could potentially create a win-win situation where heat pumps provide most of the heating energy demand with fossil fuel shaving the winter peak. With increase of heat pump efficiency and decrease of cost, heat pump will be more prepared to expand in north regions in China.

Participation of heat pumps in demand response programs harbors large potential on aiding variable renewable energy integration. Moreover, for newly added heating demand in both north and south regions of China, fossil fuel-based heating through furnaces and boilers, should be suspended in almost all situations. Such infrastructure will be obsolete in a carbon neutral world, and related investors will face stranded asset risk. Divestments of fossil fuel heating infrastructure must be part of the energy banking strategy in a carbon-constrained future.

5.2 Scalability pathway

After some initial experiences are accumulated through demonstration projects, both technology R&D and novel business model are further needed to facilitate large-scale application of heat pump technologies. In terms of technology R&D, the heat pump manufactures should focus on improving energy efficiency. Compressor is regarded as the heart of heat pump system, which also bears most of the energy loss. Currently, the adiabatic efficiency of compressors is less than 70%, whereas the adiabatic efficiency of permanent-magnet synchronous frequency-convertible centrifugal compressor could reach 75% ~ 88%. However, such high efficiency compressors mostly are applied in large-size unit, thus associated with high capital cost. Continuous R&D on small-size heat pump compressor is regarded as the first principle for improving heat pumps' energy efficiency.

For residential heat pump products, chasing better thermal comfort, especially in cold climate regions, is also very important. Measures including air distribution design and noise reduction in residential heat pump are important. For industrial heat pump products, chasing high temperature heat supply using low temperature heat source (e.g., the temperature difference between heat source and heat sink is more than 100 °C) through large temperature lift heat pump is a future direction. Such exploration has not been covered enough so far [13]. Expanding the working temperature of industry heat pumps (vapor compression heat pumps, absorption heat pumps, adsorption heat pumps, and chemical heat pumps) still needs extended R&D through both learning by research and learning by doing. Given the huge market potential brought by the elimination of coal-fired boilers, investment on such high temperature industrial heat pump should attract more attention from related companies.

Business models also play an indispensable role here. In terms of market regulation, novel business models should be explored from the perspectives of purchase, after-scale, recycle. In north China, utility companies could work on heat pump-based district heating. Such business models rely on big utility companies to supply heat as an energy commodity similar to electricity. It has been proven that heat pump-based heating could create even lower energy price than the conventional coal-based district heating if based on waste-heat recovery [34]. In such cases, heat purchase rather than heat pump purchase could be a suitable business mode [64]. For industrial heating, the success of waste heat-based heat pumps for industrial processes and steam generation on a large-scale, also proves the effectiveness of such a business modes, such pilot demonstrations for such possibilities should be designed and tested to kick off the scalability process. Moreover, the carbon tax/price will further strengthen economic advantages of heat pumps.

Customer experience is also an important dimension that should not be overlooked during the scalability pathway. Compared to traditional utility companies, which have established a quick and mature customer response system over years, the heat pump players have not found an integrated manner to provide same-level customer service. Such concerns become a social barrier for heat pump acceptance among potential users. Digitalization could be a powerful assistance in such cases, if remote intelligent diagnosis could solve most of the issues, customer service level could be largely improved with cheaper cost and quick response. Meanwhile, considering the market sharing proportion of heat pumps' further increases, reproduction and recovery on heat pumps should be considered, especially for the heat pumps' substitution caused by the high-GWP refrigerants elimination.

5.3 Policy approach

Policy design will also play important roles at various points along such a technology roadmap. Intensification of existing heat pump support policy, including but not limited to building energy performance regulation, heating emission standards, carbon taxation/financial incentive are needed to support the sustainable increase of heat pump sales and make heat pumps more competitive with their fossil fuel counterparts, eventually dominating the heating decarbonization market. Waste heat recovery heat pump for industry applications is truly worthy to be supported, thus that industry heat pump users can develop their own heat pump for specific heating application, which is more complicated than building heating and cooling. Regardless of technology advancement, public awareness of heat pump technology should be raised through active public education as well (the fact that heat pump could have COP over 100% still seems unreasonable for many policy makers who are not familiar with the technology in China). The experience from other sectors has also shown that technologies that are initially unfamiliar to the public can become mainstream options over time, if attention is paid to product standards, information dissemination and installer training. In short, design of heat pump support policy (in both residential and industry sector) should be integrated into China's carbon neutral legalization and carefully considered in the energy transition pathways.

Considering the three aforementioned aspects, a provincial heat pump development roadmap is proposed in the perspective (Fig. 12). In near-term, heat pump could accumulate development momentum from China's southern provinces. On one hand, ambient air temperature is one of the most important factors for air-source heat pump energy performance. Given the relatively higher ambient temperature, heat pump in the southern provinces tend to have higher COP and thus better economic competitiveness. Therefore, heat pumps in these provinces are more likely to be developed in larger scale in near term. Heat pump is essentially an electricity driven heating facility, thus its decarbonization potential is largely determined by the local power emission intensity. In China, lots of southern regions like Jiangxi, Hunan, Guangxi, Yunnan, are rich in hydropower, as a result, the CO_2 emission reduction potential from heat pump will be more obvious in those provinces. In middle term, heat pump could penetrate to mild climate provinces, like Hebei, Shanxi, Shandong, Shaanxi, and Hubei. The power generation mix in these provinces are more fossil fuel dominant at the current stage, so the heat pump decarbonization potential would be greater with progressive power sector decarbonization in these provinces. In long term, heat pump heating will be necessary in northeastern and northwestern provinces of China, like Xinjiang, Qinghai, Gansu, Ningxia. These provinces have abundant fossil fuel resources, thus natural gas price is relatively cheaper. The population density of these regions is smaller, and there is usually a lack of large industrial base. Therefore, it is more suitable for these regions to use natural gas in near-term at least, until in long-term heat pumps with both higher efficiency and lower cost are available.

Comparatively, in South China region with relatively higher ambient air temperature in winter (mainly over 0 °C), it is more suitable to develop distributed heat pump modes. For the northeast provinces, the main barriers come from the low ambient air temperature. Multi-stages heat pump cycle and geothermal heat pumps for residential heating might be a potential solution, yet such heat pump configuration will increase the complexity of system and undermine its reliability. Sequentially, large-scale heat pump application in such provinces needs further R&D and demonstrations.

Abbreviations
LCOH: Levelized Cost of Heating; *GHG*: Greenhouse Gas.

Greek symbol
η: Heating efficiency.

Subscripts
HP: heat pump; *NG*: natural gas; *ER*: electrical resistance.

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Authors' contributions
As the corresponding author, RZW proposed the concept and guided the whole research. HZY and CZ conducted the data analysis and drafted the manuscript, CZ suggested the decarbonization potential calculations, provided draft on energy structure, policy implement, and provided key data on the power sector and decarbonizations. BH and ZYX provided draft on compression heat pumps and absorption heat pumps respectively, ZS provided draft figures on heat pump technology roadmap. All authors contributed to the interpretation of the findings. The authors read and approved the final manuscript.

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Availability of data and materials
The availability of any original data is presented in Section 3 with detail methodology, while the detailed data in our database and we have the right to freely share or copy and redistribute the material in any medium or format.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
Ruzhu Wang is an editorial advisory board member for Carbon Neutrality and was not involved in the editorial review, or the decision to publish this article. All authors declare that there are no competing interests.

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