Estimating the potential for industrial waste heat reutilization in urban district energy systems: method development and implementation in two Chinese provinces

Kangkang Tong1, Andrew Fang1, Huajun Yu2, Yang Li2, Lei Shi1,4, Yangjun Wang3, Shuxiao Wang2 and Anu Ramaswami1,4

1 Humphrey School of Public Affairs, University of Minnesota, 301 19th Ave S, Minneapolis, MN 55404, United States of America
2 School of Environment, Tsinghua University, Beijing, 100084, People’s Republic of China
3 School of Environmental and Chemical Engineering, Shanghai University, Shanghai, 200444, People’s Republic of China
4 Both authors contributed equally to this work. Authors to whom any correspondence should be addressed.

E-mail: anu@umn.edu and slone@tsinghua.edu.cn

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Abstract
Utilizing low-grade waste heat from industries to heat and cool homes and businesses through fourth generation district energy systems (DES) is a novel strategy to reduce energy use. This paper develops a generalizable methodology to estimate the energy saving potential for heating/cooling in 20 cities in two Chinese provinces, representing cold winter and hot summer regions respectively. We also conduct a life-cycle analysis of the new infrastructure required for energy exchange in DES. Results show that heating and cooling energy use reduction from this waste heat exchange strategy varies widely based on the mix of industrial, residential and commercial activities, and climate conditions in cities. Low-grade heat is found to be the dominant component of waste heat released by industries, which can be reused for both district heating and cooling in fourth generation DES, yielding energy use reductions from 12%–91% (average of 58%) for heating and 24%–100% (average of 73%) for cooling energy use in the different cities based on annual exchange potential. Incorporating seasonality and multiple energy exchange pathways resulted in energy savings reductions from 0%–87%. The life-cycle impact of added infrastructure was small (<3% for heating) and 1.9%–6.5% (cooling) of the carbon emissions from fuel use in current heating or cooling systems, indicating net carbon savings. This generalizable approach to delineate waste heat potential can help determine suitable cities for the widespread application of industrial waste heat re-utilization.

1. Introduction
Large-scale urbanization has occurred in East Asia in the past decades, dominated by countries such as China, wherein urbanization has been accompanied with industrialization and economic growth. Since 1980 China has added more than 500 million urban residents, with 100 million added in the last decade (The World Bank 2014), along with a doubling of employment in the manufacturing and services sectors. This trend is likely to occur in many other countries worldwide, where > 3 billion more people are expected to become urban residents by the year 2050 (United Nations 2014). Studies show that 60% of these future cities have not yet been built (UNEP 2013), thus offering opportunities to rethink urban infrastructure.

One opportunity provided by the twinning of urbanization and industrialization in new emerging cities is to take advantage of co-location of different sectors (homes, businesses and industries) when planning future urban infrastructure systems to reduce overall energy use. Currently, about 20%–50% of the primary energy input in the industrial sector is wasted as heat...
In addition to reutilizing industrial waste heat within industrial processes, as suggested in deep de-carbonization pathway analyses (Sachs et al 2014), district energy systems (DES) in cities offer another heat sink for industrial waste heat reutilization. Reutilizing industrial waste heat in DES is expected to reduce the energy used for space heating and cooling in residential and commercial sectors, which are responsible for 31% of final energy use globally (Lucon et al 2014), and on the order of 13% in China.

Reutilizing high- (>400°C) and medium-grade (100°C~400°C) industrial waste heat through combined-heat and power (CHP) in DES is a well-known concept, traditionally used in second generation DES systems in the form of hot steam with a temperature higher than 100°C. The technology further advanced to third generation DES systems (constructed after 1980) that use pressurized hot water below 100°C and reduced pipeline losses. In contrast, new fourth generation DES systems use low-temperature hot water (30°C~70°C) through pre-insulated twin pipes with lower flow rates due to increased integration between intelligent heating control systems and DES systems to reduce peak demand. Such low-temperature heating networks are effective in new and retrofitted buildings with annual heating loads less than 25 kWh m⁻² and 50–150 kWh m⁻², respectively, and provide the potential to utilize the low-grade heat, (Lund et al 2014).

The potential of this new technology (fourth generation DES) to utilize low-grade waste heat (<100°C) in DES has been demonstrated to be technically and economically feasible (Connolly et al 2014, Brückner et al 2014). European national studies indicate that 31% of total European building heating demand can be technically supplied by waste heat (Persson et al 2014). A few case studies in China also indicated the feasibility of industrial waste heat reutilization to support residential-commercial space heating needs (Fang et al 2013, Li et al 2016). Generalizable methods to estimate this potential in diverse cities can contribute to customizing this strategy in different cities. Further, while district heating systems (DHS) have been studied as applications for waste heat (Brückner et al 2015), a UNEP report indicated significant global demands for cooling in cities in warmer climates (UNEP 2015), indicating the importance of also including analysis of waste heat reuse pathways in district cooling system (DCS). Lastly, because additional new infrastructure is needed for waste heat exchange through shared district heating and district cooling systems (DHS and DCS, respectively), life cycle analysis is needed to understand the net energy savings from installing waste heat reutilization networks in future cities.

To address the above gaps, our paper contributes to developing a generalizable methodology that employs energy flow analysis and heat exchange estimations coupled with life-cycle analysis of new infrastructure investment, to develop a first-order estimate of the potential for reutilizing industrial waste heat in the residential-commercial sectors of cities. We develop the methodology using publicly available data, implemented in Chinese cities. The availability of waste heat and the demand for it can vary in different cities based on climate, the mixture of industries and residential/commercial buildings, the existing infrastructure providing heating/cooling, and the potential for building new infrastructure. Waste heat itself comes in many grades—including high- and medium-grade heat that has been used in steam and hot water systems. Thus, understating and mapping different grades of waste heat with different reuse applications is a key contribution to the methodology. We note that we do not address the detailed design of DES in individual cities, rather we develop a method to estimate potential in diverse Chinese cities using public data. Learning from the implementation in two Chinese provinces, we also delineate the public datasets that can enable the methodology to be replicated in cities in the US and India, to illustrate data diversity.

Re-utilizing industrial waste heat in DES is expected to be a viable proposition, because Chinese cities have high levels of industrial activity and highly densified urban centers (Schneider and Mertes 2014, Xiong et al 2015). Studies exploring the transmission of low-grade waste heat indicate feasibility at the fence line distances of <30 km from industry to residential areas (UNEP 2015), indicating the viability of heat exchange in Chinese cities. Further, industrial activities contribute about 70% energy use nationwide in China, while the energy used in the buildings of residential and commercial sector is a small proportion (about 13%) (IEA and BERC 2015, Fridleyn et al 2014). Thus, industrial waste heat can be a viable source for residential/commercial heating and cooling today and in the future as the demand for space conditioning in cities increases (Zhou 2011, Li 2008, Zhang et al 2010a, Zhou et al 2014).

Our study is also timely, because several interesting real world experiments are underway (IEA 2016), including upgrading DHS in northern Chinese cities covering about 70% of urban residents (Oddgaard 2015, Xiong et al 2015, Building Energy Conservation Research Center 2011) and exploring industrial waste heat reuse in a few case studies, such as in Chifeng and Qianxi (Fang et al 2013, Li et al 2016). The Chinese government has highlighted using industrial waste heat in the residential sector in the 13th five-year plan period (2016–2020) to further reduce energy use (IEA 2016).

Our paper contributes to a growing interest in this topic by moving beyond case studies of district heating in Chinese cities to develop a generalizable methodology that uses publicly available datasets for making a first-order estimate of energy saving potential that can arise from reutilizing industrial waste heat in DHS and DCS in different cities in two provinces representing hot and cold climate regions in China.
2. Methodology

The basic methodology involves modeling energy flow in cities using each city’s economic data, urban population data, housing area, and each city’s existing pillar industries (cement, power plant, and steel) and DES for the base year, followed by developing and applying energy cascading and exchange computation, and implementing life-cycle analysis of proposed waste reuse infrastructure. There are six key steps:

- Modeling the present (2010 in this paper) use of energy in industrial sectors of each city using public data.
- Characterizing the industrial waste heat generated, and assessing its grade.
- Assessing the current systems used for heating and cooling in cities—including quantifying areas of the city already served by DHS, and the fuel and technologies serving the remaining floor areas not currently on DHS.
- Characterizing the present-day (2010 in this paper) primary energy use for heating and cooling demand in residential and commercial buildings of cities.
- Matching the demand for heating and cooling with the supply of waste heat in the different cities. We note that we are not doing detailed DES design, but rather mapping potential industrial waste heat availability and demand to develop a first-order estimate of energy exchange potential and direct fuel savings.
- Estimating the carbon penalty of investing in additional industry waste heat–DES infrastructure, using life-cycle analysis.

Data needed for the six-step methodology for China are illustrated in table 1, and applied to cities in the provinces of Hebei and Fujian. The two provinces describe the cases of two different climate zones—Hebei for heating and Fujian for cooling, respectively. We use the word cities to refer to built-up urban areas in China, called city propers or urban administrative districts that have been studied as the city-unit of analysis in many prior studies of Chinese and global cities (Bettencourt et al. 2007, Ramaswami et al. 2017, Chen et al. 2013). Chinese provinces are generally fully subdivided geographically into Dijishi, which translates to prefecture-level ‘cities’, but does not exclusively represent urban areas. Within the prefecture-level cities, city propers (Shiqiu) are urban administrative districts, i.e. densely built-up urban areas with low agricultural activities, where DES is a practical option. Our study focuses on these city propers (Shiqiu) as representing the cities of China, similar to previous studies noted above (Bettencourt et al. 2007, Ramaswami et al. 2017, Chen et al. 2013). We study all the city propers in each province (11 in Hebei and 9 in Fujian)—with each representing a different balance of homes and businesses relative to industries. Basic socio-economic data of these city propers are presented in table SI-1, available at stacks.iop.org/ERL/12/125008/mmedia.

Current energy use in industrial sector: The energy use data for industrial sector of year 2010 are collected from three main sources. First, fuel use in large pillar industries (power generation, cement, and steel industries) within the city boundary was obtained from a geocoded database from Tsinghua University (Li et al. 2017, MEIC 2016) delineating each plant, fuel inputs and combustion technology. Primary energy input in thirteen additional industrial sectors was linearly downscaled from Tsinghua’s dataset developed at the provincial level (Li et al. 2017, MEIC 2016) to cities based on the employment of each industrial sector obtained from the China Industry Enterprise Database (National Bureau of Statistics 2010). See table 2 for the 16 sectors. The above 16 sectors cover about 59% of China’s national energy use and thus industry specific energy flows are estimated for a majority of the industries from either direct information about the location of the steel, cement, and power plants, or the energy inputs downscaled by labor employment data.

The energy use in the remaining industries is linearly downscaled based on two-digit industrial sectoral energy use at the provincial level from the China Energy Statistical Yearbook (National Bureau of Statistics 2011) based on the employment data of these sectors in each city from the China Industrial Enterprise Dataset (National Bureau of Statistics 2010). The primary energy is assumed to be used in boilers using coal, fuel oil, or gas fuel (table 2) of efficiency 80% (Bo et al. 2015). The effectiveness of the down-scaling is assessed by comparing down-scaled industrial electricity use in cities (derived by method noted here) versus at-scale industrial electricity use data for 280 Chinese cities reported by each of the cities in their handbooks. The $R^2$ is 80%, suggesting the downsampling approach is reasonable (Ramaswami et al. 2017, Tong et al. 2017).

2.1. Estimation of unutilized industrial waste heat

Industrial waste heat is estimated as a percentage of the primary fuel inputs to each industrial sector located in a city, based on the known characteristics of each industry as reported in more than 27 Chinese industry case studies (Cai et al. 2007, Chen 2006, Fan 2014, Feng and Gao 2015, Gong et al. 2014, Hu et al. 2011, Huang et al. 2011, Huang et al. 2013, Ji 2014, Li et al. 2011, Li et al. 2015, Niu 2011, Qi 2011, Song 2003, Sun et al. 2014, Sun et al. 2015, Tang and Liu 2010, Tang 2007, Tang and Gao 2010, Tian et al. 2014, Wang et al. 2007a, Wang et al. 2007b, Wu et al. 2007, Yin 2013, Yu et al. 2012, Zhang et al. 2010b, Zhang 2013, Zhang 2008 and Zhao 2000) collected by the authors and summarized in Ramaswami et al. (2017a) (see table SI-2). The recoverable industrial waste heat is further divided into three grades—high-grade heat ($>400^\circ$C), medium-grade heat ($100^\circ-400^\circ$C), and...
| City data for heat exchange computations | China | USA | India |
|------------------------------------------|-------|-----|-------|
| **Population, economic, environmental data** | | | |
| Population and households | Chinese census (Population Census Office 2012) | US Census [www.census.gov/data.html](http://www.census.gov/data.html) | Indian Census Data (Census of India 2011) |
| Economic activity and employment by detailed sector | Reported in each city’s statistical yearbook | Metropolitan GDP from Bureau of Economic Analysis [www.bea.gov/](http://www.bea.gov/) regional; County level sectoral detail frequently not disclosed to preserve privacy; Input–Output tables are available at the county level from IMPLAN [www.implan.com](http://www.implan.com) | |
| Floor area and building density | Floor area estimate from China Regional Economic Statistical Yearbook (DCSNBS 2011); building density can from China census (Population Census Office 2012), reported every five years | Annual Housing Survey [www.census.gov/programs-surveys/ahs.html](http://www.census.gov/programs-surveys/ahs.html); City Tax Assessor’s database provide detailed residential and commercial floor area | Housing Micro Data (Census of India 2002); Housing Condition Survey (NSS 2009), commercial floor areas not readily recorded. |
| Existing district energy system details | Chinese Urban Infrastructure Statistical Yearbook (Ministry of Housing and Urban-Rural Development of China 2011) | International District Energy Association [www.districtenergy.org](http://www.districtenergy.org)/; Department of Energy-CHP database [https://docicercauservices.com/chpdb/](https://docicercauservices.com/chpdb/) | No existing district energy in India |
| Heating/cooling degree days | Estimate from NOAA/ESRL/PSD data: [www.esrl.noaa.gov/psd](http://www.esrl.noaa.gov/psd) | NOAA-Climate Prediction Center; HUD-Heating degree database | Estimate from NOAA/ESRL/PSD data: [www.esrl.noaa.gov/psd](http://www.esrl.noaa.gov/psd) |
| **Energy use in industry sector to estimate waste heat supply** | | | |
| Pillar industries—power, steel, and cement | Tsinghua Dataset (Li et al 2017, MEIC 2016) | US-Energy Information Administration-860 database. US-Energy Information Administration Manufacturing Energy Consumption Survey data, [www.eia.gov/consumption/manufacturing/](http://www.eia.gov/consumption/manufacturing/) | Industry survey (Central Statistics Office (CSO) Industrial Statistics (IS) Wing 2012–2013) |
| Other industries energy intensity by employment | China Energy Statistical Yearbook (National Bureau of Statistics 2011); China Industrial Enterprise Database (National Bureau of Statistics 2010) | | |
| **Energy use in residential/commercial sector to estimate waste heat demand** | | | |
| Electricity and energy demand in homes | China City Statistical Yearbook (Department of Urban and Social Economic 2011–2012) | Residential Energy Consumption Survey (RECS) [www.eia.gov/](http://www.eia.gov/) or IMPLAN, or city specific utility data used in climate action planning for about 400 cities/counties at ICLEI web site [http://icleiusa.org](http://icleiusa.org)/ Commercial Buildings Energy Consumption Survey (CBECS) [www.eia.gov/](http://www.eia.gov/) | National Sample Survey household survey at district level, separated as urban and rural region (NSS 2011) |
| Electricity and energy demand in commercial sector | China City Statistical Yearbook (Department of Urban and Social Economic 2011–2012); Some cities report in their annual statistical yearbook | | Mainly estimated based on national or state-level data |

Low-grade heat ($<100 ^\circ C$)—based on the waste heat temperatures characteristics in different industries; this classification derives from similar work done in EU industries (Brückner et al 2015), and represents the first application of that method to China. Unutilized waste heat by different temperature grades ($j$) arising from different industries, $i$, is estimated as

$$\text{Waste Heat}_{i,j} = E_i \times P_l \times \text{Ratio}_{i,j} \times (1 - U_l) \quad (1)$$
Table 2. Energy input, $E_i$, of industrial sectors in year 2010 in cities located in two Chinese provinces.

| Industrial sectors | Primary energy input (1000 ton coal-equivalent (tce)) |
|--------------------|-----------------------------------------------------|
|                    | Total city propers in Hebei | Total city propers in Fujian |
| Total city propers in Hebei | 55 432 | 4666 |
| Total city propers in Fujian | 26 | 16 |
| Industrial energy use at the city level | | |
| Power plant | 3047 | 26 |
| Cement plant | 20 130 | 16 |
| Steel plant | 2520-Coking | 2177 | 47 |
| | 2511-Petroleum refinery | 396 | 315 |
| | 2614-Organic chemistry raw material manufacturing | 0 | 74 |
| | 2621-Nitrogen manufacturing | 1296 | 456 |
| | 2612-Inorganic alkali | 710 | 178 |
| | 2611-Inorganic acid manufacturing | 0 | 0 |
| | 3141-Plate glass manufacturing | 722 | 210 |
| | 3131-Brick manufacturing | 1743 | 694 |
| | 3122-Lime and gypsum manufacturing | 701 | 163 |
| | 3132-Construction ceramics manufacturing | 9 | 141 |
| | 3151-Sanitary ceramics manufacturing | 328 | 0 |
| | 3316-Aluminum casting | 0 | 0 |
| | 3131-Copper smelting | 10 | 6 |
| Remaining industries energy use | 2850 | 2320 |
| Coal-fired grate boiler | 352 | 287 |
| Coal-fired fluidized bed boiler | 184 | 511 |
| Oil-fired boiler | 3177 | 1258 |
| Gas-fired boiler | | |

a Four digits is from Chinese industrial category coding system (National Bureau of Statistics 2010).

b Remaining industries energy use is downscaled from National Statistical Yearbook (National Bureau of Statistics 2011) with employment data from China Industry Enterprise Dataset (National Bureau of Statistics 2010), the boiler types are estimated based on the provincial level data from Tsinghua Dataset (MEIC 2016).

where $i$ = each industry sector (16 sectors are included in this analysis, remaining are assumed to be industrial boilers) and $j$ = 1, 2, 3 for different grades of heat (high-, medium-, low-grade) categorized by their exhaust temperatures. $E_i$ is total direct primary energy input (in thermal processes) to each industry; $P_i$ is the waste heat generated in industry $i$ as a percentage of total direct primary energy input; Ratio$_{ij}$ is the proportion of the different grades of waste heat (j) expressed as a percentage of $P_i$. $U_j$ is the current utilization rate of waste heat recovery in the $i$th industrial sector—it represents the existing energy exchange already happening in industry sectors determined from the case studies (table 2).

2.2. Estimation of current primary energy use for heating and cooling demand in residential and commercial sectors

Heating and cooling demand per unit area of conditioned space varies in China by climate regions. We use Zhou et al.’s estimation of the end-use energy use intensity (EUI) as it is comprehensive and addresses rural, urban, residential and commercial space heating/cooling in different Chinese climate zones (Zhou et al 2014). The estimated EUI of residential and commercial heating is 68.8 and 37.9 kWh sq m$^{-1}$ respectively for urban areas in Hebei (Zhou et al 2014). This EUI for heating is within the range of actual primary energy use in Chinese cities of Hebei (reported as fuel use in Tsinghua University’s dataset) after application of relevant efficiency factors of the different fuel technologies supplying the demand (tables 3 and 4), indicating concordance between the EUI approach and direct primary energy accounts.

In the current heating system in Hebei cities, space heating can come from DHS that are presently operated either with CHP or centralized boilers in shared district heating, typically operating at 70% efficiency (provincial average, estimated through the China Energy Statistical Yearbook (National Bureau of Statistics 2011), see figure 1). Areas outside the DHS network use non-district heating equipment in individual households, such as small-scale boilers and stoves in households, usually using coal and fuel oil. The amount of these fuels in these household stoves and boilers is provided by Tsinghua University’s dataset (Li et al 2017, MEIC 2016) (table 3), directly representing primary energy use.

The primary energy use associated with DHS serving the residential/commercial sector depends upon the technology of the heating systems in place currently (and the transition we propose in this paper to use waste heat in DES). The general equation to compute primary energy use intensity per square meter for heating in DHS network is shown below, accounting for the line losses and boiler efficiency.
Table 3. Energy use per capita in different heating equipment in individual households (non-DHS)—average of Hebei, China.

| Non-DHS heating equipment (downscaled data from Tsinghua university dataset) | Primary energy use (kg coal-equivalent/urban resident) | Energy efficiency of equipment<sup>a</sup> |
|---|---|---|
| Coal stove | 109 | 40% |
| Briquette stove | 4 | |
| Gas heater | 31 | 80% |
| Biomass stove | 48 | 40% |

<sup>a</sup> Zhou et al (2014).

Table 4. Comparison of primary energy intensity (downscaled from provincial data) and theoretical energy use intensity in Chinese cities in Hebei and Fujian provinces.

| End use energy intensity (kWh sq m<sup>−1</sup>) from downscaled provincial data (Tsinghua) | End use energy intensity (kWh sq m<sup>−1</sup>)—theoretical (Zhou et al 2014) |
|---|---|
| Non-DHS residential heating (Hebei cities) | 50–91 | 68.8 |
| Residential cooling (Fujian cities) | 7.8–10.3 | 6.5 |
| Commercial cooling (Fujian cities) | 9–17 | 15.1 |

Note: Residential non-DHS boiler efficiency is assumed based upon a weighted average of boilers by fuel type of coal boilers (0.6), coal stove (0.4), and gas boilers (0.8) from (Zhou et al 2014).

Figure 1. Current heating system (a) and heat exchange of reutilizing recoverable industrial waste heat in DHS (b) and DCS (c).<sup>10</sup>EUI from (Zhou et al 2014).<sup>11</sup>Pipeline loss in current DHS from (Zhang et al 2013) and in the fourth generation DES from (Lund et al 2014).<sup>12</sup>Boiler efficiency and primary energy fuel structure of DHS from National Bureau of Statistics (2011).<sup>13</sup>Primary energy use in individual heating equipment from Tsinghua dataset.<sup>14</sup>25% of medium-grade heat are assumed to be recoverable in current district heating system (Bourne and Ahern 2016), 80% of low-grade waste heat will be used as the heat source for cooling or heating (Bourne and Ahern 2016).<sup>15</sup>Coefficient of performance (COP) of chiller to utilize waste heat with different temperature ranges from 0.6 to 1.2 (UNEP 2015, Lund 2015, Ryan 2004). In this study, it is assumed that COP of chillers for high- and medium- grade heat is 1.2 (Ryan 2004, Lund 2015) and for low-grade heat is 0.65 (UNEP 2015).

Heating Fuel Intensity <sub>l</sub><sup>_primary energy</sup> = \frac{(Enduse Energy Use Intensity)<sub>l</sub>}{(1−Pipeline Loss)×Boiler Efficiency} \tag{2}

Total primary fuel needs for heating demand in residential and commercial sector in a city are estimated by multiplying the intensity in equation (2) with the floor area covered by DHS in different sectors (\(l =\) residential or commercial). Fuel structure of the primary energy use in DHS in Hebei (see figure 1(a))
is reported in its provincial energy balance sheet from the China Energy Statistical Yearbook (National Bureau of Statistics 2011). The total floor area under DHS (including delineation of residential floor area) is reported in the China Urban Construction Statistical Yearbook (Ministry of Housing and Urban-Rural Development of People’s Republic of China 2011) for heating-dominated provinces like Hebei. The floor area of non-district heating residential users is computed by subtracting DHS-residential floor area from the total household floor area, which is based on the average per capita living space reported for each city in the China Regional Economic Statistical Yearbook (DCSNB2011) (average is about 30 sq m/person; see table SI-1) and the total urban population for each city from the sixth population census data (Population Census Office 2012). The commercial floor area in Chinese cities is not readily reported. According to the data reported from Shanghai Statistical Yearbook, the commercial area is about 30% of the household floor area in 2010 (Shanghai Statistical Bureau 2011). This ratio is applied to the urban residential area to estimate commercial floor area in each city.

Cooling demand in Fujian cities is currently supplied through individual air conditioner units, and there is no shared district infrastructure for cooling in these cities. Electricity used for residential cooling is reported in the Tsinghua database (Li et al 2017, MEIC 2016), which is linearly downscaled based on the urban population. Per square meter electricity use of this downscaled electricity use data is computed based on the residential floor area in cities and 80% of the penetration rate for air conditioners in the Chinese residential sector (Bin and Jun 2012). The resulting end-use energy intensity varies from 7.8–10.3 kWh sq m−1 and consistent with the theoretical estimate of 6.5 kWh sq m−1 in the residential sector from Zhou et al (2014) (see table 4). The electricity use for cooling in the commercial sector is calculated based on the total amount of electricity use in commercial sector downscaled from Tsinghua’s energy use dataset, assuming 30% of total electricity use in commercial buildings is used for cooling in the southern climate zone (Zhou et al 2014). All our estimations use the Tsinghua University dataset (Li et al 2017, MEIC 2016) in order to scale systematically from cities to provinces, and eventually to the national scale (Ramaswami et al 2017b).

2.3. Heat exchange estimate for reutilizing industrial waste heat in DHS and DCS

In Fujian and Hebei, we estimate the impacts on the current energy system (shown in figure 1(a)) of reusing industrial waste heat in DES configurations shown in figures 1(b) and (c). The total recoverable high-, medium-, or low-grade heat is calculated by applying the suitable recovery factor to the waste heat estimated in equation (1). Only 25% of medium-grade waste heat is assumed to be recoverable, based on limitations of fouling and corrosion with sulfur containing exhaust streams; 80% of low-grade heat is assumed to be recoverable with 100% heat exchange efficiency to DES. These parameters were determined from experts in the industry (Bourne and Ahern 2016). Because the majority of high-grade heat is valued by industry for further industrial re-use or for electricity generation, we only applied medium- and low-grade recoverable waste heat to DES, providing a conservative estimate of waste heat reuse potential. Additionally, the following assumptions also make our estimate conservative: first, we only consider densely built-up areas of cities (not all city households). For urban built-up areas of the city proper’s cover from 60% to 100% of the households (table SI-1). Furthermore, low-grade heat poses less of a safety concern and studies show that transmission of low grade waste heat is feasible at fence line distances up to 30 km (UNEP 2015). Considering the fact that the areas of the cities are less than 2827 sq km and industries are in clusters, it is highly possible to expand the DES in these cities. The waste heat re-utilization computations follow three steps for DHS:

1. Medium-grade waste heat is utilized in current DHS as a heat source to replace fuel used in current DHS boilers.

2. Medium-grade waste heat that remains after replacing boilers in current DHS is used in expanded fourth generation DHS that covers the homes and businesses not presently covered under DHS.

3. Low-grade waste heat is also applied in the expanded district heating system (fourth generation) covering buildings not in the current district heating network. The buildings in the new DHS are assumed to be modestly retrofitted to achieve EUI suited to the fourth generation DES (Lund et al 2014).

For the waste heat to district cooling pathway, we considered the potential to replace air conditioning through district cooling either by electric chillers or absorption chillers. Due to the higher amount of useful work available through absorption chillers (UNEP 2015, Lund 2015, Ryan 2004), we only evaluate utilizing medium and low-grade waste heat through absorption rather than electric (vapor-compression) chillers. Hybrid cooling-heating systems are beyond the scope of this paper.

In the first-order calculation, we matched the annual supply with annual demand based on respective grades of heat, i.e. only applying medium-grade heat to supply steam and hot water in the existing DHS and only applying low-grade heat to supply warm water in the advanced fourth generation DES. We refer to this as the two tier-annual approach as the two strategies are specific to the grades of heat that are used. We evaluate the seasonality scenario, where the waste heat generation is stable across the year, but demand only
occurs in four winter months and six summer months for heating and cooling respectively (two tier-seasonal). Multi-tier heat exchange pathways are also evaluated, where existing DHS could be upgraded to advanced fourth generation DES to utilize low- and medium-grade waste heat to supply warm water, where it is available while also incorporating seasonality (multi-tier-seasonal). The sensitivity to three different DES configurations is illustrated in individual cities as well as the provincial level savings (figure 5).

2.4. Estimating carbon mitigation potential of reutilizing industrial waste heat in district energy systems

Direct carbon mitigation from fuel use savings is calculated based on the types and the amount of fuel saved in transitioning to DHS and DCS shown in figures 1(a), (b) and (c); with the application of relevant emission factors of fuel combustion from IPCC (Gómez and Watterson 2006). For district cooling, CO₂ savings are estimated based on the amount of electricity reduced and a regional grid-specific CO₂ emission factor (Song et al 2013). The annual economic benefit from fuel savings is estimated based on the fuel cost in Chinese cities (table SI-3).

Embedded CO₂ of the additional DES infrastructure is estimated using economic input–output life cycle analysis based on the capital cost of additional infrastructure attributed to the sectors of: ‘Metal products’ (sectoral number 63) for pipes, ‘Pumps, valve, compressor, and similar machinery’ (sectoral number 67) for pump, chillers, and heat exchanger, and ‘Construction’ (sectoral number 95) for installation cost and multiplied by the carbon intensity per unit output in that sector (637 g CO₂/yuan, 461 g CO₂/yuan, and 576 g CO₂/yuan for sector 63, 67, 95 respectively) obtained from the Chinese Environmentally Extended Input–Output Database in the year 2007 (Liang et al 2016). The capital cost of additional infrastructure is estimated based on the cost of physical components and the scale of facilities in the additional district heating/cooling systems minus the cost of the current individual heating/cooling equipment—i.e. homes investing in their own stoves and air conditioners (table SI-3). The useful lifetime of DES is assumed to be 25 years, within the range of 15–30 years reported by other studies (Davies and Woods 2009, UNEP 2015).

3. Results

The recoverable waste heat in cities is found to be dominated by low-grade industrial waste heat, accounting for about 70%–100% of all industrial waste heat in these cities. The remaining is mostly medium-grade waste heat (figure 2). This low-grade heat, previously unutilized, can be captured and reutilized in advanced fourth generation DES. Cities with more power plants, steel, chemical, or oil refineries, have a larger proportion of high- and medium-grade heat available (e.g. Tangshan has one of the biggest steel plants in China, figure 2), that can be used in existing DHS.

Heating demand varies significantly across cities in Hebei, because of varying population, floor areas per resident, and the current district heating infrastructure in each city. We modelled heat demand computed as ‘after the boiler’ by applying line losses to EUI, representing current steam/hot water DHS and new fourth generation DHS operated on low-grade heat (See figure 1(b)), and matched this heating demand with the recoverable waste heat of different grades (See solid and hatched bars in figure 3(a)). Matching different grades of heat leads to a range of energy savings in different cities of Hebei, ranging from 12% to 91% of the energy used for heating (figure 3(b)). When there is excess waste heat available after both grades of heat are matched in terms of supply vs demand in
current and new DHS, as much as 91% of space heating energy use can be reduced as seen in Zhangjiakou. In Shijiazhuang, although the total amount of recoverable waste heat is more than total heating demand, the medium-grade waste heat supply does not match the corresponding demand of the existing DHS, and hence only 49% of space heating energy use is reduced. The carbon mitigation potential of DHS ranged from 12%–86% of carbon emissions from reductions in current energy use for heating in Hebei’s cities (figure 3(c)). These results illustrate the complexity and the importance of matching the supply-demand of waste heat reuse by grade, which is represented in the computation process. Reutilizing industrial waste heat in district cooling systems also demonstrated a significant potential for reduction in space cooling electricity use, ranging from 24%~100% for cities in Fujian province (figure 4(b)).

Generally, the embedded carbon emissions in additional infrastructure are very small compared to the carbon mitigation amount in both DHS and DCS (figure 3(c) and figure 4(c)). The embedded carbon emissions from additional infrastructure ranged from 0.3% to 3.2% (average is 0.9%), and from 1.9% to 6.5% (average is 4.7%) for heating and cooling respectively. Reutilizing medium- and low-grade waste heat mostly has less than a one-year payback period in DHS and two-year payback in DCS in terms of carbon savings, making it an attractive low-carbon infrastructure investment.

Sensitivity analysis indicates that energy saving amount in the two-tier seasonal scenario and multi-tier seasonal scenario reduced 19% and 7% respectively for cities in Hebei province compared with the energy saving amount of the two-tier scenario (table 6). Although carbon mitigation potential decreases...
Figure 4. (a) Matching the supply of different grades of waste heat (blue) in cooling demand (red) in cities located in Fujian. (b) Energy savings from utilizing industrial waste heat in DCS as the percentage of total cooling energy use in residential and commercial sectors in cities located in Fujian province. (c) Carbon reduction from fuel savings and embedded carbon emissions from additional infrastructure (life-cycle carbon penalty) as the percentage of total carbon emissions from current cooling energy use in these cities.

Figure 5. Sensitivity analysis comparing energy savings in scenarios of two tier-annual, two tier-seasonal, and multi-tier-seasonal in Hebei’s city proper and Fujian’s cities.
slightly in the two-tier seasonal scenario, developing multiple heat utilization pathways can increase the potential of heat exchange as shown in multi-tier seasonal scenario. Another example of multiple heat utilization pathways is the hybrid cooling-heating in cities, which is beyond the scope of this research. However, it is expected the mitigation potential would further increase in cities with hybrid district energy system. In general, seasonality and waste heat utilization pathways can both influence the carbon mitigation potential. And the impacts of these factors are captured through sensitivity analysis.

For a conservative estimate, we computed the economic payback period for the most conservative two-tier-seasonal scenario, which shows the least percentage reduction. And we found that the economic payback for utilizing industrial waste heat in DHS is between 0.9–7.7 years for cities in Hebei, with the average of 2.7 years (table 5). For DCS, the pay-back time is longer, because of higher cost in the distribution network. The payback time varies from 8.7–14.2 years, with the average of 11.1 years.

### 4. Discussion and conclusion

Reuse of industrial waste heat in urban built-up areas can be a key strategy for urban energy efficiency. While high-grade heat exchange across industries is a well-known strategy for deep decarbonization pathways, the potential for using medium- and low-grade heat to heat and cool buildings in dense urban areas offers an opportunity for energy efficiency improvement for deep decarbonization. This strategy has been shown to be feasible for case studies (Fang et al 2015, Li et al 2016). This research contributes by developing a generalizable methodology to delineate the waste heat re-utilization potential in diverse cities. Developing this generalizable methodology can help the widespread application of industrial waste heat re-utilization in cities across the world, identifying where the potential is high. This study shows that heating and cooling energy use reduction from this heat exchange strategy varies widely in Hebei and Fujian’s cities in three scenarios.

### Table 5. Economic analysis in two tier-seasonal of reutilizing industrial waste heat in DES in Hebei and Fujian.

| Cities need heating | Cost of equipment (million yuan) | Cost of installation (million yuan) | Total capital cost (million yuan) | Savings (million yuan) | Total savings (million yuan) | Static payback period (year) |
|---------------------|---------------------------------|-------------------------------------|----------------------------------|------------------------|-----------------------------|-----------------------------|
|                     | Absorption heat pump            | Heat exchanger                      | Pipes                            | Fuel                   | Individual heating equipment |                             |
|                     | Shijiazhuang                    | 274                                 | 60                               | 158                    | 258                         | 751                         | 548                          | 108                          | 656                          | 1.4                          |
|                     | Tangshan                        | 337                                 | 73                               | 308                    | 430                         | 1148                        | 1005                         | 107                          | 1112                         | 1.1                          |
|                     | Qinhuangdao                     | 74                                  | 16                               | 115                    | 142                         | 348                         | 202                          | 15                           | 217                          | 1.7                          |
|                     | Handan                          | 204                                 | 44                               | 378                    | 452                         | 1078                        | 358                          | 88                           | 446                          | 3.0                          |
|                     | Xingtai                         | 45                                  | 10                               | 75                     | 92                           | 222                         | 72                           | 43                           | 115                          | 3.0                          |
|                     | Baoding                         | 45                                  | 15                               | 75                     | 92                           | 222                         | 166                          | 46                           | 212                          | 1.3                          |
|                     | Zhangjiakou                     | 150                                 | 33                               | 60                     | 114                         | 357                         | 416                          | 37                           | 453                          | 0.9                          |
|                     | Chengde                         | 43                                  | 9                                | 107                    | 123                         | 282                         | 142                          | 14                           | 156                          | 2.0                          |
|                     | Cangzhou                        | 64                                  | 14                               | 145                    | 168                         | 391                         | 114                          | 30                           | 143                          | 3.4                          |
|                     | Langfang                        | 5                                   | 1                                | 36                     | 38                           | 80                          | 18                           | 3                            | 21                           | 4.6                          |
|                     | Hengshui                        | 59                                  | 13                               | 399                    | 419                         | 889                         | 114                          | 36                           | 150                          | 7.7                          |

| Cities need cooling | Cost of equipment (million yuan) | Cost of installation (million yuan) | Total capital cost (million yuan) | Savings (million yuan) | Total savings (million yuan) | Static payback period (year) |
|---------------------|---------------------------------|-------------------------------------|----------------------------------|------------------------|-----------------------------|-----------------------------|
|                     | Absorption chiller              | Items same as above                 | Individual AC                    | Items as above          |                             |                             |
|                     | Fuzhou                          | 67                                  | 4                               | 88                     | 239                         | 398                         | 40                           | 35                           | 74                           | 9.7                          |
|                     | Xiamen                          | 203                                 | 13                              | 267                    | 729                         | 1213                        | 117                          | 102                          | 219                          | 10.1                         |
|                     | Putian                          | 40                                  | 3                               | 52                     | 143                         | 237                         | 16                           | 20                           | 35                           | 14.2                         |
|                     | Sanming                         | 30                                  | 2                               | 33                     | 93                          | 158                         | 18                           | 9                            | 27                           | 8.8                          |
|                     | Quanzhou                        | 99                                  | 7                               | 131                    | 357                         | 594                         | 67                           | 36                           | 102                          | 8.7                          |
|                     | Zhangzhou                       | 27                                  | 2                               | 35                     | 96                          | 160                         | 14                           | 14                           | 28                           | 11.2                         |
|                     | Nanping                         | 16                                  | 1                               | 18                     | 51                          | 86                          | 6                            | 7                            | 13                           | 14.1                         |
|                     | Longyan                         | 48                                  | 3                               | 54                     | 150                         | 255                         | 26                           | 15                           | 41                           | 9.5                          |
|                     | Ningde                          | 5                                   | 0.3                             | 5                      | 15                          | 25                          | 2                            | 2                            | 4                            | 13.2                         |

### Table 6. Total energy saved from utilizing industrial waste heat in DES in Hebei and Fujian’s cities in three scenarios.

| Scenario                  | Total energy saved in Hebei’s city proper (kiloton coal-equivalent) | Total energy saved in Fujian’s city proper (kiloton coal-equivalent) | Difference from two tier-annual in Hebei’s city proper | Difference from two tier-annual in Fujian’s city proper |
|---------------------------|---------------------------------------------------------------------|---------------------------------------------------------------------|--------------------------------------------------------|--------------------------------------------------------|
| Two-tier-annual           | 3786.39                                                             | 227.60                                                               | –19%                                                   | –28%                                                   |
| Two-tier-seasonal         | 3050.66                                                             | 163.60                                                               | –7%                                                    | –28%                                                   |
| Multi-tier-seasonal       | 3502.85                                                             | 163.60                                                               | –7%                                                    | –28%                                                   |
utilization in real world cities. The key finding is that low-grade heat is a dominant contributor of waste heat available to Chinese cities. It provides a good opportunity for reuse in both DHS and DCS. The life-cycle impact of added infrastructure is on average 0.9% and 4.7% of annual carbon emissions from energy use for heating or cooling respectively.

In a companion article (Ramaswami et al 2017b), the methodology developed herein for DES is supplemented by waste heat and material exchange across industries through industrial symbiosis pathway analyses, and these strategies are applied across a large number of Chinese cities. The finding from this article was that scaling up of cross-sectoral heat exchange to all Chinese cities can contribute significantly to overall carbon mitigation in China (Ramaswami et al 2017b). Learning from applying the method in China, we have also identified datasets that can enable making similar estimations in countries with very different data availability, such as USA and India. Remarkably, in all three countries, data are available to make waste heat reuse estimations, with commercial floor area being one parameter with little detail in all three countries. Further, table 1 also suggests that more open reporting of employment and GDP at the city level can do much to facilitate this method.

The generalizable methodology is intentionally conservative to provide a first-order estimate of the potential to reuse waste heat of different grades in DES. The method incorporates several assumptions that limit the exchange potential. For example, on the demand side, we only consider densely built up areas of cities (not all city households). These urban built up areas for the 20 cities studied cover from 60% to 100% of the households (table SI-1). Second, we are conservative in waste heat availability for district energy—not including high-grade waste heat, which may be used in industry. The estimation also only includes 25% of medium-grade waste heat because of chemical corrosion from sulfur containing gases. Lastly, based on other studies that indicate low-grade waste heat can be safely and efficiently conveyed over fence line distances up to 30 km (UNEP 2015), we do not limit the spatial distribution of low-grade waste heat in cities as all city areas are smaller than this dimension and industries are in clusters within cities. These core assumptions underlie a methodology that provides a reasonable first-order estimation of waste heat exchange potential across large numbers of cities.

If an individual city seeks more detailed estimates, two uncertainties in the method can be addressed with further bottom up data. Specific detail from cities on the industries, fuels and combustion technologies used will provide more information on the supply side of waste heat. Likewise utility data on heating and cooling energy would provide data on seasonality of demand. And, spatial data can improve the cost estimates of the pipe networks. Such bottom up efforts are beyond the scope and purpose of this paper as it entails detailed urban infrastructure planning. The higher order data and methods presented here are intended for high level estimation of waste heat exchange potential across large numbers of cities.

This paper has focused on heating in northern cities and cooling in southern cities in China. More detailed information and data are needed to evaluate the potential savings from hybrid waste–energy DES systems that can do both heating and cooling. The life-cycle analysis indicates that both applications will result in net carbon savings. Further studies are also needed to understand the extent to which DES can contribute to deep decarbonization and resource efficiency when coupled with an increasingly decarbonized electricity grid. Methods, such as those developed in this paper, are the first step towards connecting the role of heating networks and electricity networks together when we envision urban energy futures and transitions.

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