Low-Carbon Cities: Accounting, Infrastructure Analysis, and Transitions

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Abstract

Cities and urban areas are likely to be the important foci for greenhouse gas (GHG) mitigation efforts at the global scale. The Intergovernmental Panel on Climate Change report pointed out that approximately 71% of global energy-related GHG are associated with urban areas, which house about 54% of world population. The proportion of anthropogenic GHG associated with urban areas and cities is expected to increase in the future, when urban areas are expected to accommodate approximately 66% of world population by 2050 as predicted by the United Nations. Infrastructure which includes the provisioning of energy, transportation, water, municipal waste management, and building material plays a big role in urban energy use and GHG emissions. Studies in my dissertation investigated low-carbon cities through an interdisciplinary focus on infrastructure systems. Four chapters in my dissertations have made contributions 1) to evaluate carbon impacts of urban infrastructure at the city level to provide customized mitigation actions and scaling-up cities' carbon impact aggregately to national level; 2) to identify a new and unique cross-sectoral infrastructure action and quantify its carbon mitigation potential; and 3) to investigate infrastructure operators' motivation for low-carbon transitions and the enabling factors for the transitions from co-evolutionary perspectives. Details of each study are presented below.

Quantify carbon impacts of urban infrastructure at the city level to provide customized mitigation actions (Chapter 2): With massive urbanization and infrastructure investments occurring in China, understanding GHG emissions from infrastructure use in small and large Chinese cities with different administrative levels is important for building future low-carbon cities. This paper identifies diverse data sources to assess greenhouse gas (GHG) emissions based on the community-wide infrastructure footprints (*CIF*) method in four Chinese cities of varying population (1 to 20 million people) and administrative levels: Yixing, Qinhuangdao, Xiamen and Beijing. *CIF* quantifies GHGs associated with seven infrastructure sectors providing energy (fuels/coal), electricity, water supply and wastewater treatment, transportation, municipal waste management, construction materials, and food to support urban activities. Industrial energy use dominates the infrastructure CIF^{GHG} in all four cities, ranging from 76% of total *CIF* in Yixing to 30% in Beijing, followed by residential energy use (6-13%), transportation (4-12%), commercial energy use (2-25%), food (6-11%), cement use (3-8%) and water (about 1%), thereby identifying priorities for low-carbon infrastructure development. Transboundary footprint contributions ranged from 31% (Beijing) to 8% (Qinhuangdao), indicating that infrastructure supply chains of cities are important. GHGs from energy use are dominated by electricity (35-45%) and non-electricity coal

use (30-50%). The authors demonstrated that disaggregated infrastructure use-efficiency metrics in each infrastructure sector provide useful baseline performance data for comparing different cities.

Database development for scaling-up all cities' carbon impact aggregately to the national level in China (Chapter 3): Many studies have quantified carbon emissions from a few cities in a nation, while few studies have estimated emissions from all cities in a nation to assess their collective contributions towards national total. This paper, focusing on Chinese cities, assesses the collective contribution of all cities to national carbon emissions, the share of carbon emissions by city types, and carbon emission per capita and per GDP. This paper describes the Chinese City Industrial-Infrastructure database including fuel/electricity use and heat supply in 644 cities, in which energy use is aligned with national data with ~1% difference. It is found that direct carbon emissions from 644 Chinese cities collectively contribute to 62.4% of the national CO_2 emissions. Further categorizing these cities based on population size, economic structure, and administrative level, it is found that Midsize cities (0.5-3 million) accounted for 38.1% of national CO_2 emissions; Mixed-Economy cities contributed to about 40% of the national CO_2 emissions; and city propers (all urban administrative districts in a city) collectively contribute to 42.9% of the national CO_2 emissions. Direct emissions per capita ranged from 0.94 to 83.3 tonnes CO_2 per person (8.85 tonnes/person on average). Direct emissions per GDP ranged from 0.01 to 2.60 kg CO_2 per yuan-GDP (0.26 kg CO_2/yuan-GDP on average). Direct plus embedded emissions in electricity were also evaluated and found to have similar patterns as direct carbon emissions. These results enhance our understanding of the share of carbon emissions from Chinese cities and suggest the importance of focusing on certain city types for mitigation efforts.

Identify a new and unique cross-sectoral infrastructure action and quantify its carbon mitigation potential in Chinese cities (Chapter 4): Utilizing low-grade waste heat from industries to heat and cool homes and businesses through the 4th 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 the 4th generation DES, yielding energy use reductions from 12% to 91% (average of 58%) for heating and 12% to 100% (average of 73%) for cooling energy use in

different cities based on annual exchange potential. Incorporating seasonality and multiple energy exchange pathways resulted in energy savings reductions from 0 to 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.

Investigate DES operators' motivation for low-carbon transitions and the enabling factors for the transitions in the U.S. (Chapter 5): Advanced district energy systems (DES) using low-temperature heat, as one of the community-wide energy infrastructures, can contribute to cities' sustainability through reducing carbon emissions from heating and cooling services. However, the majority of current community-wide DES in the U.S. is not the advanced systems and need to be upgraded. This research, focusing on DES operators as the front-runners in infrastructure transitions, investigated their understanding of sustainable transitions of DES in the near future, as well as motivations and enablers for these transitions. Interviews were conducted to investigate how the business strategies of DES operators interact with factors related to ecosystem, technology, institutions, and users to influence the transitions. We conducted semi-structured interviews with fourteen DES professionals working in private companies, universities, cities, and the DES industrial associations. Interview data were analyzed in NVivo software applying the grounded-theoretical approach. Results indicate that community-wide DES in the U.S. is slowly moving from current steam-based second generation toward the fourth generation DES. Some universities, hospitals, and cities are leading this transition as units that demand sustainable and reliable energy systems. This transition in the U.S. is market driven, meaning that DES operators are motivated by the customers' demand to take transitioning actions. However, the wide-spread transition is slow in the U.S., according to interviewees, because a) fossil fuel is cheap; b) electric utilities are competitors although they could also offer DES services in their business model; and c) energy policies and incentives do not systematically consider heating service. Most DES customer's and policymakers' lack of understanding about energy choices is indicated by interviewees to be a major barrier for changing status quo. Effective Strategies identified by DES operators to overcome these challenges include work closely with users and policymakers, such as by identifying a local champion, continuously engaging with customers to explain emerging opportunities in the field, tapping technical expertise to understand the emerging technological opportunities. Future work comparing successful and shrinking DES can further shed light on the enabling factors/barriers.

In sum, I implemented multiple research methods in my dissertation to explore carbon emissions associated with cities at multi-scales, identify and quantify new cross-sectoral carbon mitigation strategies, and infrastructure operators in low-carbon urban infrastructure transitions. Studies in my dissertation chapters focused on both physical and social subsystems in cities to explore how cities with diverse activities can provide new opportunities for carbon mitigation beyond national policies through the advanced low-carbon urban infrastructure. Due to the complexity of urban infrastructure, the investigation of community-wide DES in the U.S. revealed that the challenges of changing existing infrastructure to the advanced ones are more related to users and institutional factors. Studies in my dissertation demonstrated that working under an integrated interdisciplinary framework can address key questions at both physical and social sides to investigate low-carbon urban transitions.

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Chapter 1. Introduction

Cities and urban areas are likely to be the important foci for greenhouse gas (GHG) mitigation efforts at the global scale. Reports released by the Intergovernmental Panel on Climate Change (IPCC) and other international organizations pointed out that approximately 71% of global energy-related GHG are associated with urban areas (Seto et al., 2014, UN-Habitat, 2011, UNEP, 2013), which house about 54% of world population (United Nations, 2014). The proportion of anthropogenic GHG associated with urban areas and cities is expected to increase in the future, when urban areas are projected to accommodate approximately 66% of world population by 2050 (United Nations, 2014). In practice, many cities and urban areas have recognized their significant carbon impacts and have actively committed to carbon mitigation (Bloomberg Philanthropies, 2017, Chan et al., 2015). For example, mitigation actions committed by 228 global cities aiming for 10~50% carbon reduction based on each city's 2010 emissions are estimated to reduce cumulatively 2.8 gigaton greenhouse gases by 2020 (C40 Cities Climate Leadership and Arup, 2014). If more cities aim for low-carbon development, their collective carbon mitigation can further contribute to global deep-decarbonization efforts. Examining cities' carbon mitigation potential is an urgent issue, especially when current national commitments are not aligned with the trajectories of GHG reduction to control global warming within 2°C by 2100 (UNEP, 2017).

Infrastructure systems are expected to be key contributors to GHG emissions associated with cities (Kennedy et al., 2014, Creutzig et al., 2016, Ramaswami et al., 2016). Key infrastructure systems (namely energy supply, transportation, municipal solid waste, building materials, and public space) and agri-food supply contribute to about 87% of global anthropogenic GHG emissions (Ramaswami, et al. 2016), of which a large amount is associated with cities. The 5th IPCC assessment report, for the first time in its history, emphasizes the impact of infrastructures on carbon emissions associated with cities and urban areas (Seto et al., 2014). The demand for services provided by urban infrastructure is expected to increase with the rapid urbanization in developing countries. Currently, approximately 25% to 40% of the population in developing countries live in slums without adequate basic infrastructure (UNEP, 2013). The ongoing urbanization will bring in another 2.5 billion population to urban areas (United Nations, 2014), of which approximately 60% have not been constructed yet (UNEP, 2013). At the same time, cities in developed countries need to upgrade their aging infrastructure to prevent failure (Herrmann, 2013). Infrastructure normally lasts for three to four decades once constructed. Thus, the demand for infrastructure upgrade in developed countries and urgent demand for new infrastructure in developing countries provided a great opportunity to set up infrastructure that can reduce carbon emissions long-term (Ramaswami et al., 2018b, Swilling et al., 2018). To seize this opportunity, infrastructure transitions to low-carbon development should happen now in both existing and emerging cities, as emphasized in the United Nation-Habitat report (Habitat, 2011) and in the latest IPCC Cities and Climate Change conference (Solecki et al., 2018, Ürge-Vorsatz et al., 2018). This transition process will be complicated, because the urban infrastructure is embedded in complex urban systems.

Studying infrastructure in the context of urban systems is complicated due to the multi-scale, multi-sector, and trans-boundary phenomena. A couple of theoretical frameworks of urban systems dissect the complexities of urban systems to guide studies and actions for infrastructure transitions contributing to low-carbon urban development. The first framework is a social-ecological-infrastructure system (SEIS) as demonstrated in Figure 1-1. SEIS framework emphasizes cities are embedded in cross-scale infrastructure systems (Ramaswami et al., 2016, Ramaswami et al., 2012b, Swilling et al., 2018), and the environmental impacts of urban activities are across cities' geospatial boundaries. For example, electricity used in households, businesses, and industrial sectors is supplied through a larger electric grid, which causes carbon emissions or other air pollutants outside of cities' boundaries. This is also what happened to transportation, water supply, wastewater treatment and other infrastructure systems. The trans-boundary environmental impacts of infrastructure use associated with urban activities also result in health impacts across the geospatial scale. Due to these multi-scale and trans-boundary features, social actors governing these infrastructure sectors also are cross-scale and cross-sectors. SEIS framework specified social actors into three groups: infrastructure users, infrastructure designers & operators, and policy actors as the key actors to influence actions associated with infrastructure (Ramaswami et al., 2012b). The SEIS, building upon the social-ecological system framework (Ostrom and Janssen, 2005), allows multiple theories to explore the relationships/interactions among these social actors and links their behavioral features with biophysical systems.

The second framework posited urban systems are social-ecological-technological systems (SETs) (Pickett et al., 2001, McPhearson et al., 2016, Bai et al., 2017). The SETs depicts that urban systems are comprised of three layers: ecological system, social/economic system, and physical built-up system (Bai et al., 2017, McPhearson et al., 2016). The SETs framework is built upon observations of urban ecology system and the recognition the complicated relationships between urban natural and social systems. The technological component in SETs framework has a strong emphasis on infrastructure systems, as the space to integrate technological development (McPhearson et al., 2016). Although with slightly different emphasis on urban systems, both frameworks aim to delineate multiple dimensions of the complexity of urban systems. Studies can focus on each dimension of urban system and draw the corresponding theories to investigate issues related to sustainable and/or low-carbon urban development.

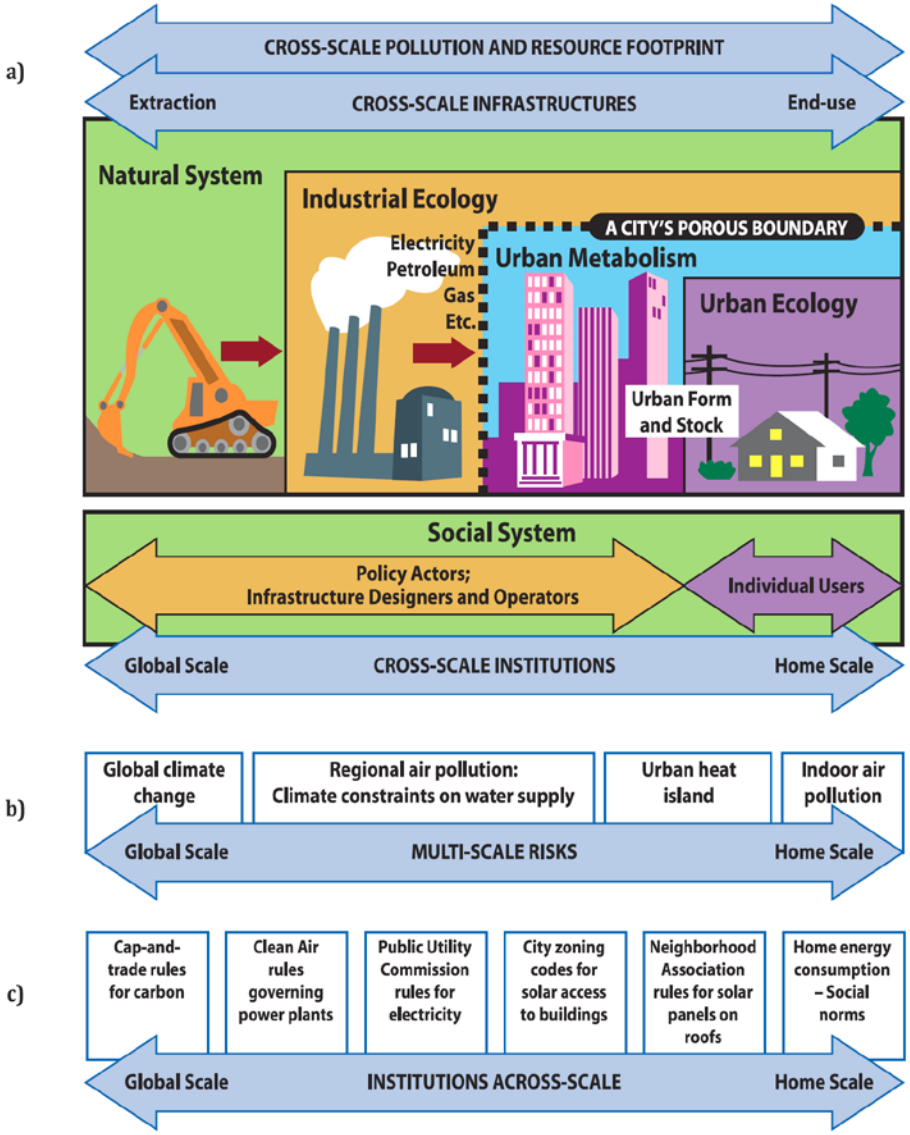

Figure 1-1. The social-ecological-infrastructural systems (SEIS) framework from (Ramaswami et al., 2012b)

Note of Figure 1-1: SEIS depicting: (a) integration across the spatial scale of infrastructures, urban metabolism, industrial ecology, and urban resource/pollution footprints with social actors and institutions; (b) multiple and multiscale risks posed to cities by infrastructure–environment interactions across scales; (c) select examples of institutions that shape energy use and greenhouse gas (GHG) emissions across scales. From (Ramaswami et al., 2012b)

Because SEIS framework focuses on infrastructure provisioning in cities, research in my dissertation adopted this framework to investigate low-carbon urban infrastructure transitions. According to the operational "map" of SEIS (Figure 1-2), three domains of studies are important for the integration of research regarding low-carbon urban development (Ramaswami et al., 2012b). First, we have to understand the current relationship between infrastructure provisioning and GHG emissions. Second, we can identify future sustainable strategies including assessment of their co-benefits and tradeoffs. Third, we need to investigate the motivations of actors within and across city boundaries and scales relating to adopting these strategies (Ramaswami et al., 2012b, Ramaswami et al., 2018a, Schultz et al., 2007, Sabatier, 1988, Feiock, 2007, Ostrom, 2015). Overall, studies in my dissertation from an interdisciplinary perspective address current challenges in each domain. Studies in my dissertation made the following contributions to each corresponding domain, which are:

1) to evaluate carbon impacts of urban infrastructure at the city level to provide customized mitigation actions and scaling-up cities' carbon impact aggregately to national level;
2) to identify a new and unique cross-sectoral infrastructure action and quantify its carbon mitigation potential; and
3) to investigate infrastructure operators' motivation for low-carbon transitions and the enabling factors for the transitions from co-evolutionary perspectives.

Through operationalizing SEIS framework, my dissertation overall demonstrates how to examine urban infrastructure transitions for low-carbon cities integrating changes in both physical and social systems.

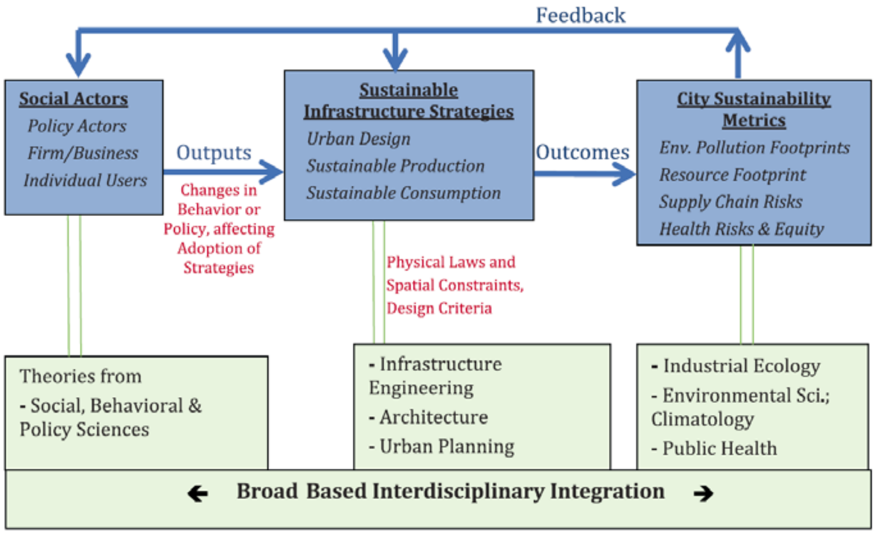

Figure 1-2. Roadmap of SEIS framework from (Ramaswami et al., 2012b)

My dissertation focuses on cities located in two nations that are the largest anthropogenic GHG emitters: China and the United States of America (U.S.). China has become the largest anthropogenic GHG emitter since 2005 (Friedlingstein et al., 2014). Furthermore, it is still experiencing rapid urbanization. Urban population in China has increased from 20% in 1978 to over 50% today (World Bank and DRCSC, 2014). In the next 20 years, Chinese urbanization rate is expected to be over 70%. The provision of basic infrastructure for accommodating the increasing urban population is expected to drive GHG emissions up. Developing low-carbon urbanization pathways effectively are critical for China's socio-economic-environmental development and expected to have a global impact on carbon mitigation. Studies from Chapter 2 to 4 focus on Chinese cities to examine carbon emissions from cities and reduce carbon emissions through reconfiguring urban infrastructure systems. The U.S. is the second largest carbon emitter and cities played a critical role in supporting carbon mitigation (Bloomberg Philanthropies, 2017). Limited studies investigated how cities can promote the low-carbon infrastructure transitions in the United States with the focus on infrastructure operators as the frontrunner of transitions. Chapter 5 focuses on community-wide district energy system in the U.S. to examine the infrastructure operators' motivation in changing the existing systems. The rational, challenges, and detailed contribution of these studies are briefly explained below.

Note that the main greenhouse gases include carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and fluorinated gases. Because carbon dioxide dominants the contribution to the greenhouse effect in these gases, the word "carbon" also refers to GHGs in general in the introduction chapter. For the other chapters in my dissertation, I specified the meaning of the word "carbon" and what greenhouse gases have been accounted for.

Carbon accounting of cities for customized city-level actions and aggregated impact in national total

Territorial-based method (often called production-based GHG accounting at the national scale), is the first method to quantify GHG emissions from various emission sources within cities' geospatial boundaries (Kennedy et al., 2009, Kennedy et al., 2010, Sugar et al., 2012). Aligning with the definition of "scope" posited by the World Resource Institute (World Resources Institute et al., 2014), pure territorial-based method accounts the community-wide scope 1 GHG emissions. Community-wide scope 2 GHG emissions are the amount of GHGs embedded in local electricity and heat services that are imported from outside of city's boundary. GHG emissions embedded in supply chains other than electricity and heating services to cities are referred to scope 3 emissions. The second method is consumption-based carbon footprinting, which estimates the embedded carbon emissions in local consumption activities in different economic sectors (household, government, or business capital formation) (Minx et al., 2013, Feng et al., 2014b, Jones and Kammen, 2011, Jones and Kammen, 2014), which is difficult to separate these emissions into scope 1, 2, or 3 to align with mitigation impacts of city-level actions. Furthermore, consumption-based carbon footprints have not considered the emission from business export (Chavez and Ramaswami, 2013). Given the fact that cities house both production and consumption activities, the community-wide infrastructure-based carbon footprinting (*CIF*), as the third method, has been developed to quantify carbon footprints of different infrastructure systems and food supply serving both production and consumption activities in cities (Ramaswami et al., 2008, Hillman and Ramaswami, 2010). This carbon footprinting method quantifies the life-cycle carbon footprints (both in-boundary emission and the embedded emissions from supply-chain) of key infrastructure providing critical services, *i.e.* energy supply, transportation, clean water, wastewater treatment, solid waste management, construction materials, and food supply (Ramaswami, 2013, Ramaswami and Chavez, 2013). *CIF* has been integrated into several international city-level carbon accounting guidance, such as BSI and ICLEI (BSI, 2013, ICLEI, 2012b). These accounting methods utilizing local data to inform customized mitigation strategies.

City carbon accounting should be able to scale up to the national or global emissions in a way that allows cities examine their mitigation impact of conducting customized actions. Many studies have focused on individual city-scale carbon accounting to inform potential customized mitigation actions. However, there have been limited efforts to provide the linkage for estimating carbon mitigation of city-level cations collectively at the national level. The monitoring of carbon emissions has been mainly at the national scale, while these national-level data has not specified the contributions from cities or urban areas in a nation, even for energy-related carbon emissions. Data from city case studies are not sufficient to scale up the carbon impact to the national level, due to the inconsistency of data sources and applied accounting methods. Previously, a few endeavors have been made to upscale cities' collective carbon impact at the national or global level with the focusing on mapping emission sources to urban areas (Marcotullio et al., 2012, Marcotullio et al., 2013). But these studies only downscaled scope 1 at the national level to urban areas, which is not as valuable to make the linkage for examining local actions and national mitigation, given the transboundary effect of urban activities. Furthermore, with all of these endeavors, our understanding of the collective carbon impact of cities is still with the medium agreement (Seto et al., 2014). To address the urgency of carbon mitigation of city-level actions and to achieve large-scale mitigation, it is important to develop robust methods that estimate the energy use and carbon emissions for all cities in a nation, consistent with national data.

The first contribution of my dissertation is to quantify carbon footprinting to customize city-level mitigation actions and to evaluate the collective carbon emissions from all cities in China. In Chapter 2, I implemented community-wide infrastructure-based carbon footprinting in cities with various sizes. Through comparing *CIF* across cities, this study contributes to the empirical understanding of city-level activities in Chinese cities for potential mitigation actions. These understandings can support developing new mitigation strategies as posited in Chapter 4. In Chapter 3, I demonstrate the development of a database covering energy use and electricity use/generations in all Chinese cities. The energy use data in this database is aligned with the national energy use data with high alignment. Carbon emissions from energy use are quantified across all cities and further analyzed by city typology. This study, for the first time, linked city-level carbon impact to the national levels considering carbon emissions from electricity import. Data developed in Chapter 3 is used in another interdisciplinary project to evaluate carbon mitigation strategies across all cities in China (Ramaswami et al., 2017b).

Identify and evaluate cross-sectoral urban industrial symbiosis strategies that are uniquely enabled by cities

We have little understanding of the unique role that cities can play in carbon mitigation. City-level carbon mitigation actions are embedded in larger infrastructure system and multi-level governance as shown in SEIS framework (Bulkeley and Kern, 2006, Bulkeley and Betsill, 2003, Ramaswami et al., 2012b, Nevens et al., 2013). City-level policies only have controls over certain infrastructure systems, and actions contributing to reducing carbon associated with cities most of the time are connected with the state and national policies. For example, U.S. cities have authority on building codes, policies of properties' energy use for sales and rent, and leverage as demanders for clean electricity (Ramaswami et al., 2012a). At the state level in the U.S., the public utility commissions have the authority to set up renewable energy goals, which can contribute significantly to carbon mitigation of cities. How much cities can do to reduce carbon emissions associated with them differs in different countries globally, due to the difference of political structure and institutions. However, it is certain that cities cannot act alone for reducing carbon emissions associated with their activities. At the same time, what cities can uniquely contribute to carbon mitigation that the other level cannot do is a question that we have and have not had sufficient understanding. To answer this question, we have to link city-level mitigation actions with what the policies are at the state and national level.

One critical action that cities can do is the integrated urban planning to arrange land use, infrastructure networks, and urban form in a way that contributes to long-term carbon mitigation (Kim, 2018). Several studies have examined the relationship between urban form and cities' carbon emissions (Makido et al., 2012, Fang et al., 2015a, Kennedy et al., 2015a, Creutzig et al., 2015). The smart growth policies, such as compact and transit-oriented planning, are found to yield carbon mitigation potential (Brown and Southworth, 2008, Barbour and Deakin, 2012, Stone et al., 2009). In addition to the urban form and land use changes, cities are a space for various urban activities, *e.g.*, industrial production, household consumption, and commercial activities. Introducing the concept of industrial symbiosis (Chertow, 2000) into the urban context, cross-sectoral urban industrial symbiosis strategies can be enabled by the colocation feature of cities. These strategies are practical actions for promoting urban circular economy (Ramaswami et al., 2017b).

The high impact cross-sectoral opportunities have to be recognized in cities' integrated planning and quantifying the carbon mitigation potential of these opportunities helps to understand the impact. Many mitigation actions treat urban activities in a segmented way (Romero-Lankao et al., 2014). In practices, carbon mitigation actions are adopted within each infrastructure sector, such as improving energy use efficiency in buildings, promoting low-carbon transportation, renewable integration, and actions in other infrastructure sectors (*i.e.*, solid wastes management, water sector) (Johnson et al., 2014). These carbon mitigation actions in cities are mainly discussed within each infrastructure system and not consider the co-location of various activities in cities. One feature of infrastructure systems is that it can connect different activities in various sectors at the same time (Prud'Homme, 2004, Ramaswami et al., 2015, Ramaswami et al., 2012b). However, we have not fully understood how cities can take the advantage of infrastructure for cross-sectoral urban industrial symbiosis actions to reduce carbon emissions. Because infrastructure reconfiguration is important to support these strategies, the integrated urban planning should incorporate the high impact strategies. Identifying these strategies and quantified their carbon mitigation potential will provide data for cities to incorporate these new strategies.

The second contribution of my dissertation is to identify a new mitigation strategy enabled by infrastructure and quantified its carbon mitigation potential, which is detailed in Chapter 4. The new identified strategy is to utilize industrial waste heat in the advanced district energy systems for heating and cooling commercial and residential buildings in Chinese cities. Because of the geospatial co-location of both production (industrial production) and consumption activities (energy use in commercial and residential buildings) in cities, district energy system can link these activities to further reduce energy use at the city level. This strategy in Chinese cities has demonstrated that cities may contribute to deep-decarbonization beyond national posited actions. The method developed in this chapter is adopted in another project to evaluate the collective carbon mitigation contribution across all cities in China (Ramaswami et al., 2017b).

Infrastructure operators in low-carbon infrastructure transitions

Chapter 5 explore the role of infrastructure operators in the district energy system (DES) transitions. A recent UNEP report aims to promote the DES as low-carbon heating and cooling choices and this is a strategy can only be done in cities. My study in Chapter 4 also have examined the carbon mitigation of promoting advanced DES in cities. The transition of DES from the existing ones to the advanced ones will be a complicated process as described in literature on socio-technical system transitions. The transition of a socio-technical regime is shaped by the interactions among niche (a comparatively isolated and protected area for innovation), current sociotechnical regime, and landscape (Figure 1-3a) (Geels, 2002, Geels, 2011, Geels et al., 2017). The outcome of this dynamic process can be a new stabilized system, lock-in existing regime, backlash of a new force, and system breakdown (Figure 1-3b) (Kemp and Rotmans, 2005). The process of transitions is non-linear and is shaped by forces from both technology and key stakeholders in our society (Figure 1-3c).

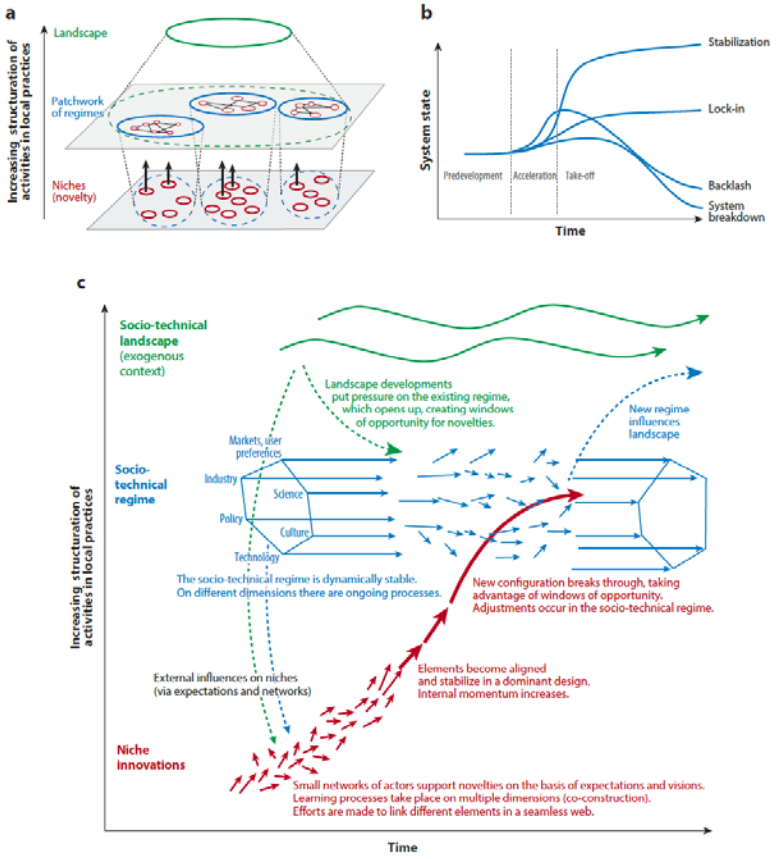

Figure 1-3. Diagrams illustrates the socio-technical system transitions from (Loorbach et al., 2017)

Note of Figure 1-3: (a) multilevel perspective model; (b) process of socio-technical regime change; and (c) the multi-phase concept illustrating the nonlinearity of transitions and different types of pathways. from (Loorbach et al., 2017)

Within these dynamic processes, different social actors play a significant role in adopting actions to shape the outcomes of a transition process (Foxon, 2011, Smith et al., 2005). The forces of changing socio-technical systems are driven by policymakers, civil society, and market players, as posited by Foxon et al (2011). Regarding infrastructure system, SEIS framework specified that users, infrastructure designers/operators, and policymakers determine the actions to change infrastructure systems associated with cities (Ramaswami, et al., 2012). The dynamics of transitions is shaped by how social actors interact with other subsystems, such as ecosystem, technology, and institutions as illustrated in Figure 1-4 (Foxon, 2011). The interactions are expected to influence social actors' motivation for taking transitioning actions. At the same time, enabling factors and barriers of taking actions lie in the interactions among these subsystems.

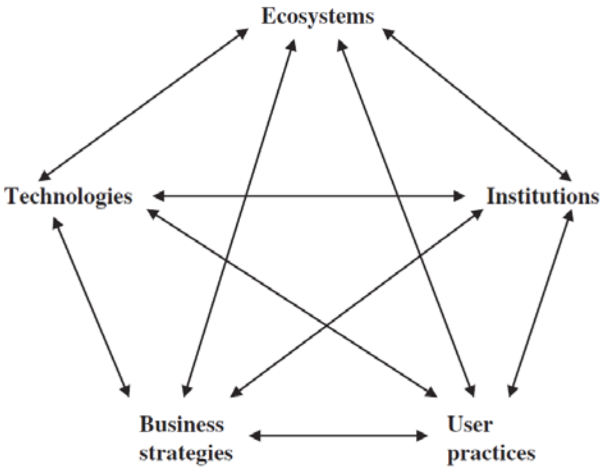

Figure 1-4. Co-evolutionary framework from (Foxon, 2011).

Empirical studies have examined user behavior changes (Schultz et al., 2007, Semenza et al., 2008, Baiocchi et al., 2010) and local public sectors (Feiock, 2007, Nevens et al., 2013), fewer studies have focused on infrastructure operators and/or owners in shaping the transitions (Ramaswami, et al., 2012). The infrastructure operators and/or owners can be either public sectors or private agencies. Infrastructure business, either the owners, operators, are the frontrunners in any infrastructure transitions. Their motivations for potential transitions have not been explicitly discussed in current transition literature. The transition process is coevolved with the interactions between infrastructure business agencies and other key subsystems. These co-evolutionary relationships are expected to delineate comprehensive pictures for potential future infrastructure transitions. Furthermore, more attention should focus on the US community-wide infrastructure to better facilitate low-carbon transitions at the local level.

The third contribution of my dissertation is to examine the infrastructure operators' motivations for taking actions for low-carbon transitions focusing on district energy system as one of the community-wide energy systems in Chapter 5. Due to no policies or laws directly promoting DES development in the U.S. at all, the transition pathways of DES in the near future has to be investigated by interviewing professionals. The motivation, enablers, and barriers of DES operators in taking transitioning actions are examined in a co-evolutionary framework with the emphasis on the interactions between business strategies and the other four subsystems (*i.e.*, users, technology, institutions, and ecosystems). The investigation on DES operators' motivation of taking action to facilitate transitions, as well as enabling factors, is expected to provide empirical evidence on what changes are needed in the society for future transitions.

Overall, I implemented multiple research methods in my dissertation to explore carbon emissions associated with cities at multi-scales, identify and quantify carbon mitigation from a new cross-sectoral strategy enabled by the advanced urban infrastructure, and investigate low-carbon urban infrastructure transitions from the perspective of infrastructure operators. These studies demonstrated a way to integrate both physical and social systems associated with urban infrastructure to guide low-carbon transitions in cities. Guided by SEIS frameworks and theories within different disciplines associated with cities, my dissertation takes an interdisciplinary perspective illustrating one way to bridge the physical environmental modeling techniques and sociotechnical system transitions for future change. This bridging is challenging due to different paradigms of conducting environmental science and social science research (Geels et al., 2016, Turnheim et al., 2015). I have demonstrated one way of doing this through operationalizing SEIS framework and focusing on research questions in different domains posited in this framework. This is the overall contribution of my dissertation to the emerging field of urban sustainability transitions. Practically, results from each study have policy implication, which is detailed in Chapter 6.

Chapter 2. Greenhouse Gas Emissions from Key Infrastructure Sectors in Large and Smaller Chinese cities: Method Development and Benchmarking

Abstract: With massive urbanization and infrastructure investments occurring in China, understanding GHG emissions from infrastructure use in small and large Chinese cities with different administrative levels is important for building future low-carbon cities. This paper identifies diverse data sources to assess greenhouse gas (GHG) emissions based on the community-wide infrastructure footprints (*CIF*) method in four Chinese cities of varying population (1 to 20 million people) and administrative levels: Yixing, Qinhuangdao, Xiamen and Beijing. *CIF* quantifies GHGs associated with seven infrastructure sectors providing energy (fuels/coal), electricity, water supply and wastewater treatment, transportation, municipal waste management, construction materials, and food to support urban activities. Industrial energy use dominates the infrastructure CIF^{GHG} in all four cities, ranging from 76% of total *CIF* in Yixing to 30% in Beijing, followed by residential energy use (6-13%), transportation (4-12%), commercial energy use (2-25%), food (6-11%), cement use (3-8%) and water (about 1%), thereby identifying priorities for low-carbon infrastructure development. Transboundary footprint contributions ranged from 31% (Beijing) to 8% (Qinhuangdao), indicating that infrastructure supply chains of cities are important. GHGs from energy use are dominated by electricity (35-45%) and non-electricity coal use (30-50%). The authors demonstrated that disaggregated infrastructure use-efficiency metrics in each infrastructure sector provide useful baseline performance data for comparing different cities.

2.1. Introduction

China is the top contributor of anthropogenic greenhouse gas (GHG) emissions in the world, with reported emissions of 10 gigatons CO_2 equivalents (CO_2 e) in 2013, followed by the United States, European Union, and India (Friedlingstein et al., 2014). Moreover, China is responsible for 57% of the total increase in global GHG emissions from 2012-2013 (Friedlingstein et al., 2014). Chinese cities play a large role in contributing to global GHG emissions, because 53% of China's population, approximately 719 million people are living in China's cities (United Nations, 2014, The World Bank, 2015). Future urban growth is expected to happen in midsized cities (1.5-5 million population) and small cities (500,000 to 1 million population) (United Nations, 2014). Quantifying GHG emissions associated with different sized Chinese cities is therefore essential to address the issue of anthropogenic GHG emissions in China.

Key infrastructure sectors that provide energy and fuel, water and wastewater treatment, transportation, municipal solid waste management, food, construction material (cement, iron, steel), and open spaces, are essential to support urban activities (Ramaswami and Chavez, 2013, Kennedy et al., 2014). Here, urban activities are referred to the use of these infrastructure sectors. These sectors have been shown as key contributors to the environmental impacts of cities, such as GHG emissions and water resource use (Kenny et al., 2009, Ramaswami et al., 2008, Chavez and Ramaswami, 2013, Kennedy et al., 2014, EPA, 2011). The Chinese government invests heavily in these urban infrastructure sectors to meet the demand for ongoing urbanization; with the total investment in urban infrastructures accounting for about 50% of total infrastructure investment in China in 2014 (Wilkins and Zurawski, 2014). Ongoing Chinese urbanization will continue to require urban infrastructure investment as a priority, which potentially will be responsible for large environmental impacts. To understand and plan for low carbon urbanization in China, it is important to understand the GHG emissions of the various infrastructure sectors associated with cities.

The most recent IPCC report emphasizes the impact of infrastructure on GHG emissions associated with cities (Seto et al., 2014). Previously, a method called community-wide infrastructure GHG footprint (*CIF*) has been developed to represent the life-cycle and trans-boundary impact of *infrastructure use* in cities (Ramaswami et al., 2008, Hillman and Ramaswami, 2010, Chavez and Ramaswami, 2013). This method recognizes that cities are served by infrastructures and their supply chain extending outside the city boundary (Ramaswami et al., 2008, Dhakal, 2009, Hillman and Ramaswami, 2010, Chavez et al., 2012, Chavez and Ramaswami, 2013, Kennedy et al., 2014). For example, in the U.S. electricity, freight, and food are often supplied from outside of city boundary traveling more than 200, 600, and 1500 miles respectively (Ramaswami et al., 2012b). Consequently, the *CIF* combines the material and energy flow associated with *infrastructure use* within the city boundary and with trans-boundary life-cycle assessment of *producing* the service. Overall, *CIF* serves two purposes: (a) In aggregation, *CIF* and the percentage of each infrastructure sector help to prioritize actions by sector; (b) disaggregated infrastructure use intensity metrics by sector help to track progress in efficiency. The benefits of *CIF* are that it informs urban planning by quantifying community-wide infrastructure use efficiency separated by various sectors (Hillman and Ramaswami, 2010, Chavez and Ramaswami, 2013, Ramaswami and Chavez, 2013), and offer diverse mitigation strategies by connecting the users with producers along the supply chain. In other words, it informs strategies that improve the efficiency of infrastructure use in the city to support cleaner production along the supply chain. The infrastructure efficiency metrics for each infrastructure sector can be particularly useful to compare across cities.

CIF has been applied to cities in the U.S. (Ramaswami et al., 2008, Hillman and Ramaswami, 2010) and has been adopted by the International Council for Local Environmental Initiatives (ICLEI) and British Standards Institution (BSI) as one approach for reporting community-wide GHG emissions (ICLEI, 2012a, BSI, 2012). Other approaches for GHG accounting, such as a purely consumption-based or a purely territorial source-based inventory, are also available in studies targeting Chinese cities (Kang et al., 2014, Geng et al., 2011, Chong et al., 2012, Zhang et al., 2012). *CIF* has a mathematical relationship with consumption-based carbon footprinting (*CBF*), which have been studied by scholars at different spatial levels (Guan et al., 2008; Hubacek et al., 2009; Minx et al., 2013; Ala-Mantila et al., 2014). This relationship between *CIF* and consumption-based carbon footprinting has been explicitly discussed in previous studies (Chavez and Ramaswami, 2013). To explicitly demonstrate the relationship between *CIF* and *CBF* at city level requires intensive data, such as infrastructure use and economic input-output data at the city scale, which is not available for Chinese cities. Thus, the emphasis of this paper is on *infrastructure use* and GHG footprinting by each infrastructure sector, not as much on aggregated city GHG accounting or comparing different methodologies of carbon accounting. *CIF* can be reviewed as complementary and overlapping the production and consumption footprints of cities (Chavez and Ramaswami, 2013; Lin et al., 2013). The differentiation of production and consumption perspective is more suited to address issues of carbon leakage.

While infrastructure focused GHG footprinting has been accomplished in one Chinese city (Lin et al., 2013), categorizing the *infrastructure use* efficiency and computing the *CIF* disaggregated by infrastructure-sectors has not yet been published for cities of different sizes and administrative levels in China. It is often assumed that data to compute a detailed *CIF* are unavailable in smaller cities and/or methods are not standardized for different city types, while it is urgent to understand data availability and the GHG emission patterns. Thus, the objectives of this research are 1) to explore the available data sets necessary to facilitate *CIF* in different-sized Chinese cities; 2) to develop standardized methodology to quantify *CIF* from cities of varying sizes; and 3) to compare the efficiency of infrastructure use, separated by the sectors (energy, transportation, *etc.*) in cities.

The four cities chosen in this paper vary by city population and administrative status, since the administrative status might influence data availability. Beijing is one of the biggest cities in China and is on the same administrative level as a province, having 19.6 million population in the year

2010 (Beijing Municipal Bureau of Statistics, 2011); Xiamen, a city with over 3.5 million population in 2010, is a sub-provincial level city, where administrative level is lower than a province but higher than a prefecture-level city (Xiamen Municipal Statistical Bureau, 2011); Qinhuangdao (QHD) is a prefecture-level city (with 3.0 million population in the year 2010) under the jurisdiction of Hebei province (Qinhuangdao Statistic Bureau and NBS Survey Office in Qinhuangdao, 2011); and Yixing is a county-level city with 1.1 million people in the year 2012 under the jurisdiction of Wuxi prefecture-level city (Wuxi Statistic Bureau and NBS Survey Office in Wuxi, 2013). We use comparative case study approach to explore the *CIF* features of these four different cities.

2.2. Methods and Data

2.2.1. Overview of CIF method

The equation to calculate GHG footprints of community-wide infrastructure use (*CIF*) in cities was:

$$\boldsymbol{CIF} = \sum_i \boldsymbol{MEFA\ use}_i * (\boldsymbol{EF}_{i,use}^{IB} + \boldsymbol{EF}_{i,production}^{IB+TB}) \qquad \text{(Equation 1),}$$

where *i* represents the *i*th infrastructure sector, such as electricity, non-electricity energy, transportation, water supply/wastewater treatment (WT/WWT), municipal solid waste (MSW), construction material, and food. This method has been implemented in eight U.S. cities and one Indian city in previous studies (Hillman and Ramaswami, 2010, Chavez et al., 2012). $MEFA\ use$ represents the material/energy flows associated with the use of the *i* th infrastructure sector. *EF* represents the GHG emission factor of producing the infrastructure service, which can be represented in two terms: $EF_{i,use}^{IB}$, the GHG emission factor for the use phase, occurring within the city boundary; and $EF_{i,production}^{IB+TB}$, the GHG emission intensity of producing the service including local production (IB) as well as the supply chain/life cycle GHG emissions occurring outside the city boundary (TB). $EF_{i,production}^{IB+TB}$ indicates that GHG from production can occur both in-boundary (IB) and trans-boundary (TB). For example, the $EF_{i,use}^{IB}$ for the use phase of electricity sector was zero, while the $EF_{i,production}^{IB+TB}$ included GHG from the local power plants to generate electricity (IB) and additional GHG from the power plants located outside the city (TB). Following the ICLEI methodology (ICLEI, 2012b), we traced the GHG emission factors of producing energy carriers up to the power plant for electricity. We also incorporated well-to-pump GHG emissions for petroleum refining of the petrol fuel used in the transportation sector (trans-boundary emissions); for food use, we included embodied agricultural and livestock GHG emissions (emissions from growing food or emissions from the fields) associated with producing that food use, which is the trans-boundary emissions associated with food sector for food produced outside of the city boundary. For cement use, we estimated the energy and calcining GHG emissions from producing that cement used locally.

For local production activity, such as an oil refinery or power plants and food/cement production located within a city, the trans-boundary contribution (TB) was computed as the amount of material/energy imported to support local infrastructure use beyond what was locally produced. For energy, the trans-boundary energy contribution is computed as the net difference between the energy that is used within the boundary and the energy produced in the boundary. It is based on an average annual net mass balance approach noted previously in Cohen and Ramaswami (2012) for electricity. The same approach was applied to the food and cement sectors, where transboundary contributions were computed as the net difference between what was used locally minus what was produced within the boundary. When in-boundary production exceeded the in-boundary use, the trans-boundary contribution to cement use was assumed to be zero. The portion of local production that supports local use of cement was shown as the In-Boundary impact of cement use and GHGs associated with the remaining cement production were included in general industrial GHG emissions. The same approach was taken for agrifood. This ensured no double-counting occurred.

The emission factors corresponding to the use phase and trans-boundary production are illustrated in (Table 2-1). The use phase combustion emission factors of different non-electricity energy carriers were adapted from the IPCC (Gómez and Watterson, 2006). Other than these standardized emission factors, the GHG emission factors of other infrastructure sectors, separated by use and production activities were collected from studies based in China (shown in Table 2-1). The emission factor of imported electricity was calculated based on sub-national grids corresponding to each city. Other studies were used to supplement the data on life-cycle emissions of food, cement, and fuel processing as shown in (Table 2-1) (Hong et al., 2010, Ke et al., 2013, Ou et al., 2010, Jing and Jixi, 2009).

The MEFA associated with infrastructure use in cities for application in Equation (1) was obtained from the data sources described in the next section. These MEFA data were normalized by population/household number or by cities' GDP, as appropriate, to inform the efficiency of each infrastructure sector, *e.g.* see Hillman and Ramaswami (2010). Generally, household MEFA use was benchmarked by total population or household number; and the MEFA use for industrial/commercial activities was expressed as a unit per GDP, based on the industrial type. These disaggregated metrics represented the efficiency of infrastructure use in each sector and were compared across cities. Detailed methods for estimating GHG emissions from each infrastructure sector are included in Appendix-1.

Table 2-1. Emission factors associated with use and producing service in each infrastructure sector

Infrastructure sectors		$EF^{IB}_{i,use}$	$EF^{TB}_{i,production}$
Non-electricity energy	Coal/coke and oil products	Varies with energy type [a]	
Electricity	Beijing and QHD (ton CO2e/MWh)	0	1.096 [b]
	Xiamen (ton CO2e/MWh)		0.777 [b]
	Yixing (ton CO2e/MWh)		0.788 [b]
Transportation	Gasoline (kgCO2e/TJ)	69551 [a]	20443 [c]
	Diesel (kgCO2e/TJ)	74351 [a]	19893 [c]
Treated water energy intensity	Electricity intensity (kWh/ton)	0.25 [d]	N/A
Wastewater energy intensity	Electricity intensity (kWh/ton)	24.3 [d]	N/A
Municipal waste	Landfill (ton CO2e/ton)	1.52 [e]	N/A
	Incineration (ton CO2e/ton)	-0.62 [e]	N/A
Construction material	Cement (energy+ calcining) (ton CO2e/ton cement)	0	0.683 [f]
Food	Food supply chain	Varies based on food products [g]	

a: (Gómez and Watterson, 2006). Detailed information see Appendix Table A1-1

b: (Song et al., 2013)

c: Calculated by data in the study done by (Ou et al., 2010)

d: Interview local officers (Qinhuangdao Wastewater Treatment Plant, 2014, Yixing Water Supply Ltd, 2014)

e: This value is the mid-point of life-cycle carbon intensity value. The electricity recovered from waster incineration makes this value negative from the life-cycle perspective, according to the research done by Hong et al (2010) (Hong et al., 2010).

f: (Ke et al., 2013)

g: (Carnegie Mellon University Green Design Institute, 2008, Wang, 2010). Detailed information sees Appendix Table A1-2.

2.2.2. Data sources identified to conduct CIF analysis in four cities

Three types data were necessary to conduct *CIF* (Table 2-2): 1) local infrastructure use data; 2) the local production of infrastructure service (if any); and 3) the energy intensity of locally produced infrastructure service (if any). Datasets used in the different cities were summarized in (Table 2-2). Infrastructure use data in the four cities *at the city scale* primarily came from three data sources: (1) the city's statistical yearbook (CSY), (2) special statistical yearbooks, such as China Urban Construction Statistical Yearbook, and (3) additional city-specific data sources, such as interviewing local officials (Table 2-2). When city-specific data were unavailable, estimations were derived by down-scaling information from available datasets at the higher administrative level or by adopting the top-down method, which was discussed in detail as follow.

Table 2-2. Data sources of infrastructure use, local production and the energy efficiency associated with local production separated by sector in four cities

2A: Infrastructure USE

		Beijing	**Xiamen**	**Qinhuangdao**	**Yixing**
		Municipality(Same as province)	Sub-provincial city	Prefecture-level city	County city
Energy (coal/fuel/gas)	Industrial activities	***CSY*** -Beijing	**At city-scale *energy balance sheet*** is created by previous research group	***CSY*** -Qinhuangdao	***CSY*** -Yixing
	Commercial activities			down-scale from provincial level *energy balance sheet*	down-scale from CSY-Wuxi
	Household				
Electricity	Industrial/commercial activities			***CSY*** -Qinhuangdao	***CSY*** -Yixing
	Household			down-scale from provincial level *energy balance sheet*	
Transportation	Publis transit	National Transportation Statistical Yearbook		***CSY*** -Qinhuangdao	
	Private cars	Beijing Transport Report			
Water supply/Wastewater treatment		***CSY*** -Beijing	***CSY*** -Xiamen		
Municipal solid waste					
Food					down-scale from *CSY* -Wuxi
Cement		Beijing Construction Report	Top-down	Top-down	Top-down

2B: LOCAL PRODUCTION

	Beijing	**Xiamen**	**Qinhuangdao**	**Yixing**
	Municipality(Same as province)	Sub-provincial city	Prefecture-level city	County city
Electricity	***CSY*** -Beijing	***CSY*** -Xiamen	***CSY*** -Qinhuangdao	***CSY*** -Yixing
Water supply/Wastewater treatment				
Municipal solid waste				
Food				
Cement				

2C: ENERGY INTENSITY of local production

	Beijing	**Xiamen**	**Qinhuangdao**	**Yixing**
	Municipality(Same as province)	Sub-provincial city	Prefecture-level city	County city
Electricity	***CSY*** -Beijing	***At city-scale energy balance sheet*** is created by previous research group	down-scale from provincial level energy balance sheet	down-scale from *CSY* -Wuxi
Water supply/Wastewater treatment			Interview local officers	Interview local officers
Municipal solid waste		National Average	National average	National average
Food				
Cement				

Note: *CSY* means City Statistical Yearbook

The city boundary of our research was based on the administrative boundary. According to the administrative division in China, the boundary of the administrative unit at each scale included some agricultural activity as well, which was also noted in terms of agricultural energy use, and the food produced locally in each city. In addition, the concept of prefecture-level cities in China includes both its urban areas ("core cities", known as *Shiqu* in Chinese) and less built-up areas. In the cities we studied, the commuter-shed is within the administrative boundary of the prefecture-level cities. The data sources from each infrastructure sector are discussed below.

For municipality-Beijing: The city statistical yearbook (CSY) for Beijing included detailed energy balance sheet (EB) and infrastructure use data for all sectors except for data on transportation and cement use (Beijing Municipal Bureau of Statistics, 2011). The infrastructure use data provided were categorized as: 1) the energy use separated by industrial, commercial, agricultural, and residential users; 2) electricity use separated by these different users; 3) treated water use in households, public service, and industrial production; 4) the amount of community-wide wastewater treatment amount; 5) municipal solid waste treatment amount; 6) food expenditure of urban households separated by food types plus the total food expenditure of visitors; (7) transportation data on vehicle number. Supplementing the transport data in CSY, the vehicle-kilometer-travelled (VKT) of buses and taxies in Beijing were obtained from the National Transportation Statistical Yearbook (Ministry of Transportation of the People's Republic, 2012) and the VKT per private car reported by the Beijing Transportation Center (Beijing Transportation Research Center, 2011) were used to estimate the fuel use of private transportation and public service. Total cement use was documented in Beijing Construction Industry Whitepaper (Beijing Construction and Development Center, 2011). The data on local production of electricity, fuel/coal, cement, and food were reported in Beijing’s CSY. The energy intensity of electricity, heating/steam, fuel/coal, water supply/wastewater treatment, and municipal solid waste treatment were reported in the detailed energy balance sheet for local production.

For sub-provincial city-Xiamen, the data were not as readily available as Beijing. Only infrastructure use data on municipal solid waste, community-wide water supply/wastewater treatment, and household urban food use (in physical unit) were documented in Xiamen’s CSY (Xiamen Statistical Bureau and NBS Survey Office in Xiamen, 2011). A separate energy balance sheet with detailed data on industrial, commercial, agrifood, and residential use of energy/electricity and transportation fuel-use computation was created by a research group (Lin et al., 2013). Xiamen’s CSY reported local production amount of electricity, treated water, municipal solid waste treatment amount, and cement, along with the energy use for electricity generation and water supply/wastewater treatment. The cement use amount was estimated from top-down data sources based on urban and rural per capita cement use at national level, as indicated in (Table 2-2).

For prefecture-level city Qinhuangdao, the publicly available datasets at-scale were further reduced. Qinhuangdao’s CSY only reported data on industrial energy use, municipal solid waste treatment, water supply in the household, industrial wastewater treatment, vehicle numbers, passengers transported by buses, and urban household food expenditure (Qinhuangdao Statistic Bureau and NBS Survey Office in Qinhuangdao, 2011). The other treated water use and the domestic wastewater treatment amount were supplemented from China Urban Construction Statistical Yearbook. Because the energy balance sheet of Qinhuangdao was not available in its CSY, it was downscaled from the data of Hebei province based on Qinhuangdao’s population proportion in this province. Local production of infrastructure service data was available in sectors of electricity, treated water and wastewater treatment, municipal solid waste treatment, and food. Energy use data for local electricity, heating/steam and refinery were derived along with the down-scaling energy balance sheet. Besides, the energy intensity data of wastewater treatment were collected through a survey with local officials (Qinhuangdao Wastewater Treatment Plant, 2014, Qinhuangdao sludge treatment plant, 2014).

For county-level city Yixing, the data availability was better in many sectors compared to the prefecture-level city of Qinhuangdao, although Yixing is at a lower administrative level. Local infrastructure use data on industrial energy use and electricity use in the commercial activities and households, treated water amount, wastewater treatment amount, vehicle number, and municipal solid waste amount was documented in Yixing's CSY (Yixing Statistical Bureau and NBS Survey Office in Yixing, 2013). With no detailed EB sheet, the down-scaling method was implemented to estimate the use of liquefied petroleum gas (LPG) and natural gas (NG) in households and commercial sector, and urban/rural household food use, based on the population proportion in Wuxi prefecture-level city, to which Yixing belongs (Wuxi Statistic Bureau and NBS Survey Office in Wuxi, 2013). The energy use data for local electricity power plants and refinery were also collected by downscaling from Wuxi's data. In addition, the energy intensity data for water supply and wastewater treatment were collected through interviewing local officials (Yixing Water Supply Ltd, 2014).

The data mentioned above, regarding the $MEFA\ use_i$ by infrastructure sectors are summarized in (Table 2-3), along with city demographic information. The demographic information includes population, the percentage of urban population (also used as urbanization rate, which was calculated based on population and this number is provided in each city's statistic yearbook), administrative land area, total GDP, GDP from secondary and tertiary industries, and per capita GDP. Secondary industry in China includes manufacturing and construction industries, while the commercial, business, and public services are defined as tertiary industries (China Statistics Press, 2011).

The four cities have very different economic structures. Beijing's GDP is mainly generated by tertiary economy, which accounts for over 75% of its total GDP (Table 2-3). Xiamen is more balanced with about 49% of its total GDP contributed by commercial activities and 50% by secondary economy, while the agriculture is very small (Table 2-3). In Qinhuangdao, the tertiary GDP contributes over 50% of its total GDP, while the agricultural sector contributes 12% of total GDP in Qinhuangdao, which is the highest agricultural proportion among four cities. Yixing's industrial sector and commercial sector comprise about 53% and 42%, respectively, of total GDP (Table 2-3).

Table 2-3. Demographic and community-wide energy and material use organized by different infrastructure sectors (industrial, commercial, and household) when breaking down possible

Type		Unit	Beijing	Xiamen	QHD	Yixing
Demographic information [a]						
Population		million	19.61	3.53	2.99	1.08
Urbanization	% urbanization by population		86.0%	88.3%	47.5%	55.2%
Geographic area		km^2	16411	1573	7523	1362
Economy	Total GDP	billion *yuan*	1411	206	93	109
	GDP of secondary industry	billion *yuan*	338(24%)	102(50%)	37(40%)	58(53%)
	GDP of tertiary industries	billion *yuan*	1060(75%)	101(49%)	44(47%)	46(42%)
	GDP/capita[b]	*yuan*/capita	71953	58338	31182	100862
$MEFA\ use_i$ ***by infrastructure sectors***						
Non-electricity energy use	Industrial sector	TJ	315699	140802	163119	143738
	Commercial sector	TJ	80439	2653	15843	3716
	Agricultural sector	TJ	14357	6617	19292	n/a
	Households	TJ	73303	8839	13337	2728
Electricity use	Industrial sector	GWh	27970	8542	7403	6636
	Commercial sector	GWh	34530	3460	748	681
	Agricultural sector	GWh	1689	127	639	81
	Households	GWh	13933	3057	1138	870
Transportation	Private car	TJ	195853	12852	19299	8112
	Vehicle ownership	Thousand vehicles	3566	285	237	128
	Public transit	TJ	28400	9257	1687	962
	Aircraft	TJ	171330	23124	n/a	n/a
	Other trans-boundary transportation	TJ	23493	51165	n/a	7546
Water supply/waste water treatment	Water use amount	million tons	1555	317	103	50
	Waste water treatment amount	million tons	1416	221	92	40
Municipal solid waste	Total treatment amount	million tons	6.34	0.95	0.37	0.24
Construction material	Cement use amount	million tons	20.6	3.7	4.3	1.7
Food use	Food use amount	Some cities report expenditure and other reports physical amount.				

Note:[a] data come from National Statistical Yearbook (National Bureau of Statistics of China, 2011) , Beijing Statistical Yearbook (Beijing Municipal Bureau of Statistics, 2011), Xiamen Statistical Yearbook (Xiamen Statistical Bureau and NBS Survey Office in Xiamen, 2011), Qinhuangdao Statistical Yearbook (Qinhuangdao Statistic Bureau and NBS Survey Office in Qinhuangdao, 2011), and Wuxi Statistical Yearbook (Wuxi Statistic Bureau and NBS Survey Office in Wuxi, 2013).

[b]: GDP per capita can either calculated by dividing permanent population or registered *Hukou* population. Except for Beijing's population, the population data for other cities are *Hukou* registered population.

2.3. Results

2.3.1. GHG emissions from specific infrastructure sectors illustrated by city

Total GHGs associated with community-wide infrastructure use, *CIF*, of Beijing, Xiamen, Qinhuangdao, and Yixing are 182, 33, 41, and 19 million ton CO_2e respectively. The distribution of emissions by sector for each city is displayed in (Figure 2-1). In the four cities, industrial energy use is the dominant contributor to total *CIF*, taking up to from 30% (Beijing) to 76% (Yixing) of total *CIF*. In-boundary transportation (public transit and local private vehicle use) accounts for a relatively smaller proportion, ranging from 3% to 9% of total *CIF* across these four cities. The results suggest that reducing GHG emissions from industrial energy use is a critical pathway for low-carbon urban development in China, particularly in smaller cities, such as Yixing.

Water supply/wastewater treatment and municipal solid waste are both small contributors to total *CIF* across these four cities, accounting for 1% to 3% of total *CIF* from each sector in the four cities. Because the plants for water supply/wastewater treatment and municipal solid waste treatment are located within the city boundaries of the four cities, the emissions from these two sectors are counted as in-boundary emissions.

GHG emissions from food use associated with trans-boundary emissions account for a larger percentage in Beijing (8% of total *CIF*) and Xiamen (3% of total *CIF*) than that of Qinhuangdao (almost 1%) and Yixing (about 1%). However, the emissions from food use account for 7% and 6% of total *CIF* in Qinhuangdao and Yixing respectively, which are mostly in-boundary emissions (Figure 2-1). This indicates that the in-boundary agricultural activities contribute for food supply in Qinhuangdao and Yixing more than that of Xiamen and Beijing, which is reflected by the higher proportion of GDP from agriculture in Qinhuangdao and Yixing.

In all four cities, household energy use (including electricity, cooking fuel, and heating fuel) is small compared to industrial energy use, contributing only 6% (Yixing) to 13% (Beijing). These observations highlighted that *CIF* should not be normalized per capita, as suggested by Ramaswami and Chavez (2013) through studying 20 US cities, especially for cities where a significant amount of emissions are contributed by industrial activities. For example, if *CIF* is divided by population, Xiamen and Beijing has the lowest per capita carbon intensity at 9.3 tonne CO_2e per capita, while Yixing reports the highest of the four cities at 17.6 tonne CO_2e per capita. However, this is in direct contradiction with the finding that Beijing residents use more energy per household than Yixing as will be illustrated in the following section. **To better compare cities, we suggest comparing infrastructure use efficiency metrics in each sector**. This is presented in the next section.

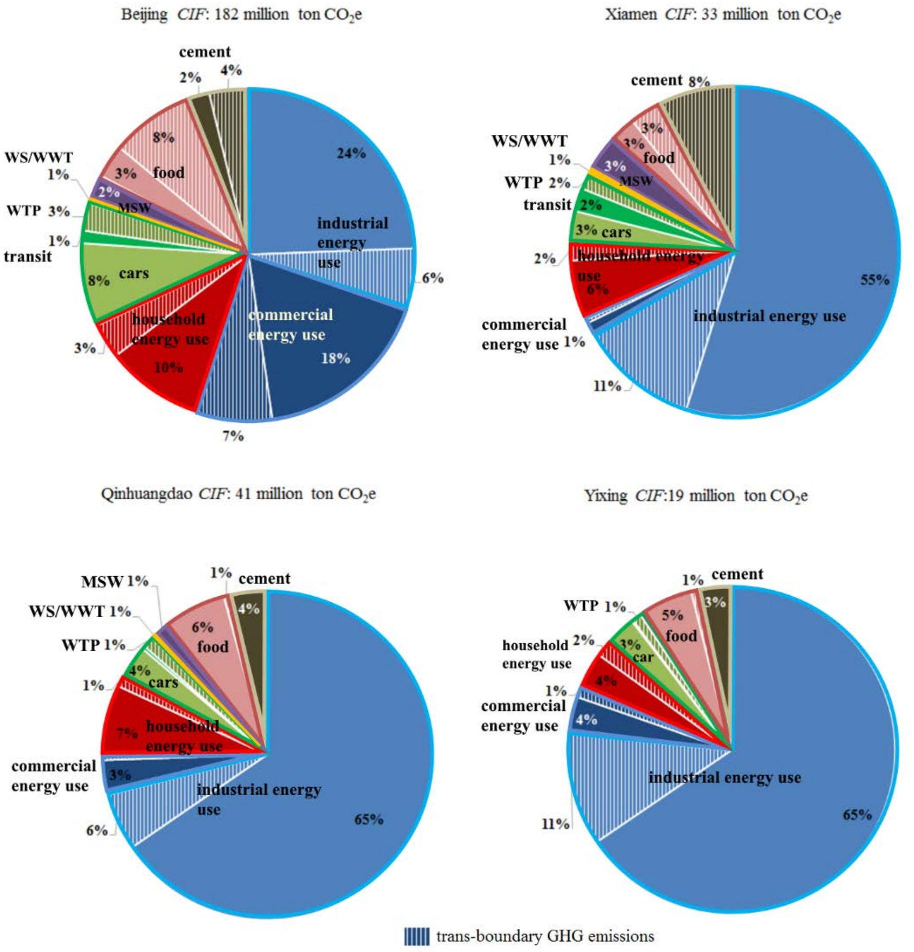

Figure 2-1. Pie charts of total CIF^{GHG} for Chinese cities of different size.

Note of Figure 2-1: The trans-boundary contributions are shown as hatched area for each infrastructure sector. WS/WWT means water supply/wastewater treatment; WTP means well-to-pump; MSW means municipal solid waste management. For some sectors, such as water supply/wastewater treatment, their contribution to total *CIF* is less than 1%, and, the label of these sectors are not shown in the pie chart in Yixing.

Total trans-boundary emissions (hatched areas in Figure 2-1) account for a high percentage of total *CIF* in Beijing and Xiamen (31% and 26% respectively); while they comprise only 8% of Qinhuangdao's total *CIF* and 16% of Yixing's. This is likely a reflection of industrial activities diminishing as cities grow larger and develop a stronger tertiary economy. Thus, cities require greater trans-boundary material and energy supply to support the increased commercial and service industries, as is the cases of Beijing and Xiamen. Indeed, 49% and 93% of their cement use in Beijing and Xiamen is imported, contributing to 3% and 6% of total *CIF* in Beijing and Xiamen respectively. In contrast, Qinhuangdao and Yixing are net cement producers and the emissions from cement use are assigned to local production (solid color); additional cement produced locally and exported elsewhere is included in industrial energy use (not shown separately). The impact of economic structure is clearly seen in the *CIF*. For example, all cities except Beijing have large industrial and small commercial energy use related footprint. This can be attributed to Beijing being the only city among the four cities with larger than 75% tertiary economy. Similarly, in-boundary emissions from food use are significant only in Qinhuangdao and Yixing, where 12% and 5% of total GDP are derived from agriculture, respectively.

Analyzing the GHG emission structure from different types of energy uses within the boundary (*i.e.*, without including the impact of imported food, imported cement, fuel use for air travel/seaports), electricity is found to be the major contributor, ranging from 37% in Beijing to 51% in Yixing (Figure 2-2). Because all four cities are net electricity importers, GHG emissions from electricity use include emissions from both locally produced electricity and imported electricity for city's use. Following electricity, the use of coal and related products (not including the coal and related product use for local electricity generation) is the second major contributor to GHG emissions from total energy use in the four cities, ranging from 32% in Xiamen to 52% in Qinhuangdao. The proportion of GHG emissions from petroleum fuel use for non-electricity related activities ranges from 5% in Yixing to 26% in Xiamen.

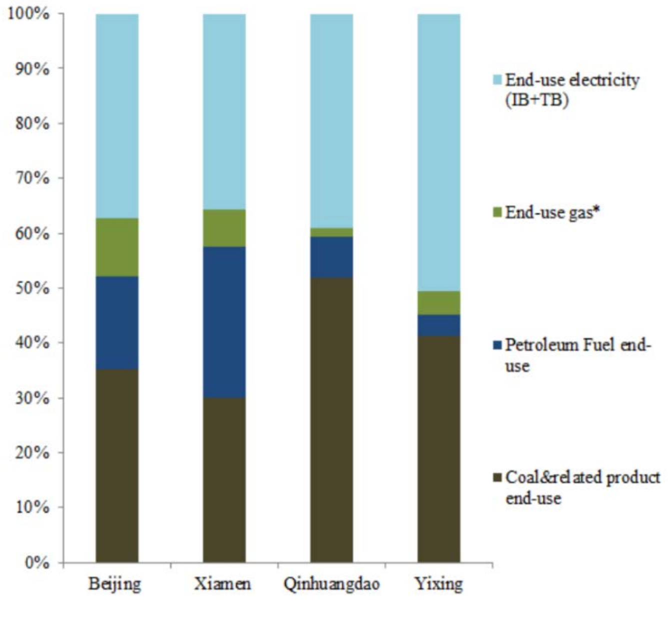

Figure 2-2. The proportion of GHG emissions from energy end-use in the four Chinese cities. Note of Figure 2-2: The coal and related products end-use are energy used in non-power-plant sectors. All cities produce and import electricity for use, as shown in light blue. *: In Yixing municipal solid waste was burned to generate electricity, which is included in its End-use gas.

2.3.2. Benchmarking of material/energy use intensity

Benchmarks of household energy use intensity suggest that households in wealthier cities, based on higher per capita GDP (Table 2-3), use more electricity (Figure 2-3a). The monthly electricity use per person in Beijing, Xiamen, and Yixing is higher than Qinhuangdao's (118MJ/person/month) and the national average (124 MJ/person/month). In addition, heating/cooling days may influence household energy use intensity. This is consistent with non-electricity household energy use in colder climates of Beijing and Qinhuangdao being 366 and 383 MJ/person/month respectively (Figure 2-3a), much higher than Xiamen and Yixing at 245 and 211MJ/person/month respectively.

Industrial energy use intensity (kJ/GDP), which is normalized by secondary industrial GDP, appears to decrease as city size increases. Thus, the energy intensity of industrial sector in Beijing and Xiamen is lower than that of Qinhuangdao and Yixing, as seen both by the metrics of electricity end-use intensity and total energy end-use intensity for the industrial sector (Figure 2-3b).

In contrast to the energy intensity of the industrial sector, bigger cities appear to yield high electricity end-use intensity in the commercial sector, although heating/cooling days may also play a role (Hillman and Ramaswami, 2010). For example, commercial electricity end-use intensity in Beijing is 100 kJ/yuan (normalized by commercial industrial GDP), which is almost twice of Yixing's (54 kJ/yuan) (Figure 2-3c). The energy intensity can make a big difference in the emission structure. Xiamen's total commercial GDP is much higher than Qinhuangdao's, however, emissions from commercial activities constitute a much smaller percentage of overall emissions in Xiamen compared to Qinhuangdao. From the commercial energy intensity benchmark of Xiamen and Qinhuangdao, the energy intensity in Xiamen is much lower in than that in Qinhuangdao. Additionally, there is a difference in GHG emission factor associated with the grids from which cities are drawing their electricity. The emission factor of Xiamen's electricity grid is 0.778 ton CO_2e/MWh, as illustrated in Table 2-1, while the emission factors of Qinhuangdao's grid is 1.095 ton CO_2e/MWh. The lower energy intensity and carbon intensity explain the fact that Xiamen's commercial emissions are smaller than that of Qinhuangdao and Yixing.

Private vehicle ownership performs differently across four cities. Beijing has the highest private vehicle ownership number (close to 200 vehicles per thousand residents) and Yixing with 119 vehicles per thousand residents ranks the second. Xiamen's private vehicle ownership is surprisingly less than Yixing (Figure 2-3d), although the urbanization rate of the former (88.3% in Xiamen) is much higher than the later (55.2% in Yixing) (Table 2-3). It suggests that other factors influence the vehicle ownership, in addition to the wealth or urbanization rate of a city, such as transit design. Such case study analyses are valuable as they can provide insights on factors to be explored in big data studies.

The quantity of municipal waste per person increases with greater urbanization rate, yielding higher values for Beijing, Xiamen, and Yixing in comparison with the lesser urbanized city-Qinhuangdao (Figure 2-3d). The average municipal waste in Qinhuangdao is the same as national average number, which is only to about 50% of Yixing's average municipal waste. The pattern of household water use efficiency is similar as the municipal waste. Qinhuangdao with 34 L/per/day is the lowest and Yixing ranks as the highest (229 L/per/day) (Figure 2-3d). The results from four Chinese cities indicate the benefit of computing both GHG per GDP and additional energy intensity metrics in industrial, commercial, and household sectors, as these show different trends with city size.

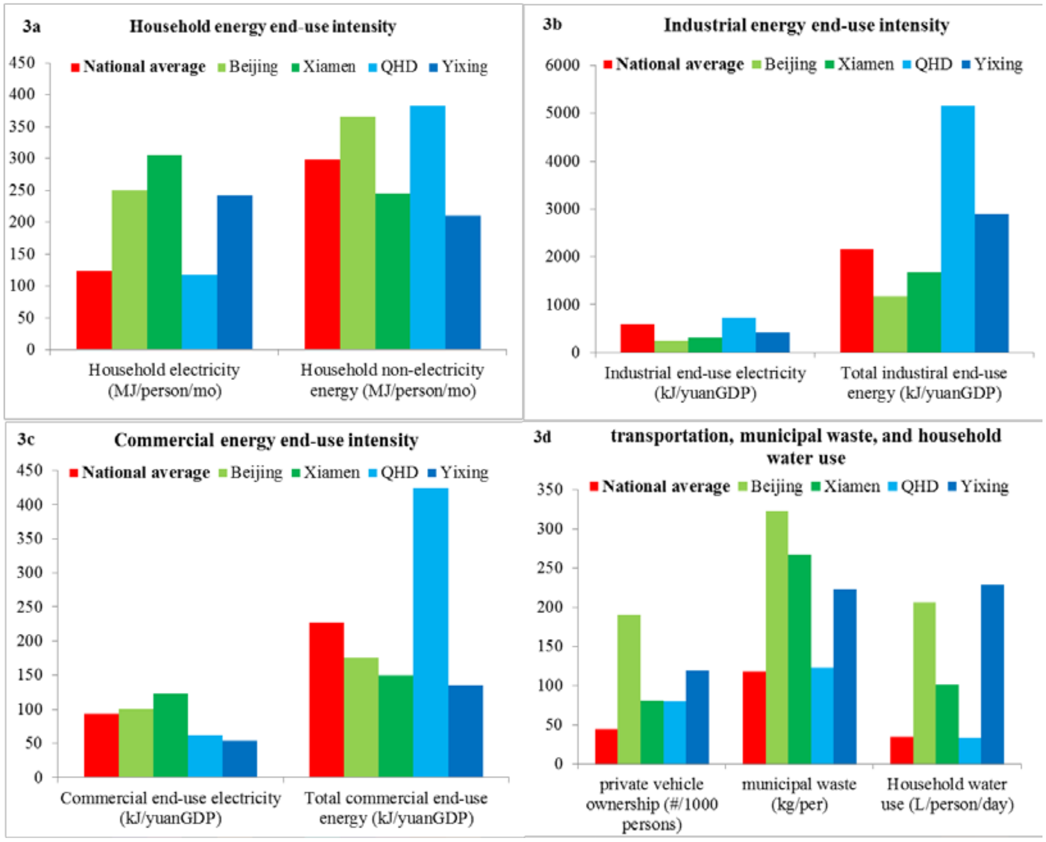

Figure 2-3. Benchmarks: Metrics of material/energy use efficiency of infrastructure sectors in four Chinese cities

2.4. Discussion

Many data sets are reported in the city statistical yearbook, which can be supplemented with additional data to conduct *CIF* analysis in Chinese cities. Normally, the statistical yearbook at each administrative-level includes the data of its direct lower level governments. For example, some of the data sets are only reported in the national statistical yearbook which includes data at the provincial level. This explains why some information is only available for Beijing, one of the four municipalities (province-level cities) in China. Similarly, county-level data from prefecture-level statistical yearbooks can supplement data sets for county-level cities. However, data sets in Yixing appeared much more robust compared to Qinhuangdao, despite the former being a county-level city and the latter being a prefecture-level city. This result reflects that data sets are not consistent across city size and administrative level. Thus, we recommend at a minimum that data on energy balance sheets, as well as additional readily available data on water supply, wastewater treatment and municipal solid waste management should be reported in a consolidated manner in each city's statistical yearbook.

Given the fact that data are not available consistently from the city's statistical yearbook, a standardized methodology is necessary to determine how to supplement the available city-level data. Surveys and down-scaling are the major strategies adopted in our research to estimate the data not directly available at the city scale. These two methods are also found in other studies focusing on estimating urban GHG emissions in China (Feng et al., 2014a, Liu et al., 2012, Wang et al., 2013). Interviews with local officers of certain infrastructure sectors, such as wastewater treatment, were used to verify downscaled MEFA data as much as possible. This approach is necessary to minimize uncertainty in filling common data gaps in Chinese cities. In addition, data in different infrastructure sectors represent the same activities across different infrastructure sectors in all cities. This action ensures that our cases are comparable across different infrastructure sectors. The data sources identified and methods recommended to collect missing data in our research are likely to provide a guide for other scholars, which will contribute to future research related to infrastructure systems in Chinese cities.

Benchmarks of infrastructure use intensity are important for comparing cities, which are developed for the first time in Chinese cities in this research and illustrated in Figure 2-3. Results from these four Chinese cities illustrate the benefit of providing energy intensity metrics separated by infrastructure end-use sectors. The comparison with national benchmarks (*e.g.*, industrial energy intensity or household energy use) allows cities to measure themselves against national targets and make improvements in infrastructure sectors that may be lagging behind national average. Likewise, specific benchmarks, such as car ownership, household municipal solid waste and water use, enable cities to track each sector over time. As China urbanizes, such detailed local infrastructure use data from cities of different sizes can provide a baseline and can help inform infrastructure improvements for future urban development.

We have shown that the understanding of GHG emissions from infrastructure use in different sectors can help to prioritize policy action. Our analysis yields four main findings valuable for policy decisions based on the *CIF* structure and benchmark of different infrastructure sectors in each city. First, industrial energy use and electricity use are major contributors to total *CIF* in these four cities, similar to the findings of others (Yu et al., 2012a). Thus, actions to improve the energy efficiency in these sectors are critical to mitigate GHG emissions. For example, there is potential for these cities to adopt waste-to-energy actions for heating homes/buildings using waste heat. This type of intervention has been estimated to be as valuable as increasing renewable energy adoption in Europe (Lund et al., 2014). Second, trans-boundary emissions are a major contributor to total *CIF*. Thus, Chinese cities need to promote clean industrial production, encourage cleaner sources of electricity generation, and focus on low-carbon supply-chain of material/energy use in cities to achieve its goals of low carbon development. These actions require support from multiple levels of government, including national and provincial policies. Third, in-boundary road transportation is presently a small contributor to GHG emissions (about 4%) in smaller cities, but is more significant in Beijing (about 8%). Therefore, low-carbon transportation modes (*i.e.*, transit) and reasonable urban planning to decrease commuting distance can be very important in cities that are growing and becoming more affluent at the same time. Fourth, household energy use is a medium contributor to total *CIF*, ranging from 6% to 13% of *CIF* in the four cities. With this being such a small proportion of total *CIF*, comparing aggregated city GHG emissions per capita is not appropriate. To better understand the carbon intensity of infrastructure use, we recommend the benchmark metric to compare across cities. Given the continued government-encouraged growth of cities in China and the long lifetime of infrastructure, they can be planned ahead with a more holistic approach to be more efficient. The location specific advantages of *CIF* at the city scale can’t be understood from similar carbon accounting approaches at the national level.

Data on construction material use at city level is a common challenge for urban metabolism studies (Liang et al., 2014, Nichols and Kockelman, 2014, Fernandez, 2007). Although the top-down data of cement use in three cities, we adjusted the cement use by the urbanization rate to minimize the uncertainty of our results. The other limitation of our research is the trans-boundary transportation. Ideally, airline, marine, and other trans-boundary ground travel from airports and seaports should be allocated to various cities based on their use of these facilities by conducting surveys as implemented in Delhi by Chavez et al (2012). However, this was not logistically possible in our study. As such, the emissions from trans-boundary transportation in these four cities are not included. As we mentioned above, the boundary of cities we studied includes the commuter-shed of each cities. Thus, trans-boundary commuter travel is assumed to be zero.

2.5. Conclusion and policy implications

Given the fact that China's rapid urbanization process is leading to substantial increases in GHG emissions, low carbon urban development in Chinese cities is critical for addressing global climate change. Key infrastructure sectors are significant contributors to GHG emissions from cities. However, few studies have focused on infrastructure sectors to better understand GHG emissions from cities of varying sizes in China. This paper identifies diverse data sources to assess GHG footprints associated with community-wide infrastructure use in four Chinese cities of different population sizes (ranging from 1 million to 20 million) and administrative statuses, namely Beijing, Xiamen, Qinhuangdao, and Yixing. The method focuses on seven infrastructure sectors that provide energy-electricity, water supply, wastewater treatment, municipal waste management, construction material, and food to support urban activities.

Available datasets are found sufficient to quantify the *CIF* in the four Chinese cities. Analysis of the community infrastructure GHG footprint shows that industrial energy use is the dominant contributor to *CIF* across four cities, ranging from 26% in Beijing to 76% in Yixing. Contributions from commercial energy use (including electricity) (10% to 22%), in-boundary transportation (4% to 8%), and household energy use (4% to 12%), food supply (3% to 9%), construction materials (3% to 6%) are followed by the water-wastewater sector, which contributes less than 1%. Electricity use and the use of coal are the two top contributors among GHG emissions from total energy use. The contribution to *CIF* from trans-boundary activities can be significant, ranging from about 40% in Beijing to 7% in Qinhuangdao. Surprisingly, GHG emissions from household energy use are a small proportion (4% to 12%) of the total *CIF*, while commercial and industrial energy use dominates the *CIF*. It is therefore inappropriate to normalize *CIF* by population. Benchmarks associated with infrastructure use demonstrate the efficiency of each sector, which together provide comprehensive information on the baseline of infrastructure efficiency within the city.

Policy makers have a clearer understanding of the drivers of GHG emissions when footprints are disaggregated into the seven infrastructure sectors. This detailed information on disaggregated GHGs emissions helps policy makers to prioritize and make achievable goals when developing climate change action plans to mitigate GHGs. For example, the *CIF* in four cities shows that the improvement of energy efficiency in the sector of water supply has less impact compared to the improvement of industrial sector energy efficiency. It also shows the cross sector opportunities. In addition, the trans-boundary footprint of different sectors informs city managers about their supply chains, for example, how much of food supply is grown locally compared to outside of the city. This can help cities to become more resilient by informing planners of the potential risks to key infrastructure supply chains. The community-wide infrastructure-based GHG footprint is not only valuable from a GHG mitigation perspective, but also essential for sustainable infrastructure planning to improve urban resilience due to the consideration of key infrastructure sector supply chains. With the benchmarks of infrastructure use efficiency, city managers can compare their infrastructure performance with other cities and monitor changes in performance over time. Additionally, data on urban material and energy flows should be monitored and reported publicly, so that future supply chain risks to the city can be identified. The application of *CIF* and associated benchmarks are critical to moving rapid urban development in China and developing countries towards sustainable urban development.

2.6. Acknowledgment

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Publication note: The content of this chapter has been peer-reviewed and published on *Carbon Management*. I led this project, which is an international collaboration with scholars from China. I initiated research ideas with others, collected data, conducted analysis, made the writing plan and contributed to the writing. I was responsible for dealing with the publication process.

Chapter 3. The Collective Contribution of Chinese Cities to Territorial and Electricity-related CO_2 Emissions

Abstract: Many studies have quantified carbon emissions from a few cities in a nation, while few studies have estimated emissions from all cities in a nation to assess their collective contributions towards national total. This paper, focusing on Chinese cities, assesses the collective contribution of all cities to national carbon emissions, the share of carbon emissions by city types, and carbon emission per capita and per GDP. This paper describes the Chinese City Industrial-Infrastructure database including fuel/electricity use and heat supply in 644 cities, in which energy use is aligned with national data with ~1% difference. It is found that direct carbon emissions from 644 Chinese cities collectively contribute to 62.4% of the national CO_2 emissions. Further categorizing these cities based on population size, economic structure, and administrative level, it is found that Midsize cities (0.5-3 million) accounted for 38.1% of national CO_2 emissions; Mixed-Economy cities contributed to about 40% of the national CO_2 emissions; and city propers (all urban administrative districts in a city) collectively contribute to 42.9% of the national CO_2 emissions. Direct emissions per capita ranged from 0.94 to 83.3 tonnes CO_2 per person (8.85 tonnes/person on average). Direct emissions per GDP ranged from 0.01 to 2.60 kg CO_2 per yuan-GDP (0.26 kg CO_2/yuan-GDP on average). Direct plus embedded emissions in electricity were also evaluated and found to have similar patterns as direct carbon emissions. These results enhance our understanding of the share of carbon emissions from Chinese cities and suggest the importance of focusing on certain city types for mitigation efforts.

3.1. Introduction

The United Nations estimates that 54% of the population lives in urban areas (United Nations, 2014), using about 67% of energy globally (IEA, 2008). This energy use results in about 71% of global energy-related carbon emissions (IEA, 2008). Different models and methods have been used to estimate the carbon emissions from urban areas and its proportion to the global total (UN-Habitat, 2011, IEA, 2008, Klaassen et al., 2005, Satterthwaite, 2008, Walraven, 2009, Marcotullio et al., 2013, Marcotullio et al., 2012). However, the Intergovernmental Panel on Climate Change (IPCC) 5th Assessment Report summarized that we are uncertain about the share that urban areas contribute to global CO_2 emissions (Seto et al., 2014). The current value of the share from urban areas was supported by limited evidence with medium agreement (Seto et al., 2014). The lack of consensus regarding the definition of urban settlements/urban areas across nations (United Nations, 2014) may contribute to this challenge in estimating urban carbon emissions.

While urban areas are defined in various ways and the United Nations uses each country's definition of urban areas in their reports (United Nations, 2014), cities are typically defined by their administrative boundaries. As administrative units, cities have certain authority to make carbon mitigation policies for local level actions. To better support cities to make these policies, several methods have been developed to quantify their carbon emissions/footprints during the past ten years (Ramaswami et al., 2008, ICLEI, 2012b, Kennedy et al., 2010, Hu et al., 2016, Feng et al., 2014b, Mi et al., 2016, Tong et al., 2016, BSI, 2013, Xu et al., 2018). The World Resources Institute introduced the concept of scopes in carbon accounting for businesses, which has been adopted in cities. Scope 1 carbon emission in cities are emissions from in-boundary activities, and scope 2 emissions are embedded in the grid-supplied electricity/steam/heating/cooling services (World Resources Institute et al., 2014). Sources of scope 1 carbon emissions in cities mainly include direct fuel use in industrial, commercial, residential, and transportation sectors, while direct emissions from agricultural activities are generally small in cities.

Currently, we only have carbon emission inventories from a subset of cities in a nation or with more focusing on global megacities (Kennedy et al., 2009, Hillman and Ramaswami, 2010, Sugar et al., 2012, Feng et al., 2014b, Xu et al., 2018, Hu et al., 2016, Shan et al., 2017, Samuel et al., 2017). Collective contributions from all cities in a nation have not often been quantified. Moreover, there is no clear quantification of the collective impact of all cities on national CO_2 emissions. This leaves a policy gap in that cities aim for climate change actions, while national policies may not provide sufficient support due to the unclear contributions from cities to the national mitigation goals. Despite the emphasis on cities, the role of cities in the Paris accord has not been as clear, because climate policies are developed and monitored at the national level. There has no monitory system linked cities' collective carbon impact to the national level. Thus, there is a need to develop a database at least reporting energy use from different sectors across all cities in one country to understand the collective carbon emissions from cities to support climate change actions.

Few nations have begun to look at this issue. Some studies have quantified scope 1 emissions from all urban areas or metropolitans in the United States (Parshall et al., 2010, Samuel et al., 2017). However, scope 1 carbon emissions do not reveal the full contribution of cities to nationwide carbon emissions given the fact that cities are embedded in a larger infrastructure. For example, carbon emissions embedded in electricity imports in cities can be very high in some cities, but scope 1 carbon emissions alone do not account for this (Hillman and Ramaswami, 2010, Ramaswami et al., 2008, Kennedy et al., 2010). Considering the impact of electricity imports, the U.S. Department of Energy and National Renewable Energy Laboratory (NREL) constructed a local energy use database for U.S. cities, including direct natural gas and electricity use in industrial/commercial/residential sectors and petroleum use in transportation (USDOE and NREL, 2015). While the database was developed, it is not fully aligned with national data due to the types of energy included. This dataset has been applied to explore the CO_2 abatement potential of city-level actions in the U.S. (O'Shaughnessy et al., 2016). Similar efforts in other countries are likely to prioritize actions in cities and the collective impact to national mitigation goals.

Assessing carbon emissions from Chinese cities is important because China has become the biggest anthropogenic carbon emitter (Friedlingstein et al., 2014, Olivier et al., 2015). Although many studies have demonstrated the carbon emissions from one city or multiple cities in China (Hu et al., 2016, Cai and Zhang, 2014, Feng et al., 2014b, Tong et al., 2016, Dhakal, 2009, Sugar et al., 2012, Wang et al., 2012, Lin et al., 2015, Zheng and Kahn, 2013, Chen et al., 2016, Lin et al., 2013, Bi et al., 2011), a review paper by Chen *et al* discussed the challenges of city-level carbon inventories in China, including lack of data and the consistency of method adopted in reporting carbon emissions across studies (Chen et al., 2017). Recently a study by Shan *et al* demonstrated a method to develop a city's energy balance sheet in China (Shan et al., 2017), in which the method was applied in several cities for demonstration. Currently, there is no unified dataset reporting energy use in each city from different sectors and no aligned data with national energy use in China. Thus, the share of carbon from cities is unknown, and carbon intensity across Chinese cities is also not clear, although China's Intended Nationally Determined Contribution (INDC) in the Paris accord emphasized the mitigation target of carbon intensity in 2030.

To contribute further to carbon emission inventories in cities, the focus of this paper is to describe the methodology for a recently developed Chinese City Industry-Infrastructure database (CCII) that covers all cities in China, including fuel use, electricity use, and heat supply in industrial, residential, commercial, and transportation sectors. The purposes of this research are to 1) describe the methodology used in a recently developed database. Through compiling multiple datasets together, the Chinese City Industry-Infrastructure has been developed to include data at multiple levels, from the national to the city level; 2) quantify the share of carbon emissions from cities categorized by population size, economic structure (Highly-Industrial, Highly-Commercial, and Mixed-Economy cities), and administrative level to national total energy-related carbon emissions; and 3) present the carbon emissions per capita and per GDP in each city group.

This study is the first attempt to develop energy use data for cities that is aligned with national data in China. As Chinese urbanization is still ongoing, this study is timely in terms of evaluating the impact of city-level energy use to national carbon emissions. Through analyzing the carbon emissions from different city groups, our results identify the hotspots for carbon emission mitigation. Carbon intensity within different city groups can be further linked to China's INDC targets to support national carbon mitigation efforts. Carbon emissions per capita and per GDP, for the first time, have been illustrated across Chinese cities by scope 1 and scope 1+2, which is a benchmarking for future mitigation efforts. Additionally, the database can be used for exploring the contribution of city-level climate change actions compared to national actions (Ramaswami et al., 2017b). This broad methodology can be applied to other countries when data are available.

3.2. Methodology

3.2.1. Methods and data sources to develop the Chinese City Industry-Infrastructure (CCII) database

This Chinese City Industry-Infrastructure (CCII) Database is an extensive database that is the first attempt to bring together detailed city-specific data on energy use (by industry sector), energy generation, and heat distribution, for 644 Chinese cities in 2010. It includes 286 city propers (*Shi Qu*) and 358 county-level cities (*Xianji Shi*). Each city proper corresponds to the sum of all urban administrative districts (*Shixia Qu*) in a prefecture-level city (*Diji Shi*) or prefecture-region (*Di Qu*). There can be more than one urban administrative district (*Shixia Qu*) within a prefecture-level city, but some datasets are reported a in aggregated way (Department of Urban & Social Economic, 2011-2012); therefore our analysis aggregates urban administrative districts to a city proper in a prefecture-level city to ensure covering all urban administration areas. Hereafter, cities refer to city propers and county-level cities. The administrative divisions in China are detailed below to further define these terminologies.

The mainland China is fully divided into 33 provincial units, including 4 municipalities (*Zhixia Shi*), 22 provinces (*Sheng*), 5 autonomous regions (*Zizhi Qu*), and 2 special administrative regions (Hong Kong and Macao). In this research, Hong Kong, Macao and Tibet are not included. Municipalities are fully divided into urban administrative districts (*Shixia Qu*) and counties (*Xian*). Provinces and autonomous regions are fully divided into prefectures, which can either be prefecture-cities (*Diji Shi*) or prefecture-regions (*Di Qu*). The administrative divisions in prefectures are complicated and vary from province to province. In general, prefecture-cities are divided into urban administrative district (*Shixia Qu*), counties (*Xian*), and county-level cities (*Xianji Shi*), although not all prefecture-level cities include county-level cities and counties. Prefecture-regions are generally divided into counties and county-level cities. All urban administrative districts (*Shixia Qu*) in a prefecture-level city (*Diji Shi*) or prefecture-region (*Di Qu*) is combined as city proper to align with other socio-economic data. Hereafter, cities refer to city propers and county-level cities, covering all urban administrative areas in China. The rest-of-province (ROP) is the areas in a province excluding city propers and county-level cities.

Data were mainly collected through at-scale data sources and downscaling from provincial or national data (Table 3-1). The methods were detailed as below in different sectors.

a) At-Scale Data for Individual Cities: The database provides city-specific data reported at the city-scale by various agencies. These at-scale data can be further divided into two types: data reported at the city level from the original data sources and aggregated data that originally reported at either the firm level or urban district level. For the latter type, the authors re-aggregated the data to match the city definition in this research.

- Readily available data from statistical yearbooks: Total population, GDP by three economic sectors (primary, secondary, and tertiary), urban density (as the population per city area), total electricity use, with residential and industrial electricity use specified in each of the cities (Department of Urban & Social Economic, 2011-2012);
- Urban and rural population: The 6th census data details urban and rural population at the level of urban administrative district/county/county-level cities. As mentioned above, each city proper equals the sum of all urban administrative districts within one prefecture-level city, the urban/rural population of each city proper is the sum of urban/rural population in all urban administrative units in a prefecture-level city. Urban and rural populations within the city units were separated, because energy use and fuels in urban and rural household are different;
- Employment by industry sub-sectors in each city was combined by the authors through adding all the employment data of each firm in city boundary up using data reported in the China Industrial Enterprise Database (National Bureau of Statistics, 2010). The China Industrial Enterprise Database (CIED) provides the firm-level employment data in each urban administrative unit, county, and county-level city for the firms with sale level over 5 million RMB in China (National Bureau of Statistics, 2010). Industrial firms in this database were categorized based on the categorization standard of Chinese industries, which provide 2-digit, 4-digit, and 6-digit categorical codes. The aggregation at which industrial sectoral levels (i.e., 2-digit or 4-digit industrial categories) was based on the usage of this employment data, as detailed later.

- Heating/cooling degree days were calculated based on historical climate data online (Ramaswami et al., 2017a);
- Non-electricity fuel-use in power plants, cement, and steel plants (three key industrial sub-sectors) along with combustion technology of individual electric power-plants, cement plants and steel plants were sourced from a firm-level air pollution database assembled by the authors (China Electricity Council, 2015, China Electricity Council, 2011, China Steel Development Research Institute, 2015, China Iron and Steel Industry Association, 2011, Zhao et al., 2008, Lei et al., 2011, Wang et al., 2014, MEIC, 2016). The individual plants were mapped to specific cities and to the rest-of-province (ROP), based on their location to provide total fuel use in cement, steel and electricity production units in cities and the hinterland areas for each province. For the power sector, the amount of coal use in each plant was reported, while the cement and steel (crude steel and pig iron) production amount was reported by the cement and steel plants respectively. We applied energy intensity of 0.0536 kg coal-equivalent/cement production, 0.011kg coal-equivalent/kg-crude steel, and 0.425 kg coal-equivalent/kg-pig iron to back-calculate the coal use amount in each cement and steel plant. These energy intensity values were calculated based on the provincial level data collected by the authors (National Bureau of Statistics, 2011, Fu et al., 2013, MEIC, 2016).
- Non-electricity fuel use for heat supply in current local district heating systems in each city was back-calculated based on the heat supply amount sourced from (Ministry of Housing and Urban-Rural Development of China, 2011), heating floor areas (at city scale data provided in (Ministry of housing and urban-rural construction of China, 2011)), heating energy demand per floor area of different climate zones (from previous studies (Zhou, 2010), proportion of heating provided by boiler (at city scale data), and the boiler efficiency and fuel-mixture reported by the provincial energy balance sheet (National Bureau of Statistics, 2011). The Chinese City Construction Statistical Yearbook also details parameters on the length, heat supply and distribution, and current coverage levels of current district heating systems in cities (Ministry of Housing and Urban-Rural Development of China, 2011). Energy use in district heating system in residential and commercial sectors in urban areas was separated based on the proportion of heating floor areas in these two sectors.

b) Down-scaling thermal energy use in 13 *Smaller Industry Sectors* from the provincial level data to each city: Remaining data not found at-scale for cities, such as thermal energy use in 13 additional (smaller) industry sectors, were downscaled from Tsinghua’s database at the provincial level (Wang et al., 2014) using Equation (2). These industrial sectors include coking, petroleum refinery, organic chemical raw material manufacturing, nitrogen manufacturing, inorganic alkali, inorganic acid manufacturing, plant glass manufacturing, brick manufacturing, lime and gypsum manufacturing, construction ceramics manufacturing, sanitary ceramic manufacturing, alumni smelting, and copper smelting. Several previous studies also applied employment data to downscale energy use to cities (Baynes and Bai, 2012, USDOE and NREL, 2015). Thus, we also used the employment data in this research. Local employment data of the corresponding industrial sectors in each city was obtained from the China Industrial Enterprises Database (CIED) (National Bureau of Statistics, 2010). We assume the linear relationship for downscaling based on previous global air pollutant emission models, such as EDGAR and GAINS (Olivier et al., 2015, Klaassen et al., 2005).

$$\boldsymbol{energy\ use_{i,j,k}} = \frac{\boldsymbol{energy\ use_{i,k}}}{\boldsymbol{worker\ number_{i,province}}} \times \boldsymbol{worker\ number_{i,j}} \qquad \text{Equation (2),}$$

In Equation (2), $energy\ use_{i,j,k}$ is the energy use amount in the *i* th industrial sector in the *j* th city, *k* refers to either electricity use or non-electricity energy use; $worker\ number_{i,j}$ is the number of workers in the *i* th city in the *j* th industrial sectors, while $worker\ number_{i,province}$ is total number of workers in the *i* th industrial in the province that city *j* located at. Energy use data in these 13 industries reported by the Tsinghua dataset was matched with 4-digit industrial sectors in the CIED according to the standard of industrial categorization. Energy use in Tsinghua Database was reported in the unit of ton coal-equivalent (tce) and assumed mainly to be coal.

<u>c) Down-scaling the other thermal energy use in the remaining industrial sectors from the national data</u>: Fuel use in the remaining 2-digit industrial sector was downscaled from the national level data reported in China Energy Statistical Yearbook (National Bureau of Statistics, 2011). Fuel use in these sectors was assumed to have a linear relationship with the employment data at the city level. The employment number of each 2-digit industries excluded the 4-digit industrial employment data explained in sub-section b) above, which was used to downscale the thermal energy use in the 13 industries from provincial level data. Energy use in the remaining industrial sectors was reported in the unit of ton coal equivalent.

<u>d) Down-scaling fuel use in commercial sector from provincial data</u>: We did not have detailed employment data as what we have for industrial sectors reported in China Industrial Enterprises Database (CIED) (National Bureau of Statistics, 2010). In previous studies, electricity use related to business activities in cities have been found to be better correlated with GDP, compared to city-wide population (Ramaswami et al., 2017a). Thus, energy use in the commercial sector of each city was linearly downscaled based on the tertiary GDP of each city, provincial total tertiary GDP, and

provincial energy use from Tsinghua's database (Wang et al., 2014). Energy use data, reported in units of ton of coal equivalent (tce), in the commercial sector from Tsinghua database detailed the fuel types (*i.e.*, coal or gas) and electricity use in different types of buildings.

e) Down-scaling household non-electricity fuel use and transportation energy use from provincial data: Direct energy use in households includes fuel for decentralized heating, cooking stoves, hot water supply, and electricity for cooling equipment (A/C) separated in urban and rural settlements. Likewise, down-scaling from provincial household energy use profiles by numbers of urban and rural population in each city was applied to estimate the various non-electricity household fuel uses (cooking fuels, and heating fuel for homes not on district energy). Household fuel use activities and associated technologies were assumed to follow the household profiles reported at the provincial scale (Wang et al., 2014). Fuel types were also detailed for different household energy use.

The transportation fuel use was also downscaled using the similar method of household non-electricity use, which was linearly downscaled based on total population in each city and the province it is located in. Data at the province level detailed the vehicle types with fuel technology (for example, cars using diesel or gasoline).

All of these at-scale and down-scaled data were mapped to individual cities and to the rest-of-provinces (ROPs) as stated above by sectors. This database includes energy use data across multi-scales from nation to city level. The national level data were used to validate the alignment of this database with the reported national total energy use.

3.2.2. Calculation of carbon emissions

Carbon emissions from each city were calculated by multiplying the amount of fuel used in industrial, commercial, residential sectors, and transportation with the carbon emission factors of fuels, which are from IPCC Guidelines for National Greenhouse Gas Inventories (Gómez and Watterson, 2006). For scope 1 carbon emissions, all fuel combustion happening within the boundary are calculated and added up to the city total, as shown in Equation (3).

$$\boldsymbol{CO_{2_{scope\,1}}} = \sum_f \boldsymbol{Fuel\,use\,amount_f} * \boldsymbol{Carbon\,Emission\,Factor_f} \qquad \text{Equation (3),}$$

in which, $Fuel\,use\,amount_f$ indicates the amount of fuel f used in a city; while $Carbon\,Emission\,Factor_f$ is the combustion carbon emission factor for fuel *f*. Carbon emissions from fuel used in power plants within city boundary is counted as scope 1 emissions.

For scope 1+2 carbon emissions, the impact of electricity importing/exporting was considered, as shown in Equation (4). Because this is the first attempt to estimate total carbon emissions from all cities in one nation with scope 1 and scope 1+2 CO2 separated, this calculation ensured less double counting.

$$\boldsymbol{CO_{2_{scope1+2}} = \sum_f Fuel\ use\ amount_f * CO2\ emission\ factor_f + (electricy\ use - elecricty\ production) * energy\ efficiency\ of\ electricity\ generation * emission\ intensity\ of\ fuel}$$

Equation (4).

Electricity use is the total amount of electricity used in industrial, commercial, and residential sectors in a city. The amount of in-boundary electricity generation for each city is calculated based on the total amount of coal used in each power plant, assuming 500 grams coal required to generate 1 kWh of electricity (Pahl-Wostl and Knieper, 2014, IEPD, 2016). Heating or cooling services are mainly locally provided in Chinese cities, and carbon emissions from them were counted as the in-boundary carbon emissions.

3.2.3. Categorization of cities by economic structure, population size, and administrative status

These cities were divided into different groups based on population sizes, economic structures (detailed in Appendix-2), and administrative levels. The Chinese government released a new guidiance in 2014 to group cities based on their population sizes (State Council of the PRC, 2014). We adopted the same grouping scheme in this research to divide cities into six population groups (Table A3-1), which are Megacities (>10 million population), Very large cities (5~10 million population), Large cities (3~5 million population), Midsize cities-I (1~3 million population), Midsize cities-II (0.5~1 million population), and Small cities (<0.5 million population). The contribution of each city group to the national population and GDP in 2010 is detailed in Table A3-1. About 90 million people lived in six Megacities (>10 million population), accounting for 7% of China's population. The 10 Very large cities and 20 Large cities housed 139 million population, taking up to 10% of the national population. Midsize cities, including 156 Midsize city-I and 268 Midsize city-II, accommodated 31% of China's population in 2010. Only about 5% of the nation-wide population lived in 184 Small cities in 2010. This distribution demonstrated that Midsize cities housed the majority of China's population in 2010.

Cities' economic structure was measured based on the contribution of secondary and tertiary GDP to city's total GDP. This categorization method has been used in city-level studies (Nelson, 1955), and have been applied in several Chinese cities (Ramaswami et al., 2017a, Ramaswami et al., 2017b). Specifically, cities, where the secondary industrial GDP percentage was higher than the national average plus one standard deviation (64.4% in 2010), were categorized as Highly-Industrial cities (83). Cities, where the tertiary industrial GDP percentage was higher than the national average plus one standard deviation (49.1% in 2010), were categorized as Highly-Commercial cities (93). The remaining cities were Mixed-Economy cities (468). The impact of economic structure on city-wide material and energy flow is detailed in Appendix-2. Total population and GDP in each group with different economic structure were presented in Table A3-2. Total population in Highly-industrial and Highly-commercial cities was much smaller than that in Mixed-Economy cities. Additionally, all Highly-Industrial cities are Mid-size and Small cities. This population cap for Highly-Industrial cities was also demonstrated in a previous study (Ramaswami et al., 2017a). Highly-Commercial cities, housing only 15% of the nation-wide population, created 25% of nation-wide GDP, and Highly-commercial cities were more likely to be bigger cities (bigger than Large City).

In addition to population size and economic structure, cities were also grouped by its administrative level: city propers and county-level cities. The population and GDP distribution within different administrative levels (Table A3-2) demonstrates that city propers accommodated about twice as many people as county-level cities, while generating 2.8 times more in terms of total GDP. Also, all county-level cities have populations less than 3 million and are classified as Midsize and Small cities.

Electricity use versus production determined the difference between scope 1 and scope 1+2 carbon emissions from a city. The feature of electricity use versus production was analyzed to understand the overall situation on electricity use across Chinese cities. Electricity consumption types in cities were categorized into three types based on the ratio between production and consumption ($ratio = \frac{electricity\ production}{electricity\ consumption}$). If the ratio was larger than 1.2, cities were categorized as electricity net producers. When the ratio was between 0.8 and 1.2, cities were categorized as electricity balanced. Cities, where local electricity generation only supplies less than 80% of the consumption, were categorized as electricity net consumers.

3.3. Results

3.3.1. Data sources and data alignment with national data

Sources of the database are shown in Table 3-1. This database was evaluated for quality and alignment with national data in three ways. First, we compared the database at the national level with data reported in the national energy balance sheet in the year 2010 (Table A3-3). The aggregated national primary energy use total from the CCII database agreed well with the official data reported in the national energy balance sheet (National Bureau of Statistics, 2011) with less than 1% difference in fossil fuel use (Table A3-1). Although there was some disagreement at the sub-category level, the differences come from accounting issues in Chinese statistical reporting systems noted by other researchers (Zhou, 2010, Zhou and Lin, 2008). Second, the effectiveness of the downscaling method was validated through comparing electricity use data between the downscaling method and at-scale data reported in other data sources. By comparing at-scale industrial electricity use data available for a subset of these cities (286 *Shiqu*) with the down-scaled industrial electricity obtained from our methods, we estimated the (likely) error of down-scaling thermal energy use for the 13 smaller industry sectors to be of the order of 20% (Figure A3-1), assuming down-scaling errors were the same for both electrical and thermal energy use in industrial sector. At-Scale data (for a subset of 286 city propers) is reported in the China City Statistical handbook (Department of Urban & Social Economic, 2011-2012). Additionally, high correlation (R^2=0.9) between down-scaled and at-scale residential electricity use was found through using data available for a subset of cities (Figure A3-2). Lastly, although we used the downscaling method, the at-scale energy use, including primary energy use in steel, cement, and power plants, as well as energy used for district heating, accounted for about 55% of national energy use demonstrated in Table A3-1. Considering the high consistency between downscaled data and at-scale data (Figure A3-1&2), this uncertainty within this dataset is further reduced.

In addition to comparing primary energy use from CCII with the national level data, total national CO2 emissions from energy use in this database were calculated and compared with other studies. At the national level ~8,800 million tonnes CO_2 in the year 2010 was found to be in the range (9.1 billion) reported by others (Olivier et al., 2015). Our value is slightly lower than others' estimate, due to the exclusion of carbon emissions from agricultural energy use and industrial processes in our database given our emphasis on energy-related emissions in cities.

Table 3-1. Data sources of China City Industry-Infrastructure Database

Data Category	**Data Item**		**Data source**
City administration area			China City Statistical Yearbook
Demographic	Total Population		China 6th Census Data
	Urban population		
	Rural population		
Economy and Employment	Total GDP		China City Statistical Yearbook
	Primary industrial-GDP		
	Secondary Total GDP		
	Tertiary GDP		
	Total workers in each industry sector	4-digit industries: 3111-Cement Manufacturing; 3210-Ironmaking; 3220-Steelmaking; 3230-Steel Rolling; 44-Electricity and Heat supply; 2520-Coking; 2511-Petroleum Refinery; 2614-Organic Chemistry Raw Material Manufacturing; 2621-Nitrogen manufacturing; 2612-Inorganic Alkali; 2611-Inorganic Acid Manufacturing; 3141-Plate glass manufacturing; 3131-Brick Manufacturing; 3112-Lime and gypsum Manufacturing; 3132-Construction Ceramics Manufacturing; 3151-Sanitary ceramics Manufacturing; 3316-Alumni smelting; 3311-Copper Smelting	China Industrial Enterprise Dataset
		The remaining 2-digit industries	
Floor area	Urban and Rural Residential Living space per person		China Regional Economic Statistical Yearbook
	Total Heating areas; Total Residential DH-heating area		China Urban Construction Statistical Yearbook
Heating & Cooling degree days	Number of days below 18C; Number of days above 26C		Collected by the Authors based on the degrees of each month
Community wide electricity, fuel, and water use	Total Electricity Use; Electricity use in Industry; Electricity use in residential sector; Total water use; Water use in residential sector; Total LPG use; LPG use in residential sector; Total natural gas use; Natural gas use in residential sector		China City Statistical Yearbook
Existing district heating system (DHS)	Total DHS heat supply		China Urban Construction Statistical Yearbook
	Total DHS-CHP heat supply		
	Total DHS-boiler heat supply		
Primary energy use in 3 pillar industries	Power plants, cement plants, and steel plants		Tsinghua Dataset
Primary energy use in 4-digit industry	4-digit in employment data stated as above		Based on at-scale employment data from CIED and provincial energy use from Tsinghua dataset
	The remaining 2-digit industries		Based on at-scale employment data from CIED and industrial sectoral energy input table from National Energy Statistical Yearbook
Energy Use in Residential Sector	Household stoves for heating		Downscaled based on population data and provincial energy use from Tsinghua dataset
	Cooking fuel		
	Heating hot water for shower (assuming the electricity cooking and electricity hot water shower is all for heating hot water)		
	Cooling-AC		
	Other electric equipment		
	District heating in residential and commercial sectors		Estimate based on data from China Urban Construction Statistical Yearbook and energy structure at the provincial level from energy balance sheet from China Energy Statistical Yearbook
Energy Use in Commercial Sector	Non-DHS Heating (Coal)		Downscaled based on tertiary GDP and provincial energy use from Tsinghua dataset
	Other primary energy use		
	Electricity Use		
Energy Use in Transportation	Total fuel use		Downscaled based on population data and provincial energy use from Tsinghua dataset

3.3.2. The share of carbon emissions from different city categories

Overall, the amount of electricity produced in cities collectively was about 85% of the consumption in cities in the year 2010, implying that the production and consumption in cities were not far from the balanced situation. When further categorize each city into the three types of electricity consumption, about 70% of cities consumed 1.2 times of their electricity production amount (Figure 3-1). Approximately 25% of cities were electricity net producers, meaning that over 20% of their electricity generation was used somewhere else, and there were few electricity balanced cities. Megacities, Very large cities and Large cities were mainly electricity net consumers. Most Electricity net producers were also Midsize cities. When introducing the economic structure, it was found that Highly-industrial cities were more likely to be electricity net producers and Highly-commercial cities were more likely to be electricity net consumers.

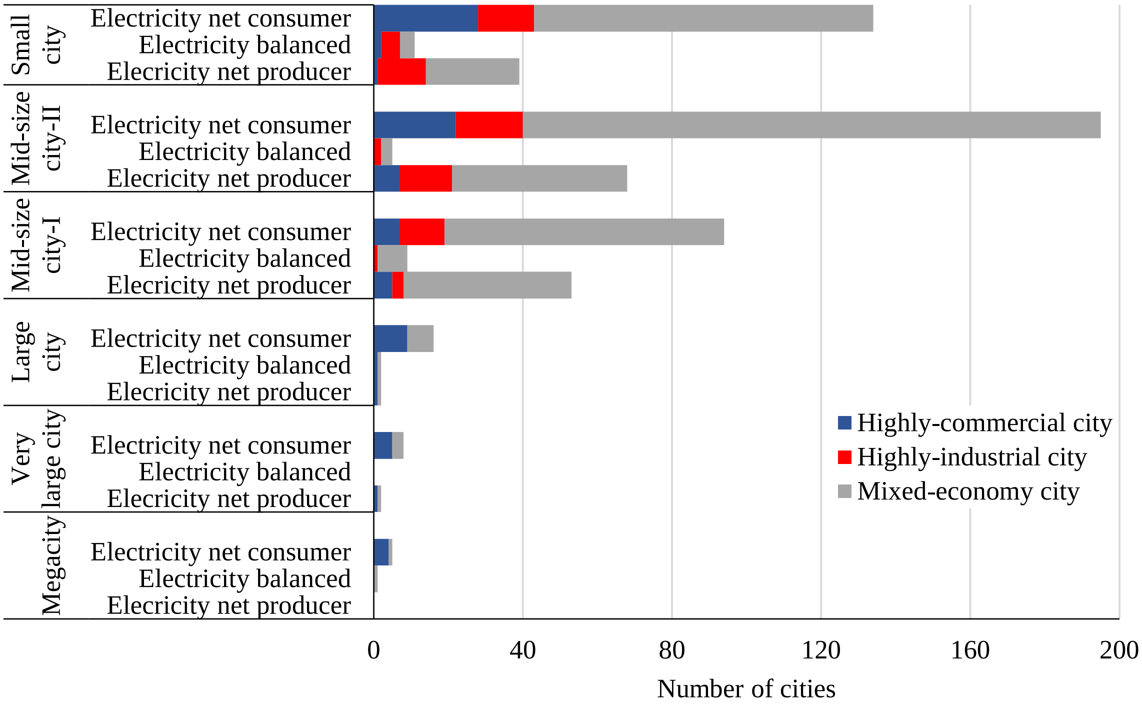

Figure 3-1. Electricity use feature in cities with various population sizes and economic structure in year 2010

Total scope 1 and scope 1+2 carbon emissions from energy use in Chinese cities were 5,493 and 5,915 million metric tonnes respectively, corresponding to 62.4% and 67.2% of nationwide energy-related carbon emissions in the year 2010 (Table 3-2). The difference was small between scope 1 and scope 1+2 carbon emissions from these cities, because the amount of electricity used in cities was only 1.17 times higher than the amount generated on average. Although the difference between electricity use and production varied among different city categories, the general patterns of scope 1 and scope 1+2 carbon emissions were similar. Figure 2 demonstrated the geospatial distribution of scope 1 emissions of cities with different economic structure.

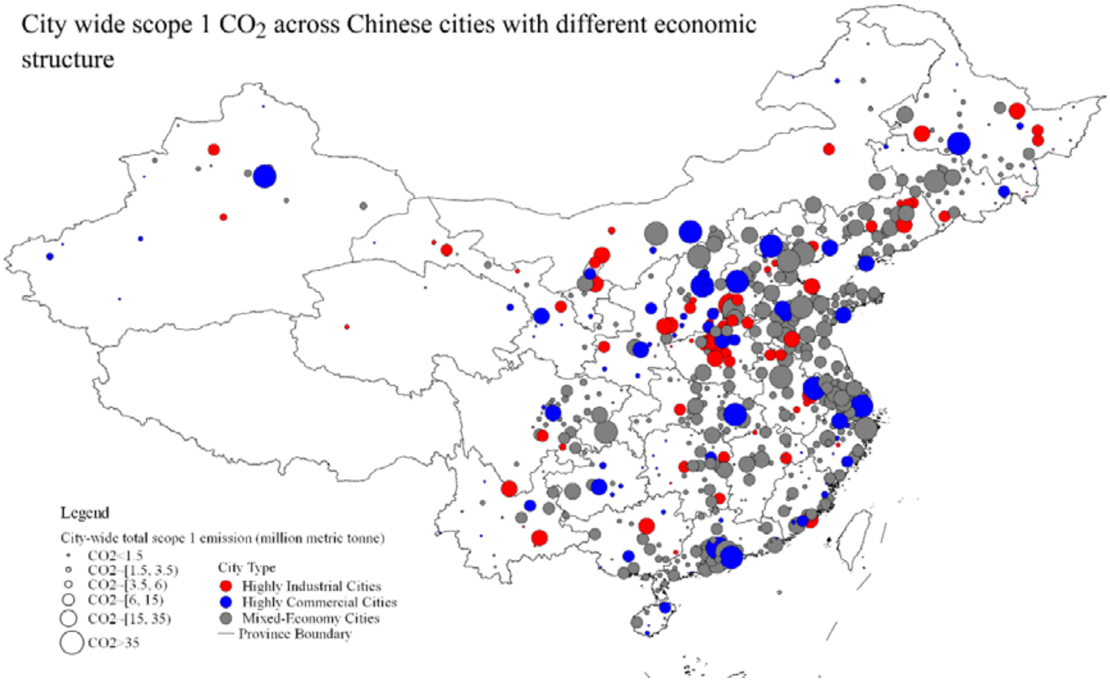

Figure 3-2. Scope 1 carbon emissions of cities with different economic structure in year 2010

The amount of carbon emissions from cities grouped by population size are summarized in Table 3-2 with scope 1 and scope 1+2 specified. The distribution of collective carbon emissions from cities with different population sizes yielded similar patterns as population distribution. Mid-size cities, housing the largest amount of population, collectively accounted for the largest proportion of nation-wide carbon emissions (38.2% for Scope 1 and 37.9% for scope 1+2). There was almost no difference between scope 1 and scope 1+2 emissions for Midsize cities, because of their general balanced electricity use versus generation. Megacities, mainly as electricity net consumers, emitted 530 million metric tonnes scope 1 CO_2 and 694 million metric tonnes scope 1+2 CO_2, accounting for 6.0% and 7.9% of nation-wide carbon emissions. Total scope 1 and scope 1+2 CO_2 emissions from Very large and Large cities contributed to 10.7% and 14.2% of total national CO_2 respectively. Scope 1 and 1+2 CO_2 from Small cities collectively contributed to ~7% of nation energy-related carbon emissions.

Table 3-2. Total Scope 1 and Scope 1+2 CO_2 emission in cities by population sizes in year 2010

Cities categorized by population scale	Scope 1 CO_2 emissions		Scope 1+2 CO_2 emissions	
	Subset sum (million metric tonnes)	% in the national total	Subset sum (million metric tonnes)	% in the national total
Megacity (>=10 million)	530	6.0%	694	7.9%
Very large city (5-10 million)	349	4.0%	496	5.6%
Large city (3-5 million)	594	6.7%	753	8.6%
Mid-size city-I (1-3 million)	1,847	21.0%	1,803	20.5%
Mid-size city-II (0.5-1 million)	1,513	17.2%	1,530	17.4%
Small city (<0.5 million)	661	7.5%	639	7.3%
Total	**5,493**	**62.4%**	**5,915**	**67.2%**

Table 3-3 illustrates the amount of carbon emissions from cities grouped by economic structure. Mixed-economy cities were the biggest contributor that collectively emitted 3,508 million scope 1 CO_2 and 3,617 million scope 1+2 CO_2 emissions, accounting for 39.8% and 41.1% of nation total energy-related carbon emissions. The number of Mixed-Economy cities was much more than the other two categories, which explains this large share. Highly-industrial cities emitted 816 and 770 million metric ton scope 1 and scope 1+2 CO_2 emissions in total, corresponding to 9.3% and 8.7% of national total carbon emissions. Total scope 1 CO_2 emissions from Highly-commercial cities were 1,169 million metric tonnes, and total scope 1+2 CO_2 emissions were 1,528 million metric tonnes. The fact that Highly-commercial cities accommodate more population and economic activities (see Table A3-1) explains their much higher emissions total than the Highly-Industrial cities.

Table 3-3. Scope 1 and Scope 1+2 CO_2 emissions in cities grouped by economic structure in year 2010

City categorized by economic structure	Scope 1 CO_2 emissions		Scope 1+2 CO_2 emissions	
	Subset sum (million metric tonnes)	% in the national total	Subset sum (million metric tonnes)	% in the national total
Highly-industrial city	816	9.3%	770	8.7%
Highly-commercial city	1,169	13.3%	1,528	17.3%
Mixed-economy city	3,508	39.8%	3,617	41.1%

When further dividing cities with different economic structure into different population size (Figure 3-3), Midsize city-I&II (0.5-3 million population) with Mixed-economy dominated emissions for both scope 1 and scope 1+2 CO_2. Within the Highly-commercial cities category, Megacities, Very large cities, and Large cities contributed to 13.4% of the national total, regarding the collective scope 1+2 emissions, while the share of Midsize and Small cities was small. For comparison, within the Highly-industrial cities category, Midsize city-II and Small cities were the large contributors.

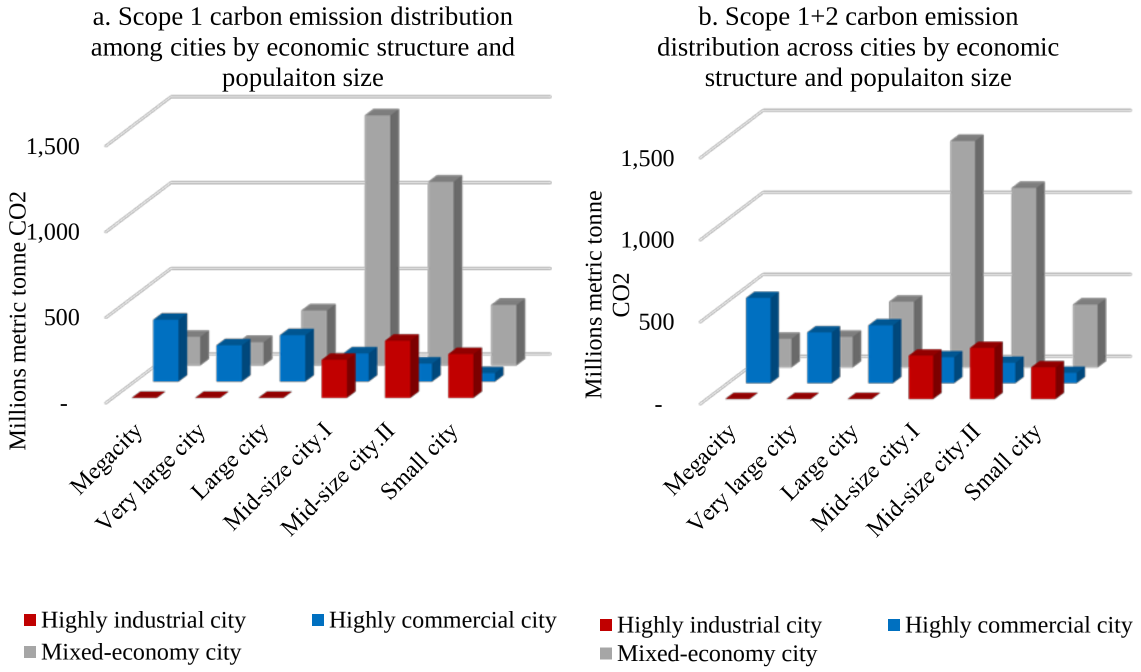

Figure 3-3. Accumulated carbon emissions from cities grouped by economic structure and population size with scope 1 (3a) and scope 1+2 (3b) demonstrated separately in year 2010

Considering administrative levels, scope 1 and scope 1+2 carbon emissions from city propers were 3,773 and 4,022 million metric tonnes, which was much higher than the total of county-level cities (1,720 and 1,894 million metric tonnes for scope 1 and scope 1+2 CO_2). This huge difference in the total amount was because city propers housed about 2 times of county-level cities' population and created 3 times more total GDP than the county-level cities. Within each administrative level, cities were further divided into different population sizes (Figure 3-4). It was found that city propers with the size of 1-3 million population were the largest contributor (about 1,400 million metric tonnes scope 1 CO_2), and both city-propers and county-level cities in the group of Mid-size city-II (0.5-1 million population) were the second largest contributors (Figure 3-4). Following these two groups, Megacities and Large cities were the third largest contributors.

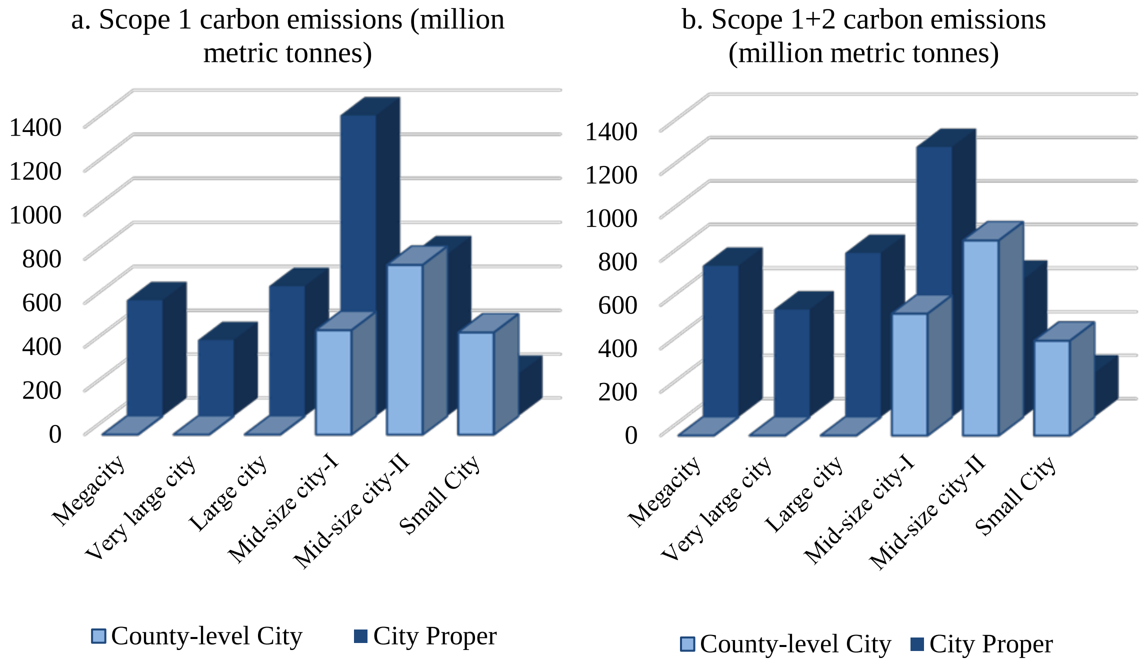

Figure 3-4. Scope 1 (Figure 3-4a) and scope 1+2 (Figure 3-4b) carbon emissions from cities grouped by administrative level and population size in year 2010

3.3.3. Carbon emissions per capita and per GDP in different city categories

Basic statistics of carbon emissions per capita and per GDP are demonstrated in Table 3-4 with scope 1 and scope 1+2 CO_2 separated. Scope 1 CO_2 per capita ranged from 0.94 to 83.3 metric tons CO_2/person, with the average of 8.85 tonnes CO_2/person. In contrast, scope 1+2 CO_2 per capita ranged from 1.89 to 85.2 tonnes CO_2/person (8.69 tonnes CO_2/person on average). Carbon emissions per GDP ranged from 0.01 to 2.58 kg-CO_2/*yuan*-GDP from scope 1 CO_2 and from 0.02 to 1.92 kg-CO_2/*yuan*-GDP for scope 1+2. The average scope 1 and scope 1+2 CO_2 per GDP was the same, which was 0.255 kgCO_2/yuan-GDP in 2010. Scope 1 and scope 1+2 CO_2 per capita or per GDP were demonstrated side by side below, unless specified.

Table 3-4. Statistics of CO_2 per capita and CO_2 per GDP with Scope 1 and Scope1+2 separated in year 2010

	Min	Mean	Max	Standard deviation
Scope 1 CO_2 per capita (ton CO_2/person)	0.936	8.846	83.30	10.383
Scope 1+2 CO_2 per capita(ton CO_2/person)	1.894	8.691	85.20	7.174
Scope 1 CO_2 per GDP (kg CO_2/yuan-GDP)	0.008	0.255	2.580	0.267
Scope 1+2 CO_2 per GDP (kg CO_2/yuan-GDP)	0.017	0.255	1.922	0.169

In general, average scope 1 and scope 1+2 CO_2 per capita in Megacity (5.86 and 7.81 tonnes/cap) and Very large city (5.13 and 7.38 tonnes/cap) were lower than that in Large city (5.86 and 10.8 tonnes/cap), Midsize City (8.12 and 8.00 tonnes/cap) and Small City (10.85 and 10.16 tonnes/cap), although the difference among these size groups was not statistically significant. Both scope 1 and scope 1+2 CO_2 per GDP in Small city (0.315 $kgCO_2$/*yuan*-GDP for both) were significantly higher than cities with other population sizes, i.e. 0.084 and 0.109 $kgCO_2$/*yuan*-GDP for Megacities, 0.098 and 0.132 $kgCO_2$/*yuan*-GDP for Very large cities, 0.143 and 0.178 $kgCO_2$/*yuan*-GDP for Large cities, and 0.240 and 0.236 $kgCO_2$/*yuan*-GDP for Midsize cities. The variation in carbon per person and per GDP was higher in Midsize and Small cities. When only considering economic structure, Highly-industrial cities had statistically significantly higher carbon emissions per capita and per GDP for both scope 1 (0.368 $kgCO_2$/*yuan*-GDP) and scope 1+2 CO_2 (0.306 $kgCO_2$/*yuan*-GDP) than High-Commercial cities (0.198 and 0.232 $kgCO_2$/*yuan*-GDP) and Mixed-Economy cities (0.245 and 0.250 $kgCO_2$/*yuan*-GDP). Regarding administrative levels, county-level cities' scope 1 carbon emissions per capita were statistically significantly lower than that of city propers, while the difference of scope 1+2 was not statistically significant within these two administrative levels (Figure SI-5). Scope 1 CO2 per GDP in city-propers (0.262 $kgCO_2$/*yuan*-GDP) was higher than that in county-level cities (0.249 $kgCO_2$/*yuan*-GDP), while scope 1+2 carbon intensity in the former (0.240 $kgCO_2$/*yuan*-GDP) was significantly lower than that in the latter (0.276 $kgCO_2$/*yuan*-GDP).

When cities were grouped by their population sizes and economic structure, it was found that the impact of economic structure demonstrated stronger influence than population sizes. Within the same population size, Highly-commercial cities generally had the lowest scope 1 and scope 1+2 carbon emission per capita, which was fluctuated around the national average. The patterns were similar for carbon emissions per GDP. In comparison, Highly-industrial cities demonstrated statistically higher carbon per capita and per GDP than other types of cities for both scope 1 and scope 1+2 CO_2 among different population groups (Figure 3-5).

When cities were grouped by their population size and administrative levels, the differences of carbon emission per capita or per GDP among different city groups were not as significant as grouping cities by population size and economic structure. Because no county-level cities were bigger cities, results here mainly focused on the differences between city propers and county-level cities with Mid- and Small sizes. Scope 1 and scope 1+2 CO_2 per capita in county-level cities were generally smaller than city propers within Midsize cities. Within Small cities, city propers demonstrated lower carbon emissions per capita and per GDP.

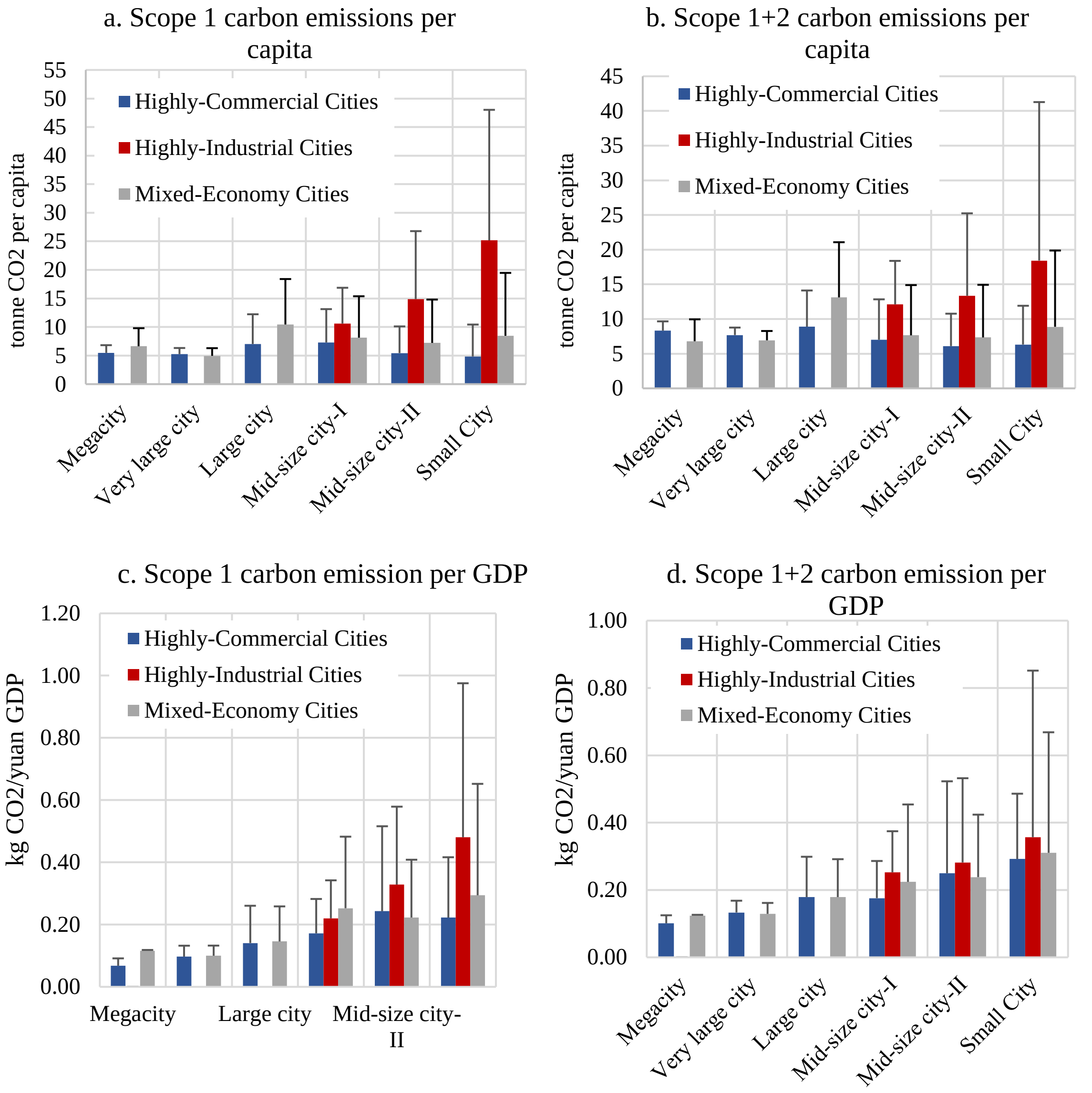

Figure 3-5. Scope 1 and scope 1+2 CO_2 emission per capita (5a & 5b) and per GDP (5c & 5d) in cities grouped by population size and economic structure in year 2010. The standard deviation for each group was shown as the error bar.

3.4. Discussion

This research describes the development of Chinese City Industrial-Infrastructure database in the year 2010. Two traditional data inquiry methods were applied: collecting at-scale data and downscaling data from either the national or provincial level. The downscaling method in this research was found to be highly effective to align with national data. Additionally, energy use in power plants, cement plants, and steel plants was collected at the city-scale, which generally accounts for over 50% of energy use with less than half of the energy use allocated to cities using the downscaling methods. The alignment of this database with national data reported in official energy statistical yearbook was within 1%, which confirms the comparability of the cities' carbon emissions from energy use to national energy-related carbon emissions.

Currently, carbon emission protocols have been developed and released by many international organizations. Cities are also mainly self-reporting their carbon emissions based on these protocols. However, not all of cities in one nation have the capacity to systematically report their carbon emissions. Furthermore, data sources and methodologies applied for city-level self-reporting are found to be inconsistent (Chen et al., 2017, Parshall et al., 2010), which makes it difficult to validate the data and evaluate whether data can be aligned with the national level data. The method described in this research can be a potential strategy for cities lacking the capacity for reporting their own data.

Overall, scope 1 and scope 1+2 carbon emissions from Chinese cities collectively account for 62.4% and 67.2% of nation-wide energy-related carbon emissions respectively in 2010. The share of nationwide carbon emissions from cities is expected to grow as more people live in cities. Midsize cities (0.5-3 million population) contribute to over 40% of nationwide energy-related carbon emissions. Although Megacities and larger cities generally have more capacity to act, their collective contribution to nationwide carbon emissions is only 16.7%, much smaller than that of midsize cities. This indicates that more studies in future should focus on midsize cities to better understand the relationship between urban activities and carbon emissions for the sake of making mitigation actions. Based on future urbanization prospects, midsize cities will also grow faster, housing a higher proportion of the future urban population; this makes sustainable urban development in these cities even more critical. When further categorizing cities of the same population sizes by different economic structure, it was found that Midsize cities with Mixed-Economy structure are the hot spots, accounting for approximately 40% of national CO_2 emissions. More mitigation actions should be discussed and implemented in these types of cities.

Regarding administrative levels, city propers have much higher total carbon emissions than county-level cities collectively, due to their more intensive economic activities and population amount. Mitigation strategies for city propers may yield higher level mitigation potential. Current, a lot of Chinese city studies focused on prefecture-level cities, which are the combination of city propers, county-level cities, and counties (ROP in this research). This research took efforts to further separate the administrative unit within prefecture-level cities. The differences between city propers and county-level cities are meaningful in a way that mitigation policies should consider the difference between these two administrative units even within prefecture-level cities.

The Chinese government included the improvement of carbon emission intensity as one of the targets in its INDC in the Paris accord. Our results systemically revealed the general patterns of carbon intensity across and within different city types. The variation has been demonstrated to be very high in Midsize and Small cities with Highly-industrial economies. Contributing to the large share of carbon emissions, Midsize cities should reduce their carbon intensity to contribute to national mitigation goals. The adjustment in economic structure is one of the potential actions, because it is found that Highly-Industrial cities yielded significantly higher carbon intensity than the other two types. Furthermore, this data provided a baseline to track the carbon intensity change in the future.

This research contributes to understanding cities collective impact on carbon emissions in a nation. This fundamental information is lacking in many counties. Although demonstrated in Chinese cites, the detailed methodology on database development potentially can contribute to more studies on revealing the share of cities in nation-wide carbon emissions. More detailed information on the share of emissions from different city group does not only reveal the emission hot spots, but also helped to identify the current research and policy gaps addressing carbon mitigation in certain types of cities, *i.e.*, Midsize and Small Chinese cities. Additionally, city-level energy use database is fundamental to evaluate low-carbon strategies (O'Shaughnessy et al., 2016, Ramaswami et al., 2017b). This will further contribute to the low carbon development in cities.

3.5. Acknowledgment

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Chapter 4. Estimating the Potential for Industrial Waste Heat Reutilization in Urban District Energy Systems: Method Development and Implementation in Two Chinese Provinces

Abstract: Utilizing low-grade waste heat from industries to heat and cool homes and businesses through 4th 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 the 4th generation DES, yielding energy use reductions from 12% to 91% (average of 58%) for heating and 12% to 100% (average of 73%) for cooling energy use in different cities based on annual exchange potential. Incorporating seasonality and multiple energy exchange pathways resulted in energy savings reductions from 0 to 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.

4.1. 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 (World Bank and DRCSC, 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% to 50% of the primary energy input in the industrial sector is wasted as heat (Johnson et al., 2008). In addition to reutilizing industrial waste heat within industrial processes, as suggested in deep de-carbonization pathway analyses (Sachs et al., 2015), 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 (100~400°C) industrial waste heat through combined heat and power (CHP) in DES is a well-known concept, which has been used in 2nd generation DES in the form of hot steam with a temperature higher than 100°C. The technology further advanced to 3rd generation DES systems (constructed after 1980) that use pressurized hot water below 100°C and reduced pipeline losses. In contrast, new 4th generation DES systems use low-temperature hot water (30~70°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, improving energy efficiency systematically (Lund et al., 2014).

The potential of this new technology (4th 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 city 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 the hotter climate (UNEP, 2015), indicating the importance of also including analysis of waste heat reuse pathways in district cooling system (DCS). Last, because the additional new infrastructure is needed for waste heat exchange through shared district heating and district cooling systems (DHS & 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 aims to develop a generalizable methodology that employs energy flow analysis and heat exchange estimations coupled with life-cycle analysis of new infrastructure investment for a first-order estimate of the potential for reutilizing industrial waste heat in the residential-commercial sectors of cities. We develop the methodology using publically available data and implemented it 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 and 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 U.S. 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, Fridley 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 (Odgaard, 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 District Heating Systems (DHS) and District Cooling systems (DCS) in different cities in two provinces representing cold and hot climate regions in China.

4.2. Method

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 in 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;
- First-order estimate of 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 4-1, 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 "city" 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., 2017a, Chen et al., 2013). Chinese provinces are generally fully divided geographically into *Dijishi*, which translates to prefecture-level "cities", but does not exclusively represent urban areas. Within the prefecture-level cities, city propers (*Shiqu*) 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 (*Shiqu*) as representing the cities of China, similar to previous studies noted above (Bettencourt et al., 2007, Ramaswami et al., 2017a, 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 A4-1.

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 4-2 for the sixteen sectors. The above sixteen 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 2-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 4-2) 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 downscaling approach is reasonable (Ramaswami et al., 2017b).

Table 4-1. Dataset to apply this method in China, U.S., and India

City Data for Heat Exchange Computations	China	USA	India
Population, economic, environmental data			
Population & households	Chinese census (Population Census Office, 2012)	US Census https://www.census.gov/data.html	Indian Census Data (Census of India, 2011)
Economic Activity & employment by detailed sector	Reported in each city's statistical yearbook	Metropolitan GDP from Bureau of Economic Analysis https://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 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 https://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 http://www.districtenergy.org/; Department of Energy-CHP database https://doe.icfwebservices.com/chpdb/	No existing district energy in India
Heating/Cooling Degree Days	Estimate from NOAA/ESRL/PSD data: https://www.esrl.noaa.gov/psd/	NOAA-Climate Prediction Center; HUD-Heating degree database	Estimate from NOAA/ESRL/PSD data: https://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, https://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 & Social Economic, 2011-2012)	Residential Energy Consumption Survey (RECS) https://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/	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 & Social Economic, 2011-2012); Some cities report in their annual statistical yearbook	Commercial Buildings Energy Consumption Survey (CBECS) https://www.eia.gov/	Mainly estimated based on national or state-level data

4.2.1. 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 collected by the authors and summarized in Ramaswami, et al (2017) (See Table A4-2). The recoverable industrial waste heat is further divided into three grades - high-grade heat (>400 °C), medium-grade heat (100~400 °C), and low-grade heat (<100 °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

$$\boldsymbol{Waste\ Heat_{i,j} = E_i \times P_i \times Ratio_{i,j} \times (1 - U_i)} \qquad \text{(Equation 5);}$$

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; $Ratio_{i,j}$ is the proportion of the different grades of waste heat (*j*) expressed as a percentage of P_i. U_i 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 4-2).

4.2.2. 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. 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 (Table 4-3&4), indicating concordance between the EUI approach and direct primary energy accounts.

Table 4-2. China Study - Energy input, E_i, of industrial sectors in year 2010

	Industrial sectors	Primary energy input (1,000 tce)	
		Total city propers in Hebei	Total city propers in Fujian
Industrial energy use at the city level	Power plant	55,432	4,666
	Cement plant	3,047	26
	Steel plant	20,130	16
Industrial energy use modelled from the provincial level data [a]	2520-Coking	2,177	47
	2511-Pretroleum Refinery	396	315
	2614-Organic Chemistry Raw Material Manufacturing	-	74
	2621-Nitrogen manufacturing	1,296	456
	2612-Inorganic Alkali	710	118
	2611-Inorganic Acid Manufacturing	-	-
	3141-plate glass manufacturing	722	210
	3131-Brick Manufacturing	1,743	694
	3112-Lime and gypsum Manufacturing	701	163
	3132-Construction Ceramics Manufacturing	9	141
	3151-Sanitary ceramics Manufacturing	328	0
	3316- Alumni smelting	-	-
	3311- Copper smelting	10	6
Remaining industries energy use [b]	Coal-Fired Grate Boiler	2,850	2,320
	Coal-Fired Fluidized Bed Boiler	352	287
	Oil-Fired Boiler	184	511
	Gas-Fired Boiler	3,177	1,258

Note: a: 4 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).

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). 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 4-3), 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.

$$\boldsymbol{Heating\ Fuel\ Intensity}_{\boldsymbol{l,primary\ energy}} = \frac{(\boldsymbol{Enduse\ Energy\ Use\ Intensity})_{\boldsymbol{l}}}{(\mathbf{1}-\boldsymbol{Pipeline\ Loss}) \times \boldsymbol{Boiler\ Efficiency}} \qquad \text{(Equation 6).}$$

Total primary fuel needs for heating demand in residential and commercial sector in a city are estimated by multiplying the intensity in Equation (6) 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 4-1a) 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 Statistic 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 Statistic Yearbook (DCSNBS, 2011) (average is about 30 sq.m./person; see Table A4-1) and the total urban population for each city from the 6th 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, commercial area is about 30% of 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.

Table 4-3. 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 [a]
Coal stove	109	40%
Briquette stove	4	
Gas heater	31	80%
Biomass Stove	48	40%

a: Source: (Zhou et al., 2014)

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 to 10.3 kWh/sq.m. and consistent with theoretical estimate-6.5 kWh/sq.m. in residential sector from Zhou et al. (Zhou et al., 2014) (See Table 4-4). 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).

Table 4-4. 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.) from downscaled provincial data (Tsinghua)	End Use Energy Intensity (kWh/sq.m.) – 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).

4.2.3. 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 4-1a) (in the same year, hypothetically) of reusing industrial waste heat in DES shown in Fig 4-1b and 4-1c. The total recoverable high-, medium-, or low- grade heat is calculated by applying the suitable recovery factor to the waste heat estimated in Equation (5). Only 25% of medium-grade waste heat is assumed recovered, 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 propers cover from 60% to 100% of the households (Table A4-1). Furthermore, low-grade heat poses less of a safety concern and studies show that fence lien distances up to 30 kilometers. Given 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:

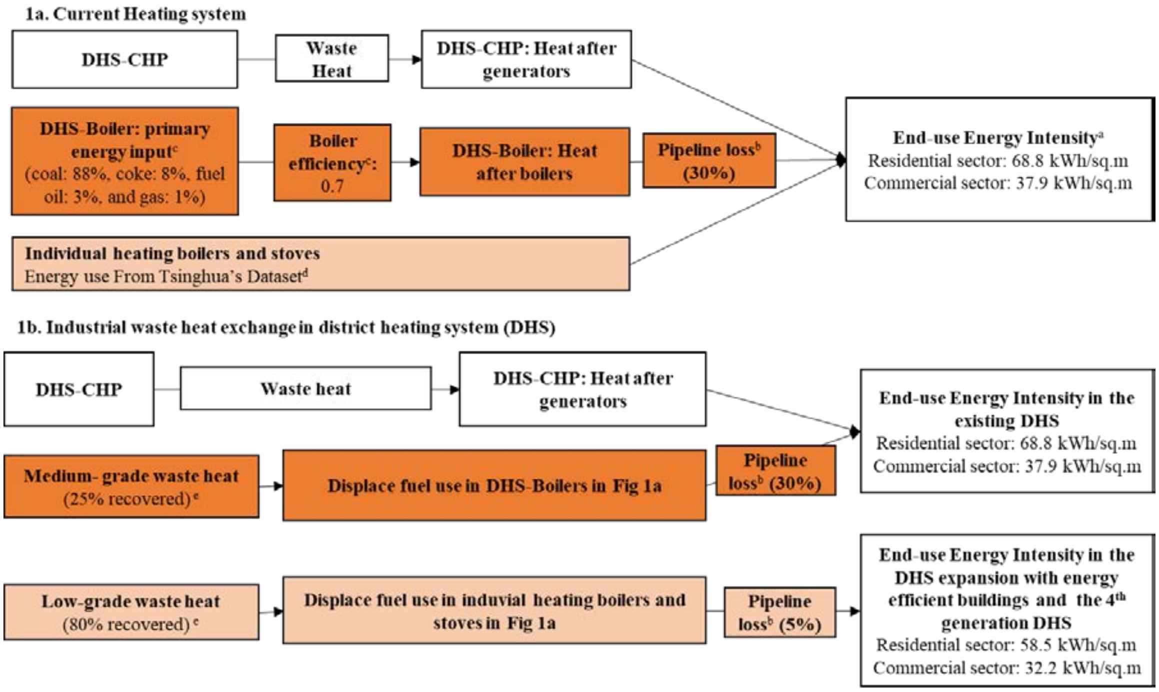
1) Medium-grade waste heat is utilized in current DHS as a heat source to replace fuel used in current DHS boilers;

2) Medium-grade waste heat that remains after replacing boilers in current DHS is used in expanded 4th generation DHS that covers the homes/business not presently covered under DHS;

3) Low-grade waste heat is also applied in the expanded district heating system (4th 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 4th 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 basic 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 expanded future 4th generation DES. We refer this as the two tier-annual approach, because the two strategies specific to the grades of heat are used. We evaluate the seasonality scenario, where the waste heat generation is stable across the year, but demand only occurs in 4 winter months and 6 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 4th generation DES to utilize low- and med-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 analyzed in individual cities as well as the provincial level savings.



1c. Cooling pathways

Status quo	Single established air conditioners with penetration of 80% for residential sector and 100% for commercial sector
Industrial waste heat exchange in district cooling system (DCS): Cooling only provided by waste heat driven absorption chiller	COP[f] for low-grade heat: 0.65 COP for medium-grade heat: 1.2

Figure 4-1. Current heating system (Fig. 4-1a) and heat exchange of reutilizing recoverable industrial waste heat in DHS (Fig. 4-1b) and DCS (Fig. 4-1c)

Notes: a: EUI from (Zhou et al., 2014).
b: Pipeline loss in current DHS from (Zhang et al., 2013) and in the 4th generation Des from (Lund et al., 2014).
c: Boiler efficiency and primary energy fuel structure of DHS from
d: Primary energy use in individual heating equipment from Tsinghua dataset
e: 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).
f: 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).

4.2.4. 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 Fig 4-1a, b, &c; with the application of relevant emission factors of fuel combustion from IPCC (Gómez and Watterson, 2006). For district cooling, CO_2 savings are estimated based on the amount of electricity reduced and a regional grid-specific CO_2 emission factor (Song et al., 2013). The annual economic benefit from fuel savings is estimated based on the fuel cost in Chinese cities (Table A4-3).

Embedded CO_2 of the additional DES infrastructure is estimated using economic input-output life cycle analysis (EIO-LCA) 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 Chinese Environmentally Extended Input-Output (CEEIO) Database in 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, from which is subtracted the cost of the current individual heating/cooling equipment – *i.e.*, homes investing in their own stoves and air conditioners (Table A4-3). The useful lifetime of DES is assumed to be 25 years, within the range of 15 to 30 years reported by other studies (Davies and Woods, 2009, UNEP, 2015).

4.3. Results

The recoverable waste heat in cities is found to be dominated by low-grade industrial waste heat, accounting for about 79% to 100% of all industrial waste heat in these cities. The remaining is mostly medium-grade waste heat (Fig. 4-2). This low-grade heat, previously unutilized, can be captured and reutilized in new 4th 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, Fig. 4-2), that can be used in existing DHS.

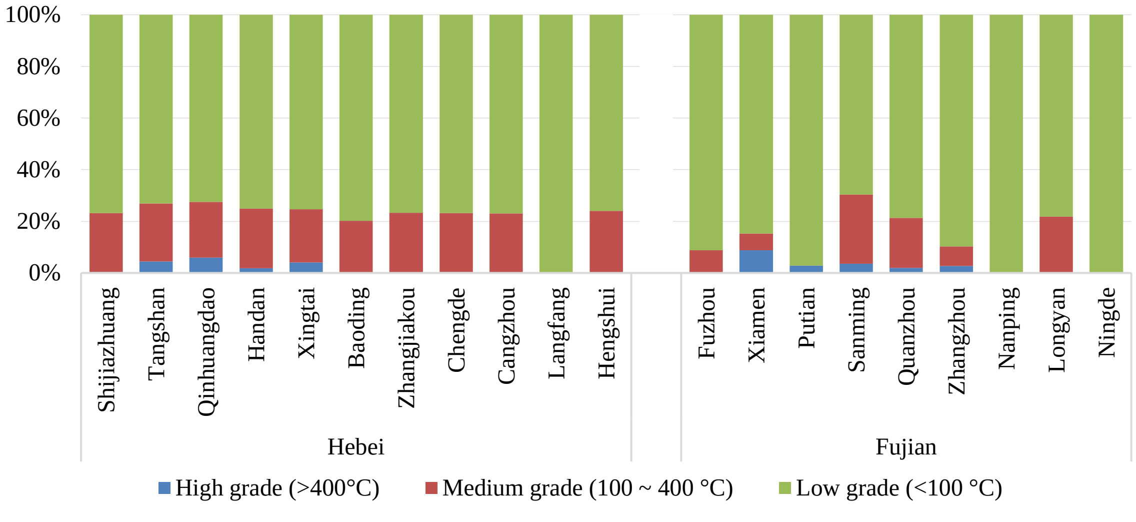


Figure 4-2. Temperature structure of unutilized industrial waste heat for cities located in Hebei and Fujian

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 4th generation DHS operated on low-grade heat (See Fig. 4-1b), and matched this heating demand with the recoverable waste heat of different grades (See solid and hatched bars in Fig. 4-3a). Matching different grades of heat leads to a range of energy savings in different cities of Hebei, ranged from 12% to 91% of the energy used for heating (Fig. 4-3b). 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% to 86% of carbon emissions from reductions in current energy use for heating in Hebei's cities (Fig. 4-3c). 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 14% ~ 100% for cities in Fujian province (Fig. 4-4b).

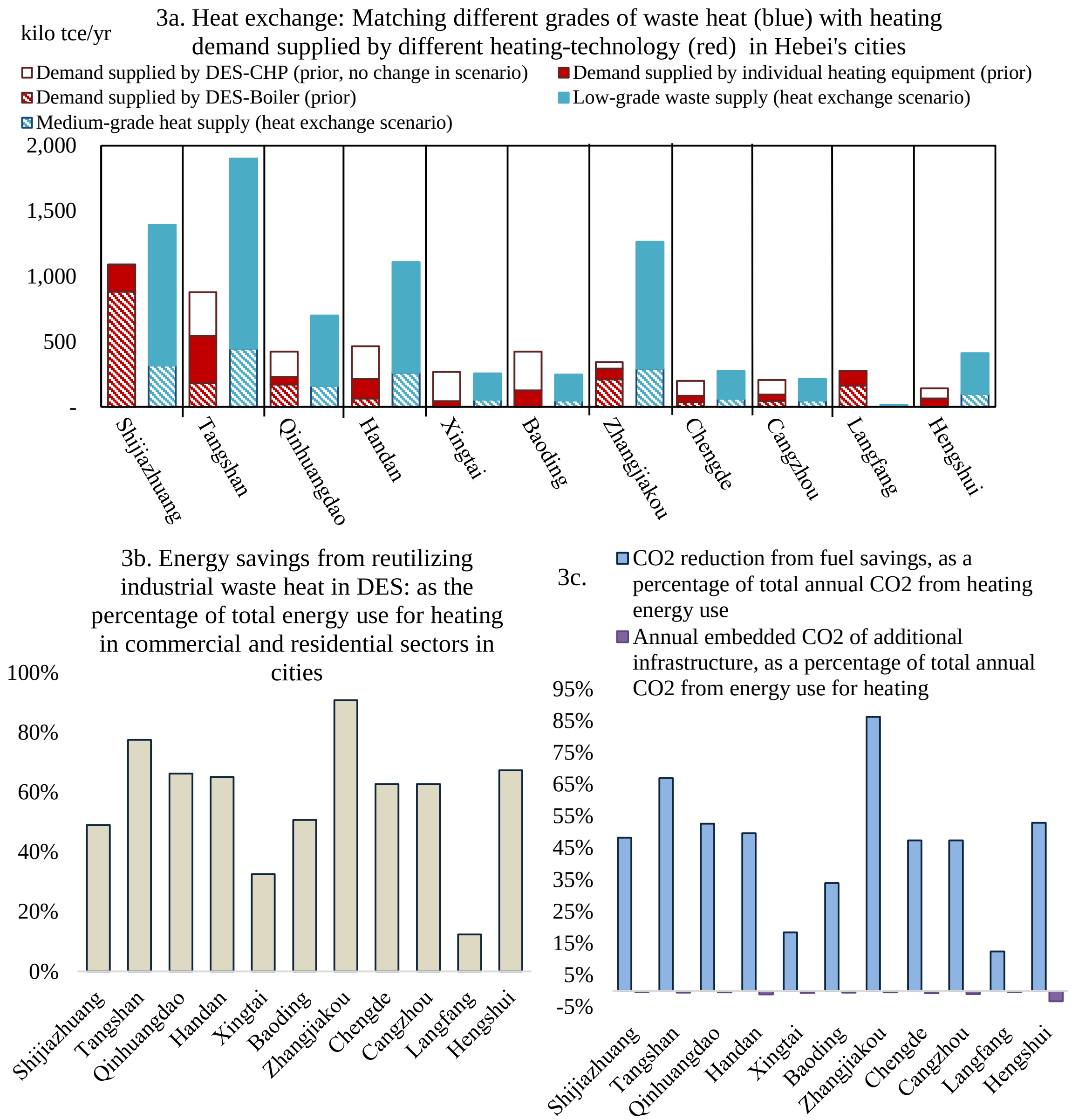


Figure 4-3. Heat exchange, energy reduction, and carbon mitigation in Hebei’s cities

Note of Figure 4-3: Fig 4-3a Matching the supply of different grades of waste heat (blue) in different demand (red) technology and heating pathways in cities located in Hebei. Fig 4-3b Primary energy savings from utilizing industrial waste heat in DHS as the percentage of total heating energy use in residential and commercial sectors in cities located in Hebei province. Fig 4-3c Carbon reduction from fuel savings in heat exchange and embedded carbon emissions from additional infrastructure (life-cycle carbon penalty): as the percentage of total carbon emissions from current heating energy use in these cities.

Generally, the embedded carbon emissions in additional infrastructure are very small compared to the carbon mitigation amount in both DHS and DCS (Fig. 4-3c and Fig. 4-4c). 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.

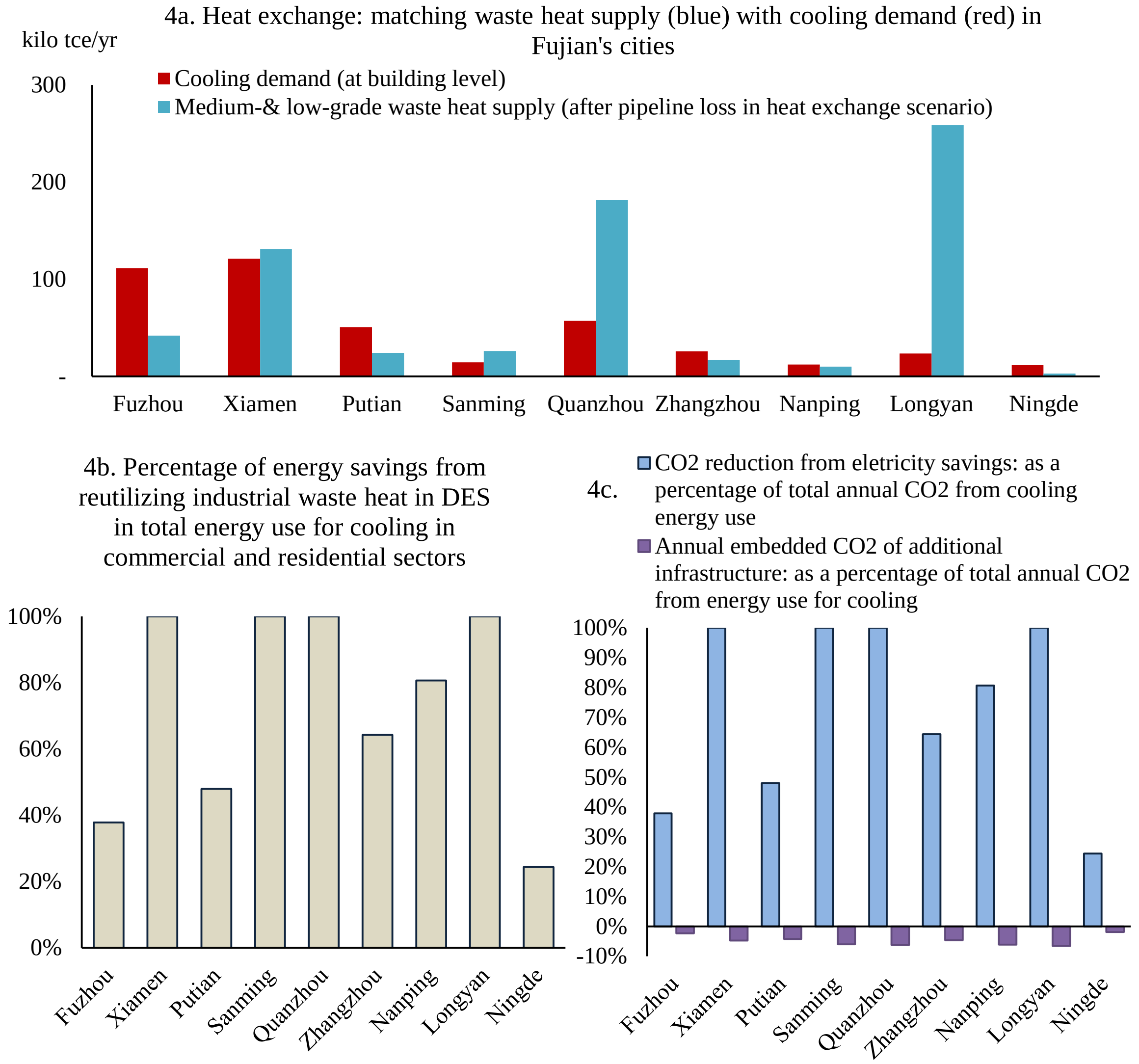


Figure 4-4. Heat exchange, energy reduction, and carbon mitigation in Fujian's cities

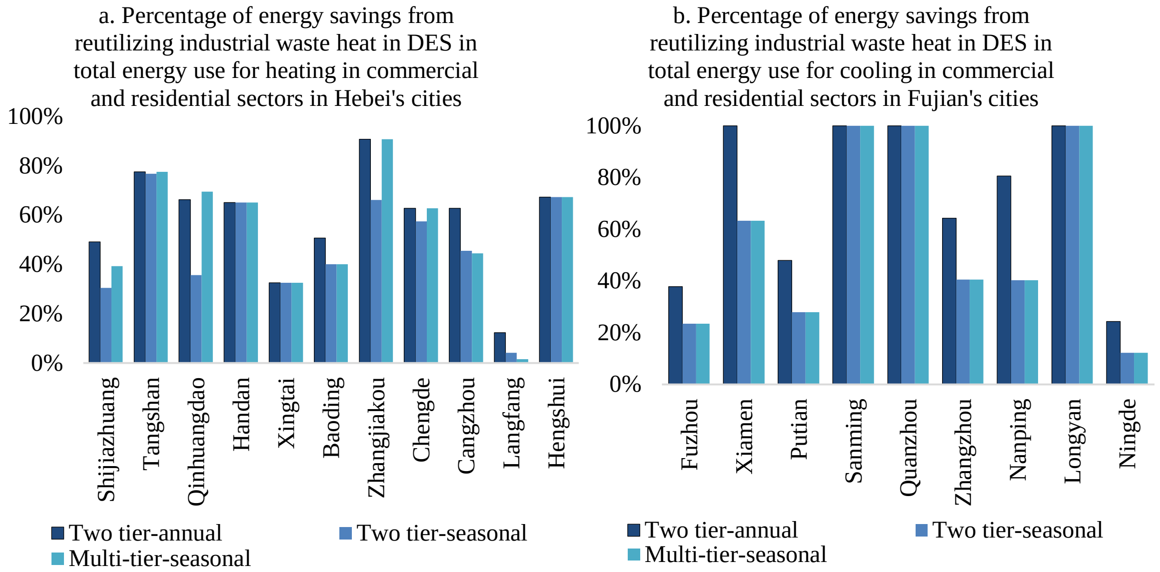
Note of Figure 4-4: Fig 4-4a Matching the supply of different grades of waste heat (blue) in cooling demand (red) in cities located in Fujian. Fig 4-4b Electricity savings from utilizing industrial waste heat in DCS as the percentage of total cooling energy use in residential and commercial sectors in cities located in Fujian province. Fig 4-4c 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.

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 two-tier scenario (Table 4-6). Although carbon mitigation potential decreases slightly in two-tier seasonal scenario, developing multiple heat reutilization pathways can increase the potential of heat exchange as shown in multi-tier seasonal scenario. Another example of multiple heat reutilization 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 reutilization pathways can both influence the carbon mitigation potential. And the impacts of these factors are captured through sensitivity analysis.

Table 4-5. 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 propers (kilo ton coal-equivalent)	Total energy saved in Fujian's city propers (kilo ton coal-equivalent)	Difference from two tier-annual in Hebei's city propers	Difference from two tier-annual in Fujian's city propers
Two tier-annual	3786.39	227.60		
Two tier-seasonal	3050.66	163.60	-19%	-28%
Multi-tier-seasonal	3502.85	163.60	-7%	-28%

For a conservative estimate, we computed the economic payback period for the most conservative two-tier-seasonal scenario (Fig. 4-5 and Table 4-6), which shows the least percentage reduction. And we found that the economic payback for utilizing industrial waste heat in DHS is between 0.9 to 7.7 years for cities in Hebei, with the average of 2.7 years (Table 4-5). For DCS, the pay-back time is longer, because of higher cost in the distribution network. The payback time varies from 3.7 to 14.2 years, with the average of 11.1 years.


a. Percentage of energy savings from reutilizing industrial waste heat in DES in total energy use for heating in commercial and residential sectors in Hebei's cities

b. Percentage of energy savings from reutilizing industrial waste heat in DES in total energy use for cooling in commercial and residential sectors in Fujian's cities

Figure 4-5. Sensitivity analysis comparing energy savings in different scenarios.

Note of Figure 4-5: Scenarios include two tier-annual, two tier-seasonal, and multi-tier-seasonal in Hebei's city propers (Fig 4-5a) and Fujian's cities (Fig 4-5b)

Table 4-6. Economic analysis in Two Tier-Seasonal of reutilizing industrial waste heat in district energy system in Hebei and Fujian

Cities need heating	Cost-Equipment (million *yuan*)			Cost-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	1,148	1,005	107	1,112	1.1
Qinhuangdao	74	16	115	142	348	202	15	217	1.7
Handan	204	44	378	452	1,078	358	88	446	3.0
Xingtai	45	10	75	92	222	72	43	115	3.0
Baoding	45	10	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	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	1,213	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

4.4. Conclusion

The reuse of industrial waste heat in urban built-up area can be a key strategy for urban energy efficiency. While high-grade heat exchange across industries is a key 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 showed to be feasible for case studies (Fang et al., 2015b, 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 based on many characteristics, including the industrial structure, the balance of homes, business, and industry in a city, as well as climate conditions, indicating the importance of this methodology in applying waste heat 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 in 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 availabilities, such as the United State 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 4-1 also suggests that more open reporting of employment and GDP at the city level can much facilitate the 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 A4-1). Second, we are conservative in waste heat availability for district energy – not including high-grade heat, which may be used in industry. The estimation also only includes 25% of medium grade heat because of chemical corrosion concern from sulfur containing gases. Lastly, based on other studies that indicate low-grade heat can be safely and efficiently conveyed over fence line distances up to 30km (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 provide 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.

4.5. Acknowledgment

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Publication note: The content of this chapter has been peer-reviewed and published on *Environmental Research Letter*. I played a leading role in this project. I collected data and conducted analysis with other collaborators. I was responsible for manuscript writing and responding to reviewers' comments for publication.

Chapter 5. Motivation and Enablers for the Sustainable Transitions of Community-wide District Energy Systems in the U.S.

Abstract: Advanced district energy systems (DES) using low-temperature heat, as one of the community-wide energy infrastructures, can contribute to cities' sustainability through reducing carbon emissions from heating and cooling services. However, the majority of current community-wide DES in the U.S. is not the advanced systems and need to be upgraded. This research, focusing on DES operators as the front-runners in infrastructure transitions, investigated their understanding of sustainable transitions of DES in the near future, as well as motivations and enablers for these transitions. Interviews were conducted to investigate how the business strategies of DES operators interact with factors related to ecosystem, technology, institutions, and users to influence the transitions. We conducted semi-structured interviews with fourteen DES professionals working in private companies, universities, cities, and the DES industrial associations. Interview data were analyzed in NVivo software applying the grounded-theoretical approach. Results indicate that community-wide DES in the U.S. is slowly moving from current steam-based second generation toward the fourth generation DES. Some universities, hospitals, and cities are leading this transition as units that demand sustainable and reliable energy systems. This transition in the U.S. is market driven, meaning that DES operators are motivated by the customers' demand to take transitioning actions. However, the wide-spread transition is slow in the U.S., according to interviewees, because a) fossil fuel is cheap; b) electric utilities are competitors although they could also offer DES services in their business model; and c) energy policies and incentives do not systematically consider heating service. Most DES customer's and policymakers' lack of understanding about energy choices is indicated by interviewees to be a major barrier for changing status quo. Effective Strategies identified by DES operators to overcome these challenges include work closely with users and policymakers, such as by identifying a local champion, continuously engaging with customers to explain emerging opportunities in the field, tapping technical expertise to understand the emerging technological opportunities. Future work comparing successful and shrinking DES can further shed light on the enabling factors/barriers.

5.1. Introduction

Community-wide energy infrastructure, defined as the distributed energy systems providing energy use to communities, emerges as a tool to support urban sustainable development. Examples of community-wide energy infrastructure include district energy systems for heating and cooling purpose and micro-grid for electricity. These energy systems are posited to reduce carbon emissions associated with energy use in buildings and transportation through utilizing locally available renewable energy (Kammen and Sunter, 2016) and other zero-carbon energy sources (Connolly et al., 2014, Ramaswami et al., 2017b). Furthermore, community-wide energy infrastructure is expected to enhance the resiliency of local energy supply as the response to extreme weathers. Overall, community-wide energy infrastructure is a local choice for achieving multiple United Nation's Sustainable Development Goals, *i.e.* affordable and clean energy, sustainable cities and communities, innovation and infrastructure, and climate action (United Nations, 2015).

In the U.S., community-wide energy infrastructure has the potential to shape the existing energy supply and demand patterns (Aznar et al., 2015). Communities in the U.S. actively take actions to reduce their carbon emissions, and community-wide energy infrastructure is one of the choices (Aznar et al., 2015, Klein and Coffey, 2016). The extreme weather events hit the U.S. more often and result in damage to cities due to the loss of utility, which drives the development of community-wide energy infrastructure to improve resiliency. The U.S. Department of Energy initiated a research project on technological development for micro-grids (Ton and Smith, 2012). DES has been under-studied in the context of sustainable transitions, although it has the potential to offer resilience. Some studies have demonstrated the advantage of promoting community-wide energy infrastructure from the perspective of engineering technical analysis, while fewer studies have focused on its societal transition pathways in the U.S. This leads to a mismatch between current practical needs and our limited knowledge in terms of changing local energy system.

District energy systems in the U.S. provide a context to study how social actors incorporate emerging technologies in constructing new infrastructure and upgrading the outdated legacy systems. No direct federal or state level policies in the U.S. support the development or transitions of district energy systems (Cooper and Rajkovich, 2012). Furthermore, no federal level carbon mitigation policies are in the place now, which can be a strong driver for countries to reconsider their energy supply system. The transition of DES is expected to be market-driven, while pathways of future transitions are unknown.

The DES potential has not been fully realized in the U.S. communities, given the fact that it is not a common heating and cooling choice (Werner, 2017). Fewer studies have explored DES transitions compared to some emerging choices (*e.g.*, community solar gardens and micro-grid). However, low-carbon heating and cooling supply systems are expected to contribute significantly to carbon reduction and the associated co-benefits, because heating and cooling energy use take upon over 60% and 30% of energy consumption in residential and commercial buildings respectively (EIA, 2016). And the proportion of district heating, which can be a low-carbon heating and cooling supply services, only takes up to 5% of total heating and cooling energy use in supplying heating and cooling in commercial buildings (EIA, 2016), thereby shown a lot of room for growth. Better facilitating environmental sustainably transitions of DES in the U.S. is expected to have significant environmental benefits.

Previous studies have developed theoretical frameworks and analytical tools on sociotechnical system transitions. The multilevel perspective analyzes the co-evolving interactions in niches, sociotechnical regimes, and landscapes to shape dramatic changes happening at the regime level as the transition (Geels et al., 2017, Loorbach et al., 2017). To be more explicit on the agency issue, the co-evolution framework proposed by Foxon and his colleagues have emphasized social actors in regulation, market, and non-profit sectors in shaping the transitions of infrastructure (Bolton and Foxon, 2013, Foxon, 2011, Foxon, 2013). This co-evolutionary framework lay out five subsystems (*i.e.*, business strategies, ecosystems, technology, institutions, and user practices) together influence the transition pathways of infrastructure systems (Foxon, 2011). Sociotechnical system transition literature generally takes a retrospective view to investigate the features and dynamics of this process (Turnheim et al., 2015, Geels et al., 2016), while possible future processes are less studied due to the challenges of data collection (Sovacool and Hess, 2017). Studies have been less specifically focused on the infrastructure operators/owners to understand their long-term and short-term practical view of changing infrastructure to be environmentally sustainable (Ramaswami et al., 2012b), although they are the front-runners for taking any actions regarding change the system for critical transitions.

This research, focusing on the infrastructure operators of community-wide DES in the U.S., aims to provide an empirical understanding of the motivations and enablers from co-evolutionary perspectives for future changes. Two main questions in this research are: 1) What environmentally friendly transitions (big changes) are occurring in community DES in the U.S. in the near-term future? and 2) From a co-evolutionary perspective, what are the motivations and enabling factors for community DES operators in the U.S. taking actions towards environmentally friendly transitions? Results are expected to illustrate the environmentally sustainable transitions of DES and short-term actions that DES operators are taking. Furthermore, we will understand how the interaction between business strategies and other four factors (*i.e.*, user, technology, institutions, and ecosystem) contribute to lock-out not sustainable operations of infrastructure systems.

The rest of the paper is arranged as follow. Section 2 details the literature on sociotechnical transitions and co-evolutionary understandings of community-wide energy infrastructure transition. The background of district energy system in the U.S. communities is detailed in Section 3. Research methods and data are discussed in Section 4. Research results were presented in Section 5. The conclusion and policy implication of this study is discussed in Section 6.

5.2. Literature Review on Sociotechnical Transitions of Urban Infrastructure

The transitions of a sociotechnical system were shaped by the relationships in niches, regime, and landscape. Innovative technological breakthrough or social reconfiguration first happens in niches, which are a comparatively isolated environment in the society. The sociotechnical regime is a stable environment for existing technical and social practices. It can be considered as a temporal balance status with a well-accepted technological and social norms. The landscape of a sociotechnical system is the general social conditions (*i.e.*, the knowledge and value systems shared by the global society) beyond niches and regime, which is extremely difficult to change dramatically. The three concepts and their relationship in explaining transition process are popularized by Geels and his colleagues in the multi-level perspective (MLP) framework (Geels, 2005, Geels, 2002, Geels, 2011, Geels, 2014). Many empirical studies applied this analytical framework to study the role of technology in shaping the transitions of a sociotechnical system, such as power generation technology and water supply system (Geels, 2005, Geels, 2002, Geels, 2011, Geels, 2014). Although the MLP framework has significantly influenced the theoretical framing in studying sociotechnical transitions, it lacks emphasis on agencies in transitions. Moreover, the definitions of niches, regimes, and landscapes are vague, which provides flexibility and confusion at the same time (Smith et al., 2005). Researchers began to construct new theories to align transition with the governance structure of a sociotechnical system (Smith et al., 2005) or with the consideration of transitions' physical feature (changes of built-up environment, geospatial boundary, and land use feature). Due to these critics, many studies adopted this framework with adjustment or posit new framework to addressing problems that could not be fully answered through using this framework.

The transition pathways are examined based on the main driving forces in this process from theoretical and practical perspectives. In the three transition models proposed by Foxon and his colleagues, the focus is on the agency as the drivers in transitions (Foxon, 2011). The agency during transitions can also be reflected to as the response to changes at niche and regime level (Smith et al., 2005, Smith and Stirling, 2010). The four transitioning contexts have integrated the political factors and agency in shaping the pathways according to the articulation, adaptive, and negotiating capacity in the process of selecting niche level innovation and landscape pressure (Smith et al., 2005, Smith and Stirling, 2010). Based on the difference of steering adaptive relationship and resource focus, the transition context can be categorized into endogenous renewal, reorientation of trajectories, emergent transformation, and purposive transition (Smith et al., 2005). Parallel but not mutually exclusive with this discussion, the difference between reproduction, transformation, and transitions, as different pathways, were also discussed further with the application of MLP framework and the integration of agencies (Geels and Kemp, 2007, Geels, 2010).

Depending on who is leading the transition, Foxon and his colleagues summarized three different transition pathways, which are government-led (policymakers are pushing the transition agenda), market-led (business entities are pushing the transition process), and society-led pathways (civil-society are pushing the transition process) (Foxon, 2013). The transition processes may be influenced by their roles, choices, and capacities, due to their social functions (Foxon, 2013). Researchers also have narrowed to specific actors to explore their roles. One study focused on the intermediaries as the niche empowering factors in UK's low-carbon district energy system innovation (Bush et al., 2017). Local government's visions of DES's development are examined to explore the potential transition pathways in the UK (Bush et al., 2016). Also, social actors' decision principle can be integrated into agent-based modeling to evaluate the transitions of urban energy systems (Busch et al., 2015, Bale et al., 2015).

Within different transition pathways, the co-evolutionary relationships among niche, regime, and landscape result in different transitions contexts (Smith et al., 2005, Loorbach et al., 2017). Centering social actors and building upon MLP, the co-evolutionary framework posited by Foxon *et al* details the five subsystems (*i.e.* business strategies, user practices, institutions, technology development, and ecosystem) in changing infrastructure systems (Bolton and Foxon, 2013, Bolton and Foxon, 2015, Foxon, 2011, Foxon, 2013, Foxon et al., 2015, Foxon et al., 2010). And this framework has been empirically tested in the context of U.K.'s energy systems, including both large-scale electricity (Foxon, 2013), localized district heating and combined heat and power technology (Bolton and Foxon, 2013), and energy storage (Taylor et al., 2013).

Responding to the sustainable development, cities and communities, as the mixture of government and geospatial entities, have become active in exploring innovative actions (Hodson and Marvin, 2010). Furthermore, emerging literature emphasized the role of infrastructure in urban sustainable and low-carbon transitions (Bulkeley et al., 2014, McLean et al., 2016). Experimentations done at city or community level for sustainable or low-carbon development are summarized based on observations of these city-level innovative actions (Hodson and Marvin, 2010, Shaw et al., 2014, Bulkeley et al., 2014, Affolderbach and Schulz, 2016). Some local experiments drive the change of urban infrastructures, such as local smart grid project (McLean et al., 2016). Among community-wide infrastructure systems, energy systems attract many attentions. Applying the co-evolutionary framework, the impact of regulation on the development of district energy systems is analyzed in the UK case focusing the regulatory agencies of the energy sectors. The conflict between national-level energy regulation and local energy system development become the major barriers for the development of district energy systems in the UK (Hannon et al., 2013, Bolton and Foxon, 2013, Foxon et al., 2015). The function of different business models in promoting the transition of infrastructure are also discussed in the context of district heating systems in the UK (Bolton and Hannon, 2016). In France, local energy transitions using district heating as a tool should consider the complexity of energy system located in (Rocher, 2014).

Based on previous studies, the socio-technical system in this research refers to the district energy systems as a way providing heating/cooling services to multiple buildings in the US. Currently, the regime of district heating system is that heating or cooling is mainly provided as steam and chilled water and relies on fossil fuel through district energy system in the U.S. The sustainable transitions of DES are referred to the processes that district energy systems nation-wide continue to be upgraded to improve the energy and water use efficiency, reduce demand, and integrate renewables, waste heat and other low-carbon heat sources. Niche innovation can happen in buildings, distribution systems, and heat generation for an individual DES system. Landscape referred to the general value, market structure, federal policies, etc. Adopting the co-evolutionary framework, the transitions of DES is investigated through revealing the relationships between business strategies of DES operators and the other four subsystems (*i.e.*, user practices, institution, technology, and ecosystem). The history of district energy system and challenges for the development is discussed in the next sessions.

5.3. Background on district energy systems and the challenges for its development in the United States

District heating systems in the U.S. have a history of over one hundred years. The first city-wide district heating system dates back to the late 1800s (Ulloa, 2007). The development of district heating systems is associated with the process of industrialization in the U.S. Many legacy city-wide district energy systems were constructed a long time ago when industries located close to residential and commercial buildings. These systems were steam-based with fossil fuel as energy sources. Regarding district cooling, the first city-wide district cooling is developed in Hartford, Connecticut in the 1960s (Werner, 2017). With technology development, the City of Saint Paul conducted the first conversion from steam-based system to hot-water-based district heating system at the end of the 1970s. Recently, some universities have been very aggressive in adopting new technologies, such as waste heat recovery, deep lake cooling, and hybrid heating and cooling systems. For example, the Stanford Energy System Innovations is using electricity and heat recovery technology to supply low-carbon heating and cooling service to buildings on campus. Cornell University has adopted the deep lake cooling technology in its district energy system. During the past several decades, there have been some innovative actions to make district energy systems more efficient and environmentally sustainable in the U.S. These actions mainly happen at the local level, which is comparable to niches in sociotechnical transition literature.

Table 5-1. Market Share of District Heating and Cooling Systems in the U.S. in the year 2012 (from (ICF and IDEA, 2018))

Heating	**Gross square footage (million sq.ft)**	**Market share of district heating**
IDEA 2012 Baseline reported sq.ft served	5,451	
EIA 2012 CBECS tables-Table B34 All buildings	87,093	6%
EIA 2012 CBECS tables-Table B34 100% heated	55298	10%
Cooling	**Gross square footage (million sq.ft)**	**Market share of district cooling**
IDEA 2012 Baseline reported sq.ft served	1,877	
EIA 2012 CBECS tables-Table B34 All buildings	87,093	2%
EIA 2012 CBECS tables-Table B35 100% cooled	37,676	5%

Note: IDEA means International District Energy Association; CBECS means Commercial Buildings Energy Consumption Survey

One recent report on the market share of district energy systems in the U.S. delineated the features of DES at the regime level through compiling data of 660 district energy systems in the year 2012 (ICF and IDEA, 2018). Table 5-1 demonstrates the market share of district heating and cooling in the U.S. through comparing the floor areas served by district heating and cooling separately in commercial buildings. In the year 2012, only 6% of commercial building floor areas are served by district heating systems. And 10% of the fully heated commercial floor areas are served by district heating. The penetration rate of district cooling is also very low. Only 5% of fully cooled commercial building areas are served by district cooling.

The majority of district heating systems in the U.S. is steam-based systems, based on the installed capacity in the year 2012 (Table 5-2). The installed capacity of hot water systems is only about 3% of installed capacity of steam systems. CHP adoption rate is low in district energy systems at the moment. Regarding fuel structure, 74% of DES is fueled by natural gas and 16% of DES uses coal in the year 2012 (ICF and IDEA, 2018). Overall speaking, DES in the U.S. is in the second generation, which is steam-based with fossil fuel as energy sources.

Table 5-2. Total Installed Capacity of District Energy System in the U.S. in 2012 (from (ICF and IDEA, 2018)

Energy generation	Total installed capacity
District heating – Steam (MW)	57,243
District heating – Hot Water (MW)	1,578
Electricity Generation – CHP (MW)	6,744
District cooling – Chilled Water (MW)	15,491

Note: CHP and steam, chilled water data may have overlap, not additive.

The market share of DES is slowly increasing annually, according to the newly added floor areas connected to DES. From 2011 to 2016, about 23 to 52 million square foot areas annually in the U.S. are connected to district energy system or re-committed to the connection for a long-term (over 10+ years) as shown in Figure 5-1. Commercial buildings and educational facilities & hospitals are the two largest drivers in annually added floor areas connected with district energy systems. The latest report predicted building floor areas connected to hot water systems in the U.S. will drive the market in the near future (ICF and IDEA, 2018).

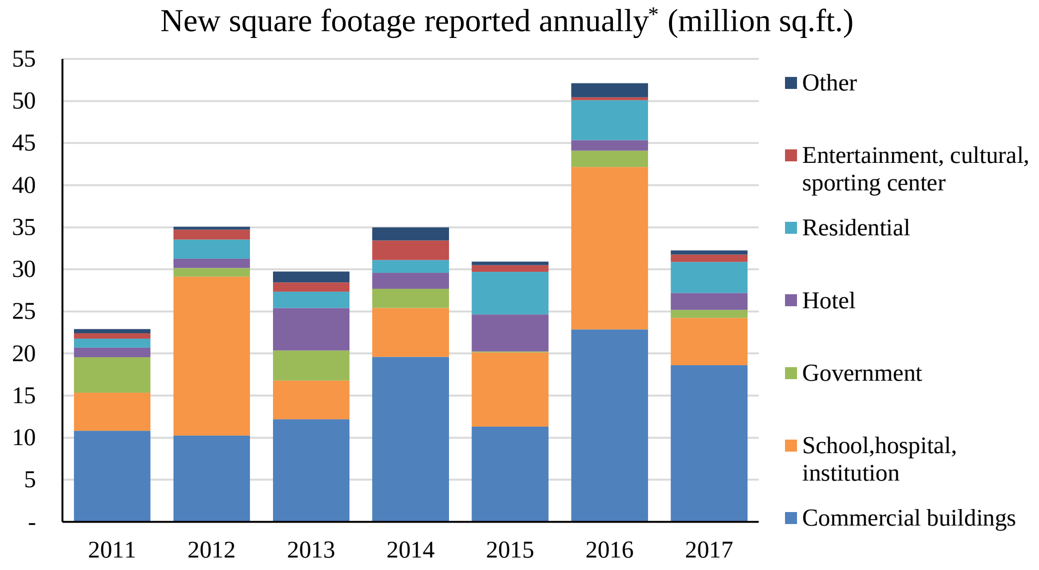

Figure 5-1. The self-reported annual newly added district energy floor areas in the U.S. with building types specified

*: New added here mean all entries are newly signed, connected or renewed customers during each calendar year. Here renewal means contractually recommitted to a long-term service agreement of 10 years or greater. Data were compiled from the website of International District Energy Association by the author.

The development of district energy system in the U.S. is not prevalent, partly due to lack of policy support. First, there are no direct policies at the state and federal level addressing the low carbon development of district energy systems. Without higher level support, district energy systems have to compete with other heating or cooling choices. Few federal policies in the U.S. support the development of district energy systems, except some technical programs initiated by different federal agencies. For example, the Environmental Protection Agency (US-EPA) has a Smart Growth Implementation Assistant program to support the development of selected communities. The Department of Energy also has a program on zero energy buildings, which provides technical support for designing zero energy buildings from individual building levels to the community level. Communities can use these technical support for their sustainable development of community energy systems.

At the state-level, there is also no policies directly support the low-carbon development of district energy system, while some policies supporting the development of combined heat and power (CHP) enable the development of DES to some extent. DESs are a heat sink for CHP. When existing DES is near to a new CHP, DES can use the heat from the system and make the whole system more economically feasible. State level policies on CHP mainly cover environmental regulations, financial support, or energy development plans (EPA Report 2015) and different states adopt a different set of policies regarding the promotion of CHP. These state-level policies may have a large impact on the low-carbon development of DES through increasing CHP adoption rate in some states.

Local policies play a significant role, considering the fact that DES is a community-wide infrastructure system. Cities and other local agencies have certain authorities to decide whether DES should be regulated as a utility or not. In addition to defining DES service, other policies also influence how DES can be developed at the local level. Although there is on big dataset on city-level DES policies, an ACEEE database on city-level energy policies sampled 62 cities/counties. Through analyzing this dataset, I found that 23 cities have developed plans to identify the potential of DES/CHP in their high-density areas. Another 4 cities have a plan to conduct a feasibility analysis on the development of district energy system. Additionally, some cities formed a municipal utility committee to oversee the development of district energy systems. These local movements are expected to contribute to DES development at a scale larger than individual projects.

In addition to the lack of policy support at multiple levels, studies have identified several other barriers for promoting district energy systems in communities. DES needs high capital investment upfront for energy generation and distribution systems. Different ways to deal with this investment should be developed according to different business models. In addition, the public doesn't understand different heating/cooling choices most of the time, as well as evaluating the benefit and cost of these choices. When natural gas or electricity is cheap, building owners are less likely to consider DES as an economic option (Werner, 2017). These are all potential barriers for DES's transitions.

5.4. Method and data

Data were collected through semi-structured interviews. The snowball sampling method was applied to recruit interviewees. In total, I conducted 14 interviews and each lasted about 60 minutes on average. The interviewees' working affiliations are detailed in Table 5-1. In total, six interviews were conducted with people working in private agencies, including for-profit, non-profit, and customer-owned companies. For public-owned facilities, I interviewed one city official in charge of a public-owned DES. Universities/colleges have been pointed out leading the transition several times during the interviews and the size of these DESs are comparable to city-wide DES. Thus, I conducted four interviews with people working in the energy department of universities. Although district energy engineering consulting companies and industrial associations do not directly operate the physical system, their role as system designers and their knowledge about the industries are valuable. Thus, I conducted two interviews with persons from two different consulting companies and one interview with a person from the industry association. The main interview protocol is attached in Appendix 5.

To reveal the transition pathways of DES and summarize actions for the transitions, data were mainly analyzed based on a grounded theoretical approach. The themes related to transition and transitioning actions were coded in In Vivo coding and inductive coding methods (Saldaña, 2015).

Table 5-3. Background of interviewees in district energy systems in the US.

Roles in DES industry	Number of interviewees
Private DES operators/managers/owners	5
Co-op DES operators/managers/owners	1
Public DES operators/managers/owners	1
Energy Department at University	4
DES industrial association	1
Private DES consulting company	2

The coded themes were further interpreted and evaluated with the alignment of four generations of DES posited in the literature (Lund et al., 2014, UNEP, 2015). The first generation DES circulates hot steam using coal in boilers, which are system built from the late 1880s to the 1930s. The 2nd generation DES circulates low-temperature steam using coal and natural gas as energy sources. Some of the DES are part of a CHP system in the second generation. The 3rd generation DES circulates hot water, with more integration of CHP, renewable energy, and high-temperature industrial waste heat as energy sources. The 4th generation DES is expected to circulate warm water with more renewable energy and low-temperature waste heat recovery. In addition to energy sources, building efficiency is significantly increased from the first generation to the fourth generation DES.

Regarding the co-evolutionary relationships between business strategies and the other four subsystems in shaping the transitions, two steps of coding were applied. At first, data were coded to separate the five components posited in the co-evolutionary framework. The definition of the five components is adopted from Foxon (2011):

> "***Ecological systems*** can be defined as systems of natural flows and interactions that maintain and enhance living systems.
> ***Technological systems*** can be defined as systems of methods and designs for transforming matter, energy and information from one state to another in pursuit of a goal or goals.
> We take a broad definition of ***institutions*** as ways of structuring human interactions. This follows the institutional economics tradition of Douglass North (1990), who defines institutions as 'the rules of the game'. These rules are taken to include, for example, regulatory frameworks, property rights and standard modes of business organisation.
> ***Business strategies*** can be defined as the means and processes by which firms organise their activities so as to fulfil their socio-economic purposes.
> ***User practices*** may be defined as routinised, culturally embedded patterns of behaviour relating to fulfilling human needs and wants."

The second step is to use inductive coding method to further analyze how the interactions between the business strategies of DES operators and the other four components motivate, enable, and hinder them to take action for environmentally-sustainable transitions. These motivations, enablers, and barriers were analyzed at both the niche and regime level. At the niche level, themes are what emerged from individual cases. In other words, local-level factors have a significant impact on the transitions of individual DES, which is considered as the innovation at the niche level. Regime practices are what adopted largely in the DES industries, which is beyond individual best practices. Factors at the regime lever are the general themes extracted from interviewees' answer in a general context and consistent themes at the niche level in this study. Coding procedure followed various methods (*e.g.*, descriptive coding, In Vivo coding, *etc.*) discussed by Saldaña (Saldaña, 2015).

5.5. Results

5.5.1. Environmentally sustainable transitions of city-wide district energy system in the U.S.

In general, community-wide DES is becoming more environmentally sustainable in the U.S. This change is happening at each key component of DES systems from energy generation to distribution and end-use phase in buildings (Figure 5-2). More and more DESs utilize low-carbon or zero-carbon energy, such as renewable energy, biomass, and surplus heat from the built-up environment (*e.g.,* heat embedded in sewage and industrial processes). The surplus heat utilization can be combined with the electrification of heating and cooling in communities supplied by low-carbon electricity grid. In addition to low-carbon energy sources, thermal storage becomes a key component in energy generation system, especially when the cost of storage is driven down by technology development. In term of the distribution system, new DESs are using hot water (around 150-200 °F) for heating purposes and are expected to use low-temperature water. Additionally, some steam-based DESs are converted to water system for integrating more low-carbon energy sources. On the building side, smart metering will provide more data to users and designers. These data can help design the system in an efficient way. All these themes pertain to 4th generation DES, according to academic studies (Lund et al., 2014, UNEP, 2015). This demonstrates that the DES in the U.S., the majority is the 2nd generation, which is slowly moving towards the 3rd and 4th generation, although without policy pressure from state and federal government. In addition to this movement, the future DES can be part of local smart energy systems with micro electric grid systems (Figure 5-2). This community-wide smart electric and thermal energy systems are posited by some researchers as smart energy systems (Lund et al., 2017). For the long-term, hydrogen-based energy system may replace current hydrocarbon energy system, but professionals do not think the current short-term actions can contribute to this transition. These results demonstrated that DES professionals' visions align with academic studies regarding the future of DES. The engineering knowledge has been diffused into the practitioners' agenda.

These environmentally sustainable transitions of DES are what we desired for; however, some steam legacy systems may be locked in their current steam systems and eventually being shut down. One of the biggest challenges to convert these legacy systems is that they are located in cities with congested underground utility systems, such as Boston and New York City. It is extremely expensive to dig up the street for public work. One interview mentioned that:

> "*To put in massive district energy systems underneath the streets of cities is very difficult, because the cities are established, and nobody likes to dig up the streets…Several years*

ago we did a modification to some piping in the city of Boston, and I believe the cost was $5,000 per linear foot."(DES_09)

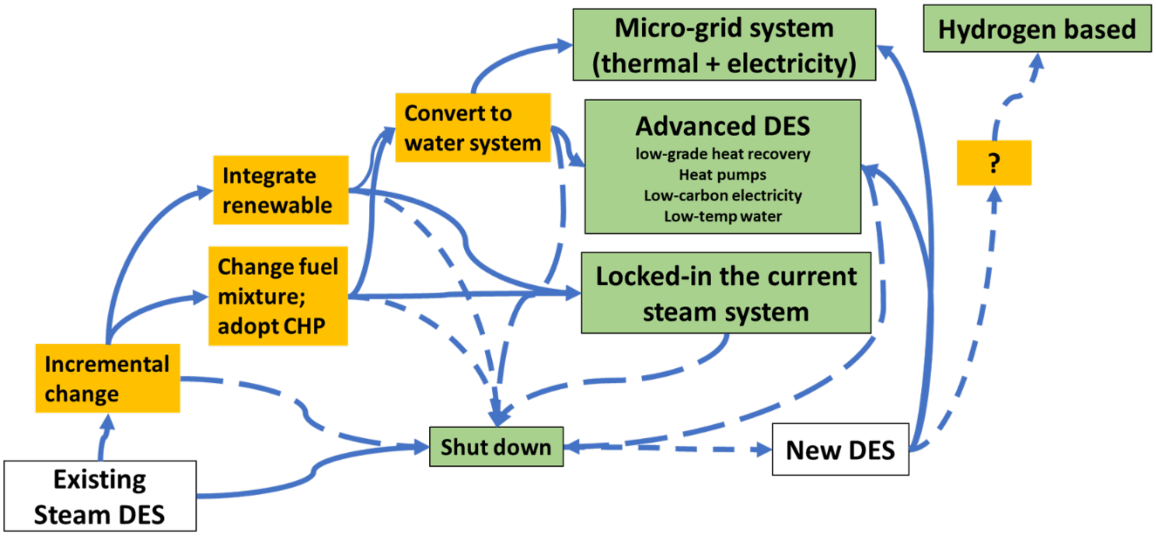

Figure 5-2. DES transition pathways in the U.S.

The scale of these transitions still remains unknown. Some DES professionals think that the market of DES is growing with these changes. This growth is led by universities/colleges, hospitals, and some cities aiming for carbon mitigation and local sustainability, as what have been shown in Figure 5-2. Others think their companies maintain the market share of DES, instead of considering it as a growing market. Nevertheless, DES professionals are acting to make the system more environmentally sustainable.

5.5.2. Five subsystems in the co-evolutionary framework and DES transitions in the U.S.

Business strategies of district energy system operators: Individual DES operators' business strategies are influenced by their ownership & maintenance models, business goals, business models, capacities, and cultures (Table 5-4). DES can be municipal-owned, customer-owned, and private-owned (for-profit or not-for-profit; regulated or non-regulated). For public- or customer-owned DES systems, the operation and maintenance may be out-sourced to a professional agency. The difference in ownership and operation model determines DES operators' business goals and models to generate revenues for capital and maintenance investment. Regarding the promotion of environmentally-sustainable transitions, the capacities of DES operators are very important. These capacities do not only include financial conditions and engineering and financial analysis skills, but also refer to the capacity to conduct community outreach and comprehensive technical-economic scenario analysis integrating possible future changes. The cultures of DES business influence whether they can be innovative and forward-looking in changing their system. Both the business capacity and culture have a strong impact on what decisions will be made by operators to change existing DES or planning out new ones.

Table 5-4. Key themes associated with business strategies of DES operators

Key factors influence business strategies	Key themes of each factor
Ownership and operational models	• Municipal-owned • Private companies (regulated or non-regulated) • Customer-owned
Business goals	• Private companies: making money for shareholders • Public/CO-OP/IOU: providing services to customers
Business models	• Mainly providing heating/cooling thermal energy • Some also provide consulting services
Business capacities	• Financial conditions • Engineering • Financial-technical-community analysis • Current and future scenario analysis
Business cultures	• Missions • Leadership • Forward-looking

Ecosystem and district energy systems: Here the ecosystem does not only refer to the natural physical surroundings of a city, but also covers the built-up environmental features within a city (Table 5-5). Three ecological factors (*i.e.*, climatic factors, built-up environment, and accessibility to the different natural resources) influence the energy demand and supply in a community, which together determines whether a district energy system is an economical choice for the community or not. Heating/cooling loads are determined by the climatic factors (heating and cooling degree days) and the building functions and density in the built-up environment. At the same time, accessibility to natural resources and energy embedded in the built-up environment together influence what low-/zero-carbon energy can be utilized locally. It has to point out that the accessibility to low-/zero-carbon energy is also influenced by technology. For example, 20 years ago it was not economically feasible to utilize renewable energy and low-grade waste heat from the built-up environment in DES, even though these resources are in the environment. In a nutshell, the interaction between DES operators and ecosystem is not the motivation for sustainable transitions of DES, while local ecological and environmental factors can enable taking these actions.

The DES transitions are influenced by the changes in natural physical surroundings of a community. Interruption due to extreme weathers drives people prioritizing resilience when considering different energy choices. This leads to the consideration of DES. Furthermore, heating and cooling days are changing due to climate change, which directly influences local demand portfolio. DES operators have to consider expanding their existing systems or changing existing service provisions. These ecological changes have direct impacts on users' preference, which further affect DES operators' strategies. In addition to responding to ecological changes, DES operators also try to minimize the associated environmental impacts of DES either due to regulation or local communities' desires. Air pollutants, carbon emissions, and water use are the three major environmental impacts that DES operators focused on.

The utilization of natural resource has a different requirement regarding logistic, especially for biomass. This logistic requirement may create additional cost. Also, the utilization of renewable energy, like wind and solar, has a different requirement regarding land use, compared to boilers. This factor has been overlooked in many discussions of renewable energy use, while it is critical for community-wide energy infrastructure. The built-up environment also may bring challenges for DES transitions. For the existing legacy district steam heating system in many cities, the cost of converting steam pipes to hot water is extremely difficult due to the congested underground utility lines as mentioned previously. The solution for this is above ground utility line, which needs a new design of DES distribution systems, such as above-ground pipes.

Table 5-5. Business strategies and ecosystem in DES transitions

Key factors associated with Ecosystem	Business strategies of DES operators for transitions with respect to factors in ecosystem		
	Motivation	Enabling factors	Barriers
• Climatic conditions • Accessibility to natural resources • Features of built-up environment • Emerging changes of ecosystem	NA	• Availability of local natural resources to support low-/zero-carbon DES, such as lake close by, biomass, etc. • Clustered users and diverse uses in build-up environment make DES cost-effective. • Climatic factor leads to high load • Users perception of DES as more reliable (than electricity) in extreme weathers.	• The logistic of natural resource use can create challenges for biomass use. • The feature of built-up environment does not support DES • Infrastructure choices influence the land use and space.

Technology and district energy systems: Recent technology development in energy generation, distribution, and end-use in buildings have made DES a low-carbon heating and cooling choice for communities (Table 5-6). Small-scale combined heat and power, heat pump, heat recovery technology (*e.g.*, deep-lake cooling, sewage heat recovery), and energy storage provide more choices for communities constructing low-carbon DESs. The cost of pre-isolated pipes for water distribution system has been driven down by technology development. The design of new buildings makes them more and more energy efficient. At the same time, smart metering in buildings contributes to better managing energy use. With the development of equipment, new software is needed to better control the whole system.

Technology development is not the motivation for DES operators to take actions for the transitions, because DES is not a high-tech industry. Furthermore, any technologies used in infrastructure system should be mature to ensure its safety. Technology has been recognized as the means for making the systems better rather than the “ends” of DES operators’ businesses.

The development of technology can either enable the sustainable transitions or create some challenges. Technology development generally drives the cost of equipment down, which is one of the largest enabling factors. For DES operators to take this advantage, they have to closely monitor technology development and be able to reconfigure the available mature technologies achieving either carbon mitigation or other sustainable goals (Table 5-6). Aligning with the electrification trend in the future, DES operators should consider the accessibility to green grid for this technical option. Furthermore, when there is a new design on the physical side, the automation of control systems should be developed to better manage energy use and improve the efficiency of the plants. If DES operators conduct innovative design on the physical side, they may need help to develop this type of software.

Table 5-6. Business strategies and technology in DES transitions

Key factors associated with technology	Business strategies of DES operators for transitions with respect to technology		
	Motivation	Enabling factors	Barriers
• Energy sources o Combined heat and power o Renewable energy o Waste heat recovery o Heat pump • Distribution system o Pipes for water system • Controllers in buildings • Energy storage • Software development • Technology development drives the cost of new options down.	NA	• Closely monitor the development of technology • Innovation is needed when combining existing technology • For electrification, access to affordable and "clean" electricity is important. • More suppliers in the market to provide equipment and software can drive the cost down.	• Do not have sufficient technical capacity to deal with the emerging technology. • DES’s competitors become cheaper with technology development. • Collecting data at the building level and different technology to support the cost-effective decision. • Uncertainty in technological development in long-term (20+ years) to avoid lock-in.

Although transitioning actions can be enabled by technology development, it also brings in many challenges. DES operators have to follow all of the latest technology development, which requires additional social capitals. Their understanding of technology development should be able to deal with the uncertainty of future development to some extent. This also contributes to lock-out the bad practices at the first place. The technology development of onsite heating and cooling units also threatens the transitions of DES, because they are the competitors and is also becoming cheaper with the technology development. One interviewee pointed out that

> "*We're always competing with customers being able to put in their own boilers. That's our competition.*"(DES_02)

When those technologies become cheaper and more efficient with the consideration of cheap fossil fuel or electricity, it makes district energy system less attractive. When more data at the building-level are collected, it will contribute to design the system in a tighter way.

Institutions and district energy systems: Energy market in the U.S. is dominated by the centralized fossil fuel energy supply system, such as natural gas and electricity (Table 5-7). Fossil fuels are subsidized and cheap in the US, due to various reasons (social equity and politics). With a low-price of fossil fuel-based energy, the externality of using them is not captured in the cost. In comparison, an environmentally-sustainable DES reduces many externalities, such as carbon emissions, compared to carbon-intensive options. But, these advantages of DES are not reflected in the price. An environmentally-sustainable DES has to be cost-competitive compared to fossil-fuel based heating and cooling choices in the current energy market. When regulations do not favor the development of environmentally sustainable DES, this market structure creates challenges for its transitions.

Community-wide DESs are embedded in a complicated urban system, any policies regulating energy generation, distribution, buildings' end-use, and public work have a strong impact on its transitions (Table 5-7). Energy policies affect what energy sources that DES can use. Local policies on franchise fees, permitting for public work, zoning and building codes, and environmental protections influence local DES's transitions. Because DESs are located within communities, environmental regulations have to ensure the operation of this system does not result in environmental problems to communities. In addition to these regulations, local economic redevelopment drives communities reconsider their energy systems.

Business strategies with respect to institutions: Without higher level policies addressing carbon mitigation, local commitments to carbon mitigation have become the main driver for DES's low-carbon transitions. The environmentally sustainable transitions of DES are motivated by cities' and universities' carbon mitigation targets. When communities want to make a change or consider economic redevelopment, they are open to different energy supply choices. This opens a window for communities understanding energy supply system more and evaluate different choices.

The most important enabling factor for sustainable transitions of DES is to solve financial problems that DES operators may encounter, especially for the up-front cost of energy generation and building-level renovation. For example, tax credits and rebate programs should consider the environmental benefits of district energy systems, which will help their environmentally sustainable transitions. Because multiple local and cross-scale stakeholders are involved in a DES project, local champions, who are willing to spend their political capitals in navigating through the process of bringing agreement, are extremely important for a successful transition. Policies encouraging building owners to connect to an environmentally sustainable DES also enable the transitions of DES. For example, LEED in the latest standard has included the reward points of a building connecting to a highly efficient DES. This drives more building owners and real estate developers considering DES.

Table 5-7. Business strategies and institutions in DES transitions

Key factors associated with institutions	Business strategies of DES operators for transitions with respect to institutions		
	Motivation	Enabling factors	Barriers
• Market structure o Centralized energy supply (electricity and NG) is dominant Fossil fuel is subsidized o Price of fossil fuel is cheap and fluctuating • Regulations o Climate change o Environmental protection o Financial policy o Zoning o Building codes o Utility policy o Public work policy	• Carbon mitigation goals • Urban economic redevelopment drive cities reconsidering their energy supply system.	• Policies make capital investment in every component of DES easier, e.g. tax credit, low-interest rate, etc. • Local policies encourage building owners to connect to DES through floor area incentive. • Building codes specify setting up heating and cooling water system within buildings • LEED points to buildings connected to efficient DES. • Local champions to advocate for the transition of DES.	• Electric utilities' business models do not consider DES in their portfolio • Local users are reluctant to fully electrify heating and cooling with the combination of waste heat recovery; low trust in the grid • Regulations have not help to create a market for all low-carbon energy, such as biogas and sewage waste heat. • Permitting process for infrastructure construction is long.

o Economic redevelopment policy o Policy design		• Regulators willing to collaborate and promote the transition.	• Regulators not familiar with DES and reluctant to revise existing policies.

Electricity utilities in the U.S. are used to own many cities' district energy system; however, these dominant market players now consider community-wide district energy system as competitors in the market. If the environmentally sustainable transitions of DES threatens electricity utilities' market share, the actions are highly possible to be blocked by them due to their political power. For a long-term, a new mechanism is needed in the market to deal with the relationship between centralized energy and community-scale DES services provisions to enhance energy infrastructure reliability and sustainability. At the moment, the negotiation among various stakeholders happened at the individual level, and the new norm has not been formed yet. The lack of rules dealing with this emerging community-scale infrastructure created burdens for DES business to play political games.

Barriers regarding regulation for DES operators taking actions are that current policies lack the integration of new ways to set up the advanced district energy systems. For example, heat recovery from sewage system is innovative, but also takes new negotiation with sewage regulation sector to ensure this action won't influence the sewage systems. This cross-sectoral discussion involved many new partners, which may create more hurdles for implementing this action. Many of the barriers are related to permitting process and policies, regarding environmental impact, cross different property lines. It takes the business a long time to get permit doing any changes to the existing system. Given the condition that many existing policies are not facilitating the DES development, DES operators have to work closely with public sectors for demanding certain changes.

Users and district energy systems: Users, as the demanders for heating and cooling service, play a central role in its transitions (Table 5-8). Users' decision principles, their understanding of different energy choices, and their value system together influence the pathways of environmentally sustainable transitions of DES. The most important decision principle is the cost-effectiveness of energy choices. Furthermore, the reliability of energy supply sometimes is also prioritized by some users. The third decision principle is sustainability, when users become more aware of the carbon and other environmental impacts of their energy system. Users have to consider the trade-off between cost and the other two criteria. Even users may value sustainability, their lack of understandings of DES constraint their decisions on promoting DES. In addition to knowing the existing heating and cooling choices, users also should be able to evaluate the cost and benefit of them from the life-cycle perspective and systems-thinking perspectives. For example, connecting to DES, users can free up some space in the building and save cost for maintaining the individual heating/cooling equipment. This benefits should be integrated when users conduct a cost-benefit analysis. Furthermore, the competition between DES and on-site heating/cooling choices is also influenced by American spirit of individualism. This individualism spirit of the U.S. may also create challenges for DES's transitions, since the transitions require collective actions within communities.

Business strategies with respect to user practices: As discussed above that business strategy of DES is to provide heating and cooling service to users, DES operators have to provide the services that users demand. The increasing demand for sustainable and low-carbon heating and cooling service has been a major motivation for the environmentally sustainable transitions of DES. But this demand does not overwrite the requirement for cost-effectiveness. In other words, DES operators should be careful to deal with the cost of taking actions for environmentally sustainable transitions.

Table 5-8. Business strategies and user practices in DES transitions

Key factors associated with user practices	Business strategies of DES operators for transitions with respect to user practices		
	Motivation	Enabling factors	Barriers
• Users' decision principles o Cost-effectiveness o Reliability o Sustainability • Users' understanding o Benefits of DES o Evaluate the cost and benefit • Users' value systems o Individualism vs collective actions	o Users and real estate developers want energy supply to be cheap first, reliable, and environmentally sustainable (carbon mitigation, energy efficiency). o Some users, like universities, have carbon mitigation goals.	• Forward-looking with the consideration of: • Future demand • Attract new users • DES operators develop a close professional relationship with users • Financial incentives for users to connect to DES • Users willing to work with DES operators towards transitions.	• Difficult to change existing knowledge and assumptions. • Capital investment plan for improving the system and the acceptance of price change among users. • Capital investment in buildings • Price sensitive users • Create agreement among various stakeholders. • Users' experience signing a long-term contract.

Considering the fact that many users do not understand the full benefit of DES, DES operators should have a professional customer service team and a community-outreach team to educate users and community members. The professional customer service team works with existing users to solve any problems they encounter when using the services. This is an opportunity to inform and educate users on evaluating the cost and benefit of DES, especially when additional capital investment is needed from building owners if they plan to connect. This visible cost makes many of building owners reluctant to connect to DES, if the benefit of connecting with a DES is not evaluated holistically. The forward-looking of DES operators on users' demand should consider future demand from users in the communities and a reasonable plan to attract new users to connect. For public owned DES, a financial incentive for users to connect is also a good practice to consider.

There are many barriers related to user practices and DES transitions. There should be an effective way to help users to lock-out their current knowledge and assumption with more forward-looking. Capital investment plans on building side are very important. When lack of a local champion, it is very challenging for DES operators to create an agreement in the local community. Once in the "death spiral" of as a local utility, it is difficult for DES to break the bad circle.

5.6. Conclusion

This research revealed the sustainable transitions of community-wide DES in the U.S. through interviewing DES operators and designers. It was found that DES is slowly moving from current 2nd generation (steam-based) towards the 4th generation district energy system, which circulates water and integrates many zero- or low-carbon energy sources with high efficiency. Mainly, cities and universities are actively involved in this transitioning process, due to their carbon mitigation goals.

This research also analyzed the motivations and enabling factors for this transition through adopting the co-evolutionary framework. It was found that the interaction between DES operators and users is one of the main motivations for DES's environmentally sustainable transitions, due to the feature of current energy supply market and regulatory structure. DES operators' revenue stream relies on the service provided to users. When there is increased demand for carbon mitigation, water conservation, and air pollutant control from users and communities, DES operators have to change the system to provide services fulfilling these requirements. Although institutional factors, such as mandatory policies on district energy system planning or carbon mitigation, can motivate the transitioning actions, it is not the case in the U.S. Local level policies, especially carbon mitigation and economic redevelopment policies, provide emerging opportunities for DES's development. The tricky part of these policies is that they are voluntary instead of mandatory. The technical pathways to reduce carbon emission vary in cities having a different natural and built-up environment. The low-carbon transition of DES competes with other low-carbon heating and cooling options. How these voluntary carbon mitigation policies can push DES's low-carbon transitions is also influenced by whether there is local leadership advocating this system.

Technology and ecosystem can be enabling factors for DES operators taking low-carbon actions, rather than motivations. Certain environmental factors and technological development may make the action more cost-competitiveness, compare to other heating and cooling choices. In other circumstance, they can be barriers as well. For example, technology development also drives individual heating or cooling facilities cheaper and more efficient.

This research demonstrated the complexity of changing district energy systems to a low-carbon and sustainable system. If DES operators want to successfully take actions for low-carbon transitions, they need more help from state and federal governments. Regarding capital investment, national-level policies can help to reduce the interest rate for up-front capital investment or provide credits for infrastructure capital investment in carbon reduction purpose. Furthermore, the education and technical support programs provided by state and federal governments are valuable to relieve DES operators' burdens to house many technical experts. State level carbon policies also are expected to push the transition at a larger scale. At the local level, city regulators have a direct role in promoting the low-carbon transitions of local district energy systems. As there are much new technology emerging and strong demand for sustainability, local regulators should be able to catch up these technological changes and revise certain policies appropriately, such as franchise fee and permitting processes. At least, their willingness to change is critical to facilitate environmentally-sustainable DES transitions.

In this research, I have found that DES operators in the U.S. are working in public and private sectors, as well as educational facilities. Due to the significant difference among these operators, their business goals vary significantly. For example for-private companies have to consider financial benefits for their shareholders when making decisions, while the internal utilities at universities have to prioritize the reliability of energy supply. The motivations of changing existing DESs among these operators have been summarized in this chapter, while the differences across these actors should be further explored in future research. Another future research direction is to further investigate how politics and political institutions influence the transition pathways of community-wide energy systems. In this research, local "champion" has been pointed out to play an important role, because they are the persons who are willing to spend political capital in the community to bring key stakeholders together. Beyond the community-level politics, political institutions of cities and state-city/county relationship are expected to influence what type of policy instruments can be adopted. For example, what role of cities can play in the transitions, operators or facilitators, may be influenced by whether they have a strong mayor or strong council. The environmental sustainable transitions can be facilitated by public sectors, while their role is not limited to be operators. Although the institution subsystem is specified in the co-evolutionary framework, how political institutions influence the choices has not been fully discussed in infrastructure transition literature.

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Chapter 6. Conclusion and Policy Implications

Studies in my dissertation investigated low-carbon transitions of urban infrastructure from an interdisciplinary perspective through adopting social-ecological-infrastructure system framework. My dissertation first examined carbon footprints of cities with both emphases on urban infrastructure sectors in cities and the aggregated emissions from all cities in China. I revealed data availability for city-level carbon accounting in the second chapter and constructed new dataset to link cities' collective carbon impact to the national level in the third chapter. Results enhanced our understanding of the relationship between urban infrastructure activities and carbon emissions. Second, I has identified a unique cross-sectoral infrastructure strategy and quantified its carbon mitigation potential in Chinese cities in the fourth chapter. This strategy is to utilize industrial waste heat in the advanced district energy systems for heating and cooling commercial and residential buildings. Results from the fourth chapter demonstrated a significant potential of reducing carbon emissions from heating and cooling energy use in Chinese cities, if existing district energy systems can be changed to the advanced ones capturing industrial waste heat. Last, I explored the environmentally sustainable transition of community-wide district energy systems in the U.S. from a co-evolutionary perspective with the focus on infrastructure operators/designers in the fifth chapter. Practitioners in DES industries have observed the near future change of moving toward the advanced ones to make it environmentally sustainable. The driving forces for this change include the increased market for low-carbon and resilience energy systems in users, universities, and some cities. Results demonstrated that the challenges of changing DES are a complicated issue due to the fact that it embedded in urban systems. These studies focused on both physical and social subsystems in cities to explore how cities with diverse activities can provide new opportunities for carbon mitigation beyond national policies through planning low-carbon urban infrastructure. The scientific contributions and policy implication of each chapter were summarized below.

Applying community-wide infrastructure-based carbon footprinting (*CIF),* I evaluated greenhouse gas emissions from seven infrastructure sectors in cities, including fuel supply, electricity, transportation, water supply/wastewater treatment, municipal waste management, food supply, and construction material. The *CIF* integrates the material and energy flow analysis and life-cycle assessment to calculate greenhouse gas emissions from infrastructure use and its supply chains. One of the contributions of this study in Chinese cities is to identify data sources. *CIF* was implemented in four Chinese cities with various sizes from megacities (>10 million population) to the midsize city (~1 million population). Industrial energy use was found to be the dominant contributor, accounting for up to 30%-70% of total *CIF* depending on the size and economic structure of cities. The contribution of carbon emission embedded in the infrastructure supply chains ranged from 8% to 31% in different cities across these four Chinese cities. Through comparing *CIF* across cities, it demonstrated the commonality and differences of contribution from urban activities related to infrastructure to carbon emissions. Furthermore, with benchmarking of individual infrastructure use efficiency across industrial, commercial, and residential sectors, *CIF* provides more information on urban systems and track cities' performance over time.

CIF is a tool supporting local governments to make customized climate change policies. Due to the consideration of multiple sectors and infrastructure systems, *CIF* also provides data through a more holistic accounting approach for carbon mitigation. *CIF* in four cities shows that the improvement of energy efficiency in the sector of water supply has less impact compared to the improvement of industrial sector energy efficiency. It also shows the cross-sector opportunities, of which has been further identified in the fourth Chapter of my dissertation. In addition, the trans-boundary footprint of different sectors informs city managers about their supply chains, for example, how much of food supply is grown locally compared to outside of the city. This can help cities to become more resilient by informing planners of the potential risks to key infrastructure supply chains. The community-wide infrastructure-based GHG footprint is not only valuable from a GHG mitigation perspective, but also essential for sustainable infrastructure planning to improve urban resilience due to the consideration of key infrastructure sector supply chains. With the benchmarks of infrastructure use efficiency, city managers can compare their infrastructure performance with other cities and monitor changes in performance over time. Additionally, data on urban material and energy flows should be monitored and reported publicly, so that future supply chain risks to the city can be identified. The application of *CIF* and associated benchmarks are critical to moving rapid urban development in China and developing countries towards sustainable urban development.

When we investigate how to customize mitigation action for individual cities, it is also important to quantify the aggregative carbon emissions from all cities in a nation. Facing the challenge of lack of data for all cities, Chinese City Industry-Infrastructure database for 644 cities in 2010 was developed through collecting at-scale data and applying highly effective downscaling schemes in the third chapter. This database includes fossil fuel use and electricity use and generation in industrial, commercial, residential, and transportation sectors, and it is aligned with the national total with less than 1% difference. I found that over 60% of China' energy-related carbon emissions came from cities. Collective carbon emissions are further analyzed based on city types, which are categorized based on the population sizes, economic structures, and administrative levels. Among cities with different population sizes, midsize cities (0.5-3 million population) collectively contributes to 40% national carbon emissions, which is a much larger proportion than megacities (>10 million population). When cities are categorized based on economic structure, mixed-economy cities contributed to about 40% national carbon emissions. City propers' collective contribution to national carbon emissions is found much higher than county-level cities, due to more urban activities in the former ones. Carbon per capita and carbon per GDP ranged from 0.94-83.3 ton CO_2/person and 0.01-2.58 kg CO_2/*yuan*-GDP respectively. Carbon emission intensity is significantly higher in smaller cities with more industrial activities.

Scaling up cities' carbon emissions to the national level aims to bridge carbon emissions across administration levels to better facilitate carbon mitigation actions. Based on the emission patterns across all cities in China, midsize and small cities are dominant contributors to national energy-related carbon emissions. However, many studies have focused on larger Chinese cities to provide empirical data supporting their mitigation actions, while their collective contribution is much smaller than midsize and small cities. In addition to reducing collective carbon impact, smaller cities' carbon intensity is also higher than other types of cities. China has committed to reducing carbon intensity in its Intended Nationally Determined Contributions (INDCs) in the Paris Accord. The larger cities have been very efficient regarding carbon emissions per GDP or per capita. In comparison, smaller cities have higher reduction potential. Thus, more attention regarding academic studies and managerial resources are necessary to shift to small and midsize cities to help them adopting carbon mitigation actions. These smaller cities, most of the time, lack managerial and/or financial capacities to monitor their carbon emissions and adopt mitigation actions. New institutions across different level of governments should be formed to address this challenge.

Industrial energy use is the biggest contributor to *CIF* and the contribution is higher in smaller cities in China. Much of industrial energy use is wasted as medium- and low-grade heat. The advanced district energy system (DES) can utilize this heat to meet heating/cooling demands in residential/commercial sectors and further mitigates energy use in cities, which is posited as cross-sectoral action. I developed a method to evaluate the carbon mitigation potential of this action in 20 Chinese cities and estimated the embedded carbon emissions from constructing additional infrastructure. I found that utilizing industrial waste heat can save 12%-84% of heating and 24%-100% of cooling energy use in these cities. The embedded carbon emissions from additional infrastructure ranged from 0.3% to 3.2%, and from 1.9% to 6.5% for heating and cooling respectively. The economic payback of this action is about 3 years in average for the heating system and less than 10 years on average for cooling systems. The new mitigation strategy identified in my dissertation is only an example of several cross-sectoral actions contributing to the urban circular economy. When this individual city-level action is scaled up to the national level carbon mitigation, it is found that over 30% more carbon mitigation compared to the mitigation potential of national level single sectoral efficiency improvement (Ramaswami et al., 2017b).

China has mandatory policies to promote district heating in cold climate and these existing policies should address the transitions of existing DES to the advanced ones in order to further reducing carbon emissions and improve air quality. Many Chinese cities have many industrial activities that generate waste heat as energy sources for the advanced DES. At the same time, waste heat is embedded in many other urban activities and infrastructure systems, such as sewage system. Promoting the advanced DES can maximize the utilization of low-/zero-carbon energy sources for heating and cooling purposes, which also can improve air quality in Chinese northern region (Ramaswami et al., 2017b). The utilization of industrial waste heat in the advanced DES is only one example of cross-sectoral industrial urban symbiosis strategies. Cities should consider an urban system in a systems-thinking and holistic ways for making mitigation policies and the integrated planning. In addition to identifying more cross-sectoral actions, policymakers in cities need to revisit the existing institutions and to form a new norm that collaboration across local governmental departments is easier when taking this type of cross-sectoral actions.

Through interviewing professionals working on community-wide district energy systems in the U.S., I found that DES is slowly moving towards the advanced DES (the 4th generation), which has high energy use efficiency and low-carbon intensity. The slow transition is mainly due to the lack of sufficient regulations supporting low-carbon heating and cooling energy supply in the U.S. Without the support, market forces play a critical role. This means that DES operators are competing with other cheap fossil fuel-based energy choices. Although more users are demanding sustainable and reliable energy supply, DES operators have to work closely with users and communities to conquer barriers related to public understanding and existing regulations (which do not catch up with technology development). To do so, DES operators have to enhance their technical and financial capacity. This brings in a huge burden on DES operators' businesses. Although technology development and the local ecological conditions can enable the adoption of transitioning actions, DES operators have to conquer the barriers in the current market and regulations. DES operators in the U.S. have to be careful about their business strategies in dealing with the sustainable transitions to balance the benefit of transition and its burden on users' bill.

To accelerate low-carbon transitions in the U.S. community-wide DES, governments at different level can play different roles, even under a federal administration who is not committed to climate change actions. Policies addressing energy security, capital investment, and technical supporting programs at both federal and state level can enable DES operators taking more actions to change the existing outdated system. For example, federal tax credit or lower interest for resilient energy supply system can relieve the financial burden regarding capital investment. Furthermore, the rebate program for commercial and residential buildings at the state level should give credits to buildings connectted to high-efficiency DES. Technical feasibility programs initiated by both the federal and state governments in supporting local community energy systems will relieve many burdens from DES operators and communities. This also solves the dilemma that local communities may recognize DES as a low-carbon heating and cooling tool, but may lack capacities (*i.e.*, technical knowledge and financial analysis) to implement the plan. These programs can support local energy infrastructure projects without getting into the political debate of climate change actions in the U.S. The driving forces of the environmentally sustainable transitions of DES are found to be at local communities for the changing their energy systems. Local policymakers should be open to new actions to better facilitate these changes. These efforts can make local level policies as an enabling factor rather than as a barrier.

My dissertation studies have demonstrate that cities can further reduce carbon emissions beyond national policies through promoting low-carbon infrastructure to take advantage of cities' co-location features. This low-carbon infrastructure design should be considered in cities' integrated planning in advance for cities' low-carbon development, while more explorations are needed to identify what actions or infrastructure design should be considered. Data collection and database development are one of the biggest barriers to study infrastrucutre use and evaluate its impact in cities. Infrastructure use data are not consistently reported in cities over time and monitored in all cities in a nation. Without these baseline data, it is challenge to evaluate the performance of different infrastructure use. Thus, we need more methods to construct new database as the first step in our research. The second challenge is to develop new mitigation strategies enabled by low-carbon infrastructure design with technology development and holistic thinking. As shown in my dissertation that low-grade waste heat recovery in district energy systems can reduce heating and cooling energy use significantly, there are many other technologies emerging to shape our infrastructure use. For example, electric vehicle and shared ride enabled by smart phone become more and more common in transportation sector. The infrastructure use change does not only influence the transportation, but also has an impact on electricity supply. The cross-sectoral impacts should be evaluated and considered. Third, it is a practical challenge for form new norms at multiple-scales when implement these cross-sectoral strategies identified in cities. The fragmentation of local government can hinder the implementation processes. The mechanism of forming these new norms should be further investigated, such as how to encourage city officials from the different departments of local government communicate formally and informally in implementing cross-sectoral strategies. In addition to fragmentation within public sectors, the collaboration should happen in both private and public sectors in promoting low-carbon infrastructure transitions. Private sectors may have limited capacity to move the low-carbon transition of urban infrastructure, under the condition that the policies failed to capture externality of energy use. The new norms also have to consider the relationship between public and private sectors.

Overall, studies in my dissertation from an interdisciplinary perspective address current challenges in three domains of studies, which are important for the integration of research regarding low-carbon urban development (Ramaswami et al., 2012b). Studies in my dissertation evaluated carbon impacts of urban infrastructure at the city level to provide customized mitigation actions and scaling-up cities' carbon impact aggregately to national level; identified a new and unique cross-sectoral infrastructure action and quantify its carbon mitigation potential; and investigated infrastructure operators' motivation for low-carbon transitions and the enabling factors for the transitions from co-evolutionary perspectives. Studies in my dissertation demonstrated that working under an integrated interdisciplinary framework can address key questions at both physical and social sides to investigate low-carbon urban transitions.

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Appendices

Appendix-1 Supplement information for Chapter 2

According to data sources identified in Section 2.2.2, it was found that the municipal level city of Beijing, with the exception of cement use, had all the data for material/energy flow analysis (MEFA) readily available, at-scale, in public data sets. For the other cities, the MEFA data came from at-scale data sources or estimations. The detailed steps on estimating MEFA and calculating the *CIF* in each infrastructure sectors are discussed below.

Community-wide electricity use: The electricity use data were separated by end-user (industrial, commercial, agricultural, and residential) and reported in the four cities (shown in Table 2-2). The amount of local electricity production is also reported. The energy intensity data of local electricity production were used to calculate the in-boundary GHG emissions. The electricity imported from the grid was calculated by subtracting the local production from the total use. This quantity was then multiplied by the GHG emission factors of the corresponding regional grid to calculate the trans-boundary GHG emissions.

Community-wide non-electricity energy use: The data of coal and coal related energy, oil and oil related energy, and natural gas uses disaggregated by end-users (industrial, commercial, agricultural, and residential users) in the four cities were assembled from the data sources presented in Table 2-2. Petroleum fuel used by each end-users was most to support the production, such as transportation happened in the factory or the tractors running in the field (National Energy Administration of China, 2012). The fuel use on transportation happened during industrial production process was not included in the transportation sector listed below. GHG emissions from the use phase of these non-electricity energy uses were calculated by multiplying the use amount with the corresponding emission factors, as shown in Equation (1). Heating and steam uses separated by end-user in Beijing and Qinhuangdao were derived from the data sources presented in Table 2-2, along with the energy intensity data to produce heating and steam in these two cities. GHG emissions from heating and steam in Beijing and Qinhuangdao were calculated by using the energy intensity data. Because little heating was used in the residential and commercial sectors in Xiamen and Yixing, GHG emissions from heating use were entirely allocated to industrial end-users. Heating and steam were all supplied from in-boundary production in the four cities, thus, GHG emissions from using heating were all in-boundary (IB).

In-boundary transportation: In-boundary transportation includes private car, public transit, and taxi use. Fuel use at scale was only available for Xiamen, while in Beijing, Qinhuangdao, and

Yixing fuel use for in-boundary transportation was estimated through the VKT as shown in Equation (A1).

$$t = (\text{Number of vehicles}) \times (\text{Vehicles kilometers traveled}) \times (\text{Fuel economy}) \qquad \text{(Equation A1).}$$

In Equation A1, *t* is the total amount of fuel use for the specific type of in-boundary transportation. Chinese fuel economy values (in fuel use per kilometer) were calculated by Huo et al. (2012a). The volumes of vehicles in Beijing, Qinhuangdao, and Yixing were taken from the data source in Table 2-2. In cities without direct available VKT data, such as Qinhuangdao and Yixing, VKT values from cities of comparable size in the Huo et al's (2012b) study were used as surrogate VKT measures (Huo et al., 2012).

Water supply/wastewater treatment (WT/WWT): The water use data and wastewater treatment amount data were all directly reported by each city as shown in Table 2-2. GHG emissions from wastewater and water supply included two parts: emissions from energy used to process the water supply/wastewater treatment and emissions from untreated wastewater. GHG emissions from energy used to process the wastewater and supply water were separated from the total industrial energy use in four cities because specific energy intensity data was collected as shown in Table 2-2. The method to estimate GHG emissions from untreated wastewater was taken from Chavez et al. (2012), based on the concentration of chemical oxygen demand and ammonia-nitrogen in wastewater and total discharged wastewater amount.

Municipal solid waste (MSW): In Beijing, the GHG emissions from solid waste treatment were calculated based on the total treatment amount and the life-cycle GHG emission factor of municipal waste treatment in previous research (Zhen-Shan et al., 2009). Based on the data of solid waste amount treated by different techniques (landfill and incineration without energy captured), the GHG emissions from municipal solid waste treatment plants were estimated in Xiamen and Qinhuangdao. The municipal waste in Yixing was incinerated and the heat was captured to generate electricity (Wuxi Statistic Bureau and NBS Survey Office in Wuxi, 2013). The amount of municipal waste was not estimated in this category. Instead, GHG emissions from this process were included in the GHG from electricity use in Yixing.

Construction material: Because of the large contribution of the cement industry to GHG emissions (Rehan and Nehdi, 2005) and limited data on other construction materials, cement was the only construction material considered in this study. Except for Beijing, the cement use data were estimated from national data (Leung, 2011, Armstrong, 2013) based on per capita consumption, accounting for the differences of rural and urban use. Local cement production in the four cities was reported in the city's statistical yearbooks as shown in Table 2-2. GHG emissions from cement included the emissions from energy use and its production process. When the cement use was locally produced, the emissions from energy combustion and processing (calcining) were allocated to the cement use sector; while the energy used for cement produced but not consumed in the city was included in the industrial energy end-use related to net export. In Beijing and Xiamen, the cement use amount was larger than its production amount, while in Qinhuangdao and Yixing the quantity of local production was much larger than its use amount. The energy intensity for cement processing was taken from previous studies focused in China (Ke et al., 2012). Energy used to produce local cement use was deducted from industrial energy use to avoid double-counting.

Table A1- 1. GHG emission factor of coal and coal related energy, oil and oil related energy used in this research from IPCC report (2006)

	GHG emission factor kg/TJ	CO_2 emission factor kg/TJ	CH_4 emission factor kg/TJ	N_2O emission factor kg/TJ	GWP of CH_4	GWP of N_2O
Coal	95071	94600	1	1.5	24	298
Coke	107471	107000	1	1.5		
Coke oven gas	44454	44400	1	0.1		
blast furnace gas	260054	260000	1	0.1		
Crude oil	73503	73300	1	0.6		
Gasoline	69551	69300	3	0.6		
Kerosene	72151	71900	3	0.6		
Diesel Oil	74351	74100	3	0.6		
Fuel Oil	77651	77400	3	0.6		
LPG	63154	63100	1	0.1		
Refinery gas	57654	57600	1	0.1		
NG	56154	56100	1	0.1		
LNG	56154	56100	1	0.1		

Food: Community-wide food use ideally should include residential food use and visitors' food use, as both uses support local activities. Only agriculture and livestock GHG emissions from producing food use included to compute GHG with food use in the Equation (1), whereas the use phase of food was considered to have zero GHG emissions. Energy used for food package/processing and transporting are not included to avoid double counting, as was done by Chavez et al (2012), Hillman et al (2010), and Ramaswami et al. (2008). GHG emissions from food use were separated by region either designated as in- or trans-boundary (IB and TB, respectively). There was remarkable detail on food flows, including food consumed by households and by visitors, readily available in Beijing (Beijing Municipal Bureau of Statistics, 2011). However, data on food use by visitors was not available in the other three cities; so the GHG emissions from food in Xiamen, Qinhuangdao, and Yixing only included the impact of household food use. Some cities report the food use in monetary units (*yuan*/person), such as Beijing; while other cities report their food use in physical units (kg/person). The food use, separated by different food types (grains, vegetable, pork, mutton, etc.), was reported in both cases. GHG emissions from food use are calculated based on the Equation (A2):

$$F^{GHG}=\sum_j (F^{IB}{}_j * EF_j + F^{TB}{}_j * EF_j) \qquad \text{(Equation A2)},$$

in which, F^{GHG} is the total GHG from food use, $F^{IB}{}_j$ is the local produced food use amount of the jth food type, $F^{TB}{}_j$ is the jth type food imported from outside of the city boundary for local use, and EF_j is the emission factor of the jth food type. When the food expenditure data were reported, the emission factors derived from the input-output table in China were applied to estimate the life-cycle emission of food use (Carnegie Mellon University Green Design Institute, 2008). If the food use data were reported in mass units, the emission factors corresponding to the physical unit of food were adopted to trace the GHG emissions embodied in its production process (Wang, 2010).

Table A1- 2. GHG emission factor from food sector by monetary or physical unit

Food item	Emission factor based on physical unit of food($kgCO_2e$/kg food)[a]	Food category	Emission Factor based on monetary unit of food (g CO_2-eq/yuan) [b]
Rice	1.42	Crop cultivation	192
Wheat	0.32	Eating and drinking place	164
Corn	0.27	Grain mill products	229
Beans	0.32[c]	Livestock and livestock products	151
Potato and related	0.28	Non-alcoholic beverage	291
Vegetable	0.12-0.40	Other food products	254
Pork	2.57	Prepared fish and seafood	190
Beef	8.65	Sugar refining	233
Mutton	13.47	Tobacco products	69.2
Poultry meat	1.54	Vegetable oil and forage	212
Poultry eggs	0.78	Wines, spirits and liquors	291
Milk	0.7		
Apple	0.12		
Cirtus	0.07		
Orange	0.06		

[a] :not include the emission from energy use of production, data from research done by Wang (2010).

[b]: from the EIO-LCA released by Carnegie Mellon University Green Design Institute

[c]:for soy beans. Regular beans is 0.16

Appendix-2 Impact of the Economic Structure of Cities on Urban Scaling Factors: Implications for Urban Material-Energy Flows in China

A2.1. Introduction

Importance of Material-Energy Flows associated with Cities: Understanding human activities at the city-scale is becoming increasingly important in discussions about human well-being and global environmental change. More than half the world's population is currently living in cities and urban areas, and this number is expected to increase to 66% by 2050 (United Nations, 2014). Economically, cities are important centers of innovation and economic activity that contributes to increasingly large shares of national GDP. Urbanization is generally believed to increase the household income of urban residents, often increasing city residents' well-being through improved access to services such as piped water supply, electricity, education and health care. *e.g.* 98% of urban households have tap water supply in China versus 68% in rural areas (China Statistics Press, 2014). However, with large-scale urbanization, the provisioning of water, energy, food and other basic services to cities - to support industrial-commercial production activities as well as household consumption activities - is contributing to large-scale environmental impacts. For example, cities are estimated to be responsible for about 67% to 76% of global fossil fuel use (Seto et al., 2014). The highly concentrated use of polluting infrastructures in cities, such as the provision of fossil fuels for urban transportation and electricity supply, is also associated with higher concentrations of air pollution in cities, which is one of the largest causes of deaths in many countries (Lim et al., 2013, Ramaswami et al., 2014, Ramaswami et al., 2016). Thus, there is wide interest in understanding material and energy flows (MEF) associated with cities, and their resulting impacts on resource sustainability, environmental pollution and human well-being.

Population-Scaling Relationships: Fundamental to understanding and comparing cities, as well as the evolution of cities as they grow, is the relationship between city size (population), wealth creation and materials-energy use. A seminal article by Bettencourt et al. (2007) provided striking evidence that as city populations increase, many characteristics of city wealth creation and material-energy use can be described using a universal scaling law [$y = a \cdot (population)^{b}$]. These general relationships were posited to be universal in different countries of the world, albeit with different scaling factors, b (Bettencourt et al., 2007, Bettencourt, 2013, Fuller and Gaston, 2009, Arbesman et al., 2009). In general, the article revealed that as city population increases, total aggregate GDP, innovation, as well as total communitywide electricity use scaled superlinearly with population (with $b>1$), total household electricity use scaled linearly with population ($b \approx 1$), while infrastructure provision, such as electrical cable length, road surface and gasoline stations were found to increase sublinearly (*b*<1). The underlying theory is that the intensity of social network interactions within cities shaping scaling of different parameters with those that achieve economy of scale being superlinear. The underlying theory is that the intensity of social network interactions in cities shapes scaling of different parameters with those that achieve "economic of scale" being superlinear.

Household Income and Urban Form Impacts on Intensity Metrics: Other researchers have tried to understand per capita household energy and transport fuel use through using large sample size (large N) data sets. Generally, analyses of household consumption data indicate that increases in household income correspond to greater household consumption of electricity, transport fuels and other goods and services (Weber and Matthews, 2008, Jones and Kammen, 2011, Minx et al., 2013). A pioneering global study of Newman and Kenworthy highlighted the empirical correlation between per capita surface transport fuel use and population density of global cities (Newman and Kenworthy, 1989). Further investigation of this phenomenon, accounting for confounding factors, found that additional factors, the so-called 5-d's (population density, diverse land uses with co-located homes and commercial activities, design for multimodal and non-motorized transport, distance to transit as well as access to jobs), are important in shaping motorized travel demand per capita (Cervero and Kockelman, 1997, National Research Council, 2009).

Place-Based Community-Wide Energy Use in Individual Cities: While the above studies help understand material-energy flows of households, several place-based studies of urban material-energy flows have studied community-wide energy use. These studies focus on individual cities and gather "at-scale" or bottom-up data on energy and material use by the whole community encompassing homes, commercial businesses and industries and government (Hillman and Ramaswami, 2010, Chavez et al., 2012, ICLEI, 2012a, Cohen and Ramaswami, 2014). In an approach termed community-wide infrastructure footprinting, the community energy use is disaggregated into use in different infrastructure sectors, such as energy supply, water and wastewater treatment, solid waste management, transportation, food supply and the use of construction materials by cities, and further separated where possible into household use, commercial use and industrial use. Comparative case studies of the community infrastructure GHG footprint have illuminated that large differences in material energy use can occur based on the economy and trade of cities – *e.g.*, by the relative proportion of production and consumption (Chavez and Ramaswami, 2013).

Economic Structure and Trade: More generally, the carbon accounting literature shows that it is not only activities within cities, but also trade across cities that shapes material and energy flows. Chavez and Ramaswami (2013) have demonstrated the theoretical relationships important in analyzing material and energy flows from three different perspectives: consumption, production and community-wide infrastructure use (Chavez and Ramaswami, 2013). This analysis has helped to classify cities in the context of net-consumers, net-producers, and trade-balanced cities (Chavez and Ramaswami, 2013). Thus, the economic structure in cities plays an important role in material and energy flows as determined from the carbon accounting literature. Further, a very large literature has shown that all GDP is not the same in terms of energy intensity. The type of GDP makes a difference: industrial sectors show a higher energy use per GDP, in contrast to commercial or tertiary activities (Sue Wing, 2008, Belzer, 2014). Thus, economic structure and trade-balance across cities are found to be important in shaping urban energy-material flows.

<u>Other External Factors</u> such as availability of infrastructure, may also affect energy use in cities. *e.g.,* 40% of the populations in Asian and African cities are living in informal settlements (Habitat, 2010) without adequate sanitation or power supply. Studies of cities in USA (Ramaswami et al., 2008) and globally (Kennedy et al., 2009, Kennedy et al., 2015b) have shown that urban energy use in the building sector is associated with heating and cooling degree days. As cities begin to act upon GHG mitigation, the choice of infrastructure at the community and/or neighborhood scale, such as distributed energy systems (UNEP et al., 2015), as well as choices of technologies at the home or vehicle scale, can also become important. The choices of technologies at the home or vehicle scale are often emphasized in shorter term technology penetration studies (Mohareb and Kennedy, 2012), which can significantly be impacted by policy choices (Ramaswami et al., 2012a).

A few recent studies are bringing together all of the above factors: *e.g.,* Kennedy et al (2015) have assessed various factors correlated with material-energy flows in mega cities across the world and indicated valuable findings with respect to population and GDP, similar to Bettencourt's scaling relationships. These studies consider cities to behave similarly and to exhibit similar scaling relationships; differences across cities, by city typology, was not examined per se.

The focus of this paper is on exploring the role of city typology by economic structure in shaping urban MEF, in conjunction with other factors such as population-GDP scaling relationship, per capita income, urban form, and ambient climate variables- all of which have been shown to be important (as described above) in influencing urban MEF. This paper focuses on China where robust data sets are available in large enough sample sizes to explore these interactions. The analysis helps to bring together the scaling and urban carbon footprinting literature.

To evaluate the role of the economic structure of cities in the context of other factors, we use a conceptual model illustrated in Figure A2-1. Figure A2-1 posits that city typology based on economic structure – *i.e.* the classification of cities as highly industrial, highly commercial and mixed-economy cities – can significantly affect important relationships such as between GDP and population (GDP-population scaling), per capita household income, as well as parameters related to urban form. All these parameters, in conjunction with environmental/background variables such as heating and cooling degree days, can be important in shaping the overall MEF associated with cities, such as total household electricity use, total water use etc., as well as intensities, *i.e.*, per unit energy and material use parameters. Single variable regression and multivariable analysis are used to explore these relationships for Chinese urban districts (*Shiqu*). According to the latest census in China, there are about 170 million urban migrants- about 30% of China's 670 million urbanities- whose household registration in their *hukou* does not reflect where they actually live and work (OSPCBM et al., 2012). Given this large-scale rural-urban migration occurring in China (Brandt and Rawski, 2008), our study also evaluates how migration-corrected population data can affect the GDP-population scaling and other population-scaling relationships explored herein.

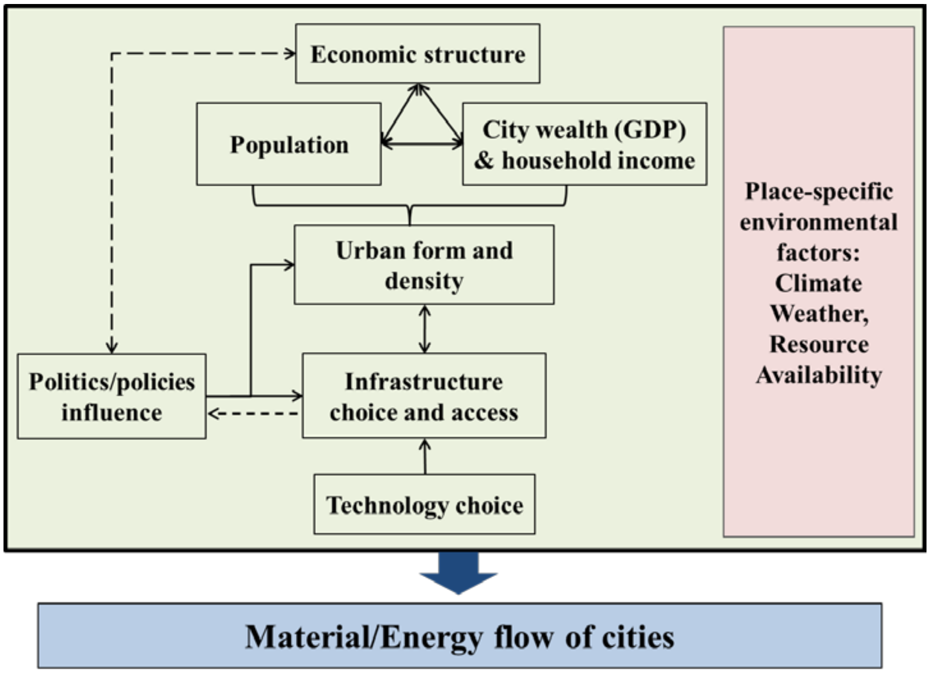

Figure A2-1. A conceptual modeling framework illustrating various factors important in shaping urban material/energy flows.

A2.2. Study Objectives

Specifically, our study explores four relationships:

(1) **Single Variable Scaling Relationships for all Cities**: We explore the GDP-Population scaling relationship of cities, as well as the scaling of various parameters with respect to both GDP and population, separately. These parameters include total household electricity and water use, citywide (i.e. household plus commercial and industrial) electricity, roads, R&D investment, etc. The two key questions we ask here are: (a) how does migration-corrected population affect

the scaling relationships? (b) Since several studies indicate that it is very difficult to determine whether population growth precedes GDP growth (or vice versa) (Ha, et al, 2015; Ciccone and Peri, 2006; Moretti, 2004; Glaeser, et al, 1995), the choice of scaling the other parameters with respect to population or with respect to GDP is a matter of perspective and choice. This is true in urban MEF studies given the correlation between GDP and population. Therefore, we apply the analysis to ask which parameters scale better with respect to population, and which parameters scale better with respect to GDP, and what is the implication of these correlates for understanding cities?

(2) **Single Variable Scaling Relationship in Different City Types:** We next apply the same analysis as in (State Council) to ask whether these scaling relationships are significantly different in city types by economic structure (*i.e.*, highly industrial cities, highly commercial cities, and mixed-economy cities). The key question we ask here is: does the city typology by economic structure affect scaling relationships?

(3) **Household Income and Urban Form in Different City Types**: We next explore the relationship between a city's wealth represented by its GDP (or GDP/capita) and its household income (or income/capita) to assess the degree to which wealth creation due to economic activity translates to household income in the different city types. We also evaluate if/how urban form varies indifferent city types, and by city size.

    Urban form is a complicated concept and has many different dimensions, including population density, the percentage of high-rise building, household density, road density etc.(Bourdic et al., 2012). Because population density is identified in the previous studies as influential factors for energy use (Jones and Kammen, 2014, Kennedy et al., 2015a), it is included in this analysis as an indicator of urban form. For example, the high-rise buildings were found to influence the energy use, due to the use of elevators and heating, ventilating and air-conditioning (HVAC) systems (Wan and Yik, 2004, Lam et al., 1997). In addition, the percentage of high-rises building and urbanization rate is also included as an indicator of urban form. Other measures of urban form were not available in this Chinese dataset, but are an important topic for future work.

(4) **Multivariable Analysis of Urban MEF**: Last, we include several parameters into a multivariable analysis to ask how the parameters noted in Figure 1, together, shape the MEF of cities. Here, we focus on total household energy use to illustrate the impact of city size (population), wealth (household income), urban form and environmental variables on energy use. The multivariable analysis is useful to answer the question of to what extent do scaling factors affect urban MEF, in the context of other variables. Are the multivariable effects

significantly different in the different city types? Our data set did not include other variables illustrated in figure A2-1 such as technology choices, which will be studied in future work.

A2.3. Methodology

A2.3.1 Definition of City Propers

We initiated this study using data from 285 city propers in China (including the 4 provincial-level cities of Beijing, Tianjin, Shanghai and Chongqing, and 281 prefectural-level cities. The term city proper (*shiqu*) refers to the urban administrative district (*shixiaqu*) or the aggregate of multiple urban administrative districts in some bigger cities -- under the jurisdiction of each provincial-city (*zhixiashi*) or prefecture-level city (*dijishi*). The city propers are the most urbanized area in the prefecture-level city, and are better suited than the prefecture-level cities to uncover the impact of urban form and density on MEF parameters such as total and household electricity and water use. In this paper, we use the term cities to refer to city propers.

A2.3.2 Taxonomy of Cities Based on Economic Structure

The 285 city propers of China were classified as highly industrial cities, highly commercial cities and mixed-economy cities based on the percentage of their secondary and tertiary GDP using criteria similar to Nelson's method (Nelson, 1955). Specifically, cities in which the percentage share of secondary GDP in the total GDP was higher than the national average (of the 285 city propers) plus one standard deviation (63.9%) were classified as industrial cities; cities in which the percentage share of tertiary GDP exceeded the average plus one standard deviation (52.6%) were classified as commercial cities; and the remaining cities were classified as mixed-economy cities. Applying the Nelson method to the year 2010, 38 cities were classified as highly industrial cities; 44 cities were classified as highly commercial cities; and the remaining 203 cities were denoted as mixed-economy cities. The list of cities in each category is provided in table SI-1. We began with the full set of 285 city propers, only a sub-set of which (239) had reported migration-corrected population. Hence, the dataset used in this paper is effectively 239 cities for models including population as a variable.

A2.3.3 Variables and Data Sources

The key data sets and variables studies in this paper are grouped as follows

- **Wealth**: Total GDP data for individual cities, as well as the percentage arising from primary, secondary and tertiary economic activity are reported in China City Statistical Yearbook 2010 (Department of Urban & Social Economic, 2011-2012).
- **Population**: The population in the city propers was obtained from two different data sets. The China City Statistical Yearbook notes the population of registered urban residents, *i.e.*, those who have the *hukou* to live in that city. However, this does not represent the

population that is using urban infrastructure, which needs to be corrected for migration into and out of the cities. The migration-corrected population was computed from the Year 2010 census data as the total resident population, including residents with and without *hukou*, minus those with *hukou* but living abroad (OSPCBM et al., 2012). Consequently, the Year 2010 was the chosen year of analysis.

- **Per Capita Household Income** was obtained from China Regional Statistical Yearbook 2010 (DCSNBS, 2011).
- **Urban Design**: The two variables include the population density in the built area (using the migration-corrected population), and the percentage of households that live in 10-story buildings or higher and are provided in the Sixth National Population Census of China (from the Sixth Population Census Data in 30 provinces). These two variables were not highly correlated among themselves, and hence were used to represent gross population density (the former) and urban form (the latter).
- **Household and City Wide Resource Consumption**: The variables representing MEF of cities including household electricity, water, natural gas and LPG consumption, and city-wide electricity and water consumption were taken from China City Statistical Yearbook (Department of Urban & Social Economic, 2011-2012). The word city-wide is used to indicate household plus commercial-industrial-agricultural energy and water use, which is often reported in separate categories.
- **Environmental Variables**: The environmental variables include the heating degree days in January of 2011, and cooling degree days in July of 2011 in the cities. The data for 2011 was used as the nearest proxy, because 2010 HCDD were not readily available.

A2.3.4 Analytic Methods

The above data sets are applied in five different analyses as shown below.

Single Variable Population Scaling Relationships of All Cities: We first evaluate the population-scaling relationship, including of GDP and other city parameters using both urban residents and migrant-corrected populations for all 239 Chinese cities. This explores the sensitivity of scaling to migration in developing economies undergoing rapid urbanization such as China. In this and all subsequent analyses, we use migration-corrected population. All 285 cities are assumed to behave similarly and we adopt the approach of Bettencourt *et al.*(2007) for non-categorical modeling in Equation (State Council):

$$\ln(y) = a + b \times \ln(\text{population}) \qquad \text{(Equation A3)},$$

where y is the variable of interest (GDP, total and household electricity, total and household water consumption, etc.), and a and b are constants. Bettencourt *et al.* 2007 used registered urban populations (Bettencourt et al., 2007). Here we evaluate the same relationships using both registered urban population and migration-corrected population derived from the census, to compare the difference. The latest census data shown that there are almost 170 million migrants in cities and towns (about 25% of total population in cities and towns in 2010) without correspondingly registered *hukou* (OSPCBM et al., 2012), the migration-corrected population is more indicative of the people living in Chinese cities compared to registered population.

Single Variable Population-scaling and GDP-scaling Relationships of All Cities: We then assess how other household and citywide parameters are correlated with GDP and with population separately, to assess whether GDP or population yields better correlations (improved R^2) to represent scaling of these parameters. Standard statistical methods are used for the single variable regressions.

Single Variable Scaling Relationships in Different City Types: We then explore the same scaling relationships as noted in (State Council), in different types of cities classified by economic structure, to test the hypothesis that the different city types exhibit different scaling relationships. We explore if city typology affects scaling relationships of all the other parameters, with respect to both population and GDP.

As an example, if we are exploring GDP-population relationships in city categories, the non-categorical model (Equation A3) is compared with Equation (State Council) (below) where two dummy variables I_2 and I_3 represent the potential differential behavior of highly industrial cities and highly commercial cities, respectively, from all cities.

$$\ln(y) = b_1 \times \ln(\text{population}) + b_2 \times \mathrm{I}_2 \times \ln(\text{population}) + b_3 \times \mathrm{I}_3 \times \ln(\text{population}) + \mathrm{a}_1 + \mathrm{a}_2 \times \mathrm{I}_2 + \mathrm{a}_3 \times \mathrm{I}_3$$

and

$$\mathrm{I}_2 = \begin{cases} 1, & if\ a\ city\ is\ an\ industrial\ city \\ 0, & otherwise \end{cases}$$

$$\mathrm{I}_3 = \begin{cases} 1, & if\ a\ city\ is\ a\ commerical\ city \\ 0, & otherwise \end{cases} \qquad \text{(Equation A4).}$$

The significance of each term is then evaluated using t-statistics. If b_2 and b_3 are found to be significantly different from zero, then ($\widehat{b_2} = b_2 + b_1$) represents the slope and hence the scaling factor for industrial cities, ($\widehat{b_3} = b_3 + b_1$) represents the scaling factor of the highly commercial cities, and b_1 the scaling factor of the remaining cities with a mixed economy. If b_2 and b_3 are not significantly different from zero, it implies that city categories have no significant impact on the scaling characteristics of the variable being studied (y). The normality assumption of residuals is checked using the Kolmogorov-Smirnov one-sample test. The adjusted R^2 is also reported and compared with the same for the non-categorical case. Whether $\hat{b}$ is significantly different from 1 is also evaluated using t-statistics.

(4) City Typology Impacts on Household Income & Urban Form: Following the same approach as in Equation (A4), we assess if city typology significantly affects the relationship between per capita wealth creation and per capita household income. In the same manner, we also explore how urban form of cities varies in the different city types. We used two measures of urban form: (State Council) regional population density computed as the migration-corrected population divided by the build-up (constructed) land area reported for each city proper (*Shiqu*); (State Council) The percentage of homes that are situated in 10-storey or higher buildings, which is indicative of the prevalence of high rises. We used the percentage of homes in 10-storey and above (as opposed to percentages of homes in 3-storey or 6-storey buildings) as it was not significantly correlated with the regional density and hence could be used in multivariable regression (variance inflation factor <2).

(5) Multivariable Regressions Describing City MEF in Different City Types. The combined impact of city type, population, GDP/household income and other urban design (form and density) and environmental variable on MEF are explored using multivariable regression. As an example, we explored total household electricity use as:

$$\ln(hh\ ele) = \sum_{i=1}^{3}(b_i \times I_i \times \ln(pop) + c_i \times I_i \times ln(income/cap) + d_i \times I_i \times \ln(highrises) + f_i \times I_i \times ln(pop\ density) + g_i \times I_i \times \ln(CDD) + h_i \times I_i \times \ln(urbanization\ rate) + a_i \times I_i) \qquad \text{(Equation A5),}$$

and

$$\ln(hh\ ele/capita) = \sum_{i=1}^{3}(b_i \times I_i \times \ln(pop) + c_i \times I_i \times ln(income/cap) + d_i \times I_i \times \ln(highrises) + f_i \times I_i \times ln(pop\ density) + g_i \times I_i \times \ln(CDD) + h_i \times I_i \times \ln(urbanization\ rate) + a_i \times I_i) \qquad \text{(Equation A6),}$$

Where I_1=1, I_2 and I_3 are dummy variables as defined in section A2.3.4, and a, b ,c, d, f, g are constants. In identifying the predictor variables, care was taken to address collinearity among the variables through analysis of variance inflation factor (Kunt, et al. 2004). The multivariable regressions allow the exploration of the relationships represented in Figure A2-1, which shows the combined effect of city types as well as income, urban design/form and environmental variables.

A2.4. Results

Benefit of Using Migration-corrected Populations: The use of the more representative migration-corrected population improved the R^2 of the population-scaling relationships substantially. As seen in Supplementary Materials, for the GDP-population scaling, the R^2 is 0.662 using registered urban populations, and increases to 0.800 when migration-corrected population is used. A similar effect is seen for all parameters considered. In most cases, the numeric value of two scaling factors (b) are not significantly different with registered-population and migration-corrected population. However, there were a few notable findings with migration-corrected population. Total household electricity is found to be superlinear in scaling with respect to migration-corrected population, which may be a unique finding for Chinese cities. This is different from previous work, where total household electricity is noted to exhibit linear scaling with population (Bettencourt *et al*. 2007). In all subsequent analysis, we report migration corrected population.

A2.3.1 Single Variable GDP-Scaling and Population-Scaling Relationships of various MEF Parameters for All Cities

Table A2-1 shows the results of scaling of various MEF parameters of cities, explored both with respect to population, and, with respect to GDP. The MEF parameters capture electricity use, water-use, LPG use, etc., reported as citywide (homes and businesses) totals and separated as residential (household) and business use. Businesses encompassing industrial, commercial and any agriculture/primary sector businesses. The results indicate that GDP and population are themselves highly correlated (with R^2 = 0.800), with superlinear-scaling (b =1.222). This indicates accelerated GDP creation with population increase. For the remaining variables, since GDP and Population are themselves highly correlated, the choices of scaling with respect to population or with respect to GDP is one of perspective and choices. Population-scaling embodies an implicit perspective of household consumption as dominant driver for citywide MEF, while GDP-scaling views economic development as the dominant driver. The theory of carbon accounting in cities indicates that cities are both part consumers and part producers with only a portion of local production serving local consumption (Chavez and Ramaswami, 2013). Thus, metrics arising from both consumption perspective (per capita) and production perspective (per GDP) can apply. One of the unresolved dilemmas in urban sustainability science is the question of representing city-wide environmental metrics by the per capita or per GDP unit.

As seen in Table A2-1, for most variables in China, the correlation with respect to GDP is greater for parameters pertaining to citywide MEF, as well as business activities , which tend to scale linearly with respect to GDP (see the rows bolded where the difference in R^2 exceeds 10%). Population-scaling yields better correlation for total household related parameters. We can also note that the correlation (with respect to both population and GDP) is much weaker (<0.4) for LPG and gas use, which may be due to diverse household energy use for cooking and heating in different cities, compared to electricity and water use. The population-scaling is linear only for LPG use and superlinear for the other household MEF parameters, such as household electricity and household water consumption, when migration-corrected populations are used.

No prior study has compared such dual scaling for cities both with respect to population, and with respect to GDP. Because cities are both part-consumers (households) and part-producers, with the production not necessarily serving local consumption, the dual functionality of cities helps explain the duality of scaling relationships. Population appears better suited to household-related MEF, while GDP better represents MEF pertaining to businesses that generate GDP, and the total community-wide MEF parameters of Chinese cities.

Table A2-1. The population-scaling and GDP-scaling relationships for various response variables, considering all Chinese cities. Bold notation indicates where GDP-scaling is significantly better correlated (>10% differential) compared with population-scaling

LN(response variable)		with respect to LN(**POPULATION**): ALL CITIES (n=239)			with respect to LN(**GDP**): ALL CITIES (n=239)		
		$\hat{b}$	linearity	Adjusted R^2	$\hat{b}$	linearity	Adjusted R^2
R&D expenditure		1.572*** (0.080)	super-l	0.617	1.269*** (0.048)	super-l	**0.749**
Road surface area		0.977 *** (0.038)	linear	0.736	0.741 *** （0.025）	linear	0.785
Electricity use	City-wide	1.124*** (0.055)	super-l	0.641	0.926*** (0.028)	sub-l	**0.821**
	Household	1.153*** (0.033)	super-l	0.841	0.835*** (0.025)	sub-l	0.829
	Business	1.132*** (0.063)	super-l	0.581	0.957*** (0.033)	linear	**0.781**
Water use	City-wide	1.127*** (0.049)	super-l	0.686	0.900*** (0.028)	sub-l	**0.817**
	Household	1.135*** (0.042)	super-l	0.758	0.843*** (0.029)	sub-l	0.783
Gas use	City-wide	1.470*** (0.140)	super-l	0.340	1.188*** (0.098)	linear	0.404
	Household	1.318*** (0.133)	super-l	0.315	1.037 (0.095)	linear	0.358
LPG	City-wide	1.206*** (0.088)	super-l	0.446	0.898*** (0.063)	linear	0.463
	Household	1.082*** (0.085)	linear	0.411	0.793*** (0.062)	sub-l	0.413
LN(GDP) ~ LN(POP): $\hat{b}$ = 1.222 ***(0.040), Adjusted R^2 = 0.800							

Note: Values in parentheses are the standard deviations (* p-value<0.05, ** p-value<0.01, *** p-value<0.001). Super-l means superlinear and sub-l means sublinear.

A2.3.2 City categories reveal different population-scaling characteristics in different city types

Categorical modeling with migrant-corrected population further reveals that the categorization of cities by economic structure yields important differences in population-scaling relationships. Industrial cities emerge as much different from the other two in many significant ways, highlighted in the shaded boxes in Table A2-2, where the scaling factors have shifted from being super linear (Super-l) to sublinear (Sub-l), or vice versa. Most importantly, the highly industrial cities show almost sublinear scaling of GDP with respect to population (b = 0.88 ± 0.17), indicating patterns of diminishing GDP as population increases, while this relationship has been observed to be superlinear for all Chinese cities in non-categorical scaling (Table 1) and in all previous city studies worldwide (Bettencourt et al., 2007). The nominal GDP-Population scaling factor for industrial cities is 0.879, which is significantly lower than commercial cities and mixed-economy cities (1.324 and 1.262 respectively) (Figure A2-2 and Table A2-2). In contrast, the scaling factor for all cities is 1.222 (Table 2). Likewise, population-scaling of community-wide water and electricity use, show significantly different patterns and changes in form (super to sub linear) for industrial cities compared to commercial and mixed-economy cities.

Meanwhile, the highly commercial cities, *i.e.*, cities with a predominant tertiary economy, show distinct superlinear scaling characteristics in household water and LPG consumption, significantly different from industrial and mixed-economy cities. For example, the Population-scaling is superlinear for household water consumption in highly commercial cities (b=1.280), whereas the nominal scaling factors for industrial and mixed-economy cities are 0.934 and 1.054 respectively, and are not significantly different from 1 (linear).

The population-scaling characteristics of household electricity and natural gas consumption, and R&D investment did not show significant categorical differences across city types (Table A2-2). The scaling of the above parameters with respect to GDP is included in Table SI-4 and also reveals scaling differences across city categories.

Table A2-2. Population-scaling relationships of different parameters in different categories of cities categorized as highly commercial, highly industrial and mixed-economy cities. Migration-corrected populations of the cities are used in all cases. Grey boxes represent MEFA parameters that are significantly different in city categories, compared to All-Cities.

LN(response variable)		ALL CITIES (n=239)			ALL CITIES CATEGORIZED INTO DIFFERENT CITY TYPES						
					Industrial (n=38)		**Commercial (n=44)**		**Mixed-Econ (n=157)**		Adjusted R^2
		$\hat{b}$	linearity	Adjusted R^2	$\hat{b}_2$	linearity	$\hat{b}_3$	linearity	$\hat{b}_1$	linearity	
Population		0.654 *** (0.021)	sub-l	0.800	0.536 (0.094)	sub-l	0.710 § (0.033)	sub-l	0.615 (0.026)	sub-l	0.833
R&D expenditure		1.269*** (0.048)	super-l	0.749	Not significantly different						
Road surface area		0.740 *** (0.025)	sub-l	0.785	Not significantly different						
Electricity use	City-wide	0.926*** (0.028)	sub-l	0.821	**0.497 §§§ (0.138)**	sub-l	**0.954 (0.048)**	**linear**	**0.956 (0.036)**	**linear**	0.828
	Household	0.835*** (0.025)	sub-l	0.829	**0.434 §§§ (0.126)**	sub-l	0.887 (0.039)	sub-l	0.813 (0.029)	sub-l	0.860
	Business	0.957*** (0.033)	linear	0.781	**0.505 §§§ (0.161)**	**sub-l**	0.983 (0.056)	linear	0.996 (0.042)	linear	0.791
Water use	City-wide	0.900*** (0.028)	sub-l	0.817	0.651 (0.133)	sub-l	**1.000 § (0.048)**	**Linear**	0.860 (0.036)	sub-l	0.822
	Household	0.843*** (0.029)	sub-l	0.783	**0.715 (0.133)**	sub-l	**0.949 §§ (0.048)**	**Linear**	0.769 (0.036)	sub-l	0.804
Natural gas use	City-wide	1.188*** (0.098)	linear	0.404	Not significantly different						
	Household	1.037 (0.095)	linear	0.358	0.685 (0.424)	linear	0.750 (0.164)	sub-l	1.065 (0.120)	linear	0.412
LPG	City-wide	0.898*** (0.063)	linear	0.463	Not significantly different						
	Household	0.793*** (0.062)	sub-l	0.413	**0.876 (0.286)**	**linear**	**0.982 § (0.105)**	**Linear**	0.715 (0.077)	sub-l	0.472

Note: Values in parentheses are the standard deviations (* p-value<0.05, ** p-value<0.01, *** p-value<0.001). **§** in the columns under categorical modeling indicates whether the scaling factors of commercial and industrial cities are significantly different from mixed-economy cities (**§** p-value<0.05, **§§** p-value< 0.01, **§§§** p-value <0.001). Super-l means superlinear and sub-l means sublinear.

In addition, Figure A2-2 shows another unique characteristic of the highly industrial cities, *i.e.*, that there seems to be an apparent limit to their population at about 2.2 million people. Figure A2-2 suggests that such Highly industrial cities may not provide scope for continued population growth without further diversification of the economy, compared to the highly commercial and mixed-economy cities. Cities that belonged to the industrial city category in both the 2010-year and the previous years have a specialized resource-based economy. For example, oil industry is the main industry in five cities, namely Panjin, Daqing, Dongying, Karamay, and Puyang, which are Highly industrial cities over 10 years. Some cities with special natural resources, *e.g.*, mineral resources or hydropower system, also fall into the category of Highly industrial cities over 10 years, such as Jiayuguan, Yichang, etc.

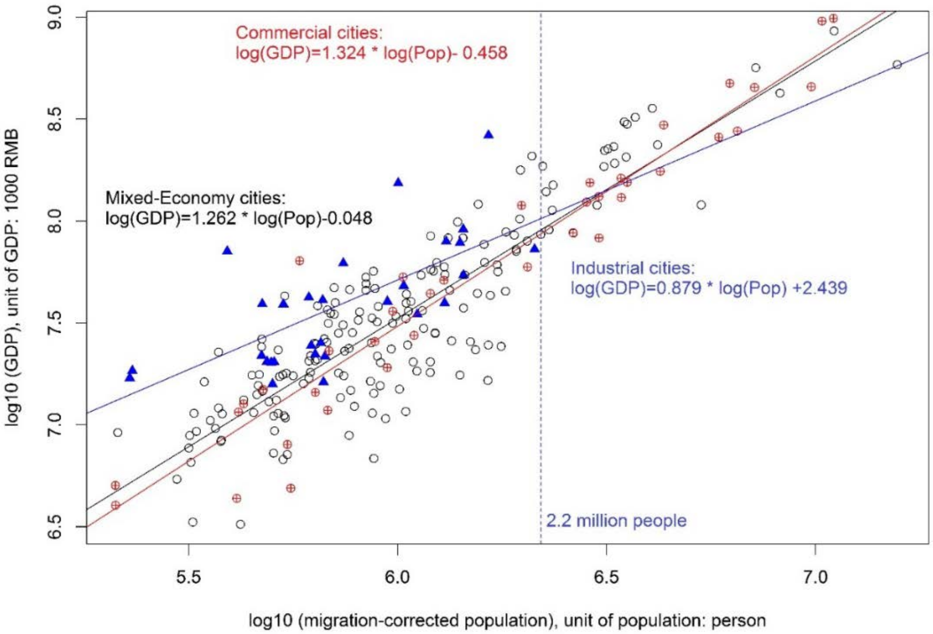

Figure A2-2. Scaling of GDP versus migration-corrected population in Chinese cities categorize by economic structure as Industrial, Commercial and Mixed-Economy. Both population and GDP in this figure is on the base-10 logarithm to illustrate the population cap better.

A2.3.3 City categories differentially shapes GDP to income conversion

Consistent with Figure A2-2, we also explore how city wealth (*i.e.*, GDP per capita) translates to household incomes, with both data being derived from different sources. In non-categorical modeling, a statistically significant and positive correlation is found between the average per capita household income and average per capita GDP (Figure A2-3), confirming that urban household income increases with the increase in city wealth (GDP). In contrast, categorical modeling reveals that the per capita GDP to income conversion is significantly higher in commercial cities than the other city categories (see Figure A2-3), nearly double (slope of 0.42) that of the industrial cities

(≈0.21). This suggests that a larger portion of the GDP created can be converted to personal income in commercial cities as the per capita GDP grows, which may be a major driver of the different and escalating superlinear household resource consumption characteristics in mixed-economy and commercial cities as seen in Table A2-2.

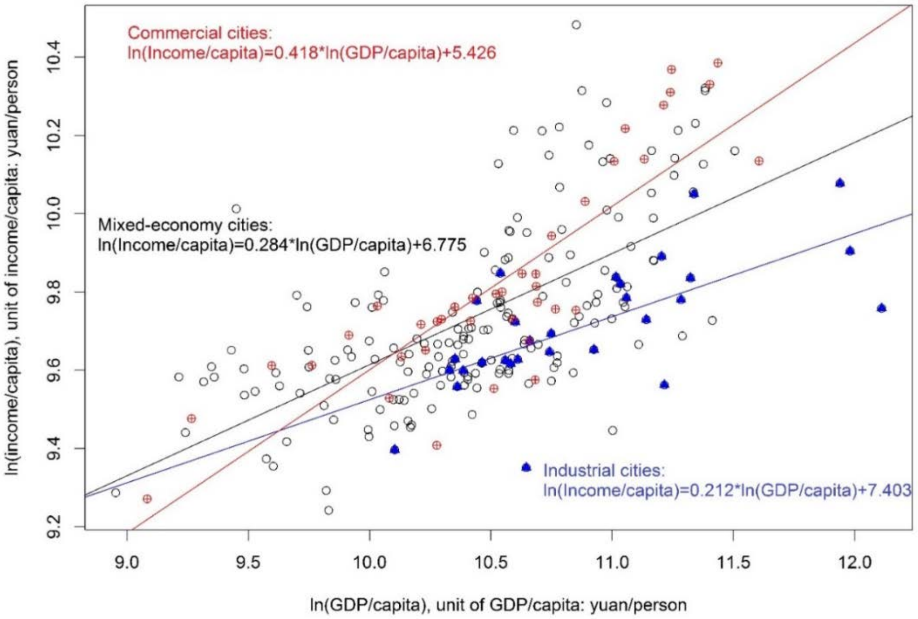

Figure A2-3. GDP per capita to urban household income per capita conversion in different city categories

A2.3.4 <u>City type and Urban Form</u>

Both population density and urban form are positively correlated with city population size, indicating that as cities grow, both density and percentage of homes in high-rise buildings are increasing. Analysis of these regressions found that urban density-population didn’t show any differences in different city types. However, the percentage of homes in high-rise buildings increase deeply in industrial cities, as population grows (coefficient is about 3.7% per 100,000 population), and significantly larger than that of the other city types. Since the highly industrial cities have an apparent limit on the population (Figure A2-2), their average population density and percentage of homes living in higher-rise buildings are smaller than other type of cities (Figure A2-4). Overall, the highly commercial cities have a much larger percentage of homes in 10-story buildings and higher average urban density, compared to the other city types (Figure A2-4). Density and urban form are important parameters that can shape transportation and building energy use. Therefore, understanding patterns of urban form parameters as city population grows, and by city typology, is important.

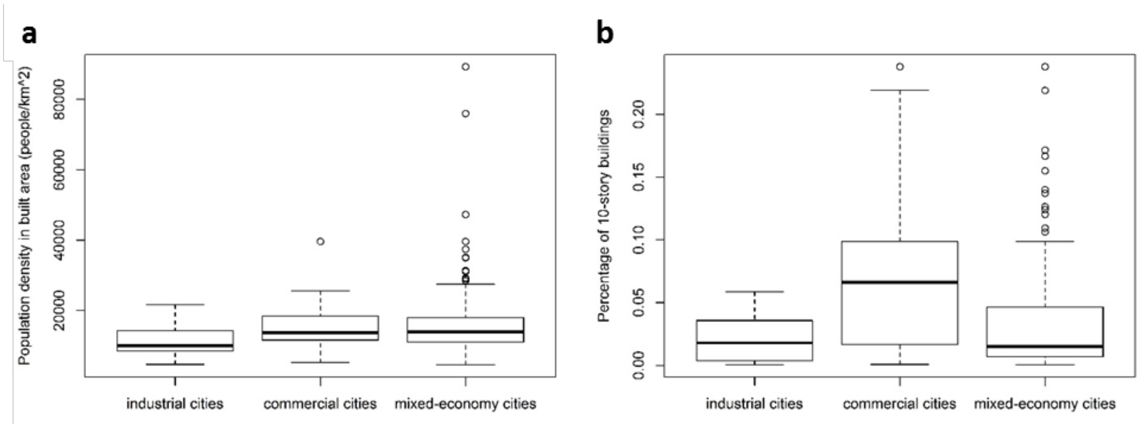

Figure A2-4. Boxplots of average population density (a) and percentage of homes in 10-story buildings (b) in different city categories.

A2.3.5 Multiple variables impact household electricity consumption differently in City Types

Correlation analysis of total household electricity use reveals (See Table A2-3) a population size effect, plus an income effect, and an urban form effect. All three variables show a significant and positive correlation with total household electricity use, *i.e.*, an increase of each of these variables results in an increase in total household electricity use. The positive correlation between the percentage of homes in high-rises and total electricity use, is likely due to the use of elevators. The two additional variables beyond population size, improve the correlation coefficient of total household electricity use only slightly, and are significant only in certain city types. It is interesting to note that the population scaling factor of total household electricity for all cities (non-categorical) now becomes linear, when other variables are included in the regressions, i.e., the *b* value is now 1.019 ± 0.038 for all cities (Table A2-3), which is linear compared to *b* = 1.153 ± 0.033 in the non-categorical single variable analysis (Table A2-1 & A2-2). Categorical modeling also reveals large changes in the scaling factors between Table A2-2 and Table A2-3. This illustrates that the scale factors are highly sensitive both to city categories (Table A2-2), as well as the inclusion of additional significant variables (Table A2-3).

It is interesting that the per capita electricity use intensity (household electricity/capita) does not show a population size effect for commercial and mixed-economy cities. Household income and percentage of homes in high rises positively correlate with electricity intensity. These variables explain about 55% of the variation in per capita electricity use intensity, indicating that other variables or idiosyncratic features of cities, perhaps relating to technology, policies or inequalities in consumption, may shape electricity use intensity. Neither total household electricity nor intensity (household electricity/capita) is significantly impacted by average population density or CDD. The lack of correlation with CDD may be because of the relatively low penetration of air conditioners in households in China in 2010.

The "*b*" values in Table 3, since they represent the slope of an ln-ln relationship, effectively denote elasticity. Thus, the nominal "*b*" value in Table 3 indicates that in non-categorical modeling, all other parameters being the same, total household electricity can be expected to increase by 10.19%, 3.0%, 1.0%, and 12. 6% when population, income per capita, percentage of homes in high-rises, and urbanization rate each increase by 10% (independently). For household electricity use intensity (in non-categorical modeling), the elasticities derived from the "*b*" values (Table A2-3) indicate 3.0%, 1.0%, and 12.6% increase in intensity with a 10% increase in income, the percentage of homes in high-rises, and urbanization rate each independently.

Table A2-3. Categorical multi-variable modeling of total household electricity consumption in 2010. All variables are at natural logarithm scale as illustrated in Equation (A5) and (A6) in Section (A2.3).

Electricity consumption	**City type**	**Population in 2010**	**Per capita household income in 2010**	**Percentage of homes in 10-story buildings in 2010**	**Urbanization rate in 2010**	**Population density in built area in 2010**	**Cooling degree days in July, 2011**	**Adjusted R^2**
hh electricity use in 2010	Mixed-economy cities	0.967 ±0.053(***)	0.516 ±0.153(**)	0.103 ±0.035 (**)	1.325 ±0.268 (***)	Insignificant		0.942
	Industrial cities	0.525 ±0.215 (*)	Insignificant	0.164 ±0.086	Insignificant			
	Commercial cities	1.037 ±0.115 (***)	0.719 ±0.411	Insignificant	1.079 ±0.563			
	Non-categorical modeling	1.019 ±0.038 (***)	0.299 ±0.093 (**)	0.102 ±0.030(***)	1.258 ±0.217(***)			0.938
per cap hh electricity use in 2010	Mixed-economy cities	Insignificant	0.516 ±0.153(**)	0.103 ±0.035(***)	1.325 ±0.268 (***)			0.635
	Industrial cities	-0.475 ±0.215 (*)	Insignificant	0.164 ±0.086	Insignificant			
	Commercial cities	Insignificant	0.719 ±411	Insignificant	1.079 ±0.563			
	Non-categorical modeling	Insignificant	0.299 ±0.093 (**)	0.102 ±0.030 (***)	1.258 ±0.217 (***)			0.612

Note: "hh" means household and "insignificant" means not statistically significant. * indicates whether the scaling factor is significantly different from 0. (* p-value<0.05, ** p-value<0.01, *** p-value<0.001).

A2.5. Discussion

This study has explored both population-scaling as well as GDP-scaling relationships of several commonly reported parameters important in understanding the MEF of cities. While prior scaling studies of citywide MEF have focused on population-scaling only (Bettencourt, *et al*. 2007), we find for Chinese cities, that household MEF-related parameters correlate better with population, while activities solely pertaining to businesses and industry scale, and many communitywide parameters, correlate better with GDP. For example, for business-related electricity use, the R^2 for GDP- and population-scaling are 0.781 and 0.581 respectively (Table A2-1). The scaling with respect to GDP of production-related flows has been documented in the literature (Shiu and Lam, 2004). Because cities contain both household consumers and producers, the latter often producing to serve exports, our findings suggest that a dual approach to scaling might better represent the aggregate MEF of cities. This has important implications for downscaling: for example, when energy use data are downscaled from the national or provincial level to that of cities, our results suggest the dual approach, *i.e.*, downscaling household electricity and fuel use by population, and commercial industrial electricity and fuel use by GDP can provide first order estimates of aggregate city MEF. Parameters like road surface area, which is used by both producers and consumers, correlate to a high degree and to similar extents with both population and GDP (R^2 are 0.736 and 0.785 for population- and GDP-scaling respectively).

For countries experiencing large-scale urban migration and inter-urban movement, efforts to use more representative migration corrected populations can yield better correlated population-scaling relationships, as our results indicated.

Exploring population- scaling relationships for different city types based on economic structure yields insightful results. We find that the different city types are very different in GDP-population scaling relationships. Highly industrial cities exhibit an apparent limit to their population size, and their wealth (GDP) increases sub-linearly with population. These cities also exhibit statistically lower conversion of GDP per capita to average income per capita. In contrast, highly commercial cities exhibit superlinear GDP increase with population, and greatest conversion in GDP to household wealth. Urban form parameters are also influenced by population differently in the different city types.

Multivariable analysis indicates sensitivity of total household electricity to population (city size), household income per capita, and to urban form (percentage of population in high-rises). Per capita household electricity use appears to increase with household income, and with the percentage of homes in 10-storey or above buildings. No significant impact of urban density is seen in Chinese cities. Most interestingly, the scaling factor of total household electricity, which was linear in single-variable regression, has become sublinear in industrial cities ($b \approx 0.9$) in categorical modeling, and even more so in categorical and multivariable modeling ($b \approx 0.6$) . This shows that scaling factors are not only sensitive to city types, but also to the inclusion of other significant variables.

In sum, we find that different city types exhibit very different population-scaling relationships, as well as different characteristics of household income creation and urban form, which can affect their associated MEF. The study of city types provides insight on urbanization processes as cities grow and transition from secondary to tertiary economies, or, may become locked into industrial economies. These industrial cities tend to be small, with population around 2 million. According to the UN, these are the type of cities that are expected to be at the forefront if urbanization and house more than 60% of future urban populations in Asia and Africa. Further study of different city types is important to understand the trajectories of future urbanization.

Lastly, our study suggests care should be used in considering universal scaling coefficients for all cities. Indeed, we show that the characteristics of such scaling relationships, *i.e.*, superlinear, sublinear and linear, can be widely different among city types by economic structure, and are also sensitive to inclusion of other relevant variables (Shalizi, 2011, Clauset et al., 2009) and statistical method application (Clauset et al., 2009). Overall, study of differences across city types is important to understand wealth (GDP), household income urban form, and MEF. By initiating exploration of these differences, this paper advances our understanding of urbanization, city types, and pathways to a more sustainable urban future.

Acknowledgment

The authors gratefully acknowledge financial support from NSF PIRE (grant number PIRE-1243525). AR developed the conceptual framework and developed the study design of city types by economic structure. DJ and KT developed the database and implemented the data analysis; JZ provided insight in urban districts and city taxonomy in China. AR and JZ supervised the research process and reviewed the work.

Appendix-3 Supplement information for Chapter 3

Table A3-1. Population and GDP distribution in cities grouped by population sizes and economic structure

City category by population size	Total population (million population); % in national total population)				
	Highly-commercial Cities	Highly-industrial Cities	Mixed-economy Cities	Subset sum of population	% of in national total population
Megacity (>=10 million)	62	0	27	**89**	**7%**
Very large city (5~10 million)	41	0	27	**68**	**5%**
Large city (3~5 million)	39	0	31	**71**	**5%**
Mid-size city-I (1~3 million)	23	22	178	**223**	**17%**
Mid-size city-II (0.5~1 million)	20	23	147	**191**	**14%**
Small city (<0.5 million)	9	11	43	**63**	**5%**
Total	**195**	**56**	**454**	**705**	**53%**
	Total GDP (10^9 yuan), % in national total GDP				
	Highly-commercial Cities	Highly-industrial Cities	Mixed-economy Cities	Subset sum of GDP	% in national total GDP
Megacity (>=10 million)	5034	0	1441	**6475**	**15%**
Very large city (5~10 million)	2309	0	1528	**3837**	**9%**
Large city (3~5 million)	2269	0	2255	**4524**	**10%**
Mid-size city-I (1~3 million)	964	1223	7404	**9591**	**22%**
Mid-size city-II (0.5~1 million)	602	1102	5072	**6776**	**16%**
Small city (<0.5 million)	217	631	1306	**2153**	**5%**
Total	**11394**	**2956**	**19007**	**33357**	**76%**

Table A3-2. Population and GDP distribution in cities grouped by administrative levels and population sizes

City category by population size and administrative level	Population (million persons, % in nation-wide population)				GDP (10^9 yuan, % in nation-wide GDP)			
	City propers		County-level cities		City propers		County-level cities	
Megacity	89.11	7%	0		6,475	16%	0	
Very large city	67.85	5%			3,837	10%		
Large city	70.74	5%			4,524	11%		
Mid-size city-I	151.80	11%	71.23	5%	6,372	16%	3,218	8%
Mid-size city-II	74.94	6%	115.79	9%	2,676	7%	4,100	10%
Small city	18.10	1%	45.38	3%	717	2%	1,436	4%
Total	**472.54**	**35%**	**232.40**	**17%**	**24,602**	**61%**	**8,755**	**22%**

Table A3-3: Comparison of Bottom-Up Data Utilized in the China City Industry and Infrastructure Database (developed in this paper) versus China's National Statistical Yearbook Energy Balance Table (NBS, 2011, Top-Down analysis). (Ramaswami et al., 2017b)

Sector/Item	Our Bottom-Up Data (10,000 ton coal-equivalent (tce))	Data Source of Chinese City and Infrastructure Database	National Energy Balance Sheet (10,000 ton coal-equivalent (tce))	Difference
Total coal use in powerplants	**108,000**	Tsinghua University (individual plants >6MW)	**110,000**	**2%**
Thermal Input to Industrial production:		Tsinghua University	Industrial Sector - Fossil Inputs: 134,485 - Heat supply fossil inputs (primary): 13,716	**-12%**
- Steel	32,437			
- Cement	14,845			
- Brick	8,161			
- Lime	3,513			
- Glass	778			
- Coking	5,009			
- Ammonia	5,859			
- Ceramics	3,722			
- Alumina	2,640			
- Copper	276			
- Other chemical	2,541			
SUM OF Above sectors	**79,781**			
- Other Industries	**50,587**	Downscaled from National Statistical Yearbook based on employment at county level (CIED database) and industrial energy use statistics (NBS, 2011)		
Total of Industrial sector, excluding powerplants	**130,368**		**148,201**	
Residential and commercial Thermal Inputs (primary):	-Direct fossil fuel inputs: **24,317** - Primary Energy District heating supply:**16,039**	Direct fossil fuel inputs down-scaled from Tsinghua University Provincial data; District heating data from China Urban Construction Yearbook(Ministry of Housing and Urban-Rural Development, 2011) with energy conversion from Provincial Handbooks	- Direct fossil fuel inputs: 19,917 - Heat Supply (in primary energy units): 6121	35%* (**see note below**)
Transportation	**38,373**		**34,770**	9%
Agricultural and Other Thermal Inputs	Not included in our work		**8,065**	NA
SUM OF ABOVE EXCLUDING AGRICULTURE	**317,097**	**This dataset combining all the above sources**	**319,009**	**-0.6%**

Footnote: Several studies note apparent differences in sub-sectors, e.g., between bottom-up data and statistical yearbook data caused by categorization differences. Zhou et al (2008, 2010) note that bottom-up energy use in homes and commercial buildings appears larger compared to the national energy balance sheet, because of classification differences, and as the latter reports housing for industry workers within the industrial energy use category (Zhou, 2010, Zhou and Lin, 2008).

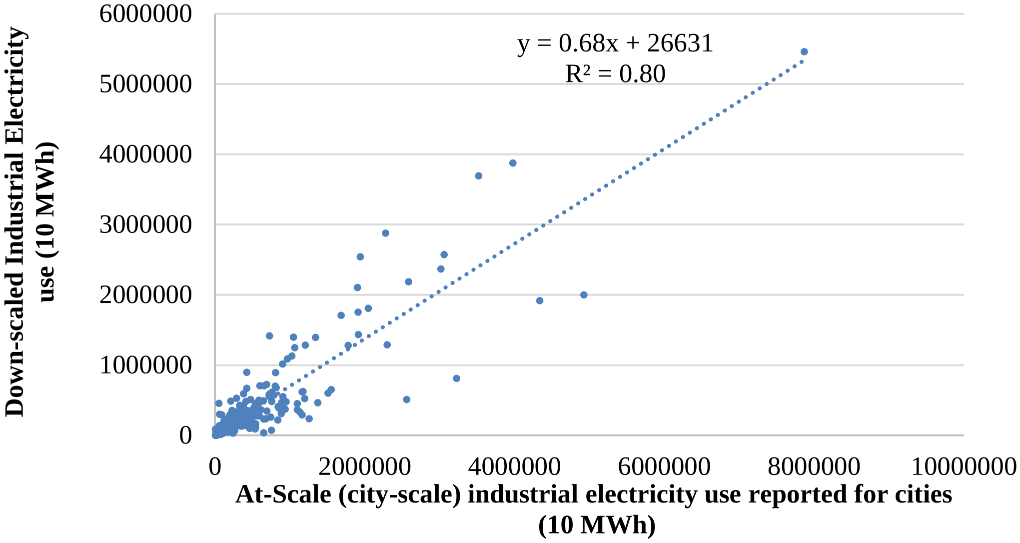

Figure A3-1: Effectiveness of downscaling industrial energy use (electricity end-use is shown here) from national data to individual cities by employee, compared to at-scale data. From (Ramaswami et al., 2017b)

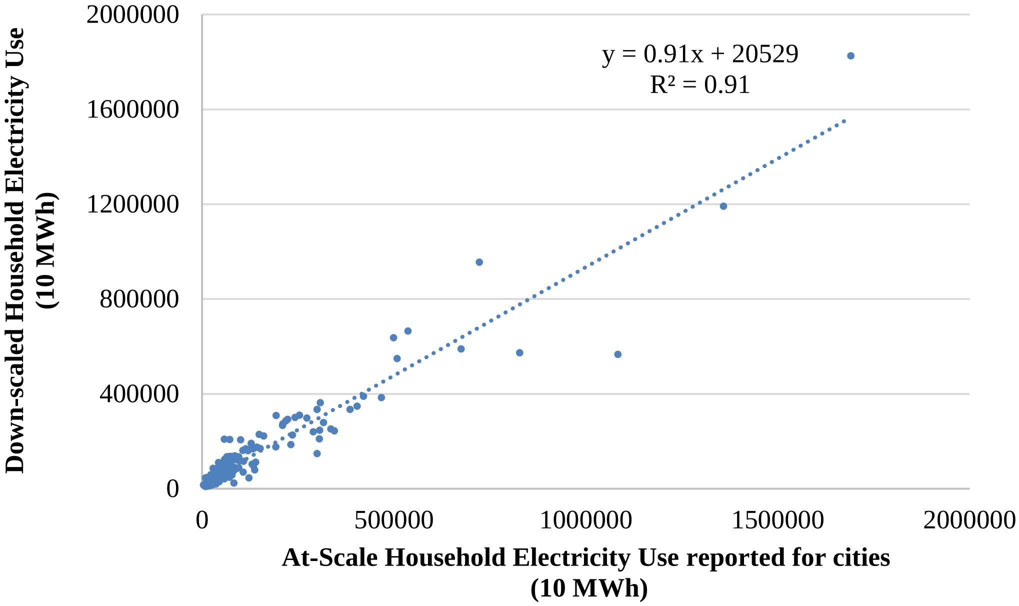

Figure A3-2: Effectiveness of Downscaling Household energy use (electricity end-use is shown here) from provincial data to individual cities by household numbers, compared to At-Scale data. From (Ramaswami et al., 2017b)

Appendix-4 Supplement information for Chapter 4

Table A4-1. Socio-economic factors of the selected cities (*Shiqu*)

City Name*	Area	Total Pop	Urbanization Rate	Pop Density	Total GDP	% of secondary GDP	% of Tertiary GDP	Urban HH living space per person
	Sq.km	1,000 persons	%	person/ sq.km.	billion *yuan*			sq.m./person
Hebei Province	187,693	71,854	44%	383	2,039.43	53%	35%	30.9
Shijiazhuang	213	2,832	98%	13294	226.26	29%	70%	29.3
Tangshan	1,232	3,187	67%	2587	53.10	61%	35%	25.3
Qinhuangdao	363	1,030	94%	2837	54.45	41%	58%	29.3
Handan	434	1,445	91%	3330	21.71	58%	41%	28.9
Xingtai	115	670	100%	5827	54.34	65%	35%	34.2
Baoding	312	1,139	91%	3649	36.15	60%	39%	34.2
Zhangjiakou	376	1,061	87%	2821	20.64	56%	42%	27.7
Chengde	760	634	85%	835	42.93	58%	40%	25.2
Cangzhou	183	537	93%	2933	33.43	51%	48%	32.3
Langfang	292	868	61%	2973	17.25	42%	51%	34.4
Hengshui	273	522	75%	1913	25.41	60%	31%	29.9
Fujian Province	124,000	36,894	57%	298	1,473.71	51%	40%	37.2
Fuzhou	1,043	2,882	97%	2763	154.36	37%	63%	33.2
Xiamen	1,573	3,521	88%	2238	206.01	50%	49%	32.6
Putian	2,284	1,922	57%	841	71.05	59%	32%	38.9
Sanming	1,178	373	88%	316	22.75	55%	40%	37.4
Quanzhou	850	1,433	80%	1686	82.59	56%	42%	41.6
Zhangzhou	401	705	87%	1758	34.90	47%	50%	35.3
Nanping	2,660	467	64%	175	17.64	55%	33%	34.1
Longyan	2,678	661	69%	247	40.97	64%	31%	42.9
Ningde	1,537	428	59%	278	12.68	31%	54%	39.1

Table A4-2. Parameters to estimate recoverable industrial waste heat from different industries sectors (Ramaswami et al., 2017b)

Industrial sector	Industrial Process	P_i; Waste Heat as a (%) of unit input fuel	$Ratio_i$, Ratio of different grades of industrial waste heat (as % of P_i)			Current Waste Heat Utilization Rate, U_i
			High grade (> 400°C)	Medium grade (100-400°C)	Low Grade (<100°C)	
Power plant[a]		50%		25%	25%	
Steel [b]	Sinter (sintering machine) & Pellet (pellet machine)	8%	58%	42%	-	17%
	Pig iron (blast furnace)	19%	56%	20%	24%	31%
	Converter steel(basic oxygen furnace)	5%	100%	-	-	33%
	Hot rolled steel(hot rolling)	5%	71%	29%	-	27%
Aluminum[c]	Electrolytic aluminum production	50%	-	100%	-	11%
Alumina [d]	Alumina production	12%	31%	69%	0	47%
Copper [e]	Copper production	53%	99%	1%	0	
Clinker	Shaft kiln clinker & rotary kiln clinker [f]	30%	100%	-	-	
	New dry-process clinker [g]	30%	-	100%		
Cement [h]	NCMT (NSP)	42%	-	100%	-	
Glass [i]	Float process Exhaust gas from Glass melting furnace	35%	100%	-		
Brick [j]	Brick production	40%	-	100%	-	
Lime [k]	Lime production	30%	-	100%	-	
Ceramic [l]	Building ceramic production	30%	-	100%	-	15%
	Sanitary ceramic production	20%	-	100%	-	
Coke [m]	Machine coke oven	87%	81%	20%	-	80%
Petroleum products [n]	Refinery	25%	-	70%	30%	
Ethylene [o]	Ethylene production	5%	-	100%	-	
Other[p]	Industrial boilers	20%			100%	-

Note:

a: Approximately 50% of waste heat is available from the power plant distributed between medium grade steam of which 25% is recoverable due to sulfur dioxide fouling and low grade hot water of which 80% is recoverable (Bo et al., 2015)

b: (Cai et al., 2007, Wang et al., 2007a)

c: (Huang et al., 2011, Huang et al., 2013, ZHANG et al., 2010b, Tian et al., 2014)

d: (Li et al., 2011, Zhang, 2008, Niu, 2011)

e: (Song, 2003)

f: (Yin, 2013, Zhang, 2013)

g: (Zhang, 2013, Wang et al., 2007b, Tang, 2007)

h: (Ji, 2014)

i: (Hu et al., 2011, Tang and Liu, 2010, Yu et al., 2012b)

j: (Yin, 2013)

k: (Chen, 2006, Zhao, 2000, Gong et al., 2014, Fan, 2014)

l: (Yin, 2013)

m: (Feng and Gao, 2015, Qi, 2011, Sun et al., 2015)

n: (Tang and Gao, 2010)

o: (Wu et al., 2007)

p: Industrial boilers are optimistically estimated to be 80% efficient with the remaining 20% available as low grade waste heat which we assume 80% to be recoverable.

Table A4-3. Cost of the components in district energy system from various global cases

Component		**Equipment cost**	**Installation cost**	**Unit**	**Reference**
Heat Exchanger		71,000	22,00	*yuan*/Megawatt	(Li et al., 2015, Li et al., 2016, Sun et al., 2014)
Absorption Heat Pump		326,000	98,00	*yuan*/Megawatt	
Absorption Chiller		1,073,000	537,000	*yuan*/Megawatt	(Zabala, 2009)
Network cost	District heating	1,484,000	1,480,000	*yuan*/kilometer	(Li et al., 2015, Li et al., 2016, Sun et al., 2014)
	District cooling	1,400,000	3,267,000	*yuan*/kilometer	(Zabala, 2009)
Cost of Individual Heating equipment		200	n/a	*yuan*/watt	Internet product profiles
Cost of Individual Air Conditioner	Residential	1		*yuan*/watt	
	Commercial	6		*yuan*/kilowatt	
		Price	**Coal equivalent transfer**		
Fuel	Coal	410 *yuan*/ton	0.7 tce/ton coal		(Li et al., 2016)
	Natural gas	3500 *yuan*/ton	1.6757 tce/ton LNG		
	Electricity	0.65 *yuan*/kWh	3.50E-4 tce/kWh		

Notes: a. Currency transfer rate: 1 US$=6.8 *yuan*

Appendix-5 Supplement information for Chapter 5

A5.1. Interview protocol

Motivations and Enabling Factors for Environmentally Sustainable Transitions of City-wide District Energy Systems in the U.S.

Section goal: understand how DES professionals define environmentally sustainable DES, and understand what environmentally sustainable transitions that DES industry are going through.

1) According to your knowledge and opinions, how do you define "environmentally-friendly" in the context of DESs? (or what are the characteristics of an environmentally sustainable DES?)
2) How do you think DES will be evolved in the next 10 or 20 years? OR Could you talk about what are environmentally sustainable transitions that district energy industry is going through?

Section goal: understand what actions the company has taken to align with these changes, and the motivations, enabling factors, and barriers are for city-wide DES operators to take actions for making environmentally sustainable transitions.

3) What type of actions that your company/customers/department have been taken to align your DES business with the future change in this industry?
4) What type of business strategies in your company/customers/department influence your decisions to take aggressive actions or not at the moment? The aggressive actions can be changing energy sources, changing the distribution system (converting to hot or warm water system).
5) Now I will ask you about your business strategies and customers, what are the strategies attracting new customers and keeping the old customer? And how do these strategies influence taking the actions that you mentioned?
    a. What attract customers to join DES?
    b. What are the strategies to keep customers?
6) How do environment and natural resource shape your business (Now I will ask you about your business strategies, in terms of the environment and natural resources)?
7) Now I will ask you about business strategies and technology development. How does technology development affect your business strategies in deciding to take more aggressive actions or not?
    a. How do new technology in your and other industries affect your business?
    b. How do the factor in the cost if upgradation or change this energy system, etc. influence the business strategies?
8) Do you see other sectors like power, agriculture or wastewater impacting your business strategy in deciding to take more aggressive actions or not?
9) How do policies at city/state/federal have the large impact on your industry?
    a. What are the enabling policies for taking these actions?
    b. What the policies may bring trouble for DES development for taking these actions?

Section goal: understanding who are leading these transitions, what change the industry is facing, and who are success, who are struggled during this change.

10) Coming back to the transitions, what are the biggest drivers to the transition?
11) Could you name some DESs in the U.S. who are leading this environmentally-sustainable transition? Or do you know some legacy system closed down or struggling?
12) You describe the transition is coming, how do you think your industry should be changed?
    a. How does the gas/electricity utility industry should change?
    b. How about the DES industry specifically?
13) Is there anything we've missed that would be important to know about the motivations, enabling factors, or barriers of district energy systems' environmental sustainable transitions?