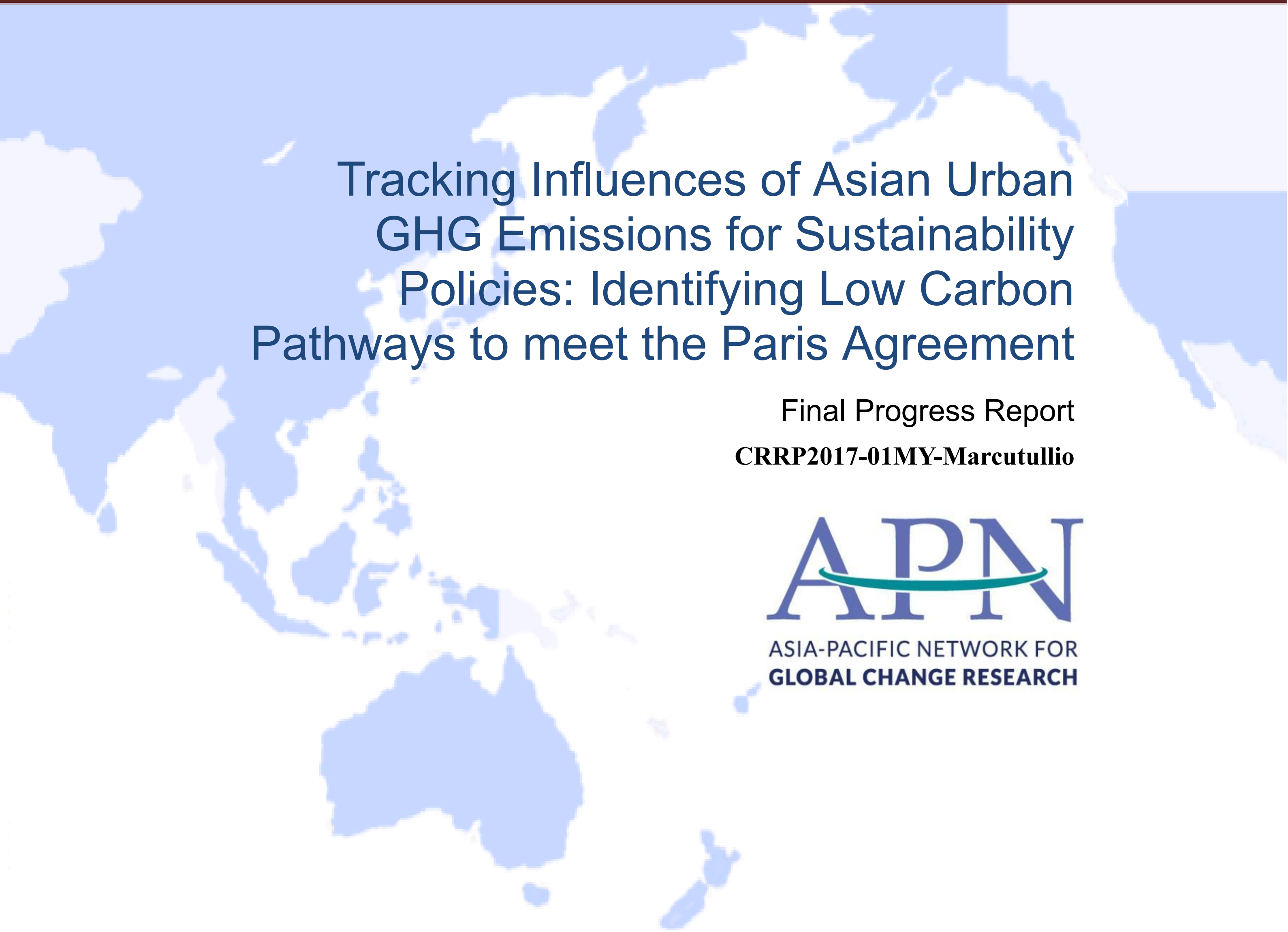

Tracking Influences of Asian Urban GHG Emissions for Sustainability Policies: Identifying Low Carbon Pathways to meet the Paris Agreement

Final Progress Report

CRRP2017-01MY-Marcutullio

APN
ASIA-PACIFIC NETWORK FOR
GLOBAL CHANGE RESEARCH

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Part 1 – Project work and results

1. Introduction

Over the past decades, Asia has undergone rapid urbanization. This transformation has accompanied increased energy demand and subsequent greenhouse gas (GHG) emissions. From 1990 to 2010, the number of urban residents in Asia grew by over 800 million, increasing the Asian share of global urban population from 45 to 52% while Asian CO_2 emissions increased from 6 Gt to 14 Gt, increasing its share of global GHG emissions from 39 to 54%. Further urbanization portends even higher emission levels. The recent Paris Agreement (2015) has drawn attention to the dramatic actions necessary to keep emissions low and therefore climate stable. Organizations such as UN-HABITAT & UNESCAP (through the creation of the Northeast Asia Low Carbon Cities platform) and Asian governments are moving to develop low carbon cities. Application of mitigation policy for low carbon societies is complicated, however, by the unique regional development conditions (socially, physically, economically and politically). Policies appropriate elsewhere may not work in the Asian context making it necessary to understand the historical dynamics associated with regional urban development, energy use and GHG emissions. To address this challenge, we propose urban case study historical analyses of emissions and their driving forces in Asian cities.

Keywords (Urban, GHG emissions, GHG Inventory, Energy policy):

2. Participating countries

China (Beijing), Taiwan (Taipei), Thailand (Bangkok), South Korea (Seoul), Japan (Tokyo), and the USA (New York City) (for details see table on next page)

3. Objectives

The original objectives of the project are fourfold:

a) To develop historical sub-city (administrative district) level energy and GHG inventories for Seoul, South Korea; Taipei, Taiwan; Beijing, China; Bangkok, Thailand; Tokyo, Japan and New York City, USA;
b) To identify forcing variables for energy use and GHG emission changes over time, including socio-economic, institutional/policy and biophysical variables, for sub-city units and metropolitan areas and test the strength of these variables on both the home city and use these results to synthesize efforts across different cities;
c) To develop a collaborative research network that will continue to engage in and inspire similar research
d) To disseminate results and engage with the policy community and stakeholders at different scales to seek comments and improvements and influence change.

Participants in the APN project

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4. Outside Funding secured

Outside funding secured for related research

2021-2022	*Hunter College, PSC-CUNY Grant* ~ US$3,500, PI: Peter J. Marcotullio. This project was to perform the analysis of residential energy use historical and spatial inventories of the New York City Metropolitan and GHG emissions at high resolution for determinants of change analysis
2020-2021	*Hunter College, PSC-CUNY Grant* ~ US$3,500, PI: Peter J. Marcotullio. This project was to develop a framework for generating a residential energy use historical and spatial inventories of the New York City Metropolitan and GHG emissions at high resolution for determinants of change analysis
2018-2019	*Advanced Science Research Center Seed Grant*, ~ US$30,000, PI: Peter J. Marcotullio, co-PI Andrew Reinmann. Peter J. Marcotullio's part is to estimate historical cooling energy demand in New York City
2018-2019	*Hunter College, PSC-CUNY Grant* ~ US$3,500, PI: Peter J. Marcotullio. This project will result in the generation of historical and spatial inventories of Northeast, USA on-road transportation energy use and GHG emissions at high resolution for determinants of change analysis
2017-2018	*Hunter College, PSC-CUNY Grant,* ~ US$3,500, PI: Peter J. Marcotullio. This project will result in the generation of historical and spatial inventories of Northeast, USA residential energy use and GHG emissions at high resolution for determinants of change analysis
2018-2019	Ministry of Science and Technology, Taiwan, for the Graduate Students Study Abroad Program, Po Ju Huang, Ph.D. candidate at National Taipei University (NPTU) for a visiting fellowship at Hunter College, CUNY, where he undertook research on energy use and GHG emissions embedded in building in Taipei
2019-pres.	Ministry of Education, Culture, Sports, Science and Technology of Japan (MEXT) GPSS-GLI fellowship at the University of Tokyo for Jelena Aleksejeva, Ph.D. candidate at the University of Tokyo, working with Alex Gasparatos. She was employed one day per week at NIES with Prof. Yamagata, Global Carbon Project, undertaking research for this project.

5. Summary of project results

Meetings

- Convened three research workshops (see Appendix A). The first in Taipei, the second in Beijing, and the third in Tokyo. The Tokyo workshop also included a policy engagement conference held at the University of Tokyo.

6. Summary of outputs and outcomes

The Bangkok team:

Student engagement:

- Subina Shrestha, MA student (AIT) worked on the project

Publications:

- White paper submission to the project, Subina Shrestha and Shobhakar Dhakal, (2019) “Bangkok Metropolitan Region: Greenhouse Gas Emission Inventory and Drivers” presented at the Tokyo Workshop, November 19, 2019.

The Beijing team:

Publications:

- Wang, C., Zhan, J., Li, Z., Zhang, F., Zhang, Y., (2019) Structural decomposition analysis of carbon emissions from residential consumption in the Beijing-Tianjin-Hebei region, China. *Journal of Cleaner Production* 208, 1357-1364.
- Chapter submission for edited volume, Zhihui Li, Xiangzheng Deng, Chao Wang, Lu Peng (2022) “Industrial transformation and residential sustainable consumption for the promotion of low-carbon urbanization in the Beijing-Tianjin-Hebei region of China”

The Seoul team:

Publications

- White paper submitted to project, Kwangik Wang (2022), “Seoul’s Emissions and Carbon Mitigation Policies”

The Taipei team:

Student engagement:

- Engaged in year-long student exchange for capacity building between team members from National Taipei University (NTPU) and Hunter College, CUNY. Po Ju Huang, Ph.D. candidate from NTPU, spent a year studying at Hunter College, New York, at the Institute for Sustainable Cities, with Peter J. Marcotullio. Po Ju was able to obtain the funding necessary for the exchange, from his national government, due to his work in the project.
- Po-Ju Huang received Ph.D. from National Taipei University through work on the project

Publications:

- Po-Ju Huang, Shu-Li Huang, Peter J. Marcotullio (2019) “Relationships between CO2 emissions and embodied energy in building construction: A historical analysis of Taipei”, *Building and Environment* 155: 360-375

The Tokyo team:

Student engagement:

- Jelena Aleksejeva, Ph.D. student at the University of Tokyo worked with the Tokyo project team.

Publications:

- Chapter submitted for edited volume, Jelena Aleksejeva, Gerasimos Voulgaris, Yin Long, Alexandros Gasparatos (2022) “Co-evolution of energy and climate change mitigation policies in Japan and Tokyo”
- Yin Long, Yida Jiang, Peipei Chen, Yoshikuni Yoshida, Ayyoob Sharifi, Alexandros Gasparatos, Yi Wu, Keiichiro Kanemoto, Yosuke Shigetomi & Dabo Guan (2021) “Monthly direct and indirect greenhouse gases emissions from household consumption in the major Japanese cities,” *Scientific Data* 8:301 https://doi.org/10.1038/s41597-021-01086-4
- Yin Long, Yoshikuni Yoshida, Yuan Li, and Alexandros Gasparatos (2022) Spatial-temporal variation of CO2 emissions from private vehicle use in Japan, *Environmental Research Letters* 17 014042 https://doi.org/10.1088/1748-9326/ac4293
- Special issue of *Sustainability*, entitled “Local Government Responses to Catalyse Sustainable Urban Development”, which includes studies addressing climate change policy

The New York City team:

Student engagement:

- George Golub, MA student obtained degree through work on transportation energy use and emissions;
- Nicholas Rio, undergraduate worked on the residential energy inventory
- Allan Lu, MA student worked on the residential energy inventory
- Jessica Stretton, MA student obtained degree through work on energy in New York and helped with the project
- Gowri Anand, MA student worked on the review of Asian GHG emissions for the project

Presentations at conferences:

- Presentation of residential research at an international conference entitled, *Energy and Society in Transition: 2nd International Conference on Energy Research and Social Science*, 28-31 May 2019, Tempe, AZ, USA;

Publications:

- Peter J. Marcotullio, (2018) “The Asian urban energy system: An overview of trends and challenges,” in Sara Hsu (Ed), *Handbook of Sustainable Development in Asia*, Routledge, pp 191-122, which is an overview of energy use and future challenges for cities in the Asia region.
- Chapter submission for edited volume, Nicholas Rio, Allan Lu and Peter J. Marcotullio (2022) “Geography of Residential Energy Use in the New York City Metropolitan Region, 1993 – 2009”.
- Allan Lu, Nicholas Rio and Peter J. Marcotullio (in preparation) “Geography of Residential Energy Use in the New York Tri-Date Region, 1993 – 2009”.

Full project

Web-page development:

- Developed project web-page which will be deployed in March 2022 containing the results of the project

Publications:

- Edited volume that will include chapters from the Beijing, Tokyo and New York City teams. Peter J. Marcotullio, Joshua Sperling, and Andrea L. Pierce (in preparation) *Urban Energy Systems, Climate and Equity: Changing Conditions and Future Prospects*, Part of Series on Energy and Climate Change, Edited by Gerard M Crawley, World Scientific Publishers, based in Singapore.
- White paper literature review and summary of research for the project, Peter J. Marcotullio, Xiangzheng Deng, Zhihui Li, Alexandros Gasparatos, Jelena Aleksejeva, Shu-Li Huang, Po Ju Huang, Shobhakar Dhakal, Subina Shrestha, Kwangik Wang, Gowri Anand, and Jessica Stretton "Tracking influences of Asian Urban GHG emissions for Sustainability Policies: Identifying Low Carbon Pathways to Meet the Paris Agreement".

A list of the agendas for the meeting that were convened is included in Appendix A.

7. Self-evaluation of Work Performed to Date

The project aimed to advance research in sub-city historical analysis of CO2 emissions in Asian cities and help to highlight information to the policy making audience particularly the driving forces of change. The project's outputs are listed below.

Workshops

- 3 workshops held in different Asian cities

Publications:

- 4 journal articles and one chapter published
- 1 journal article in preparation
- 3 chapters submitted to an edited volume

Student engagement:

- 1 Ph.D. student graduated with research based on this project
- 1 MA students graduated with research based on this project
- 3 MA students researchers that worked on the project
- 1 undergraduate student researcher that worked on the project

Policy engagement:

- 1 Policy engagement conference held at the University of Tokyo, 20 November 2019

We attach, in Appendix B a full summary of the research including both an review of the literature and summaries of the different teams methods and findings.

The major barrier experienced by the project was the emergence of COVID-19 pandemic that required significant adjustment of the research. Just when the project team had reached the stage of engagement with policy makers, it became difficult if not impossible to convene meetings. We had to readjust our mechanisms of highlighting the research so we turned to web-page development. Outside of this, our general assessment is that the project has been successful. The different teams attacked the challenge in different ways, but all had interesting findings which provide for a better understanding of Asian urban GHG emissions.

Appendix A

APN Project
Tracking Influences of Asian Urban GHG Emissions for Sustainability Policies: Identifying Low Carbon Pathways to Meet the Paris Agreement
NTPU Taipei Campus, Center for Global Change and Sustainability Science
Scoping meeting agenda
26-27 October 2017

Thursday, 26 October
Meet in lobby of Brother Hotel at 8:30 am for 15-minute walk to campus

Welcome 9:00 am – 9:15 am
    Shu-Li Huang (Welcome to NTPU)
Introduction to the project 9:15 – 10:00 am
    Peter J. Marcotullio "Tracking Influences of Asian Urban GHG Emissions for Sustainability Policies: Identifying Low Carbon Pathways to Meet the Paris Agreement"
    Q & A
Break: 10:00 – 10:30 am
Presentations 1: 10:30 – 12:00
    Douglas Price & Peter J. Marcotullio, "New York City"
    Q & A
    Shu-Li Huang, Taipei"
    Q & A
    Xiangzheng Deng, "Beijing"
    Q & A
Lunch: 12:00 - 1:00 pm
Presentations 2: 1:00 – 2:30 pm
    Subina Shresta, "Bangkok" (Remote – skyped)
    Q & A
    Alexandros Gasparatos and Jelena Aleksejeva, "Tokyo"
    Q & A
    Kangik Wang, "Seoul"
    Q & A
Break: 2:30 – 3:00 pm
APN Updates: 3:00 – 3:30 pm
    Mr. Xiaojun Deng, *Communications and Development Officer APN*
Group photo 3:30 – 3:45 pm
Final discussion 3:45 – 5:00 pm
    Research methods, Data (local, downscaled, inferred, other)
    Geographical units (sub-urban units), Historical analysis (how far back)
    Sources (IPCC, end use, other), Policy engagement, other
Dinner: ~ 6:30 pm, TBA

Friday, 27 October
Meet in lobby of Brother Hotel at 8:30 am for 15-minute walk to campus

Summary of Discussion of research methods and way forward: 9:00 – 10:00

Research methods and data
Project length and research schedule
Projected research outputs
Other

Break: 10:00 – 10:30 am

Logistics 10:30 – 12:00 am

Payments
Monthly Conference call set up
Policy engagement meetings
Research assistance
Next meeting
Other…
Final words

Meeting Adjournment ~ 12:00 pm

Lunch: 12:30-1:30 pm, Brother Hotel

APN Project
Tracking Influences of Asian Urban GHG Emissions for Sustainability Policies: Identifying Low Carbon Pathways to Meet the Paris Agreement
The Institute of Geographic Science and Natural Resources Research, Chinese Academy of Sciences
Beijing, China
First Working Group meeting agenda
14-15 November 2018

Wednesday, 14 November
Participants arrive at Hotel
Your accommodations include breakfast!

Thursday, 15 November
Meet in lobby of Hotel at 8:45 am for 5-minute walk to Chinese Academy of Sciences (see attached map 1)

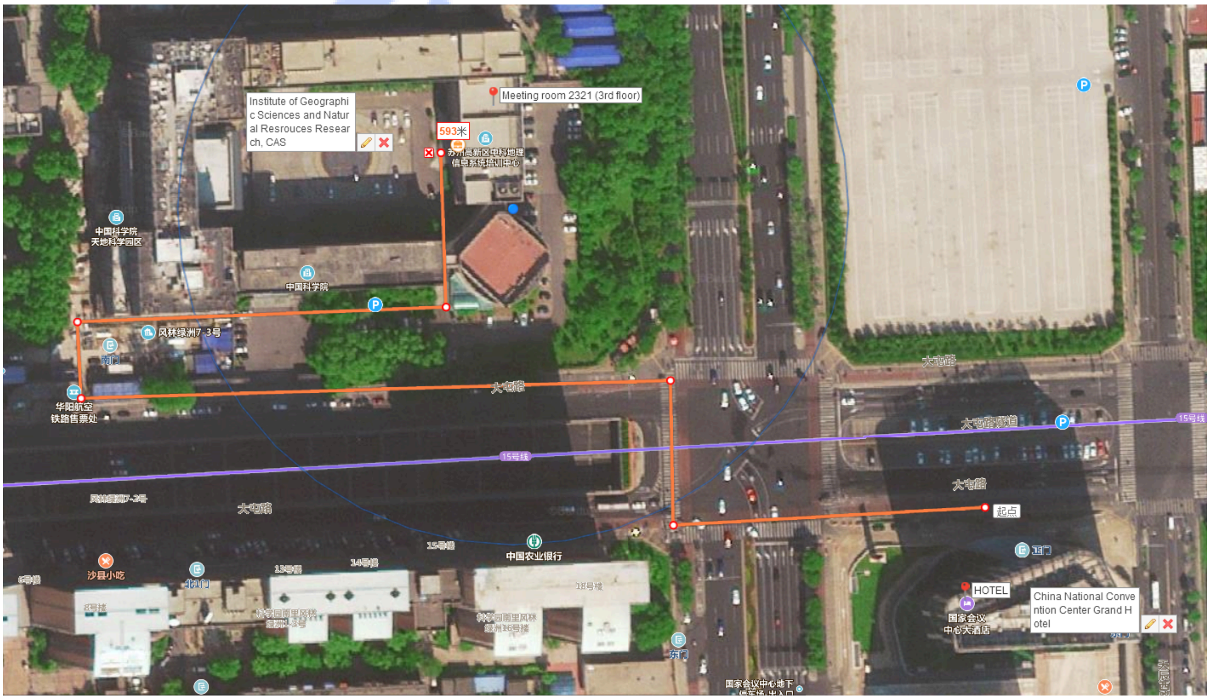
Welcome 9:00 am – 9:15 am
    Xiangzheng Deng (Welcome to the Institute of Geographic Science and Natural Resources Research, Chinese Academy of Sciences)
Introduction to the Working Meeting 9:15 – 10:00 am
    Peter J. Marcotullio "Tracking Influences of Asian Urban GHG Emissions for Sustainability Policies: Identifying Low Carbon Pathways to Meet the Paris Agreement"
    Q & A
Break: 10:00 – 10:30 am
Presentations for Beijing 10:30 – 12:00 pm
    Xiangzheng Deng, Chinese Academy of Science "History of energy use and GHG emissions in Beijing, Introduction"
    Q & A
    Zuihui Li, Chinese Academy of Science "Energy use and GHG emissions in Beijing"
    Q & A
Lunch: 12:00 - 1:00 pm
Presentations for Tokyo Metropolitan Area: 1:00 – 2:30 pm
    Ayyoob Sharifi, Global Carbon Project, "Bottom-up Mapping of CO2 emissions in Tokyo Based on the Local Climate Zones Classification System"
    Q & A
    Jelena Aleksejeva, University of Tokyo, "A Comparative Analysis of Urban and Suburban Utilization of Roofs for CO2 Reduction"
    Q & A
Break and Group photo: 2:30 – 3:00 pm
Presentations for Taipei Metropolitan Region 3:00 – 4:00 pm
    Shu-Li Huang "Historical emissions from Taipei Metropolitan Region"
    Q & A
Dinner: ~ 6:30 pm, Meizhou Dongpo Restaurant (see attached map 2)

Friday, 16 November

Meet in lobby of Hotel at 8:45 am for 5-minute walk to Chinese Academy of Sciences

Logistics call-in from Douglas Price: 9:00 – 9:30 am
    Research assistance payments
    Other grant questions
Plenary for the 2nd day 9:30 am – 10:00 am
    Peter J. Marcotullio, Review of day 1
Presentations for Bangkok Metropolitan Region: 10:00 – 11:00
    Subina Shrestha, Asian Institute of Technology, "Historical energy use and GHG emissions in Bangkok Metropolitan Region" (Skyped in: TBA)
    Q & A
Presentations for New York City Metropolitan Region: 11:00 – 12:00 pm
    Peter J. Marcotullio, Hunter College, "Historical energy use in the USA by sector, 1960-2016"
    Q & A
Lunch: 12:00 - 1:30 pm
Presentations for New York City Metropolitan Area: 1:30 – 3:00
    George Golub, Hunter College, "County scale estimations of New York State historical transportation energy use, 1980 - 2009"
Break: 3:00 – 3:15 pm
Summary of Discussion and the way forward 3:15 – 4:00 pm
    Alex Gasparatos (moderator)
    Next year's workshop and international policy engagement meeting in Tokyo
Wrap up and meeting Adjournment ~ 4:00 pm

Workshop group picture



Hotel and workshop locations

APN Project

Tracking Influences of Asian Urban GHG Emissions for Sustainability Policies: Identifying Low Carbon Pathways to Meet the Paris Agreement

18-20 November 2019

Monday, 18 November

Participants arrive at Hotel
Hotel Forest Hongo

Thursday, 19 November

Meet in lobby of Hotel at 9:15 am for 5-minute walk to University of Tokyo (see attached map 1)

Welcome 9:30 am – 9:45 am
    Alex Gasparatos (Welcome to the University of Tokyo)

Introduction to the Final Working Meeting 9:45 – 10:00 am
    Peter J. Marcotullio "Tracking Influences of Asian Urban GHG Emissions for Sustainability Policies: Identifying Low Carbon Pathways to Meet the Paris Agreement"
    Q & A
Presentations for Beijing 10:00 – 11:00 pm
    Zuihui Li, Chinese Academy of Science "Energy use and GHG emissions in Beijing"
    Q & A

Break: 11:00 – 11:15 pm

Presentations for Taipei Metropolitan Region 11:15 – 12:15 pm
    Shu-Li Huang "Historical emissions from Taipei Metropolitan Region"
    Q & A
Lunch 12:15 -1:30 pm
Presentations for Presentations for Tokyo Metropolitan Area: 1:30 – 2:30 pm
    Jelena Aleksejeva, University of Tokyo, "A Comparative Analysis of Urban and Suburban Utilization of Roofs for CO2 Reduction"
    Q & A
Bangkok Metropolitan Region: 2:30 – 3:30
    Subina Shrestha, Asian Institute of Technology, "Historical energy use and GHG emissions in Bangkok Metropolitan Region" (Skyped in: TBA)
    Q & A
Break and group picture 3:30 -4:00 pm
Presentations for New York City Metropolitan Region: 4:00 – 5:00 pm
    Peter J. Marcotullio, Hunter College, "Historical energy use in the USA by sector, 1960-2016"
    Q & A
Final discussion- wrap up 5:00 – 5:30 pm
    Peter J. Marcotullio - Project assessment and final steps for completion

Dinner: ~ 6:30 pm

Thursday, 19 November

International Policy Engagement Session

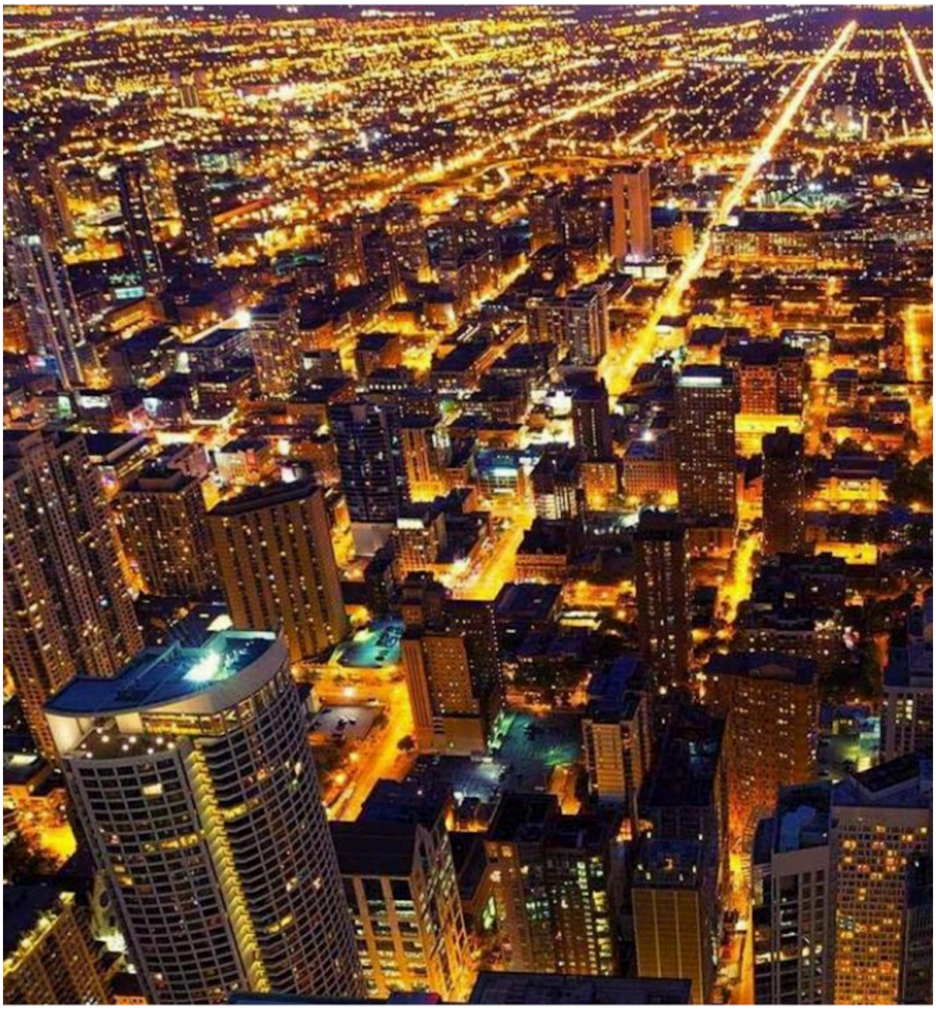
Sanjo Cnoference Hall

Energy use and GHG emissions at the sub-city level: How can this help policy

9.30 – 9.45	Opening Remarks - P. Marcotullio
9:45	Session 1: Case studies from selected cities APN project Results of analysis and policy implications Peter. Marcotullio - NYC Po-Ju Huang - Taipei Subina Shresta - Bangkok Zhihui Li – Beijing-Tianjin-Hebei region
11:00	Session 2: Panel from Global Carbon Project Peraphan Jittrapirom – Global Carbon Project Yoshiki Yamagata – Global Carbon Project Takuro Kobayashi – Global Carbon Project Takahiro Yoshida – Global Carbon Project
12:30	Lunch
13:30	Panel with practitioners and scholars Noriko Kono – PADECO, Co. Ltd Peter J. Marcotullio – Hunter College, CUNY Yuko Nishida – Renewable Energy Institute, Tokyo Giles B. Sioen – Future Earth's Japan Global Hub Yoshiki Yamagata – Global Carbon Project Peraphan Jittrapirom – Moderator
15:00	Closing remarks Yoshiki Yamagata

TRACKING GHG EMISSIONS AT THE SUB-CITY LEVEL: METHODS AND IMPLICATIONS FOR MEETING THE PARIS AGREEMENT AND CATALYZING DECARBONIZATION

20 NOVEMBER 2019



Quantifying urban GHG emissions and understanding their drivers has gradually become a priority for many local governments across the globe. Many different bottom-up and top-down approaches have been mobilized to estimate GHG emissions at the sub-city scale. These techniques use different types of data and achieve different levels of resolution ranging from the building, to the neighborhood and the ward level. Such disaggregated information can provide a wealth of insights that can inform the development of better-informed policies and practices to assist efforts to meet the Paris Agreement or more ambitious decarbonization pathways. This symposium will highlight different approaches for quantifying GHG emissions at the sub-city scale and for different sectors. It will draw from case studies in major cities such as Beijing, New York, Taipei and Tokyo to outline the different methods, tools and datasets that can be mobilized to estimate emissions at the sub-city level from the top down and the bottom up.

TRACKING GHG EMISSIONS AT THE SUB-CITY LEVEL: METHODS AND IMPLICATIONS FOR MEETING THE PARIS AGREEMENT AND CATALYZING DECARBONIZATION

The themes outlined across the different presentations will be discussed by a panel of practitioners, policy-makers and academics working at the interface of cities and GHG emissions. This event will be jointly organized by the Institute for Future Initiatives, University of Tokyo and the Global Carbon Project (GCP). It will bring together the international partners of a project funded by the Asia Pacific Network for Global Change Research and the work conducted at the National Institute for Environmental Studies (NIES), Japan.

20th November 2019

Sanjo Confrence Hall, University of Tokyo

Symposium flyer

Further pictures and information can be found at:
http://www.gasparatos-lab.org/news/joint-symposium-on-tracking-greenhouse-gas-ghg-emission-at-the-sub-city-level

Appendix B

Tracking influences of Asian Urban GHG emissions for Sustainability Policies: Identifying Low Carbon Pathways to Meet the Paris Agreement

Draft Project Summary Report for the APN

1 March 2022

Peter J. Marcotullio, Xiangzheng Deng, Zhihui Li, Alexandros Gasparatos, Jelena Aleksejeva, Shu-Li Huang, Po Ju Huang, Shobhakar Dhakal, Subina Shrestha, Kwangik Wang, Gowri Anand, and Jessica Stretton

Introduction

Through the Paris Agreement of COP 21, 12 December 2015, a legally binding international treaty on climate change signed by 196 world leaders representing the various parties, the international community recognized the importance of climate change and committed their economies, through Nationally Determined Contributions (NDCs), to address anthropogenic causes. The agreement reflects concern due to current dramatic changes in planetary systems resulting in violent weather-related extreme events (fires, heat waves, typhoons, storm surges), rising seas, glacier melt, changes in precipitation patterns and other impacts. Support for actions from the IPCC provides evidence that the net damage costs of climate change are likely to be significant and will increase over time if nothing is done to change emissions levels (IPCC, 2013).

Despite national commitments however, there remains a significant “emissions gap”, a difference between “where we are likely to be and where we need to be”(UNEP, 2018). Specifically, the emissions gap is the difference in the total greenhouse gas (GHG) emissions by 2030 between what is necessary to keep global warming limited to 2°C or under (1.5°C) and those under the current trajectory. The necessary trends in GHG emissions have been estimated by the Intergovernmental Panel on Climate Change (IPCC) and published in a Special Report on Global Warming of 1.5°C (IPCC, 2018) and its underlying studies. Estimates suggest that the gap for GHG levels by 2030 under the NDCs is approximately 15 $GtCO_2e$ (range: 12–19 $GtCO_2e$) for below 2°C scenarios and about 32 $GtCO_2e$ (range: 29–36 $GtCO_2e$) for below the 1.5°C scenarios (UNEP, 2020).

As the world continues to urbanize, residents of cities have become the focus of concern for the emission gap as well as the potential solution to emissions reductions. Scholars are concerned because urban activities are responsible for around 70% of global CO_2 emissions (Grubler et al., 2012) although urban residents are responsible for a smaller percentage of total GHG emissions (Marcotullio, Sarzynski, Albrecht, Schulz, & Garcia, 2013). The high share of GHG emissions is due to a number of factors including, *inter alia*, the large number of urban residents, the higher wealth found in cities compared to the national rural counterparts and the fossil fuel use related activities found largely in and around cities. Among the entire urban population, those living in the largest cities and wealthiest cities are responsible for the largest share of emissions (Marcotullio et al., 2013; Moran et al., 2018; Seto et al., 2014). In a recent “carbon footprint” analysis, CO_2 emissions from approximately 13,000 cities were estimated for the year 2013. The top 100 highest-emitting cities (which account for approximately 11% of the global population) account for 6.2 Gt CO_2 (with a range of ± 33%) or 18% (the share of the mean value) of the global carbon footprint (Moran et al., 2018). The top 500 highest-emitting cities account for approximately 20% of the global population and 9.9 Gt CO_2 (with a range of ± 33%) or 27.5% (the share of the mean value) of the global carbon footprint.

At the same time, organizing societies around dense settlements may help to address climate change as urban residents in wealthy nations are typically more energy efficient than their suburban and rural counterparts; they have a lower carbon footprints. This is due to*, inter alia*, sharing housing stock (i.e., living in apartment buildings), using less transportation energy and working in commercial rather than industrial sectors. This results in an increasing energy efficiency potential with the size of cities (Bettencourt, Lobo, Helbing, Kuhnert, & West, 2007; Bettencourt & West, 2010; Ribeiro, Rybski, & Kropp, 2019). Moreover, governance of urban areas can respond more quickly to climate change demands than national political units (Bulkeley & Kern, 2006). Scholars are basing much hope on implementing effective mitigation policies to promote the low carbon cities (Wiedmann & Allen, 2021). These hopes have been supported by evidence, as within the past few decades, there has been an uptick in city or municipality-level climate action, with cities coming up with their own policies to mitigate their enormous emissions (Gouldson et al., 2016; Rosenzweig, Solecki, Hammer, & Mehrotra, 2010).

Given these dual trends associated with urbanization and climate change many eyes are on the Asian region, as it is undergoing rapid urbanization and economic restructuring. China has emerged as the largest GHG contributor, accounting for over 30% of annual emissions (Gouldson et al., 2016). The entire Asian region, as defined by the UN contributes over 57% annual emissions (Andrew & Peters, 2020). As the region urbanizes, however, Asian urban residents can take advantage of the lessons learned in other countries and avoiding locking into energy-intensive infrastructure and behaviors (Gouldson et al. 2016). According to the World Bank, fast-growing cities in the East Asia and Pacific region will define the region's energy future and its greenhouse gas (GHG) footprint (Ostojic, Bose, Krambeck, Lim, & Zhang, 2013). There remain opportunities for low carbon energy futures for Asian cities, but measures need to be taken immediately.

The necessary tools for low-carbon urban futures includes measurements of carbon emissions from cities. There has been significant research on Asian urban GHG emissions at the case study and regional levels (for reviews see, Dhakal, 2009; Marcotullio, Sarzynski, Albrecht, & Schulz, 2012). These studies have improved our understanding of the relationship between urbanization and changes in energy use and emissions (Dodman, 2009; Hoornweg, Sugar, & Trejos Gómez, 2011). However, due to a number of different factors there is no comparable standard that allows for urban stakeholders to see how they stand on the global scale (Bader & Bleischwitz, 2009; Lombardi, Laiola, Tricase, & Rana, 2017). In addition, differences in climate, economic structures, building stocks, transportation systems, fuel mix, and population size and structure makes it difficult to draw generalizable comparisons between cities (Dhakal, 2010). Scholars are now turning to studies of factors within cities to identify leverage points for emissions reduction strategies (Bulkeley & Betsill, 2005). This paper reviews studies of urban GHG emissions and highlights the advances undertaken in the Asian region. The review also includes a summary of cutting-edge emissions research on several cities in the region undertaken through a generous grant from the Asian Pacific Network for Global Change Research (APN). The findings suggest that studies have moved from examining the city as a black box to examining specific sectors and geographic locations within cities. These advances are helping our understanding of the complex drivers of urban GHG emissions and provide leverage for actions for that identify low carbon pathways to meet Paris Agreement.

The manuscript first presents review background to outline the landscape of urban GHG emissions research. The second section presents a literature review which includes a brief overview of the complexity of carbon emissions inventories, results of urban GHG emissions studies with a focus on research in Asia and a review of the determinants of urban GHG emissions. The third section briefly describes the methods used in the different urban studies of the APN project. This research includes examinations of residential and industrial emissions in the Beijing-Hebei-Tianjin area, a contemporary historical view of emissions from Bangkok, embedded emissions in the building stock of Taipei, emissions history and policies in Tokyo, and policies to reduce emission in Seoul. We also include a study of residential emissions in the New York City metropolitan area. The fourth section overviews the results from each study, and the last section concludes by providing key themes identified across papers from the study.

2.0 Literature review

2.1 GHG emissions from cities

Urban GHG emission inventories are complex. The variety of data necessary to complete an inventory, the scarcity of specific types of information, the variety of methods that can be used to estimate emissions and the definitions used in the analysis, translates into difficulty creating a standardized global agreed-upon protocol. While there has been significant progress over the past few decades in inventory and analysis development, work to generate an agreed-upon protocol continues (see for example, Relative Carbon Footprint RCF[1], Publicly Available Specification PAS 2070[2] and Global Protocol for Community scale GPC[3]). The importance of these protocols in defining GHG emission outcomes, necessitates a critical overview of selected theoretical and practical limitations.

2.1.1 The complexities of carbon accounting techniques

In principle, comprehensive inventories would include estimates for all major GHGs and the major source activities of these emissions related to urban activities. Obtaining such comprehensive emissions data for cities is challenging. Most often, urban inventories are limited by available data at the appropriate scale. In order to present the uncertainty in urban GHG emission inventories, we outline three sets of choices for urban carbon footprint analysts: the methods to use estimate emissions, the scope of the analysis, and the emissions and sectors of interest. This rationalization follows Bader and Bleischwitz (2009) and Lombardi et al. (2017), both of whom provide an extensive review of these and other issues.

Generally, there are numerous ways in which to develop GHG inventories. As Kates, Mayfield, Torrie, and Witcher (1998, p. 22) suggest for urban emission protocols, “there is no end to the minutiae of detailed information that is necessary to fully characterize greenhouse gas emissions and emission

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[1] https://www.cleanmetrics.com/blog/2021/03/13/rapid-carbon-footprinting-rcf/
[2] https://emsmastery.com/2013/12/05/pas-2070-a-specification-for-assessing-city-greenhouse-gas-emissions/
[3] https://ghgprotocol.org/greenhouse-gas-protocol-accounting-reporting-standard-cities

reduction opportunities." The diversity of details creates challenges for urban GHG researchers, who in turn have responded in a variety of different ways.

The most accurate GHG measurements are sensed or directly measured observations, but the most common approaches use estimates based upon emission factors (WBCSD and WRI, 2004), as in national scale studies by the IPCC, International Energy Agency, or U.S. Energy Information Administration. General approaches to providing urban GHG emission estimates include building inventories. These inventories can be distinguished as top-down versus bottom up and consumption versus production-based approaches. The first distinction applies to the scale and origin of the raw data. The bottom-up approach begins with local information about the study area and relevant activities. The bottom-up approach is often relatively comprehensive in the number of included activities, and accurate in its measurement. Such comprehensiveness and accuracy, however, require extensive data, processing time, and expertise, which can be challenging for small or resource-constrained local governments and researchers. Various tools have been developed to assist cities in conducting bottom-up emissions measurements (ICLEI, 2009). It is difficult to compare bottom-up estimates from cities, as identical data and methods across cities is not typical.

An alternative approach is to construct local emissions profiles from national-, regional- or global-scale emissions measurements, using a consistent methodology. This top-down approach can range from simple to more complex, hybrid methodologies. For instance, a simple top-down analysis could estimate local emissions using only the number of people living or working in the local area and the average GHG emissions per person according to national statistics. Such simple approaches can be misleading where cities have emissions source activities that vary substantially in intensity from national averages. In addition, simple approaches do not provide insight when comparing across cities, as any apparent variation reflects only the scale of the cities rather than any meaningful differences in the actual location or source activities of emissions. For this reason, most top-down urban emissions inventories are tailored to local circumstances and data availability, even if relying heavily on national, regional or global statistics. For instance, local emissions from electricity production could be estimated by multiplying the amount of electricity produced locally in megawatt-hours (using production data from the power plant) or by the regional or national average GHG emissions released per unit of electricity. Similar estimates could be made for other activities, where outcome estimates and relevant "multipliers" are available. Transportation emissions could be estimated using fuel sales or the registered vehicle population of the urban area (assuming they would be mainly used in the urban area) or on monitored transport activity (which could include emissions from transit vehicles). Allocating responsibility for the sale, consumption and emissions of bunker fuel for national and international flights and shipping is a challenge, with alternative solutions depending on the scope of analysis. While top-down methods are preferable when data are difficult to obtain at the local level, the approach brings significant uncertainty (Cai et al., 2019). A review of the urban carbon cycle argues, however, that top-down approaches have been under-utilized (Pataki et al., 2006).

Another important decision for GHG analysts is whether to use a consumption-based approach or a production-based approach. The consumption-based approach estimates emissions associated with fuels, products and services used by the city, whether they are locally produced or imported. The results include sources of emissions beyond the physical boundary of the city. For example, a consumption-based approach examines the emissions related to the production of imported goods that were emitted elsewhere, but the goods are consumed within the city. Alternatively, a production-based analysis only includes emissions from economic activities by firms, households and activities within the boundaries of a city. For example, in the transportation sector, production-based methods ignore emissions that occur outside a city even though the driver may be an urban resident. Many studies of urban GHG emissions limit their analysis to emissions from within cities as estimating emissions for imported products requires special data often not available at the urban scale. Grubler et al. (2012) suggest that these embodied emissions (consumption-based) can be substantial.

A related issue to the consumption-production distinction is the definition of the scope of the project. There are at least two important decisions here. First, how is the urban area defined, meaning what is the geographic extent of the project, and second, what scope to use for the emissions, meaning how does the analysis include the different production and consumption related emissions. In terms of the definition of urban, identifying the exact urban boundaries for measurement is of particular importance in generating measurements that represent conceptually comparable spheres of economic and social activity. For comparative international studies, the definition of urban creates challenges, as countries define “urban” in different ways (United Nations, 2010) and obtaining relevant and comparable data at similar urban geographies is difficult. Researchers, particularly those in Asia, often identify difficulties in drawing boundaries to account for the emissions produced by the city (Shan et al., 2017).

As a result, urban GHG studies use a number of fundamentally different urban definitions. Urban analysts sometimes restrict measurements to political or administrative borders of a municipality, often to help in sustainability or climate change action plans (City of Sydney, 2008). Such approaches risk missing important drivers of energy demand that are outside of their administrative boundaries. The impacts of sprawled development on GHG emissions will be missed if the analysis is restricted to the urban core. While some researchers suggest that the definition of the city should match the extent of policy maker constituents (Parshall et al., 2010), others open the analysis to the wider metropolitan region (Chicago Climate Task Force, 2008) or use urban agglomerations as the geographic boundary for GHG emission inventories (M. A. Brown, Southworth, & Sarzynski, 2008).

The second aspect of scope focuses on the location of emission sources. The World Resources Institute and World Business Council for Sustainable Development (WRI/WBCSD) protocol (WBCSD and WRI, 2004), has been adapted for use by researchers (Kennedy, Ramaswami, Carney, & Dhakal, 2009) and is used as a ‘Global Protocol for Community Scale GHG Emissions’ (Fong et al., 2014). In an effort to harmonize the approach with IPCC methodologies, the protocol distinguishes between three scopes of emissions. Scope 1 emissions are those from sources under the direct control of the organization, such as finances, factories or vehicles. In the urban context, Scope 1 emissions are typically produced within the geographical boundary of the city. Scope 2 emissions are from energy consumed by the organization, where the emissions are produced elsewhere. In the urban context, Scope 2 emissions include releases outside the geographical boundary of the city that relate to energy consumption within the city, including electricity and heat. Scope 3 emissions, also called upstream or embodied emissions, are associated with extraction, production and transportation of products or services used in urban activities. These emissions include those from waste, aviation and marine transport, and embodied in fuel, food, building material, and water.

The notions of Scopes 2 & 3 suggest that emission estimates should be consumption based. That is, researchers argue that reliable carbon 'footprints' not only identify where GHG emissions are produced, but where goods and services that create the emissions are consumed (Bader & Bleischwitz, 2009; Dhakal, 2010). In response to these concerns, researchers argue that urban GHG inventories should, at least, include emissions from thermal power plants located outside urban areas (Kennedy et al., 2009), which would translate into a Scope 2 analysis. A Scope 3 analysis would additionally require researchers to not only include the upstream emissions embodied in goods and services imported and consumed within the city, but also to subtract those emissions of exported goods and services consumed elsewhere to balance the net-effect of trade and avoid double counting of emissions. Methodologies for such analysis include material flow analysis, life cycle analysis, and extended input-output analysis.

Scope 3 emissions can be sizeable, particularly where urban residents rely on goods (such as food/drink, clothes, electronic items, building materials, vehicles, etc.) produced outside the home city boundaries (Grubler et al., 2012). A study of London suggests that consumption-based emissions are more than the total of the Scope 1 and Scope 2 emission levels (Greater London Authority, 2014). Hillman and Ramaswami (2010) have developed a "hybrid life cycle-based transboundary greenhouse gas emission footprint," which identifies several key Scope 3 items (embodied energy for food, water, energy and shelter). Their study of eight US cities suggests that including these items increases GHG emissions from urban areas by 47% on average over techniques that only examine GHG emissions from within the urban boundaries. Whether this type of research is replicable in other places remains an open question.

Most studies do not include Scope 3 emissions, and if they do, it is on an *ad-hoc* basis. Sub-national Scope 3 analyses have been performed at the household level in Asia for India and China (Pachauri, 2004; Pachauri & Jiang, 2008). A consumption-based emission accounting for Chinese cities suggest that megacities such as Shanghai, Beijing and Tianjin import approximately 70% of their emissions from other regions (Z. Mi et al., 2016). Studies of individual urban consumption based embodied energy and related carbon emissions include Singapore (Schulz, 2010), the embodied energy in residential buildings, infrastructure and vehicles in Adelaide, Australia (Troy, Holloway, Pullen, & Bunker, 2003), and the GHG emissions associated with food consumption in Delhi and Calcutta (C. Sharma, Dasgupta, & Mitra, 2002).

The final set of issues for GHG researchers is which emissions and sectors to estimate. Methods for GHG emissions estimates vary by the gas quantified. Research has identified a number of greenhouse gases that could be included in analyses. The most substantial anthropogenic GHG emissions include carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulfur hexafluoride (SF_6). Considerable natural fluxes occur with the first three of these constituents of the "Kyoto basket", while the last three are entirely of anthropogenic origin. These last gases are emitted in smaller quantities, but are potent climate forcers (US EPA, 2011). They are also increasing in importance, as predictions suggest that HFC emissions may rise to between 9% and 19% of total GHG emissions by the year 2050 (Stohl et al., 2010; Velders, Fahey, Daniel, McFarland, & Andersen, 2009).

Atmospheric warming potency varies greatly among the different chemicals. Typically, researchers standardize GHG calculations by creating carbon dioxide equivalents (CO_2e) estimates for each gas with global warming potentials (GWP). GWPs, which is the relative measure of how much heat a GHG traps in the atmosphere, vary over specific time intervals; (20, 100 or 500 years) and have changed over time. For example, the GWP values presented in the 3rd and 4th Assessment Reports of the Intergovernmental Panel on Climate Change (IPCC) are different.

Urban researchers largely focus on CO_2 emissions. The CO_2 compound accounts for approximately 80% of all anthropogenic GHG emissions, is relatively long lived in the atmosphere, and therefore researchers consider it the most important gas for effects like long term warming (IPCC, 2007). An early study of GHG emissions from 14 urban areas around the world, for example, singles out CO_2 as representative of GHG emissions (Harvey, 1993). Another early study, Baldasano, Soriano, and Boada (1999), focuses on CO_2 emissions in their inventory for Barcelona. Recent studies remain focused on CO_2 emissions Aumnad Phdungsilp (2010) develops a baseline for Bangkok's "carbon futures" from emissions factors for fuel demand, where fuels are translated into tons of oil equivalents and then into resulting CO_2 emissions using specific emission factors. While Mitra, Sharma, and Ajero (2003) examine a number of gases including CO_2, CH_4, CO, NO_x, hydrocarbons, black carbon and organic carbon, they focus on CO_2 emissions comparisons among Indian cities. Dhakal (2009), in an analysis of GHG emissions from Chinese cities, uses emission factors for fuel consumption in tons of oil equivalents, tons of carbon, or tons of CO_2 depending upon the scale of the analysis. Sovacool and Brown (2010, p. 4861) create inventories for 12 major metropolitan centers, including those in Asia, and claim that the footprints were "almost entirely based on CO_2 emissions." One review study suggests that for urban areas, levels of GHGs other than CO_2 remain unknown (Dhakal, 2010).

There are, however, some exceptions to the limiting of urban GHG inventories to carbon dioxide emissions. Jha et al. (2008) compares sensed and computed data for CH_4 and N_2O emissions from municipal solid waste management practices in Chennai, India. Kennedy et al. (2009); Kennedy et al. (2010) examine 10 urban areas and consider CO_2 and CH_4 emissions. Methane, CH_4, is often examined, particularly from landfills and wastewater treatment plants (Wunch, Wennberg, Toon, Keppel-Aleks, & Yavin, 2009; Zhang, Xu, Feng, & Chen, 2019).

Finally, researchers have a wide range of possible sectors or end-uses that could be included in the analysis. Among the most important are waste and wastewater, energy supply, transport, commercial and residential buildings, industry, agriculture and forestry (Dodman, 2009; Kennedy et al., 2009; Weisz & Steinberger, 2010). Not all studies, however, include all of these sectors and indeed GHG emission inventories vary greatly in this regard. Early studies include only a few sectors. Harvey (1993) identifies residential, transportation, and commercial and industrial sources for his study of 14 cities. Baldasano et al. (1999) mix sources and fuel types including vehicle traffic, natural gas, propane, electricity, and municipal solid waste, in their study of Barcelona. Mitra et al. (2003) emphasize the importance of the energy sector for Delhi and Calcutta, but also include emissions from cement and steel production. Some later studies include a larger number of sources. Phdungsilp (2010) includes residential, commercial, industrial and transport in a study of carbon emissions from Bangkok. Sovacool and Brown (2010) study energy use in buildings and industry, transport, agriculture and forestry, and waste. Parshall et al. (2010) focus on transportation, industrial, residential, commercial, and electric power sources for US cities.

As can be imagined from the options identified in this brief overview it may be difficult to find bottom-up studies that were undertaken in different cities with exactly the same methods, making comparisons between cities difficult (Lombardi et al. 2017). Alternatively top-down studies that cover several cities have other limitations, largely related to data details. Notwithstanding these limitations, carbon accounting for cities is perceived to be a valuable tool to inform climate action plans and therefore address climate change. Given uncertainties, great variation exists amongst aggregate urban emission estimates (Satterthwaite, 2008). Despite the drawbacks, former Mayor Bloomberg of New York City, argued strongly for carbon accounting for the city, often stating, "you cannot manage it if you cannot measure it" (Bloomberg, 2011). Work continues on methods and empirical analysis of carbon emissions from cities.

2.1.2 Global GHG urban emissions studies

There have been, at least, four global studies that estimate the urban contribution to GHG emissions, each with different attempts to use a standardized methodology. The first was from the IEA, in their 2008 *World Energy Outlook* report (IEA, 2008) which estimates that urban energy use in 2006 accounted for more than two-thirds of the world's energy and that CO_2 emissions from energy use accounted for more than 71% of global CO_2 emissions. A more recent estimate suggests that for 2005, between 60-80% of final global energy use is urban (central estimate of 75%) (Grubler et al., 2012) and that globally cities are responsible for between 53% and 87% (central estimate 76%) of CO_2 emissions (Seto et al., 2014). Neither of these estimates, however, consider all GHG emissions. Often CO_2 emissions from energy use are confused with total GHG emissions. If, however, 71% of total energy related CO_2 emissions were estimated, the amount of total GHG emissions is approximately 56% (0.71 x 0.8). Indeed, an estimate of GHG emissions made for the year 2000 suggests that for CO_2, N_2O, CH_4 and SF_6, cities were responsible for approximately 37% to 49% of total GHG emissions (Marcotullio et al., 2013).

The most recent study created a globally consistent, top-down, gridded global model of city footprints (GGMCF) by downscaling national carbon footprints (CFs) into 250 m gridded cells (Moran et al., 2018). The downscaling was constrained by population, purchasing power, and existing subnational CF studies from the US, China, EU, and Japan. While the study does not include specific urban characteristics, such as urban form, carbon intensity of electricity, or building infrastructure, the researchers argue that it does provide a consistent approach to comprehensive results for every city in every country of the world. In this analysis, CO_2 emissions from approximately 13,000 cities were estimated for the year 2013 (Moran et al., 2018). The authors main point is that the top 100 highest-emitting cities (which account for approximately 11% of the global population) account for 6.2 Gt CO_2 (with a range of ± 33%) or 18% (the share of the mean value) of the global carbon footprint. The top 500 highest-emitting cities account for approximately 20% of the global population and 9.9 Gt CO_2 (with a range of ± 33%) or 27.5% (the share of the mean value) of the global carbon footprint. We use the data from this approach to identify patterns in the Asian region and compare these results to previous studies.

There are some interesting patterns that emerge from the modeling that pertain to Asia. First, among the top 20 largest global urban emitters, 16 are from Asia. This finding is compatible with current estimates that Asia is responsible for 57% of total annual CO_2 emissions (Andrew & Peters, 2020) and has the largest share of the largest cities in the world (United Nations, 2020). Among the 20 global cities with the largest per capita CO_2 footprint, 14 are from Asia. These 14 cities are completely different from the 16 Asian cities with the largest total CO_2 emissions.

From these data a selection of approximately 230 of the largest urban Asian CO_2 emitters are pulled to examine intra—regional patterns. Analysis of this sub-set suggest three patterns of note. First, among Asian urban centers there is a general trend of increasing total CO_2 emissions with population size (**Figure 1**). As urban areas grow in population, their carbon footprint increases. Second, adding an income variable suggests that the positive relationship between population size and CO_2 emissions remains across income groups (across income groups the total CO_2 footprint increases with population size, but those with higher income have larger footprints than those with lower incomes (**Figure 2**). This trend seems to be consistent until the very largest category of population size, where the middle-income cities emit more than those of high-income. Third, per capita carbon footprints follow an opposite trend across income and population size within the region in most cases. That is, as population size increases for cities, the carbon footprint per capita shrinks. This trend seems to be true for the high-income and middle-income cities. It is not as evident for the low-income cities, where population size does not seem to influence per capita footprints (**Figure 3**). The trend is evident when examining the total carbon footprint and the carbon footprint per capita of the 15 largest emitters from the region (**Figure 4**). In this figure it appears that as the size of the urban population increases, the footprint decreases.

From this analysis, following the argument of Moran et al (2018), it would seem that targeting a few larger localities for carbon reductions may be the efficient policy strategy. What is interesting for this study is that with the cross-national comparison several general patterns in urban GHG emissions become apparent. At the same time, whether the exact carbon footprints are accurate remains uncertain.

2.1.3 Asian GHG regional urban emissions studies

Due to local data limitations, many urban analysts perform urban GHG analysis at the provincial or larger geographic regional levels (H. Bai, Qiao, Liu, Zhang, & Xu, 2016; Cai, Li, Dhakal, & Wang, 2018; Q. Chen et al., 2017; Long et al., 2020; Shan, Liu, et al., 2016). Regional studies have applied similar protocols across a limited number of different cities. Sun et al. (2021), for example, present a spatial overview of CO_2 emission characteristics for East Asian megacities. Using the IPCC administrative territorial-based accounting scope, they determined the emissions for individual major metropolitan centers. They estimate Beijing's emissions at ~160 Mt CO_2e, Shanghai's emissions at ~275 Mt CO_2e, Tokyo's emissions at 65 Mt CO_2e, and Seoul's at ~50 Mt CO_2e. For Beijing, Tokyo Metropolis, and Seoul, 90% of carbon emissions are concentrated on 8.93%, 55.95%, and 74.17% of the land area, respectively. This demonstrates the highly uneven spatial distribution of urban carbon emissions and how the spatial distribution varies widely from city to city. For China, the study suggests that the spatial distribution of urban CO_2 emissions correlates closely with transportation infrastructure. Using the Japanese Open-Data Inventory for Anthropogenic Carbon Dioxide (ODIAC) database, emissions estimates results for Beijing were consistent with those of previous studies that locally quantified emissions from Beijing (S. Li, Zhou, Wang, & Hu, 2018; Shan, Guan, et al., 2016). The ODIAC dataset for 2017 emissions suggests that for Bangkok, Beijing, Delhi, Shanghai, and Tokyo total emissions are ~20Mt CO_2, ~160 Mt CO_2, ~10 Mt CO_2, ~185Mt CO_2, and ~50 Mt CO_2, respectively (J. Chen, Zhao, Zeng, & Oda, 2020).

Within countries research has also based urban emissions upon regional data. In China there has been significant work in this area. For example, two studies examine 182 and 305 Chinese cities (Cai et al., 2018; Shan et al., 2018). Using the China High Resolution Emission Database (CHRED) with gridded emission data, Cai et al. (2019) reports that Beijing, Shanghai, and Guangzhou emitted 162.25 Mt CO_2, 285.01 Mt CO_2, and 84.42 Mt CO_2 respectively in 2015. Since CHRED takes CO_2 emissions calculated using data from China's national statistics at the reference level, the authors claim that results are more consistent than inventories at the provincial level (Cai, Wang, Yang, Mao, & Cao, 2017). After reviewing various studies in China, Han et al. (2020) conclude that national-level data-based emission inventories produce large differences in emissions levels among the three provincial-level cities: Beijing (the capital of China), Tianjin (municipality), Shijiazhuang (the provincial capital of Hebei), but that while some cities have larger ranges in uncertainty, there is still relatively good agreement among estimates.

Efforts at regional urban inventories for South Asia include Ramachandra, Aithal, and Sreejith (2015), who examine CO_2 and other non-CO_2 (namely CH_4 and N_2O) greenhouse gases using India national GHG inventories for the quantification of sector-wise GHG emissions for major megacities. Results suggest that the carbon footprint of Delhi, Greater Mumbai, Kolkata, and Greater Bangalore are 38.6 Mt, 22.8 Mt, 14.8 Mt, and 19.8 Mt, respectively.

2.1.3 Asian GHG local urban emissions studies

Local Asian urban GHG inventories have largely been generated for megacities or provincial capital cities (C. Feng et al., 2015; Huang, Zhang, & Liu, 2018; Z. Mi et al., 2016; R. Zhao & Li, 2016). Many city governments implement GHG inventories to help determine how to mitigate emissions, and which policies might be most effective. Though some governments have a long-standing record of their annual GHG emissions, other localities neither have the time nor resources (and particularly the data) to build a fully-fledged inventory. Therefore, most of the local GHG inventories are from the major metropolitan centers in the region.

The Seoul Metropolitan Government (SMG) reports that 2019’s total emissions were approximately 46.3 Mt CO_2e. Energy related activities made up 90% of emissions (Seoul Metropolitan Government, 2021). For 2020, SMG reports that total GHG emissions were 45.2 tons. The inventory includes details for different sectors. For example, the building sector, which accounts for the largest share of greenhouse gas emissions, accounted for 68.9%, which is similar to 2019 (68.8% estimated). Within the building sector, GHG emissions from households have been increasing (1.4% year-on-year between 2019 and 2020) while the emissions from the commercial sector has been decreasing (1.2% year-on-year, between 2019 and 2020) (Seoul Metropolitan Government, 2021). Research confirms the importance of the building sector’s contribution to Seoul’s GHG emissions. Kim and Jeong (2018) estimated around 25.0 – 26.0 Mt CO_2e for Seoul in 2015.

The Tokyo Metropolitan Government (TMG) has made their inventories accessible and has done so since 2012. In 2018, Tokyo total GHG emissions were approximately 63.9 Mt CO_2e, and demonstrate a declining trend since 2012 (Tokyo Metropolitan Government, 2021). Tokyo's commercial and residential sector emissions continue to increase while transport and industrial decrease. The share of commercial and residential emissions in Tokyo is larger than that of Japan overall, demonstrating the importance of the buildings sector in Asian cities. Electricity emissions continue to increase. This trend is further corroborated by a study by Jiang, Long, Liu, Dowaki, and Ihara (2020), which identifies the low shares of gasoline in Tokyo's total direct household emissions. Using a city-scale multi-regional input-output table, Long and Yoshida (2018) examine the difference in direct and indirect emissions for Tokyo. They point out that the transportation sector accounts for the largest share of direct emissions in Tokyo while the energy supply, construction, and private service sectors account for the largest share of indirect emissions.

In their climate action plan, the city of New Taipei announced that they emit approximately 18 Mt CO_2e in 2014, with 72.6% from stationary energy sources and 24.9% from transportation, 1.96% from waste, 0.02% from industrial processes and 0.06% of agriculture, forestry and land use (City of New Taipei, 2015). The residential, commercial and institutional buildings sector have the highest share of emissions with 7.4 Mt CO_2e, accounting for 56.0% of the emission of the stationary energy sector.

The Government of the Hong Kong Special Administrative Region reports that their 2018 emissions totaled at 40.6 Mt CO_2e, with electricity generation and town gas production making up 65.6% of the total (Hong Kong, 2021). Y. Zhou, Shan, Liu, and Guan (2018) use the IPCC territorial emission accounting approach to estimate 2016 emissions for Guangzhou and Hong Kong respectively. They suggest that Hong Kong's emissions are 47 Mt CO_2. Guangzhou emissions are higher at 66 Mt CO_2. As landfill area is becoming scarce in Hong Kong, Dong, An, Yan, and Yi (2017) focus specifically on the waste sector, reporting that in 2013 emissions were about 2.0 Mt CO_2e from this sector or over 4% of total emissions. The Hong Kong transportation sector emissions levels are estimated by To (2015) at 35.8 Mt CO_2e. Electricity consumption is approximately 30.8 Mt CO_2e (To & Lee, 2017).

In Southeast Asia, the Singapore National Climate Change Secretariat in their 2020 report stated that Singapore's GHG emissions in 2017 totaled 52 Mt CO_2e, which is a 34.8% increase from 2000 levels (National Environment Agency, 2020). Primary emissions came mainly from the industry sector (46% of total), followed by the power sector (39% of total). Singapore stands out for its high share of industrial emissions compared to other large Asian metropolitan centers of medium to high income.

The Japan International Cooperation Agency (JICA), a governmental aid agency, has partnered with several cities in the region to help generate climate action plans. In Bangkok and Ho Chi Minh City (HCMC), JICA has helped to create a GHG inventory. The Bangkok Metropolitan Administration (BMA) estimates that its year 2013 emissions suggest that the energy sector is the highest source of GHG emissions energy (25.6 Mt CO_2e), followed by transportation (13.8 Mt CO_2e), waste and wastewater (4.55), and green urban planning (-0.045). Total emissions are 43.9 Mt CO_2e (Bangkok Metropolitan Administration, 2015). In a more recent review, the BMA reported for 2016 that emissions for energy are 25.8 Mt CO_2e, while transportation emissions have decreased to 12.4 Mt CO_2e. Waste and wastewater remain at approximately 4.5 Mt CO_2e, and green urban planning is -0.045 Mt CO_2e (Bangkok Metropolitan Administration, 2017). According to a research report, however, the BMA is underestimating the importance of the waste sector. For example, Thitanuwat, Polprasert, and

Englande (2017) suggest that this sector is emitting 7.1 Mt CO_2e annually. The CO_2 emissions for HCMC's stationary energy and transportation sectors are approximately 17 Mt CO_2e (Bangkok Metropolitan Administration, 2017). Together these sectors' emissions comprise 91% of total emissions and removals from the city. The total GHG emissions are 38.5 Mt CO_2e per year. Within the stationary energy sector, manufacturing industries and construction make up almost half of emissions, which is confirmed by Van et al. (2021). Tran (2019) reports that transportation GHG emissions from the passenger transport sector in HCMC account for 12.3% of total GHG emissions from the city. Nguyen, Takeuchi, and Misra (2020) also report that the transport sector is responsible for a large portion of total emissions, responsible for over 22.0 Mt CO_2 in 2016. As in many major metropolitan centers, emissions from HCMC account for a disproportionate share of national emissions. While HCMC's population share is 9% of total national population, the emissions from the city account for 16% of the national GHG emissions.

Kuala Lumpur City Hall reports their 2017 emissions to be 25.1 Mt CO_2e (Kuala Lumpur City Hall, 2021). Overall, the transportation sector (Scope 1 & 2) generates the largest share of emissions in the Kuala Lumpur inventory, accounting for 56% of total emissions. Within the transportation sector, on-road transportation is the dominant source of emissions (99.4%, 13.9 Mt CO_2e), with the remainder deriving from electricity consumption by rail transport (0.6%). Stationary energy (Scope 1 & 2) and the waste sector (Scope 1 & 3) are responsible for 41.3% (10,4 Mt CO_2e) and 3.1% (0.8 Mt CO_2e) of total emissions, respectively.

The Environmental Agency of DKI Jakarta reported that the province of Jakarta's total emissions in 2018 amounted to 57.6 Mt CO_2e (DKI Jakarta, 2020). Further estimates suggest that the transportation sector accounts for a large share of total emissions. Sodri and Garniwa (2016) estimate that for 2014, transportation emissions are approximately between 43.0 to 45.0 Mt CO_2e per year.

In South Asia, Gouldson et al. (2016) estimate that 2014 emissions for Kolkata are between 23 and 24 Mt CO_2e, with the residential sector contributing most to the total emissions. These estimates include energy use and emissions from the metropolitan area, using direct consumption of fuels and waste facilities (Scope 1 emissions) and those produced while generating the electricity consumed within the city (Scope 2 emissions). Using the GAINS model, Majumdar et al. (2020) report that in 2015, the Kolkata Metropolitan City (KMC) emitted approximately 20.3 Mt of CO_2, 74.8 kt of N_2O, and 25.2 kt of CH_4. The power plant sector contributed the largest share (66%) of CO_2 emissions, followed by light- and heavy-duty vehicle exhaust (15%), and residential combustion (10%). The agriculture sector contributed the majority of N_2O and methane emissions, 97% and 87%, respectively.

M. Sharma and Dikshit (2016) calculated Delhi's 2014 GHG emissions load to be 37.9 Mt CO_2e with electricity generation/consumption contributing 43% and vehicles contributing 32% of total. Nagar, Sharma, Gupta, and Singh (2019) estimate 2014 emissions to be at 41.6 Mt with major contribution from power plants (46.8%), vehicles (29.7%), municipal solid waste burning (7.6%) and domestic cooking (6%). Transportation emissions in Delhi and Bangalore contribute the largest share of total emissions (32% and 43.5% respectively), and the domestic sector emissions are most important in Mumbai and Kolkata (32.7% and 42.78% respectively).

2.1.4 Asian Intra-urban emissions levels

While it is well documented that the major metropolitan centers of nations, particularly those in Asia, are responsible for a large part of the emissions for their country, the distribution of these emissions by source, sector and urban location are less well understood. Specifically, the spatial layout of a city, the fuels as part of the primary supply, the energy consuming industrial processes as well as other characteristics, which are responsible for varying levels of emissions within the city require further exploration. Few previous studies have examined urban emissions at the sub-city scale and particularly spatially, even fewer distinguish among spatial emissions by the sector. Indeed, research in these areas are only beginning to be published (Pan, Li, Zhu, & Dang, 2017; S.-H. Wang, Huang, & Huang, 2018; X. Yang, Wang, Sun, Wang, & Zheng, 2018; Zhu et al., 2019). For example, examining 38 Beijing residential communities, Yang et. al (2016) estimate residential and transportation emission levels for each community, separating out the levels into electricity, cooking, and heating emissions for residential emissions and private car and taxi for transportation emissions. S. Wang, Shi, Fang, and Feng (2019) analyze CO_2 emissions for the manufacturing industry, transportation, service industry, and housing sectors, as well as the total emissions, for the entirety of the metropolitan area using a downscaling analysis.

Increasingly, satellite remote sensing is used to detect the atmospheric CO_2 concentration, with the advantage of enabling a stable, continuous, and large-scale observation (G. Broquet et al., 2018; Goldberg et al., 2019; Chaerin Park, Jeong, Park, Yun, & Liu, 2021). Zhu et al. (2019) use a high-resolution carbon emission spatially gridded ($1km^2$) dataset for Shanghai from 2010 to 2015 to generate fossil fuel emissions. Pan et al. (2017) uses a similar method to study CO_2 emissions in Shanghai by energy type, usage type, and facilities. Sun et al. (2021) also use a $1km^2$ resolution CO_2 emission gridded data for a number of Asian megacities: Seoul, Busan, Incheon, Daegu, Tokyo, Kyoto, Osaka, Chiba, Beijing, Tianjin, Shanghai, and Chongqing.

2.2 Factors influencing GHG emissions

To appropriately target energy and carbon intensity reduction strategies, researchers have identified a variety of factors that influence urban carbon emissions. Examples of recent findings from Asian urban GHG determinant studies include economic growth (Z. Mi et al., 2017; S. Wang, Zhou, Li, & Feng, 2016), urban population (Jiang, Long, Liu, Dowaki, & Ihar, 2020), industrial structure (Z.-F. Mi, Pan, Yu, & Wei, 2015; X. Zhou, Zhang, & Li, 2013), consumption patterns (Z. Wang & Yang, 2016), technology (K. Feng, Hubacek, & Guan, 2009) and climate characteristics (Yamagata, Yoshida, Murakami, Matsui, & Akiyama, 2018). Generally, for urban research, this literature can be divided into social, biophysical and infrastructural determinant factors (Chester et al., 2014; Hutyra et al., 2014; Marcotullio et al., 2014). This sub-section reviews studies on factors influencing urban GHG emissions and highlights those studies in Asia.

2.2.1 Income and economic structure

As is evident in all urban GHG emissions studies, the cities with higher incomes tend to have the higher levels of emissions than those with lower incomes (Marcotullio et al., 2012). The majority of research in this field has found that wealth and income lead to increases in per capita energy use (Kahn, 2009; Kraft & Kraft, 1978; Satterthwaite, 2009; Weisz & Steinberger, 2010). For example, generalized studies of cities undergoing development processes find a positive correlation between income and GHG emissions (McGranahan, Jacobi, Songsore, Surjadi, & Kjellen, 2001; McGranahan &

Songsore, 1994). Cross-national comparisons of urban GHG emissions and local or regional GDP demonstrate that income covaries with GHG emission levels (Hoornweg et al., 2011; Kennedy, Ramaswami, Carney, & Dhakal, 2011; Sovacool & Brown, 2010). At the household level, Weber and Matthews (2008) find a positive relationship between income and CO_2 footprints in the US. Household-level studies in a variety of different countries (Netherlands, India, Brazil, Denmark, Japan, and Australia) have also found positive correlations between income and energy use (Cohen, Lenzen, & Schaeffer, 2005; Dey et al., 2007; Lenzen et al., 2006; Pachauri & Jiang, 2008; Vringer & Blok, 1995; Wier, Lenzen, Munksgaard, & Smed, 2001). The consensus is that wealthier cities have higher CO_2e emissions, all else equal.

Studies of the relationship between income and urban emissions in Asia suggest the strong influence of wealth. For example, Sugar, Kennedy, and Leman (2012) indicate that China's growing urban emissions are mainly driven by the country's rapidly expanding economy, which is associated with urbanization. The growth of the Chinese economy and per capita emission share a close positive relationship (Meng et al., 2017; S. Wang, C. Shi, et al., 2019). Net capital formation, or the investments in urban development including infrastructure, accounts for between 37%–69% of consumption-based emissions in the nation (Meng et al. 2017). In Beijing, Fan and Lei (2016) report that the successive growth of economic output is the dominant factor influencing the increase in transportation carbon emissions. Ahmad, Baiocchi, and Creutzig (2015) report that income and electricity are driving emissions in India's cities, particularly in high-emitting urban centers, such as Delhi.

Of particular interest in these trends is the per capita emissions. Using a temporal decomposition analysis model, H. Li et al. (2017) report that economic scale effect is the dominant driving force leading to the increases in both national and regional CO_2 emissions. M. Wang and Feng (2017) corroborate this statement in their study using a decomposition analysis based on the logarithmic mean Divisia index (LMDI) method. Even at the very small scale, the relationship is clear. For example, Ramachandra, Bajpai, Kulkarni, Aithal, and Han (2017) report that Bangalore's domestic sector per capita energy consumption increases proportionately with family income. They argue that the economic levels in respective wards are an important parameter in the domestic energy consumption and also GHG emissions.

A second aspect of the relationship between GHG emissions and income is the speed of economic growth, which is related to infrastructure and institutional development. That is, the level of development of a city conditions the effect of economic and income growth on urban energy demands. For example, Poumanyvong and Kaneko (2010) find that Asian nations with low-income levels experience decreasing energy use per capita with urbanization and increasing income, which they argue, may be due to fuel switching. They hypothesize that urbanization is associated with increases in household income, facilitating a transition to modern fuels, which initially curbs emissions and aggregate energy use (O'Neill, Ren, Jiang, & Dalton, 2012). Achieving this interactive effect likely requires that energy policies be put in place to facilitate energy source substitution (Bailis, Ezzati, & Kammen, 2005). In a paper analyzing provincial-level thermal power carbon emissions in China from 2005 to 2015, Liao, Wang, Zhang, Song, and Zhang (2019) found that increase in emissions was larger in developing provinces compared to those more developed provinces, such as Beijing and Shanghai, and economic activity played an especially important role in raising carbon emissions (see also, Wu et al., 2019).

By contrast, continued urbanization and growing economic development in medium and high-income countries is associated with increasing energy use per capita. The impact of urbanization on aggregate GHG emissions is most pronounced in middle-income countries (Poumanyvong & Kaneko, 2010), where cities are growing the fastest. For example, perhaps the fastest growing city in history was Shenzhen, which grew from a small fishing village in the 1960s to a city of over 11 million by 2010. This growth was fueled by the nation's rising GDP and economic advantages that were realized in the city. This is important as a recent projection suggests that in the near future, between 2019 and 2035, the top fastest growing cities in the world will be in Southeast and South Asia (Oxford Economics, 2018).

Focusing specifically on the Guangdong province, Pei et al. (2018) corroborate this idea, with Guangzhou experiencing rapid urbanization and emitting by far the most CO_2 in the province from 2005 to 2013, totaling 102.36 TgC. This relationship also holds for the Yangtze River Delta region (Xia et al., 2019). S.-H. Wang et al. (2018) analyze the relationship of spatial planning and carbon dioxide emissions in Taipei. They indicate that total CO_2 emissions of four sectors in the Taipei Metropolitan Area increase with increases in the growth of urban planned zones, all of which facilitate economic development. However, they also conclude that the compact development and transit systems are believed to be the cause of decreasing per capita CO_2 emissions.

The highest carbon footprints are not necessarily from the high-income urban groups, however, but rather than from middle-income class. This fact has been borne out by the regional studies of urban GHG emissions describe above. In individual urban research on the Chinese cities of Shanghai and Beijing, arguably middle-income cities, the GHG emissions levels are higher than those of developed cities (Moran et al, 2018). This could be due to comparisons of the different functional types of cities, that is, cities with different economic structures. For example, in many middle-income developing countries, due to globalization flows over the past decades, industrial activities have concentrated in their larger cities (Lo & Marcotullio, 2000; Marcotullio, 2003), making these cities' carbon emissions per capita higher than those in developed world cities of comparable size. This comparison was identified in Asia and related to the importance of industrial emissions for some cities (Dhakal, 2009). A study done by Pan et al. (2017) suggest that the most critical point source emissions in Shanghai are coal-fired power plants and iron and steel plants indicating that the Shanghai industrial sector constitutes the major sector of CO_2 emissions. L. Xu et al. (2019) indicate that for cities examined in China the most important GHG emissions sectors vary. In Beijing, the service sector is important. For resource-oriented cities, the mining sectors are important. However, for all cities examined, the electricity production was the most carbon-intensive sector. They point out that urban carbon footprints vary by income and could therefore be influenced by different policies based upon income.

Using a structural decomposition analysis (SDA), Wei et al. (2017) also confirm that the economic structure change and the rapid economic growth led to the significant increase in CO_2 emissions growth in Beijing. In a study of Beijing's 2010 to 2017 carbon emissions and driving forces, Cui, Yu, Zhou, and Zhang (2020) also come to the conclusion that the main factor increasing emissions is economic output effect, followed by the population scale effect. A study done by Song, Guo, Wu, and Wang (2015) on the Yangtze River region comes to a similar conclusion. L. Zhao, Zhao, and Wang (2017) examine Beijing's emissions from 2001 to 2012 and Shen et al. (2018), who focus on Beijing's four developmental stages (before 1991, 1991 to 2004, 2004 to 2022 and 2022 to present) find the same. In their study of Beijing, Shanghai, Tianjin and Chongqing from 2001 to 2005, Shi, Sun, Lin, and Zhao (2019) conclude that manufacturing was a key driving force and that development of manufacturing and improvement of resident living standards in the cities led to an increase in carbon emissions.

Finally, increasing wealth is related to consumption. Long, Yoshida, and Dong (2017) report that high individual household carbon footprints (IHCFs) are concentrated around Tokyo, particularly from recreation-related sources. Education- and transportation-related carbon emissions are also concentrated around Tokyo and its surroundings (in terms of the Tokyo Metropolitan Area) but to a lesser extent than recreation consumption. This is similarly reported in a 2018 study, which conclude that electricity consumption is a major emissions source, with electricity-driven CO_2 emissions reaching a high of 1.18 tCO_2/capita in Tokyo (Long & Yoshida, 2018). In the case of Hong Kong, Dou et al. (2021) report that while direct energy-related emissions (Scope 1) are stable, indirect emissions (Scope 2 plus Scope 3) are currently growing approximately twice as much as their direct emissions. In Dhaka's transport sector, Iqbal, Allan, and Zito (2016) determine that the consumption-related emissions varies with system characteristics. Underpinning transportation consumption was the use of air conditioning, speed levels, fuel type, and periods of congestion and stopping, as the major influencers of CO_2 emissions are from passenger cars. Beijing's emissions demonstrate that with the increase in consumption scale is related to an increase in residential CO_2 emissions (C. Wang, Zhan, Li, Zhang, & Zhang, 2019; Z. Wang & Yang, 2015). Yuan, Ren, and Chen (2015) also demonstrate that per capita consumption has a positive effect on residential CO_2 emissions.

2.2.2 Population size and structure

Urban emissions vary with population size. Larger population size co-varies with higher urban energy demand and associated GHG emissions (Hoornweg et al., 2011; Jones & Kammen, 2014; Marcotullio et al., 2013). Liddle (2014) argues that concentrated population and economic activity require higher energy-intensive processes across a number of sectors (agriculture, transportation, buildings, industry, and waste management).

Mega-cities, as the largest concentration of population, are highlighted by Folberth, Butler, Collins, and Rumbold (2015), who found that between 20 and 30 of the world's megacities are responsible for 3% to 12% of the annual global total emissions of GHG gases (although the modeling analysis did not include all emissions from electricity production– see scoping and boundary issues in above sub-sections). The research is further supported by Marcotullio et al (2013) and Moran et al (2018) both of which found a disproportionate share of CO2e emissions from a smaller set of large cities. Folberth, Butler, Collins, & Rumbold (2015) project that with 2005 levels of emissions (no future increase or decrease in emissions), global megacities alone would be responsible for 25% of the total global warming over the next 100 years.

This issue is an important issue for Asia as the center for population and large cities.   The UN data allow for the examination of the shift in the location of these cities, regionally. **Figure 5** demonstrates that for the current period, developing Asia has the largest share of cities in all categories. This was not always true, and most of the cities in the region were small during the 1955—1970 period.

The relationship between population and GHG emissions also is scalable. At the prefectural household level, Shigetomi et al. (2018) conclude that the number of households have a positive, significant effect on CO_2 emissions, indicating that recent demographic trends are responsible for the increase in CO_2 emissions observed in most of the prefectures from 1990 to 2015. This is also observed in a study focusing on all Tokyo households, which was conducted by Long et al. (2019) using a city-scale input-output table and consumption inventories. Zhan, Liu, Wu, Li, and Wang (2018) examined Chinese residential emissions at the building scale in Guangzhou through a hybrid life cycle assessment (LCA) model. The results demonstrate that operational CO_2 emissions accounted for the greatest portion (81.42%) of a building's total emissions, indicating that the energy structure of the residential sector is heavily dependent on the population. At the city scale, for Hong Kong, Huang, Lv, Chen, and Zhu (2019) conclude that population density, GDP per capita, and trade openness have significantly positive effects on net CO_2 emissions increases in Hong Kong Special Administration Region (SAR) from 1990 to 2015, with population density taking the leading role. Population growth in Beijing is a primary reason for increasing carbon emissions (L. Zhao et al., 2017).

Not only does total population affect emissions levels, but the demographic structure is also important. Using the STIRPAT model, Z. Yang, Fan, and Zheng (2016), in a study of Beijing, observed that changes in population age structure exerts significantly positive impacts on carbon emissions. Important factors include household size and the floating population.

It is important to note that the relationship of urban population to per capita emissions changes over time, particularly for developing nations. With the onset of rapid development, urban per capita energy use and emissions are typically higher than non-urban (Marcotullio et al., 2012). As nations and their provinces grow in wealth, however, the pattern shifts. This is due do to a number of different factors, such as shared resources (apartment buildings, shifts in economic activities, etc.). Shan, Liu, et al. (2016), for example, note that more developed cities in China, such as Beijing and Shanghai, have lower CO_2 emission intensities (i.e., are more efficient energy and emissions wise), because of their greater service industry, which is less direct energy dependent.

2.2.3 Urban form, physical urban size and stock

Increasing income and population are not the only important factors that influence emissions. Focusing more on Beijing and its residential emissions, Z. Yang et al. (2016) estimate that urban form, specifically the relationship between a community and energy-saving building attributes and neighborhood amenities, influences carbon emissions. Their results demonstrate that emissions decrease when there are more attributes and amenities within the building and the vicinity of the residents. These results points to the importance of urban planning policies that could help to reduce emissions. Research from X. Xu, Ou, Liu, Liu, and Zhang (2021) indicate that the total building volume is also important in explaining accelerating CO_2 emissions. Creating this infrastructure alone is associated with a massive consumption of energy.

Importantly, the urban form of cities in the region is changing. T.-L. Chen, Chiu, and Lin (2020) in their systematic review of urban form in East and Southeast Asian cities find that, although the population density in built-up areas is higher than in previous years, annual population density is declining significantly in East and Southeast Asia. This signals a similar trend of urban development processes to those in Western cities. With this trend and the shift in energy use per capita trends, we could expect higher emissions per capita in suburban and ex-urban areas than those in cities as the region continues to develop.

Zhu et al. (2019) look at Shanghai's 2010–2015 emissions from a spatial and urban form perspective and conclude that factors such as urban development intensity, traffic, and industrial land have stronger power to determine CO_2 emissions in the areas outside the Outer Ring, while factors such as population density and population have stronger impacts in the other two inner areas. These results point to the importance of transportation choices. Using a combined method of an LDMI and Granger causality test, Luo, Zeng, Hu, Yang, and Shao (2021) state that for CO_2 emissions in Shanghai from 1995 to 2017, the number of motor vehicles is the most important driving force of CO_2 emissions.

Certainly, there is a relationship between sprawling cities and GHG emissions through increased personal transportation and this has been identified as an important factor in Asia. In Bangalore, Y. Wang, Yang, Han, Li, and Ramachandra (2017) reported that more dispersed and extensive urban sprawl and a prevalence of two-wheeler motorbikes cause higher emissions in Bangalore. In Guangzhou, W. Yang and Zhou (2020) used a decision-tree analysis to determine that socio-demographics have more significant impacts on CO_2 emissions from commuting and social trips than neighborhood built environments, while for CO_2 emissions from recreational and daily shopping trips, built environments have more significant impacts than socio-demographics. Car ownership is the most crucial determinant of CO_2 emissions for almost all types of trips except shopping trips, which are most affected by built environments around neighborhoods, like the distance to city public centers and bus stop density. W. Yang, Chen, Cao, Li, and Li (2017) report similar findings through a Travel Intelligent Query System, stating that Guangzhou's CO_2 emissions are negatively affected by land-use mix, residential density, metro station density and road network density while bus stop density, distance to city centers and parking availability near the workplace have positive effects on CO_2 emissions. Andong and Sajor (2017) report findings in their case study in Manila, stating that the convergence of multiple interacting factors such as urban sprawl, lack of affordability of housing near the centers of employment, high dependence of commuters on public transport and longer distance travel by commuters are primarily causes of the increase in CO_2 emission from the transport sector. Ma, Liu, and Chai (2015) report that the increase in urban area helps to create a job—housing spatial mismatch which is another important factor on transportation in their study of Beijing. This was also identified by S. Li et al. (2018) in a study about Chinese megacities Beijing, Shanghai, and Guangzhou, as well as for Seoul (Lee & Suzuki, 2016).

Finally, the increase in urban land is not only related to energy-use GHG emissions, but also to those related to land use change. C. Wang, Zhan, Zhang, Liu, and Twumasi-Ankrah (2021) explore this relationship by investigating how urban carbon balance is affected by land use dynamics in the BTH region by calculating carbon emissions and sequestration by the land type present. Based on his conclusions of the study, rapid urbanization has led to the increase of built up land, so far as to take over carbon sink areas, leading to the continual increase in emissions. L. Wang, Pei, Geng, and Niu (2019) provides a similar conclusion, showing that the dramatically increasing carbon emissions of land use were mainly caused by built-up land in China from 1999 to 2015, and demonstrating an inverted U-shaped Kuznets curve relationship between economic growth, urbanization, and carbon emissions. Similarly, using the Integrated Valuation of Ecosystem Services and Trade-offs (InVEST) to calculate the carbon sequestration (carbon stocks), S. Wang, C. Fang, et al. (2019) demonstrated that land urbanization showed significant negative correlations with carbon sequestration.

2.2.4 Climate

Another general aspect of urban development that helps to distinguish carbon related emissions is geography. In this case, we are not considering that urban areas of similar size, income and growth rate in one type of climatic zone have higher or lower emissions than those in another, but that the source of the emissions could be different, requiring different mitigation policies. For example, cities in cool climates might focus more on carbon emissions from cooling demand than for heating demand. Certainly, there are studies that demonstrate the differences in energy demand from climatic variables. For example, Shipper (2004) demonstrated that space-heating energy use varied in the United States, Australia and Germany across heating degree days.

Other researchers suggest climate has played a significant role in urban carbon emissions. Research suggests Beijing’s residential service demand is influenced by its cold climate, causing heating to make up the majority of the service demand (Chan Park, Xing, Hanaoka, Kanamori, & Masui, 2017). This trend of demand matches that of the Seoul metropolitan area but differs from poorer Chinese provinces due to economic status; access to more amenities causes an increase in energy use and thus, emissions to adjust to the colder climate. While climate affect energy consumption patterns in Asian rural households (Xing, Hanaoka, Kanamori, Dai, & Masui, 2015a, 2015b), the impact of climate does not seem to be as great as in wealthier Asian locations.

2.2.5 Fuel type

A final category of emissions influences is the fuel type used in the major energy generation and use prime movers within the city. Sugar et al, for example, suggests that unusually high emissions are due, in part, to the share of coal in thermal power generation. In the Kolkata Municipal Corporation (KMC) area, CO_2 emissions are driven by the quantity and type of fuel used. In the KMC area, the projected energy requirement increases with increasing population and vehicular fleet volume, as well as activities in other sectors (Majumdar et al., 2020). Goel and Guttikunda (2015) and colleagues report similar drivers for Delhi’s transport emissions. Andong and Sanjor (2017) suggest that low fuel efficiency of public utility vehicles is an important factor in explaining the increase in CO_2 emission from the transport sector of Manila.

2.2.6 Summary

Across Asia, there have been rising emissions and increasingly, these emissions are emanating from activities of urban residents. Urban industrial and transportation emissions appear to be the most important direct emission sources. Important indirect sources include rising household and residential energy use as income and hence consumption increases. What also seems evident is that the region's cities are generally following a pattern of development not too different from those in the now developed world, including a hallowing-out of the core, decreasing population densities and increasing areal size of cities. While emissions are typically lower for Asian economies than their North American and European counterparts at similar levels of income (Marcotullio & Schulz, 2007), whether they can avoid high emissions levels per capita does not seem evident. China's per capita emissions levels now exceed those of Europe (Global Carbon Project, 2021), with little sign of stabilization. There is opportunity, however, to avoid the lock-into high fossil fuel use and subsequent carbon emissions. In the future, policies will probably be the main influencing factor on lowering carbon emissions.

3. Methods from the different project teams

As discussed previously, there are a multitude of different ways to study urban GHG emissions. Each team in the APN project focused on different issues and used different methods by which to quantify GHG emissions. In this section we briefly overview the different methods used for each project.

3.1 Bangkok

Thailand developed its first national GHG inventory report in the year 1994, followed by subsequent inventory reports in 2000 and 2011. However, comprehensive sub-city level inventories have only started to be explored (see, Ali, Pumijumnong, & Cui, 2017; Ali, Pumijumnong, & Cui, 2018; G. Chen, Wiedmann, Wang, & Hadjikakou, 2016; A. Phdungsilp, 2017). The Bangkok team developed a historical inventory of GHG emissions at the sub-city level: the Bangkok Metropolitan region (BMA) at the provincial level with a focus on the residential, commercial, industrial and transportation sectors. The team used secondary data to calculate the associated sectoral emissions from 2008 to 2016. It is important to note that the study has estimated only electricity–based emissions from residential and commercial sectors (due to data limitations) and only focused on CO_2. The team used proxies indicators and made specific assumptions for each sector. Calorific values and emission factors for fuels were collected from the IPCC 2006 guidelines, with the emission factors for power generation collected from Thailand Energy Policy and Planning Office.

3.2 Beijing

The Beijing team developed comprehensive indexes using the stochastic frontier parametric approach (SFA) to measure relative carbon emission reduction efficiency (Fall, Akim, & Wassongma, 2018; Feizabadi, Bagherian, & Moghadam, 2019; Silva, Tabak, Cajueiro, & Dias, 2017) in order to study carbon emission performance and mitigation potential of 39 industrial sectors in the Beijing city, Tianjin city and Hebei Province (BTH) (36°05′-42°37′N and 113°11′-119°45′E) region. According to data from the National Bureau of Statistics of China, the BTH region covers an area of 0.22 million km^2, with a population more than 110 million persons in 2017 (21.3 million persons in Beijing, 15.6 million persons in Tianjin and 75.2 million persons in Hebei), accounting for 8.06% of the total population of China. In 2017, the GDP was approximately 8.06 trillion Chinese Yuan (CNY), accounting for 9.74% of the nation's total. Industrial development has been an important part of regional economic growth in recent years and by 2017, accounted for 30.90% of the regional GDP. In Hebei, during 2017, the industrial share of GDP exceeded 40%.

Variables included capital, labour, energy use, GDP (desirable outputs) and CO_2 emissions (undesirable outputs) (Guo, Liu, & Wang, 2013; Lin & Wang, 2015). The inputs were classified as belonging to 1 of 39 sectors (Y. Bai, Deng, Zhang, & Wang, 2017). The original data were derived from the Beijing Statistical Yearbook, the Tianjin Statistical Yearbook, the Hebei Economic Yearbook and the China Statistical Yearbook (2011-2017). The economic data from each sector were converted to 2010 price levels, including capital and GDP. Estimates of the capital stock for each sector were based on the perpetual inventory method. Energy consumption was converted into standard coal equivalents (Tce). The carbon emissions were calculated according to the IPCC method (IPCC, 2006; C. Wang et al., 2019). The team captured the total factor carbon emission performance (TFCP) and carbon emission mitigation potential (CMP) for 39 industrial sectors in each of the three sub-regions from 2010 to 2016. The study also calculated the carbon emissions from residential consumption in the BTH region and analyzed the influence of impact factors on the indirect residential carbon emissions.

3.3 Seoul

The Seoul team evaluated the progress of green growth policy in Seoul and the Republic of Korea with suggested methods for improving the efficiency and enforcement of policies that respond to climate change. After reviewing national and local plans for low carbon development for the province and city, the team included a description of actions by sector for energy production, air quality, transportation, resource recycling, water use, local ecology, and urban agriculture. They also conducted an analysis of the CO_2 emission in the building sector focusing on socio-economic driving forces. Energy consumption is calculated per year per building from natural gas use. The emissions were spatialized using a kernel density function. Building sector The spatial distribution of emissions data were then compared to visually to the spatial distribution of population, number of buildings (houses), number of businesses, local GDP, and other factors.

3.4 Taipei

The Taipei team identified the CO_2 emissions within the building stock of the city. They divided buildings into types classified in accordance with the urban development context and spatial characteristics of Taipei. The calculation of embodied energy of buildings was conducted through the emergy synthesis, systematically quantifying all the primary materials required for the construction of each type of building during the construction process and converting all different materials into the common unit of solar emergy (sej) (M. T. Brown & Buranakarn, 2003). The densities of emergy storage (sej/m2) of different building types were also obtained and the use of raw materials for constructing each building type was used to estimate CO2 emissions during the construction process. Estimates were performed based on the “Building Material Production and Transportation CO_2 Emission Chart” issued by the Architecture and Building Research Institute of Taiwan's Ministry of the Interior (MOCA), delineating the building types of high and low CO_2 emissions. In order to analyze the spatial distribution of emergy storage and building—CO_2 emissions in Taipei City, this study examined the sub-city and neighborhood-scale. This research used both district and neighborhood scale aggregations. Presenting results from the different scales allowed for distinctions between daily consumption CO_2 emission and urban development intensity.

3.5 Tokyo

The Tokyo team examined the change in energy use, GHG emissions and national and local mitigation policies from 2000 to the present. The analysis used data obtained at various levels. The focus was on evaluating the differences in policy intent and effects of the different levels of governments, particularly after the 2011 earthquake and to assess the effect of energy these policies on energy use and emissions. Both conditions can have major ramifications for managing energy consumption and meeting emissions reductions targets both at the national and city levels.

3.6 New York City

The New York City team use a variety of on-line data sets from the national level to generate a historical spatialized map of residential energy use from 1993 to 2009 for the New York metropolitan area, as defined by the Regional Plan Association's (RPA). The analysis of the data included three major steps including developing regression equations for the four different residential energy end uses (space heating, water heating, cooling and appliance use), spatializing the outputs of these regressions using census data and then generating emissions from the energy use data based upon fuel used. The spatialized residential energy use was then aggregated into different urban units (core, inner suburban, outer suburban and exurbs) and compared. The results were validated by comparing the total energy use and GHG emissions data to state databases.

4. Results of the project teams

The key findings of each different team are provided below.

4.1 Bangkok

The Bangkok team identified five major findings for GHG emissions and four suggested drivers for lower emissions levels. The first major finding is that for the BMA overall, is that overall the trend of total CO_2 emissions is increasing from 2008 to 2016. The rate of increase is 0.94% per annum. The second finding is that the highest levels of emissions were in the transportation sector, followed by the industrial sector, then commercial sector and finally the residential sector. Transportation accounts for 43% of total emissions in Bangkok Metropolitan Region (BMR) and within the transportation sector the largest fuel source is diesel. The third finding is that there was a significant decrease in 2011, which was due to flooding experienced across the country, but largely in the Bangkok region. This flooding was most severe in the Ayutthaya and Pathumthani provinces. As a result of the flooding electricity related emissions dropped significantly. Finally, the rate of increase in electricity consumption was higher (3% increase for buildings) than the rate of increase of electricity related emissions (approx. 1% increase in emissions) from 2008 to 2016. This suggests an energy and or carbon intensity efficiency during this period. From these results the team suggested that the drivers for future low carbon actions are to increase the share of renewable energy in power generation, increase energy efficiencies, particularly in the buildings sector, continue to develop mass transit to encourage less private vehicle use and promote electric vehicles.

4.2 Beijing

The major findings of the Beijing team include identifying the trend of total carbon emissions in the BTH region, which increased from 542 Mt CO_2 in 2010 to 649 Mt CO_2 in 2016. Carbon emissions in Hebei increased from 439 Mt CO_2 in 2010 to 565 Mt CO_2 in 2016 and contributed the largest proportion (87%) of the increase during this period. Carbon emissions in Tianjin increased slightly from 44 Mt CO_2 in 2010 to 48 Mt CO_2 in 2016, while those in Beijing decreased slightly from 59 Mt CO_2 in 2010 to 36 Mt CO_2 in 2016.

The sub-regional CMP of most industrial sectors decreased from 2010 to 2016. Processing of Food from Agricultural Products (sector 7), Manufacture of Foods (sector 8), Manufacture of Beverages (sector 9), Manufacture of Nonmetallic Mineral Products (sector 25), Smelting and Pressing of Ferrous Metals (sector 26), Manufacture of Transport Equipment (sector 31) and Production and Distribution of Electric Power and Heat power (sector 37) in Beijing have the greatest potential for reducing carbon emissions. The total residential carbon emissions increased from 257.50 Mt CO_2 in 2002 to 673.34 Mt CO_2 in 2012 in the BTH region, reflecting an increase of more than 150%. In addition, carbon emissions in Hebei were 3.86 times that of in Beijing and 10.58 times that of Tianjin in 2012. Clearly, residential carbon emissions from urban areas were far higher than that from rural areas, with urban carbon emissions being 1.51 times higher in 2002, 2.66 times higher in 2007, and 2.79 times higher in 2012. Moreover, indirect carbon emissions were higher than direct ones. The contribution of indirect emissions to total emissions comprised more than 60% in Beijing and Tianjin, and more than 70% in Hebei. Three impact factors exhibited positive effects on the growth of indirect emissions in the three sub-regions, i.e., intermediate demand, consumption level, and population size.

The paper suggests three overall policy initiatives to help in the effort. First, the BTH region is not homogeneous in terms of carbon emission intensities, the TFCP, CMP, and even the relationship between the TFCP and CMP among the industrial sectors. Therefore the region will benefit from a detailed industrial layout plan, supporting continuous promotion of regional economic development and advocating coordinated development among the 3 sub-regions. Second, the formulation and implementation of policies related to carbon emissions reduction should concentrate on technology innovation and improvements and industrial structure adjustment. Third, different policies and regulations should be implemented for specific sectors, such as the Manufacture of Nonmetallic Mineral Products sector (sector 25) and the Gas and Water Production and Supply sector (sector 37). Other suggestions can also be proposed for local carbon reduction strategies and industrial restructuring and updating.

4.3 Seoul

The findings from the Seoul team argues that the Seoul Metropolitan Government's green growth policies were developed before the national policies, demonstrating that Seoul leads the country in low carbon mitigation strategies. Recently, the Seoul government supplemented its existing green policies, seeking to facilitate citizen participation, and to divide action plans between citizens, companies and the government. However, achievement was not inclusive and there were difficulties in evaluating future plans.

From the GHG emissions analysis the team identified a number of potential policies and innovative plans fundamentals. First, the city must establish an organized system that connects spaces, the environment, energy and resource cycling. Green growth plans, urban planning and management needs to reflect various socio-economic and physical factors that help to create green cities. Plans must be specialized to physical spaces, environment, energy, resource cycling, transportation, infrastructure and climate change. Second, policy must focus on urban restoration. When selecting green city model target areas, urban revitalization areas must be a priority, and the sites need to reflect various examples of applied planning elements. Third, policy must focus on spatial planning for local energy. Local energy plans can help to identify the current conditions of energy consumption and GHG emissions status. This requires a local energy consumption inventory and enhanced demand estimations. Finally, policy must enhance governance systems. To stabilize governance systems, there must be guidelines to provide solutions by forming the consultative groups that are inclusive of stakeholders.

4.4 Taipei

The Taipei team found that among the five building types studied, 13 to 24 story steel-reinforced, concrete buildings have the highest emergy density (7.59E+15 sej/m^2) and brick buildings have the lowest emergy density (1.25E+15 sej/m^2). The results show a correlation between emergy densities of different building types and the density and height of the buildings. At the same time, however, the unit emergy value (UEV) of building materials is also associated with the emergy density of different building types. The buildings with higher density and stories tend to use more construction materials with higher UEV (e.g., reinforced, concrete and steel) and result in higher emergy density. Results suggest that the building types with higher emergy densities also generate higher building–CO_2 emission. The correlation of emergy storage and building-CO_2 emissions is related to two factors: building materials and the construction technology.

Emergy storage density of buildings is clearly related to building-CO_2 emissions. By calculating the correlation between the emergy of different building types and the building-CO_2 emissions during construction process, the team was able to describe this relationship: the higher the accumulated emergy storage for that building type, the higher the CO_2 emissions, with the same being true conversely. They conclude that emergy synthesis can effectively be utilized to assess CO_2 emissions derived from building construction.

4.5 Tokyo

The Tokyo team found that the Tokyo Metropolitan Government has been a clear frontrunner in energy consumption and GHG emission reduction efforts within Japan, possibly even influencing the agenda of the national government towards the adoption of more ambitious targets and individual initiatives. Apart from consistently setting more ambitious emission reduction targets than the national government, the Tokyo Metropolitan Government has enacted some truly innovative policies and initiatives ahead of the rest of the country. Some examples are the Cap-and-Trade program, the rapid switch to LEDs, and the energy-labeling scheme, among others.

Two further general findings were identified. The first is that in some cases city governments can be more ambitious and proactive in emission reduction targets than national governments, even in the wake of unanticipated events. The second is that despite good intentions and clear efforts, many of the factors affecting the effectiveness of energy consumption and emission reduction policies are beyond the reach of city governments. Both conditions can have major ramifications for managing energy consumption and meeting emissions reductions targets both at the national and city levels.

4.6 New York City

The project examined both the geographic and temporal differences and changes in residential energy use for the metropolitan New York City region. The team identified a number of findings. First, the tri-state region's total residential energy use was about the same from the start to the end of the period (although there were fluctuations). The five-year average during the start of the period registered approximately 1.4 quadrillion British Thermal Units (quad BTU) and the five-year average at the end of the period was approximately 1.44 quad BTU. However, there were some dramatic changes in energy services. For example, energy for space heating dropped by approximately 16.4% from over 1.06 quad to 880 trillion BTU. At the same time, energy for cooling increased from 840 billion to 21 trillion BTU or by over 2400%. Energy use for appliance use also increased by 80% from 160 trillion to 289 trillion BTU during the period.

Second, energy use per household and total energy use by geographic region also shifted. Residential space heating energy dropped across all geographic areas. At the same time, energy for water heating, cooling and appliances all increased. Energy for cooling increased by the greatest amount relatively, across sectors. The greatest absolute increase in total energy use was for cooling in the outer suburbs, which increased from 720 billion to 15.8 trillion BTU. The next largest increase in residential energy use was in the inner suburban metropolitan area where cooling energy increased by 6.7 trillion BTU, from 380 billion BTU in 1993 to 7.05 trillion BTU in 2009. Energy for appliance use also increased differentially across geographies during the period. The greatest increases were experienced by the inner and outer suburban areas, which increase appliance energy use by 80.5% and 85.6%, respectively.

Finally, the energy use per household also changed over time, demonstrating differences across space also. In terms of total residential energy, the only geographic area that didn't change was the outer suburban metropolitan areas. All other regions experienced drops in average total household energy use. The patterns across sectors are similar to those of the total residential energy use per energy service. The greatest drop in average household energy use was in space heating, which dropped across all geographic regions. Alternatively average energy use per household increased for all other sectors. The largest increases were in appliance energy use. Average residential energy use per household was lowest in the core city and higher in the suburban areas in terms of total and across all energy end uses.

5.0 Discussion and conclusions

5.1 Asian urban GHG emissions

GHG emissions from the region are significant and the major metropolitan centers are large and growing contributors. In most cases, national and urban emissions are increasing, although the APN research teams identified stable emissions over the past few years in Beijing and Tokyo.

Across the region the important activities related to the growth of emissions include: 1) the building of cities and subsequent creation of concrete related CO2 emissions; 2) vehicle (passenger and freight) use; 3) industrial manufacturing energy use and industrial processes and 4) growing residential consumption. Within these urban centers there is significant differences among sub-city units. It seems that industrial centers and new commercial centers have the highest emissions levels. This is probably due to the economic activities and demand for transportation in these areas. That is, industry and transportation are important sectors of GHG emissions in Asian cities. However, there is also high embedded energy and CO_2 in buildings in these areas due to their size and the materials used in their construction. Particularly important are the concrete and steel structures.

5.2 Potential policy pathways

The major Asian metropolitan centers are leading national low-carbon efforts. The studies in this project identified this for Tokyo and Seoul as national leaders in carbon reduction strategies. It is also true for Taipei and Bangkok. This suggests that some of the major metropolitan cities are leading the region's efforts in meeting the Paris Agreement. Specific policies for low-carbon development across these centers varies. Certainly, all cities share the need to reduce emissions from growing passenger car use. This may be beyond the control of local governments, however. Industries, in those locations where manufacturing is an important contributor to economic wealth, can be regulated to help reduce emissions. In this case, both urban planning and city regulations requiring lower emissions is possible. Enhancing laws that encourage energy efficiency in both energy use and industrial processes could help here. Finding ways to lower carbon related consumption is challenging. Some options include enhancing the sharing economy, which has enhanced potential in dense settlements compared to more dispersed spatially organized units and encouraging the circular economy. In parts of Asia the rates of recycling and waste reduction are already high, however.

5.3 Future research suggestions

The review and papers in the project demonstrate the importance of sub-city and sectorial GHG analyses. The future of urban GHG emissions analysis is certainly a focus on higher resolution spatially disaggregated analyses. Promising studies using satellite images that can pick up CO_2 emission signals are interesting and potentially extremely useful. There will still be the need, however, for consumption related emissions analytics. Nevertheless, identifying neighborhoods and areas of high emissions levels allows urban stakeholders to target these areas for reductions and efficiency exercises.

While the larger cities make up the lion's share of emissions across the region and the world, they are also typically the most efficient and lower per capita GHG emission urban centers. Interest should also be targeted to medium size and smaller cities. Policies from the larger cities serve as models for other cities and more emphasis could be focused on policy migration from larger to smaller centers. This will probably require a transfer of skills and capacities.

Asia will remain the center of industrial activity, population growth and increasing CO_2 emissions over the next few decades. It is therefore urgent to identify ways in which the region's cities can become more efficient and less polluting. There are both hopeful and threatening trends emerging. Whether the region can leap-frog over the problems experienced by the developed world remains uncertain. Work on urban GHG emissions will continue to play an important role into the medium-term future.

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Figures

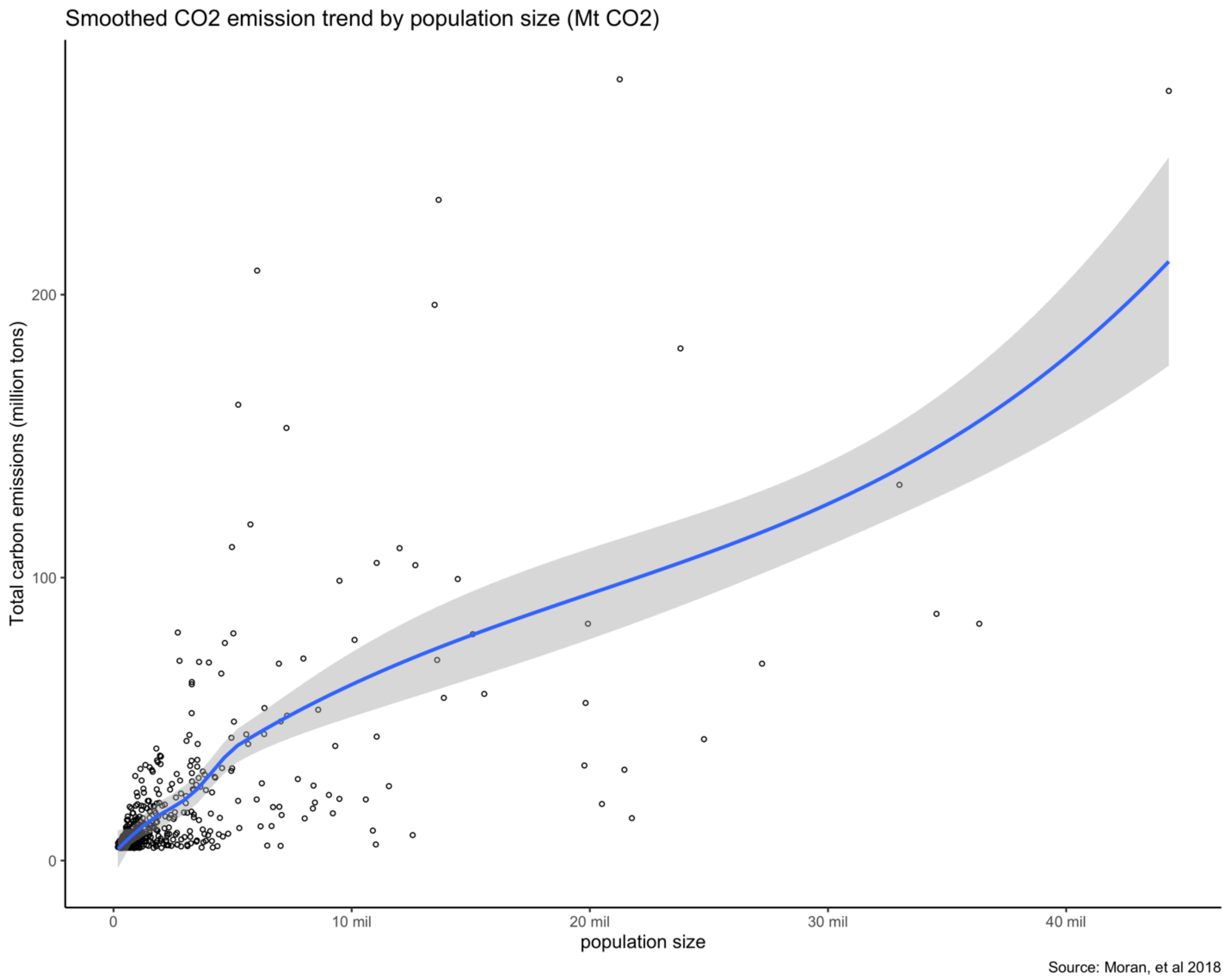


Figure 1: Size of urban population and total carbon emissions

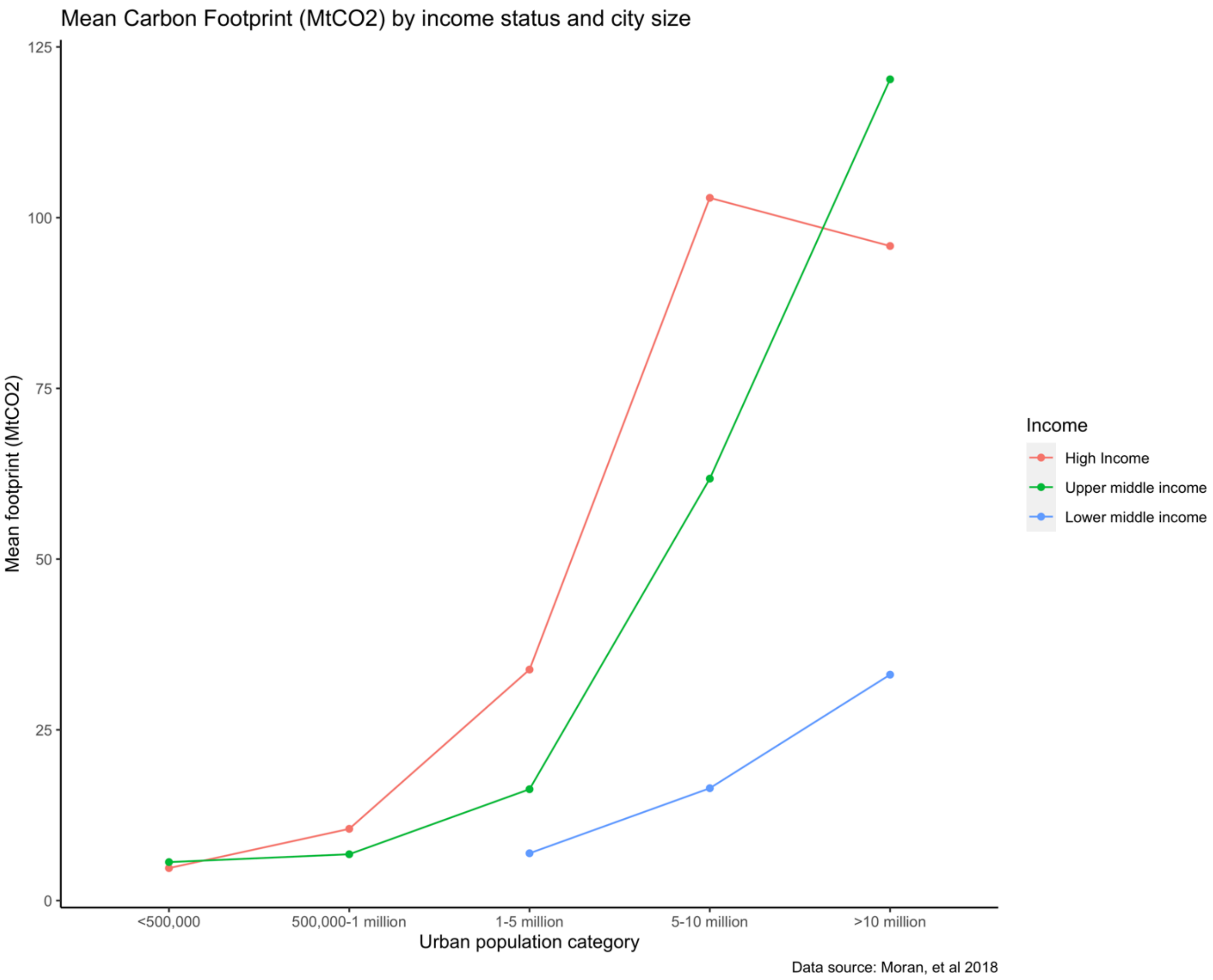
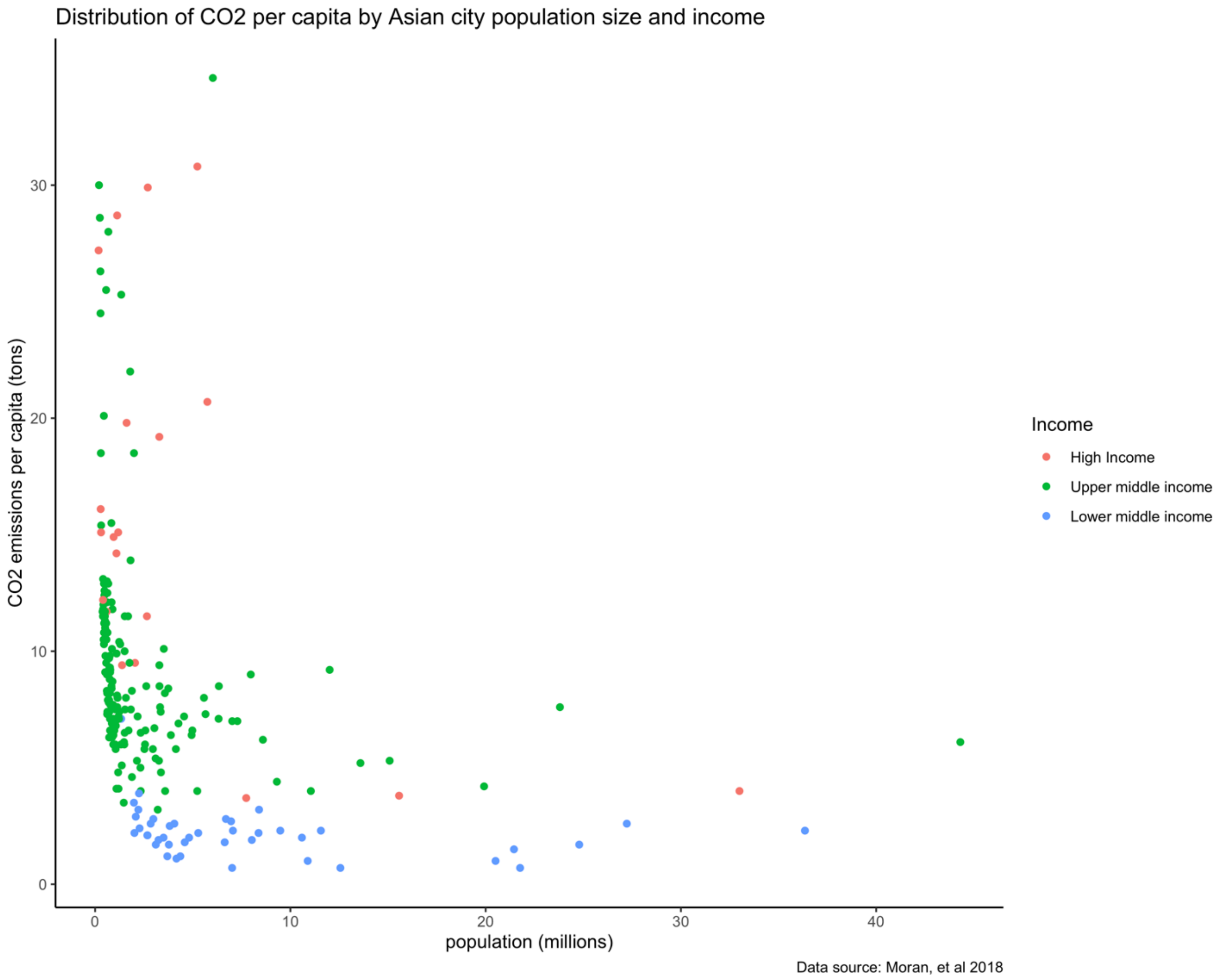
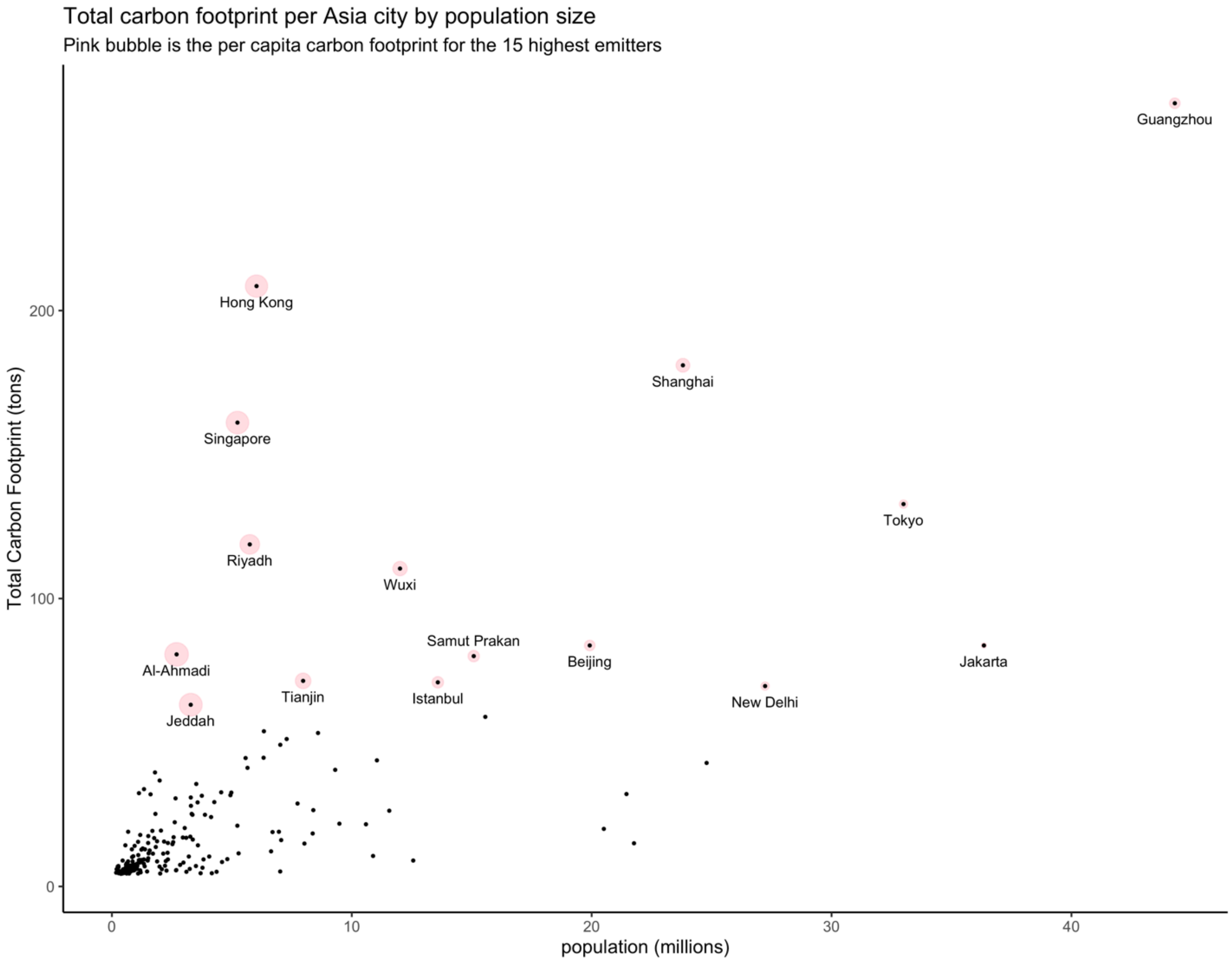


Figure 2: Urban population by income category and carbon footprint



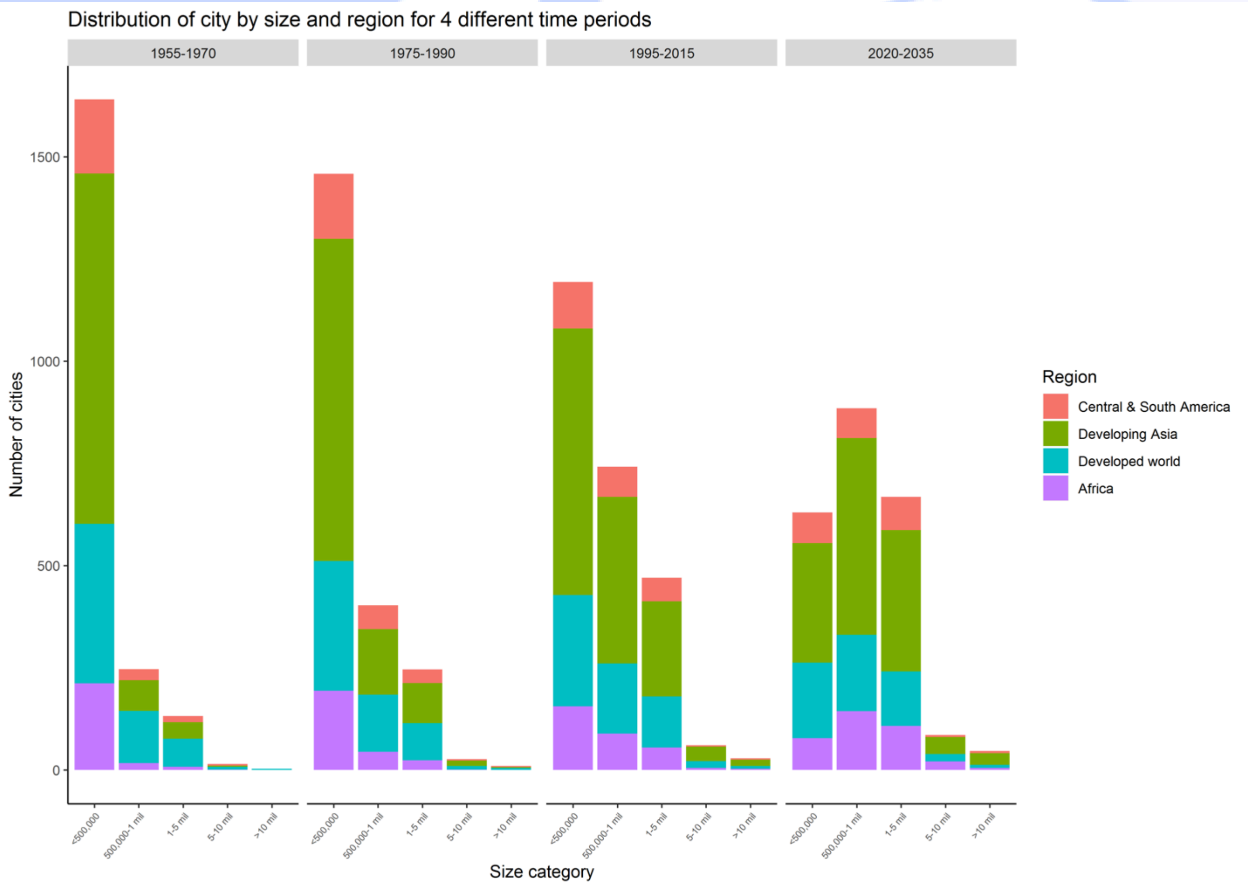
Data source: Moran, et al 2018

Figure 3: Population and CO_2 emission per capita by income category



Data source: Moran, et al 2018

Figure 4: Population size, total carbon footprint and per capita footprint for the 15 largest Asian urban GHG emitters. This chart is a partial reproduction of a chart produced in Moran, et al., 2018.



Source: UN 2018

Figure 5: Distribution of cities by region and size