Resource use in the Chinese building sector: foundations for analyzing urban transition

by

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B.S. Earth and Environmental Engineering, Columbia University (2011)

Submitted to the Engineering Systems Division
in partial fulfillment of the requirements for the degree of

Master of Science in Technology and Policy

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

June 2014

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Abstract

Around the world, people are moving to cities in order to become wealthy, especially in developing countries undergoing socio-economic transition. This will dramatically change the way that society consumes resources, in terms of both materials and energy. We will need to better understand how resource use changes as development happens in order to focus efforts to reduce that resource use.

China is undergoing this transition as it enters the global stage, and with global implications for resource use. The building sector in China is especially resource-intensive, fundamentally driven by the country's urbanization, and plays a prominent role in the Chinese economy, making it a good candidate for the study of how systems adopt sustainable practices.

I approach this problem in two ways. The first is quantitative, using k-means statistical clustering on longitudinal resource use data from Chinese statistical yearbooks, in order to identify and compare transitions across provinces in China. In comparing the evolution of the building sector across provinces, my analysis suggests that development pathways are more distinct than discrete development stages. I identify two development pathway 'types' in China. The first is an urban path taken by Beijing, Shanghai, and Tianjin – the three most heavily urbanized provinces. All other provinces follow a general business-as-usual path, though I also identify sub-pathways to further differentiate between the other 27 provinces. These development typologies are one means of quantitatively operationalizing the abstract notion of transition. Identifying such pathways may highlight opportunities for learning between provinces within the same path, and one could apply similar methods to other scales of analysis (e.g. urban or national).

My second approach is qualitative, driven by interviews conducted primarily in Beijing with various stakeholders in the Chinese building sector. In this analysis, I discuss the particularities of the actors and processes involved in Chinese real estate development, identify opportunities for and barriers to reduced life-cycle energy use in buildings, and describe three distinctive and ongoing sustainability experiments with the potential for significant resource use reductions. This research emphasizes the need for integrated approaches to both research and practice in approaching sustainability transitions, and provides a set of complementary frameworks for their analysis.

Thesis Supervisor: John E. Fernández
Title: Professor of Architecture
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Acknowledgements

At our very first meeting, after I described my research interests John Fernández said something to the tune of "That's what I'm planning to write my next book about." This was a harbinger of good things to come. Since then he has given me an incredible amount of trust to pursue my research interests – which I sometimes worry about, but only until we meet and my confidence is reliably restored. For his guidance, curiosity, excitement, and overall support I am extremely grateful.

I have also benefitted enormously from the support of the other members of MIT's Urban Metabolism Group – Jonathan Krones and Karen Noiva. I am thankful to both of them for their mentorship and feedback throughout the research process. Further, it is said that 'you are your own strongest critic'; but Jonathan has been mine, and my work is substantially better for it. And I may not have done any of this in the first place if he hadn't convinced me to apply for the Technology and Policy Program (TPP) in Fall 2010.

I am lucky to have had the support of the MIT-SUTD International Design Centre along with increasingly many cohabitants. The IDC has provided a dynamic space in which to work, a wonderful community to be a part of, and it will be an exciting place to watch grow.

It has taken a village to raise this thesis, and I am indebted to the many people who have provided critical feedback over the course of the research and writing process. First Ryan, for agreeing to give me feedback on my written draft the week of his own thesis defense, and who along with Yael has helped me make Building 9 my home away from TPP. Both of them, along with Kate and Nathan, have provided extremely useful feedback and constant moral support over the course of this final semester.

I received helpful comments on earlier pieces of this work from members of the Regional Studies Association (RSA) at the first RSA Research Network on governing the sustainability transition in October 2013; members of the Energy Foundation's and Natural Resources Defense Council's Beijing offices; Neuwrite Boston; and Jinhua Zhao as part of his Fall 2013 course, *Urbanizing China* (which he could not have started teaching at a better time). I also thank Jinhua for assisting with the research proposal for my interview analysis. Jinhua, Steve Hammer, and Chris Zegras have each provided guidance, and along with John have all fueled my interest in urban sustainability by imparting their collectively encyclopedic knowledge of cities.

The interviews I conducted in China, which comprise half of this thesis work, would not have been possible without the generous support of Sean Gilbert and MISTI-China, as well as Kevin Mo and the Energy Foundation China office, who graciously hosted me in their office during my six-week stay in Beijing. I was also welcomed and assisted tremendously during my time there by amazing support networks of both friends and other building energy experts, among them the interview participants.

The research and writing processes have been eased by free and/or open-source software like Mendeley, R/RStudio, LaTeX/Lyx, the Internet, and the invaluable communities that fall under the umbrella of Stack Exchange. And many thanks to MIT, for filling in the gaps when free software doesn't quite cut it.

I am starting to run out of synonyms for "thankful", but it is almost done so I will persevere. My family has provided endless love and support, and in particular I would like to award my mother extra credit for being the last person to read my thesis before its submission.

TPP has been my surrogate family for the past two years, providing a vibrant and diverse group of people; ideas; and perspectives, from which I have benefitted tremendously. I hope I have been able to contribute in kind.

Finally, I thank the residents of Sciarappa, my home for the past two years. Ingrid, Mac, and Mark showed me what thesis writing looks like, and I am honored to have carried on a tradition of TPP thesis-writing in these hallowed halls. Brenden, Mac, and Tom have kept me grounded this year, and made me excited to come home each night. I want to especially acknowledge Brenden, who has bought more than his fair share of the groceries this semester, and kept me well-fed me in the final days of the writing and editing process. Many more unnamed friends provided support in various forms, ranging from "You can do it!" messages to cookie care packages ordered from overseas. Well, I *did* do it; thank you; and the cookies were delicious.

Commentary

Two brief thoughts about the writing process before jumping in.

First, academics are generally complicit in fostering an institutionalized fear of failure. Too often, the fancy reports and papers one reads (and occasionally writes) as an academic obscure many of the most important lessons to be learned from the process of scientific inquiry and research more broadly, which is to say its shortcomings. There is perhaps one good reason for this, however; for one, academic writing is long-winded enough as it is. I attempt here to strike a balance between under- and over-sharing, though this being my one and only masters thesis I have probably erred on the side of presenting more information rather than less.

And second, in spite of its best efforts, science remains a value-laden undertaking. While I have had an enormous amount of guidance and assistance over the course of the past two academic years, I am ultimately the person responsible for this piece of writing and I try to be clear about this where I think it matters. I will also try to make clear the distinctions between my interpretations, my opinions, and ideas or analyses best attributed to the Urban Metabolism Group at MIT (denoted in a few instances by the use of the first person plural).

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Chapter 1

Introduction

1.1 Preamble

China is in the midst of a remarkable period of development, urbanization, industrialization, and increasing resource use. China's development is relatively unique for two primary reasons – it is home to 1.35 billion citizens and a single-party governmental system led by the Communist Party of China. The former reason makes it an essential topic of study for those interested in sustainability. China's ability to develop sustainably has profound implications for global sustainability outcomes in light of its population and in light of other developing countries' potential to learn from China's experiences.

Chinese urbanization is also littered with contradiction that reflects the country's ongoing transition. The socialist government manages an increasingly market-driven economy. Urbanization is an explicit policy goal of the central government, yet also actively impeded by its policies. Local governments are beholden to GDP growth targets yet have little ability to independently collect revenue. Architectural design in the country is lamented for its repetition, while China supports much of the world's most innovative design work.

These contradictions are brought about by the development process itself, which has many complex facets and significant implications for sustainability. As development occurs, many interrelated things happen. Average income rises, and resource use[1] along with it. The composition of industry shifts both in nature and spatial organization – people and firms alike becoming increasingly concentrated in cities. This increased concentration of people and firms yields productivity gains, further increasing wealth. Cities' existence is thus reinforced by development; more of each begets more of the other.

[1]When I refer to resource use throughout the remainder of this thesis, I use the term to comprise both materials and energy use. I choose the word 'use' to maintain generality, rather than distinguishing between the production and consumption of goods, both of which may be considered relevant to sustainability in different contexts. I consider 'resource use' to be interchangeable with 'environmental impact' and 'environmental sustainability', which is a simplification that ignores the possibility of decoupling resource use from its environmental implications, namely by using low-impact and/or renewable resources. This is a simplification which I consider to be valid in the short term – as long as resource use and environmental impact remain strongly correlated – but (hopefully) not in the long term.

The increased resource use associated with development presents a significant challenge in the context of global sustainability, and development takes place primarily in cities. Yet the relationship between development processes and their resource use implications is not well-understood. This is especially important for the parts of the world for which significant development remains. To make this development sustainable, policy mechanisms and design principles that reduce long run resource use must be employed, with a particular eye towards the urban setting.

The building sector is one of the most important in China.[2] Construction in China alone comprises 6.9% of the country's GDP [42], and more building floor area is constructed in China every year than exists in New York City. This development is cement and steel intensive, these two industries being two of the most energy intensive globally – together accounting for just over 11 percent of global CO_2 emissions. By mass, China produces nearly half of both cement and steel globally.

This development has coincided with an extraordinary poverty alleviation success story – Chinese poverty falling from over 80% in 1981 to approximately 12% in 2010.[148] Environmental sustainability should not come at the expense of this social progress, presenting the fundamental challenge of sustainable development: how can we reduce the resource intensity of development without slowing it down from a social perspective? And in the Chinese building sector: how we can reduce resource intensity, and what are the roles of different actors in accomplishing that reduction?

The building sector may be described as a complex socio-technical system – a large network whose properties are determined by both human actors and technological elements, which interact in a variety of ways. To understand how to reduce the resource intensity of the building sector[3] first requires an understanding of the system's primary actors and their capacity to influence the system. I highlight the importance of this sector's relationship with urbanization, and explore the role of urban policies in shaping the building sector's resource intensity.

The process of achieving this reduction in resource intensity requires a transition away from resource intensive practices. It is through the lens of transition that I analyze the historical evolution of resource use and consider the possibilities for a transition to reduced resource intensity in the Chinese building sector. This work contributes to our understanding

[2] I take the building sector to include all actors in the economy whose work impacts the life-cycle energy use of buildings as well as the construction of major related urban infrastructures – in this thesis, most notably roads. These actors include material producers, e.g. of cement and steel; real estate, design, and construction firms; as well as professionals specialized in operational building energy use.

[3] When I discuss the building sector's resource use as a whole, I will speak in terms of its resource intensity, meaning the resource use per-unit-something. This 'something' could be building sector GDP; constructed floor area; number of buildings; or number of housed people (in the context of residential building), for example. While absolute reductions in resource use are the ultimate goal, the resource *intensity* terminology acknowledges that the act of building (1) uses resources by necessity and (2) is not in and of itself undesirable. We should instead focus on ensuring that building practice use as few resources as possible over the course of their lifetime.

of this resource-intensive sector, and the ideas and analyses that follow build foundations for future efforts to understand the nature of transition towards more sustainable development.

1.1.1 Preview

In the remainder of Chapter 1, I describe the challenges that motivate this research at several levels, place it in the context of my research group's broader agenda, and state the research questions I hope to address. I review several areas of relevant literature in Chapter 2, and draw connections between the largely siloed approaches that contribute to our current understanding of resource use in cities. I outline my particular approach to addressing these challenges in Chapter 3, which includes two primary components:

- a quantitative, machine learning method for identifying high-level transition and comparing provincial development pathways in the Chinese building sector

- a qualitative, interview-based approach to understanding the institutional context for sustainability transition in and prospects for reducing the resource intensity of the Chinese building sector

I then present the two resultant analyses in Chapter 4. The quantitative analysis is historical, in which I use k-means statistical clustering to develop a typology of provincial resource use transition in the Chinese building sector. Then I propose a theoretical framework, which forms the foundation for my qualitative analysis of triggers of and barriers to reducing the resource intensity of the Chinese building sector.

In Chapter 5, I speculate on the nature of resource use transition, discuss urban sustainability, and present some of my personal views on the future of the Chinese building sector, before summarizing some possibilities for future work. I discuss the policy and institutional implications of my analysis in Chapter 6, and conclude in Chapter 7.

1.1.2 Contribution

This thesis makes contributions in four areas, which I designate as academic, theoretical, methodological, and practical.

Academically, I draw several areas of inquiry together under the umbrella of resource use and sustainability transition, building primarily on the contributions of industrial ecology and socio-technical transitions literature. Transition is the common thread running through the analysis, and sustainability transition is concerned with how to reduce resource use in socio-technical systems. I connect transition with material flows and typological analysis using statistical clustering of resource use data. I explore urban sustainability transition in the theoretical framework, and consider the roles of various sectoral actors in enabling transition towards lower resource intensity in the Chinese building sector.

Theoretically, I add to existing transition frameworks by organizing my discussion around triggers and barriers of transition. I argue for integrating sectoral and geographic lenses, in particular with respect to cities. I also present some speculative theories to frame future transitions research, and propose several definitions that may prove useful in guiding theory development with respect to socio-technical transition at multiple scales.

Methodologically, I test a quantitative, machine-learning based method for generating a typology of historical development. Because the k-means algorithm yields distinct clusters, applying it to longitudinal data allows me to observe distinct transition from one cluster to another. The typology I generate in this case is focused on resource use, but this is not a requirement for future work; a similar method may be applied to socio-economic or even categorical data, for example from a survey. The particulars of the method may have to be altered (particularly in the latter case), but the fundamental approach would be the same. In general, machine learning provides many opportunities for quantitatively robust approaches to typological analysis. I also take an incremental step towards marrying quantitative and qualitative approaches to understanding sustainability transition, particularly at the urban scale.

Practically, I provide a centralized understanding of building sector actors, and short case studies of ongoing sustainability experiments in Chinese building sector. I also detail current mechanisms of knowledge transfer and discuss many of the fundamental drivers of resource use in the sector. In my analysis of transition in the Chinese building sector, the mere fact that I attempt to highlight information of potential use to practitioners and policy-makers distinguishes my work from much of the socio-technical transitions literature, much of which has thus far been motivated by theory-building.

1.2 Motivations

I take the time here to review the diverse and interrelated motivations for this work. Some will be referenced explicitly, while others remain below the surface of my analysis. These motivations are broad and provide a foundation for much of the ensuing discussion.

1.2.1 Sustainability

Sustainability stands on three essential pillars: environmental, social, and economic. This research is concerned primarily with environmental sustainability, though I struggle to imagine a case where it would be responsible to entirely separate any of the three from the others. Environmental sustainability is in itself still quite broad, so to be slightly more specific my primary interest is in mitigating climate change. Accomplishing this goal can, should, and in many cases must go hand-in-hand with many other aspects of sustainability, not least of all improvements in local air quality. So, to be perfectly clear: when I refer to 'sustainability' throughout the remainder of this thesis, please note that I refer only to *environmental* sustainability, and generally to environmental sustainability in the context of climate change mitigation – except where otherwise clarified.

System limits

For the purposes of this research, environmental sustainability means that human resource consumption rates do not exceed the natural system's capacity to provide non-declining well-being to the world's human inhabitants. In the language of economics, this is the same as allowing for the substitutability of natural resources. This is what is commonly referred to as 'soft' sustainability, in that it does not place absolute priority on the preservation of natural resources, per se, but rather prioritizes the well-being of humans over the global ecosystem with which we coexist.

There are, however, limits to this substitutability. It has long been speculated that we will begin to exhaust certain natural resources, by harvesting and using them faster than their natural rate of replenishment.[103] Economic thinking leads one to believe that the market will take care of this, provided that goods in the market are priced appropriately. This may indeed be true in theory, but appropriately pricing market goods has been difficult to do in practice.[4]

For resources that we do risk exhausting, being able to predict when this will happen (and for which resources) is not easy, but several researchers have attempted rough estimates. Meadows et al. (students of Forrester[5]), through their work with the Club of Rome, may be best known for making the case for global environmental system limits – and the exceeding thereof, termed 'overshoot' – though not without controversy.[138] Whether or not you agree with their modeling methods and/or conclusions, human well-being is dependent on the preservation of the global ecosystem in many ways, the most obvious of which is the global climate system.[109] Interest in modeling system limits and the risk of overshoot persists, most recently with the HANDY model of Motesharrei et al..[140]

Counterfactual, where art thou?

There are limits to the resource use-driven burdens that the human system can place on the global ecosystem without breaking it. One of the primary challenges of sustainability is that it is difficult to measure, because it is hard to predict with any real certainty when we will reach those limits. Evidence of the pressures that human society is placing on natural systems continues to mount,[107] but we are forced to measure progress towards a sustainable society against a hypothetical baseline. Having at this point identified sustainability as a worthwhile enterprise, we will now never know what the world looks like absent some consideration of sustainability in decision-making around the world.

[4] See: all of the UN climate change negotiations to date.

[5] Forrester was among the first to attempt to model the dynamics of the urban system, focused primarily on topics of interest to urban economists (see Section 2.1), though his model is based largely on intuition rather than grounded in theory.[62]

Absent predictive capacity with respect to system limits, and without a meaningful benchmark against which to measure our success (or lack thereof), it will be a huge challenge to guide development in such a way as to ensure that we do not come upon these limits too suddenly. Many of the complex systems that together make up human society may be resilient even to rapid changes, but gradual change is in general preferable to sudden or dramatic shifts in resource availability. Facilitating a transition towards a less resource-demanding global economy should be an overarching priority, and will be eased by proactive efforts.[146]

1.2.2 Urbanization

The city provides a particularly useful lens for approaching these challenges. While more attention has been paid to national and international governance, this higher level approach has thus far been impeded by political and institutional barriers, largely due to concerns on the part of the three countries with the most at stake in such discussions – the USA, India, and China. While these efforts are worthwhile and should be pursued aggressively, parallel efforts at the city level can be valuable for three primary reasons.

First, local decision-making is generally more agile when it comes to progressive and/or experimental policy implementation. While the stakeholder networks remain complex and monied interests are often powerful, the institutional barriers are nonetheless lower than at the national scale. Urban policy-makers have a relatively direct connection to their constituency and as a result may more urgently feel (and see) the need to improve sustainability outcomes, especially when they are tied directly to constituents' quality of life.

Second, cities are largely responsible for the implementation for regionally, nationally, or internationally mandated sustainability efforts. Many national and subnational policies ultimately require local government action and/or oversight.

Third, energy use and its resultant air pollution, including greenhouse gas emissions, are concentrated in cities, alongside the economic activity that demands it. About 75% of energy use takes place in cities [87] in spite of the fact that carry just slightly more than half of global population.[185] Similarly, roughly 80% of global economic activity is generated in cities, where wealth creation also outpaces population growth.[80, 22] Cities, in short, are much more than the sum of their parts, reflecting the phenomenon that urban economists refer to as agglomeration.

Agglomeration leads them to consume much more than they produce, making cities problematic.[158] There are spatial organizations of humanity that would likely result in lower environmental impacts – Odum and Odum explore some alternative possibilities, for example.[146] While these thought experiments may prove fruitful in the long term, cities are the short term reality. No matter your feelings about cities as an artifact of modern human civilization, we are already seeing the consequences of short-sighted development and the burdens of large-scale retrofitting, urban redesign and infrastructural repair.

For these reasons, in many respects global sustainability will live or die in cities. The topics I explore in this thesis are intended to be applicable to cities in general, but the cities that stand to benefit most from this work are those whose supporting infrastructures remain largely unbuilt, and which will house the multi-billion person increase in urban capacity anticipated in the coming decades.[185] It is for these cities that infrastructural lock-in is still avoidable; path dependency is most easily affected in cases where the path has not yet been built. This period of urbanization may not be repeated, so we may not have another opportunity at this scale after this, the "urban" century.

These as-of-yet smaller cities present substantial challenges. Key questions regarding how sustainable urban infrastructure can be financed given limited local resources; how to build institutional and technical capacity in small but rapidly growing cities; and how to integrate sustainable practices into other aspects of development without disrupting them must be addressed in the very near term. We will not have another opportunity to get them right the first time.

1.2.3 Globalization

The urban economies that drive cities' progress are as varied and complex as the groups of people, firms, and government actors that comprise them. Globalization is the fundamental enabling condition for the stark differentiation of these urban economies that makes direct, 1-to-1 comparisons inadequate, generally speaking. Understanding the impacts of trade, which is regulated primarily at the national level, will be essential to understanding the global sustainability implications of local resource consumption and production patterns.

These trade dynamics are clearly visible in this work, though they are not its primary focus. The implications of trade patterns in the globalized economy are that we can in effect only measure changes in sustainability at the national/regional scale (basically, as far as sound trade data allow), and only absolute sustainability at the global scale; everything less is merely relative.

But relative to what? Benchmarking cities against other cities, countries against other countries, or companies against other companies provides an opportunity to share best practices, promote and share successful efforts, and outwardly grow a city's reputation. Increasingly, due to the challenge of making meaningful comparisons between cities with respect to sustainability, practitioners are focused on comparing current efforts to past performance. This is hardly a revolutionary idea, and at first glance may even appear to be a step backwards in sophistication.

A "keeping up with the Joneses" approach remains more common, and it does have distinct benefits. Learning from others' experiences is not only natural but a necessary exercise in informing sound policy. Demonstrated successes form the backbone of many arguments for sound policy, environmental and otherwise; in cities and beyond. But for the examples of these 'model' cases to be used effectively, context must be considered thoughtfully. The level of nuance required can easily get lost in a sea of comparative metrics and (in the case of urban sustainability) various green city indices that seek to compare cities using a single number. When different sectors of the urban economy are weighted arbitrarily in such indices, incentives for sustainability improvements become distorted, to the extent that any relevant municipal stakeholders take them seriously.

1.2.4 Development

The general tension between development and sustainability may be the most fundamental dilemma for climate change mitigation efforts. On the one hand, we have the impending threat of climate change. On the other, there are still more than a billion people who still lack reliable access to electricity.[151] Many of these people live in cities, at times within a stone's throw of electricity distribution lines and other infrastructure built to service the wealthy.[164]

The first priority of development efforts must be improving the well-being of the world's poorest citizens, but sustainability principles should be adopted in any and all situations in which development outcomes may be minimally affected by their inclusion. This is a delicate and difficult balance to strike. A focus on cities provides some reason for optimism however, as urban areas tend to draw poor citizens with the allure of economic opportunity.[80] Knowing that there will be an influx of population to cities as economic development processes progress, low-, no-, or hypothetically even net negative-cost urban policy and design interventions (altered zoning restrictions, master plans, and certain tax policies, or choice infrastructure investments, to name a few) can ease the environmental pressures commonly associated with development and increasing incomes more generally.

In many ways, the root cause of our sustainability challenges is population growth. The combination of sheer number of people and their spatial distribution across the globe creates these challenges, in some cases distributional and in all cases complicated. Policies for population control are uncommon, and by most policy-makers viewed as off-limits – China's one-child policy (which was recently relaxed[36]) being by far the largest and most widely known exception. Population growth should be treated as an exogenous (given) parameter, while acknowledging that increased incomes, education, and access to birth control will reduce birth rates in the longterm.

1.2.5 Technology

Being in a masters program called "Technology and Policy", I would should make clear how exactly my research is related to technology, as this may not be obvious. Urban infrastructure is a clear example of Verbeek's (2006) conception of technology as policy, inasmuch as urban infrastructure is a human artifact (in many cases one that is explicitly technological – a traffic network, for example) that limits our ability to change development trajectory. Such dependencies are also visible in economic path dependency, which can itself be in no small part a result of technological lock-in, as in the case of industries that rely on large or expensive machinery to support their operations and, as such, are costly to relocate.

Lock-in

The concept of lock-in – akin to path dependency, and general stubbornness to change – is fundamental to this research effort, and comes in many shapes and sizes. In cities, pervasive highway infrastructure makes it hard to transition away from energy- and carbon-intensive driving habits. Energy inefficient building stock is costly to retrofit and requires the mobilization of a distributed group of property owners and tenants.

These are just two urban examples of what Unruh refers to as carbon lock-in [188], a broader challenge for sustainable development. Carbon lock-in is the particular case of lock-in due to carbon-intensive infrastructures. It is also worth noting that not all lock-in is technological: the institution of urban planning has been accused of forming unhealthy habits of practice in the past[110]. Planners remain imperfect to this day.

Avoiding this lock-in of carbon-intensive infrastructures and institutions should be a primary concern of urban planners and policy-makers more generally. Responsible stewardship of the environment is increasingly tied to our careful stewardship of cities. The decision-making process of planners and policy-makers should strive to minimize the resource demands (and potentially adverse social impacts) of growth, with particular attention to considerations of institutional and infrastructural lock-in.

Techno-optimism

There is sometimes a tendency to assume that technology will come to the rescue in the end; that innovation will save us from ourselves. I consider myself an optimist, and as such might be at risk of sympathizing with this worldview; however, I find it to be a particularly dangerous one. There is no question that technology in the form of fuel efficient cars, various ICT platforms, and the smart grid, will make urban life more resource-efficient; more sustainable. But this 'techno-optimism' is an especially risky form of moral hazard, whose proponents – and forgive me if this sounds overly dramatic – appear willing to "bet the farm", where the farm in this case might alternatively be described as "the fate of human civilization as we know it".[109]

1.2.6 Policy

In terms of affecting sustainability outcomes, policy-makers control the most important levers. They do not wield their power alone, nor do they operate in a vacuum, but they are the stakeholder group empowered with the greatest influence in matters of sustainability. With great power, as they say, comes great responsibility, and policy-making brings with it a constant fear of unintended consequences in spite of (generally) good intentions.

The goals of public policy might be divided into the four goals of equity, efficiency, security, and liberty.[175] Sustainability may or may not deserve an explicit place on this list, but it should be understood as a fundamental requirement of the urban or any other human system. Policy-makers ought in theory to be concerned with the continued flourishing of their constituencies – but reality is rarely so simple. The long-term risks associated with climate change are not evenly distributed throughout the world, so incentives for sustainability policy-making are spatially inconsistent. Distribution of the risk associated with climate change inaction runs across generations, making it temporally inconsistent. Finally, our understanding is inconsistent, with respect to how the activities of a given city impact global sustainability.

For these reasons, in my focus on policy for urban sustainability outcomes I will not limit myself only to a discussion of local government policy. National and sub-national governments also have key enabling roles to play, and many sustainability outcomes (especially in the presence of collective action problems [149], pervasive in the sustainability context) would be improved by regulation at larger scales. Similarly, policy in an equally meaningful sense may be enacted at the level of an industry, or even by an individual firm, and the role of such informal, often voluntary policies should not be ignored.

1.2.7 Design

The extent to which these policy outcomes are achieved depends on the success of two design processes: those that inform the choice of the policies themselves, and those that take place within the context created by those policies. The design of 'good' policy is a complex and iterative process, generally involving many stakeholders.[175] Anyone hoping to influence policy must keep this messiness squarely in mind.

In the dialog surrounding environmental sustainability, the second design process has perhaps been neglected as a point of leverage. A focus on designers, in the more traditional sense, does seem inefficient when compared to the top-down policy approach, but this is part of a trade-off between messiness and labor-intensity. Improving the design process of a single designer will in general not take a lot of work, but countless designers are collectively responsible for the buildings, streets, and landscapes that ultimately comprise the physical space of cities.

Whether planning cities, neighborhoods, individual developments, buildings, or interior spaces, someone – in most cases, a collection of people – decided to orient the built environment in this particular way. The same can be said of transportation and electricity distribution networks, other infrastructure systems, and the internet.

These design choices are what policy ultimately hopes to influence, but a bottom-up approach prioritizes the actors who wield the most direct influence over the system in question. These two approaches (bottom-up and top-down) are not mutually exclusive, however, and should be considered as complements rather than substitutes.

1.2.8 Transition

Because the notion of sustainability is on the one hand normative (something we *should* strive for), and on the other hand hypothetical (something we have *not yet observed*), it is a concept that lives in the future. While we have a rapidly growing understanding of what it would mean for different types of systems to be sustainable, our understanding of how to achieve such 'sustainable' outcomes is relatively limited.

One reason for this lack of understanding is a dearth of longitudinal evaluation. Long-term sustainability studies are uncommon, in large part because sustainability science is such a young field. Sustainability and 'unsustainability' are also both notoriously difficult to identify without the perspective of hindsight.

So in order to understand the ways in which sustainability is changing, in most cases we need to somehow make due with what we've got. The change we want to understand is two-fold, with the first being a descriptive knowledge of historic sustainability changes, to serve as a performance baseline of sorts. The second and more important (though in part reliant on the first) is understanding prospects for change moving forward. These opportunities to alter the trajectory of our resource use provide the greatest hope for minimizing humanity's environmental footprint.

Actually effecting change in the real world may require a different knowledge set altogether; one that would provide a necessary and practical complement to the understanding of sustainability dynamics. Even with a perfect understanding of what types of change are hypothetically possible and which of those is desirable, achieving such desirable options is rarely straight-forward.

Understanding historical change, identifying prospects for future change, and understanding mechanisms for effective change are all aspects of *transition*, the process of change in a system's properties over time. Transition is, as this description suggests, a general concept focused on systems change. A *sustainability transition* is such a change that results in an incremental reduction of resource intensity. The ability to selectively pursue sustainability transition is the name of the game. This transition can occur at many scales, and in fact we would probably like it to occur at all of them, to the extent possible.

While it may be possible for the more general notion of transition to be considered objectively, *sustainability* transition is a normative concept. I do not think this is a bad thing, but to nonetheless defend my focus on this normative goal, I assert first that sustainability (all else equal) is an objectively 'good' thing. It is good when we do not run out of resources; money; well-being. Second, and relatedly, the need for sustainability is absolute in the long term, by definition, and thus a transition towards sustainability is inevitable if humanity is to flourish.

1.3 Magnitude

This section begins with a brief history of this thesis' evolution, particularly in the context of our group's research agenda. I then pose two types of questions that guide this research. The first type are those that cannot be answered by this thesis alone; these are the fundamental questions that motivate my research. The second type are those questions to which my thesis directly contributes.

1.3.1 History

Here I briefly discuss some of the origins of this work in the context of the Urban Metabolism Group's broader agenda, as background for the finished product that follows. I also highlight pieces of an aspirational vision that may inform future research efforts.

The fundamental inspiration for this research is the global urban resource typology compiled by our group.[162, 59] To arrive at this typology we group 131 cities according to nine resource use indicators derived from year 2000 data, identifying eight distinct clusters (or 'types') visualized in Figure 1-1. The resource use profile of each cluster is defined by the average resource use of between 4 and 29 cities, depending on the cluster. The arms of these 'radar' plots are proportional to the mean of each resource's use across the cities contained in a given cluster.[6]

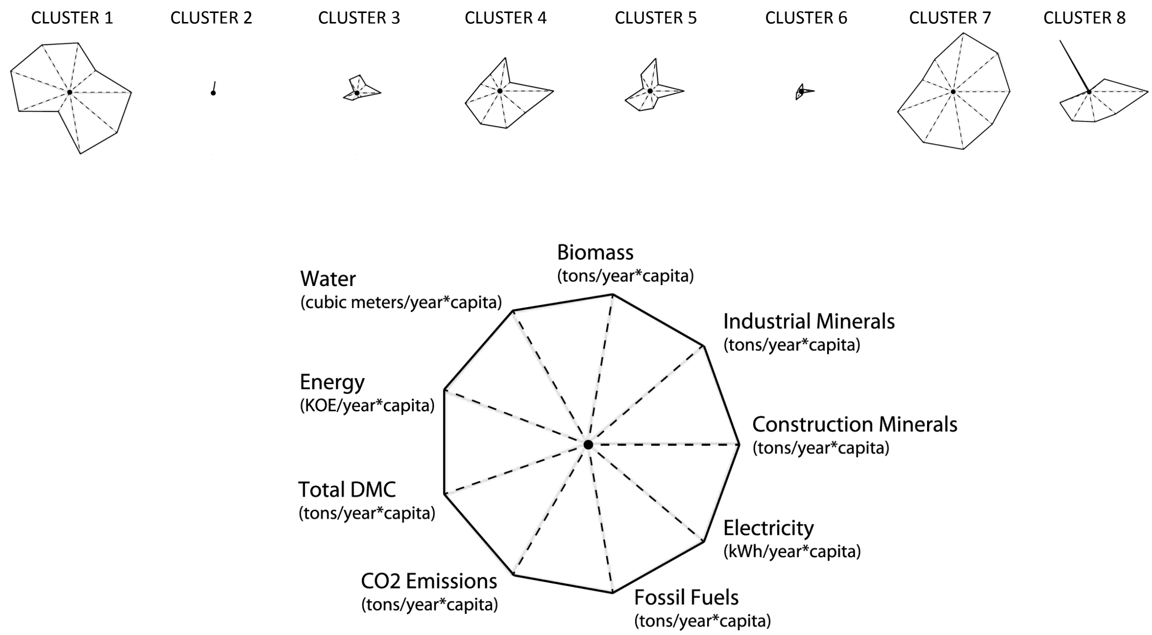
Upon examining these results my first question is, to what extent are these distinct groups (observed at a snapshot in time) reflective of urban development's long-term resource use trajectory? How consistent is that trajectory across cities in different regions, developing at different times? A development model that proposes distinct stages of growth with distinct resource use profiles is not new (see, e.g. Berkhout et al. [18], Niza and Ferrão [143]), but I propose distinguishing between development stages *on the basis of* their resource use – a slightly different proposition. I will refer to this idea as the stage-model development hypothesis. This stage-model development hypothesis motivates the clustering analysis, as a means of identifying such resource use stages (see Section 4.1), and informs both the framework (presented in Section 4.2.1) and the speculative transition dynamics discussed in Section 5.1.

After conducting earlier versions of the clustering analysis in early fall of 2013 the next question became, what might cause or allow a city to move from one such stage to another? This motivated the qualitative analysis, which I began planning in October. In the end I was able to spend six weeks in Beijing developing the qualitative analysis and conducting the bulk of its interviews.

This thesis falls under the umbrella of the Urban Metabolism Group's broader interest in understanding the way that resource use in cities differs between cities and changes over

[6] The methods used to generate these 'radar' plots are similar to those that I utilize in my analysis; for a more detailed explanation of how to interpret them, see Section 4.1.1.

Figure 1-1: Global urban resource typology results



(courtesy of Karen Noiva)

time. Two recent masters theses use a system dynamics approach; Quinn (2008) to explore the resource consumption of housing in New Orleans, and Noiva (2011) to model changing water consumption in Singapore.[155, 145] In a third, Saldivar-Sali (2010) constructs the first iteration of the global urban resource typology mentioned above, using a classification tree analysis. This work has since been further refined, yielding the results presented [superficially] above.[162] The typology results are also presented by Ferrão and Fernández in *Sustainable Urban Metabolism*.[59] In his dissertation, Quinn (2012) uses a spatial approach to model energy and material use in cities.[156]

The notion of transition adds a new dimension to this exploration. Early on in this project we discussed the much grander aspiration of developing a process schematic of urban development. It is clear now that such a project will require quite a few more masters theses; my thesis serves as a small step towards this rather lofty goal.

1.3.2 Motivating questions

How does resource use change as cities develop? What constitutes a meaningful transition in urban resource intensity? How could one measure such a transition?

Which policy levers are available at different levels of governance to effect transition towards lower resource use in cities? In the face of rapid economic and population growth, what urban planning and policy decisions will minimize environmental impacts of growth without impeding development?

1.3.3 Thesis questions

In spite of the fact that I cannot provide answers to the above questions, here are the two that I hope to most directly address, through my quantitative and qualitative analyses, respectively.

> How does resource use in the building sector vary over time and across Chinese provinces, and can we see evidence of development 'stages' in that variation?
>
> Which actors influence the resource intensity of the Chinese building sector, and to what extent?

Chapter 2

Literature

Cities around the world are growing in population, physical size, and economic importance. With cities already accounting for about 70% of global greenhouse gas emissions [105, 106], more than a billion new urban inhabitants projected by 2030 [185], and incomes rising alongside this urbanization, sustainable urban development has never been more important. Our understanding of what sustainable urban development looks like, and how to do it, is rapidly evolving.

Urban metabolism can be a useful metaphor for understanding sustainability in the urban context. The metabolism of a city can be thought of as all the activities in that city that contribute to its material and energy use. It is natural, and indeed useful for most people to think of these activities in economic terms. After all, it is the urban economy that draws people to cities in the first place, in search of the employment opportunities (not to mention other benefits) that arise due to agglomeration effects.

Different types of urban economies have different implications for urban resource use. We are slowly building an understanding of the ways that cities use resources in different types of economies and the way that this resource use may change over time. Towards this end, many literatures contribute to understanding some of the mechanisms by which resource use may be guided toward some normative end goal; namely a more sustainable one.

The lines between city-focused disciplines is frequently blurry, and this literature review will follow suit. I will still provide disciplinary headings, but they are more guidelines than rules. In sequence, I discuss urban economics, urban planning, urban metabolism, urban typology, sustainability transitions, and Chinese buildings. This last section also serves as the primary background for the qualitative analysis in Chapter 4.

The common thread throughout this chapter is urban resource consumption, to which each of these research areas directly contributes. In this chapter I draw connections between these literatures and lay out the foundations of knowledge on which this thesis is built.

2.1 Urban economics

Cities greatest strength and weakness is agglomeration, which is simultaneously the reason that the size of urban economies scale super-linearly with population and that serious crimes do, too.[22]

Urban economics is relatively young and has made significant contributions to our understanding of development. The field has focused significantly on understanding the basic dynamics of urban land use and transportation choices, and their impact on individual and firm behaviors.[125, 68] One of the more thorough reviews of cities' role in the economy is provided by Glaeser, who argues that an increased focus cities has the potential to solve many of society's ills. Glaeser tells us that at their core, cities are about people, and namely bringing them closer together. With an abundance of small, innovative firms; strong educational institutions; less restrictive zoning requirements; and high densities, cities can flourish not only economically but sustainably, as well.[80]

Urban economics more generally provides tools for exploring the externalities that result in large part due to cities' high population density. Of these externalities, congestion may be the most often studied, though there is a growing understanding of sustainability impacts as well, both in terms of greenhouse gas emissions[82] and public health outcomes more generally.[25, 17] Economics more generally also provides many useful tools for the consideration of urban development. One of those is the concept of the Kuznets curve,[126] which Grossman and Krueger [86] apply to environmental impact, proposing that environmental impacts first rise, then ultimately fall over the course of development. If this hypothesis is true, then a key task for sustainability advocates is to identify the conditions that enable moving beyond the threshold after which environmental impacts of interest begin to decline, then recreate them on an accelerated time scale.

There are plenty of observed examples that seem to support the environmental Kuznets curve hypothesis, but also some notable skeptics of the theory.[172] Ooi is among those who attempt to discredit the environmental Kuznets hypothesis, in this case by using air pollution data from Southeast Asian cities.[150] This analysis shows that decreases in pollution do not necessarily correlate to higher incomes, though it is hard to conclude that this refutes the Kuznets hypothesis, as it may merely reflect the fact that these cities have not reached the threshold beyond which pollution would be expected to fall. Further, it may well be the case that Kuznets curves take on different shapes for different cities, and even for different economic sectors within cities. For example Fernández, writing with respect to the Chinese context but using generalized principles, proposes that a similar curve for building materials use may more likely rise and fall slightly before stabilizing to reflect the continued need for maintenance, repair, and rebuilding of the urban built environment.[57]

Urban economics also highlights that competition between cities can lead to economically inefficient outcomes. For example, disparate tax rates in adjacent cities may lead to undesirable outcomes that may be addressed by either common governance or a standardized tax code [30], which is a result worth keeping in mind in discussions of local as opposed to national or subnational governance of financial and environmental challenges alike. For example, inconsistent pollution regulations may incentivize industrial relocation from areas with strong to areas with weak pollution control policies. Holmes makes an argument in favor of standardized tax codes in the context of state policy in the US and its influence on the location of manufacturing firms.[99]

Glaeser provides an useful overview of local versus national governance and other urban policy debates, including those surrounding land use regulation, private versus public service provision, and various approaches to mitigating the negative consequences of density.[81] Bulkeley undertakes a more thorough discussion of urban governance as it pertains to climate change in particular, concluding that while urban governance offers potential for effective and novel approaches to climate change mitigation and adaptation alike, a 'stubborn gap' remains between cities' rhetoric and action on these matters.[31]

2.2 Urban planning

Urban economics in many respects shares an agenda with urban planning, a discipline that dates back to the first human settlements.[1] Economists and planners are both ultimately concerned with peoples' well-being. For economists, this might mean maximizing aggregate utility to achieve economic *efficiency*; for planners, *livability* and *accessibility* are two concepts that underlie much of dialog about designing 'good' cities.

Neither word is easy to define. Partners for Livable Communities define livability to be "the sum of the factors that add up to a community's quality of life—including the built and natural environments, economic prosperity, social stability and equity, educational opportunity, and cultural, entertainment and recreation possibilities."[152] This definition suggests the essential importance and sweeping generality of the concept, the latter of which makes it somewhat intangible.

Accessibility might be considered a subset of this more general 'livability' ideal, and has been operationalized in an assortment of creative ways. Lynch (1984) discusses the broad theory of access including its various components, available approaches to improving access, and some of its social dimensions. For Lynch, the three key components of access are diversity (of things to access), equity (of access across different social groups), and control (of the accessed systems), which when considered together make clear how variable accessibility might be even within a single city.[133] Geurs and van Wee (2004) have conducted a more recent review of various accessibility indicators, and emphasize the importance of accounting for transport, land use, and temporal components of accessibility in such indicators. While this inevitably increases these indicators' complexity, the authors have a few practical suggestions to ensure that their interpretability is preserved.[77]

[1] The earliest known such settlement is in Turkey, and was formed roughly 10,000 years ago.[135]

Much of modern urban planning takes place under the banner of New Urbanism, which in large part originated with Jane Jacobs' urban manifesto, *The Death and Life of Great American Cities*. Jacobs puts forth basic principles for sound urban design, including mixed uses, fine urban grids, and sufficiently dense development to ensure a vibrant streetscape. Strategies for minimizing the environmental footprint of cities (while maintaining livability) are surprisingly well agreed upon in urban planning communities, and bear a striking resemblance to the principles of good city building put forth by Jacobs. It is also worth noting that Jacobs' work focuses in large part on the importance of strengthening neighborhood economies within cities, as she emphasizes the relationship between a city's design, its productivity, and its residents' well-being.[110]

The rigorous, quantitative study of these strategies is a relatively recent development, so proponents of high density, mixed use development cannot yet claim absolute victory. Nonetheless, these two guiding principles, supported by strong public transportation systems, do appear to be relatively robust in promoting sustainability, and are commonly bundled together under the umbrella of 'smart growth'. Indeed, in a report issued by the Urban Land Institute, Ewing et al. conclude that the US is unlikely to meet its climate change mitigation goals absent a comprehensive smart growth agenda to reduce urban carbon emissions.[54]

The spatial layout of a city, its urban form, is also a strong determinant of its resource use. While urban form may also have indirect impacts on building energy use itself, the influence of urban form on resource use has been explored primarily in the context of its effect on travel behaviors. This relationship is highlighted in the work of Newman and Kenworthy, who identify an inverse relationship between population density and vehicle miles traveled across a sample of global cities.[142]

Further evidence has born out that urban form and transportation behavior are tightly interrelated, but the precise relationships between the two systems remain largely unknown.[41] Planning research continues to shed new light on the subject, however. Ewing and Cervero, for example, find that the combined impact of various built environment measures can be significant with respect to influencing travel behaviors; they go so far as to estimate travel elasticities for several built environment measures.[55]

Scholars of the built environment-transportation relationship and the gospel of smart growth more generally tend to pit urban development against its suburban counter-part, with suburbs in the developed world commonly representing all that is bad and wasteful in urban planning. The phenomenon is real: Kim (2007) has examined urban density gradients historically in the US context, showing monotonic declines over time.[122] Suburbanization's causes are many, but among the enabling conditions is the construction of highway systems that ease commuting from areas with low-cost land.[14]

Planners and economists alike are surely searching for opportunities to conduct the equivalent of a randomized experiment – or even to find a reasonably good natural experiment –

in urban design. The nature of the planning process does not lend itself well to experimentation for the sake of learning, and perhaps more importantly comparing two neighborhoods within a city, let alone neighborhoods in two different cities or comparing cities themselves, introduces enormous barriers to drawing generalizable conclusions. The collection of often subtle traits that when taken together give each city its unique character, fascinating countless urbanophiles and world travelers, makes them difficult to study as a general phenomenon – returning to the dilemma of counterfactual comparison posed in Section 1.2.1.

Geography can also be an influential factor in determining resource use. Physical geographical constraints artificially increase the densities of many of the world's cities perceived to be most sustainable, for example New York City, Singapore, and San Francisco. Most of the 'sustainable' cities in Europe were constructed primarily under the implicit geographic constraints imposed by the absence of modern transportation options capable of facilitating long commutes. Geography also influences climate, the single largest determinant of building energy use.[119]

2.3 Urban metabolism

Urban metabolism – as a metaphor and phenomenon – presents a unifying framework that enables a holistic understanding of resource use in cities. All of the activities above (and all the others that take place in cities, in theory) may be thought of as components of the city's metabolism, and the sum of their environmental impacts constitutes the environmental impact of the city itself. Urban metabolism as a phenomenon is not tied to any particular methodological approach, though it is most commonly operationalized as material flow analysis at the urban scale.

The concept was born in a 1965 paper from Wolman, which imagined the resource flows necessary to support a hypothetical city of one million people.[197] While full metabolic accounting has only been conducted for a small handful of cities (e.g. Barles [13], Niza et al. [144], Yang et al. [202]), the metabolic metaphor has informed the study of urban material and energy flows, particularly in the realm of greenhouse gas accounting.[45, 120] The study of these resource flows has also expanded to take into account some of the more complex aspects of urban development,[59] and to engage different stakeholder groups in the analytical process itself (e.g.Ramaswami et al. [157]).

As a direct consequence of their high population densities, the ecological footprint of cities extends well beyond their administrative boundaries and into the surrounding hinterland. This creates a spatial challenge in accounting for environmental impacts. Vandeweghe and Kennedy [191] and Glaeser and Kahn [82] each use census data (the former Canadian; the later US data) to analyze the spatial dimension of per-capita greenhouse gas emissions as you move from the center of cities into the suburbs, both finding that emissions tend to increase away from city centers.

Where granular spatial data are not available, one must choose an appropriate boundary for her urban metabolism analysis. This choice of boundary presents a significant methodological challenge, especially because data availability often constrains that choice absent some form of data scaling. Data scaling often requires fairly significant assumptions, but some consistencies in urban scaling properties, with respect to population at least, have been identified by Bettencourt et al.[22, 23, 21] Ultimately, different choices of urban boundary tell different stories, each of which can be useful depending on the analytical context.[35]

Boundary considerations quickly give rise to the challenge of accounting for trans-boundary resource flows. For example, how should individual cities account for emissions that result from the production of material goods that will be consumed elsewhere? Chavez and Ramaswami (2013) highlight three approaches to urban greenhouse gas footprinting and propose a simple typology of cities on the basis of whether they are net importers or exporters of embodied greenhouse gas emissions.[35] Such a distinction can be useful at other scales as well (e.g. provincial, regional, national). Greenhouse gas inventories are not the only means of benchmarking urban sustainability – a growing list of organizations and researchers have proposed alternative sustainability indexes comprised of various indicators (e.g. EIU [53], UCI [184]).

In light of data limitations and the challenge of choosing an appropriate boundary, Singapore provides an interesting case study as an urban nation-state, for which trade is measured in a fairly comprehensive and detailed way, and in time series no less.[166] In his study of Singapore's metabolism, Schulz concludes that material *input* is a better predictor of GDP growth than material *consumption*, and does not observe the dematerialization of the Singaporean economy up to the present.[166] Singapore's history, governance, location, and the heavily trade-dominated nature of its economy limit the generalizability of results derived from its study. One other study from Decker et al. (2000) considers resource use over time, concluding that after long periods of growing resource consumption, some developed cities show signs of stabilization in their resource consumption.[2][45]

Because historical metabolism-relevant data (often derived from trade accounting) are predominantly available for countries rather than cities, others have conducted thorough comparative studies mostly at the national scale. Such analysis can be useful for this thesis for two primary reasons. The first is that cities may in some cases (generally less explicitly than for that of Singapore, however) behave like small countries, from a socio-metabolic perspective; and the second that an understanding of the broad socio-metabolic trends identified in Krausmann et al. may provide a theoretical foundation for the understanding of changing material use in cities.[124]

While pre-industrial lifestyles allowed people to more or less continue 'living off the land',[124] modern cities concentrate people in a way that cannot be supported by the ma-

[2]This could potentially represent the beginning of a transition in line with the environmental Kuznets hypothesis.

terials and energy available within the urban boundary.[158] Thus, if you define sustainability as the ability to subsist while using no more physical space than your ecological footprint permits, cities are decidedly incapable of being sustainable. In light of this, Odum and Odum (2006) have imagined futures in which human settlements must be located near hydropower resources and other convenient geographic features, in concentrations sufficiently small as to allow the immediate surroundings to support those settlements, without the need for such complex international trade and electricity transmission networks, for example.[146] Some components of this vision, ultimately one of absolute urban self-sufficiency, may be fulfilled by practices like urban farming, or Graedel et al.'s "urban mining".[84]

Sustainability is ultimately determined at a global scale, so the spatial imbalance of resource use in cities is not inherently problematic. Challenges of spatial concentrations of populations persist and must be addressed. We may only be able to judge the sustainability of cities ex-poste, as we do not actually know for certain what 'sustainable' resource use looks like – only that we cannot consume at a rate faster than the natural system can replenish in the long-run, and that we need to achieve sustainable resource use sooner than later. We have strong indicators that current practices are unsustainable (by observing impacts on the global climate system, e.g. IPCC [107]), and a reasonably good understanding of the challenges at hand, as well as some of the practices that would be more sustainable.[119]

Where does this understanding bring us? The city is an essential point of intervention in climate mitigation discussions, and there is opportunity to reduce carbon lock-in through urban planning interventions in the cities where this massive development will take place.[7] To avoid the carbon "lock-in" that may be associated with various development patterns or infrastructure investments,[188] local planning strategies must evolve to account for the global, long-term consequences of their decisions.[8]

This is easier said than done. Bai (2007) outlines two major barriers to using a global lens to frame local decision-making: the 'scale' and 'readiness' arguments. Scale arguments may be comprised of spatial, temporal, and/or institutional considerations, all related to a perceived lack of jurisdiction.[3] For Bai this set of arguments ultimately boil down to to a lack of understanding the potential co-benefits of climate action and local governance. The readiness argument contends that there is a lack of capacity at the local level to deal with these global challenges.

To address these [often legitimate] concerns, Betsill (2001) has argued that local policies addressing global issues still must be advocated using a "think locally, act locally" approach, which justifies decision-making primarily on the basis of local benefits. Bai agrees, with the caution while this is for the most part true even in the developing world, issues of unintended and net climate-adverse impacts are a distinct possibility in contexts where stark differences in the status of urban and rural development persists.[8] Cities in large part arise precisely because the incomes of their residents are so much higher than those of residents in rural

[3] e.g. "It is not our place to meddle because _"

areas. Incomes in cities are generally higher than in their hinterlands and rural areas, even when accounting for increased costs of living.[80] This is an especially critical point for consideration in the developing world, where the difference between rural and urban life is often the difference between extreme poverty and opportunity.

Greenhouse gas emissions can be mitigated in cities as at the national level by using explicit greenhouse gas policy like cap and trade or a carbon tax, but many alternatives are available that are more in line with the "think locally, act locally" approach. The list of complimentary policies with other environmental and/or economic benefits continues to grow, with particular opportunities in other air pollution controls (e.g. Yedla et al. [203], Matus et al. [137]).

The design of cities themselves is increasingly recognized as a key component of comprehensive greenhouse gas mitigation strategy, as scholars and practitioners alike have increasingly called for urban metabolism as a potentially important tool in guiding sustainable urban planning and design (e.g. Fernández [58], Kennedy et al. [118]). This design comprises not only the planned layout and urban form of a city, but also the design of supporting infrastructure systems on a larger scale as well as the design of individual buildings on a more granular one.

Infrastructure has been increasingly a focus of researchers interested in urban sustainability.Hodson et al. (2012) argue for a focus on urban infrastructure from a materials flow analytical perspective.[97] And indeed, some work on this subject has been undertaken. Kennedy et al. (2009) review best practices in urban infrastructure performance from a greenhouse gas mitigation perspective, though available data are limited. In a separate study, Chavez and Ramaswami (2013) propose a definition for what exactly constitutes an "essential" urban infrastructure system, and conclude that those systems that meet their criteria[4] include the provision of electricity, fuel, food, cement, iron/steel and water/wastewater.[35]

While most urban metabolism work has focused on improving understanding of individual cities, there has been an increasing focus on comparing resource use across cities (e.g. Kennedy et al. [120], Sovacool and Brown [171], Hillman and Ramaswami [95]). While these studies are a good starting point, they do not account for the fact that many of the cities being compared are fundamentally different. To help determine when cities are comparable, and in what respects, it may be useful to categorize cities into narrower groups, within which comparison makes more sense.

2.4 Urban typology

In all comparative studies, variability across cities and across the regional/national contexts in which they operate presents a significant challenge in drawing general conclusions. For

[4] Primarily the correlation between provision of each given type of infrastructure and GDP, as a measure of 'community productivity', though an exception is made for water/wastewater, which does not meet this criteria

this reason, it can be useful to separate cities into groups within which comparison is easier. This is convenient for the study of urban resource use as a phenomenon, but may also be important in terms of developing a taxonomic understanding of policy applicable to cities of different 'types'. Such understanding must always be applied with an understanding of context, but can potentially be facilitated by understanding these different 'types' of cities, to the extent possible, as a baseline. A typology broadly could be the result of any attempt to organize cities into groups on the basis of some set of characteristics. There are many possible such characteristics, including on an economic, demographic, geographic, or structural basis, for example.

There are many ways to distinguish between cities, and as such there will never be a single, definitive typology. Previous efforts have focused primarily on cities' economic attributes. Modern city classification work dates back to at least 1937, when Ogburn looked at the social characteristics of cities.[147] There seems to have been a fair amount of interest in economic classification in the late 60s/early 70s, including work that anticipates the significant power of population in predicting the qualities of different cities.[88] Atchley developed a typology built on indicators of both sector employment and population [5], while Jones and Jones use a broad sampling of socio-economic data from the US census and identify types supported by principal component analysis.[113]

We also see significant renewed interest in the past decade or so. Beaverstock et al. and Taylor focus on 'world cities', using different approaches the same problem – the former with a typology informed by service sector characteristics [15], and the latter using firm networks more generally.[177] Furdell and Wolman develop a sub-typology of 'weak-market' cities in the US[69], and Strumsky and Thill use a statistical approach to explore knowledge creation in American cities.[176] In general, this work appears to have been concentrated largely in the US and developed-world.

Some typologies are historically based, as in Benevolo's "History of the City".[16] Ducruet highlighted some unique characteristics among port-cities specifically.[52] Gil et al generate spatial clusters on the basis of geographic features.[79] Frenchman and Zegras (2012) have done some interesting work developing neighborhood scale typologies in Jinan, China.[65] The notion of typology is perhaps strongest in the architecture and urban form literature, making the extension to the larger, city-level scale a natural one.

Florida provides a quasi-typology of a different sort, distinguishing between cities based on their appeal to certain demographic groups, namely his proposed 'creative class'.[61] Another qualitative approach comes from Bai and Imura, who propose a stage-model of urban development comprised of four conceptual stages of urban development. This work also introduces a temporal component to typological research, and explores transition in urban systems. The staged progression is formed on the basis of local priorities, beginning in a state dominated by concerns regarding urban poverty, moving to one focused on addressing industrial pollution, to a third focused on reducing consumption, and finally to a hypothetical eco-city state. In Bai's conception of urban sustainability transitions, cities need not necessarily follow this pathway in a linear fashion and may instead skip one or both intermediate steps.[5] The example provided is Shenzhen, China, which Bai and Imura argue has largely avoided a state of concern surrounding industrial pollution by virtue of implementing an effective green growth strategy.[10]

If one considers Bai and Imura's stage-model to be a sort of typology, it is among the first to focus on resource use – even though it is more theoretical than empirical. Studies that empirically classify cities on the basis of their resource use are historically sparse – which makes sense given that empirical studies of urban resource use are relatively new – though there have been increased efforts in the past several years. This has begun to change only recently. Saldivar-Sali (2010) and Ferrão and Fernández (2013) have developed a global urban resource typology, using classification tree analysis to divide 132 cities into groups on the basis of their resource use. Khamis, looking at cities in the UK specifically, used a similar approach.[121]

Even when focusing at the urban scale, one may still look to national-scale work for inspiration. Krausmann et al's socio-metabolic regimes are an interesting case of a resource-based typology of sorts, particularly because the 'typology' of these regimes has an explicit temporal component.[124] Another interesting approach is presented by Chavez and Ramaswami, who propose a simple typology on the basis of embodied greenhouse gas imports and exports – net-producing, trade-balanced, or net-consuming.[35]

There seems to be growing interest in this idea from practitioners as well, as evidenced by the focus on typologies in the UNEP City-Decoupling report published last year,[187] and in a 2010 report from KPMG on "city typology as the basis for policy".[123]

Besides facilitating sustainability performance benchmarking, another contribution of typology research is that it can also identify potentially interesting case studies by highlighting consistent patterns and/or outliers. A third contribution is that understanding types of cities may tell us something about the possibilities for transitioning between these types through time. This is one of our group's major interests. Finally, typologies carry the allure of helping understand the *nature* of cities, to the extent that such a thing exists.

Whether for reduced transportation costs, educational benefits, the draw of creative endeavors, or otherwise, all cities have their own attractions that contribute to unique growth dynamics. This, varying geography, resource availability, governmental structure, and other historical factors make comparison between cities challenging. Yet efforts to better understand patterns in urban development offer the opportunity to improve our ability to increase the quality of life and sustainability of cities moving forward.

[5] Bai does not consider the possibility of skipping a poverty-focused state, perhaps for good reason.

2.5 Sustainability transitions

The city is a prime example of a complex socio-technical system. A growing field of study focuses on understanding sustainability in the context of socio-technical transitions – long-term shifts towards more sustainable socio-technical systems. Focusing on urban transitions, I seek to identify characteristics of transitions that lead to sustainable outcomes.

Potential barriers to transition include infrastructural and institutional lock-in, political capture, financial constraints, technological limitation, and a host of other potential confounding factors.[136] Opportunities for sustainable transitions arise during periods of technological innovation, when the interests of relevant parties align at multiple scales.

I divide this section of the literature review into two parts. In the first I review the qualitative literature on socio-technical transition as it pertains to sustainability transition, with a focus on urban analyses. In the second part, I review various quantitative approaches to understanding sustainability transition, again with a focus on cities.

2.5.1 Socio-technical transitions

A rapidly evolving literature has coalesced around socio-technical transitions, seeking to answer questions along the lines of "What are the fundamental means by which technological change occurs?". Among the most influential theories in the area are the strategic niche management (SNM) and multi-level perspective (MLP) frameworks, the latter building directly on the former. SNM advances the idea that systems innovation takes place at the 'niche' level, where experimentation on the part of small-scale actors leads to proof-of-concept and eventually broader adoption of successful innovations. Core to the approach of SNM is the notion that these experiments can be actively managed and facilitated by system actors from governments to private companies, entrepreneurs, and NGOs.[116] The MLP, initially proposed by Geels (2002), builds on the SNM approach by proposing three 'levels' of socio-technical systems relevant to the study of socio-technical innovations: the niche, regime, and landscape – as of yet, cities' place in the MLP hierarchy is not well-established, in part because it could potentially take on the role of any of the three depending on context.[75]

Geels has published updates (e.g. Geels and Schot 2007), case studies (e.g. Geels 2006), and responses to other scholars' criticisms of the MLP theory (e.g. Geels 2010) over the course of the dozen years following its initial proposing, slightly refining the MLP along the way. Alongside the development of the MLP by Geels and many others, interest in socio-technical transitions has grown significantly and led to multiple meta-theoretical frameworks, intended to generalize the transition process. Two of these are proposed by Smith et al. (2005) and Geels and Schot (2007).

The literature of sustainability transitions is housed within the broader context of socio-technical transitions, apparently seeking to answer the slightly narrower question of "What are the means by which existing systems move towards being more sustainable?". Smith et al. propose a sustainability transitions framework that places transition pathways in four quadrants defined by two axes of internal vs. external resource locus, and low vs. high coordination requirements in terms of the steering of an adaptive system response. Their four categories of transition are endogenous renewal, purposive transition, emergent transformation, and reorientation of trajectories.[169]

One of the oft-noted limitations of MLP is that it remains poorly defined at any spatial level, which is particularly important to keep in mind when talking about a particular spatial lens – in this case, the city.[6] This has led some to propose clarifications or special cases of the MLP as applied to cities (e.g. Bai et al. [12], Coenen et al. [38]) a relationship which Geels (2010) views as taking three potential forms: (1) city as primary actor, in cases where national systems are agglomerations of local systems, (2) city as incubator of niche innovations, which are then scaled to the national level, and (3) city as having a limited role due to lack of leverage in incumbent national systems.

There is growing interest in urban sustainability transitions. *Cities and Low-Carbon Transitions* (2010) features contributions from several prominent socio-technical transitions scholars, as well as multiple case studies focused on the urban scale or within the urban context.[32] More recently, a 2013 UNEP report on city-level resource decoupling[7] draws heavily on the sustainability transitions literature.[187] The authors focus on urban infrastructures, and place emphasis on intermediary organizations as important agents of change, following Hodson et al.[97] The report frames transition pathways according to their position on a four quadrant grid defined according to considerations of "integrated" vs. "networked" systems, and new construction vs. the retrofit of existing infrastructures. Their notion of "networked" systems implies a focus on a specific type of infrastructure, while "integrated" systems require a broader approach intended to influence multiple infrastructure networks.[187]

In an earlier paper, Hodson and Marvin ask "Can cities shape socio-technical transitions and how would we know if they were?", and respond with a framework for urban socio-technical transitions. This framework is not sustainability-focused, focusing more generally on evaluating transitions on the basis of whether goals have been achieved and whether innovative practices have been institutionalized.[96]

Following the advancement of the SNM and MLP, others have more recently explored the use of experiments in influencing urban sustainability transitions, particularly in an Asian context (e.g. Bai et al. [11], Berkhout et al. [19]). Further, Bai (2008) focuses specifically on the dynamics of urban transition in China, highlighting the importance of municipal leadership, information dissemination, and citizen awareness as key to positively influence

[6] I would argue that while it is useful to understand the spatial dimension of transition, the economic dimension is likely the more dominant. Spatial distance plays a decreasing role in inhibiting transition as the economy continues to become more global. At the same time, the distribution of wealth seems to play an ever-growing part in determining resource use and social outcomes alike around the world.

[7] Resource decoupling is the separation of environmental impact from service provision; the process of enabling the same human needs to be met at a reduced environmental impact.

the transition.[9] Bai et al. have also explored dynamics of scaling experiments horizontally amongst and vertically across scales of governance through time, noting three major obstacles to vertical up-scaling (i.e. from the local to national scale) and down-scaling (i.e. from the national to local scale) of technology, institutional, and policy experiments.[12]

The concept of 'lock-in' is implicit in the MLP and permeates its structure. In Geels' conception of the MLP, the meso or regime level resists change due to the entrenched interests of the diverse actors that make up that regime.[71] Systems' natural resistance to change can be conceptualized as lock-in, and in the context of climate change mitigation as *carbon* lock-in, as in two complementary papers from Unruh (2000, 2002) that respectively explore the concept of lock-in itself[188] and potential means of escaping it [189]. The author proposes three possible escape mechanisms: (1) cost effectiveness of sustainable technological substitutes for fossil fuels (developed at the 'niche' level), (2) recognition of the adverse effects of fossil fuels, and by reasonable extension high unsustainable resource use more generally, or (3) occurrence of a focusing event that may serve as a direct and urgent call-to-action.[189]

When sustainability transitions literature is more specific, its focus often shifts to sectors and industry segments, which has potential to be useful in the urban context as local governments are increasingly encouraged to carefully manage their economic portfolio in order to create sustainable and talent-attracting economies.[61] Further, a shift towards service-based industry is widely considered one of the primary vehicles for improving the environmental performance of a city, though doing so may result in net adverse sustainability outcomes and/or increases in trans-boundary resource flows, further complicating sustainability accounting at the urban scale.[8, 35] Maintaining an emphasis on sectoral sustainability, even at the city level, makes such trans-boundary considerations more tractable and thus may reduce uncertainty when predicting the outcomes of a potential sustainability intervention.

Comparability is a lingering and pervasive challenge. Two frameworks provide a foundation for comparative analysis and understanding of urban transitions.

The first is proposed by Hodson and Marvin (2010) and focuses on the management of transitions. Institutional planning, stakeholder engagement, and the role of intermediary organizations are central themes, in the vein of strategic niche management. Hodson and Marvin also highlight the essential point that the experience and observation of transition heavily depends on perspective; transition is a subjective and generally normative undertaking. The authors also explicitly acknowledge that the framework's applicability will be diminished in developing world contexts.[96]

Bai et al. use a qualitative approach to analyze 30 sustainability experiments in Asia, applying a framework that is rather more descriptive than forward-looking, separating past transitions into the five categories of: triggers, actors, linkages, barriers, and pathways. Case studies are divided further on the basis of pathways (or outcomes, alternatively), which could include up-scaling or 'mainstreaming' of a given innovation; experiment multiplication; or the addition of further experiments.[11]

2.5.2 Quantitative transitions

There have been several efforts to explore sustainability transitions from a quantitative perspective, but none that attempt to move the field toward a systematized approach. Various metrics will be of interest depending on the nature of one's focus within sustainability writ large, and the metrics will in turn have a wide spectrum of applicability depending on data access, which is generally limited for cities. I will first review quantitative approaches to sustainability transitions at larger scales (but which may still be applicable to similar explorations in cities), then explore efforts to quantify sustainability transitions specifically at the urban scale.

When considering sustainability in cities, trans-boundary environmental impacts are a primary consideration that must always be kept carefully in mind, and which greatly limit our ability to draw definitive conclusions with respect to whether or not a city has become more or less sustainable over time.[164, 8]

The socio-metabolism literature within industrial ecology considers resource use transitions from an initial hunter-gatherer regime, to an agrarian regime, and ultimately to an industrial regime.[124] Focusing almost exclusively on the transition between the latter two regimes, others have applied this framework to the developing Asian context, exploring a variety of quantitative indicators (alongside qualitative considerations) to better understand progress along this generalized transition pathway.[165] Their analysis is conducted at the national level, and the indicators considered include: industrial structure (economic size and employment in agricultural, industrial, and service sectors as percentage); trade balance (net value of imports and exports); energy supply (percentage of energy production from different sources); energy intensity of labor; economic productivity of labor; and population density.

Industrial structure has also been pursued in the context of resource use and sustainability by Tian et al. (2011), who use index decomposition analysis to consider the primary drivers of carbon dioxide emissions at the regional level in China. The authors find that the relative size of industrial sector is the largest influence in determining overall CO2 emissions, and observe broad trends delineating between three types of development pathways, categorized as (1) high CO2/high GDP, (2) moderate CO2/high GDP, and (3) high CO2/low GDP.[181]

Energy supply is commonly used to analyze progress towards more sustainable energy mix in the US and otherwise, including a study by Fouquet (2010) considering changing energy supply over time, which estimates energy derived from various sources going back several hundred years in the UK. Tracing the rise and fall of various fuel types can be illustrative, though the presentation of results primarily in terms of percentage can enable one to lose a sense of the scale of the modern energy challenge.[63]

We may also look to field of economics broadly for some inspiration, as economic transitions have been researched for some time. Neoclassical economic models consider changing capital intensity, or the capital/labor ratio, as being a primary indicator of an economy's state. Endogenous growth theory, on the other hand, places a relatively higher value on the importance of knowledge and technology as indicators of economic progress. Finally, ecological economics values natural capital and views its depletion and decreasing access to ecosystem services as detrimental in the context of sustainability transitions.[74] Economic language commonly references 'transition economies', which may refer to the specific phenomenon of transition from a centrally planned to a market-based economic system (as in the case of China); but could also refer separately to gradual changes in economic structure, along the lines of transition from a heavy manufacturing to service-driven economies. Niza and Ferrão (2006) discuss 'transitional economies' in reference specifically to resource use transition, conceptually similar to the socio-metabolism discussed above.[143]

The International Institute for Applied Systems Analysis' *Global Energy Assessment* (2012) discusses transitions in the context of energy systems across several of its chapters (e.g. Patwardhan et al. [153], Riahi et al. [159], Grubler et al. [87]). One interesting concept introduced in its primary energy model is that of the technological "branch point", at which a choice between two possible regimes is made (e.g. between conventional-fueled vehicles and electric). Such decision points may have profound impacts on long-term infrastructure considerations – as I discuss in more detail in Section 5.1.2.

Few inter-temporal analyses have been conducted at the urban scale, limiting the potential for the exploration of transitions from an urban metabolic perspective. Kennedy et al. (2007) explore *The Changing Metabolism of Cities*, attempting to draw some conclusions from a comparative analysis of urban metabolism studies through time, though the focus is not on transitions, per se. This analysis draws primarily on inter-city metabolic comparisons, limiting its generalizability given the significant contextual differences between the cities studied. Further limiting this analysis is the fact that even in cases where one city's metabolic profile is examined through time, the comparison is between studies with different data sources conducted by different researchers at different times.

Among the most interesting quantitative contributions to urban sustainability transitions comes from a comparative study of Chinese cities undertaken by Dhakal (2009, 2011). In two complementary papers, Dhakal explores the dynamics of change at multiple levels of analysis in China. The first considers cities' energy intensity (measured per dollar of GDP) vs. their per capita income. Another set of simple yet informative analyses considers changes in the share of overall urban emissions from the transportation and industrial sectors over time. Largely as a result of the former (energy intensity vs. per-capita income) analysis, Dhakal proposes high, medium, and low-resource intensity development pathways, with low-intensity pathways more reflective of the development patterns in eastern Chinese cities. These eastern cities happen to be dominated by the service sector and host warmer weather pattern than their central and western counterparts, which tend to be simultaneously more energy intensive and less economically productive.[47]

In the six cities analyzed by Ooi (2007), the following trends are observed as income rises: access to public transportation decreases, air pollution indicators like SO_x and NO_x concentration increase, infant mortality increases, and life expectancy decreases.[150] These are broad trends only observed in six Southeast Asian cities during a fixed study period, so the results are not necessarily robust to other contexts. But the quantitative approach taken is clear, relatively straight-forward, and replicable in other places.

Bai et al. (2010) and Broto and Bulkeley (2013) have made two of the most valuable contributions towards a general understanding of urban sustainability transitions. While much of the socio-technical transitions literature is abstract or driven by independent case studies, these two papers conduct meta-analyses of large groups of case studies in order to extract general trends. In their analysis of 30 case studies in 11 Asian countries, Bai et al. use a five-tier framework to highlight important *triggers*, *actors*, *linkages*, *barriers*, and *pathways* in urban sustainability experiments. They conclude that public policy triggers and local government actors are most prominent in determining the success of experiments, though in most cases there are multiple triggers. Further, Bai et al. note that political will is an essential component of upscaling policy to higher levels of governance.[11] Broto and Bulkeley analyze 627 urban climate change experiments in 100 cities around the world, with a focus on the actor networks and technologies utilized in these experiments. They also find local government to be a key enabler, but that the private sector has played a particularly strong role in Asia. Broto and Bulkeley observe that urban infrastructure, the built environment, and transportation are the most common sectors for experimentation.[28]

What does one do with such experiments if they are successful? Bai et al. (2009) explore the role of vertical (across different levels of government) and horizontal (among similar actors, e.g. firm-to-firm, city-to-city) institutional linkages in policy scaling, filling a gap in the socio-technical literature and codifying some of the systemic barriers to up-scaling experiments as well as down-scaling well-intentioned policies.[12]

2.6 Chinese buildings

While the statistical methods employed here are designed to be applicable to other settings, providing context to the analysis remains essential. When considering what to do given the results of the fairly high-level analysis that follows, the implications on policy are, as ever, wholly dependent on the historical, institutional, and cultural setting; in this case, that of China. One must be cognizant not just of what desirable urban policy might look like in theory, but what types of policies are and are not feasible in practice. This question does not have a static answer, nor does it generally have one that is applicable to China as a whole. China is large and diverse in its geography, demographics, economy, and culture – it is in most cases overgeneralizing to talk about China as a single, unified entity. This limits the granularity of potential policy considerations in the scope of this work, but at the same time makes the analysis richer for the diversity embodied across the provinces analyzed in this dataset.

This final section of my literature review focuses first on resource use in the building sector with an emphasis on building materials, about which less is commonly known. I then discuss some of the key institutional considerations that influence the resource intensity of Chinese urbanization, and which serve as useful background for my qualitative analysis.

2.6.1 Resource use

China completed construction of 694 million square meters of building stock in the first 11 months of 2013 alone, of which 543 million was residential buildings. An additional 6.4 billion square meters are under construction, including 4.7 billion square meters of residential building stock.[8][43] Building energy use globally is responsible for approximately 32% of final energy use; or 19% of energy-related greenhouse gas emissions.[108] This total does not include life-cycle energy use or emissions, which are substantial. The cement and steel industries are two of the most carbon intensive in the world, accounting for approximately seven and five percent of global CO_2 emissions, respectively.[70]

Many factors are at play in determining the demand for new construction in cities. Dipasquale and Wheaton's four-quadrant model provides a useful perspective, cataloguing many of the primary system drivers of interest to the real estate sector. Among them are the floor area of existing building stock relative to new construction; the value of land and/or property; the costs of construction; and the property depreciation rate.[49]

Paired with an understanding of some of China's unique institutional factors, this basic understanding of the system is essential as a baseline for understanding opportunities for improved sustainability moving forward. The other component is understanding the state of life-cycle energy use in buildings, including both operational energy use and the embodied energy of materials (embodied energy, for short). I will touch on operational energy use briefly, but focus my discussion on the embodied energy in building materials, and in particular on the cement and steel industries that are responsible for the bulk of this.

The basic principles of building energy use and efficiency are well-understood. There are now many relatively high profile building energy efficiency research efforts, among them the US-China Clean Energy Research Center, with significant work on which to draw. DOE (2008) summarizes lessons from the US context, and Levine et al. (2012) look at global best practice following the fourth revision of the IPCC reports.[50, 128] Zhou et al. review the potential impact of energy efficiency (as well as a few other 'low-carbon' policies) in China, finding that building codes are the most effective policy strategy under the assumption of 100% compliance.[204] Policy discussions with respect to Chinese buildings tend to focus on new buildings due to the volume of future construction and the ease of designing for

[8] For reference, New York City contains approximately 502 million square meters of building area (PLUTO [Primary Land Use Tax Lot Output] data, via Jenna Tatum, NYC Mayor's Office, personal communication, 6 May 2014).

efficiency rather than retrofitting for it after buildings are already constructed.

Fridley et al. (2012) focus on Suzhou, China, finding that as a percentage of total urban energy use, 19% was embodied in building materials and 12.5% derived from buildings' operational usage.[66] Others focused exclusively on buildings (mostly in the developed world) find the proportion of life-cycle energy use to be in the range of 10-20% embodied energy of materials for individual buildings.[163, 186, 78] This result is dependent on differences on operational energy use and the assumed lifetime of building, which can range from 30-100 years and tends to be shorter in China than in the developed world.[3] There is some evidence, however that the energy use breakdown is similar in China; Aden et al. (2010) analyze building energy use in Beijing and find that 20% of life-cycle energy use is embodied in materials and construction.[1] Beijing may not be a typical case in China, however, and it is possible that – as in the Suzhou study above – the proportion of energy embodied in materials is higher.

In an analysis of Chinese commercial buildings, for example, Fridley et al. find that the energy embodied in building material manufacturing ranges from 21.5% of life-cycle energy use in hotels to 49.9% for schools. For office buildings, they estimate that material manufacturing accounts for 43.5% of life cycle energy use.[67] Operational energy use remains greater than the embodied energy of materials in all cases except for schools, and policy makers and practitioners maintain a focus on operational energy use (Kevin Mo, personal interview, 14 Feb 2014).

The energy embodied in building materials carries significant environmental impacts as well, particularly in China where the energy used in cement and steel production is highly coal-intensive. Horvath reviews environmental impacts across the American construction industry's supply-chain, providing a useful summary of the industry's resource use implications.[101] I now discuss the cement and steel industries, which make up the largest of these impacts.

Most countries dominant cement uses are for (1) infrastructure, (2) domestic housing, and (3) other building types. Cement boasts a relatively small international trade volume due to low value by weight and relatively high global accessibility to the necessary materials.[3] Ke et al. (2012) find a strong correlation between cement output and fixed asset investment, further noting that 60% of China's fixed asset investment is in the construction and buildings sector. The authors also review several other studies that suggest an impending or potentially already present peak in cement demand, which could lead to reduced profit margins and capacity surplus in the cement industry. A similar peak or plateau is anticipated in the steel industry, according to Allwood et al. (2012).

In another paper, Ke et al. (2013) observe that growth in cement demand has been tightly coupled with GDP growth, and note that the particularly high cement industry emissions in China are due primarily to the combination of outdated (though rapidly improving) production capacity and a coal-dominated electricity mix. China has been the largest cement producer in the world dating back to 1985, and currently accounts for nearly 50% of total cement production – which amounts to almost 15% of total Chinese greenhouse gas emissions.[9]

The Carbon Trust (2011) notes that China may export steel in approximately 30% excess of its consumption. China also imports some steel – primarily contained within consumer products, though in small quantities as a raw material as well. The same report also notes that international steel production costs vary fairly significantly, with one of the strongest drivers being differences between the pollution control standards to which industry is held.[178]

Of total steel consumed globally, about 56% is used in construction, including both buildings (approximately 40%) and infrastructure more generally.[44] Steelmaking alone accounts for roughly a quarter of global industrial greenhouse gas emissions, and thus 9% of global emissions from energy and industrial processes, making this the largest polluting industrial sector in the world.[44] More than 45% of global steel is produced in China, where the process is relatively inefficient and fueled primarily by heavily polluting coal-fired energy.[91]

Both the cement and steel sectors have significant potential for emissions efficiency improvements in the short- and long-term, particularly in China where production facilities are largely outdated. With incentives for closure of old plants, or tightened environmental regulations, the country could achieve significant reductions. Not all of these would come at a heavy economic cost; for example, a technology survey by Hasanbeigi et al. (2013) showed that fuel and electricity efficiency was cheaper than continuing to buy fuel 'inefficiently' for 18/20 of the technologies surveyed, with cogeneration and heat recovery being the most cost-effective measures.[91]

2.6.2 Institutions

In the contexts of climate change mitigation, human development, and urbanization, there has been an increased focus on China in recent decades, and for good reason. 300-400 million people are expected to move to Chinese cities, primarily from rural areas, by 2030. The infrastructure investment required to support these urban residents is enormous and represents a significant opportunity for interventions that may result in more sustainable development pathways.[196]

The success of China's economic development is extraordinary, with poverty declining at unprecedented scales – the extreme poverty rate (as defined by the World Bank) has fallen from over 80% in 1981 to approximately 12% in 2010.[148] It is hard to disentangle poverty

[9] I will argue later that the bulk of this production is destined for domestic consumption (see Figure 3-1). If exports (even among provinces) were common, we would expect to see fairly significant variation and find it difficult to identify a particular, dominant trend. This does not appear to be the case; while there is some variability, the fairly strong correlation between these two indicators suggests that exports are low. The same cannot be said for the steel industry, which exhibits much more erratic behavior and does not demonstrate a clear trend (see Figure 3-2).

alleviation from urbanization from economic growth. Urbanization drives both poverty alleviation and economic development; economic growth is concentrated in cities and attracts the poor with the prospect of opportunity; and poverty alleviation and economic growth can be mutually reinforcing (see e.g. Glaeser 2011). This development has, perhaps not coincidentally, occurred largely during a period of significant structural change in China, as the central government gradually transitions from its historically socialist structure towards increasing free-market economic tendencies. A top-down versus bottom-up tension seems to be ever-present in Chinese policy dialogs, and the line between the two approaches is frequently blurred.

The scale and pace of development in China presents an enormous challenge of public goods provision, further complicated by shifting demographics both societally and geographically. Two major policy institutions impose restrictions on migration patterns, slowing but by no means stemming the tide of [generally] eastward population shift. The first is the Chinese hukou system, which effectively restricts the transfer of public goods provision for Chinese migrants, easing some of the burden on government in the short term. But reform seems inevitable as the proportion of migrants in cities increases over time.[199] This policy likely does slow urban migration, but that does not make the social challenges of rapid urbanization go away; indeed, it exacerbates many of them. The Chinese government will need to find away to better integrate migrant populations into cities, who continue to arrive in search of economic opportunity in spite of the lack of government support from the hukou system.[198]

The second, also ripe for reform in the near-to-medium term, is the land ownership system in China. Urban land in China is publicly owned, and leased to developers on 40-70 year contracts. These leases supply one-time revenue injections for local governments, helping in large part to fill a financing gap left by the discrepancy between tax revenues (approximately 70% central, 30% local government) and total government spending (approximately 50% central, 50% local government). The nature of this system necessitates that local governments continue to lease land each year to developers by purchasing farm land from villager collectives, predominantly at the urban fringe.[201, 134] This results in continuous expansion of the urban boundary, though this expansion is limited by land quotas set by the central government. This system does not provide a sustainable source of government revenue in the way that a more conventional property tax might, for example – hence the speculation of future reforms.[24] Reforming this system is no easy task. Hong and Brubaker (2010) detail many of the challenges that will need to be addressed by any efforts to reform the property tax system.[100] In the meantime this system remains largely supported by continued demand for new construction.

For a comprehensive summary of China's urbanization challenges, a recent report from the World Bank, written in collaboration with Chinese government officials, proposes six areas of policy focus needed to make China's urbanization efficient, inclusive, and sustainable:

land management, hukou, urban financing, environmental, and local governance reform.[180] These issues are consistent with those identified by previous work, as in Chinadialogue's *Reimagining China's cities* report (2013) – another detailed account of many of the social and environmental implications of urbanization.[37]

Multidisciplinary research

I have attempted throughout this literature review to highlight some of the relevant connections between typically siloed approaches to understanding urban development. While my analysis takes advantage of some of these connections, many remain to be explored more formally. A number of the topics discussed above are not directly addressed in this work, but by exploring these disciplines' various and often complimentary approaches to understanding urban resource consumption I have attempted to highlight some possibilities for the more direct integration of their research agendas.

Chapter 3

Approach

The number of factors that influence patterns of urban growth and development is staggering, suggesting the need for interdisciplinary research methods. With an eye towards understanding transition, typology, and a hypothesized stage-model of development, I employ a hybrid approach that combines machine learning and interview-based research methods grounded in industrial ecology and the socio-technical transitions literature.

This thesis is comprised of two core analyses. In the quantitative analysis, I propose and test a model intended to help understand the nature of changing resource intensity in the Chinese buildings sector during a period of rapid urbanization. In the qualitative analysis, I use a series of interviews conducted with actors who have expertise in various aspects of the Chinese building sector in order to identify opportunities for reduced life-cycle environmental impacts in building development, design, and operation phases. The qualitative analysis relies on a theoretical framework intended to facilitate an understanding of what transitions in resource use look like at the urban scale. This chapter starts by laying some foundations for the analysis, then describes the clustering analysis methods; the approach to creating my theoretical framework; the interview analysis methods; and concludes with discussion of the limitations of this approach.

3.1 Analytical foundations

Before describing the specific methods used in my analysis, I briefly discuss the motivations for using sectoral (throughout) and urban (primarily in the qualitative section) lenses in my analysis. Regarding the general utility of a sector-focused analysis and its pairing with a geographic awareness, I go into more detail in Section 5.2.4.

3.1.1 Sector-level analysis

Urban metabolism is a fascinating concept, and greenhouse gas accounting studies have become more comprehensive in their ability to account for cities' metabolic complexities.

Urban metabolism is also hard to operationalize. Given the challenges of metabolic data collection in the vast majority of cities, a standardized, whole-city urban metabolic approach is aspirational – though in a more perfect world, local decision-makers would better account for the local, regional, and global impacts of urban resource use.

One may instead focus on narrower sectors of the urban economy, which in many cases better reflect urban governance structures. Local government agencies focus on issues like transportation, buildings, waste, and water.[1] While planning across these departments can and should generally be more integrated, there are practical limits to the coordination of which these resource-limited[2] agencies are capable.

Consequently, a sectoral metabolic approach can better account for the capacity of local government to influence sustainability outcomes. Local governments have varying capacities to influence the resource intensity of various sectors of the economy. The choice of appropriate sector for analysis may benefit from consideration of the local government's administrative structure. This consideration will at times conflict with a desire to maintain comparability across cities, which would require consistency across researchers in drawing system boundaries. Researchers and practitioners would need to develop standardized analytical methods to achieve such consistency; the appropriate resolution of this tension will depend the nature of their analytical goals.

If and when researchers vary the scope of their analysis according to differences in local governments' administrative structures, they will inevitably inhibit inter-city comparability, to an extent. But in general, I expect that the limitations of comparability be less stifling for sector metabolism than it is at the urban metabolic scale.

This is not argument an argument against whole-city urban metabolism studies, or against inter-urban comparisons, which still provide significant value. Sectoral comparisons can also be applied using data from urban metabolic studies, which is generally organized by sectors at a high level anyway. Siemens' *Green City Index* report provides a useful example of sectoral performance benchmarking in the context of broader urban sustainability metrics; and the Urban China Institute's *Urban Sustainability Index* reports follow a similar approach.[3][53, 129]

Researchers must make sectoral considerations explicit if they want urban metabolism-informed systems thinking to become more common in the policy-making setting. Still, sectors should not be analyzed in a vacuum. Whenever appropriate, cross-sectoral linkages must be accounted for when such relationships are necessary to understanding sectoral sustainability impacts. This presents a renewed challenge of choosing the appropriate system

[1] Sectors may also be interpreted in the more traditional sense of different industrial sectors (e.g. health-care, manufacturing) depending on local government priorities. While I hesitate to draw boundaries around what size of sector would be appropriate for analysis, priority should be given to sectors that have relatively significant sustainability impacts.

[2] Resources here meaning time and money.

[3] Though these reports (like many others) also emphasize a single aggregate metric for urban sustainability to achieve a general sustainability 'ranking' that I find to be fairly arbitrary.

boundary, which requires a careful balancing of lean, simple approaches and more complex, integrated systems modeling.

3.1.2 Urban analysis

With all of this focus on sectors, why is this work particularly relevant at the urban scale? In terms of the ability to *manage* sustainability transitions – that is, to influence and/or guide them purposefully – local governance is the most direct level of influence that is still able to consider systems-level sustainability outcomes in its decision-making.

While sustainability-driven policy and governance at higher levels remains essential (especially in the Chinese context, where local policy-making ability is limited), urban sustainability governance itself, as well as its relationship to sustainability governance at higher levels, are poorly understood and present a significant opportunity for further study.

The focus of sustainability transitions literature on diffusion of innovation is useful given a historical lack of knowledge sharing between local governments, which are by their nature more distributed than their national counterparts. With a growing list of organizations focused on sharing best practices among cities (e.g. C40, The World Bank, UN-Habitat, and ICLEI, to name only a few), this is a particularly important and dynamic time to explore possible urban sustainability interventions.

3.2 Quantitative analysis

This analysis uses k-means statistical clustering to sort 993 data points into groups ('clusters') of similar data, as a means of testing the proposed stage-model of urban development (see Section 1.3.1). The question at hand in the quantitative analysis is, how does resource intensity of the building sector vary over time and across Chinese provinces, and can we see evidence of development 'stages' in that variation? This analysis also serves to demonstrate an approach to understanding resource use on a sectoral rather than whole-economy level.

Because these data – which are publicly reported in Chinese provincial statistical yearbooks – tell us about provinces rather than individual cities, this isn't strictly an urban analysis, though it does still tell us something useful about urbanization for three reasons. First, urbanization in China during the study period (1978 - 2012) was rapid, pervasive, and inseparable from the country's development more generally, with China's urbanization rate growing from 17.9% to 52.6%.[42] Second, the growth of the building sector is itself enabled primarily by this urbanization, so any analysis of buildings is urban in that respect.

Finally, four of the provinces analyzed also represent municipalities, so there is in fact some opportunity to look directly at cities – and importantly, to compare the development trajectories of provinces at different stages of urbanization[4]. While urbanization figures at the provincial level are not available, the combined population of each province's three largest three cities (relative to the province's total population) may serve as a crude proxy. Table A.2 in the Appendix highlights significant variation in this urbanization indicator. Even among the four 'municipal' provinces, the extent of urbanization according to this metric varies from 27.2% (Chongqing) to 89.3% (Shanghai).

This method is also designed to be easily replicated in other contexts and for other resource-using sectors. Besides the ease of access, using public data further demonstrates that this approach is repeatable, potentially for any set of cities, provinces, or national government reported data.

As another means of ensuring replicability, I conduct the analysis in open-source software, using R (via the RStudio graphic user interface), with the base software supplemented by many additional packages[5], for which I am very thankful (for a full list, see Appendix, Table A.1).

This statistical approach is intended to lend some quantitative rigor to the sustainability transitions field, and to illuminate some useful patterns in the context of this Chinese building and construction sector case study. In that respect as well I am in a sense testing two more ideas – first that this 'big data' statistical approach is able to contribute to a field that otherwise relies almost exclusively on detail-oriented, case study-based research; and second, that we can learn something useful about urban sustainability and climate change mitigation potential by benchmarking sectoral performance across comparable entities.

3.2.1 Data collection

The dataset I used for the clustering analysis comes from Chinese provincial statistical yearbooks, via China Data Online.[40] Statistical yearbooks are released annually at national and subnational levels and are the primary source of publicly reported data on various dimensions of Chinese society. In the case of buildings, data for some indicators are available going as far back as 1949, though not necessarily for all provinces. The administrative designation of some provinces has changed over time, and new provinces have been formed, which complicates analysis in some cases. Chongqing, for example, was designated as a provincial-level city in 1990 and only since then have its statistics been compiled separately from those of Sichuan province, to which it used to belong.

Data are available for nearly all provinces and all indicators analyzed here from approximately 1978 to 2012, providing 35 years of panel data across indicators for 30 Chinese provinces (data for Hong Kong and Macau were not available and thus are not included in this analysis; data for Tibet was incomplete). The data comprise 89 indicators, of which

[4]Indeed, the comparison of development pathways between the urban and 'non-urban' provinces turns out to be quite important.

[5]The data and entire, annotated code are freely available by email, but omitted from this document as they will be more useful as separate digital files: accuardi@mit.edu

ten are directly relevant to the building sector, and six used in the clustering analysis.[6] I retrieved all data from China Data Online.[40] The result of this effort is the dataset that forms the basis for the quantitative analysis.

There is some uncertainty regarding the quality of data from Chinese statistical yearbooks, especially given a relative lack of transparency in data collection methods. In this analysis, I do not seek to draw conclusions that require precise accuracy, however – in fact, this analysis would remain valid for data which preserve relative indicator values and which are reported on the correct order of magnitude. Figure 3-3 and its discussion in Section 3.2.3 provide the most dramatic example of data inconsistencies in the dataset.

3.2.2 Indicator selection

The goal of the modeling itself is to identify high-level development patterns within the building sector in the form of a typology of transition pathways that can test the stage model development hypothesis. With this in mind, I seek indicators that together paint a comprehensive picture of building sector resource use. I have included six indicators in this analysis: steel production-, cement production-, electricity production-, square feet of building area constructed-, kilometers of highway construction-, and GDP-per-capita.[7]

The choice of indicators for the clustering analysis is informed by both data availability and modeling goals. Clustering implicitly assigns equal weight to all of these indicators, which one might not necessarily care equally about. One could account for this by explicitly assigning greater weight to some indicators as compared with others. In this case, I choose not to do so in order to avoid making a value judgment on the behalf of potentially relevant stakeholders. Different stakeholders may assign different values to each given indicator, so this decision is also intended to preserve generalizability to the extent possible. It is most important that the indicators be chosen carefully given data availability constraints.

In selecting indicators, one must be conscious of the distinction between production and consumption indicators. Neither is 'better' than the other; rather, each provides different information. Going into this research, we wanted to explore the material and energy consumption induced by construction processes. The available data in the Chinese context, however, are largely production-oriented, which is understandable given the relative ease of data collection for material and energy production.

The mix of indicators ultimately reflect a combination of consumption and production values, though in some cases the two are closely related. Directionality (i.e. production versus consumption) is fundamental to the understanding of material flows, but using a uniform set of either production or consumption indicators is not crucial to this study because production and consumption alike tell stories about how the sector itself is changing.

[6] Detailed explanations for the specific meanings of each variable are available via the National Bureau of Statistics of China.[141]

[7] I include Q-Q plots showing the distribution of each of the six indicators relative to a randomly sampled normal distribution with equivalent characteristics in the Appendix (see Figure A.1).

Further, production indicators are often much more relevant to local environmental outcomes (air pollution in particular), which often drive decision-making for sustainability. It would be ideal to have both, but in this case it is not an option.

The selection criteria for indicators in this case are intended to comprise life-cycle building resource use, though the balance of indicators included tends to favor materials use (embodied energy/emissions) rather than operational energy use. With this and the lack of granularity in the electricity data in mind, my analysis will focus more on embodied energy concerns, which are also less well understood. Embodied emissions are also determined almost wholly by decisions made during design and construction processes, giving them particular significance during this period of extreme construction in China.

Why were each of the final six indicators (steel, cement, electricity, building area, highway length, and GDP) chosen?

Building area constructed (per capita) is chosen because building square footage most directly represents the scale of new constructed space in a given province, and is the primary indicator for local (within province) construction demand. This indicator is potentially subject to some imperfections, as one might expect project construction time to create a lag between actual and perceived construction demand – which this indicator, expressing only completed construction projects in each given year, does not take into account. Building area constructed should also be a strong proxy for embodied energy of buildings, subject to considerations of material intensity uncertainty.

While estimates are available at the national level, provincial level data for urbanization rates (e.g. percent of population living in urban areas) are not available. There are tools available, especially spatial mapping, that allow one to estimate these rates at present day, but these generally do not provide for the annual, historical estimates that would be necessary to compliment this dataset. Building area and highway length constructed-per-capita are the two indicators most likely to be reflective of urbanization rate in this analysis.

Steel and cement production (per capita) are chosen because they together make up the primary components of the building and construction sector's embodied emissions. These resource production indicators do not necessarily correlate with resource demand in each province. Of particular note is the relative trade mobility of each material. Neither is particularly attractive to ship long distances, but between the two steel is much more likely to be exported in significant quantities. For this reason, I chose to include both materials. Production quantities in both cases are total values, so include not only steel and cement used for buildings, but also for infrastructure as well as other goods and services.

In the case of cement, the yearbook data show that these two are quite tightly coupled (see Figure 3-1). This is not the case for steel, where production is concentrated in the region surrounding Beijing and comprising Tianjin, Hebei, Liaoning, and Shandong provinces (see Figure 3-2).

I have also included the annual length of highway constructed (per capita). This is

Figure 3-1: Built area versus cement production

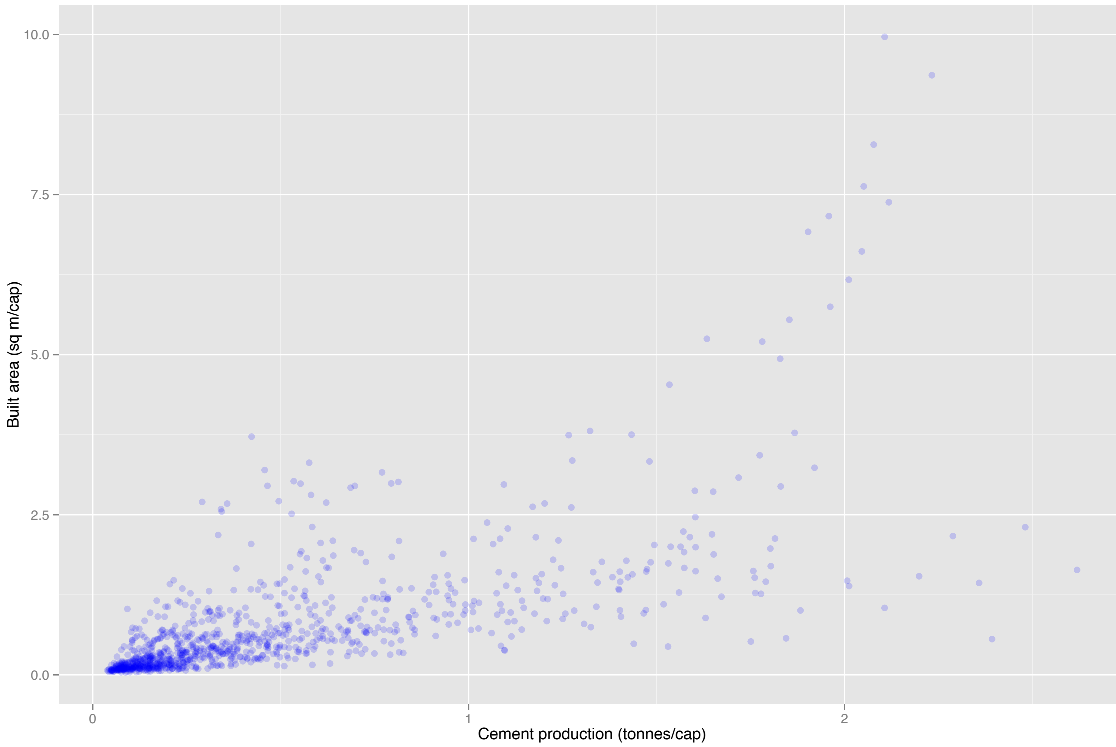
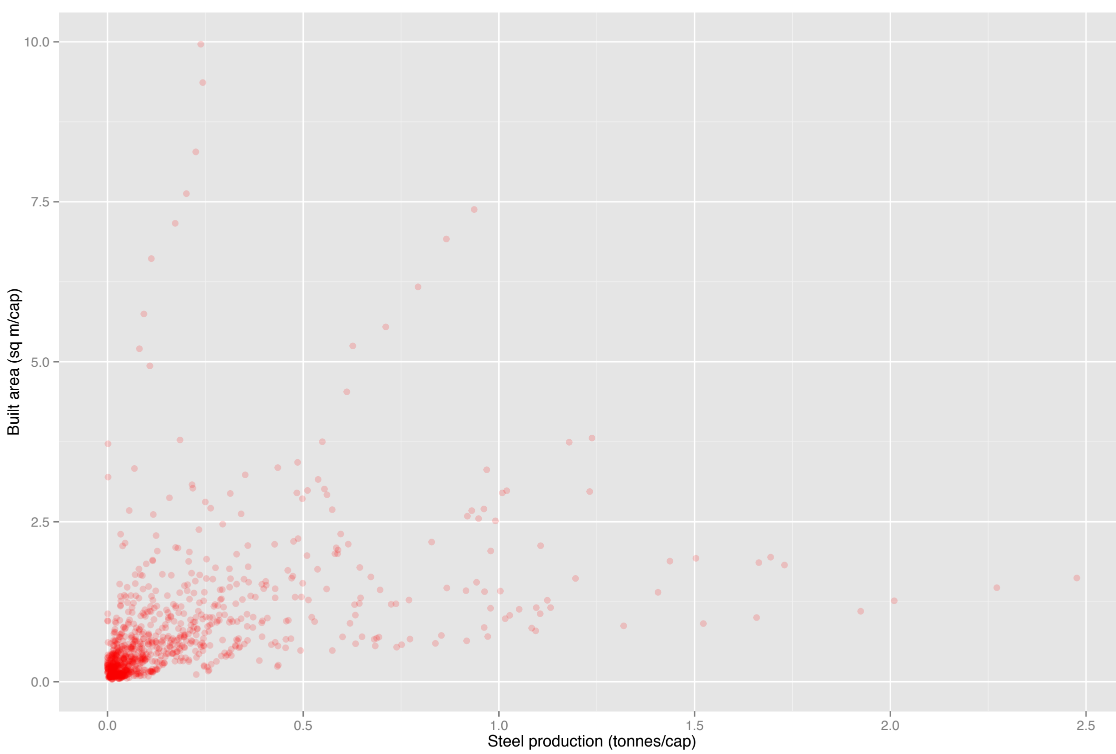


Figure 3-2: Built area versus steel production



because highway and building construction together account for a significant percentage of cement and steel use at the national level, but they may not be perfectly correlated. While the initial scope of analysis was constrained to buildings themselves, the inclusion of aggregate cement and steel production values encouraged me to widen the scope to include this second area of construction in order to add a second consumption indicator and potentially better represent local differentiation in the production/consumption balance of construction materials.

Electricity production (per capita) is included as the primary component of emissions production during buildings' use phase. Electricity production in any given province may be exported and a significant proportion utilized in industry, as well as some other non-building-related capacities. Also complicating electricity's inclusion is its distinctly different relationship with time. Whereas a building is constructed as a discrete, one-off event, electricity consumption is a consequence of that construction that recurs and changes over the course of each building's lifetime. So while the building and material indicators roughly reflect incremental additions to the built environment, with this dataset it is not easy to estimate the incremental *addition* of electricity production (or consumption, for that matter). Total production is thus related most closely to the total building stock, and thus provides one window into the high-level state of the building sector.

Finally, GDP-per-capita is included as a proxy for a development and as a consumption indicator. From a public policy perspective, the ultimate goal of development has less to do directly with sustainability and everything to do with increasing human welfare.[8] While the limitations of GDP-per-capita as an indicator in this regard are well-documented [174], I still use it as an imperfect stand-in for the human development component in this sustainability transition model. As a key driver of government decision-making, the primary performance evaluation metric for government officials, and a stand-in for resource consumption, I expect this to be a strong determinant of each province's development stage.

3.2.3 Data preparation

Data are structured with each column representing one indicator, and each row representing a province in a given year. This analysis assumes that all unique province/year combinations are independent from one another. Omitting entries with missing values for one or more indicators, the dataset analyzed here has 993 rows (unique province/year combinations) and five columns (indicators).

Tibet is the only province omitted from the dataset, as its data for the research period are too incomplete for analysis to be meaningful. Several other provinces do not have fully complete datasets, ranging from one missing year in some cases to a later start date for others

[8] Sustainability is still an indirect consideration, inasmuch as it impacts human welfare – which it does and will do in increasingly obvious ways, though it is understandable that sustainability has not in most cases become a major priority for governments in the developing world. Exceptions to this rule are typically those countries most vulnerable to the impacts of climate change, perhaps most famously the Maldives.

(e.g. Chongqing, where data are available only from 1990). One strength of the analysis is that it does not rely on perfect data, so these relatively smaller flaws are acceptable for my purposes. Entries with missing values are omitted from the dataset, as are entries with zero-values. It would have been possible to estimate some of the missing data points using interpolation, but the value added by the additional data points is outweighed by the potential inaccuracies of the estimated values. All indicators are scaled on a per-capita basis to account for the significant range in size across the 30 provinces and facilitate cross-provincial comparison.

Two indicators required preparation beyond per-capita scaling: highway construction and GDP. Highway construction is reported in statistical yearbooks as "total length of highway constructed", rather than the *annual addition* of highway. To estimate the latter, which better aligns with the other indicators as an annual rather than aggregate metric, I calculated the year-to-year difference for each year. Because the highway length data go farther back in time than 1978, these estimates are available for every year in the dataset of interest (1978-2012).

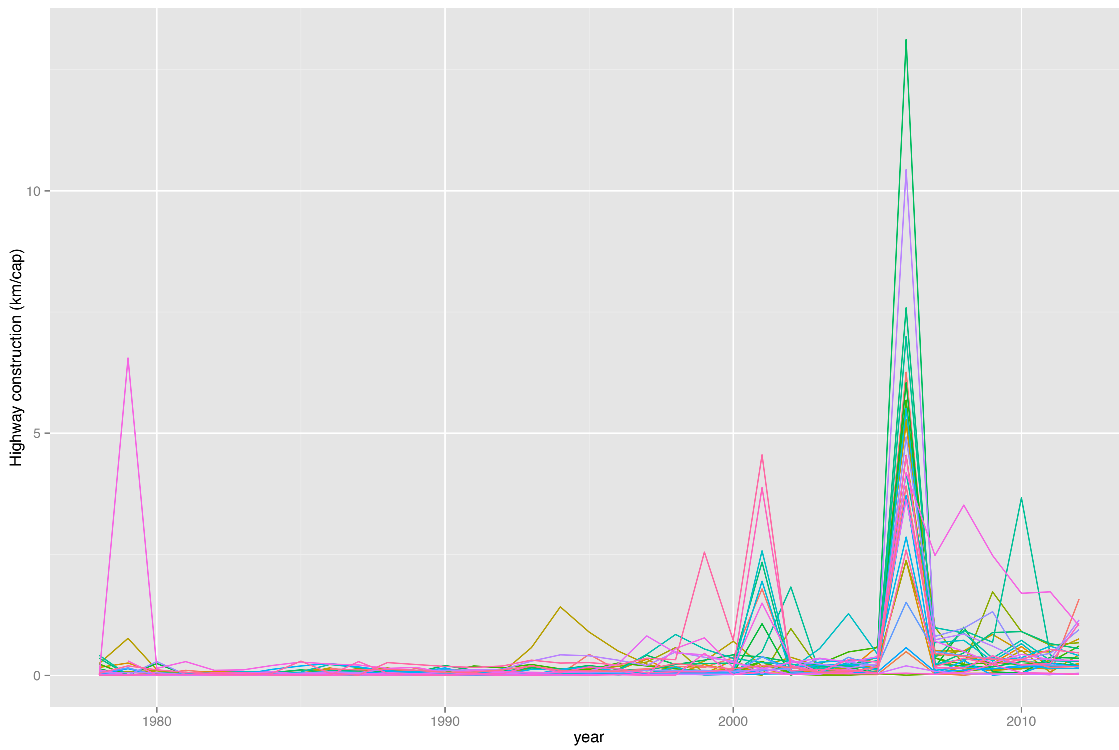
After the first pass at doing this, a few inconsistencies in the highway construction data became apparent. There are some negative and zero values, for example. I find both of these scenarios (zero or net negative highway construction) unlikely. Zeroes likely arise from a lack of granularity (in terms of significant figures) in the highway construction estimates. With these issues in mind, I adjust negative values to zero and follow a statistical rule of thumb [51] to add half the smallest significant figure to all highway length data points.

There are three major discontinuities in the data where one can observe abnormally high spikes in construction, in some cases two orders of magnitude higher than a typical annual per-capita increase. As shown in Figure 3-3, these peaks occur in 1979, 2001, and 2006.

The 2001 peak is to an extent explained by government policy [131], but – while such explanations may exist – I have not found a satisfying explanation regarding the other two. This effect of these peaks in the analysis is reduced in two ways. The first is by assuming that the peaks represent misreported or otherwise inaccurate data, and redistributing some of their value across the rest of the dataset. This is accomplished by subtracting total value from these peaks in proportion to the value added above, where I eliminate the negative and zero values. Because this artificially inflates the total highway construction, I make the somewhat arbitrary choice of eliminating the total inflation by subtracting the inflation from each peak year in proportion to each peak's magnitude.

The second way the analysis accounts for these peaks is by interpreting 'transitions' between clusters in the final result to occur only when each province has consistent cluster membership for two or more years. Given the peaks in highway construction data, one would expect skewed cluster membership in those peak years (and, in fact, skewed cluster means overall to the extent that this is an artifact of poor data quality). This is in fact the case, and I discuss my approach to adjusting for these effects in Section 3.2.5.

Figure 3-3: Highway construction versus time



3.2.4 Cluster model selection

Statistical clustering is a means of sorting individual members of a dataset into statistically similar groups. Given an input of 'k', the number of clusters, the k-means algorithm forms k groups and assigns membership in one of those groups to each data point (in this case, each point is represented by a unique province-year combination) by minimizing statistical distance among members of the same group (the 'within group sum of squares', or WSS) and maximizing statistical distance between separate groups. Clustering is valuable because it is an unsupervised algorithm – meaning it does not require one to make any assumptions about data structure or grouping prior to the analysis.

Two fundamental choices determine the results of one's cluster analysis: the choice of model (algorithm), and the choice of the parameter k. In order to select the appropriate model, one must first settle on the goal of the modeling process. One of the primary goals is to test our proposed stage-model of urban development, and another is to more broadly identify development trends within the buildings sector. At the same time, I would like to carry out the statistical clustering in a manner that aligns with accepted practice in data mining, in order to make sure that the clusters themselves have meaning.

To determine how to optimally accomplish these goals, I weighed several criteria: some are statistical metrics commonly used to measure cluster quality, and some are strictly subjective. For quantitative validation, I used the clValid package to compare both internal and stability metrics across a range of potential algorithms and k-values. These results show k-means to be high performing across internal and stability metrics for a range of k-values.

I also visually inspected the clustering results for k-means and hierarchical clustering using principal component analysis in order to visualize the distinctiveness of the formed clusters. Figure 3-4 shows a comparison between k-means and hierarchical clustering results, with the k-means clusters appearing much more visually distinct.

Hierarchical clustering tends to be heavily influenced by outlier data points, in part because of the way clusters are formed – typically by horizontally cutting the hierarchical tree, a process that does not take into consideration whatever might happen below that 'cut'. When choosing between approaches, one must strike a balance between seeking relatively uniformly sized clusters and unequally sized but highly distinct ones. Hierarchical clustering is adept at identifying the latter, while k-means clustering generally tends towards the former. The strong performance of k-means in the validation metrics and its tendency to form more uniform clusters in this case made it a more attractive choice.

After deciding to use k-means, I also used the gap statistic as an additional means of validating the choice of k (see Figure 3-5). The gap statistic measures the distance between within-cluster sum of squares (WSS) for a range of clustering outputs and the WSS of a null reference distribution of the data (higher values are more desirable).[182] The combination of the internal validation metrics, gap statistic analysis, and a sprinkling of my own intuition lead to my selection of k = 9.

In this case, parsimoniousness (choosing a lower k-value) finds itself to be partially at odds with my modeling goal. With too few clusters defined in the clustering model, the opportunity to yield multiple, distinct cluster progressions diminishes. In the analysis, each province moves from one cluster to another, and to another, and this movement comprises each province's development pathway. More clusters thus provide a greater opportunity for branching and differentiation in these development pathways (see: on this page, also in Section on page 55). It is with these factors in mind that I chose to use k-means clustering with k = 9 clusters.

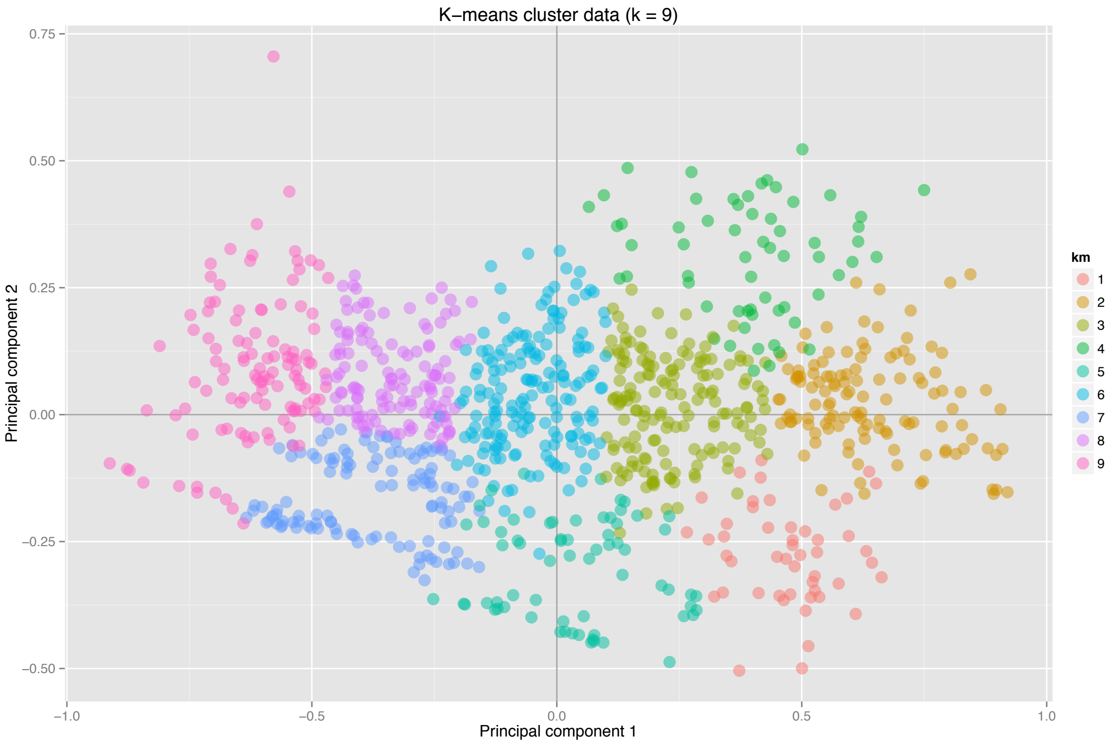
3.2.5 Pathway identification

While statistical clustering itself has been in use for several decades, applying this method to time series data is fairly uncommon (though not unprecedented; see Liao [130]). This relative novelty is both a strength and potential weakness of this work.

Having defined a set of clusters as above, I analyze each province's progression from one cluster to another through time. This analysis is enabled by an assumption of independence across unique province-year data points that comprise the clustering data set.

I have defined a 'stage' in this analysis by a period of two or more years in which a province maintains consistent cluster membership. Setting a two-year minimum is a simple measure I have used to eliminate 'false' stages that may be artifacts of the data and the clus-

Figure 3-4: Principal Component Analysis of Cluster Membership



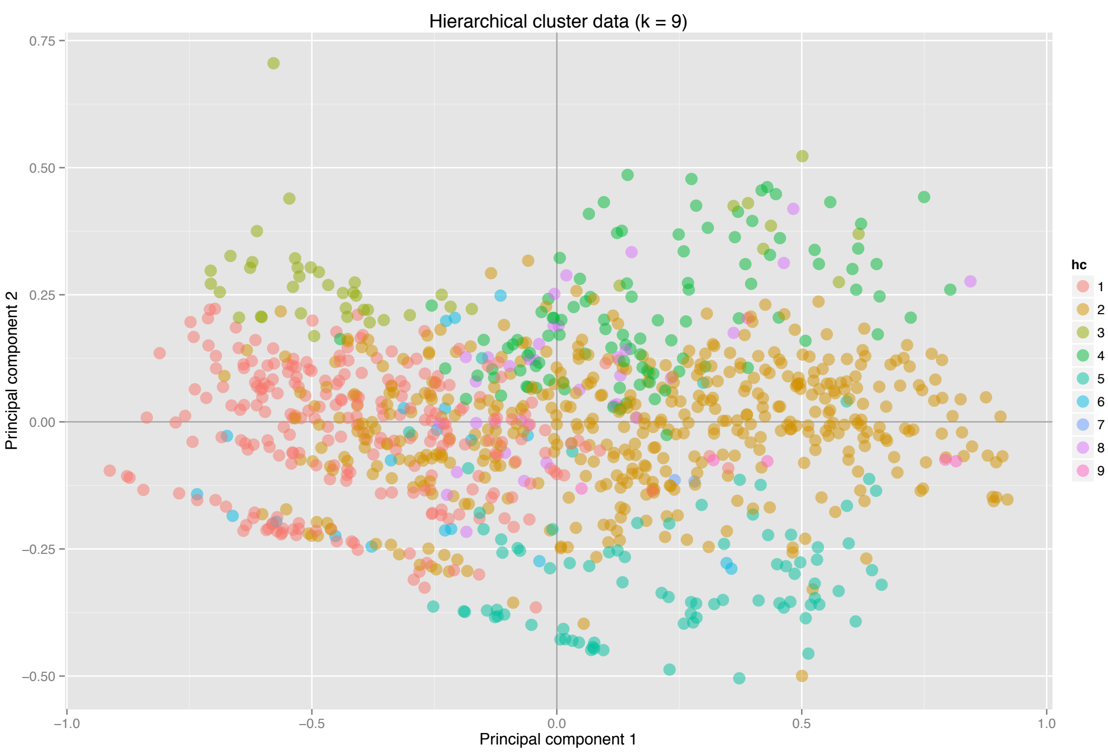
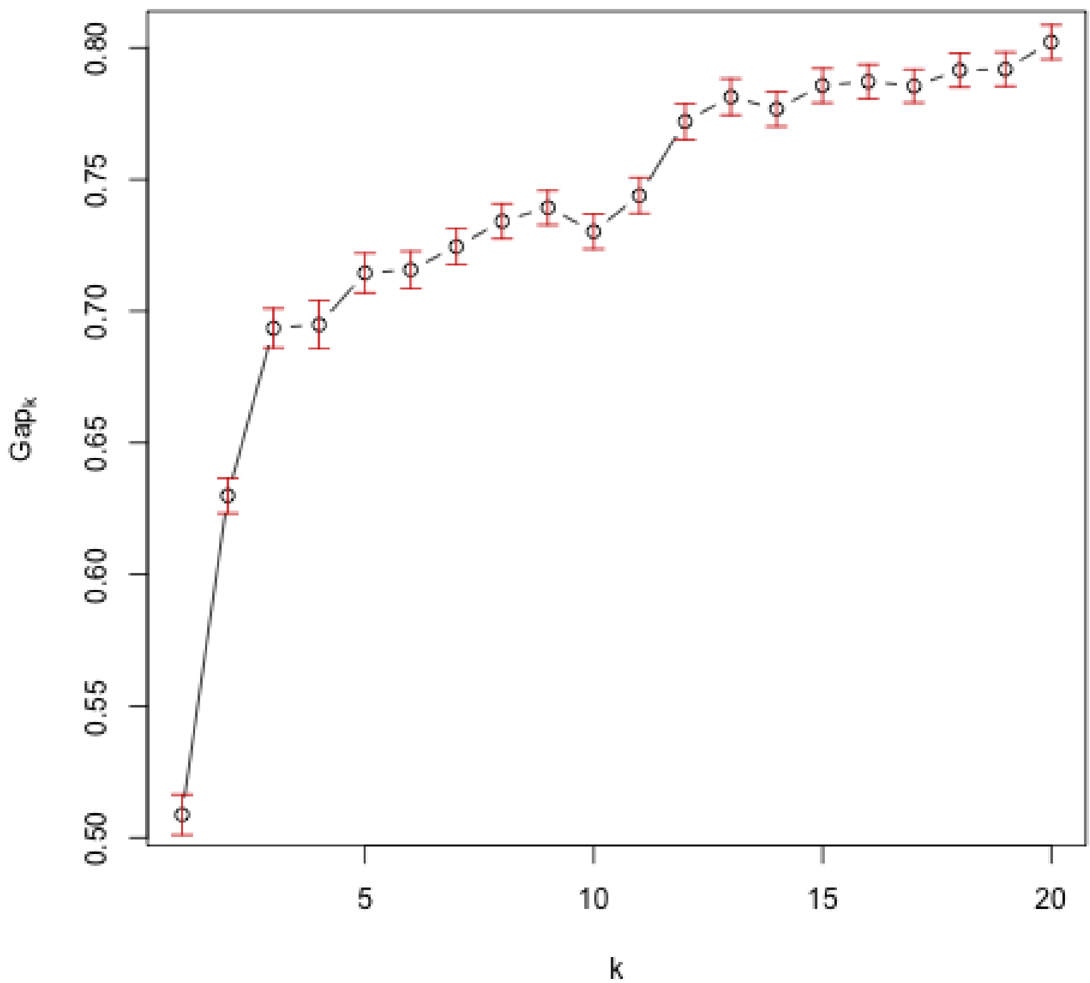


Figure 3-5: K-means Gap Statistic



tering algorithm rather than indicative of any meaningful transition. Setting the threshold for stage identification at two years rather than one should strengthen the result, provided that one does not ignore single-year fluctuations that may still hold meaning, whether in terms of affecting conclusions or highlighting shortcomings in the data and/or approach.

For each province, I record the full stage (cluster) progression from 1978 - 2012, including any anomalies that may be of interest. For example, I found it useful to note instances where there is not a stage transition but rather a back and forth (e.g. 3 –> 4 –> 3 –> 4) from year to year, which likely indicates either that a province sits right on the border between two stages or that there is not a significant difference between the two (or more) clusters.

Having recorded the pathways for each province (see Table 4.2), I then group similar observations together. I group provinces with identical pathways first, then proceed to combine groups with decreasing similarity until the groups remaining appear entirely distinct.[9] Importantly, I pair this procedure with analysis of the overall temporal distribution of cluster membership.

3.3 Qualitative analysis

My qualitative analysis is motivated by a desire to understand which actors influence the resource intensity of the Chinese building sector, and to what extent. I also place this question in the context of transition, first by proposing a theoretical framework in order to organize the discussion of how urban resource use is influenced by actors in five governing systems.

I use interviews with subject matter experts and practitioners in the Chinese building sector to develop an understanding of its institutional context and the role that various actors play. However, the interviews go beyond achieving this basic (though valuable) understanding, exploring both opportunities for knowledge transfer within the sector and ongoing experiments that may result in its reduced resource intensity moving forward.

3.3.1 Theoretical framework

With this theoretical framework, I seek to answer the question, "how do transitions in urban resource use come about?". What are the possible mechanisms of urban sustainability transition? Here, the goal is to provide a comprehensive categorical structure, within which to place possible triggers of sustainability transition. While I set out to do this with cities in mind, the result is quite general and may be applied to other scales of analysis.

This framework is intuitively motivated, though rooted in urban theory. To start, I brainstormed a broad range of possible transition triggers (see Table 3.1), then sorted the resultant triggers into the shortest possible list of distinct conceptual categories. I find the resultant list of transition categories (economic, social, technological, political, and natural)

[9] This informal process is theoretically similar to the hierarchical clustering algorithm.

Table 3.1: List of possible transition triggers

Category	Triggers
Economic shocks	Exogenous (regional, national, international) shocks, e.g. market crash
	Local economic shocks, e.g. layoffs in a concentrated industry
Infrastructure construction	Telecommunications, sanitation/drinking water, or transportation network expansion
Demographic shift	Age distribution or major immigration/emigration
	Changing lifestyle choices, e.g. changing marriage age, family structure, graduation rates
Political shift	Long term shifts in electorate preferences; short term shifts due to election results
	'Voluntary' change, e.g. new climate action plan; 'involuntary' change, e.g. in response to unexpected disaster
Increased capacity	Horizontal sharing, e.g. industry associations, city government workshops
	Vertical sharing, e.g. publications, trainings, hiring new staff/consultants
Industrial shift	Influx or decline of major industry
	Shift in industrial composition (eg. heavy industry to service)
Disaster	Natural, e.g. earthquake, flood, hurricane, drought
	Manmade, e.g. nuclear accident, war, blackouts, trade restrictions

to be fairly comprehensive, though gaps may remain and many types of transition trigger do not fit neatly into only one of these categories. These categories and their relationships with resource use as well as with each other are detailed in Section 4.2.1.

For what it's worth, I consider this framework to be in part validated by Frank Geels socio-technical regimes[72] and Lawrence Lessig's constraints on human behavior[127]. Geels' five regimes map fairly closely to my governing systems, though he does not include a natural regime, and distinguishes between science and technology where I have grouped them together. Lessig's four constraints on human behavior are law, social norms, markets, and 'architecture'[10]. With this latter category, Lessig describes something "that will sound much like "nature""; and more specifically "the world as I find it, understanding that as I find it, much of this world has been made" (p. 663).[127] In effect, this 'architecture' category comprises my 'natural' and 'technological' categories. With this in mind, Geels' regimes and Lessig's behavioral constraints map to mine roughly as depicted in Table 3.2.

[10] As he proposes these constraints, Lessig also notes clearly that he "[does] not mean that these are the only constraints on behavior" (p. 662).

Table 3.2: Framework comparison

Lessig	Geels	Accuardi
Law	Policy	Political
Social norms	Socio-cultural	Social
Markets	User and market	Economic
[Architecture]	–	Natural
Architecture	Science + Technology	Technological

3.3.2 Interview analysis

Again the first step in determining the appropriate method is to determine the research goal itself. In this case, the topic of interest is forward-looking: "What levers are available, and to which actors, to reduce the resource intensity of the Chinese buildings sector?"

Within the scope of a masters thesis, there is only so much one can learn about a topic – and 'Chinese buildings' is a large one. With this in mind, I conduct interviews with experts in China, relying on their varied perspectives to supplement my own work and to provide a forward-looking point of view that is not so easily found in historical data.

In selecting interview candidates I try to account for the range of primary actors who influence sustainability outcomes over the course of a building's lifetime (see Table 4.4). I identified candidates through a variety of mechanisms, including personal and professional networks, and in particular from the recommendations of professionals working in the space. The sustainability and buildings expert communities in Beijing are not enormous, it turns out, so I formed connections relatively rapidly.[11]

I reached out to interview candidates primarily via email, making first contact to gauge potential interest before sending a standard template email to participants describing the research project and interview protocol. With participants' permission, I recorded our conversations and later transcribed the recordings for future use.

The analysis presented here is itself not informed by the cannon of interview research literature, but for the purposes of this work this is not necessary. These interviews are intended primarily to bring practitioner knowledge into the [public] research domain. I attempt to provide the practitioners' perspectives on barriers to reducing the resource intensity of the building sector, as well as potential mechanisms for transition to lower resource intensity moving forward.

My approach to analyzing the interviews and organizing the results of the interview analyses is informed by the theoretical framework, which is detailed in Chapter 4.2. I outline the structure of decision-making and resource-use influence along the development process on the basis of my understanding of the building sector, drawing from all 15 interviews. I

[11] In addition to many others who provided valuable recommendations, Kevin Mo and the EF China staff were especially helpful with respect to identifying potential interview candidates.

also code participant comments to correspond with triggers of and barriers to change across the five governing systems (economic, social, political, natural, and technological), selecting three case studies that cover a diverse range of relevant transition mechanisms. I then validate this analysis by reviewing it with a Chinese buildings and real estate expert.

3.4 Limitations and opportunities

This thesis takes an incremental step towards marrying quantitative and qualitative approaches to understanding sustainability transition, and in doing so serves as a bridge between several research communities – most notably, those focused on urban metabolism and socio-technical transitions. I also draw a theoretical connection between the notions of transitions and typology in the context of urban systems, using a hypothesized stage-progression development model. In my analysis I construct a sub-typology that differentiates between Chinese provinces' development pathways in the buildings sector, applying machine learning techniques to publicly available longitudinal data. Further, I analyze transitions in China, a country which merits but has not yet seen significant consideration in the sustainability transitions literature.

It is uncommon for materials flow analysis (MFA) to include data in time series, and while this is not a full MFA, the indicators I use in the quantitative analysis are either direct material production indicators or intended to be proxies for material consumption. I also add to past work considering urban transitions, furthering our understanding of transition triggers by contributing a five-governing system framework, and proposing a hybrid urban-sectoral analytical lens.

These are some of the reasons to be excited about this work, but here I also present several reasons to interpret the results of this analysis critically. These limitations should be kept in mind while exploring the analysis that immediately follows.

3.4.1 Clustering limitations

Space

This model does not account for the spatial relationships of provinces, nor for the impact that climate might have on the data utilized. I do not expect that this should influence the results significantly, since in the buildings sector climate would primarily impact heating and cooling loads. In this analysis, electricity is the only indicator I am using to consider building energy use, and even then it is only electricity use in general rather than building electricity use in particular. Further, heating in China – particularly in the north – is primarily supplied by coal and thus would not show up in these indicators in the first place.

My results would, however, be fairly easily put in a spatial context. Maps showing various development pathways (especially if maps could themselves show temporal changes) would be an excellent addition.

Data

I set out to conduct analysis on data that are relatively accessible, but Chinese statistical yearbook data carries a trade-off of unknown quality. There may not be a single person with perfect knowledge of this dataset's quality, given that the data are collected and estimated at the level of each province. It is uncertain to what extent reporting practices are standardized across provinces. In some cases, performance incentives for government officials effectively encourage misrepresentation of reporting. One would expect this to be especially true for GDP data, though perhaps less so for construction data. It is, however, possible, that building and construction data would be misrepresented as part of an effort to pad GDP numbers. The coverage of the data is also imperfect and not wholly consistent across provinces, as described in Section 3.2.3.

Statistics as art

An important caveat for almost any statistical analysis is that statistics is often as much an art as a science. One must keep this in mind when interpreting results, as overgeneralizing based on one's results is a [statistically] significant risk. I have made an effort to clearly justify the subjective decisions I made throughout the analysis. The analysis itself is also experimental, and thus not easily compared with others to test its validity. If it is utilized and/or improved upon in the future, its merits may be more readily evaluated.

3.4.2 Interview limitations

Language barrier

I do not speak Chinese. This obviously limited the number of people with whom I could speak in China, and likely affected some peoples' willingness to openly share their experiences with me, both formally (through the interview process) and informally. As a relative outsider to the Chinese building community, however, I also bring a useful perspective – it can be valuable to ask the 'stupid' questions that experts often take for granted.

Lack of granularity

In some respects, it would be more valuable to conduct interviews of this nature earlier on in the thesis process. One of the main consequences of the later timing is that I did not have extensive time to revisit the interview content and iterate on the data gathered. This limitation is exacerbated by the broad scope of analysis and discussion in the interviews;

more in-depth analysis of one or two particular cases is an alternative and valuable approach. The broad scope of this thesis is also a strength, as much of my analysis is fundamental to understanding opportunities for system change in Chinese buildings. Further, systems-level thinking is needed to integrate the complex array of concerns faced by policy-makers and practitioners.

Chapter 4

Analysis

The analysis presented in this chapter is comprised of three complementary sections: a quantitative analysis of historical resource use trends in the Chinese building sector, a qualitative analysis of institutional considerations in the Chinese real estate development process, and a theoretical framework to contextualize the qualitative analysis.

The quantitative analysis serves two primary purposes. The first is to explore inter-provincial and inter-temporal variation in the Chinese building sector's resource use. Second, it operationalizes the stage-model development hypothesis using statistical clustering to form possible development 'stages'.

Affecting the high-level resource use that the quantitative analysis explores will require many interventions on smaller scales. The qualitative analysis builds an understanding of the institutional context for these interventions and identifies several specific examples of sustainability experiments in the Chinese building sector. While the quantitative analysis is historical, my qualitative analysis focuses on understanding the building system as it stands today, while also considering the prospects for future transition towards lower resource intensity.

First, I detail the results of the quantitative anslysis. Second, I describe the theoretical framework to build context for the discussion of barriers to and possible triggers of transition. Third, I analyze my interview results by describing building sector stakeholders and walking through the real estate development process. Fourth, I discuss opportunities for reduced embodied and operational energy in Chinese buildings, as well as some of the means by which knowledge in these realms is transferred among stakeholders. Finally, I review three case studies and highlight mechanisms for potential sustainability transitions demonstrated by each.

4.1 Clustering analysis

I chose my final statistical clustering method on the basis of a combination of objective statistical metrics, theory, intuition, and the method's ability to answer my research ques-

Table 4.1: Normalized cluster means

Clust.	Cement	Steel	Elect.	Built area	Hwy. length	GDP	# Prov.	# Obs.
1	0.641	0.872	0.605	0.713	0.253	0.820	8	49
2	0.859	0.834	0.667	0.692	0.542	0.755	27	121
3	0.649	0.745	0.496	0.539	0.420	0.539	29	160
4	0.696	0.761	0.556	0.527	0.756	0.575	25	61
5	0.397	0.827	0.595	0.508	0.113	0.554	8	66
6	0.495	0.668	0.373	0.423	0.371	0.390	29	177
7	0.319	0.616	0.304	0.282	0.088	0.275	20	116
8	0.353	0.605	0.243	0.252	0.325	0.284	24	130
9	0.156	0.561	0.101	0.165	0.277	0.155	21	113

tion. The final model uses the k-means algorithm with k (the number of clusters) equal to nine. I used six indicators pertinent to the building sector at the provincial level in China: annual constructed building area, annual constructed length of highway, cement production, steel production, electricity production, and GDP. All of these indicators were per-capita adjusted, log-scaled, and normalized on a 0-1 scale before running the clustering analysis.

4.1.1 Clustering results

Cluster means – within each cluster the average values of the six indicators – are a simple way to characterize each resultant cluster. These are presented in Table 4.1, which also contains columns to indicate the number of provinces that are members of that cluster at some point in their development pathway ('# Prov.'); and to indicate the total number of data points that are members of each cluster across the dataset ('# Obs.'), illustrating the size of each cluster.

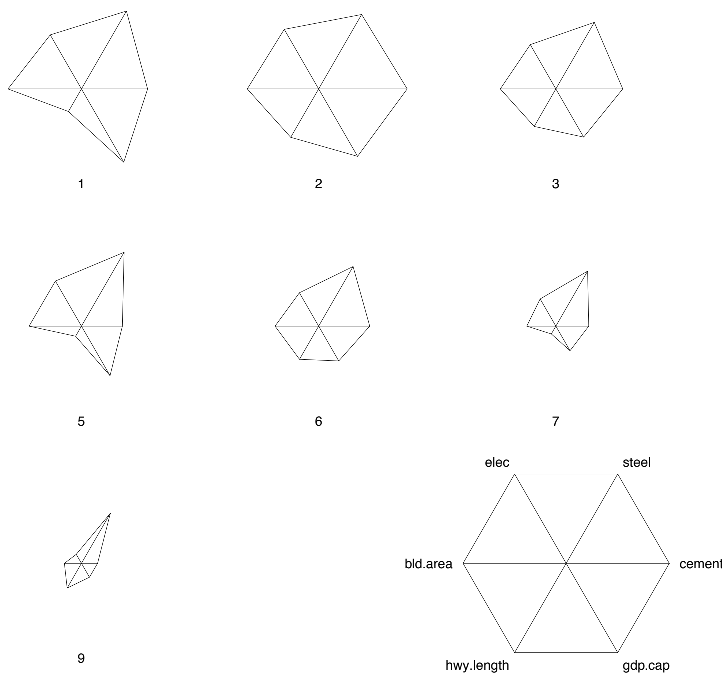
The cluster means are also visualized in Figure 4-1 using radar plots, which represent each cluster mean as a single hexagonal plot. The length of each radar plot's 'arms' is proportional to that arm's normalized indicator value, with the relevant indicators identified in Figure 4-1's key. Longer arms thus mean larger values, but one cannot easily compare the values of one indicator with another due to the scaling and normalization processes. One can, however, still compare the same indicator across clusters. The numbering of the clusters is not meaningful; in this case, they are merely ranked in descending order of annually constructed building area.

These are simple mean averages so variability within each cluster may be fairly significant; this is something that may merit further exploration.

I characterize these nine clusters as follows, based solely on their mean values, or 'centers':

1. The first cluster is characterized by the highest GDP, built area, and steel production means among all clusters; has high electricity production; medium cement production; and low highway construction. This cluster is dominated by three out of the four urban provinces: Beijing, Shanghai, and Tianjin, which together comprise 80% of Cluster 1

Figure 4-1: Cluster mean radar plots (k = 9)



observations.[1] This is also the cluster featuring the smallest total membership, with only 49 observations across the dataset.

2. The second cluster is characterized by high values nearly across the board, with the highest means for cement and electricity production and second highest for each other indicator. 27 out of the 30 provinces analyzed are members of Cluster 2 in at least one year during their pathway – all except Shanghai, Tianjin, and Hainan.[2] No province is a member of Cluster 2 prior to the year 2002, and all provinces except Beijing, Shanghai, Tianjin, and Hainan (for which there is no 2012 entry) are members in 2012.

3. The third cluster is characterized by medium-high indicator values nearly across the board. As such, it is basically a downscaled version of Cluster 2, as is clear from a glance at Figure 4-1. Shanghai is technically the only province that never enters

[1]The fourth, Chongqing, did not become a province-level municipality until 1990, and its boundaries are defined such that it is significantly less urban from a density perspective. While the population densities of Beijing, Shanghai, and Tianjin are each greater than 1,000 persons/km^2, Chongqing's density (within its provincial boundary) is only 370 persons/km^2. This is closer to the population density of Sichuan (170 persons/km^2), the larger province of which it used to be a part, and still less than the total population density of Guangdong (590 persons/km^2).[40]

[2]Beijing is also only a member of Cluster 2 for one year, 2006 – and probably shifted into that cluster due to that year's spike in highway construction (see Section 3.2.3).

Cluster 3, and the cluster's total membership also appears to be deflated due to some 'theft' on the part of Cluster 4 in 2001 and 2006.[3]

4. The fourth cluster is characterized by medium indicators in all categories except highway construction, for which it has the maximum mean across all clusters. Membership in Cluster 4 is dominated by the years 2001 and 2006, with 8 and 24 observations in those two years, respectively – accounting for more than half of the 61 total observations. In the raw data, these two years see significant spikes in highway construction (see: Section 3.2.3), which seems to lead to the formation of this cluster in the first place. Nonetheless, Cluster 4 membership does persist outside of these two years in several provinces: namely, Gansu, Guizhou, Qinghai, Shaanxi, and Sichuan. These five provinces share borders in central and western China, suggesting that this cluster's characteristics may be somehow particular to that region.

5. The fifth cluster is characterized by medium cement and electricity production, built area, and GDP; low highway construction; and high steel production. The 'shape' of Cluster 5 is similar to that of Cluster 1, with all indicators except steel production notably downscaled. This is reflected in the membership of Cluster 5, which overlaps with the membership of Cluster 1, though dominated even more so by Beijing, Shanghai, and Tianjin, which together comprise 83% of Cluster 5 observations.

6. The sixth cluster is characterized by medium-low indicator values nearly across the board, similar in shape to (but smaller in size than) Clusters 2 and 3. As is the case for Cluster 3, Shanghai is technically the lone province that is never a member of Cluster 6. This cluster also has the largest total membership, with 177 observations across the dataset.

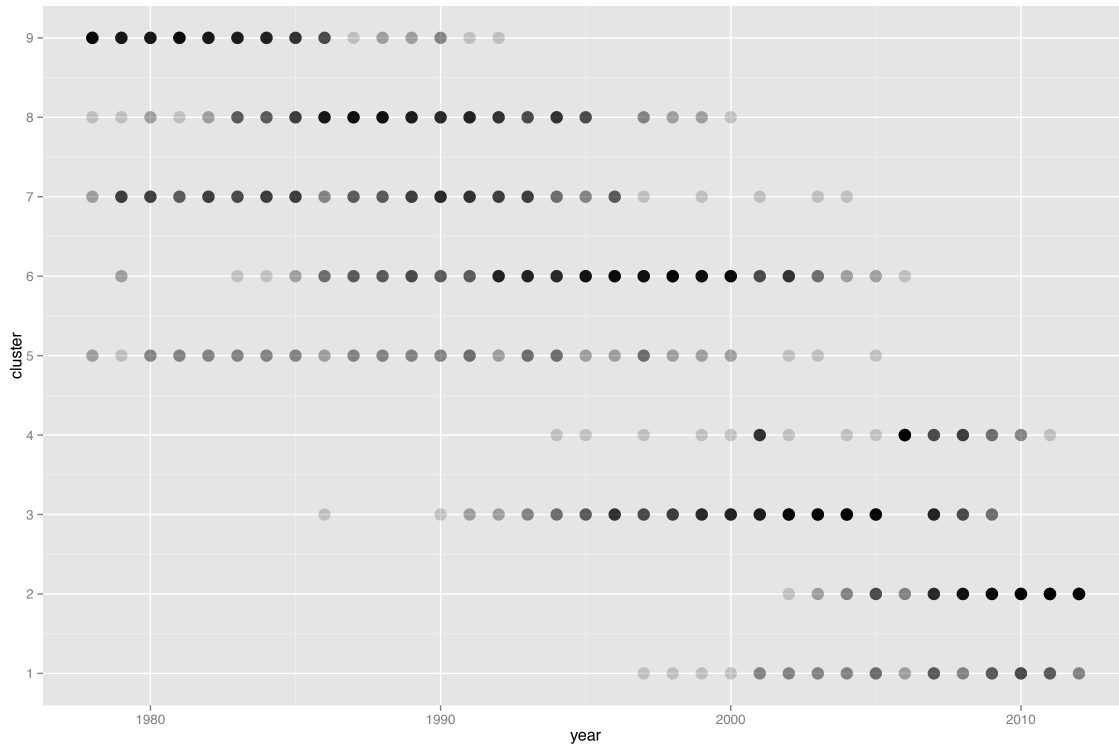
7. The seventh cluster is characterized by relatively low indicators across the board[4], and the lowest highway construction of all clusters. Membership is moderately well-distributed across provinces, but there remains some concentration, particularly in Gansu, Hubei, Ningxia, and Qinghai provinces, located in central and western China.

8. The eighth cluster is characterized by relatively low indicators across the board, similar to Cluster 7 except with respect to highway construction, which for Cluster 8 is notably higher (though still lower than that of Cluster 6). 24 provinces call Cluster 8 home at some point in their pathway.

[3] I propose that such 'theft' is indicated by instances where a multi-year series of Cluster 3 memberships is interrupted by single-year Cluster 4 membership in the two years when Cluster 4 membership is unusually high – 2001 and 2006. This argument is reinforced by the fact that, besides the highway construction indicator, the means for Clusters 3 and 4 are similar.

[4] Steel production appears fairly moderate on the normalized 0-1 scale, but this is due to the fact that the range is skewed (see Q-Q plots in the Appendix, Figure A.1).

Figure 4-2: Temporal distribution of cluster membership



9. The ninth cluster is characterized by the lowest cement production, steel production, electricity production, built area, and GDP means across all clusters; and medium-low highway construction. 21 out of the 30 provinces included in this analysis appear in Cluster 9 at least once.

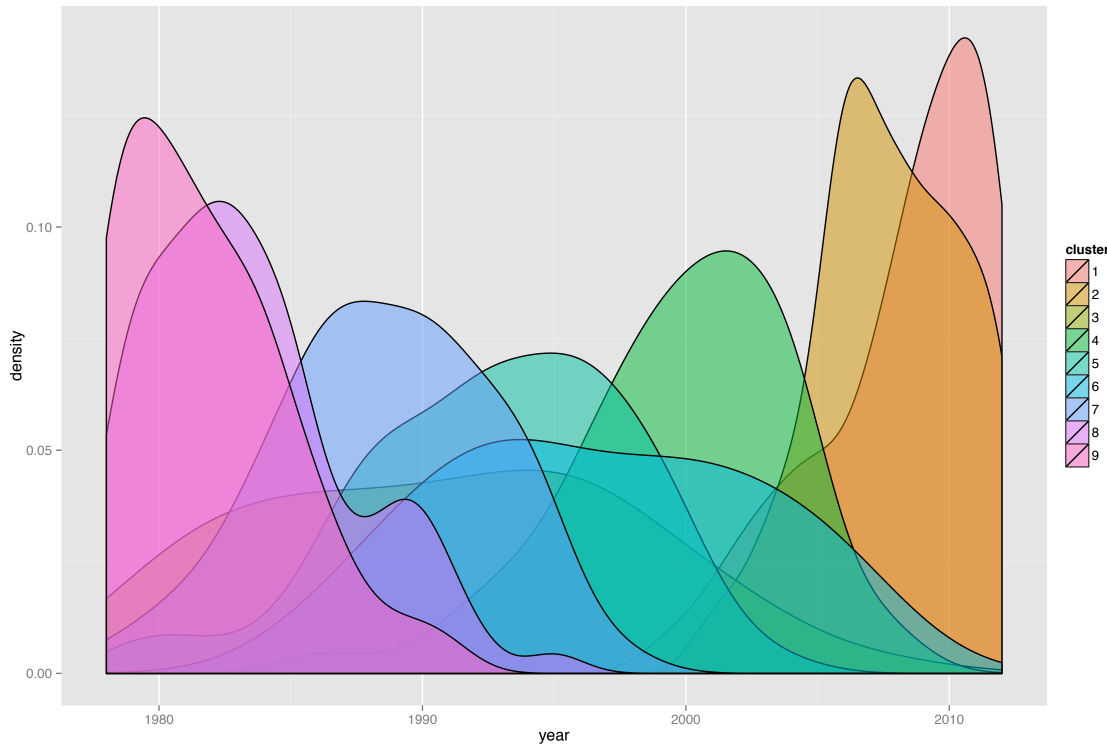
One of the major appeals of clustering analysis is its potential to represent discrete development 'stages' by allowing provinces to have different cluster membership at different times. This opens the door to tracing the cluster membership of each province through time. I term the full progression of cluster membership through time for each province to be that province's cluster "pathway". The cluster pathway and the comparison of these pathways is the core of the analysis. These pathways represent transition stylistically as the move from membership in one cluster to membership in another.

Some visualization can help facilitate this comparison. Figure 4-2 shows broad trends in aggregate, with opacity proportionate to the concentration of cluster membership in each year (darker = higher concentration); as of 2012, all provinces have entered clusters 1 or 2.

Figure 4-3 shows the temporal density of clusters over time. The density curves have area equal to one; so their relative heights are not meaningful. These curves merely represent the temporal distributions of each cluster in a different way.

Two generalized pathways emerge from this analysis, which I have characterized as 'urban' and 'business-as-usual' (BAU) pathways. These pathways proceed from cluster to

Figure 4-3: Temporal cluster density



cluster as shown in Table 4.2.

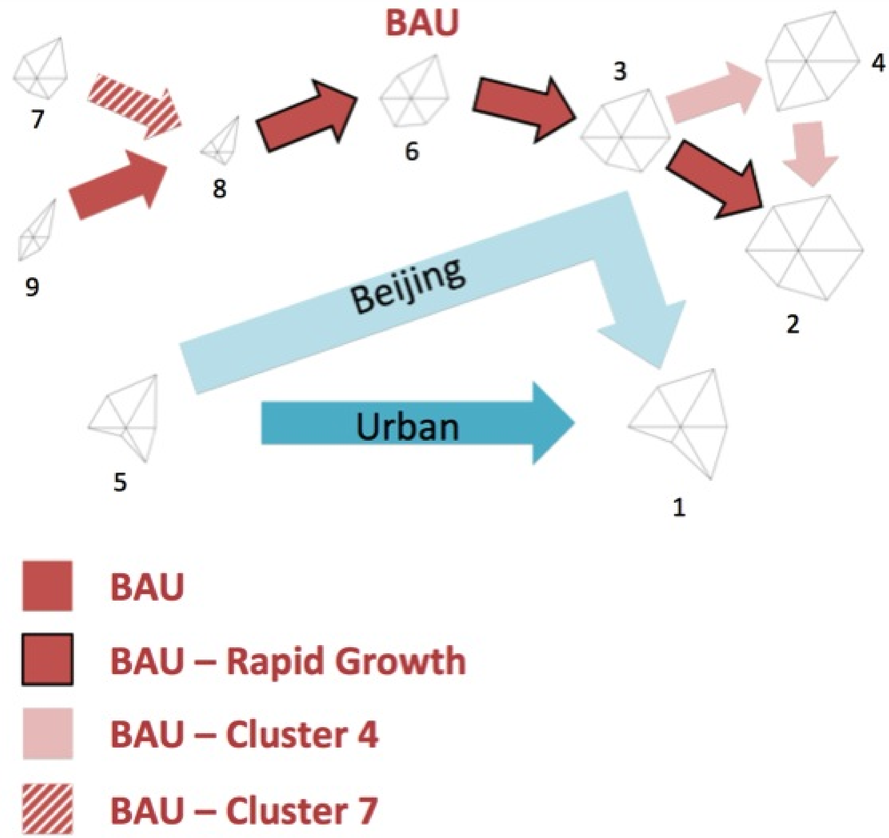
Clusters 4 and 7 are notably absent from these two pathways. Cluster 4 is not consistently represented in the pathways of the 30 individual provinces. The clear influence of outliers in the highway length indicator on Cluster 4's shape limits its generalizability. Besides spikes in membership in 2001 and 2006, it was only included in the cluster progressions of five provinces – which were all otherwise similar to the BAU path. Cluster 7 is also not consistent across a sufficient number of provinces to merit inclusion in the generalized pathways; though provinces with membership in each of these clusters will be explored as possible sub-typologies of development in Section 4.1.2.

The clear emergence of these pathways is itself an interesting result. One of the hypothe-

Table 4.2: Generalized provincial pathways

Pathway	Cluster progression	Sub-pathway	Sub-progression
Urban	5 –> 1	Beijing	5 –> 3 –> 1
BAU	9 –> 8 –> 6 –> 3 –> 2	Cluster 4	9 –> 8 –> 6 –> 3 –> 4 –> 2
		Cluster 7	7 –> 8 –> 6 –> 3 –> 2
		Rapid growth	8 –> 6 –> 3 –> 2
		Chongqing	3 –> 6 –> 3 –> 2
		Hainan	9 –> 7 –> 8 –> 6 –> 7 –> 6 –> 3

Figure 4-4: Generalized provincial pathways



ses giving rise to this work in the first place was that transitions may be observable between identifiable development 'stages', each characterized by a recognizable resource use profile. While I have used clustering in hopes of identifying clusters as proxies for such stages, the differentiation between clusters themselves appears to be less meaningful than the complete provincial development pathways into which those clusters are organized.

4.1.2 Variation across provinces

By grouping provinces into one pathway or another, I have effectively created a two-group typology. In the first group, provinces following the urban pathway include Beijing, Shanghai, and Tianjin. All 27 other provinces follow the broad BAU pathway. The variability within these two pathway 'types' – and in particular within the much larger BAU type – is not captured in this two-group typology, so I draw further distinctions to explain variation across provinces and to propose a sub-typology of development pathways. These pathways are displayed in Figure 4-4.

Shanghai and Tianjin both transition from Cluster 5 to Cluster 1 in 2001. Beijing demonstrates slight variation from the generalized urban (5 –> 1) pathway, making a detour to Cluster 3 as an intermediate step (5 –> 3 –> 1). Beijing transitions from Cluster 5 to 3 in 1991, and then from 3 to 1 in 1997.

The BAU type in general has higher cement production and highway construction, but lower electricity and steel production, building construction, and GDP than its urban counterpart. In broad strokes, BAU-type provinces progress from Cluster 9, with low indicators across the board, to Cluster 2, where all indicators are significantly higher. Growth in all six indicators is monotone increasing through the generalized cluster progression (9 –> 8 –> 6 –> 3 –> 2), with the largest changes observed in electricity production, cement production, built area, and GDP. The equivalent changes in the urban-type pathway are less pronounced, in part because they are separated into only two cluster stages and in part because the urban type provinces had a developmental head-start.

I identify several possible sub-typologies, which could be further explored through a separate clustering study that would analyze cluster progressions only in the non-urban 'BAU' provinces. Here, I will highlight five distinctive cases: those that pass through Cluster 4 (Gansu, Guizhou, Qinghai, Shaanxi, Shanxi, and Sichuan); those that pass through Cluster 7 (Gansu, Heilongjiang, Hubei, Jilin, Ningxia, Qinghai, and Shanxi); Chongqing (and its unique relationship with Sichuan province); Hainan; and Jiangsu and Zhejiang.

The first sub-type transitions from Cluster 3 –> 4 –> 2 (while otherwise more or less following the generalized BAU pathway), with membership in Cluster 4 persisting for three or more years and beginning in 2005 or 2006. While the majority of provinces' membership in Cluster 4 appears to be a statistical anomaly confined to 2001 and/or 2006, these provinces' membership persists for several years, suggesting a more distinct and meaningful transition. Because Cluster 4 is characterized by particularly high highway construction, provinces in this sub-type are likely to have had rapidly growing highway systems during this era. This period aligns well with the implementation of China's 'Go West' policy, which was announced in 2000 to catalyze development in five out of the six provinces (all but Shanxi) in this cluster.

The second sub-type is distinct because of the prevalence of Cluster 7 membership in the early years of the study period, with a generalized progression of 7 –> 8 –> 6 –> 3 –> 2. Cluster 7 is characterized by low highway construction relative to Cluster 8, which is otherwise similar. These seven provinces are geographically disperse, though it is worth nothing that none are among the provinces typically considered part of the eastern region (Jilin and Heilongjiang are commonly grouped with Liaoning as China's northeastern provinces). The lack of highway construction at this early stage indicates that the development of these provinces likely lagged behind the eastern provinces while investment in 'eastern' development was still the central government's priority.

There is an interesting overlap in membership between the Cluster 4 and Cluster 7 subtypes, which includes Gansu, Qinghai, and Shanxi provinces. This overlap suggests that an approach like fuzzy clustering may provide useful results, since it allows for the sorting of individual data points into multiple clusters. In this way, a fuzzy clustering approach

Figure 4-5: Map of Chinese provinces

(Wikimedia Commons)

explicitly acknowledges the fact that these clusters do not represent clearly delineated groups.

Without considering time, Chongqing's development pathway (the third sub-type) at first appears quite distinctive, as it skips 9 & 8 and follows a 3 –> 6 –> 3 –> 2 pathway; but Chongqing effectively came into existence in 1990, when it separated from its 'parent' province, Sichuan. The fact that its cluster membership is different from Sichuan's at 'birth' provides further evidence that urban resource use is distinct from provincial resource use, and generally outpaces it. This result challenges practices of data scaling, even from the provincial level in China down to the urban scale.

Hainan is another unique case, whose pathway (9 –> 7 –> 8 –> 6 –> 7 –> 6 –> 3) is both frenetic and uncertain due to missing data at both ends of the time series. Hainan stands out not only because of its unique pathway, but because it is an island and thus may be expected to develop in a distinctly different manner from the mainland provinces.

Jiangsu and Zhejiang together comprise the fifth BAU sub-type, not because they deviate from the typical pathway (they are 8 –> 6 –> 3 –> 2 and 6 –> 3 –> 2, respectively) but because they advance cluster membership earlier than any other provinces in the group. They are high outliers in per-capita building construction and outgrow their BAU-type peers in GDP growth. These observations are reinforced by their geography, which places them in close proximity to Shanghai and along the east coast.[5]

These five sub-types represent only one means of dividing the results of this clustering analysis, and they are also visualized in Figure 4.2. These sub-typologies add some nuance to the higher-level distinction between urban and BAU provinces.

What is it, in the end, that distinguishes the urban type from the BAU type? In general, the differences are fairly intuitive given the distinct difference in scale between the urban-type and BAU-type provinces. Further, in part because they are effectively cities and in part because of their particular histories, the three urban-type provinces were already significantly further along in their development at the beginning of the study period. Their development was also accelerated by their trade-enabling coastal geography and the central government's explicit priority for development along the coast and in its major cities.

These historical realities explain the distinctly lower highway construction, the clearest differentiating factor between the urban and BAU types. While highways have been expanded significantly in the urban-type provinces, their highway infrastructure was already more robust on a per-capita basis by virtue of the fact that highway infrastructure in cities will always be more concentrated at the urban scale compared with others.

Comparing the two types across the other five indicators requires some temporal nuance, as those relationships are not consistent through time. The period of time during which Cluster 5 is dominant for the urban provinces also sees the BAU provinces transition from Cluster 9 –> 8 –> 6. The transitions from Cluster 5 –> 1 (urban) and 6 –> 3 (BAU) occur in 2001, with the following 11 years dominated by Cluster 1 for urban provinces, and

[5] Anecdotally, public perception of these provinces reflects a general understanding of these trends.[29]

seeing the transition from 3 –> 2 (in 2008) for BAU provinces. This temporal comparison highlights a limitation of this analysis, which is that comparing trends among these clusters must be heavily qualified by noting that they are averages across large groups of data points, so do not reflect the dynamic nature of changing resource use year-over-year.

In the early years of this analysis, Cluster 5 indicators are significantly higher than Cluster 9 indicators in every category except highway construction. By the time BAU provinces have transitioned to Cluster 6 (1992; following the Cluster 8 transition in 1986), they have caught up in cement production but continue to lag in the remaining for areas. Because cement production is correlated to constructed building area, the fact that cement production in the BAU type overtakes the urban type while building area does not suggests that urban type provinces had already begun to outsource cement production beyond their provincial boundaries.[6] Comparing clusters after 2001, the urban type continues to produce less cement and construct less highway, produce more steel, create more GDP, and construct more building area.

4.1.3 Explaining provincial variation

From this analysis, three things are clear. First, geography plays an important role in determining provincial development pathways in China, as development tends to move slower as provinces are further from the coast (or far to the north). Second, the planning priorities of the Chinese central government have played a significant role in shaping the country's developmental geography. Third, and more generally, provincial-level municipalities and [non-city] provinces in China have undergone distinct development pathways with respect to the building sector, though this differentiation appears to come from the rapidly rising tide of urban development – the effects of which are dampened in provinces that do not happen to also be cities.

The three urban-type provinces are exclusively in the east. The fourth provincial-level municipality, Chongqing, is in central China. Its removal from the coast and associated disconnect from the more developed eastern economic system, from trade routes, and from a longer history of economic development, make its pathway less distinct from the non-city provinces. Further, its larger geographic scope is likely to similarly dampen its city-like behavior in this analysis.

A handful of possible quantitative approaches are available to help explain the observed cluster membership variation in my analysis. I use regression-based random forest classification [26] to test the capacity of different variables to predict cluster membership. The most effective predictor is GDP, which is capable of explaining cluster membership in nearly

[6]While the same evidence of outsourcing is not evident in the other clusters, there is ample evidence to suggest that steel and electricity production have seen similar trends. Liu et al. observe particularly high rates of electricity import in Shanghai and Beijing[132], and the yearbook data I use in my analysis here makes clear a dramatic turnaround in steel production in the urban provinces, most notably in Shanghai. This is also visible in the Appendix (see Figure A.2).

80% of cases. The second and third most influential predictors are constructed building area and year, at 72% and 69%, respectively; electricity and cement production predict 67% and 66%; steel production is a weak predictor at 45%, and highway length weaker still at only 12%.

With the exception of year, all of these are obviously variables included in the analysis itself, so one might expect them to have similar predictive capacity. Trends in steel production and highway length are less consistent across provinces, however, and while that in some cases can make them influential in the output of the clustering algorithm it does not lend itself well to predicting cluster membership overall. On the other hand, I expect GDP to be related roughly to the stage of a province's development, and thus in general to be a relatively good predictor of cluster, which in this analysis is meant to be a proxy for that development stage. The logic is similar for built area, cement production, and electricity production. It should also not be surprising that year is a good predictor, as development during the study period followed a fairly consistent trend over time.

Using analysis of variance (ANOVA) to evaluate clustering results is tempting, but I resist this temptation for two reasons. First, this dataset does not satisfy the assumptions required for two-way ANOVA (normal distribution of errors, independent observations, equal variance). Second, ANOVA effectively compares differences in the means of distinct populations – in this case, the clusters – to test whether they are significantly different (statistically); yet, the k-means algorithm is explicitly designed to optimize for distinct cluster means, making the ANOVA test somewhat redundant.

In an earlier draft of this analysis, several of the heavily steel-producing provinces together formed distinct pathway: Tianjin, Hebei, Shandong, and Liaoning. Given the annual steel production trends shown in the Appendix (see Figure A.2), this was not a surprising result. In the final analysis, I do not observe such a pathway. This may be in part due to my introduction of the highway construction indicator between these two, which was not included in this earlier analysis; additionally, I updated the data scaling and preparation methodology in between the previous analysis and this final version.

I bring this up only to highlight that this clustering can fail to capture trends that for some provinces are of great importance, even when relevant indicators are included in the analysis. The rise and in some cases the fall of the steel industry could have significant consequences with respect to the sustainability impacts of a given province and the surrounding provinces alike.

The pervasiveness of the "business-as-usual" (BAU) type is a surprising result; I expected to see clearer differentiation among provinces. The mechanics of the k-means clustering algorithm and the sheer size of the BAU pathway's membership suggests that it is defined more by the distinctness of the urban pathway than by any particularly strong characteristics of its own. The sub-typology compensates for this to an extent, but the differences in those pathways are subtle and one must dig a layer deeper than the generalized development pathways to find it in the analysis.

The BAU pathway itself is useful, however, because it can potentially shed light on what development looks like under the 'default' scenario, providing a benchmark against which to measure and/or plan improvements in development trajectories. By understanding the BAU pathway, those seeking to influence transition may be better able to gauge their success in escaping the aspects of system lock-in that typically lead to the default outcomes observed in the BAU-type provinces.

4.1.4 Quantitative conclusions

The timing of transitions between clusters appears meaningful in some cases, as for the widespread transition observed in central and western provinces following the implementation of China's "Go West" policy. This also serves as a clear example of the implications of various types of policy on high-level resource use.

This approach to the longitudinal clustering of resource use data offers a means of understanding high-level trends in development processes at various scales, and can improve practitioners' ability to compare sustainability performance. While I use statistical clustering in hopes of identifying clusters as proxies for such stages, the differentiation between clusters themselves appears to be less meaningful than the complete provincial development pathways into which those clusters are organized. This suggests that historical trends of resource use, and not just current resource use, should be taken into account when contemplating policy decisions with resource use implications.

At the same time, the mechanics of the k-means clustering algorithm and the sheer size of the business-as-usual pathway's membership suggests that this pathway is defined more by the distinctness of the urban pathway than by any particularly strong characteristics of its own. My sub-typology compensates for this to an extent, but this distinctness highlights the fundamental difference in urban versus provincial resource use.

Urban resource use is distinct from provincial resource use, and generally outpaces it. This result challenges practices of data scaling, even from the provincial level in China down to the urban scale. The data limitations of this study also suggest the need for improved data collection and standardization practices in China.

The tradeoffs in a machine learning analytical approach depend strongly on the choice of indicators and timeline; many combinations of both, as well as analysis of other sectors and spatial scales, make the list of possible future applications of this method substantial.

4.2 Framework

In this section I organize the thinking that guides my qualitative analyses, and which may prove useful to those wishing to understand sustainability transition. This framework provides structure for the discussion of potential triggers of and barriers to transition, and comprises five governing systems – economic, social, political, natural, and technological – that place transition dynamics in a broader societal context.

4.2.1 Governing system analysis

What drives urban sustainability transitions to occur? What prevents them from occurring? How can we compare transitions occurring in different cities around the world, or even within a single country?

In order to even begin to address these questions I find it helpful to construct a framework within which to discuss them. Towards this end, I build on a framework proposed by Bai et al. [11].

Bai et al. use a qualitative approach to analyze 30 sustainability experiments in Asia, applying a framework that is rather more descriptive than forward-looking, separating past transitions into the five categories of: triggers, actors, linkages, barriers, and pathways. Case studies are divided further on the basis of pathways (or outcomes, alternatively), which could include up-scaling or 'mainstreaming' of a given innovation; experiment multiplication; or the addition of further experiments.[11]

I use this framework as the structure of my qualitative analysis. I discuss Bai et al.'s linkages primarily in the context of knowledge sharing; pathways primarily in terms of specific, generally ongoing sustainability experiments in the Chinese building sector; and actors in approximately the same sense that Bai et al. do. Finally, triggers will be generalized transition triggers, and along with barriers will be put into the context of the theoretical framework that immediately follows. This framework extends the work of Bai et al. by adding the following proposed modification.

To analyze sustainability transitions I find it useful to differentiate between triggers of and barriers to transition, and suggest that these triggers and barriers may fall into five categories – economic, social, political, technological, and natural – which constitute the broad systems that together govern resource intensity and, ultimately, sustainability outcomes. At the risk of challenging the reader to brainstorm exceptions, I intend that these five categories can provide a comprehensive framework for placing transition triggers and barriers alike into context. The five systems proposed are as follows:

- **Economic** – Economic changes influence resource use indirectly, and arise from firm decision making in response to consumer demand. The economic system of interest does not just comprise the urban economy, as changes in national (and even global) economies can have significant localized impacts.[39] Some local economies are more resilient to changes in the larger economies of which they are a subset, but that is dependent on both the nature of the greater system changes and the structure of the local economy in question.

- **Social** – Social changes tend to happen over the course of longer time scales, but can induce large changes in resource use patterns. Fertility rates, family structure, education choices, and fuzzy considerations like "conservation ethic" can add up to make significant contributions to sustainability outcomes; all of these things fall under the umbrella of 'cultural norms'. These changes are difficult to purposefully influence, and even when doing so is possible it can be ethically questionable. Some social transitions may be steered, however, by social movements. Barriers to such movements are often political or institutional, though a potentially larger challenge is embodied by Olson's collective action problem.[7][149]

- **Natural** – Change in the natural system comprises both rapid (natural disaster) and gradual (climate change) impacts, and can have a wide and uncertain range of consequences in terms of resource use outcomes. One might expect a hurricane, for example, to increase resource use on net. Even though local resource use probably decreases in the short run when people are displaced from from their homes, those people are consuming resources elsewhere. Clean up and/or rebuilding efforts also require an influx of resource use, and significant waste is created in the process.

- **Political** – The political system exerts significant influence over resource flows by virtue of its ability to set policy. At the local level, this influence is derived from multiple levels of governance, including national, subnational, and increasingly international influence. It is not only explicit policy decisions that can influence resource flows: indirect consequences of various political processes can have significant impacts as well. The perception of a potential or impending change in policy; the threat of instability; or the election/appointment of an ally to a particular industry, can all influence the way that resources are consumed in cities.

- **Technological** – Understanding 'technology' in a broad sense (as in Section 1.2.5), the influence of technological choices on the daily lives of individuals, on the resource-intensity of local firms, and of the built environment generally on direct energy use and transportation decisions alike, is hard to overstate. A tradition of architectural style, for example in a historical preservation district, can constrain choices for material use, not to mention the energy performance of the buildings themselves. Information and communication technologies (ICTs) have the potential to rapidly induce changes in material and energy use, as a broad array of mobile apps and gadgets enables the 'smart city'.

Keep these descriptions of how these five systems influence resource use in mind as I consider some fundamental questions about these systems' relevance to transitions.

[7] The collective action problem represents the increasing challenge of coordination in large groups of people, which has historically scaled super-linearly. Technological opportunities to overcome collective action problems are increasingly common, for example the use of online social networks to facilitate organizing on various scales.[168]

4.2.2 Who wields influence in these systems?

Actors within these systems are in many cases able to influence resource use outcomes. In this section I discuss who some of the key actors are within these systems that are capable of doing just that. With respect to the natural system, which does not act purposefully, I instead discuss the role of human influence in altering the way the natural system acts.

- **Economic** – Actors in the economic system are somewhat disperse as supply and demand are determined by firm networks and consumers writ large. The economic system these actors comprise extends far beyond urban economy, as changes in national (and even global) economies can have significant localized impacts.[39] Some local economies are more resilient to changes in the larger economies of which they are a subset, but that is dependent on both the nature of the greater system changes and the structure of the local economy in question. The economic failure of the automotive industry in Detroit has affected resource use in the city, for example.

- **Social** – The media, various marketing efforts and advocacy organizations, the internet, and social interactions writ large collectively influence the cultural norms that shape resource use. This set of actors is thus highly distributed, and the ability to actively effect any kind of normative, directional change is an uncommon talent. Most transitions in this arena are likely emergent phenomena more than the result of any particular agenda. As such, the social drivers of resource use-influencing trends are difficult to pinpoint.

- **Natural** – It may now be a legitimate question to ask whether human influence or that of nature itself exerts a stronger impact on the natural system, but the answer is relatively immaterial. In either case the body of evidence suggesting that humans collectively exert significant influence over the natural systems, and in particular the climate system.[107] Because reducing impacts on the natural system is the ultimate goal of this entire undertaking, this is a special case in which the influential actors are basically comprised of the sum total of all the actors relevant to the other four governing systems.

- **Political** – The government is the primary actor in the political system by way of its ability to set policy, though it is not alone. The level of influence that various groups are able to exert over the political system will vary significantly from country to country and city to city depending on the legitimacy of the government, the structure of the political system, citizen engagement, and political capture from influential firms or industries. One would hope that preferences of local citizens are influential, though the degree to which that is true varies. Firms and industrial lobbyists can also exert considerable political influence particularly in cases where an industry represents an outsized proportion of a local or regional economy.[173]

- **Technological** – Technological change is enabled by a vague set of 'innovators', who in turn are supported by various private and public sector actors. Technology is often designed in response to consumer needs and demands, but it is also capable of shaping those demands in a coevolutionary process.[192] The public sector can provide incentives and direct investment to firms who are developing new technology, as in various cities' support of particular industries – for example those who follow the example of Silicon Valley in supporting the tech industry.[8] Local governments exert fairly direct influence over the built environment, though national and subnational government, as well as multilateral organizations, are also often part of decision-making for major infrastructures like the highways that connect cities to each other and their surroundings.

4.2.3 When do these systems impact resource use?

Each of the five systems may act as a trigger of or barrier to altering resource use, though they each do so at different time scales. It is challenging to dramatically reduce resource use at short time scales, though undesirable resource use 'shocks' are possible. At longer time scales, both types of change are possible.[9]

- **Economic** – The economic system is dynamic in both the short and long-term. Gradual economic growth (medium to long-term) and economic crashes alike may trigger transition, while the structure of the economy itself may be a barrier. Other attributes of the economic system, for example the inequality of wealth, may also act as barriers to transition. The economic considerations of firms may act as triggers (when this calculus changes, for example – though while this may be in response to other economic issues, it is perhaps more often in response to changes in technological and political systems) or barriers to transition, for individual firms or aggregations thereof. The impacts of change in the economic system can be quite immediate, but almost never without long-term impacts.[10] The dynamic and complex nature of the economic system both makes it hard to measure such long-term impacts or attribute them to any particular cause, but they are ever-present.

- **Social** – Even the most successful social movements generally take many years of concentrated effort and activism to achieve success, and few social movements have ever truly ended. Fixing one social problem generally highlights another, hopefully of smaller magnitude. Shocks to social systems will be extremely rare, for the same

[8] Cities can also be entrepreneurs themselves; see, e.g. Mesh [139].

[9] For the purposes of this discussion, I consider short term to be on the order of 0-5 years; medium-term to be on the order of 5-20 years; and long-term to be anything greater.

[10] A persistent frustration of contemplating transition is that it is fairly common for negative consequences to occur in dramatic and unexpected fashion; positive change, however, almost exclusively comes about gradually over longer periods of time.

reasons that social movements are hard to catalyze. Within individual cities, immigration can occur quite rapidly relative to the size of a city, and thus is capable of effecting meaningful change in social dynamics on short time scales of 5 years or less. In general, social change will tend to occur on medium to long time scales, both as triggers and barriers to change.

- **Natural** – Changes in natural systems generally occur on extremely long time horizons, though some of the most relevant changes in natural systems manifest themselves at more or less discrete moments in time, as in the case of extreme weather events or natural disasters. Other weather events like drought may occur over the course of weeks or months. Drought as a temporary change should be distinguished from long-term changes in climate, as one decade's drought may be the next decade's business as usual. Even the impacts of gradual, long-term changes may manifest as short-term impacts, for example if sea-level rise crosses a particular threshold beyond which it results in significant impacts.
- **Political** – Triggers in the political system are mostly relevant on short time scales due to the importance of election cycles in political decision-making, although individual legal and policy choices can have profound impacts in the medium-to-long term. Different governmental structures also provide different limits with respect to term limits and election dynamics. This is further complicated by the reality that bureaucratic considerations often limit the speed at which political change, even when desirable, can occur.[2] With respect to transition barriers, both short and long-term effects are prevalent. Political considerations limit feasibility depending on who is in power and who wields influence over the government.
- **Technological** – Technological changes are probably occurring now more frequently than at any time in history. Yet significant changes from the perspective of the socio-technical transitions literature – meaning regime-level adoption of an innovative technology – often take more than 50 years, due to lags in adoption.[136] Barriers to adoption vary depending on the technology and the level of systems lock-in. Change in infrastructural systems, for example, may be accomplished over long periods of planning and construction. On the other hand, innovative ICT solutions may both be implemented and become widely adopted on relatively short time scales, though truly pervasive adoption generally takes at least a decade.

4.2.4 Where do these systems impact resource use?

Actors in each of the five systems exert influence over resource use at different spatial scales. In the cases of the economic and social systems, I suggest that geography's role is diminishing – but even in those cases it is valuable to maintain a spatial perspective on the influence of transition.

- **Economic** – Economic changes can take place at scales anywhere from hyper-local to international. Local economic changes have varying dependencies on economic changes at higher levels. It is the conditions of the urban economy that ultimately matter, but these are not independent of economies of other scales. The resiliency (inelasticity, in economic terms) of local economies to other, higher level economies is thus an important determinant of a city's susceptibility to transition.

- **Social** – Demographic transitions are most relevant at the national scale, in large population centers, and near geopolitical boundaries where immigration has strong impacts. While local and national identities are still relevant to social transition, community-forming niches are increasingly decentralized as information flows more freely over the internet and across geopolitical boundaries through globalized trade networks. Social movements can take shape anywhere from the local to the global scale, with transition barriers growing as that scale increases, due to the collective action problem.[149]

- **Natural** – Within the natural system, the relevant geographic scope is 'all', but communities vulnerable to the impacts of climate change will be most directly impacted. Rising sea levels place coastal regions at particular risk. Extreme weather conditions like drought affect a wide range of vulnerable geographies. Geographic features like mountains, coastline, or rivers constrain and/or guide urban development by nature of being physical barriers to urban expansion, as in the cases of Hong Kong and San Francisco. Significant natural changes to these geographic features are not likely to occur on time scales relevant to urban development, and thus are unlikely to be significant triggers.[11]

- **Political** – Political changes are largely constrained by political boundaries, though they are not immune to outside influence. Such outside influence will generally be exercised horizontally at the national level (i.e. across nations) or vertically within nations (i.e. between central and local governments). This is likely changing somewhat with the rise in international, cities-focused organizations like ICLEI and C40, though the impact of such organizations is still not pervasive.

- **Technological** – The geography of transition depends on the nature of the innovation in question, but can be relevant at all scales. For most technologies, the original innovation likely occurs in a city or perhaps a small set of cities, then spreads gradually to others.[12] Changes in the built environment may also be mandated in a top-down

[11]Technological changes to overcome these natural geographic features may, however, be triggers to transition, as in cases where new land is artificially added to cities.

[12]While particular technologies must be adopted by individuals or firms, their spread may in fact be traced city-to-city as local network effects remain important in technological adoption. For an example, one may look to any number of tech start-ups whose presence grows, at least initially, by city (Zipcar is an easy example).

fashion by central government, for example in the case of large-scale infrastructure projects like highway networks.

4.2.5 Summary

The theoretical framework laid out above illustrates the ways in which 'actors' in these five high-level governing systems influence resource use, and is used in the qualitative analysis that follows in order to contextualize my discussion of transition dynamics in the Chinese building sector. The result may be applicable at various scales both sectoral and spatial, and is summarized in Table 4.3.

Table 4.3: Theoretical framework summary

System	How	Who	When	Where
Economic	Industry; consumer demand	Firms; 'consumers'	Short - medium	All scales
Social	Cultural norms	Citizens; media	Long	Regional; national
Natural	Climate change; disaster	Humanity; earth systems	Short - very long	Vulnerable areas
Political	Policy; power dynamics	Government; its influencers	Short - medium	Political boundaries
Technological	Built environment; ICT	"Innovators"	Medium	All scales

4.3 Interview results

The quantitative analysis in this chapter is useful for understanding historical changes in resource use in the Chinese building sector, but it does not help us understand why resource use has changed, or how the sector's resource intensity might be reduced in the future. The qualitative analysis that I present in this section begins to fill these gaps – first by exploring the institutional context of the building sector in terms of its actors and their roles in the real estate development process; second by considering triggers of and barriers to reducing resource intensity in terms of embodied and operational energy in buildings; third by exploring the means by which building sector actors share information; and finally, by considering three case studies of experimentation that demonstrate potential mechanisms for altering resource use outcomes in the Chinese building sector.

My interviews in Beijing were ambitious in scope, so I do not attempt to cover their outcomes in full. Instead, I will focus on what I consider to be their core contributions, which are fourfold – consolidating knowledge about how exactly the development and design processes work in China; exploring ways in which that process is influenced by various stakeholders; discussing knowledge sharing practices among building stakeholders; and providing a few specific examples that demonstrate how altering these processes may yield improved sustainability outcomes moving forward. The second and fourth contributions utilize the framework proposed in Section 4.2.1.

I conducted 15 loosely structured interviews in total, with a range of stakeholders.[13] These stakeholders are primarily (though not exclusively) affiliated with international firms and organizations that have a presence in China. The types of stakeholders with whom I spoke are listed in Table 4.4; construction firms and experts with building materials-specific expertise are absent, though I do not believe this is limiting as I still spoke with several individuals with a background in these areas.

Table 4.4: Summary of stakeholders interviewed

Stakeholder	# of interviews
Real estate firms	1
Architects/designers	4
Cement and steel industry	2
Energy efficiency specialists	2
Sustainable cities experts	3
Buildings sector experts	3
Others	2

I provide a listing of sample interview questions in the Appendix (see Table A.6), which provides some insight into the topics I covered in conversation with interview participants. The interviews were relatively open-ended, however, and I followed their natural flow when unexpected and interesting topics arose.

The structure of the one-hour interviews touched on four discussion topics: general background, energy and materials use, current state of building policies, and best practice sharing. The background discussion generally consisted of clarifying the particular role of the firm and individual(s) with whom I was speaking with respect to buildings. This was often one of the most important sections of the interview, as it provides the basic understanding of different actors' roles and how each interacts with and perceives the others. This part of the interviews forms the basis of the first two contributions, which focus on various building sector actors and summarize how the real estate development process works in China (see Sections 4.3.1 and 4.3.2).

The second and third discussion topics inform my analysis of means to improve sustainability outcomes, which is spread over the embodied and operational energy sections (see Sections 4.3.3 and 4.3.4, respectively), in addition to the specific cases in Section 4.3.6. Finally, the best practice sharing discussion topic informs my knowledge transfer analysis, in Section 4.3.5.

[13]A complete listing of participants is included in the Appendix. See: Table A.5

4.3.1 Characters

I will first provide my understanding of the key stakeholders, their priorities, and begin to describe some of their interactions before detailing the development process itself. These descriptions are generalizations, so there will be exceptions; but they generally reflect the content of my interviews.

- **Government** – Government comprises all local, regional, and national agencies/officials who regulate land use and the built environment (e.g. mayors as well as the Ministries of Construction and of Housing and Urban-Rural Development). The Chinese central government has a difficult job, and a unique structure challenged by near-continuous reforms as the economy becomes increasingly market-driven. Much of the government's focus in the past several decades has been on increasing GDP and elevating hundreds of millions of its citizens from poverty. With increasing affluence and the increasing concentration of people in cities, they are adapting to the growing social pressures that arise from urbanization. One approach to adapting to these pressures is to effectively slow them, which they have accomplished by maintaining a unique suite of policies including hukou and land ownership/finance schemes (see Section 2.6 for a refresher). The land ownership and financing structures in particular incentivize local government to maximize lease revenues from land sale, resulting in increasing costs for developers and accelerated infrastructure construction. GDP remains the first priority for the central government, and perceived to be the primary performance evaluation metric for local governments as well, though there is some ongoing experimentation with alternative metrics for local officials.[190] This is exacerbated by the fact that land leasing makes up a significant percentage of local government revenues, making local governments reliant on a steady stream of high priced land leases.

- **Developers** – Developers are all public and private entities who acquire land and finance building construction on that land. Making money is firms' (and often local government's, in this context) primary directive. As is true for many industries in China, real estate development is in the midst of fairly significant consolidation; large developers become ever larger. When land costs rise, profit margins fall and pressure mounts to cut costs elsewhere. Firms negotiate with government to relax restrictions on development, while also remaining responsive to the desires of government officials, whether that means an increased concentration of public housing or a sustainable (either LEED or Three Star certified) design. These are neither 'bad' nor surprising behaviors; indeed, they are perfectly rational. Government developers often prioritize monumentalist design, and in any case their objectives are more diverse than developers'. Public construction projects can be used to increase societal well-being, alter perceptions of the government, test innovative design or construction techniques, in addition to their functional purposes.

- **Designers** – Designers are the set of non-government, non-developer, non-LDI individuals and organizations who determine the characteristics and form of the built environment. For the purposes of this discussion, however, I group them together because the challenges and concerns expressed to me were consistent across stakeholder groups. The lines between architects, landscape architects, urban designers, and private urban planners can be blurry, as government and development firms often expect broad expertise from the firms they hire. Indeed, the larger firms have capacity to specialize to a large extent, and thus can work on projects of varying scope. For smaller firms, this is a barrier to entry and requires significant flexibility. Interviews and informal conversations alike point to a persistent focus on monumentalist design, primarily driven by government. This attracts designers with ambitions to work on projects on large scales, seeking to capitalize on the robust market for new construction and make names for themselves. The scale and diversity of opportunity to design high-visibility projects – particularly following the 2008 financial crisis and the Chinese government stimulus package in 2009 – has attracted many international firms, and understandably so. At the end of the day however, designers' say in the process is more limited than in the US or European contexts. In general, a design firm's work is completed and then handed off to local design institutes (LDIs), who then work with the developer to complete final construction documents.

- **LDIs** – Local design institutes are the public or private institutions endowed by the government with the ability to certify final construction documents. LDIs play a crucial role in urban design processes at all scales. LDIs are generally public, though the number of private LDIs is slowly growing. LDIs are contracted separately from design firms, but can be hired to do the same work, and often collaborate with private firms during the primary design phase. After the design firms' work is complete (whether building-level, landscape-level, or at larger scales), LDIs are responsible for producing the final, construction-grade documentation that will reflect the ultimate, constructed project. The role of LDIs, whether public or private, is to ensure that building codes and regulations are met while satisfying the requirements of the developers that hire them.

- **Construction firms** – Construction firms are the private firms that physically piece together the built environment. Like developers, construction firms seek profits. While the choice of materials, structure, and the resultant construction techniques are generally dictated by the construction documents developed by LDIs (with developer and designer input), construction firms with specialized knowledge have the opportunity to influence these choices, particularly when they have existing relationships with relevant firms. Construction firms also generally oversee demolition processes, giving them a crucial role in determining materials recycling and/or reuse outcomes.

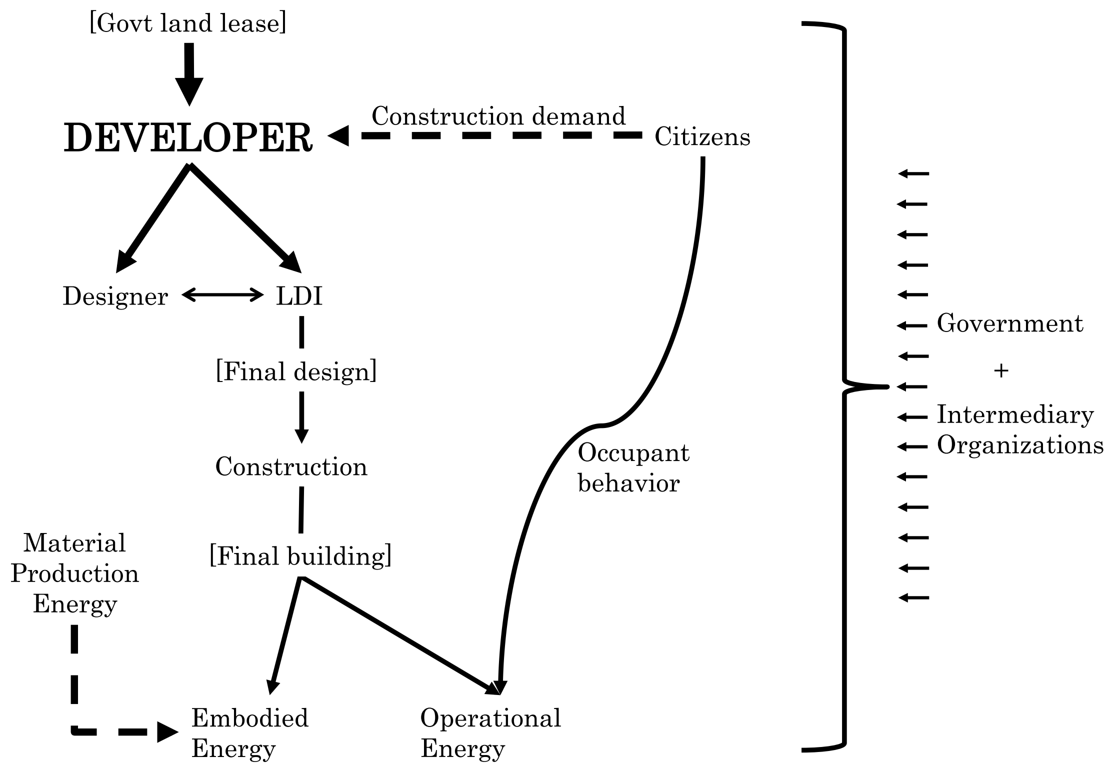
- **Property management companies** – Property management companies are private firms responsible for the rental/leasing and maintenance of buildings. They are profit-seeking enterprises as well, though their business model tends to rely on steady steams of income rather than large, one-time infusions. Property management companies are generally empowered to affect operational energy use in buildings, but may have limited incentive to do so if utilities are paid directly by tenants. These companies generally have limited-to-no connection to the design of the buildings they ultimately operate; they may be hired by building owners, or they may be the owner, having purchased the building either from a previous owner or direct from a developer.

- **Intermediaries** – Intermediary organizations can be any type of firm not included above, but which captures value of some kind in the building development process. Intermediary organizations can act in any number of supporting roles throughout the development process, from consulting to project design to financing. NGOs, multilateral organizations, specialized consulting firms, or even international governments can have roles of varying scope in all types of development project; from an energy efficiency consultancy providing input on a single-building project, to the Singaporean government's financial and direct participatory involvement in the Sino-Singapore Tianjin Eco-city.

- **Citizens** – Citizens are the tenants of the built environment; in residential settings, this can be anyone, and in commercial buildings it is typically employees of private firms. The two major sets of government policies that guide China's urbanization, those regarding land ownership/finance and hukou, effectively divide China's citizens into three groups. These groups have similar fundamental needs and desires, but require different types of support in order to have those needs met. Citizens possessing an urban hukou receive the most support from the government, primarily in the form of access to social programs. Migrant workers make up a significant percentage of total residents, particularly in the largest cities. Rural villagers living outside the city are significantly affected by urban development, as land at the frontier of urban development is seized by the local government for future lease to raise revenue. Beyond the urban fringe, populations are increasingly densified in order to free up further land for development. In all of these cases, citizens are remunerated for their 'trouble' – though in addition to the extreme lifestyle changes brought about by these land purchases, this remuneration sometimes falls short of government promises.[111]

I have visualized the relationships between these primary stakeholders and their impacts on life-cycle energy use in Figure 4-6. This stakeholder map serves as the foundation for Section 4.3.2, in which I outline the development process and the particular opportunities for and barriers to positively affecting buildings-sector sustainability outcomes. Arrows indicate influence, with larger heads representing the strength of that influence. Dotted lines indicate

Figure 4-6: Stakeholder map



indirect or aggregated influence, for example in the case of construction demand.[14] The role of both government and intermediary organizations runs throughout the process; government through regulation, and intermediary organizations through other avenues of influence.

4.3.2 The development process

Development projects can arise in a variety of different ways and can involve the participation of any number of different stakeholders. Here I outline my general understanding of the development process in order to highlight some of the important institutional relationships that have the potential to strongly influence sustainability outcomes. This understanding is derived from the full set of interviews I conducted, also drawing on principles discussed in Section 2.6 of the literature review.

The government must initiate development projects, either by proposing the project directly or making land available for lease[15], which is put on the market along with a list of

[14] For residential development, this line is even less solid given the likelihood that a developer will sell the development rather than leasing individual units.

[15] This process also generally requires a fair amount of advance planning, including infrastructure construction and considerations (both social and financial) of population displacement where relevant. This is particularly important for sites that are on the fringe of the city – which is where most new construction

restrictions (floor area ratio, zoning, public housing requirements, etc) for real estate firms to bid on.

Before going further, a note on land. High land values drive real estate speculation, especially in big cities. The local governments leasing land to developers have the incentive to set prices artificially high in order to raise revenue. This revenue is limited by the facts that (1) there is a ceiling on the total area of land that the local government is able to sell, due to quotas set by the central government, and (2) there is no mechanism for annualized land revenue or property tax, meaning that each lease provides only a one-time injection of revenue. As the government continues to sell increasingly scarce land further and further from the center of the city, land values in the central city rise in response.

This increase in value is generally a safe bet from the perspective of the developer, but in order to capture it the developer is obligated to build something. In some cases, the developer does not care what they build, because they know that the building is not the valuable part of this transaction; that would be the rights to the land itself. This can result in a nearly complete disregard for the quality of construction, including mandates for lowest possible construction costs and fast turnarounds in order to fuel profits. Because labor is cheap and construction regulations not strongly enforced, buildings rise at a breakneck pace.

Having leased a plot of land and decided what to do with it, the developer then delegates the design. Developers may assign design responsibilities to a particular firm (likely one with whom's work the developer is already familiar), carry out the design in-house, or put out a request proposals and choose a designer from the resultant submissions. International design firms tend to carry an air of prestige, in addition to a price premium. Accordingly, major international firms are hired primarily for the most prominent, well-funded projects. Developers may instead decide to hire a local design institute (LDI) on the basis of cost saving.

Developers can also solicit proposals by holding a formal competition. Submitted designs are typically judged by a panel of expert designers, who it should be noted may have a different conception of what constitutes a good design than the developer. This becomes important in the final design phase, because once the winning design is chosen the developer then finalizes it with a LDI, often without further direct input from the winning designer. This may result in a final product that looks radically different from the proposed design.

Competitions have the potential to generate significant business for designers, both directly (if a submission is chosen) and indirectly (through the exposure). This can be especially valuable for smaller firms. One urban design firm I spoke with spent approximately half of their time working on competitions. There are local and international competitions; international firms rather intuitively favor the international competitions, as they perceive these competitions to carry more prestige and to be more transparent.

Returning to the more general process, once the developer hires a designer, the designer

occurs.

generally works together with a LDI to develop a final product that reflects the developer's vision. This is in many cases a co-creative process involving all three parties, though one that can be challenging for designers. A developer's initial vision for a project will often lack both detail and clarity, providing a major source of frustration, and one which leads to a need for significant design overhauls and unusually many design iterations. These changes can be time-intensive, presenting a challenge for smaller firms with fewer financial and personnel resources (Eva Castro, Holger Kehne, Chuan Wang [Plasma Studio], personal interview, 12 Feb 2014).

Once the LDI has certified the final construction documents, construction firms are generally paid and managed by the developer (though in some cases they may be chosen and/or managed by designers). The Ministry of Construction or another relevant government body may inspect the construction site during the construction process to ensure that regulations are being followed, though this is not guaranteed and is a stage of the development process that is particularly susceptible to the influence of corruption. Once construction is complete, the developer either sells the property to a new owner or leases it out to tenants, whether those tenants be residential or commercial.

The difference between residential and commercial development is substantial and worth highlighting. In China, commercial development refers to all non-residential building construction. Besides a difference in building use patterns, the construction processes for these two types of development carry distinctly different incentives for developers. While it is relatively common for developers to build and operate commercial projects, residential developments are dominated by build-and-sell practices, which are driven both by a desire for rapid return on investment and by real estate speculators, willing to purchase residential units at above-market costs. The decision between selling and leasing has significant resource use implications, as a result of the incentives created in each market.

A building is more likely to be of lower quality when developers care more about the value of the land itself than the building itself, which is often the case for residential construction in particular. Because residential buyers are generally either first-time home owners or real estate speculators interested in capturing long-term land values, developers are able to build lower quality buildings while still turning sufficient profit. In some cases, residential units in a new building are sold before construction begins. Since commercial buildings make profit by leasing space to more discerning commercial tenants, the residential 'build-and-sell' approach is less common and incentives are stronger to produce high quality construction (Kevin Mo, personal interview, 14 Feb 2014). This distinction is important, as nearly three quarters of building projects currently under construction in China are residential.[43]

While the majority of building projects in China are new construction and will continue to be for quite some time, renovation or retrofit is also worth considering. The process in this case is similar to the above, but starting from an existing building and under constraints of zoning and possibly historical preservation, depending on the specific location of a property.

There remain uncertainties surrounding the retrofit process, particularly with respect to how ownership is transferred at the end of long-term land leases. Further, I have found little information (in interviews and otherwise) regarding end-of-life building materials recycling in China. Kevin Mo directs the Energy Foundation's buildings program in Beijing, and was skeptical of companies claiming to recycle significant quantities of building materials – in particular concrete, which is harder to capture value from than steel, for example (Kevin Mo, personal interview, 14 Feb 2014).

4.3.3 Embodied energy of buildings

There are a number of factors that influence both embodied and operational energy use in buildings. My interviews touched on both types of energy use, but in them I focused more on the embodied energy of materials (which I will refer to as embodied energy, for short), as in general the sector's understanding of embodied energy is relatively limited. In my interviews, people generally understood the concept, but did not have a strong background in it.

I consider four major factors to strongly influence the life-cycle embodied energy of a building: building quality, balance of building supply and demand, material choice and sourcing, and the industrial efficiency of material production. I will explore each of these using examples placed within the context of the five governing systems framework.

First, residential buildings in China have a reputation for having low quality, a reputation which was supported by my interviews. Oft-cited reports of collapsing buildings do not reflect business as usual – and construction in major cities does tend to be of higher quality – but these stories are indeed reflective of serious problems in the construction industry. How widespread these problems are, however, remains largely a mystery. What is it exactly that drives this poor construction?

Politically, the combination of local governments' land use financing mechanism and their focus on economic goals (namely GDP) puts pressure on the real estate system to deliver new buildings as fast as possible. Real estate developers, without fear of significant penalties, accelerate the development process to increase profits. Construction firms cut costs and corners. The pervasiveness of these practices is unclear – but it is the combination of rent-seeking behavior from construction firms, developers and the government alike that drives prices up and quality down (Kevin Mo, personal interview, 14 Feb 2014).

Another political concern is the enforcement of construction standards, which by most accounts is not strong. The only accounts I heard of high rates of compliance with Chinese building codes cited government reports, for which there are strong incentives for officials to overreport compliance.

Lynn Price and Ali Hasanbeigi of Lawrence Berkeley National Lab's China Energy Group acknowledge that enforcement is an issue, but also highlight the importance of building capacity to improve construction practices. According to Price, "... the need for extensive enforcement would be less burdensome if overall construction quality was significantly improved. The standard practices are relatively poor, and the capacity of construction enterprises overall needs to be increased." (Lynn Price and Ali Hasanbeigi, phone interview, 3 Feb 2014). It is also worth considering that stricter enforcement can itself drive firms to adopt improved practices, but this is not an 'either/or' choice. There is ample room for increased capacity for improved construction practices and stronger enforcement practices.

Perhaps even more fundamental, is another social barrier to change in the residential sector: demand for housing in China comes disproportionately from citizens purchasing a home for the first time. In the largest cities where land values are highest, there are limits to how many apartments one person or family can own, which limits demand from would-be individual investors. Home ownership remains a powerful status symbol in China, with these first-time buyers focused much more on the ownership itself than the quality (or qualities) of the apartment (Kevin Mo, personal interview, 14 Feb 2014). This provides developers with a blank check to build structures to the minimum possible standard of quality, knowing that they will be purchased.

This blank check of residential development is reinforced by a second category of home-buyer, the speculator, who also impacts the the next major embodied energy-determining factor: the balance of building supply and demand. Wealthy citizens often seek to invest in real estate by buying apartments in growing cities, knowing that as more people move to cities the values of those apartments will rise. Such activity is so pervasive that some major cities now limit the number of apartments that individuals can own.

Speculation gives rise to the phenomenon of Chinese 'ghost cities'. These neighborhoods or regions with large, unoccupied property developments are the poster child for the over-supply of buildings. These 'ghost cities' are primarily made up of residential buildings, due to the incentives discussed in Section 4.3.2.

This economic driver complements a social one, highlighted by analysis from the China Energy Group, whose building construction model forecasts significant declines in construction demand on the order of 5-10 years from now, primarily as a consequence of shifting demographics. For the time being, it is not clear that overbuilding is truly happening in the aggregate, in spit of the anecdotal [ghost city] evidence to the contrary. While there may be some overcapacity at present, long-run implications are the focus here. Before it was filled with businesses as it is today, Milton Friedman described Shanghai's Pudong district as, "Not a manifestation of the market economy but a statist monument for a dead pharaoh on the level of the pyramids".[4] Similarly, many of the currently empty developments will come to be filled in time. But as rural citizens' and business' migration to cities begins to slow down, so too should the construction to support said migration. If development otherwise continues in line with the China Energy Group's forecasts and such a decline in cement and steel demand is not visible in the next decade or so, there will be compelling evidence that over-building is occurring (Price and Hasanbeigi, phone interview, 3 Feb 2014).

Third is material choice and sourcing, which is dependent on both the accessibility and ultimate decision-making on the part of designers and, more importantly, developers. Accessibility has more than one meaning in this context. Less energy-intensive and otherwise more sustainable materials need to exist in the first place; need to be known to the designer and/or developer; and need to be affordable enough to justify purchasing.

Material selection thus has essential technological, social, and economic components. Technologically, the availability of sustainable materials is limited by both the set of materials that has been invented and the local availability of that material. The quality of the construction materials themselves is generally low across China. Price put it simply in our conversation: "The overall quality of building materials is pretty terrible in general, even in the big cities" (Price and Hasanbeigi, personal interview, 3 Feb 2014). As long as this remains true, designers and structural engineers must take the realities of material quality into account in order to ensure that buildings are safe (most importantly) and can last long into the future.

An additional [economic] factor is a general lack of reliable information on building materials – in particular, which types are available and what their environmental impact is. This is not a problem unique to China. Even if there were much higher demand for sustainable building materials, this lack of information would limit the efficiency of materials selection for designers and developers.[16] Further, price signals that endogenize the environmental and social impacts of material production could move the market towards less energy-intensive materials.

Last but not least is industrial energy efficiency. This is fundamentally a technological problem. Industrial firms, especially cement and steel producers, can be energy intensive, and thus have a major incentive to reduce energy use. Their willingness and ability to do so is limited by knowledge of feasible technological alternatives, access to those alternatives, hesitancy to disrupt production cycles, and high capital costs. These considerations are also affected by ongoing industrial restructuring both in general (away from heavy manufacturing and towards a more service-driven economy) and within particular industries, where production has tended to become more concentrated across a smaller group of large firms. With respect to the cement and steel production, Hasanbeigi et al. have evaluated opportunities for improvement much more thoroughly than I can hope to do here, highlighting the enormous potential for savings in these industries.[90, 89] The China Energy Group and Energy Foundation together played key roles in establishing the Top 10,000 Enterprises Program, which begins to address these challenges on a large scale, and which I will discuss in more detail in Section 4.3.6.

[16] This is the problem at which GIGA (discussed in Section 4.3.6) is taking aim.

4.3.4 Operational energy of buildings

The two general factors influencing operational energy for buildings are the design of a building itself and its day-to-day operations and maintenance. The choice of an energy efficient design requires the knowledge of how to accomplish this as well as the interest in doing so, on the part of both designer and developer. This means the technological choices regarding building structure itself, as well as the selection of the building's infrastructure, e.g. the HVAC system.

Final outcomes of the design process are sensitive to the incentives for developers and building owners, which in turn depend on the nature (commercial/residential) of the building as well as the structure of the development process (build-and-sell/build-and-operate). Split incentives between owners and residents are prevalent in housing and commercial rental situations, and are further exacerbated when the developer has no intent of operating their property. This means that the developer will never see energy costs, and thus does not have an incentive to make the building energy efficient. Such situations are especially common in the residential sector, where build-and-sell is standard practice; in the commercial sector, build-and-operate is more common.

The natural system plays an large role in operational energy use, as climate is extremely influential in the heating and cooling loads of buildings. In the case of China's heating system, climate also contributes indirectly to the problem of split incentives, as heating in northern China is publicly provided – meaning that residents do not individually see their heating bills. Maintenance and building systems commissioning (a technological challenge) also suffer from split incentive problems when the end user and building owner are not the same party and financial responsibilities are divided between capital and fixed operating costs.

Occupant behavior is also a major factor, from a social system perspective, though in many cases it is constrained by technology. One example common in China is provided by air conditioning, which is generally provided by individual, window-mounted units. While window AC units are less energy efficient than central cooling systems, people also generally use window units only when they need them, while centralized systems often run 24 hours/day. Several interview participants noted that they did not feel Chinese citizens are conscious of their energy usage yet – but as this example highlights, many of the technologies that Chinese consumers use are less energy intensive, at least for the time being.

4.3.5 Knowledge transfer

Knowledge transfer plays a key role in enabling transition towards more sustainable building systems in China. Such transfer can occur horizontally or vertically in the form of technology, analytical capacity, policy, or otherwise. Horizontal transfer is made within an individual stakeholder group; for example from firm to firm, or from local government to local government. Vertical transfer is made from an 'expert'[17] organization or firm in one stakeholder group to an organization or firm in another; for example from an NGO, industry association, or central government, to local governments or firms. Intermediaries, whose specialized knowledge is often the reason for their existence, frequently play a key role in the knowledge transfer process.

The notion of transfer implies the prerequisite of knowledge accessibility. In order to move information from one place to another, knowledge must both exist and be available to find. For example, scientific publishing puts knowledge in a domain primarily accessible to academics; science journalists, on the other hand, bring this knowledge to a more public forum.

The purpose of knowledge sharing at a fundamental level is capacity building. Capacity building is an unsexy undertaking; but an essential one to effect lasting change. In the context of Chinese buildings, knowledge of sustainable practices has largely been developed relatively recently. My interviews highlighted many conventional means of sharing knowledge, as well as several novel mechanisms. The presence of international organizations with expertise in building sustainability goes back to the 1990s, and the list of those organizations operating in China has grown over time. I will also highlight a few examples of new organizations and approaches to sharing knowledge among buildings sector actors in China.

When I asked interview participants where they go to find and where they go to share new knowledge, the most consistent responses were those that one would expect to hear from almost anyone in almost any industry (though with some nuanced differences between stakeholder groups): searching the internet[18], attending conferences or workshops, informal interactions, and reading publications. While few explicitly mentioned research or business partnerships as a mechanism for sharing knowledge, we discussed examples of such partnerships in nearly all of my interviews.

The less obvious responses also say more about ongoing transition in the Chinese buildings sector. These more interesting forms of knowledge sharing include: novel forms of social media use, new organizational structures adapting to the particular values of Chinese stakeholders, the creation of new intermediary organizations, and international travel and experience as a key enabling condition for embracing change within leadership structures.

A number of participants, but in particular the architects and designers, have begun to use social media to source and promote information. One instance worth highlighting is UNEP's use of the WeChat social network. In China, WeChat's role most closely mirrors that of Facebook in the US, though it is also becoming the default messaging service for casual communication. Communication on WeChat is more personal than on a network like Weibo (similar to Twitter), because communication on WeChat requires both parties' acceptance of the relationship, similar to the request-and-accept protocol on LinkedIn or

[17]Expert in the sense of possessing some sort of specialized knowledge that is of interest to a 'non-expert'.

[18]Practitioners' reliance on basic internet search is a useful reminder that China's blanket restrictions on access to the open web serve to inhibit innovation on many levels.

Facebook.

Jiang Nanqing at UNEP has leveraged WeChat as an organizational tool to create dialogs on the topics of various UNEP focus areas, including sustainable consumption. By starting a group chat with a diverse group of practitioners, she and others can share announcements and ideas relevant to their shared interests. Such conversations have led directly to, among other things, an event series called Sustainable Consumption Week – in this case, knowledge sharing begets more knowledge sharing (Jiang Nanqing, personal interview, 13 Feb 2014). One can imagine that a building energy WeChat group or forum or email listserv (whatever platform is most likely to see regular use from the relevant participants) might serve a similar purpose and create similar opportunities. This is an extraordinarily easy, almost zero-risk undertaking with a high potential upside. This semi-informal communication channel provides a forum for exchanging ideas and strengthening ties within a community of practice, but its ability to facilitate the direct spread of technical knowledge is limited.

This private dialog within stakeholder groups is important in that it creates a safe space for conversation. In the face of many calls for various institutions to report energy-use data, decision-making practices, and financial metrics, firms and governments alike remain hesitant to move towards complete transparency.

Recognizing this skepticism at an international level, C40 Cities' outreach model explicitly acknowledges the novelty and uncertainty surrounding transparent reporting. Their clients are local governments that in general recognize the value of transparency but are not yet ready to publicly report their progress. While large local governments understand almost across the board that sustainability and climate change mitigation are important, recognizing their importance is different from being confident in their ability to successfully do something about it. As such, they are quite rationally resistant to embracing complete accountability. The innovation of C40's approach is to accept this and to work with cities to develop their expertise in private by default, with publications using anonymized and aggregated data, alongside select member-approved case studies. The assurance of privacy is extremely valuable in creating open channels for communication both vertically (from C40 to its members) and horizontally (from member to member).

In addition to organizations like C40 that are adapting to current stakeholder realities, I also observed evidence that new intermediary organizations are being founded to fill knowledge gaps. GIGA, an open database for sustainable materials selection, and the Built Environment Group, a high-performance building energy consultancy, provide two examples. I will focus on the Built Environment Group here and discuss GIGA in the next section.

Yi Jiang founded the Built Environment Group (BEG) in 2012, having previously received her PhD from the MIT Building Technology Program and worked for several years with the United Technologies Research Center, first in the US and then in Beijing to supervise a joint research program with Tsinghua University. BEG's clients include some of the largest real estate developers in China, to whom she and her 15 full-time staff provide technical expertise and support (Yi Jiang, personal interview, 14 Feb 2014). This support leads to improved building-level outcomes, but also reflects these large firms' desire to remain ahead of the sustainability learning curve. To be clear, this does not mean that large real estate developers are building sustainably across the board – more accurately, they recognize the value of *knowing how to build* sustainably. This distinction is important, as it acknowledges the current reality in China, which is that there is not yet significant demand for energy efficient buildings in China. Large developers (1) recognize that this will not forever be the case[19], and (2) have the financial resources to invest in future capacity for green building design.

Her business interests have also led Jiang to incorporate a new non-profit organization called Sustainable Built Environment, whose explicit focus is on expanding knowledge of green building practices in China. The organization is still in the early stages, but is already engaged, for example, in running technical workshops at relevant conferences. The non-profit's work will promote green building in general and help build institutional capacity for change, complementing BEG's consulting business (Yi Jiang, personal interview, 14 Feb 2014).

Yi's experience highlights a theme that strongly emerged from my interviews, and which I had not considered before my time in Beijing: the role that international education, travel, and exposure play in Chinese sustainability efforts. This was cited by interview participants in nearly all practice areas, as an important determinant of openness to and understanding of sustainability concepts.

I expect that the nature of my own connections[20] biases my participant pool in the direction of living in this reality, though that does not temper its importance. Given the expense of international travel and education alike, Chinese citizens with the resources to travel or study abroad are already likely to come from a relatively wealthy background.

The role of international education in knowledge transfer and the motivations behind BEG's work together point towards the snowballing inertia of privileged expertise, concentrated among a relatively small, highly educated elite. This is as an informational market failure; many of those who would benefit most from improved understanding of building sustainability have the least access. While this is evident in my analysis, it is not unique to the Chinese buildings sector. Some of the forces clearly at play here, which one may conceptualize (in system dynamic terms) as 'reinforcing loops', include:

- Academic institutional lock-in, resulting from elite academia's revolving door, both at top-tier Chinese schools and internationally (influence of wealth and legacy factors in admission/access)

[19] And indeed, are seeing evidence of the beginning of this transition towards increased demand. There is significant growth in the number of LEED and Three-star certified projects in the country over time.

[20] Connections that in large part are built (directly and indirectly) on my relationships from Columbia and in particular MIT, two institutions with major Chinese partnerships, and with large Chinese student populations.

- Vertical institutional lock-in, due to the ease (for 'experts') of working with partners that already have a working knowledge of sustainability concepts
- Horizontal institutional lock-in, arising from network-interactions of large, well-resourced actors with each other, e.g. biggest firms, largest cities
- First-mover institutional lock-in, or the 'snowballing' of sustainability expertise once the seeds of such expertise are already in place

It is unclear to what extent this is a good or bad thing; or whether one can draw any normative conclusions here at all. These forces may encourage actors to tackle the low-hanging fruit from the perspective of identifying low institutional barriers to change. But these low-hanging fruit are not necessarily the same as the fruit of maximizing impact per dollar invested.

It is also important to note that there are some countervailing forces; Yi's new nonprofit (along with quite a few other organizations) has the potential to enable the distribution of knowledge, while her consulting firm likely acts to further concentrate it. One would expect the sort of diffusion enabled by this type of organization would also happen naturally over time, though more slowly. It is also important that this particular case originated in the market rather than being supported by government. While one may consider catalyzing the more 'equitable' spread of information to be part of the state's role in minimizing the informational market failure described above, the actor networks that distribute such information in practice appear anecdotally to be increasingly diverse. These networks include a range of actors that include government as well as private, civil society, multilateral, and other nonprofit organizations; these different actor groups are increasingly required to collaborate in order to successfully adapt to changing climate-related stresses on the urban system.[6]

Lastly, China's role in the global economy is itself undergoing an important transition, with significant implications for knowledge transfer – and particularly the international 'import' of knowledge – moving forward. The country's rapid rise from poverty and increasing geopolitical power will in the long-run reduce its priority from the perspective of developed-world international governments and multilateral organizations alike. Carolyn Szum of ICF International has worked in building energy efficiency for about 12 years, working on the energy star building efficiency program and helping to develop the associated Portfolio Manager tool in the US, before transitioning to share lessons from this work with rapidly growing cities in Asia. Something that stood out in our conversation was that there are increasing opportunities for the US to learn from China's work in building energy efficiency, in particular in the context of the LEED and China's Three Star certification systems (Carolyn Szum, personal interview, 12 February 2014). This sentiment was echoed by several other participants, who reiterated the opportunity for bi-directional knowledge exchange with respect to these two building energy efficiency certification programs.

These practitioners generally view LEED and Three Star as complementary programs in China. While there is considerable overlap between the two (Three Star was modeled in large part on the LEED system), there are also notable differences. The difference most commonly referenced in my interviews was that building developers or owners can apply for LEED certification either for design *or* operations, whereas Three Star certification requires both design and actual performance data review. This can be a significant difference, as a 2008 analysis from the New Buildings Institute (and commissioned by the US Green Buildings Council) showed that the actual energy performance of LEED buildings was significantly worse than modeled for 25% of the LEED-certified projects analyzed.[183] On the other hand, the Three Star certification is also viewed as more burdensome, does not yet have a neighborhood-level certification option (as LEED does), and is sometimes favored because of its international recognizability.

The fact that the relatively young Three Star program (founded in 2006) is comparable to the well-established LEED program (founded in 1998) suggests quite a high rate of knowledge transfer in this space; in some respects, the Three Star "student" has also developed the capacity to teach.[21] Bai et al. (2010) highlight cases in which local innovations in Asia have been developed, demonstrating that the region does not only rely on an influx of ideas from the developed world.[11] The example of Three Star takes this argument even further, however, demonstrating the impressive rate at which innovation is occurring in China – to the point where it may be outgrowing LEED in some respects. This is a small indication that the transfer of best practices is beginning to become more balanced between China and the developed world.

4.3.6 Selected sustainability experiments

Here I provide examples to highlight cases in which various stakeholders influence buildings' life-cycle sustainability outcomes. While I earlier laid out a broad range of hypothesized transition triggers (see Table 3.1), this section focuses on specific, experimental approaches that were cited during my interviews. I consider sustainability experiments in this context to be a special type of trigger, defined by being purposeful, using an untested approach (and thus having an uncertain outcome), setting an explicit goal to reduce resource use, and having the possibility for up-scaling in order to achieve substantially greater resource use reduction[22].

First, GIGA's business model highlights the role of intermediary organizations and more transparent information in making building material systems more efficient. Second, the Top 10,000 Enterprises Program showcases the value of institutional partnerships and policy up-

[21] This does not say anything, however, about how openly LEED or any other certification system will embrace lessons from Three Star. Those with whom I spoke about this matter were skeptical of this possibility, which would (if valid) be an unfortunate reality.

[22] This is similar to Berkhout et al.'s definition: "...planned initiatives that embody a highly novel socio-technical configuration likely to lead to substantial (environmental) sustainability gains" (p. 262).[19]

scaling. Finally, the renovation of Beijing's Dashilar neighborhood provides an example of design-oriented solutions driven by social considerations.

These are short cases, intended to highlight different types of transition triggers rather than to emphasize the specific interventions of these actors. The cases are derived from a small sample of my interviews focused on the Chinese building sector, but the identified triggers are sufficiently general to be relevant to other sectors. Further work of this nature can add to the resultant list of transition triggers capable of reducing resource use in urban settings.

GIGAbase.org: intermediary organizations and more perfect information

GIGA (short for 'Green Ideas Green Actions') aspires to be the Wikipedia of green building. Ryan Dick and Raefer Wallis co-founded GIGA in 2008, following up on their role in designing of China's first 'carbon neutral' hotel, URBN, in Shanghai. Under the pressure of various requests for information on how exactly they had achieved carbon neutrality, they built a relatively modest database, cataloguing the materials used in Shanghai project and listing their environmental attributes (Ryan Dick, phone interview, 20 Mar 2014).

While Dick and Wallis initially conceived of this as a simple tool to allow them to send the equivalent of a single hyperlink to carbon-neutral design skeptics and enthusiasts alike, they soon realized that this sort of database could be a useful tool for developers and designers. Their current product[23] provides environmental, technical, and price information on a wide range of building materials and design-relevant products, scored and ranked according to ranking criteria developed by GIGA. Architects, designers, firms that manufacture relevant materials, and anyone else for that matter, are empowered to add product information to the GIGA database. Companies who provide verified information are rewarded with higher product rankings; transparency in and of itself is valued in the ranking algorithm. The site also provides several other features designed to appeal to developers, designers, materials suppliers, and eventually to construction firms. Suppliers have a market for their products, and can also benchmark their materials' performance against those of other suppliers. Designers and developers can take advantage of the material information database to manage their projects and select specific materials to fill their needs using the GIGA platform (Ryan Dick, phone interview, 20 Mar 2014).

It is worth noting that Dick and Wallis are both Canadian. As for any firm operating in a foreign context, they have needed to build an understanding of their market in parallel with their building of the software platform itself. One example of the way this challenge has manifested in their growth is in structuring their business model. Initially conceived as a non-profit organization, GIGA's leadership team eventually realized that many potential partners were skeptical and distrusting of their 'altruistic' motivations. Once they developed a for-profit model, these tensions largely subsided – though they still raise some eyebrows

[23] Viewable at www.gigabase.org – though subscription is required to access their full offerings.

with their '.org' web domain (Ryan Dick, phone interview, 20 Mar 2014).

GIGA may do for building materials what the US Embassy did for air pollution in China. The US Embassy is widely credited for catalyzing transparency in real-time air quality monitoring in China, beginning in 2008 when it started publicizing hourly air pollution measurements taken atop its building in Beijing.[46] It has also made these data available through an API (application programming interface) that allows software developers to integrate these measurements into mobile and web applications. Today more than 170 cities publish real-time air quality data, providing urban citizens with important public health knowledge, providing potential urban migrants with information that may affect their decision, and providing a transparent indicator of progress in reducing that air pollution. Both the US Embassy's and GIGA's interventions operate on the economic principle that transparent information creates more efficient markets and thus more desirable outcomes – in this case, environmental outcomes.

The power of transparency (when paired with a crowdsourced database) comes is derived from architects and developers to exert leverage over material providers. This is demonstrated by an example Dick provided in our conversation. After an architect uploaded some products from a carpet company, the company received an automated email from GIGA's system – an optional feature designed to encourage firms to manage the information on their products' pages once they have been publicly listed in the GIGA database. The carpet company promptly called GIGA, requesting removal from the database. In Dick's words:

> ... they came to our office and they said, "Hey, we really like your platform, it's really cool, the goals that you have are amazing, but how do we get off your platform? We don't want to be there." ... they felt they were better than most of the other providers that were [in the database], but they hadn't provided any verified information. They were showing up lower than carpet companies that they were in fact better than (Ryan Dick, phone interview, 20 Mar 2014).

That carpet company is now an active participant in GIGA's database. This type of user acquisition may be key to enabling the GIGA's growth, as it has potential to create a sort of self-sustaining inertia. Until the service's network effects reach that stage of growth, it relies on a combination of online outreach and in-person events in major cities, which GIGA increasingly hosts in order to ensure that the events' content aligns with GIGA's goals (Ryan Dick, phone interview, 20 Mar 2014).

GIGA's platform must grow substantially in order to significantly impact sustainability in buildings, and its success has been limited thus far in getting information about structural building materials into its online database. Dick acknowledged that most of the products listed in its database thus far are interior components, though Dick is committed to bringing the high-impact, core construction materials industries onto the GIGA platform. This hasn't happened yet, which Dick attributes to the fact that these materials are largely hidden in the finished building. The building occupant does not usually see the concrete, steel, or aluminum that comprise the building's internal structure, or think about the environmental impacts of glass; and these materials generally contribute the vast majority of a building's embodied environmental impacts.

Intermediary organizations like GIGA play a key role in enabling sustainability transition. It is also notable that GIGA operates entirely within the private sector, in contrast with the following example – public policy is not the only important transition trigger. GIGA's work supports transparency and thus improved informational efficiency for designers and developers by providing material manufacturers with a new means of communicating their products' performance traits. Its material performance database reorients incentives to encourage informed materials choice – enabling resource efficient choices without constraining designers' decision space. The use of a Wikipedia-like platform also has potential to create self-sustaining growth and impact in the long term, using a technological and economic approach to improve technological outcomes.

Top 10,000 Enterprises Program: institutional partnerships and policy up-scaling

China's Top 10,000 Enterprises program is unparalleled in its ambition to bring energy efficient practices to China's largest "10,000" industrial enterprises.[24] What started as an energy efficiency pilot project with just two facilities in China's Shandong province in 2003 grew over the course of less than ten years into a mandatory national policy of unprecedented scale. Having demonstrated proof of concept, the success of two iron and steel industry firms ballooned into a mandated national efficiency program for the Top 1,000 firms across nine industries (see Price et al. [154] for a more thorough analysis of the Top 1,000 Program's origins and efficacy). With continued successes – and an enormous energy saving opportunity – have come increased ambition on the part of the Chinese government, and with the 12th Five-Year Plan (FYP) 1,000 became 16,000.

The extraordinary rise of this program was enabled by the work of several key partners, including the Energy Foundation, LBL's China Energy Group, the China Energy Conservation Association, and partners at Peking University (He Ping, personal interview, 12 Feb 2014). The pilot-phase work was also conducted in partnership with the Shandong provincial government. These partnerships form strong networks of financial, political, and technical support that can make policy efforts successful. Such partnerships were clear in different forms across many of my interviews – for example in the nature of the work of organizations like the Energy Foundation and World Resources Institute; in the academic partnerships formed by design firms like reMIX and Plasma Studios; and in Yi Jiang's work with the Institute of Green Building Technologies at Nanchang University, which she continues alongside her other endeavors.

The central government needed to be engaged strategically. The projects' stakeholders ensured that representatives from China's National Development and Reform Commission

[24]In practice, more than 16,000 enterprises are included.

(NDRC) were present to hear the results from the Shandong pilot once it had proven to be a success (He Ping, personal interview, 12 Feb 2014). The Top 1,000 Enterprises Program was announced in April 2006 in support of the 11th FYP national energy intensity target[25], to be administered at the provincial level. The Program provided support in the forms of training and financing for participating firms, capitalizing on the fact that these 1,000 enterprises alone accounted for 33% of China's national energy consumption in 2004.[154]

Top 10,000 Enterprises Program grows this effort by an order of magnitude. The sheer volume of training necessary to build capacity for energy efficiency efforts in so many enterprises is staggering. The provincial administration of the Program allows the government to decentralize trainings; starting with a sort of meta-training, or "training of the trainers", in which provincial delegates are educated centrally before going to spread the gospel of energy efficiency with individual companies in their own provinces (He Ping, personal interview, 12 Feb 2014).

Industrial energy efficiency efforts now primarily originate from the central government, though this central government program was inspired by localized efforts in Shandong province. But what is it that makes some enterprises more proactive than others in pursuing energy efficiency? While technical and financial capacity are important, He emphasized the value of individual leadership at the highest levels of industrial enterprises. A willingness to take on such leadership was cited as a key criterion for establishing partnerships in many of my interviews with intermediary organizations.

Even when enterprises are proactive, evaluating their success – much less the overall success of the Top 10,000 Enterprises Program – presents a major challenge. Data collection is not widespread, nor is it open, and nor is it reliable where it does exist. While these are significant limitations, the central government is also working to establish a standardized energy monitoring platform for use across the Program. Besides real-time monitoring, there are also third-party monitoring options, though these are limited as well. While third party monitoring and verification organizations are essential to improving program evaluation moving forward, only 26 such organizations are currently certified to work in China – not nearly enough to support industry at the scale of the Chinese economy (He Ping, personal interview, 12 Feb 2014). The market to support more of these third party organizations exists, and it is up to the Chinese government to ensure that new organizations are certified when they are eligible and qualified.

The Top 10,000 Enterprises Program is an impressive policy-making accomplishment, though enforcement and evaluation are lingering challenges. As a case study, it provides a clear example of the policy up-scaling process typical of the Chinese central government – a process which is increasingly recognized by organizations like the China Energy Group and Energy Foundation that seek to inform and influence policy. It also demonstrates the key enabling role of partnerships across a diverse array of institutions to support that up-scaling

[25] A 20% reduction in energy per unit of GDP in 2010 relative to 2005 levels.

process.

Dashilar redevelopment: equity and material reuse by design

Local governments in China are empowered to seize land from rural villager collectives, but doing so requires that these displaced villagers be compensated for being forced to relocate. As is true in the US[26] and elsewhere, redevelopment on land that is currently inhabited often requires a financial settlement with current residents. This type of relocation compensation plays an increasing role in Chinese development. The former (forced relocation for villager collectives) is more common, as the majority of real estate development occurs at the urban fringe, as the city's boundary encroaches on agricultural land. This case focuses on redevelopment, whose role will increase as Chinese cities become increasingly built up.

reMIX studio is a small architecture and design firm in Beijing. The three co-founders and partners – Chen Chen, Nicola Saladino, and Federico Ruberto – are planning a project unlike most real estate endeavors in China: refurbishing small residential housing units in central Beijing. The Dashilar subdistrict is just south of Tiananmen Square in Beijing, near the center of the city. Dashilar's history and location mean that the neighborhood is preserved by zoning restrictions, though a revised neighborhood master plan (passed by the local planning authority in 2006) technically allows for some sweeping changes. This plan, while still on the books, has largely been ignored, and the government does not appear to have any intention of implementing it (Chen Chen, Nicola Saladino, and Federico Ruberto [reMIX studio], personal interview, 11 Feb 2014).

Instead, the state-owned real estate developer managing the neighborhood's renovation is interested in taking a non-traditional approach. Saladino emphasizes the stark change of plans as he describes reMIX's approach: "... before it was about massive expropriation, and hundreds of neighbors would be moved out. Now it's a one-to-one negotiation, and part of the strategy is about creating a flexible tool so that if one neighbor doesn't want to move out you are able to define another target within the area somehow." (reMIX studio, personal interview, 11 Feb 2014) Rather than applying a blanket renovation requirement for the entire neighborhood and forcing residents' relocation, this developer wants to make it *desirable* for residents to pursue such renovations – with some financial support.[27]

reMIX hopes to design a tool that will enable the developer to identify the best candidates for renovation, in order to make the one-to-one negotiations as efficient and effective as possible – an otherwise time-intensive process. By finding individual households willing to go forward with the renovation process and who are well-distributed throughout the

[26] See, for example, the example of Herber Sukenik, who was allegedly paid $17 million by a real estate developer to vacate his apartment in New York City.[85]

[27] The exact amount of financial support is not clear, but the idea is that residents would be compensated based on their location and the duration of their displacement during the renovation period. After the renovation is complete, they would have the option of either remaining in place or accepting compensation to relocate elsewhere (reMIX studio, personal interview, 11 Feb 2014).

neighborhood, reMIX seeks to establish renovation 'nodes' that provide visible evidence of success within the neighborhood, and which in turn generate more interest in pursuing renovation from other nearby households. Even with the help of such a tool, the speed of the development process will be "impossibly slow" relative to the standard Chinese model (reMIX studio, personal interview, 11 Feb 2014).

What's in it for the government? Improved opportunities for commercial development in the area, lower resistance from centrally located residents in the nation's capital, and reduced relocation costs for the residents who would be displaced in a 'development-as-usual' scenario. Effectively, reMIX hopes to create a framework that will enable such bottom-up neighborhood transformation. To accomplish this, reMIX is running a design workshop to develop their ideas. Saladino describes some of the project goals, constraints, and motivations:

> This workshop is about precisely helping them to establish a strategy about which nodes to operate on and how to create some sort of clusters; to revitalize the whole neighborhood starting from very small...
>
> At the same time the area has some historical value, so... many of the properties are [protected] and the whole neighborhood has a limitation about maximum heights and volumes that you can build. That's made the whole operation of demolition and reconstruction anti-economical. (reMIX studio, personal interview, 11 Feb 2014)

The neighborhood's zoning restrictions effectively force the reuse of as much of the existing structures as possible. This reduces resource use locally, but strict historical preservation restrictions on zoning introduce a significant inefficiency given the extraordinary demand for building space in central Beijing.[28] These restrictions are not under the control of the developer, nor the designer, so they are exogenous.

reMIX's proposed model of development could help ease a transition to more frequent redevelopment as cities age and property values increase. If reMIX's model is successfully implemented in Dashilar, it could provide the groundwork for inclusive redevelopment strategies in other Beijing neighborhoods and beyond. This style of participatory, opt-in redevelopment appears to be more equitable for residents, and it would encourage material reuse under existing zoning restrictions.

Synopsis

These cases highlight several enabling triggers for reducing resource use in the building sector (and beyond):

[28] See Glaeser [80] for a thorough discussion of the role of historical preservation in urban economic inefficiency.

- More perfect information (triggered by GIGA's ICT platform; in turn triggered by zero carbon hotel experiment).[29]

- Designing systems for self-sustaining network growth (triggered by GIGA's ICT platform; also a goal of reMIX's Dashilar project).

- [Policy] up-scaling (Top 10,000 Enterprises up-scaled from successful Top 1,000 program, which was in turn up-scaled from Shandong pilot project; using the term in a slightly different sense, GIGA also hopes to up-scale its user base over time)

- Multi-stakeholder collaboration (all cases build on collaboration of some sort, but the Top 10,000 Program is a particularly good example; triggered by existing networks between and technical capacity within these organizations)

- Direct design intervention (reMIX's Dashilar project; intervention triggered by technological pressures of aging building infrastructure, strategy triggered by social pressures)

This short list of triggers only begin to cover the range of possible avenues for inciting reductions in the resource intensity of the building sector. The contexts for the three case studies explored in this section are all quite different, but some of the lessons are more general. With a much greater volume of analysis, future research may begin to explore a more comprehensive taxonomy of sustainable transition triggers. It may also be of interest to understand the extent to which these triggers compliment and may substitute for each other, towards the creation of a transition schematic of sorts. Some triggers will support, while others may be at odds with, each other. This would not only be a useful guiding tool for policy-makers and other actors seeking to reduce resource use, but could also shed light on more fundamental questions about the nature of transition – some of which I begin to explore in the next chapter.

4.3.7 Qualitative conclusions

Many actors influence sustainability outcomes in the Chinese building sector. Their interactions are complex, and attempting to direct the sector (or any system) towards sustainability must be done carefully.

Much of government's effectiveness in this role hinges on its ability to influence incentives for these actors. In the Chinese building sector, many of these incentives are counterproductive not just from an environmental sustainability perspective, but from economic and social ones as well.

A second fundamental role of the government is to build capacity. This includes both the fostering of practitioner networks and the development of technical capabilities, which

[29] The case of US Embassy sharing air pollution data similarly demonstrates the value of more perfect information, though it may be considered an instance of quasi-diplomatic, horizontal transfer rather than 'up-scaling'; though it did also result in eventual up-scaling to many more cities as well.

the government is well-positioned to build given its ability to convene various experts. The government also needs to support the development of intermediary organizations, which are crucial to transferring knowledge between various building (and other) sector actors.

Transferring knowledge to small- and medium-sized cities is a growing component of this capacity building role, which may be facilitated by the use of non-traditional approaches like supporting travel for government officials – a goal which can be accomplished in parallel with the convening mentioned above. This is already happening in some cases, but the number of local government officials for whom such education will be necessary is large so further effort will be required.

Outside government, project evaluation is a persistent challenge.[30] Firms and organizations must be conscious of their efforts to manage data and tracking in order to ensure that successes are robust and replicable.

Overall, many exciting sustainability experiments are ongoing with potential for significant impacts in the long-term. In several respects, China is beginning to leapfrog best practices at the frontier of building sector sustainability; however, standard practices lag behind. While China's distinctive institutional history in some respects limits the generalizability of these conclusions, there is much for other countries to learn from China's urbanization with respect to sustainability in buildings and otherwise.

4.4 Research gaps

This is not a topic in danger of becoming obsolete. Sustainable urban development is not a challenge that can be 'solved'; there is no one-size fits all prescription that will allow cities to develop sustainably, because economic, social, political, natural, and technological contexts interact in complex ways.

The first opportunity for future work is in furthering quantitative approaches to transitions analysis. Besides explorations of other sectors and other datasets, researchers must continue to test other methods as well as to codify available approaches and clarify what types of information can be garnered from which approaches. To further my analysis, one could levelize the average magnitude of indicators across years over the duration of the time-series to reduce the impact that increasing magnitude over time has on the clustering results. Re-clustering the provincial data may also yield informative results if certain provinces are removed from the clustering dataset, for example the distinctive urban provinces.

More advanced clustering algorithms are also capable of explicitly incorporating time-series considerations into the analysis. While my approach makes the significant assumption that data entries for a given province but from different years are independent of one another, other approaches are able to compare whole time series datasets. One option could be to employ the iSAX algorithm, which could allow one to group provinces directly on the basis

[30] Likely also in government; though my interviews do not speak to this.

of their longitudinal trends, rather than indirectly via comparing independent observations through time.[167, 33]

Alternative quantitative approaches could include index decomposition analysis, econometric analysis, or polynomial curve fitting paired with analysis of first and second derivatives to understand the purely mathematical dynamics of transition. The construction of simple probability distributions also has potential to be informative.

Novel visualization methods may enable more thorough exploration of the clustering results (or other transitions analyses), particularly for larger datasets for which it is hard to deeply understand the inner workings of the data. My analysis is not spatially explicit, which would also be a rich avenue for exploration, particularly with respect to visualizing spatial differences in the analysis.

There is also surprisingly little city-relevant policy analysis relevant to higher levels of governance. In reviewing urban climate change governance literature, there is a clear lack of organized knowledge with respect to the means by which national and sub-national government can enable urban climate change mitigation (and adaptation) efforts. This is a key area for future study.

The typology literature reviewed in Section 2.4 leaves room for many future contributions, both quantitative and qualitative. One interesting example is provided by C40 Cities, which groups its member cities together on the basis of their stated policy interests, expressed by their choice of C40 working groups in which to participate (Yan Peng, personal interview, 17 Feb 2014). The set of municipal policy preferences expressed in this process could potentially provide a practical means of generating an urban typology.

One of the valuable aspects of a machine learning approach is its ability to generate leads for possible case studies. What is it that leads to the differentiation in the buildings sector development pathway of Hainan relative to mainland provinces? What is it about Jiangsu and Zhejiang that led to their relatively rapid progression through the business-as-usual pathway? What caused the slight variation in Beijing's pathway (into Cluster 3) relative to the other two urban pathway provinces?

My interviews also highlighted many possible case studies of various aspects of transition processes that merit deeper exploration. At a high level, my relatively short foray into the world of Chinese buildings has clearly demonstrated that this is a rich space characterized by rapid change. Many specialized programs, trends, and actors could support in-depth study. In addition to the examples I mention in Section 4.3, the work of particular Chinese real estate or design firms, increased use of prefabrication in Chinese buildings, the impact of China's circular economy law, or the propagation of a particular architectural style through the lens of transition.

As a general comment, the motivation for my qualitative analysis largely originated in acknowledging the limitations of my quantitative analysis to reveal pathways for future change. Besides being forward-looking, the qualitative analysis also helps explain some of the mechanisms for transition much more directly than quantitative analysis can. While I do consider the two analyses to be complementary, future research should more closely integrate quantitative and qualitative approaches to maximize the interaction between the two.

Ultimately, many of the above explorations could add up to create a generalized transition taxonomy, or schematic. In the end, any transition reflects a collective choice[31] on the part of the actors with an interest in that transition. But what of the alternatives? This notion of transition as choice implies a series of branch points in a system's evolution. What are the most important branch points? At what scale can they be defined? How do these branch points interact with and affect each other? Beginning to answer some of these questions would surely help planners and governments identify decisions and opportunities that may lead to undesirable lock-in, and to better understand the consequences of such decisions in the long term.

[31]Emergent phenomenon might also be a fair description; but I like 'choice' (or collective choice) because the emergent phenomenon of transition is a consequence of the actions and decisions made by the full set of stakeholders relevant to the transition in question.

Chapter 5

Discourse

> *"But Zak, I want to know what you* think *about all of this."*
> – Someone, hopefully

Plenty of my thoughts are embedded (both implicitly and explicitly) in the preceding and following chapters, but this chapter will be especially dense with my own opinions and musings. While these opinions are informed by the body of research that I have conducted, as well as that to which I have been exposed, they are quite different from the 'conclusions' of my research. Both musings and conclusions have an important place in the scientific process, and if anything the former is too often neglected. These thoughts should, however, be considered separate from my analysis.

Intuition and speculation form the foundations of scientific exploration, and my first goal in this chapter is to lay some of these foundations. Without the constraints of data, my speculations may highlight interesting and unexplored areas for future research. Relatedly, my second goal is to lay bare some of the inner workings of my thought process as I have considered the challenge of urban sustainability, highlighting some of the values that inform this research. I accomplish these two goals by first discussing various aspects of transition; second discussing the nature and challenges of sustainability in cities; and finally, discuss the challenge of sustainability transition in the Chinese context.

5.1 On transitions

Transition is an essential concept to understand in the context of global sustainability goals, and we must understand it from many angles. 'Transition' is not a word that in and of itself calls to mind a specific meaning, since it is used in such a variety of contexts. I am not prepared to speculate on how we should define transition beyond noting that any general definition (even one specific to the sustainability context) is not likely to be much more useful than the one Google provides: "the process or a period of changing from one state or condition to another". One might add the words "... more sustainable state or condition", but then questions of defining sustainability and whether one wants to limit the directionality of transition to something that moves towards "more sustainable". Beyond that, I leave the semantics of transition alone.

The other challenge I want to make explicit is that transition is dynamic in its nature, and thus hard to identify – much less analyze in a rigorous way. Something about the analysis of transitions will always be slightly dissatisfying, because transition processes are ongoing. Without the benefit of hindsight, it is hard to know if a transition is occurring and to what extent it has occurred. Socio-technical transition scholars have been navigating this tension for some time now and often successfully, but it is not a tension that will go away.

5.1.1 The stage model hypothesis

In Section 1.3.1 I introduced the notion that urban developmental stages may be recognizably distinct on the basis of their resource use patterns. What is it exactly that would give rise to such stages? Simply put, lock-in would.

In this engineer's mind, processes of developing lock-in are conceptually similar to chemical reactions. When structural (whether physical, institutional, or otherwise) barriers impede change, there is some threshold of effort that will enable a system to overcome those barriers (see Figure 5-1).[1] The requisite effort threshold may take many forms, and can be placed in the context of the five governing systems proposed in Section 4.2. For example, if one wants construction practices to change, such a threshold may be represented by economic shifts in consumer demand, political shifts like implementing new building codes, or technological shifts like a new technique that improves practices at lower cost.

Transitions triggers relevant to cities include, for example, changes in the distribution and magnitude of wealth; changes in environmental or air quality; access to clean water, sanitation services, and electricity; changes in accessibility in the sense of transportation and urban planning; changes in the integrity of and/or trust in government; or changes in institutional and technical capacity within the city. These comprise only a small subset of possible factors relevant to understanding urban transition processes. This list alone points towards the extreme complexity of transitions, which again makes modeling and analysis difficult. However many factors there may be which influence transitions, there are at least as many approaches that one may take to analyze those transitions.

My clustering analysis is one of many possible approaches to this challenge. It begins to shed some light on these issues, and provides a means of considering the high-level resource use trends that we should ultimately strive to impact.

The representation of 'transition' in my clustering model is quite crude indeed; the 'thresholds' between development stages in the buildings sector being represented by moving from membership in one algorithmically-defined cluster to another. This effective 'discovery'

[1] Higher 'activation energy' does not tell us about the stability of the system's resultant state, following a successful transition; though, change at the transformation level (see Section 5.1.2) will be harder to reverse.

of development stages is both the primary appeal and drawback of this machine learning approach. Qualitative definitions of stage have not to my knowledge been attempted, and the most productive approach to doing so would probably require comprehensive efforts in sectors, though not necessarily the same ones outlined in Section 5.2.4, which are merely sectors for which changing resource intensity should be measured. The types of sectors that list does not include are those that reflect the services that cities provide their residents in various capacities: living wages, clean water, energy access, and public safety, to name a few. If my proposal of development thresholds is valid, I would expect indicators like this to play key roles in enabling transition from one resource use stage to another. It is unlikely that any individual service or resource-using sector is capable of altering a city's development stage.

Rather, such large-scale change would be enabled by the alignment of many different transitions, each of which has achieved sufficient activation energy to overcome barriers to system change. When the right set of multiple, complimentary transitions aligns, this can result in what I distinguish as system transformation. This is reflected in Figure 5-1, where transformation is depicted as movement to a relatively low-energy state. This is intended to convey that transformation is recognizable by way of its associated system lock-in. While individual transitions may be relatively easily reversed, the alignment of complimentary transitions enables a new, lower-energy state. The threshold for transformation is thus a much stricter condition, as it requires many smaller sets of transition conditions to all have been met.

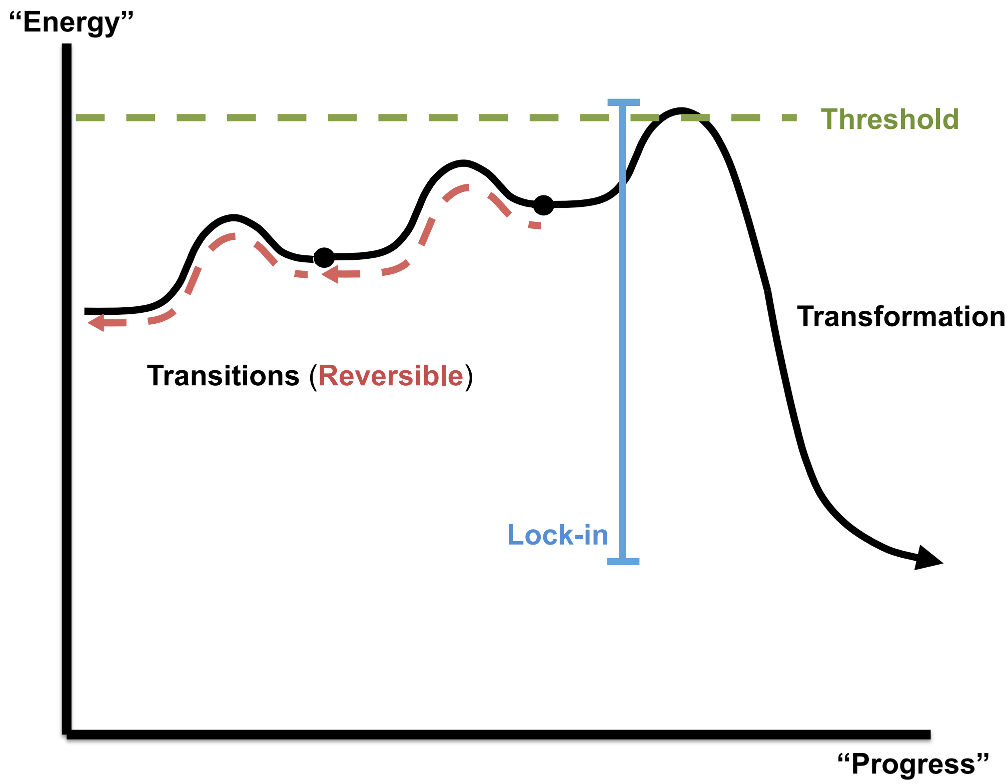
5.1.2 Transition and transformation

Transformation – relative to transition – thus implies more drastic change. One way to conceive of transformation (T) is as the sum of many smaller types of transition (t): $T = \sum t_i$. The use of summation here is a crude mathematical abstraction, because the complementary (or countervailing) effects of various transitions interact in much more complicated ways. In this representation, the transitions themselves collectively become triggers of a resultant transformation.

Transitions are not uni-directional, and may in many cases be reversed – though if reversal does not require substantial effort, I would be skeptical that transition had occurred in the first place. Transformation may also be reversible at least in theory, but in practice this would be a herculean task.

This thinking also applies to 'unsustainable' transition; when a city's resource use increases, such an increase is not necessarily permanent. It is also possible that unsustainable transition in the short term may enable sustainable transition in the long term; sometimes best practices are easiest to define in response to clearly identified developmental mistakes.

Figure 5-1: Activation energy in transition and transformation



One failed policy experiment resulting in a publicly blighted neighborhood provides a clear example of what not to do for all future decision-makers.

Transition and transformation must be defined relative to the system of interest; as in industrial ecology, the choice of system boundary has important implications for the resulting transition analysis. Transformation for an individual building looks different from a neighborhood's transformation; for an economic sector; or for an entire city. The amount of time necessary to achieve transformation on these scales is also variable. A building could foreseeably undergo a meaningful transformation within 1-2 years; a neighborhood, perhaps as fast as 5-10 years; an economic sector (within a city) perhaps 10 or more; and an entire city generally on the order of decades. These are intended as rough estimates, primarily to make the point that temporal scales vary within and across the different systems about which a sustainability advocate cares.

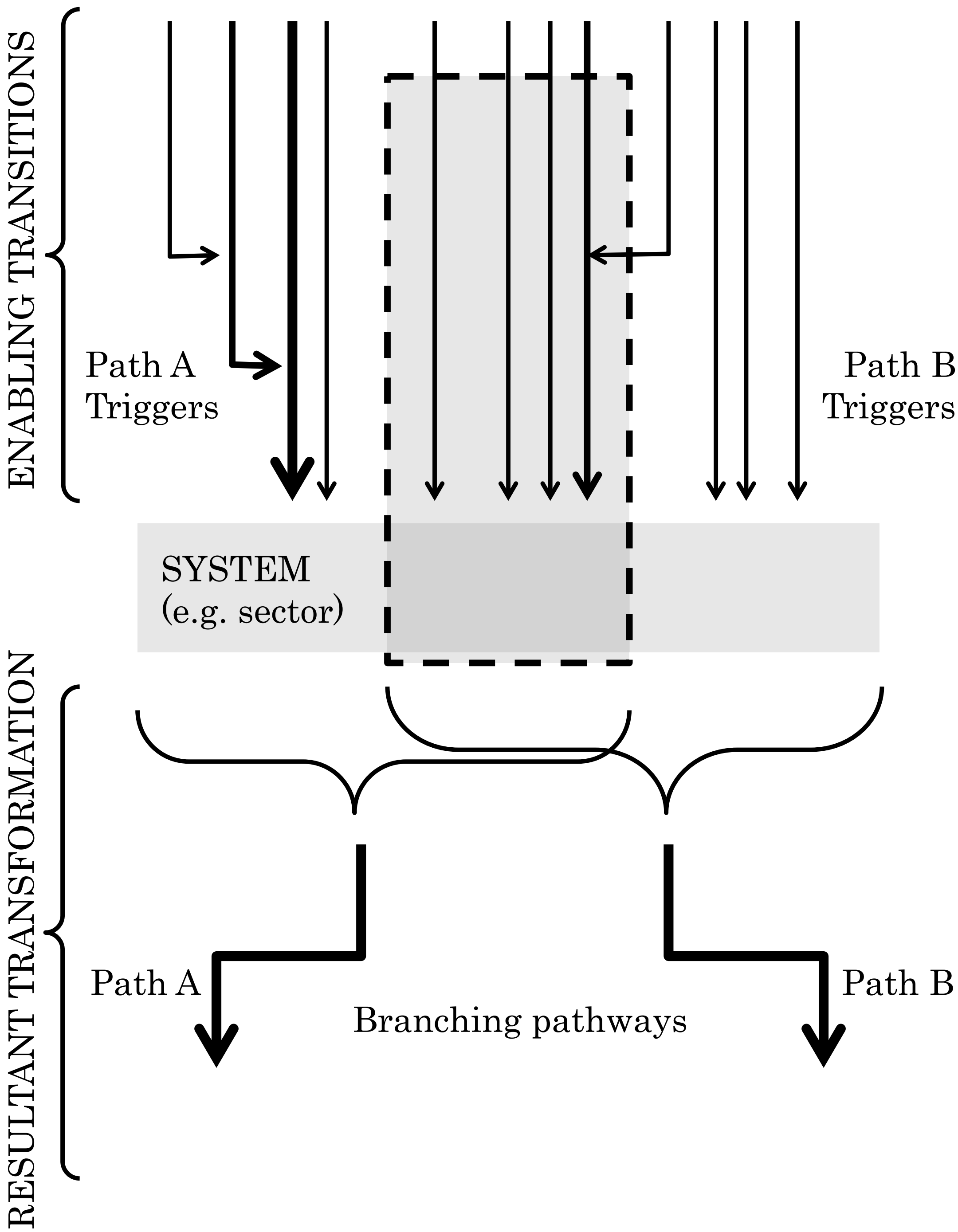
Transition is rife with path dependency. Consider the automotive transportation system – Table 5.1 provides a few of the reasons that petroleum-based automotive travel in American cities is resistant to change (barriers), and provides a few examples of opportunities to induce transition (potential triggers). These lists are not anywhere close to comprehensive, but highlight some of the different types of transition that might together add up to effect transformation in the way that citizens use the transit system, in this case. Transitions towards more sustainable transportation behavior might be comprised of increased use of biofuels; electric vehicle adoption; making driving less ‘cool’ (or non-automotive transport more cool); raising the cost of driving; or altering political incentives. Some of these are easier than others, though all for different reasons. Some are complementary (auto industry pivot to EV production along with EV infrastructure), while others are substitutes (congestion pricing and tolls; potentially – but not necessarily – biofuels and EV infrastructure). The existence of substitutive triggers indicates that there is a path dependency in the system, while complementary triggers comprise the transitions that together effect system transformation. In the example of the automotive system, transformation might be a shift in transportation mode from petroleum to electric or biofuel-powered vehicles, or it might be a dramatic change in driving habits (e.g. a reduction in miles driven).

Table 5.1: Barriers and Opportunities for Transition in Automotive Transport

Barrier	System	Potential trigger
People are behaviorally adapted to (and often like) driving cars	Social	Public transit and electric vehicle marketing campaigns;
The social and environmental impacts of driving are not accurately priced	Economic	Carbon pricing; gas tax; congestion pricing; road tolls
Politicians perceive the auto industry to comprise an important sector of the economy	Political	Campaign finance reform; subsidize auto industry pivot, e.g. to EV production
Fueling infrastructure is already built around petroleum-based fuel stations	Technological	Adapt biofuels to use existing infrastructure; gradually build new electric charging network
The built environment is in many cases designed to support automotive lifestyles	Technological	Updated zoning requirements; new transit development; better design for new cities

I consider transformation as a branching process, as represented in Figure 5-2. The branching arms below represent transformation in one direction or another, induced by the triggering transitions above. This simultaneously represents the complementary transitions that together ‘add up’ to transformation and the potential path dependence of transformation. I also represent transition processes as complementary to each other, as they may support one-another. The policy up-scaling process demonstrated by the Top 10,000 Enterprises Program demonstrates such an additive process.

Figure 5-2: Transformation processes



One common worry of policy-makers is that they will effectively be 'choosing winners and losers' when they implement policy supportive of or invest in a particular technology rather than any other. From this perspective, the set of common triggers in my framing constitutes the set of interventions that can support multiple possible outcomes, without the need to prioritize development of any particular sector.

Figure 5-2 does not represent the possibility of transition thresholds described in Section 5.1.1, which may also play an important role in transformation processes. With respect to this model's relevance to the stage-model development hypothesis, the implication would be that different developmental stages are accessed by particular sequences of branch points. This reinforces the choice of sectors as an analytical lens, as transition and transformation may occur in parallel both within and across sectors. While transitions may be hard to identify on their own, potentially resultant transformations should be more clearly identifiable, since they represent more drastic change.

Transition and transformation processes will generally not happen over night.[2] It does appear that sustainability outcomes are gradually improving over time, but it also seems dangerous to attribute that to any natural property of the development process. This is a basic problem of moral hazard; if we believe that development will tend towards sustainability through some kind of natural process, we risk complacency. In reality, progress towards sustainability in development has arisen due to the dedicated efforts of many actors, both independent and coordinated.

To the extent that sustainability outcomes are in fact improving in general, it is also clear that this improvement is not occurring uniformly. When it comes to cities, some are becoming more sustainable and others becoming less so.[3] Those cities that increasingly struggle to meet the needs of their citizens risk entering a negative or regressive transition, which I take to be a type of collapse.

5.1.3 Collapse

There are many possible mechanisms of collapse, just as there are for sustainability transition. Remaining focused on cities, collapse may be driven, for example, by the decline of a local industry (among the triggers of collapse in the case of Detroit); or by natural disaster, as in the case of Hurricane Katrina and New Orleans. Cities experiencing rapid growth may also observe a decline in public health indicators like access to clean water, electricity, and sanitation services, as infrastructure development – particularly in poor areas – typically lags population growth.[164] In general, understanding the conditions that give rise to various types of collapse is an important complement to understanding the conditions that give rise to desirable transition.

I consider cities to be catalysts for the creation of well-being, in that they serve to

[2]Some types of triggers may, however; particularly in the social (e.g. protest or conflict) and economic (e.g. stock market crash) systems.

[3]Here I refer to sustainability in the broader sense, as pertaining to environmental, social, and economic sustainability.

accelerate development and bring about improvements to residents' and migrants' quality of life. This process of well-being improvement is far from perfect, but in functional cities it generally holds. Building on this image of the city, I consider collapse to be any prolonged period of time during which urban residents' well-being is instead declining.

The prospect of collapse should motivate proactive approaches to sustainability transition. Collapse and sustainability are something close to antonyms; if a system were sustainable, it would not collapse, by definition. I should note that while collapse itself may have very little to do with resource use, it will have resource use implications; however in this discussion, the term 'sustainability' is used in its broadest sense, to mean environmental, economic, and social sustainability.

Collapse can come in many forms. The suite of Chinese policies maintained to some extent in order to slow migration to cities – primarily land finance and hukou – indicate that the Chinese government is motivated by a certain fear of collapse; one which may be result from migration that is too rapid. Hausmann et al. argue that economic diversity is a key enabler of economic growth at the national level [94, 92], which suggests that it may be possible for a lack of economic diversity to contribute to system collapse. And given that many cities are larger than many countries, I find it feasible that Hausmann et al.'s arguments could just as well apply to urban economies. Many cities have experienced collapse due to human factors, including war as in the case of Rome or, more recently, Sarajevo. Cities can also be subject to the whims of economies that are outside their control; exogenous (national or international) economic shocks can negatively impact local economies, for example resulting in significant job loss. Finally, while the natural system plays a relatively small role in my analysis, it becomes relevant in the context of possible collapse. Besides the already mentioned possibility of natural disaster (e.g. a hurricane or earthquake), localized economies may be susceptible to food supply disrupting drought, or sea level rise in the longer term.

While not desirable, per se, collapse is not necessarily all bad. Holling (2001) discusses four phases in the natural cycles of complex socio-ecological systems, termed exploitation, conservation, release, and reorganization.[98] Release is analogous to collapse, but it is the phase that follows release that presents a potential silver lining. Following the collapse ('release' phase), Holling proposes that socio-ecological systems under go a reorganization phase, during which innovation peaks. Cities that undergo collapse have an opportunity to reinvent themselves, and in doing so innovate in ways that may later be transferred to other cities – even those that have not undergone collapse.

Collapse is a strong word, and brings to mind a process of sudden and dramatic change. But a city's collapse need not be sudden or dramatic to be meaningful. Collapse could be a gradual and relatively invisible atrophy of urban welfare; an erosion of social cohesion, of community. These predominantly social transitions are not easy to observe, let alone measure. How can a city begin to repair itself if it is not obviously broken in the first place? In the context of Chinese urbanization, this topic has garnered fairly signifiant anthropological and journalistic attention.[102, 198, 111]

This form of gradual collapse is especially problematic, because it may not yield the potential reorganization benefit of other more 'traditional' collapse mechanisms. Reorganization may only come about as a result of more dramatic collapse, when the necessity of innovation is obvious and pervasive.

When urban collapse does occur, it is often followed by calls for public investment as a form of recommitment to the city's future. Glaeser, on the other hand, argues that government should not artificially prop up cities in decline of one sort or another, rather focusing efforts on helping residents rather than their geography:

> Helping poor people is simple justice; helping poor places is far more difficult to justify. Why should the government effectively bribe people to live in declining areas? Why should growing areas be handicapped simply to keep people in older places? (Glaeser [80], p. 256)

Glaeser's argument is directed more at US federal government than at the city government in question; it seems reasonable to expect the latter to use its resources to support rebuilding to the extent possible.

In a sense, Holling's reorganization phase lends further support to this line of thinking, if one is to take the long view on urban development. Public investment in a city that has undergone collapse may have the unintended consequence of stifling innovation – by reducing the need for it. On balance, in the long run the opportunity cost of reduced innovation[4] could offset the local benefits of short term investment.

5.2 On sustainable cities

Cities are a common theme throughout this thesis, even though the analysis roams from provinces to buildings to central governance to private firms. What does it mean for a city to be sustainable? How are cities currently approaching sustainability, and what are the limitations of those approaches?

5.2.1 Dynamic urban metabolism

Urban metabolism is a cool idea: the city is an organism. It needs different types of food to sustain its operation, in the form of both materials and energy. Within the city, these resources are transformed into more useful products and then wastes are discarded. Everything that goes in must remain as a stock, or else come out as either a valuable or waste product. The city is subject to the influence of the outside world, and also influences it.

[4] And the elimination of potential spillover effects of that innovation, if successful.

Urban metabolism is a metaphor for the way a city works, intended to describe the phenomenon of resource use in urban areas. The urban metabolism metaphor is useful because it provides a comprehensive lens for contextualizing the complex interactions between different pieces of the urban system. For urban sustainability nerds, urban metabolism is the ultimate systems thinking framework.

The strength of this comprehensive approach is also its greatest weakness. By providing a model that theoretically incorporates every activity in cities, the urban metabolism metaphor sets an impossibly high standard for itself.

Accordingly, data availability constrains the application of the urban metabolism metaphor. Few comprehensive studies of whole-city urban metabolism have been published (see Section 2.3), with many others greatly narrowing the scope of analysis in the absence of comprehensive data.

Acknowledging the practical limitations of whole-city urban metabolism research becomes especially important when one considers the dynamic nature of metabolism. The city is filled with endogenous relationships that affect resource flows. Because we are only beginning to understand the nature of these dynamics, analyzing urban metabolism as a snapshot in time (over the course of one year, most commonly) fails to address the crucial question of how that metabolism has changed over time.[5]

The biological 'metabolism' metaphor also suggests the possibility of system evolution, which could be analogous to emergent transition and aligns nicely with the stage-model development hypothesis. An evolution metaphor is also nice in that it creates a parallel to species differentiation, in line with typological distinctions. In line with my discussion in Section 5.1.2, transformation would result in distinct 'species' of the system, and would emerge through a combination of natural selection and random genetic mutations, which recall the notion of threshold-enabled transition.

Evolution also suggests a slow, natural, and emergent phenomenon, which is something that we frankly do not have time for. Rather than evolution, we need a metamorphosis; a complete transformation. It has become clear that a natural, evolutionary progression of development – one which does not require active stewardship and purposive, sustainability-driven interventions – is not sufficient for meeting sustainability goals.

This can be a hard pill to swallow for scientists intent on solving problems. There is no single answer to the question of "what makes a city sustainable?" when it is posed in the real world – not yet, perhaps not for quite a long time, and in any case not soon enough to inform planning efforts in the short term.

Many climate change and sustainability researchers more generally are plagued by a

[5] Accounting for temporal dynamics is uncommon even for relatively straightforward greenhouse gas accounting exercises. The rare instances of whole-city, time-series urban metabolism studies rely on exceptional data availability, as in the case of Singapore, for which national trade data are readily available.[166] Most cities are neither islands nor nations, however, so researchers will have to get lucky in order to find similarly comprehensive data.

nagging sense that their work does not provide answers. This instinct has the potential to be destructive, for example when it acts as a barrier either to further research or to new researchers' entry into the field. But on the whole it is probably a useful instinct, since researchers' work almost inevitably does not provide definitive answers; the limitations of sustainability research should be explicitly acknowledged.

More importantly, this instinct should drive society to acknowledge that we must act on climate change in the face of significant uncertainty. All climate change mitigation and adaptation efforts are experimental in some respects, because they are all still relatively new. Uncertainty is thus compounded in both the problem and solution, making flexibility essential to the future of sustainability planning.

5.2.2 Cities networked; cities alone

In addition to the uncertainty surrounding the secret sauce of urban sustainability planning, it would be nice to know how to measure that sustainability. This turns out to be quite challenging as well, but I see two parallel paths forward.

The first: to measure urban sustainability performance for a given city only against the benchmark of that city's historical performance (absent compelling evidence for direct comparisons with other cities, or even comparisons with other functional geopolitical entities). I do not define 'compelling', which must be evaluated on a case-by-case basis. Rather than attempting to compare cities with completely different economic structure, spatial layout, history, and cultural context, we should measure improvement from a fixed baseline, accounting for changes in those various drivers over time. We need to make as much progress as possible, in every city around the world.

The second: to develop an approach for analyzing the sustainability of city networks as whole entities rather than as disparate parts. It is not obvious to me what a relevant scale of city network would be, nor how it would inevitably vary depending on what aspect(s) of sustainability one wishes to analyze. Such a network could be regional (e.g. cities in northeastern China), international (e.g. major trading partners of Singapore), national (e.g. French cities); or could occupy other scales.

These networks would probably be best defined according to sectors or the resource in question (e.g. considering water for cities within a particular watershed, or cities served by the same natural gas pipeline or electric grid). For some resources, the appropriate scope may be global, in which case the approach may have limited utility. There are many problems for which using an urban lens does not help provide a solution. But by thus acknowledging inter-city economic specialization, researchers could better account for differences in resource production and consumption rates that currently make benchmarking challenging. This seems unlikely to facilitate comparison between cities or between such hypothetical networks, for that matter, but could make judgements regarding urban sustainability more meaningful.

5.2.3 Global [urban] governance

Global sustainability governance remains likely to be the most effective means of achieving climate change mitigation goals, by minimizing the role of the collective action problem. Until an internationally binding climate change treaty is in place (and perhaps even once it is), cities provide a possible interim and/or complementary approach to mitigation, potentially accounting for more than 75% of global energy use.[87] To what extent could cities influence global sustainability outcomes, and how should they go about doing so?

A shift towards addressing global problems presents a significant political economy challenge for local government. If a local government were to prioritize global sustainability issues in a way that was perceived to reduce the government's efficacy in managing urban affairs, its citizens would be justifiably upset. This motivates a "think locally, act locally" approach to urban climate change governance, promoted[6] by Bai [8] and Betsill [20]. In order to justify globally relevant sustainability measures, such measures need to have clear local benefits.

In cases where cities cannot independently justify sustainability interventions because they are perceived to be outside local government's scope of work, higher levels of government will need to intervene. The mechanisms available to national governments wishing to support local government actions are not well understood, and this seems to be an essential avenue for future study. At minimum, I hope to see increased dialog between various levels of governance, working to coordinate policies and approaches to avoid the inefficient overlap of sustainability agendas.

To what extent should governments be empowered to regulate sustainability in the fist place? Top-down government intervention is not necessarily a good thing, particularly when relevant sustainability goals can reasonably be met through other avenues. Before regulating a sustainability transition, one should first ask whether it is possible to effect such a transition in other ways, and if so what would the trade-offs be of doing so.

Further, local government generally has limited influence over sustainability outcomes. In *Municipal Bureaucracies & Integrated Urban Transitions to a Low Carbon Future*, Aylett (2011) observes that:

> Over the course of interviews with municipal leaders, department heads and civil society groups, it became clear that even though we talk about 'the city' this vision of a unified purposeful actor makes little sense. 'The city' is made up of numerous entities, each one constrained and motivated in its own ways.[7] [6]

This sentiment simultaneously conveys the challenge of organizing to create sustainable change within a city and suggests the huge potential of bottom-up, civil society driven

[6] With some caveats, on Bai's part: namely, that the scope of concern for local government should be expanded both spatially and temporally when possible, particularly for cities in the developing world.

[7] With this quote in mind, I will note that in the few cases where I do refer to 'the city' as a 'unified purposeful actor' of this sort, I rather intend to reference this *set* of entities.

sustainability interventions.

Such civil society-driven interventions or those that generally garner popular support must ultimately also gain political support. Unfortunately, these stars do not always align. In a review of urban environmental indicators in six southeast Asian cities, Ooi (2007) highlights that while popular support and political will can independently achieve modest environmental goals, the combination of the two is essential to achieving large-scale change.[150]

Shifting local government focus towards creating a supportive, sustainability-enabling regulatory environment also avoids a problematic trend towards a sort of presumptive governance. Celebrating notions like Florida's 'creative class' [61], there seems to be a certain tendency among cities to develop a vision of what citizenship *should* be, rather than focusing on what citizenship currently is. In effect, this trend points towards cities trying to create rather than to meet existing needs of urban residents. Why look at the needs of your citizens today, when you could imagine what you would like them to be in the future?

Things are never so black and white, and it remains a perennial challenge for city government to balance between meeting the needs of its current population, attracting more residents, and attracting more *wealthy* residents to grow the tax base, which subsidizes the less wealthy ones as result. The importance of attracting wealthy residents is clear when viewed from this perspective, though my intuition is that cities around the world would be better places if governments focused more on their current residents rather than worrying about the residents and firms who might migrate there in the future.

5.2.4 Sectoral geographies

So-called 'world cities' are generally designated as such due to their prominent role in the global economy. London and New York are widely cited for their sustainability leadership, with impressive local efforts and two former mayors that have played major roles in establishing the C40 Cities network, whose mission is largely to take advantage of world cities' outsized role in the global economy to reduce greenhouse gas emissions. Other cities around the world look to these cities as examples – yet they have only scratched the surface of what is possible for urban sustainability. To earn the designation of 'world city', cities should need to embrace their role as global citizens, striking a balance between governing to address local challenges and governing to address global ones.

The rhetoric of world cities demonstrates an important disconnect standing in the way of finding this balance. On the one hand, cities celebrate local sustainability efforts, whether those efforts are comprised of bike lanes, new green space, public transportation, LEED-certified development projects, or otherwise. On the other hand, cities emphasize their role in the global economy; "our GDP is larger than that of [several small-to-medium-sized countries]", or "we are the financial capital of [geographic region]". Both of these sets of claims intentionally place cities in an international context, though the reality of sustainability efforts is not necessarily so. Sustainability advocates regularly trumpet the complementarity of sustainability and economic growth. The most commonly cited example of the integration of these two goals is green jobs creation, which is a noble goal but remains an almost strictly local undertaking. Independent, local green jobs and green growth efforts may add up to more than the sum of their parts, but this integration could be more effective with a bigger picture approach.[8]

For sustainability and economic growth to become truly complementary, broad economic and local urban planning efforts need to be integrated. I argued in Section 3.1.1 for the value of focusing on 'sectors' as a lens for sustainability efforts, and have argued almost throughout for increased attention to urban governance. The next step is to overlay these two approaches, with city government taking an active role in supporting sectoral economies' transitions towards sustainability.

Attracting particular industries or accelerating a general shift towards a service-based economy are business as usual in this case, but cities can work with sectoral actors to enable industrial growth that both supports urban development and improves global sustainability outcomes. In the developing world in particular, this is part of enabling industry to grow more sustainable in place, rather than creating incentives for industrial relocation, for example.

This hybrid urban-sectoral model would also facilitate the transfer of knowledge between cities. In light of their demographic and economic diversity, cities writ large are only comparable in terms of their physical infrastructures, for example urban form and transportation networks. These infrastructures are hugely important, but they are only part of the story.[9] Distinctions between whole urban economic structures are much more challenging to reconcile, but this challenge may be greatly reduced when sectors are isolated.

Sectors of interest

There can be no definitive list of sectors worthy of in-depth study. The importance of any given sector in an urban economy varies from city to city. As a starting point, I focus on high-level sectoral distinctions rather than industrial sectors, which I have instead crudely grouped together under the heading of 'industry'. Here I highlight buildings, industry, electric power, transportation, waste, and water, as potentially high-impact focus-areas.

The buildings sector is consistently high-impact with respect to energy use and greenhouse gas emissions in cities, accounting for as much as 80% of energy use (as in the case of New York City). Buildings are sufficiently diverse such that they are commonly divided into four sub-groups each worthy of attention, defined by distinctions between: commercial versus residential buildings, and new construction versus renovation. While my study is

[8] Some examples of cities that have moved in this direction are presented by Fitzgerald (2010) in *Emerald Cities*.[60]

[9] I would also argue that urban form (or, the built environment) and transportation should themselves be considered as sectors in this context.

broad and cuts across each of these sub-sectors, each is more than rich enough to support independent analysis.

The industrial sector is the most challenging to define, as it is the most amorphous and distributed. This also makes it the most difficult to influence. In the broadest sense, the industrial sector is all of the firms that comprise an urban economy. In most cases, however, the industrial sector comprises only energy-intensive manufacturing industries – the kind that might be built on relatively cheap real estate, along rivers for easy access to shipping routes.

The electric power sector is – at least for the time being – highly centralized, making the pathway to change clearer (if not necessarily simpler). Local governments' ability to influence the power sector varies from almost not at all to almost complete control. The electric power sector is particularly important given its direct relationship with buildings, industry, and increasingly with transportation.

Surface transport is distributed with respect to its users, though concentrated in its control. As for each of the three preceding sectors, it represents a significant (though variable) percentage of urban energy use and greenhouse gas emissions in all cities. The impact of the transportation sector can be measured by fuel use or vehicle miles traveled, for example, and is strongly influenced by the availability and robustness of public transportation.

Waste generally represents a smaller percentage of urban greenhouse gas emissions than buildings, transport, and industry, but its impact is still significant, particularly where waste management practices are not advanced.

Water use can use significant energy, but it is also important for two other reasons. First, water is the largest non-gaseous material flow through cities on a mass basis. Second, water scarcity is an immediate challenge for many cities that draw on nearby surroundings for water supply. Treatment can also be energy intensive, both for drinking and waste water.

Other sectors that may be worthy of consideration include fuel, food, air travel, and freight.[34] Narrower, perhaps industry-specific analysis may also be appropriate, particularly in cities where one or only a few industries are heavily concentrated and thus exert disproportionate influence on urban sustainability outcomes.[10]

In reality these sectors remain connected and one must not lose sight of this fact – but focusing on individual opportunities for sustainability interventions makes the challenges more tractable, their potential solutions more actionable, and their transferability much more likely. All of these factors are important, but transferability is especially crucial. The cities pioneering sustainability efforts are likely to be the largest, best-resourced cities in the world. Their ideas spread first to other large, well-resourced cities, and continue to propagate slowly 'down the chain' to the medium- and smaller-sized cities. The spread of ideas propagates within and across geopolitical borders, with the increasing role of international knowledge-

[10]Hidalgo and Hausmann suggest that such industrial concentration can be detrimental to long-term economic sustainability, which should also be a concern for local governments with long-term vision.[94, 92]

transfer facilitating organizations.

These medium- and smaller-sized cities are both highly distributed and among the most important to reach, because they are forecasted to see the largest growth and thus the largest increases in resource use.[185, 87] Inasmuch as these increases reflect improvements in well-being, this is generally a great thing – but the opportunity to integrate sustainability into development practice (rather than after development happens) is too large to squander.

5.2.5 Sustainable urban development

The tension between economic development and climate change mitigation is the elephant in the room when discussing sustainable growth. Of the two, development is generally considered more pressing; any argument for prioritizing mitigation is almost out of hand dismissed as inhumane. At the same time, sustainability is often a very good long term investment. A paradigm of "clean up while you grow" is likely much cheaper in the long term than one of "pollute now and clean up later".[11] [166]

Even if everyone can agree that investing in green growth would be a good idea, there is still reason to have pause. How can developing countries afford to pay a premium for more sustainable development while so many other societal challenges persist?

They generally cannot. They need help from developed economies and multilateral organizations to finance sustainable development projects. This sort of investment is still relatively new and far from straight-forward, but remains one of the keys to unlock sustainability leapfrogging in development.

Sustainability transition in the developing world must be approached with humility, because it is a distinctly different enterprise than sustainability transition in the developed world. Cities and regions in the relatively well-studied parts of the world (primarily western Europe and the US) operate in a post-industrial, high wealth, almost fully-built context. Cities being analyzed from the perspective of sustainability transitions are in general already well-established. Urban growth in the US and western Europe is a story of major metropolises getting slightly bigger, and less a story of new metropolises rapidly growing.

In these contexts, researchers ask how we can transition from our existing urban infrastructure to more sustainable infrastructure? In the developing world, that question is sometimes still relevant, but remains secondary – the primary question from a sustainability perspective being, how can we transition from the business-as-usual development pathway to a development pathway that will result in the construction of more sustainable infrastructure in the long run? This is a question of avoiding possible undesirable outcomes; of attempting to develop sustainably the first time, rather than correcting mistakes after the fact.

[11] To paraphrase a former boss (who was speaking in reference to building energy efficiency, though the lesson applies equally here), the outsized benefits of air pollution regulation mean that failing to invest up front in reducing it is "like leaving dollar bills on the floor".

But this is only the primary question *from a sustainability perspective*; and there are many other valid perspectives. The existing challenges in developing world cities are often so fundamental; so pervasive, that sustainability is not anywhere close to the table where decision-makers discuss important issues on a day-to-day basis. If your city does not have functional education, healthcare, or food systems; if it has many more people than jobs; or if it is overrun with corruption, it is hard to add sustainability to the existing priority set.

Sustainable transition is a normative concept, and as such it should not be *imposed* on developing economies. Fortunately it also should not have to be imposed, as developing countries – and cities in those countries, especially – increasingly recognize the importance of addressing climate change, even when they do not yet have the capacity to expand that priority set. In order to add sustainability to their agenda, the case must be made for sustainability as a means of supporting all of these other priorities. There are many ways in which environmentally sustainable development can improve social and economic outcomes, and many ways in which the reverse is true; social and economic progress can further environmental sustainability efforts.

In order to capture these co-benefits, capacity in the developing world must be increased, and this capacity must go beyond the developmental support that cities would have had otherwise. The sustainable urban development project must be undertaken as a partnership between those in the developed world with excess capacity and those in the developing world who do not yet have enough.

5.3 On Chinese buildings

After spending a short time in Beijing and doing a fair amount of reading and discussing sustainable development in China, in this section I present some of my impressions and understandings of the Chinese building and environmental landscape.

5.3.1 Anecdote

Air pollution

I was not much concerned about smog, as I was not in Beijing for long enough to be at risk of physical harm due to the high pollution environment, which results from the concentration of industry around the city. The steel industry is a substantial contributor to the industrial smog, being concentrated in the surrounding region and Hebei province in particular. The costs of high pollution are quite apparent, though. The money that people spend on pollution-filtering masks each year alone must be non-trivial. More importantly, the government seems to be worried that air pollution is a barrier to attracting the world's best and brightest. This concern is warranted, especially with respect to mid-career professionals who are thinking about starting a family. Spending a year or two living in smog is one thing, but raising children in it is quite another.

Residential development

Hutong neighborhoods seem surprisingly under-developed. In hutong neighborhoods in the old/central city the zoning is quite strict and limits structural change, but even taking this into consideration it was hard to reconcile the rapidly escalating rents, gentrifying neighborhoods, and central location of the hutongs with their buildings' general state of disrepair. These apparently contradictory observations are likely themselves reflective of ongoing, neighborhood-scale transition.

One architect I spoke with believes that many of these run-down buildings remain occupied, with tenants deferring maintenance and possibly sale in hopes of capitalizing on relocation costs when would-be developers come knocking. This was an informal conversation, but it does support the interview outcomes in Section 4.3.6 regarding the impact of resident relocation costs in real estate development.

Commercial development

I couldn't help but feel like the newer commercial buildings in Beijing were larger than they need to be. Not larger in terms of absolute size, but larger in terms of the size of interior spaces. To the extent that this feeling would be backed up by an actual analysis, it is likely driven by a combination of developers wanting to attract tenants with impressive spaces, and architects reinforcing that behavior by wanting to design impressive spaces. This is not a problem, per se, but it does seem inefficient given the pretty extraordinary demand for space in Beijing. I discuss the prospect of overbuilding in Section 4.3.3, though that discussion is more relevant to the total square meters of floor area constructed. This spatial inefficiency has to do with building volume rather than floor area, and while 'inefficient' building volumes would increase the embodied energy of a building, the implications for operational energy use may be more important. Either way, their magnitude relative to buildings' total life-cycle energy is unclear.

Design

Architectural and urban design practice in China represents such a large percentage of total architectural and urban design work globally that it appears to have shifted the focus of the entire global design industry. This is not a permanent shift, since new construction will slow down in the coming decades, but it presents challenges in the short term.

Some of these challenges are contextual, as the increased demand for design work forces firms inexperienced in the Chinese market to adapt their preexisting design knowledge to a new setting. Learning curves in these cases are steep and vary based on the experiences (and locations) of design firms. Some have established dedicated Chinese offices, while others practice remotely and travel as needed.

Other challenges are procedural, as engaging in design work necessitates an understanding of the cultural context, business environment, and often complex or unpredictable work flow processes. This is a practical and also an educational challenge with respect to training young designers who may eventually enter the Chinese development space.

With design outcomes ultimately decided by real estate developers; real estate developers being driven by profit; and profit being contingent (among other things) on the speed of development, it is hard to see how design outcomes can take longer-term planning into account without setting explicit requirements within design processes. Even if one considers this desirable, it would need to come from government as the residential real estate industry has little-to-no incentive to cater to the long-term interests of home buyers, nor the long-term interests of the economy at large. While some general design regulations like zoning or restrictions specific to historic preservation districts are quite common, regulating design of the entire residential sector is in many ways antithetical to design's nature as a creative enterprise. China does have a history of rather heavy-handed regulation, but it is in the midst of a clear though complex transition towards a more market-driven economy.

At the same time, design itself is not always treated as a creative enterprise in China. Several designers I spoke with shared the experience that design is often viewed by developers as a service more than a creative process. Eva Castro of Beijing's Plasma Studio put it this way:

> The understanding of the profession of a designer is less related to human disciplines as it would be in the West, less related to the creative process of being an artist, which by definition means having an agenda; developing a way of thinking of your own. The profession of an architect, of a landscape architect, is defined as a service provision, which is one thing we have fought our whole lives against. (Eva Castro, personal interview, 12 February 2014)

This perception is historically rooted, as LDIs used to be exclusively state-owned and the only organizations legally allowed to engage in design. It also strongly colors design outcomes and may be among the fundamental drivers of the massive, undifferentiated construction patterns for which China is well-known. It also presents a barrier to entry for designers entering the work force, and may reduce the longevity of careers in China. Many international designers are building their portfolios in China before moving on to other, potentially more 'designer-friendly' markets as soon as possible, which is not necessarily a problem but also may result in higher turnover and lower local knowledge retention for the profession. This may result in lower rates of experience accumulation in the field within China, but to some extent it also ensures a steady injection of fresh ideas. It could also be a good thing from the perspective of not institutionalizing overcapacity in the design field, since new construction rates will slow down over time.

Massive, undifferentiated real estate development is not unique to China, nor is it the only development trend for which the country is famous. As I mention in Section 4.3.1, there is also quite a lot of monumentalist, high-profile design work that fosters an international community of ambitious designers working on projects in China. To some extent, the large, monotonous developments pay the bills for designers and in effect subsidize the more creative, artistic designs that pique the interest of the most ambitious design firms. As is true in many professions, the most glamorous work does not always help the financial bottom line. These two extremes are not always recognized in popular coverage of Chinese development, and the contrast between them is one of many apparent contradictions.

5.3.2 Outlook

As demonstrated by the examples in Section 4.3.6, there are many exciting projects underway in China that have potential to greatly improve sustainability outcomes in the Chinese buildings sector in the short and long terms. What's more, the learning derived from practice and experience of stakeholders in this evolutionary process will benefit less advanced developing countries as they navigate many similar challenges, whether directly or indirectly.

To the government's credit, it has applied and is applying many innovative approaches to tackling climate change, many of which are more progressive than those applied in much of the developed world in spite of the fact that China has not committed to any binding international climate change treaty. The Top 10,000 Enterprises Program; US-China CERC research partnership; development and promotion of the Three Star rating system; and commitments to carry out energy-saving retrofits in publicly owned buildings are just a few examples on a long list of admirable efforts that the central government has supported.

Intermediary organizations both complement and drive further change in the government. Firms like GIGA and the Built Environment Group play key roles in accelerating the accumulation of knowledge in building sustainability, and the best practices that they develop and support will lay the foundation for future policies to come. The non-profits and NGOs that operate in China will continue to play key roles in improving sustainability outcomes by connecting international research and best practice to established connections in Chinese government, academia, and industry.

There are barriers that reduce the speed at which transformative change can occur. As in the case of GIGA (see Section 4.3.6), some of these barriers are cultural and require firms or organizations to adapt. Others are institutional; one person I spoke with was in the process of establishing a new China office for their organization, and had to navigate significant bureaucratic red-tape in order to begin officially operating under the banner of that organization.

Those organizations who have invested the time, money, and effort to build and maintain a Chinese presence have done so by building strong relationships with domestic partners. Most of the non-profit and NGO staff with whom I met either had direct experience working at key Chinese ministries and research institutes, or else had developed relationships with those ministries and institutes over the course of their work at an already-established organization.

One important role of these organizations is to facilitate public-private partnerships. I was impressed by the impact by the successes and optimism on the part of the private firms and entrepreneurs with whom I spoke, but they were almost uniformly steering clear of direct involvement with the government as long as they remained in the early stages of building their businesses. It seems like government and these small firms alike could benefit from partnership, but that would require increased support mechanisms on the part of government, and trust on the part of small firms and entrepreneurs, which must be earned over time. Small business can help incubate micro or niche-level innovations that have potential to develop applications on larger scales.

Part of the problem is that while the Chinese government is to an extent open to policy and practice experimentation[12], there are also definite limits to the speed at which China is comfortable making changes. Dramatic policy changes in an economic system as large and diverse as China's are likely to cause unforeseen problems. From this perspective, the central government's conservative approach to transition is more reasonable. And indeed, many of the changes necessary to reorient adverse incentives in the development process are intimidating in scope. The extent to which the government's hesitancy to act inhibits system change is, however, problematic. As transition is deferred, the incumbent regime (made up of various actors, policies, and practices) becomes more and more entrenched.

The philosophy of that regime challenges the foundations on which urban development throughout history has been built. The Chinese government's approach to urbanization highlights a difference between urban agglomeration as a phenomenon and urban agglomeration as a government policy. The phenomenon of urban agglomeration in many respects is indicative of economic progress; people migrate to cities in pursuit of economic opportunity. Chinese leaders have clearly recognized that urbanization has been a strong indicator of social progress.[205, 112] Urbanization rates and economic development are correlated, but the causality runs in both directions; economic development begets urbanization begets economic development. In system dynamic terms, one might call this a reinforcing loop.

It is impossible to know exactly what urbanization in China would look like under a different policy regime. But Chinese policy disrupts what has historically been the natural order of this reinforcing loop. I would go as far as to call urbanization an emergent phenomenon of development; a sort of natural corollary to the process rather than an engineered performance target. There is a particular irony in a Chinese national policy that has long served to slow the migration of people to cities through institutions of hukou and land use financing, while simultaneously setting explicit urbanization targets and developing a comprehensive national urbanization strategy.

The Chinese government has exercised unprecedented influence over rural-urban migration patterns. This level of intervention goes beyond an attempt to slow urbanization rates,

[12]Take, for example, the three distinctly different vehicle ownership policies implemented in Beijing, Shanghai, and Guangzhou.[56]

imbuing the development process with normative vision for what a modern society should look like. China's approach to urbanization is essentially one of the largest social engineering experiments in history.

So far, it is hard to be optimistic about the experiment's results. Government is charged with acting in the public's best interests, though as an institution it too often fails to optimize for these interests more than a few years into the future. The central government in China is no exception, and remains focused on relatively short time horizons, failing to internalize the value of long term planning. Easy fixes in policy-making are rare, and this holds true for managing urbanization or even more narrowly for the Chinese buildings sector. But current Chinese policies' poor land use incentives and unchecked real estate development process are leading to visible social, financial, and environmental problems; problems that live in cities, but which have national implications. Even the best efforts of nongovernmental actors can only do so much to improve sustainability outcomes when the system in question is structurally unsound.

The central Chinese government is not short on capacity to act with respect to making the fundamental changes that would be necessary to overhaul the real estate development process: reforming land ownership and financing, reorienting performance incentives for local government leaders, tightening regulations and oversight in the construction industry, developing energy data transparency efforts, and fostering the creation of intermediary organizations to build and distribute expertise, to name a few. This could happen most efficiently through an act of courageous and visionary leadership, mandated from on high. Absent such a turn of events, a gradual transition towards sustainability will continue to be driven by social pressures, technological improvements, economic opportunities, and policy experiments at the local and provincial levels; all of which can increase the likelihood of policy adoption at the national scale.

Chapter 6

Implications

The recommendations in this Chapter come in two forms. The first proposes a general application for the type of quantitative analysis employed in Section 4.1. The second is derived from the qualitative analysis (Section 4.3), and is thus more specific to the Chinese context; these recommendations include vague concepts like capacity building and fairly obvious suggestions like stronger financial penalties for regulatory noncompliance. But many vague concepts are also extremely important; and many obvious suggestions merit repeating both because there is power in repetition and because sometimes what seems obvious to experts and practitioners is not so obvious to everyone else. In general the central Chinese government is the relevant audience, but I will make clear when I intend to address possible actions on the part of other actors, whether in government or otherwise.

6.1 Climate action planning

The quantitative analysis does not provide guidance with respect to which types of policies would be useful to reduce resource intensity; it is a descriptive model, not a prescriptive one. The dataset does highlight provinces with particularly high resource use in various respects, which is useful to know from a policy-making perspective.

The clustering analysis and resulting development pathways do, however, have important implications for *how* policy can be made. When governments plan their sustainability strategy, they generally look to others for best practices in order to inform their own policies, and an analysis like mine can support a government in their choice of where to look for examples.

In the case of Chinese provinces, the pathways I identified represent the important distinguishing factor; provinces that share development pathways within the buildings sector might look to one-another for guidance, especially in cases where one province is at a more advanced stage of the shared development pathway. Alternatively, provinces who are dissatisfied with their current pathway can look to others who appear to have either changed course, or who occupy a different (but more desirable) pathway altogether.

This comparative process builds on the foundation of the provincial development typology, which need not necessarily be formed using machine learning techniques. Acknowledging that in many cases – particularly in the developing world – data will be sparse, typological distinctions may be constructed from census or separate survey data. The importance of having some useful data in the first place is hard to overstate, and building infrastructure for standardized data collection should be a priority for any country without it.

6.2 Policy for Chinese buildings

What follows here are recommendations primarily derived from the qualitative analysis (see Section 4.3). I divide the discussion here into three sections. The first focuses on drivers of cultural or structural change in the buildings system; the second on embodied energy; and the third on operational energy. I speak here in terms of energy rather than resources because I expect this language would be more accessible to policy-makers. While "operational resource use" and "operational energy use" are approximately interchangeable[1], "embodied energy" comprises the energy intensity of building materials in terms of their extraction, processing, manufacturing, use, disposal, and transportation, in addition to the energy requirements of construction processes and other non-envelope material use, for example water.

The primary audience for these recommendations is the Chinese central government, for two reasons. First, local governments have limited ability to set policy in the Chinese governmental system. Local policy decisions must generally have central government support; and further, local politicians feel the need to have that support if they aspire to rise further on the political path. And second, many of recommendations are for strucutral change that can only be addressed at the central government level.[2]

6.2.1 Effecting structural change

The role of travel as a means of being exposed to new ideas regarding sustainability was a surprising and surprisingly pervasive observation in my interviews (see Section 4.3.5). In terms of building capacity among local governments, China would do well to acknowledge the value of travel explicitly, for example by earmarking small travel funds for local officials, with preference to who do not have international travel experience. It will never be feasible to send all mayors (let alone other government employees) abroad to do field research, but local government officials from small cities and remote provinces would likely have quite a lot to learn even from trips within China, for example to some of the coastal cities who have pioneered sustainability efforts in China.

[1] Unless one considers maintenance-related material use to be 'operational'.

[2] Even when policy can be set at the local level, it is often inefficient to do so as competition to attract business, for example, can give rise to a regulatory 'race to the bottom'.

There are more opportunities to grow capacity in small cities, and these are increasingly important as small cities become medium-sized cities and begin to grow more rapidly. The central government already carries out many forms of training for local government officials, often surrounding specific policy efforts. Such capacity building is essential, if for no other reason to begin to familiarize small governments with the basic principles of sustainability and energy use minimization so that these are concepts incorporated into early-stage design and development; not just late-stage development and the retrofitting or 'repair' of the already-built environment.

The firm of one of my interviewees is in the process of compiling its best sustainable design practices into a handbook for the use of other Chinese architects and designers. The Chinese government can support resources like this and the many others developed by organizations like the Energy Foundation and research units like the China Energy Group at LBL, by serving as a clearing house of published information and compiling it in a centralized [online] directory. Further, the central government can leverage its convening power both directly and through its various research arms and state-owned enterprises to organize expertise in easily communicated ways, whether written or otherwise. Such materials in any form should be designed to help local government officials and building sector professionals who do not have the same resources, experience, and networks that those operating in Beijing, Shanghai, or Hong Kong do.

While it has been said many times before and will be said many times more before it has happened: China must reform its land ownership and financing system. The incentives are too backwards and the risks of further delaying action too great. As an alternative, or perhaps a compliment to that reform, reorienting performance incentives for local government leaders would go a long way towards encouraging a more holistic, long-term planning process.

6.2.2 Reducing embodied energy

My interviews suggest that existing building standards are relatively strong. China should, however, anticipate a rise in building demolitions down the road and implement requirements for material recycling or reuse in demolition and rebuilding projects. To the extent this is possible given the state of specific building structures, it significantly reduces the need for trucking materials to and from land-fills, or to and from other producers to the construction site in question.

The government has a unique opportunity with the Top 10,000 Enterprises Program to push the boundaries of what is achievable in government intervention. This will require a delicate hand, as so much of what is important about the Top 10,000 Enterprises Program has to do with the need that it highlights for workshops and other firm-to-firm and firm-to-government (and vice-versa, on occasion) information sharing.

The Top 10,000 Enterprises Program highlights a dire need for more consistent enforcement of existing policies. Part of the problem is that current penalties (e.g. for poor construction or not meeting energy efficiency design) are much too small to actually discourage undesirable behaviors. These penalties need to be stronger, or else monitoring and evaluation needs to be more centralized in order to avoid the problem of local government performance incentives, which currently encourage underreporting of noncompliance.

Intermediary/third-party measurement and verification firms are necessary partners in this effort, but there are not enough certified organizations equipped to carry out the type of measurement that is required for building performance and construction quality. Part of the problem is that it can be challenging for people to achieve that certification. The process of being trained and/or certified as an intermediary measurement and verification firm (or any other type, for that matter) needs to be streamlined to encourage entry into the market, rather than artificially constraining it. Increased enforcement efforts could improve the life-time of buildings as well by forcing improved construction practices on firms across the board.

The origins and development of the Top 10,000 Enterprises Program should be memorialized as a case study for how to effect policy change within the Chinese system. The involved partner organizations had impressive foresight with respect to early engagement with key stakeholders, transparency in programming, thorough data collection to facilitate verification, and a keen awareness of timing in the cases of both the 11th and 12th five-year plans. Their story of adapting organizational strategy to the Chinese government's policy development model is an excellent example of using contextual awareness to improve resource use outcomes.

6.2.3 Reducing operational energy

One of the major barriers to reducing operational energy use in China lies in the complexity of the Chinese consumer. Demand for housing is extremely high and largely comes from either first-time buyers or real estate speculators. More efficient building designs are desirable, but will likely arrive with higher energy use from more energy intensive appliances and behavioral patterns once residents are wealthier. It is not easy to alter the course of these trends.

One possible avenue for creating long term shifts in consumer demand is through data transparency efforts. This is a major challenge in the face of extraordinary hesitancy to share data at almost every turn. Government may choose to ignore that hesitancy by mandating reporting, for example following the example of New York City to require buildings above a certain size threshold to report their monthly energy use.[179] Alternatively, government could offer incentives to firms who share their data as a means for building acceptance. And as always, cities and government can build trust and demonstrate proof of concept by pioneering data transparency efforts on their own.

Local governments would also do well to engage building owners with large portfolios of owned space, as they have the greatest incentive to proactively address energy use in their buildings (since their energy bills are the highest). In general, government should identify the potential partners who will most strongly benefit from a given, desirable policy.

One of the most interesting examples, and one that merits repetition and further innovation, came from the city of Kunming, in China's Yunnan province. Kunming is working to increase real estate developer accountability in large-scale development projects.

In general, once a city awards a real estate contract to a developer, the developer takes the reigns and completes the project in whatever way it pleases. This is especially problematic when the developer's vision conflicts with the city's master plan, or worse with the city's site-specific vision for the site in question. Kunming's innovation, developed in partnership with the Energy Foundation, is to alter the contract itself in order to extend accountability further into the contract. This is the primary leverage point that cities are empowered to use in their interactions with real estate developers, since developers cannot move forward with projects before they have leased land. Such contracts may be extended with further reporting and monitoring requirements (for example the data transparency efforts mentioned above – which would also be an interesting experiment in terms of applying outcomes-based evaluation).

6.2.4 Transitional governance

Theories from the socio-technical transitions literature make clear that a key role of governments in fostering innovative approaches to sustainability is to create an environment in which innovative ideas can be both tested and up-scaled (from the 'niche' to the 'regime' scale, in the language of the multi-level perspective). The transformation process illustrated in Figure 5-2 highlights the value to government of in particular supporting niches that are capable of supporting multiple innovation pathways. This philosophy of governance emphasizes flexibility and support rather than top-down mandates. This approach may not be realistically possible in China for some time, but may be more readily applicable in other contexts.

Governments must increasingly approach policy-making with a clear understanding of institutional barriers to change and a clear vision for future development. Only with an understanding of the desired transition can incentives and policies be structured to support it. These incentives and policies must be considered holistically and with an appreciation for their complimentary (and sometimes conflicting) roles. Policy-making remains an extremely complex and messy optimization process; it is hard enough to make sound policy decisions as it is. Sustainability concerns are most important at longer time scales than government is traditionally equipped to consider, and accounting for sustainability in current decision-making must be done in the face of enormous risk and uncertainty. Balancing these dynamics is no small task, but also a necessary one for policy-makers to actively engage for the foreseeable future.

Chapter 7

Conclusion

China is in the midst of one of the largest societal transformations in history, as it continues to bring more of its 1.35 billion residents out of the poverty frying pan and into the global economy fire. This process brings with it substantial resource use implications at local, national, and global scales. The country's ongoing urban migration, which will bring more than 300 million new people into cities by 2030, positions Chinese cities as ground zero of this transformation.

Like all societal transformations, this is a complex process made up of many smaller, interacting parts – each of which is also subject to its own transition dynamics. With respect to their resource use implications, these parts may be categorized as different sectors of the economy (building, industry, transport, power generation, etc); analyzed at different spatial scales (urban, provincial, regional, national); put into the context of society's broader governing systems (economic, social, political, natural, and technological); or a combination of these approaches, as I have done in this thesis.

I consider urban sustainability through a sectoral lens to reduce the complexity of the analysis, and emphasize the need to maintain a spatial awareness throughout the sectoral approach. I choose to analyze the building sector, in light of its resource intensity and fundamental relationship to urbanization – new urban residents require new housing, new buildings in which to work, new support infrastructure to provide those buildings with electricity and water, and new roads (on which to drive new cars).

My quantitative analysis uses k-means statistical clustering to identify resource use development typologies for Chinese provinces. A two-path typology emerges – one taken by the three primarily urban provinces, and the other comprised of the remaining 27, within which I further identify a developmental sub-typology that appears to demonstrate the influence of China's "Go West" policy on provincial resource use in the building sector.

The distinguishing feature of this machine learning analysis, however, is that the pathways taken by individual provinces are much more distinct than the stages that comprise those pathways. This observation suggests that policy-makers should approach best-practice sharing and peer learning by considering the arc of development rather than the current state of affairs alone.

The limitation of the quantitative analysis' explanatory power leads me to pair it with an interview-driven qualitative analysis, which contributes essential institutional background and allows for a practical exploration of transition dynamics in the Chinese building sector. In short, bad incentives in the building system cause resource-inefficient outcomes. Real estate developers currently dominate the building landscape, which is and will for years to come be focused on new construction. The ability to change existing incentives and/or set new ones lies ultimately with the central government, which needs to fundamentally alter the building system in order to significantly improve sustainability outcomes. This overhaul should include (but not be limited to) land use and local government financing reform, stricter enforcement of building standards, and institutional and technical capacity-building for small-to-medium sized local governments.

There are many indications of positive ongoing change. At a high level, China's technical and institutional capacity is becoming robust, shifting from a question of building that capacity to a question of distributing it beyond the country's largest coastal cities. Sustainability experiments with the potential for significant short- and long-term impacts are ongoing in both public and private sectors, and across ICT, architectural, and industrial systems design.

In general, China's governance has not transitioned to keep pace with its development. Planning for sustainability transition requires both an understanding of preexisting sources of system lock-in and a vision for an improved future. Decision-makers must then think carefully and strategically about what smaller transitions are necessary to build the capacity for larger system transformation. Success in achieving resource-efficient urban systems – in China and elsewhere – will look like a mosaic of complimentary sustainability transitions.

Moving forward, academic research needs to develop integrated analytical approaches to understanding key triggers and measuring sustainability outcomes of transition. It is hard to imagine quantitative or qualitative methods standing alone. In particular, we lack an understanding of path dependency and the mechanisms of escape from incumbent developmental pathways in various contexts. This will require analysis at the scales of granular systems and particular sectors, as well as integrative analysis to understand the interactions between those component parts. My sector-focused approach and five-system theoretical framework provide examples of possible integrative approaches.

In this thesis, *Resource Use in the Chinese Building Sector*, I focus the bulk of my discussion on cities, analyze data from provinces, and give policy recommendations to the central government. Perhaps my thinking has been corrupted by the many contradictions inherent in the study of Chinese urbanization; but to me these apparent contradictions are not contradictory at all. Rather, their analytical relationships reflect the type of interconnected thinking that will be necessary to achieve the complex ambition of sustainability transition – in cities and beyond.

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Appendix

Table A.1: Software supplements

R packages utilized
car [64]
clValid [27]
factoMineR [104]
fpc [93]
cluster [161]
ecodist [83]
ggplot2 [193]
knitr [200]
MASS [160]
plyr [194]
randomForest [26]
reshape2 [195]

Figure A.1: Q-Q plots for clustered indicators

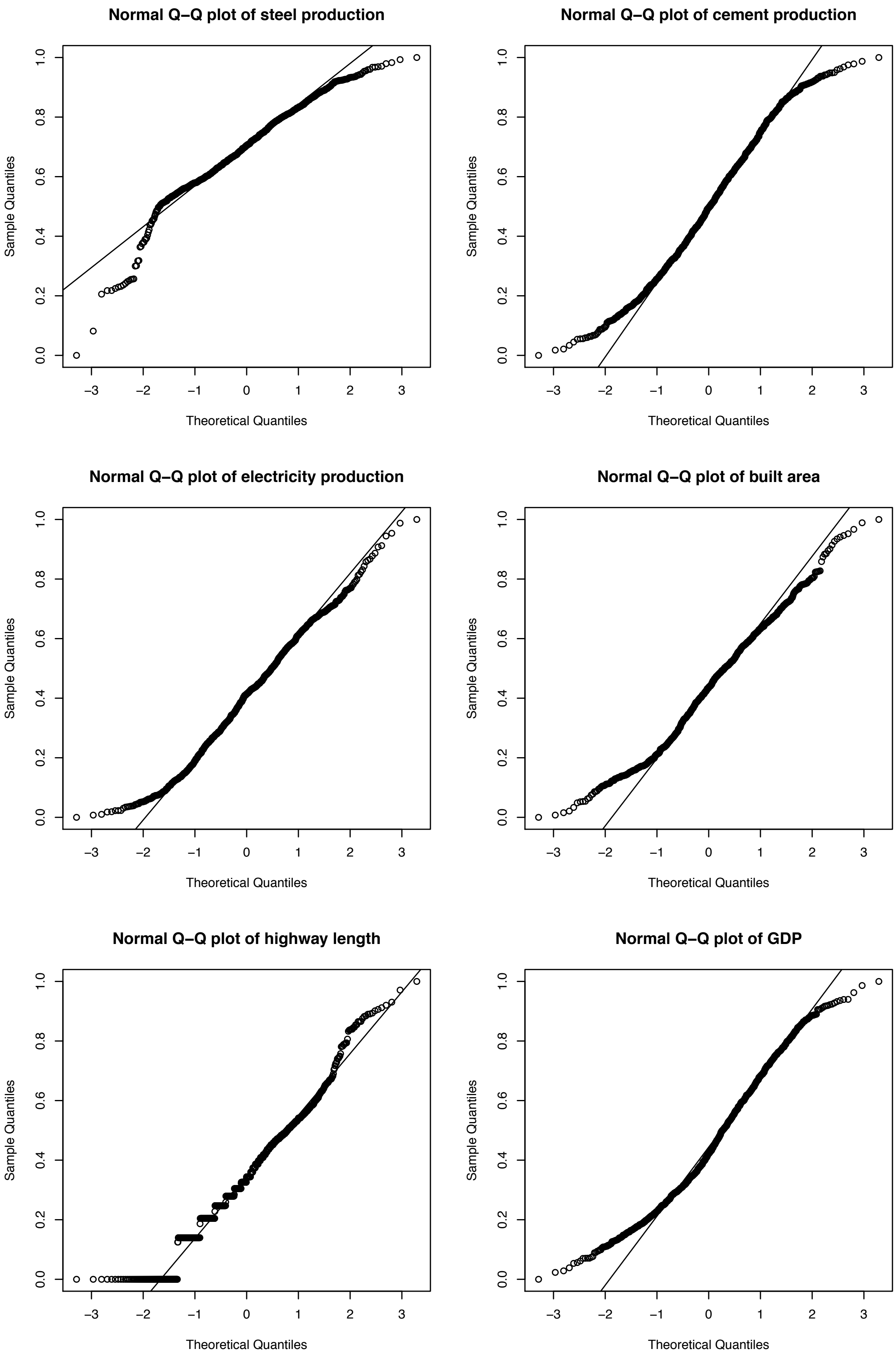

Table A.2: Urban population by province (2010)

Province	3 largest cities	Urban pop. (millions)[1]	Prov. pop.	% of total prov. pop.
Anhui	Hefei	3.10	59.5	9.16
	Lu'an	1.24		
	Huainan	1.11		
Beijing	Beijing	16.45	19.61	86.0
	Miyun	0.26		
	Yanqing	0.15		
Chongqing	Chongqing	6.26	28.85	27.2
	Wanzhou	0.86		
	Hechuan	0.72		
Fujian	Xiamen	3.12	36.89	19.3
	Fuzhou	2.82		
	Jinjiang	1.17		
Gansu	Lanzhou	2.44	25.58	13.1
	Tianshui	0.54		
	Baiyin	0.36		
Guangdong	Shenzhen	10.36	104.32	26.2
	Guangzhou	9.70		
	Dongguan	7.27		
Guangxi	Nanning	2.66	46.02	10.9
	Liuzhou	1.41		
	Guilin	0.96		
Guizhou	Guiyang	2.52	34.75	11.1
	Zunyi	0.72		
	Liupanshui	0.62		
Hainan	Haikou	2.05	8.67	33.7
	Sanya	0.45		
	Danzhou	0.42		
Hebei	Shijiazhuang	2.77	71.85	8.27
	Tangshan	2.13		
	Baoding	1.04		

Table A.3: Urban population by province (2010; cont'd)

Province	3 largest cities	Urban pop. (millions)	Prov. pop.	% of total prov. pop.
Heilongjiang	Harbin	4.60	38.31	19.2
	Daqing	1.43		
	Qiqihar	1.31		
Henan	Zhengzhou	3.68	94.03	6.57
	Luoyang	1.58		
	Xinxiang	0.92		
Hubei	Wuhan	6.84	57.24	16.3
	Xiangyang	1.43		
	Yichang	1.05		
Hunan	Changsha	3.19	65.70	8.08
	Hengyang	1.12		
	Zhuzhou	1.00		
Inner Mongolia	Baotou	1.90	24.71	17.4
	Hohhot	1.50		
	Chifeng	0.90		
Jiangsu	Nanjing	5.83	78.66	16.1
	Suzhou	4.08		
	Wuxi	2.76		
Jiangxi	Nanchang	2.22	44.57	7.96
	Pingxiang	0.72		
	Jiujiang	0.61		
Jilin	Changchun	3.41	27.45	19.6
	Jilin	1.47		
	Siping	0.51		
Liaoning	Shenyang	5.72	43.75	25.4
	Dalian	3.90		
	Anshan	1.50		
Ningxia	Yinchuan	1.16	6.30	27.9
	Shizuishan	0.40		
	Wuzhong	0.23		

Table A.4: Urban population by province (2010; cont'd)

Province	3 largest cities	Urban pop. (millions)	Prov. pop.	% of total prov. pop.
Qinghai	Xining	1.15	5.63	26.3
	Golmud	0.19		
	Datong	0.14		
Shaanxi	Xi'an	5.21	37.33	18.55
	Baoji	0.87		
	Xianyang	0.84		
Shandong	Jinan	3.53	95.79	9.72
	Qingdao	3.52		
	Zibo	2.26		
Shanghai	Shanghai	20.22	23.02	89.3
	Chongming	0.34		
	–			
Shanxi	Taiyuan	3.15	35.71	14.4
	Datong	1.36		
	Changzhi	0.65		
Sichuan	Chengdu	6.32	80.42	10.2
	Mianyang	0.97		
	Nanchong	0.89		
Tianjin	Tianjin	9.29	12.94	76.1
	Jinghai	0.29		
	Baodi	0.27		
Xinjiang	Urumqi	2.85	21.82	16.7
	Korla	0.43		
	Kuytun	0.37		
Yunnan	Kunming	3.28	45.97	9.42
	Xuanwei	0.58		
	Qujing	0.47		
Zhejiang	Hangzhou	5.16	54.43	19.2
	Wenzhou	2.69		
	Ningbo	2.58		

Figure A.2: Annual steel production by province

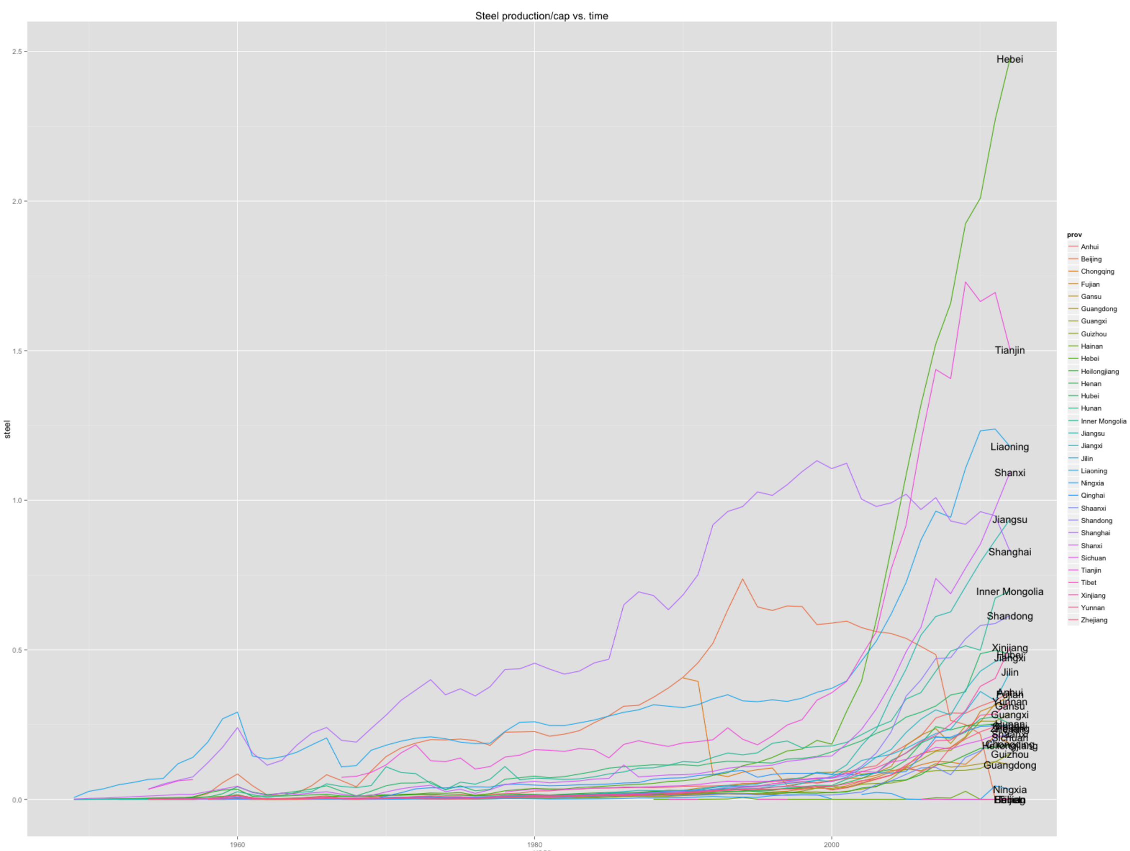

Table A.5: Interview participants

Name	Title	Organization[2]
Eva Castro Holger Kehne Chuan Wang	Partner Partner Partner	Plasma Studio
Chen Chen Federico Ruberto Nicola Saladino	Partner Partner Partner	reMIX studio
Ali Hasanbeigi Lynn Price	Senior Scientific Engineering Associate Staff Scientist and Group Leader	Lawrence Berkeley National Laboratory China Energy Group
Ping He	Director, Industry Program	Energy Foundation China
Anders Hove	Manager, Cleantech Advisory	Azure International
Nanqing Jiang	China National Officer	UN Environment Program
Yi Jiang	CEO	Built Environment Group
Hongpeng Lei	Energy Pillar Lead, Sustainable and Livable Cities Initiative	World Resources Institute
Kevin Mo	Director, Buildings Program	Energy Foundation China
Yan Peng	East Asia Regional Director	C40 Cities
Naifei Sun	[Designer]	[Design Firm]
Carolyn Szum	Lead Managing Consultant	ICF International
Jonathan Woetzel	Director/Founder	McKinsey & Company/Urban China Initiative
Wensi Zhai	[Project Manager]	[Real Estate Industry]
[Anonymous]	[Sust. Cities Expert]	–

Table A.6: Sample interview questions

Question(s)	Audience
What is the role or mission of your organization in the building sector?	all
What are your ongoing projects, and which are you most excited about? Why?	all
In which cities or regions do you primarily work? How has this changed in the past several years	all
In what ways do you consider embodied emissions in your sustainability considerations, if at all?	designers, developers
Why does construction quality have a bad reputation in China, and to what extent is it deserved?	all
How do you make decisions about energy and materials use in your design process?	designers
When are energy efficiency retrofits attractive to Chinese building owners?	efficiency specialists, building generalists
What are best practice project examples in (design/energy efficiency/land use planning/etc)?	all
How do you engage in the policy-making process, if at all?	all
In what major ways does existing policy influence your work?	designers, developers
How effective are current policies at improving sustainability outcomes in the building sector?	building generalists
What are the major barriers to enforcement of existing policies?	building generalists
How do sustainable building practices and policy vary between large and small cities?	building generalists
What are examples of interesting ongoing policy experiments?	building generalists
Who do you perceive to be leaders in sustainable building practices?	all
How do you learn about innovative sustainable building practices? How do you share your own successes?	all
How do you evaluate the success of your organization's knowledge sharing or capacity building activities?	all
How do you evaluate the performance of your projects more generally?	all