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- Infrastructure and social institutions are inextricably linked
- Infrastructure GHG assessment views systems as static and isolated
- Process, complexity, and management challenges exist for reducing emissions

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Positioning infrastructure and technologies for low-carbon urbanization

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Abstract The expected urbanization of the planet in the coming century coupled with aging infrastructure in developed regions, increasing complexity of man-made systems, and pressing climate change impacts have created opportunities for reassessing the role of infrastructure and technologies in cities and how they contribute to greenhouse gas (GHG) emissions. Modern urbanization is predicated on complex, increasingly coupled infrastructure systems, and energy use continues to be largely met from fossil fuels. Until energy infrastructures evolve away from carbon-based fuels, GHG emissions are critically tied to the urbanization process. Further complicating the challenge of decoupling urban growth from GHG emissions are lock-in effects and interdependencies. This paper synthesizes state-of-the-art thinking for transportation, fuels, buildings, water, electricity, and waste systems and finds that GHG emissions assessments tend to view these systems as static and isolated from social and institutional systems. Despite significant understanding of methods and technologies for reducing infrastructure-related GHG emissions, physical, institutional, and cultural constraints continue to work against us, pointing to knowledge gaps that must be addressed. This paper identifies three challenge themes to improve our understanding of the role of infrastructure and technologies in urbanization processes and position these increasingly complex systems for low-carbon growth. The challenges emphasize how we can reimagine the role of infrastructure in the future and how people, institutions, and ecological systems interface with infrastructure.

1. Introduction

The urban built environment consists of complex systems that enable activities resulting in the use of carbon-based energy and the emissions of greenhouse gases (GHGs). The built environment includes human-made and human-impacted land use and activities that are supported by technologies, hard infrastructure (roads, buildings, power lines, water systems, landfills, etc.), and soft socio-institutional infrastructure (economic, political, demographic, and sociological factors) that shapes the hard infrastructure. Its complexity arises as a result of urban design and current use having decentralized regulatory and operational authority. Furthermore, the decomposition to analyze the components of the built system (e.g., the analysis of power plants or individual households) will not necessarily reveal emergent behavior (e.g., citywide GHG emissions) [*Ottino*, 2004]. Buildings and roads that cover most land in a city (and whose use demands energy) are the result of decades of policies, planning, engineering, social preferences, and cultural norms; when combined with energy supply infrastructure, socio-political factors, and economic signals, these features result in the travel and building use that dominate a city or region's GHG emissions. The sociological-ecological-technological systems (SETS) that affect GHG emissions via the built environment are complex and still poorly understood [*Romero-Lankao et al.*, 2014]. Significant efforts have been made to improve our knowledge of the technical complexity of the built environment for helping achieve GHG emissions goals, yet reductions in most major cities to levels that may avoid major environmental consequences have not occurred [*NRC*, 2010]. As cities take stock of the strategies employed or considered over the past few decades to reduce GHG emissions (or to avoid GHG emission for cities early in the urbanization process), they will need to reconsider whether environmental sustainability is a property of how the city operates and is managed, or a quality that results in the urban system delivering acceptable GHG emissions levels [*Ehrenfeld*, 2009]. In doing so cities will need to reassess the role of built environment systems, how they are locked-in (socially, economically, and technologically) to twentieth-century designs, and how GHG emissions reductions can be achieved by physically and institutionally restructuring the systems.

Decoupling GHG emissions from urbanization processes is a critical challenge at this point in history, as both developed and developing regions are increasingly asked to confront potential climate change impacts and sustainability goals. Sustainability principles call for the inclusion of environmental, social, and economic considerations. GHG emissions reductions are an important dimension of environmental sustainability at time when atmospheric carbon concentrations have rapidly increased and a large fraction of world's population is industrializing [*Seto et al.*, 2012]. They are a subset of the environmental impacts that also includes damages to human health, reduction in ecosystem quality, and resource depletion [*Jolliet et al.*, 2003]. We focus on GHG emissions as an important dimension of environmental sustainability and discuss the importance of understanding their relationship with social and economic systems as we seek to decouple GHG emissions from urbanization processes.

The activities that generate GHG emissions are enabled by infrastructure, which is an evolving manifestation of the urbanization processes. There is a tendency to study infrastructure as fixed systems, leading to static views of the city [*Chester et al.*, 2010]; but urbanization is a process, not an end state [*Marcotullio et al.*, 2014], and infrastructure will co-evolve with the city. The evolution of infrastructure may occur more quickly or slowly depending on the system, and ultimately how a city is constrained by this rate of change may end up limiting its ability to reduce GHG emissions. As such, urbanization processes create different urban forms and infrastructure systems, which result in different patterns of carbon emissions. We use the term "carbon" to describe CO_2 and CH_4, the often dominating contributors to GHG emissions.

Research on engineered systems, technologies, and carbon emissions has largely focused on material use, transportation, building use, water use, energy generation, and waste generation in developing regions, where infrastructure is often mature. There appears to be less understanding of system sustainability, climate mitigation and adaptation, infrastructure growth, and health outcomes in rapidly urbanizing developing areas, like China and India [*Romero-Lankao et al.*, 2012], where populations could triple by 2100 [*Fuller and Romer*, 2013], very likely simultaneously increasing their wealth and consumption. Decoupling GHG emission from urbanization processes in developed regions (where infrastructure is locked-in and standard-of-living expectations are focused on the consumption of often remote and energy-intense resources and services) will require solutions to different challenges than in developing regions. Given the complexity of the topic, we focus on research in developed regions. Throughout the synthesis, we try to identify the significance of our findings for developing regions. The state-of-the-art knowledge, gaps, and challenges identified for developing regions are therefore important areas for further research to begin expanding beyond the developed world perspective.

The growth of cities is predicated in part on the dominant energy technologies of the time. Over the past two centuries, these technologies have both emerged with, and largely relied on fossil-based energy. There is a feedback between infrastructure and the technologies we deploy. In the United States, declining costs of electricity resulting from the deployment of fossil-intense mixes in the first half of the twentieth century allowed home energy use to rise through energy-intense building appliances, larger structures, and a greater number of devices per home [*Alliance*, 2013]. In the United States, political decisions favoring disproportionate funding for roadways created short automobile trip times affecting mode choice ultimately leading to a prevalence of personal automobiles. Combined with tax policies promoting larger homes and exurban growth, this led to the deployment of suburbs in the mid-twentieth century. Long-distance vehicle travel and long-distance water conveyance would not have been possible without the innovation of technologies (e.g., automobiles, large-volume water pumps, and air conditioning) and the lowering of their costs that was possible through reliance on fossil energy. Today, the infrastructure and technologies that support and contribute to long-distance supply chains for material provision

[*Brunner and Rechberger*, 2002], increasing travel congestion [*TTI*, 2012], inequitable air quality impacts [*Grineski et al.*, 2007], decreasing water supplies [*de Wit and Stankiewicz*, 2006; *USBR*, 2012], long-distance conveyance [*Bartos and Chester*, 2014], dwindling and intensively used energy supplies [*BCG*, 2008], and an inability of the hinterlands to assimilate vast amounts of waste [*Cohen*, 2006] are of concern. Urbanization over the past two centuries has fueled massive economic growth and undoubtedly significantly improved quality of life for much of the world's population. Prior to 2000, before modern sustainability principles became part of mainstream values, technologies and infrastructure were deployed without an extensive understanding of their impacts. As urban populations grow and become more affluent, access to resources becomes strained [*Brunner and Rechberger*, 2002; *Kennedy et al.*, 2007] and extreme climate events become more frequent, new knowledge is needed about how to position infrastructure and technologies. Yet, we are only starting to understand the process of urbanization from an interdisciplinary viewpoint, acquiring knowledge of the social, environmental, and economic drivers [*Marcotullio et al.*, 2014; *Hutyra et al.*, 2014]. This knowledge is badly needed to guide engineers and planners to achieve 21st century GHG emission reductions and sustainability goals.

As cities become increasingly aware of the potential vulnerabilities to climate change, there is increasing interest in decoupling urban growth from carbon-based energy use. The challenge is that modern urbanization is predicated on complex, increasingly coupled infrastructure systems. Until energy infrastructures evolve away from the carbon-based fuels that are critical to the urbanization process and daily life, GHG emissions are unavoidable. Further complicating the challenge of decoupling urban growth from GHG emissions are lock-in effects and interdependencies. In addition to technological lock-in, the impact of urban morphology as a whole on energy consumption outlives the lifespan of the individual infrastructure units—the roads, buildings, grids, and pipe networks—which in themselves are long-lasting due to high fixed costs, increasing returns, and network externalities [*Unruh*, 2000, 2002; *Unruh and Carrillo-Hermosilla*, 2006]. The lens through which engineers and planners view urban growth sans carbon is often one in which they ignore how (i) decades or centuries of investment in existing GHG-intense systems has locked us in to future growth patterns that limit our ability to decouple carbon emissions from growth and (ii) engineering projects at large scales will be increasingly interdependent with socio-institutional and information systems. This means that for mature infrastructure in developed regions our ability to decouple urbanization processes from GHG emissions may be constrained. The greatest opportunity for configuring cities for low GHG emissions may be in developing regions. The majority of urbanization in the next 50–100 years will be occurring in medium-sized towns in Asia and Africa where existing infrastructures are not currently established and motorization is rapidly taking place [*Chen and Kan*, 2008]. Once the infrastructure that defines the urban morphology is established, the emissions are locked-in with the capital stock turnover limited to incremental changes. As half of urban land in existence in 2030 is yet to be developed [*Seto*, 2013], the next decades offer a critical window of opportunity to influence how cities are built and what their collective impact on the global carbon cycle will become [*Seto et al.*, 2012]. The way that these cities urbanize and the type of infrastructure developed will have large impacts on GHG emissions in the future [*Davis et al.*, 2010]. There are unique challenges and opportunities ahead for reducing GHG emissions from the built environment, and these often vary by geographic region, socio-economic conditions, and other factors.

In this manuscript, we first establish how the relationship between built environment-engineered systems (specifically infrastructure and technologies) and GHG emissions has largely been viewed as static and independent systems. As such, efforts to reduce carbon emissions from these systems often focus on technological fixes such as vehicle shifts, electricity mix changes, and appliance efficiencies. There is a dearth of knowledge on how these systems are part of complex urbanization processes that are often governed by cultural, political, economic, social, and institutional factors. As we start to develop this knowledge, we draw from a body of literature in core technological systems areas (transportation, buildings, water, energy, and waste). Having characterized the state of built environment and technologies GHG emissions analysis, we propose several challenges that future research should address to develop a more systematic understanding of the relationships between urbanization, infrastructure, and technology use. While we focus on the relationship between GHG emissions and urbanization, we acknowledge that GHG emissions reductions are rarely a prime goal for urbanization. We understand that complex systems cannot be understood or defined through single issue perspectives. However, given the importance of climate change, we focus on improving our understanding of how GHG emissions may be managed, given the other dimensions, constraints, values and complexities of the urban system. In doing so we hope to identify where new data, knowledge, tools, methods and research findings can inform future urbanization processes in ways that help develop healthy, resource-efficient, and low-carbon infrastructure systems that successfully support current and future societies, globally, with their local priorities while addressing multiple urban risks.

2. A Typology of GHG Emissions Assessments of Engineered Systems

Assessments of GHG emissions from infrastructure systems (e.g., transportation, buildings, energy use, water use, and waste management) tend to view systems as static and existing in isolation (with other physical systems as well as with the institutions that manage them). In the following subsections, we focus on the major engineered infrastructure systems and the dominant technologies they are associated with, and for each characterize the state-of-the-art technology and infrastructure urban GHG assessment knowledge. It is important to distinguish between infrastructure systems (i) that deliver functionality (buildings and transport) and demand resources, and (ii) that supply energy, resources, and information to allow other systems to function. Through this review the reader will see that fields that study the use of technology and the direct operation of infrastructure (e.g., engineering and urban planning) tend to ignore the complexity and increasing coupled nature of these systems and tend to be focused on mature systems in developed regions. Furthermore, they do not directly address the physical or institutional "lock-in" of infrastructure. While there is a call for developing complexity theory for urban-built environment systems [*Li et al.*, 2007; *Ehrenfeld*, 2009], there is currently very little research that has embraced these principles.

2.1. Transportation and Fuels

The GHG emissions quantification of urban transportation systems has established linkages between urban form and infrastructure and is inextricably linked to fuel (and increasingly electricity) production. There is well-established literature on how different urban forms and transportation infrastructures achieved through regulatory or market-based policy instruments and spatial planning can lead to very different urban GHG trajectories [*Antrobus*, 2011]. The current transportation literature is largely based on case studies of cities in developed regions. At an urban scale, transportation GHG emissions have largely been studied assuming static infrastructure. Reducing impacts through shifts to more efficient modes of travel, lowering congestion (since higher speeds tend to require less fuel per kilometer traveled up to a certain speed), and encouraging the adoption of cleaner fuel vehicles (such as electric) through subsidies, technological gains, and the strategic deployment of refueling/charging infrastructure have been considered [*NREL*, 2007; *Barth and Boriboonsomsin*, 2008]. Because transportation is a derived demand (i.e., the destination activity or consumption has utility while the transportation itself is chosen based on the least disutility), there is a rich history studying the socio-economic, infrastructure, economic, and policy drivers of transportation, prior to GHG emissions assessment [*Givoni and Banister*, 2013].
As GHG emissions assessment has become more prevalent, significant efforts have been made to link micro-, meso-, and macro-scale travel in cities with their resulting emissions. The assessment of passenger and freight transportation has increasingly considered the life-cycle impacts of and interdependencies with fuel supply. There have also been efforts to contrast mobility and accessibility through the GHG assessment of teleworking. The focus on mode shifts, fuel shifts, and improved operation efficiency are important for reducing transportation's carbon contributions, but these strategies have largely ignored the possibility of a limiting function from urban form that dictates how much emissions can be reduced based on, for example, the widespread deployment of automobile infrastructure and dependent built environment (e.g., buildings) that have been structured around it [*NRC*, 2009]. Also, efforts to understand how institutional drivers affect our ability to reduce GHG emissions from transportation systems are weak [*Kimball*, 2014].

2.2. Buildings

Studies of buildings often focus on the life-cycle or use phase energy use of subsystems (e.g., lighting, Heating, Ventilation, and Air Conditioning (HVAC), and appliances), how significant each of these subsystems are in total energy use, the reductions that can be achieved by particular technologies (e.g., efficient lighting, improved insulation, passive heating and cooling designs, and smart sensing), and the corresponding GHG emissions that occur from power generation [*Pérez-Lombard et al.*, 2008]. Studies of how buildings across cities systematically result in demand for energy and result in GHG emissions are sparse. Studies that do evaluate buildings across neighborhoods or larger areas in a city tend to focus on questions of density tradeoffs [*Norman et al.*, 2006; *Chester et al.*, 2013b; *Jones and Kammen*, 2013; *Nichols and Kockelman*, 2014]. This multiscale research is valuable but does not contextualize energy use within the historical growth patterns (and influencing policies), socio-economic drivers, and granular geospatial outcomes across the urbanscape [*Reyna and Chester*, 2014]. As such, cities are left with nonspecific information about how the demand for energy use produces GHG emissions that can be attributed to building activities. Furthermore, while there have been a plethora of life-cycle building studies [*Masanet et al.*, 2012], the gross heterogeneity of building types and uses across a city or larger region make generalization of findings challenging. Despite these challenges, there does appear to be attempts at better understanding the spatial and social drivers of building energy use in cities. *Fissore et al.* [2010] found that total carbon emissions (auto and air travel, space heating and cooling, etc.) varied by a factor of 4, suggesting that individual behaviors at both long time scales (purchase of a home) and short time scales (thermostat setting) need to be understood in order to understand urban GHGs. With increasing access to computing and visualization power for big energy datasets, research has begun to emerge that provides granular insight into the effects of building systems [*Gurney et al.*, 2012; *Howard et al.*, 2012; *Pincetl et al.*, 2014].

2.3. Water

Because the cost of water is the result of conveyance, distribution, and treatment, embedded energy analyses of infrastructure are common. The GHG emissions assessment of water use often focuses on the characterization of the embedded energy associated with infrastructure processes. When characterizing the significance of infrastructure, studies tend to exclude the energy use associated with the use phase (household, irrigation, cooking, industrial, etc.) [*Stokes and Horvath*, 2009; *Siddiqi and Anadon*, 2011]. There is a clear distinction in research where the analysis of technologies responsible for conveyance, treatment, and distribution are separated from behaviors and activities associated with use. Studies that aim to estimate the interconnectedness of energy provision (and ultimately the associated GHG emissions) include use phase effects and tend to emphasize the significance of regional energy expenditures for water (e.g., *CEC* [2006] found that 19% or roughly one-fifth of California's electricity use in 2001 was associated with water use, of which 15% of this energy use was associated with agriculture). While the science of water-energy interdependencies at regional scales is somewhat formed (albeit typically focused on water-stressed regions), there exists little knowledge at urban scales. Water-energy studies tend to be regional (often state or multistate) and at an urban or sub-urban scale there exists only some knowledge of the GHG impacts of provision and the household, commercial, or industrial drivers of water consumption. *Sahely and Kennedy* [2007] developed a model of the City of Toronto's urban water system that included the drivers of household water consumption (population, temperature, and demand reduction technologies) and quantified the life-cycle GHG emissions from the system. Energy and GHG impacts of the provision of urban water infrastructure are also being assessed [*Venkatesh and Brattebø*, 2011]. Also as utility data become more prevalent there is an emerging body of research that is unpacking the socio-economic drivers of water consumption [*Chang et al.*, 2010; *Mini et al.*, 2014a, 2014b].

2.4. Electricity

Urban electricity GHG emissions analysis is based on either a consumption or production framing with consumption studies viewing electricity as a derived demand of other systems and production studies as an isolated system. An understanding of electricity consumption at sub-urban scales is poor and cities tend to define their electricity use based on their geopolitical boundaries or the utilities serving them. The consumption of electricity is often bundled with other infrastructure (e.g., building use or electrified transportation modes) in demand-centered analyses [*Howard et al.*, 2012]. When the electricity generation, transmission, or distribution system are analyzed as a stand-alone infrastructure, then it can be viewed from either a consumption (electricity that is generated to meet the needs of a geopolitical region) or production (electricity that is generated within a geopolitical boundary) framing. Modern day cities rely on resources from the hinterlands to supply high densities of people and activities, and separate people from environmental impacts. Electricity demand in a city is typically not fully generated within the geopolitical boundary. Furthermore, because electricity is generated first and foremost based on reliability goals, geopolitical boundaries (whether a city, region, or larger state) cannot be analyzed as an electricity infrastructure island [*Marriott and Matthews*, 2005]. Most commonly, the GHG emissions assessment of urban electricity use focuses on the entire city or the service providers and their power generation mix [*Gurney et al.*, 2012]. Studies that focus on reducing the GHG emissions intensity of electricity generation tend to focus on one of two strategies: (i) changing the electricity mix to rely on lower to no carbon sources [*Jacobson and Delucchi*, 2011] or (ii) changing demand through pricing or load balancing technologies to reduce the use of carbon-intense fuels during peak times [*Delucchi and Jacobson*, 2011]. There is also a body of research that focuses on the impacts of the infrastructure itself [*Pacca and Horvath*, 2002; *Bumby et al.*, 2010]. Electricity generation systems are by nature complex and heavily interdependent with other infrastructure, including that of information. As electricity cannot be stored in large quantities cost-effectively, supply must meet demand at any given moment therefore requiring continuous information. The dimensions of technical complexity have been embraced by those studying electricity generation GHG emissions. However, complexity that includes geospatial and social drivers within the urbanscape and the increasingly coupled nature of these systems with computing remain largely unexplored.

2.5. Waste

Limited knowledge exists about the GHG emissions associated with waste management and urban-scale knowledge for most cities is nonexistent. Models exist for estimating the GHG emissions associated with waste management including landfilling, recycling, reuse, and incineration [*EPA*, 2013] but assessment typically starts with the waste having already been generated. The knowledge of how urbanization processes produce waste management systems, how those systems produce GHG emissions, and how the systems are and should be evolved to reduce GHG emissions from urban waste management is largely undeveloped. Cities are now beginning to follow ICLEI protocols to quantify waste management impacts and assessments are starting to be performed [*Kennedy et al.*, 2009, 2014]. *Finnveden et al.* [2005] have studied the life-cycle GHG emissions from waste—generally supporting the preferred choice of recycling, then incineration, then landfill—and [*Mohareb et al.*, 2011] compared different methods of determining waste GHG emission for cities. However, there is often limited systematic knowledge at an urban or sub-urban scale of how resources are consumed, turned to desirable and undesirable products, and waste is generated [*Pincetl et al.*, 2014]. Researchers have identified the need for improving information on the socio-economic, commercial, and industrial drivers of waste generation as well as the configuration of the infrastructure [*Murphy and Pincetl*, 2013].

3. Environmental Assessment Frameworks for Engineered Systems

There are several approaches to assess the technical complexity of environmental effects of engineered systems and technologies. In particular, life cycle assessment (LCA) and urban metabolism (UM) have emerged as the key frameworks for assessing engineered systems in cities. These frameworks have been valuable in quantify the energy use and GHG emissions that results from activities and infrastructure services, how the effects are allocated to people, and how they change over time. However, LCA and UM do not address deeper complexity issues such as the myriad nontechnical decisions that affect urban form and structure, the rules that guide growth, nor their physical and spatial organization [*Batty*, 2003]. However, LCA and UM produce valuable insight into the energy use and GHG impacts of physical processes and activities across complex technical systems.

LCA research on urban technological systems have largely focused on characterizing the (i) the significance of upfront construction/manufacturing and supply chains emissions, (ii) the marginal effects of policies and decisions, and (iii) the complexity and interconnectedness of often just two systems, critical as they might be. The use of LCA for large systems assessment began in the 1990s [*Hendrickson et al.*, 2006]. By the end of the 1990s, the framework had been adopted by engineers to assess conventional and alternative vehicles [*Lave et al.*, 1995; *MacLean and Lave*, 1998], structures [*Horvath and Hendrickson*, 1998; *Guggemos and Horvath*, 2005], and electricity generation [*Pacca and Horvath*, 2002]. The focus of these studies was to develop an understanding of the significance of construction, manufacturing, maintenance, and supply chain process emissions in the life cycle of engineered systems. They also established the need for indirect systems, specifically, the supporting infrastructure that delivers functionality (e.g., buildings and transport infrastructure) or foundational flows of energy. By the mid-2000s, driven by a need to better understand the complexity of large-scale biofuel adoption that was resulting from renewable energy policies, LCA thinking around policy and decision assessment greatly improved. Whereas in the past GHG assessment tended to focus on looking back from a particular point in time (whether that be present day or some point in the future) and comparing the average effects from two alternatives, LCA practitioners advanced thinking about how to look forward and frame analytical system boundaries around the marginal effects changes to engineered systems. These two framings are known as attributional (or retrospective) and consequential (or prospective) LCA. While policy and decision-focused consequential LCA initially focused on the GHG emissions of biofuel adoption and its effects on travel [*Plevin et al.*, 2014], it has since been applied across building, water, energy, agriculture, and waste management systems including public transportation [*Thomassen et al.*, 2008; *Chester and Martin*, 2009; *Mathiesen et al.*, 2009; *Chester et al.*, 2013a]. While LCA practitioners seem to naturally embrace complexity and interdependency, the overall approach is to focus primarily on the construction/manufacturing of the technology and infrastructure, the supply chain processes (without geospatial or temporal information on where and when impacts occur) that are needed to support the systems, and sometimes the coupling of generally two technological systems (e.g., water and electricity, transportation and land use, and buildings and electricity) [*Stokes and Horvath*, 2009; *Mashayekh et al.*, 2012; *Chester et al.*, 2013b; *Nichols and Kockelman*, 2014]. This LCA work has produced valuable insight into how significant upfront GHG emissions in the development and creation of technologies and infrastructure are, how systems rely on global supply chains that produce emissions outside of the geopolitical boundary where the engineered system is deployed, and how large the reliance is of one system on a secondary system. Yet LCA practitioners have not seemed to effectively position the framework to alter urbanization processes to change growth trajectories to reduce future GHG emissions. This is due to the fact that engineered systems GHG emissions analysis have not embraced the full complexity of the systems, most notably how infrastructure and technologies are ultimately not managed by engineers but by institutions that have been structured over the past century to maintain service based on goals that are locked-in and do not necessarily align with 21st century sustainability visions.

Urban metabolism is a framework that equates the inputs, outputs, and metabolic processes of living organisms to that of a city and recent efforts have attempted to integrate engineered systems. Like LCA, UM is a systems-oriented framework that can provide valuable insight into the impacts of complex systems and has helped in developing more standardized city-scale GHG inventory methods consistent with national-scale and state-level data and benchmarks. Developed primarily in the second half of the twentieth century, UM calls for the identification of energy, material, water, nutrient, and waste flows into and out of a city, how inputs are transformed into desirable and undesirable products, and how resources accumulate [*Kennedy et al.*, 2007]. Environmental intensities can be joined to these processes to produce, e.g., GHG emissions assessments of macro city behavior [*Kennedy et al.*, 2009]. However, unlike LCA, UM practitioners do not naturally characterize the interdependencies of systems. To improve the applicability of the framework for policy and decision making, UM practitioners will need to developed advance methods for assessing these interdependencies. Recent efforts by LCA practitioners have focused on integrating the two frameworks to address these interdependencies. This work either joins embedded assessments of infrastructure processes with flows [*Pincetl et al.*, 2014], includes the supply chains of cities and combines UM (or more specifically, material and energy flow analyses (M/EFA) with LCA to highlight GHG accounting methods that more effectively address spatial scale and geopolitical boundaries [*Hillman and Ramaswami*, 2010], or characterizes how changes in behavior or technologies can reduce flows and their associated impacts. The UM framework is valuable for improving our understanding the city as a demand center for both energy and key urban materials, how cities behave, convert resources, and generate local and remote impacts. However, UM (whether or not integrated with LCA) is limited to some extent in that it does not directly address why engineered systems are designed and operated the way that they are, how they promote the continued use of GHG emissions-intense technologies, and how interdependent they are with many other hard infrastructure and soft institutions.

The emergence of infrastructure and its resulting GHG emissions are the result of decades and if not centuries of policies, decision, cultural preferences, social norms, and economic signals, and LCA and UM do not rigorously incorporate institutional and social factors. The lack of integration of institutional and social factors results in a limited ability to apply the frameworks toward meaningful transitions of infrastructure, even as infrastructure and technologies are constantly changing.

4. Dynamic Systems and GHG Emissions

Engineered systems are constantly changing. The rate of change can differ significantly with infrastructure and technologies: buildings persist in the urban stock for many decades [*Reyna and Chester*, 2014], the automobile fleet turn over in about one decade, and information and communication technologies are changing on a much faster scale. As systems change, they can become more integrated with other technological systems and affect behavior. Examples include automated vehicles, electric vehicles, smart routing (including navigation, signs, and signals), smart appliances, drip irrigation and renewable energy. Disruptive innovations offer the potential to improve the energy efficiency of several key technologies but it remains unclear for many of these technologies if rebound effects will counteract these benefits. Within respective systems there is some research on how disruptive technologies might reduce GHG emissions [*Barth et al.*, 2013; *Bartos and Chester*, 2014]. Disruptive technologies can either reduce the energy intensity of infrastructure and technologies per unit of service delivered, or decouple energy use from carbon-based fuel sources (e.g., renewable energy) [*Thomas*, 2009; *UNEP*, 2009]. However, how institutions set the preconditions to ensure that technologies contribute to GHG reductions by avoiding indirect or rebound effects remains unexplored. A framework for characterizing how during urbanization processes there may exist opportune moments when investments should be made in disruptive technologies to avoid lock-in and long-run indirect impacts does not exist. Institutional barriers in the systems themselves or in interconnected systems may prevent these technologies from achieving rapid deployment. One major challenge is to reconfigure institutional structures historically geared toward rapid development to structures that promote sustainability, with broader power sharing and greater transparency.

5. Challenges for the Advancement of Engineered Systems for Urban Carbon Reductions

There have been efforts to improve the interdisciplinary research of engineered systems, however, physical, institutional, and cultural constraints may continue to work against us. To directly address these constraints, we identified challenges in three themes (process, complexity, and management) that we believe are core future research areas that if addressed, will open pathways by which infrastructure can be repositioned to support urban GHG reduction goals. Research that embraces the wickedness of the challenges of reducing the GHG emissions intensity of engineered systems is going to be more likely to understand and embrace the complexity of the systems and solutions. Solutions will need to include many stakeholder views and academics alone may be poorly positioned to overcome barriers [*Leeuw et al.*, 2012]. Recommendations for overcoming the challenges must be embedded in effective, deliberate, and participative models, some of which builds on social science theories (e.g., analytic deliberation and community-based participatory research) [*Ramaswami et al.*, 2011]. These engage the public in two-way learning regarding environmental, social, and economic priorities, enabling planners to understand the implications of alternative action and reducing the hegemony of the technocracy.

5.1. Process Challenges

5.1.1. Urbanization as a Process

There remains a weak understanding of urbanization as a process and how the deployment of infrastructure and use of technologies affects GHG emissions in different stages of urban growth and for different types of growth (e.g., infill development and suburban sprawl). While there has been a great deal of research in developing countries to characterize baseline GHG emissions and develop forecasts for how those emissions might change under different technology and energy changes, there is little knowledge of how cities grow and whether this growth must be fueled by carbon-intense activities. This is especially important for developing regions, particularly China and India, where smaller rapidly industrializing cities (less than 1 million people) will dominate future urbanization and are already home to greater than 60% of the world's urban population, compared to the megacities that house about 10% of the global population [*UN*, 2006]. The existing research on the deployment of infrastructure for urbanization is in its infancy. *Davis et al.* [2010] estimate that the trajectory for the *existing* global electricity infrastructure coupled with vehicle travel and other fuel use will produce 282–701 Gt CO_2 emitted by 2060 resulting in a mean warming of 1.3°C above preindustrial levels. These emissions would likely avoid key impacts of climate change and they therefore conclude that the sources of emissions that are yet to be developed are the most threatening. *Müller et al.* [2013] estimate that a globalization following Western infrastructure patterns will result in 350 Gt CO_2 from materials production, which is 35%–60% of the remaining 2050 carbon budget if the average temperature increase is to be limited to 2°C. Based on the energy use characteristics of 22 global cities, *Kennedy et al.* [2014] recommend that cities consider local climate, energy mix, transportation diversity, and income factors before deploying new infrastructure for GHG reduction goals. Yet a systematic framework that can assess the relationships between people, activities, and infrastructure form, under various political, social, economic, and cultural norms is inimical to a firm understanding of the design principles for maturing and mature infrastructure during urbanization.

5.1.2. Sociological, Ecological, and Technological Systems (SETS)

The decoupling of GHG emissions from urbanization will require a better understanding of how technological systems interface with sociological and ecological systems. While significant progress has been made in the understanding of coupled human-natural systems [*Liu et al.*, 2007; *Collins et al.*, 2010] and socio-technical systems [*Miller et al.*, 2013], there is still a clear need for comprehensive frameworks that link infrastructure planning for low GHG emissions futures in urbanization processes that improve human well-being and ecosystem services. The transitioning of urban SETS to be more resilient and sustainable in a climate-impacted future requires integrating (1) technical knowledge and know-how regarding the construction, maintenance, and adaptation of infrastructure; (2) knowledge about interactions and feedbacks in urban SETS, including dynamic models able to make use of multiple sources of information from local knowledge to big data; (3) an understanding of organizations that build, manage, and maintain infrastructure; the background knowledge and data flows that they generate and utilize; and the social and political context in which they are embedded; (4) social norms that shape the acceptability, reliance, and accessibility of infrastructure; (5) understanding the interface between human behavior and infrastructure; and (6) values and visions for a more desirable future. Strategies adopting only technological approaches fundamentally limit progress in our understanding and governance of the sustainability of urban systems [*Hommels*, 2005]. A transformation in our understanding of infrastructure and urban systems as coupled SETS is urgently needed to provide a pathway for comprehensive, multicriteria assessment in the context of an uncertain and climate-constrained future [*Park et al.*, 2013].

5.1.3. Lock-in

Urbanization since the nineteenth century has tended to produce forms of infrastructure that are not flexible nor easily upgradable and require fossil energy consumption in their construction and use. Wholesale transformations to low-carbon systems will need to develop: (i) innovative strategies for unlocking current infrastructure and (ii) new forms of infrastructure that result in low carbon emissions that are flexible and adaptable. In developed and developing countries, the dominant forms of infrastructure are those that require large capital investments and therefore long time periods before investments can be recouped. In developed countries, these decade- and sometime century-old infrastructures are largely configured around technologies that were dominant or were perceived to be disruptive including cars and centralized electricity generation. The management of these infrastructures is still based on single objective service goals such as maximizing vehicle throughput on a network or delivering low-cost electricity reliably. While these operating principles are valid and needed, new objectives are beginning to emerge that include GHG emissions reductions, broader sustainability goals, and principles of resilience to extreme climate events. Yet while scenarios for achieving these broader goals emerge, significant transitions have not yet occurred and it must be acknowledged that the managing institutions of these infrastructures are themselves locked-in to administrative, political, and economic constraints that may prevent them from adopting new principles.

Lock-in can occur because of the difficulty of changing the physical layout and operation (e.g., busways rather than railways), or the institutional objectives that create inertia, and lead to an inflexibility when windows for intervention to low GHG emissions futures are identified. Flexibility takes on different goals for developing and developed regions. In developed regions with mature infrastructure, flexibility may need to focus on repurposing and refurbishing systems for low GHG emissions use. For example, the historical tendency toward centralization of power production entrenches reliance upon fossil fuels and results in low efficiencies and high GHG emissions; decentralization, would favor coupled heat and power systems, thereby increasing efficiency, allow greater flexibility of fuel sources, and reduce GHG emissions. In developing regions with maturing infrastructure, efforts to add flexibility may need to focus more on how complex systems can enable low GHG emission emergent behaviors, and how the process for designing infrastructure can be changed so that twentieth-century principles are not wholly followed.

5.2. Complexity Challenges

5.2.1. Coupled Resilient and Low-Carbon Infrastructure Change

With the growing risk of climate change impacts, cities may need to reimagine infrastructure to both assist with lowering GHG emissions and improve resilience to extreme events. The challenges of meeting either goal are difficult enough and meeting both will require new research and knowledge that has not yet been developed. Climate change is widely considered one of the greatest challenges to global sustainability and extreme events are the most immediate way that people will experience impacts. With large concentrations of people, locations (e.g., near shorelines), and increasingly complex and interdependent infrastructure, cities are particularly vulnerable to extreme events [*IPCC*, 2012]. As we recognize the feedback between designing infrastructure to reduce vulnerability to extreme events and how that infrastructure may affect GHG emissions from activities, it is expected that coupled strategies (that increase resilience and reduce GHG emissions) will be desired.

Emerging knowledge of the coupling of infrastructure with sociological and ecological systems should be joined with GHG emissions assessments of how that infrastructure is used [*Marcotullio et al.*, 2014; *Hutyra et al.*, 2014]. Traditional risk-based engineering approaches to infrastructure design focus on minimizing the risk of failure by investing in hard, structural, resistant elements that are fail-safe in contrast to more flexible, diverse, ecologically based approaches that minimize consequences of failure [*Park et al.*, 2013]. While a fundamental rethinking of what makes infrastructures resilient to climate extremes is urgently needed, this rethinking should be supported by science that links infrastructure design and behavior for GHG reductions.

5.2.2. Increased Coupling

Our systems are becoming more and more coupled with each other and with information, and this increased coupling will make it challenging to deploy GHG reduction strategies by targeting a single system. The couplings occur across hard infrastructure, soft infrastructure (institutions), and individuals, and ever more so digital information. Without recognizing these interdependencies, it is unlikely that large-scale reductions in GHG emissions are possible [*Miller et al.*, 2013]. Large-scale scenarios for estimating the potential for GHG emissions reductions are common. *NREL* [2011] estimates that it is possible to meet 80% of U.S. electricity demand with renewable sources by 2050 and the transitioning of the electricity grid to this configuration will require both technological innovation as well as regulatory and energy management institution restructuring. While future scenarios for large-scale reductions in GHG emissions from transportation have been described for sometime, emissions have continuously increased over the past half-century, until 2011 when the economic recession and possibly cultural factors from the coming of mobility age of the millennial generation have stunted this increase [*PIRG*, 2013]. This stability in GHG emissions until very recently has occurred because increases in efficiency have been largely counter balanced by increases in housing size, use of air conditioning, vehicle miles traveled, and air travel, that is, choices made by individuals. Furthermore, research on the large-scale transition to nonautomobile travel (i.e., biking, walking, and transit) has not sufficiently addressed how the land use (in particular buildings) configuration of cities has often grown around automobile infrastructure and technologies. Similarly, while reductions in municipal water consumption have occurred in cities in water-scarce regions, water systems are still largely reliant on increasingly strained sources and critically linked with thermoelectric and hydroelectric power generation facilities. Research at the coupling of hard infrastructure is available but tends to treat these interdependencies as part of static systems. Research at the interface of hard infrastructure and the institutions that manage them is less common, and there remains large knowledge gaps in how transitions of engineered systems for GHG emissions reductions must include strategies to overcome institutional barriers that are configured maintain operational principles that were established in the past and are now vested interests, and to understand how consumers choose to utilize energy.

The embedding of digital information into infrastructure and its use may present opportunities for GHG emissions reductions though there is little knowledge of the potential benefits of exercising this coupling. The pervasiveness of low cost computing and its distributed nature has resulted in innovative methods for collecting data on infrastructure and its use. This information, whether delivered to infrastructure managers or people has the potential to create new insights and behavioral feedback for GHG emissions reductions. Smart thermostats could result in building energy use reductions, smart phones can suggest to drivers to delay their trip or reroute to avoid congestion [*Hu et al.*, 2014], and water pipe sensors could help utilities regulate how assets are being ineffectively utilized. The interface of infrastructure and information offers opportunity for not only an improved understanding of how systems function and are used, but possibly more importantly how the deployment of new infrastructure can be more effectively deliver function while reducing GHG emissions. In some cases, the deployment of new infrastructure could be avoided altogether through strategies to reduce energy usage, especially during peak periods.

5.3. Management Challenges

5.3.1. Transition Management

Our knowledge of how infrastructure systems and technologies affect GHG emissions in cities has improved significantly, yet the awareness of these relationships and how we should be transitioning mature infrastructure and design new infrastructure for maturing regions has not made its way into policy and decision making. Furthermore, GHG and climate research is largely global in its focus on impacts and experts seem to be unable to anchor climate change action in regional and local contexts [*Shaw et al.*, 2009]. While there is still a great deal to learn about the positioning of infrastructure and technologies for low GHG emissions urbanization, efforts to structurally embed the knowledge in urban development and the institutions that govern this process remain limited. The awareness of these processes culminates with a focus largely on developing protocols for accurately and consistently measuring GHG emissions from cities [*ICLEI*, 2012] and reduction strategies that often target technological and behavioral changes (e.g., deploying more renewables, shifting more people to public transit, biking, and walking). Institutional knowledge and intelligence around the design of infrastructure and the relationships between SETS for long-term GHG emissions reductions during urban growth is not developed.

Transition management science is needed to establish the appropriate knowledge generation and methods for overcoming lock-in barriers at different stages of urbanization and infrastructure change. The scenario knowledge that has become so pervasive over the past several decades is valuable but by itself does not address the drivers of physical and institutional lock-in, and what strategies are appropriate for overcoming barriers that maintain lock-in. Infrastructure transition can be characterized as the large-scale, long-term development of new physical systems in which some core components (whether physical or institutional) significantly change. During a transition, the system passes through different phases from pretransitional to acceleration to stabilization to post-transitional, each requiring different types of knowledge, and boundary conditions can be set by other systems which can slow down or strengthen the transition [*Rotmans and Kemp*, 2003; *Wiek et al.*, 2006]. Infrastructure will not evolve by itself but through a process of mutual adjustment between people and the institutions that govern it. Participatory capacity for climate change action at the local level where the sources of emissions and the mechanisms of adaptation reside must be developed [*Shaw et al.*, 2009]. Scenario assessments are important for building target knowledge but system knowledge (comprising concepts and data about the relevant systemic structures, micro- and macro-processes, linear and nonlinear interrelations, etc.) and transformational knowledge are also needed. These knowledge need to be coupled to appropriate incentivizes. At the same time there must be an acknowledgement of the self-organizing patterns of complex systems that lead to evolutionary processes with decentralized and supportive facilitating processes, which in themselves lead to “learning” by infrastructure managers and their institutions [*Wiek et al.*, 2006]. Too often are infrastructure and technology transitions to low GHG emissions states expected to occur simply by recognizing that futures are possible.

5.3.2. Coordination

The fragmented ownership of infrastructure and technologies that both supply and demand energy produces a challenge in coordination for transitions. The ownership of urban infrastructure, in particular, can be highly fragmented, particularly on the demand side (e.g., vehicles and building stock) leading to a need for multiple strategies for transitional incentivizes and more robust tools for assessing the effectiveness of the incentives in the planning, implementing, monitoring, and evaluating of GHG emissions during urbanization [*Wiek et al.*, 2006]. In the United States there are 3200 utilities who own a part of the electricity grid [*Martin et al.*, 2013], in Los Angeles county, California there are approximately 2.3 million privately owned buildings, and in Phoenix, Arizona 33 cities, municipalities, and native American reservations contribute to regional transportation planning (and the system is ultimately managed by several institutions within each zone). While coordination at higher levels of government is important, centralized top-down master planning that micro-manages local institutions is likely to work against the natural growth and use patterns of infrastructure and technologies in cities and stunt the evolutionary learning process. The historical evolution of London's railway infrastructure and energy systems shows that private sector investments can be poorly coordinated, wasting valuable capital and requiring later strategic consolidation before functioning effectively [*Casson*, 2009; *Rutter and Keirstead*, 2012]. The question is how to coordinate the actions of individual agents in such a way that system-wide performance improves. Furthermore, the political fragmentation of urban systems, and devolution of power from elites to community and interest organizations, has greatly complicated the ability to implement systemic projects (NIMBY, etc). Coordination challenges vary significantly in different contexts. The relationship between centralized institutions, local government, and private actors significantly affects the ability to form integrated spatial planning strategies for infrastructure development.

6. Conclusion

Integration must occur by engineers, planners, and urban scientists in recognizing the complexity and interdependence of the built environment systems and technologies toward recognition of the coupling of hard and soft (institutions and policies) systems, and how these coupled systems interface with the environment. In particular, there needs to be a greater balance between engineered approaches and behavioral approaches for reducing GHG emissions. Currently, training of those who design and sometimes manage engineered systems is often highly focused, concentrated on developing technical expertise with little knowledge of sociological and ecological domains, nor their interrelationships. The question looms as to whether the era of this type of training is over. We must also recognize that the value systems that engineers promote (e.g., reliability, robustness, and efficiency) should be more inclusive of social, environmental, and cultural value systems. This requires us to bring together other disciplines into the redesigning process, and training on how to effectively work across different disciplines will be needed.

The 21st century will likely see a reimagining of infrastructure systems that were deployed largely in the twentieth century and as climate impacts grow coupled with rapid urbanization in developing countries, the decoupling of carbon from urbanization processes will gain importance in policy. Challenges at sometimes generating consensus at the national scale, cities (where global populations are amassing and the impacts of carbon emissions will be most likely to affect people) are poised to become innovators of infrastructure solutions and technology use that if planned appropriately can steer global development away from carbon emissions.

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