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## Infrastructure ecology: an evolving paradigm for sustainable urban development

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### ABSTRACT

Increasing urbanization places cities at the forefront of achieving global sustainability. For cities to become more sustainable, however, the infrastructure on which they rely must also become more productive, efficient and resilient. Unfortunately the current paradigm of urban infrastructure development is fragmented in approach lacking a systems perspective. Urban infrastructure systems are analogous to ecological systems because they are interconnected, complex and adaptive components that exchange material, information and energy among themselves and to and from the environment, and exhibit characteristic scaling properties that can be expressed by Zipf's Law. Analyzing them together as a whole, as one would do for an ecological system, provides a better understanding about their dynamics and interactions, and enables system-level optimization. The adoption of this “*infrastructure ecology*” approach will result in urban (re)development that requires lower investment of financial and natural resources to build and maintain, is more sustainable (e.g. uses less materials and energy and generates less waste) and resilient, and enables a greater and more equitable opportunities for the creation of wealth and comfort. The 12 guiding principles of infrastructure ecology will provide a set of goals for urban planners, engineers and other decision-makers in an urban system for urban (re) development.

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### 1. Introduction

Urban infrastructure systems (UIS) can be defined as the framework that connect and integrate the flows of capitals (social, cultural, financial, natural, technological and human) in the context of urban systems. UIS enable people, energy, water, materials, and money to flow into, within, and out of cities and are durable

features of the urban landscape that can persist for decades to centuries. Also, UIS have far reaching local, regional and global impacts that result from waste generation, and resource and energy demands. Prudent design is essential given their long life and the large capital investments needed to build them. To create more sustainable urban areas, we must optimize resource and energy investments, minimize impacts and maximize the creation of comfort and wealth. To achieve this goal, it is imperative to examine the interconnections within urban infrastructure systems (UIS). But while it is understood that UIS components are interconnected – for example, transportation and energy – each component generally has been designed and optimized in

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a stove-pipe manner, without much concern for the interactions between these components. This is wasteful and results in sub-optimal solutions. Keeping in mind that we will double the infrastructure that will be required over the next few decades (PwC, 2015), there is an opportunity to create integrated UIS that are more integrated, sustainable, and resilient. This paper presents the concept of *Infrastructure Ecology* – the interdependence between the different components of UIS as well as their interplay with their ecological and socio-economic components – as a means to better understand and design UIS. There is critical difference between the existing conceptualization of ‘urban ecology’ and the concept of ‘infrastructure ecology’ as proposed in this article. Urban ecology focuses on the interaction between urban and ecological systems, i.e. coupled human–environmental systems (Wu, 2008). Infrastructure ecology, au contraire, considers urban infrastructure systems as ecological systems using deep analogies. Infrastructure ecology creates a transdisciplinary approach whereas urban or landscape ecology is more of an interdisciplinary approach, i.e. brings in a set of specific disciplinary practices together to look a common issue, but does not create a new approach.

The concept of infrastructure ecology can be applied specifically to UIS when the components are considered as an interlinked and interdependent system constituting a ‘Material–Water–Energy–Land Use–Transportation–Socioeconomic Nexus’. This integrated infrastructure ecology approach has been only recently developed and the available research body is lean (Brown, 2014; Xu et al., 2012, 2010). This concept draws on practices from ecology and uses case-studies to conceptualize UIS as complex adaptive systems that act like ecosystems, and show how an infrastructure ecology approach can increase the sustainability and resilience of UIS.

## 2. Urban infrastructure systems (UIS): definition and concept

We distill UIS into six commonly shared components: 1) socio-economics, 2) drinking water, storm water and wastewater infrastructure, 3) energy systems, 4) transportation infrastructure, 5) land-use, and 6) the natural environment. While this *component classification* of UIS is a predominantly *engineering* perspective, it is actually the flows between these components that characterize the UIS. When analyzed holistically, UIS function analogously to complex ecological systems; by exchanging information, material and energy among themselves, as well as drawing resources from and transferring waste to the environment. In addition, the UIS are interconnected with the socio-economic systems (Fig. 1). The land use type, e.g. residential, commercial, etc. determines the water, energy and transportation demands for that particular parcel of land. The traditional engineering paradigm, however, has often focused on optimization of the infrastructure components separately, largely ignoring their interdependencies. It must be noted that the UIS framework as presented herein departs significantly from the conceptualization of urban metabolism frameworks. Urban metabolism primarily focuses on the input–output of resource and waste flows in an urban system, with emphasis on the flows (Kennedy et al., 2007). The UIS framework places a greater emphasis on the interdependence between the infrastructure components. The UIS framework presented herein is a generalizable framework universally applicable for all urban areas. Other sectors like industrial and commercial can be added onto this framework, if they are present in a particular urban area. In addition, with the emerging emphasis being placed on the interdependence of energy, water and food (Bazilian et al., 2011; Finley and Seiber, 2014), a future expansion of this framework would include food as a sector within the framework.

At the systems level, this stove pipe thinking has led to sub-optimal UIS. In recent years there has been some focus on two of

the more prominent interactions between the UIS components: the one between water and energy, popularized as the ‘Water–Energy Nexus’, and the one between energy and transportation. Some typical inter-relations are shown in Table 1. Moreover, these interrelations are not only dependent on the infrastructure options chosen, but also vary widely with the demographics, climate and geography of the regions. For example, the connection between water and energy has been examined in detail; the creation of energy consumes water, and energy is used to convey, treat and distribute water. This becomes a serious consideration in times of dry, hot summers as both energy and water demand increase, thus straining the water–energy co-dependency. A potential solution lies in the large scale implementation of air-cooled microturbines deployed for the production of combined heat and power (CHP). A preliminary analysis revealed that implementation of air-cooled microturbines, which supplies ATL’s residential cooling and heating demand, would reduce ATL’s reliance on central grid power and corresponding ‘water for energy production’ (WFE) by 60% (Frankland, 2013) and would reduce the total energy consumption by ~25% owing to a higher efficiency of energy generation and reduced loss in transmission. Furthermore, the use of air-cooled microturbines would reduce the CO<sub>2</sub> footprint by 45%, as compared to the CO<sub>2</sub> footprint of the grid electricity production using the average US electricity mix. Another potential solution lies in the use of heat recovery from wastewater. A wastewater heat recovery system employed in Vancouver (False Creek Energy Utility) supplies 70% of the heating requirements for a mixed-use community of 12,000 residents and reduces GHG emissions by 50% as compared to the conventional alternatives of residential gas or electric heating (City of Vancouver, 2012). In Amarillo, TX, the annual reclamation of 7.7 billion gallons of municipal wastewater effluent is productively used in power plant and industrial cooling, reducing aquifer withdrawals (Welch, 2012). In addition to the approaches mentioned above, there exists a suite of potential alternatives, like LED street lighting, efficient fenestration design, etc. for integrated UIS design that can aid in sustainable urban growth (Pandit et al., 2012).

To further elucidate the constraints of stove pipe thinking in UIS optimization where each of the infrastructure services are optimized separately, consider the interrelations between energy, water and transportation infrastructure. One of the primary targets of current transportation planning and development is to reduce the carbon footprint of personal automobiles. The transportation sector is essentially separate from the electrical energy infrastructure network. If combined together, however, electric vehicles could reduce the carbon footprint of personal transportation by 27% and reduce US petroleum consumption by 50% (Kintner-Meyer et al., 2007). There is, however, a caveat. Under the present US electricity generation mix of fossil fuels, nuclear, and renewables including hydropower, vehicle electrification would exert further demand on water requirements for energy production. For example, if all personal transportation in the metropolitan Atlanta, Georgia region (USA) was electric, the increased water demand (evaporative loss) needed to produce the electricity to charge the fleet of electric vehicles would be almost identical to the current domestic demand (estimated at 100 million gallons per day (Yen, 2011)). ATL is already experiencing problems with water shortages in drought years and delivering enough water to downstream users in GA, FL and AL. Increasing the water demand by another 100 MGD would make the inter- and intrastate water resource allocation enormously challenging.

Another approach to reduce the carbon footprint of transportation is to switch to alternative fuels to power personal automobiles. A similar conundrum exists when biofuels are chosen as the preferred alternative to conventional gasoline for automobiles.

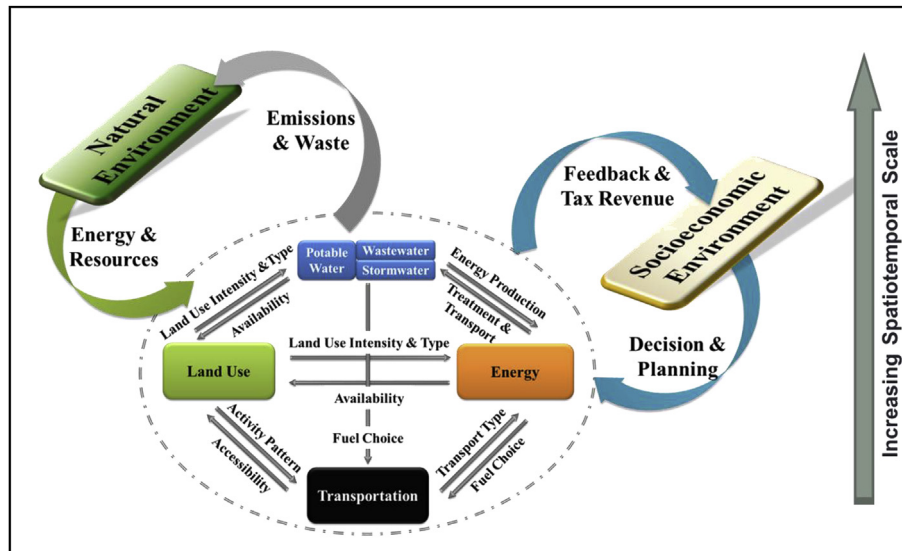


Fig. 1. Interconnectedness within the urban infrastructure system (UIS) and the interrelation of UIS with natural environmental systems and socio-economic systems.

Table 1

Examples of existing interrelations between different components within the UIS.

Type of interrelation	Examples of interrelations
Water ↔ Energy	Water is required for energy generation, either directly as in hydroelectric power production or indirectly for cooling purposes in thermoelectric generation. The US average (weighted) evaporative consumption of water for power generation over all sectors is around 2.0 Gal/kWh (U.S. DOE, 2006). Energy is required to convey/collect, treat and distribute/discharge water/wastewater. About 4% of US electricity consumption is to convey water/wastewater and storm water (responsible for 80% of the share) and treat water/wastewater and storm water (EPRI, 2002; U.S. DOE, 2006).
Energy ↔ Transportation	Energy is required to power the transportation fleet. As of 2011, 28% of US primary energy consumption is for the transportation sector (U.S. EIA, 2012). Fuel used for transportation alters the demand in energy sectors. A 50% penetration of Plug-in Hybrid Electric Vehicles could increase the total electricity demand by 6–9% depending on the region (Denholm and Short, 2006).
Land use ↔ Transportation	Land use patterns dictate the travel pattern of the residents. Increased regional accessibility for more central area residents result in a 10–40% decrease in driving compared to their counterparts at the urban fringe (Litman and Steele, 2012). Transportation planning often has a prescriptive effect on the growth pattern of an urban region. Empirical estimates suggest that one new highway built through a central city reduces its central-city population by about 18% (Baum-Snow, 2007).
Water ↔ (Energy) ↔ Transportation	The choice of transportation fuel has a significant effect on the water footprint. Both electrification of transportation with the current US energy mix or use of biofuels has a net negative impact in terms of water footprint (Dominguez-Faus et al., 2009; Harto et al., 2010; Yen, 2011).
Land use ↔ Energy ↔ Transportation	The pattern of land-use affects the energy consumption pattern for transportation, household electricity use and home heating. Urban core residents emit 2–6 tons of energy-related CO <sub>2</sub> per household less than their suburban counterparts, on average (Glaser and Kahn, 2008).
Land use ↔ Water ↔ Energy	Land-use patterns incorporating rainwater harvesting options can lead to energy savings via water savings. Use of rainwater harvesting and other Low Impact Development techniques in the urban area of southern California would result in a savings of 573–1225 GWh per year (Garrison et al., 2009).

Notwithstanding the potential conflict between ‘crops for food’ and ‘crops for fuel’, the water footprint for biofuels may be 10 to 1000 times higher than conventional gasoline on a life-cycle per vehicle mile traveled (VMT) basis depending on whether the feedstock crops are irrigated or not (Dominguez-Faus et al., 2009; Harto et al., 2010). Currently, agriculture primarily focuses on food, fiber, and feed and if fuel is added to the mix, this will put further stress on the environment due to increased use of fertilizers and pesticides. For example, large areas in the Gulf of Mexico are experiencing hypoxia and more intensive farming will only exacerbate the problem in the Gulf and worldwide, where more than 400 coastal areas are experiencing similar problems (Rabalais et al., 2002; Selman et al., 2008). These problems illustrate that the impact and functioning of UIS cannot be evaluated fully without an understanding of how material and energy flows among the components.

### 3. Interrelation between UIS and socio-economic environment

Socio-economics are the drivers of UIS planning, implementation and development. The primary factors guiding the (re)development of UIS originates from the socioeconomic realm, e.g. revenue generated from the neighborhood, stakeholder preference, and sociopolitical development agenda, to name a few. Thus, social and economic forces often set the context that defines how UIS components interact. Despite the influence of socio-economic factors UIS development traditionally has been a largely technical exercise, successful implementation of sustainability principles in UIS require an integration of socio-economics. As shown in Fig. 1, urban dwellers inform policy makers about their needs, requirements and qualms about their current UIS, and the tax revenue generated within an urban area dictates the level of

infrastructure investment, the selection of development options, and the location of the infrastructure. Citizen involvement and capacity building therefore can play an important role in developing sustainable UIS.

In congruence with the traditional engineering paradigm, most urban water systems are a manifestation of “big-pipe design”. The first step is to scrape off the natural ecology and replace it with hardscape. In turn, this creates a storm water runoff problem, which is then solved by storing the storm water and caring it away in a big pipe. This has transformed rainfall, a rather pure form of natural water to a nuisance to manage, i.e. *urban storm water runoff*, which requires centralized treatment before being discharged into surface waters. The big pipe objective always has been to convey water in and out of the city underground rather than bringing it to the surface and extending its utility through rainwater harvesting and reclamation of gray water for nonpotable uses and creation of green space.

Conventional storm water management practices include two major approaches: combined sewer systems (CSS) and separate sewer systems (SSS). As the name suggests, in CSS urban storm-water runoff is mixed with the municipal sanitary sewer and both are treated together at a centralized wastewater treatment plant. In SSS, there is a dedicated network of pipelines to convey the urban stormwater runoff volume. Among these two options, CSS more often pollute receiving water bodies through combined sewer overflows (CSOs). During events of high rainfall or snowmelt events, the combined volume of urban runoff and municipal sewer overwhelms the capacity of the wastewater treatment, and hence the polluted water from the combined sewer is discharged directly to the receiving water bodies without receiving any treatment. While SSS are able to address these concerns albeit with its own set of problems, in older cities where much of the city lays on top of CSS, CSS cannot be replaced without replacing much of the existing infrastructure. This is prohibitive because the capital cost to replace the system would be too high. In addition, both CSS and SSS are energy intensive processes as both systems must treat the additional volume of stormwater.

One alternative to CSS and SSS is Low Impact Development (LID). The implementation of LID techniques and other “green infrastructure” to manage urban stormwater provides an example of infrastructure ecology, specifically the interrelationships between stormwater management, creation of green infrastructure, and socio-economic development. LID techniques for stormwater management include strategies like bioretention basins, rain gardens, green roofs, cisterns for rainwater harvesting, and permeable pavement among others. The primary goal of LID implementation is to mimic the predevelopment site hydrology (Dept. Env. Resources, 1999). LID techniques can be passive natural treatment strategies that require negligible amounts of energy for stormwater detention and treatment. LID techniques not only improve the quality of the runoff but also regulate the quantity of the runoff. They reduce the runoff volume, flatten and often reduce the runoff peak, and increase infiltration (depending on the hydrologic conditions) thereby enhancing groundwater recharge. One novel LID technique that is gaining in popularity in a number of cities across the U.S., including Chicago, Seattle, and Los Angeles, is the “greening” of urban alleyways (Wolch et al., 2010). While the primary objectives for this greening of gray infrastructure are to control the quality and quantity of storm water runoff, municipalities are increasingly aware of other co-benefits. In addition to enhancing ecosystem services like flood control, stream bank restoration, and erosion control, implementation of LID techniques results in a suite of other benefits. These benefits include improved human health by providing recreational opportunities, reduced air and water pollution, decreased heat mortality, reduced heat island effects,

increased neighborhood cohesion and walkability, increased esthetic value of the neighborhood, and increased tax revenue and property values (American Rivers et al., 2012; Bowler et al., 2010).

There is strong evidence that LID can lead to higher property values. There is a price premium on housing developments that use LID due to the greater green space and lower energy costs (Fig. 2). In turn, higher property values generate more tax revenues and lower stormwater abatement costs for the municipalities. This has been the case in Seattle, where the city’s Natural Drainage Systems Program applied LID practices to local streets to improve storm-water runoff management with the co-benefits of enhanced streetscape and traffic easing. Property values there increased by an estimated 3.5–5.0% compared to properties in the same zip-code that did not use LID techniques (Ward et al., 2008). In a similar instance, the City of Philadelphia was deliberating between building storage tunnels for CSO control in watershed areas or to deploy LID techniques. Their deliberations determined diverting 25% of the runoff through LID would result in a net projected benefit of \$2.0 billion (in 2009 USD) over a 40 year period. Using LID for 100% of the runoff increases the net benefit to \$4.5 billion over the same timeframe. Approximately 40% of the projected benefit results from increased recreational opportunities and augmented property values in the area (Philadelphia Water Department, 2009). The other key categories contributing to the net benefit are reduced heat-stress mortality (–37%) and enhanced water quality and aquatic habitat (+12%) (Philadelphia Water Department, 2009). As a means to improve the environmental sustainability for cities, LID changes the ecology of urban infrastructure by disconnecting stormwater management from the municipal wastewater infrastructure and connecting it with more natural ecosystems, for example, stormwater irrigation can improve street tree health and longevity. LID indirectly changes the linkage between urban ecosystems and the socio-economic environment in cities. As a result, LID reorganizes the ecology of engineering, ecological, and socio-economic infrastructure and augments the sustainability of the urban system holistically (Tzoulas et al., 2007).

Sustainable alternatives of urban infrastructure development like LIDs (another example is distributed combined heat and power generation) can provide significant economic, like increased tax revenue, increased property value, etc. and social benefits, like increased recreational amenities and development of a preferred neighborhood. Other examples include but are not limited to, urban parks (Chiesura, 2004), sustainable streets (NYC DOT, 2014), LED street lighting and fenestration design (Pandit et al., 2012), to name a few.

#### 4. Infrastructure ecology: the synergistic effects of infrastructural symbiosis

Designing UIS using an infrastructure ecology approach alters and reorganizes energy and resource flows, allowing one to consider the potential synergistic effects arising from *infrastructural symbiosis*. Infrastructural symbiosis can be defined as “the synergistic and symbiotic interrelations that exist in terms of flows between the different interconnected capitals in an urban infrastructure system”. While individual technologies do exist to incorporate some of these effects, their application remains fragmented and many more technologies/approaches could be invented. A model of infrastructure symbiosis based on synergistic UIS planning and design is outlined in Fig. 3. The effects and interrelations depicted here are not exhaustive, but provide a blueprint for holistic integrated infrastructure planning and design. Taking the potable water, wastewater and stormwater sector as an example, Fig. 3 shows three alternatives for municipal water supply (both potable and non-potable) compared to the traditional

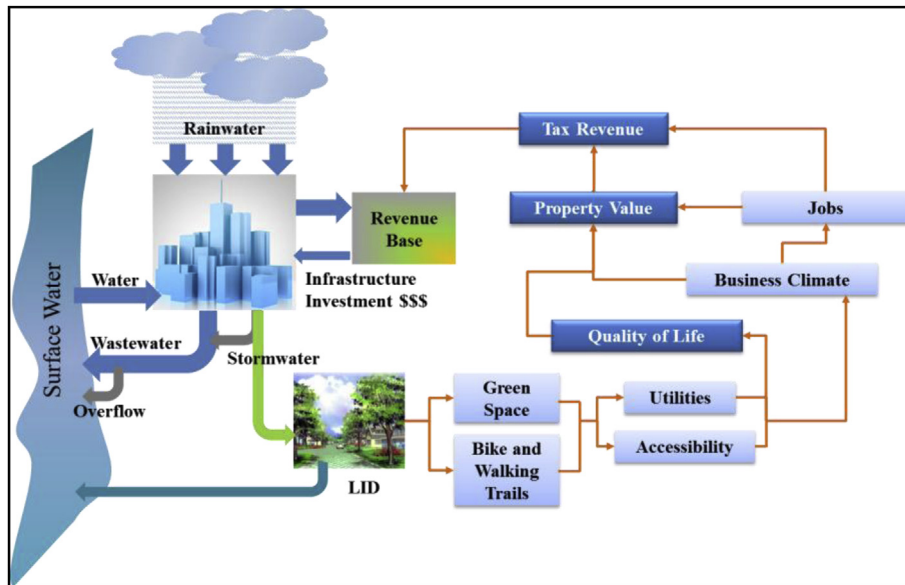


Fig. 2. Schematic showing how the implementation of LID techniques for urban stormwater management affects the socio-economic environment.

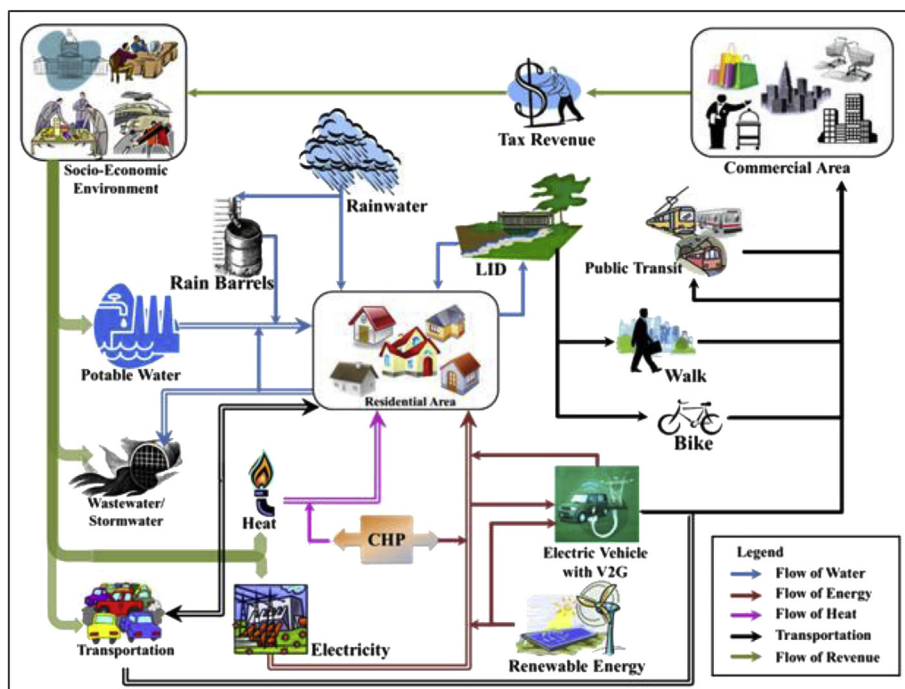


Fig. 3. An example of infrastructural symbiosis for the proposed infrastructure ecology model. Note: LID: Low Impact Development; CHP: Combined Heat and Power; V2G: Vehicle-to-Grid. Double lines indicate conventional flows of water and energy; Single lines indicate the reorganizations obtained through infrastructure ecology; The depiction of water and energy flows is restricted to the residential area only for the sake of clarity. Water and energy flows to the commercial and other areas are present and share the same benefits of infrastructural symbiosis as with the residential area.

engineering approach of centralized water supply: 1) rainwater harvesting, 2) local reclamation of wastewater, and 3) retrieval of stormwater treated with LID techniques. All of these options provide an urban community with a local water supply that has a significantly lower energy footprint. The reduced energy consumption stems from two aspects: 1) the energy needed for distribution is significantly lower, and 2) the volume of water that needs to be processed for either drinking water or sewer treatment is reduced significantly. For example, a study of the City of Atlanta

revealed that application of LID techniques to collect rainwater in all the residential areas would reduce the demand on the central supply system by over 30% or  $\sim 10 \text{ BGYr}^{-1}$ . This reduction in water demand yields an energy savings of 8.2 GWh and a 5000 ton reduction in energy-related  $\text{CO}_2$  as Carbon emission on an annual basis – and this is in addition to the suite of other benefits discussed above (Jeong, 2013).

A progressive urban infrastructural ecology developed by the City of Lille, France capitalized on energy and nutrient recovery

from municipal wastewater and solid waste treatment facilities to produce biomethane for its public buses. A new organic waste recovery station bio-digests 700,000 tons of municipal domestic organics, combined with agricultural residue and wastes from the food processing industry. More than 34,000 tons of residual sludge is returned as compost to neighboring agricultural areas. The fleet of over 100 buses is fueled by 4 million cubic meters of treated biomethane, displacing 5 million gallons of diesel annually (Brown, 2014).

If the flows within the energy (heat and electricity) sector are similarly reorganized, certain phenomena emerge that could not be realized in a traditional UIS engineering approach. As discussed previously, implementing air-cooled microturbines in a CHP framework nearly eliminates the WFE footprint of electricity production. For a typical single-family house in Atlanta, GA this annual WFE savings (evaporative loss) is equal to 33% of their annual domestic water demand, a feat rarely achieved through implementation of low-flow or smart water fixtures. It might be noted that for typical centralized power generation plants, the withdrawal amount is 10 times that of the evaporative loss. This significant reduction in WFE makes the electrification of personal automobiles a far more attractive option. For example, a single 60 kW air-cooled microturbine running at its full annual capacity would have the capacity to charge ~175 electric vehicles, assuming an approximate consumption of 250 kWh per vehicle per month (Adele, 2010). The heat generated from the turbine can be utilized for buildings with low electricity and high heating demand, like warehouses. In addition, implementation of LID techniques creates preferred neighborhoods, which increases the accessibility in those neighborhoods by bringing places to live, work and play closer. A more accessible neighborhood means lower vehicle miles of travel and considerably reduces concerns about the limitations of batteries and vehicle range. This could increase the adoption of electric vehicles. Additionally, a large network of electric vehicles coupled with Vehicle-to-Grid (V2G) technology could enable large-scale deployment of decentralized renewable energy generation. One of the challenges in large-scale deployment of renewable energy, such as photovoltaics, is their significant variability on a minute-by-minute basis. This variation, in turn, requires utilities to increase the amount of spinning reserves, which greatly reduces the benefits of utilizing renewable energy. V2G allows energy to be exchanged both to and from the vehicle using the battery as an energy-storage device. In the US, a 30% V2G penetration could reduce the peak demand by 180 GW (Inage, 2010). The accumulated synergistic effects of this particular model of infrastructure ecology is significant: this effectively “free” energy storage helps achieve reduced water and energy consumption, lower dependence on centralized systems, larger share of renewables in the electricity mix, reduced vehicle-miles traveled and an increase in tax revenue.

## 5. Cities as complex systems: scaling of urban systems

Urban systems are also analogous to ecological systems in terms of the human and social dynamics that take place within the urban systems. While the previous discussion highlighted the interrelations between the different components of the urban infrastructure, social and natural environment, this section attempts to include the human factor, i.e. how the population size affects the dynamics of the urban systems. The structure and nature of human social networks changes qualitatively as populations become more urbanized. Networks progress from predominantly close kin relations to more goal-oriented relationships among a much larger set of social possibilities (Milgram, 1970; Wirth, 1938). One of the better known scaling relations for human organization is Zipf's law, wherein one collects a set of cities with differing populations. Then

one plots the population on the ordinate and rank in population on the abscissa. Zipf's law states that a city's population is inversely proportional to the city's population rank among other cities (Gabaix, 1999; Krugman, 1996). However, Zipf's law is an empirical regularity, i.e. the law has described cities for many countries and time periods but no satisfactory theoretical explanation has yet been produced to relate its functional form with human and social dynamics (Bettencourt et al., 2008).

In addition to the remarkable observation of Zipf's law, power law distributions expressing the change in specific urban indicators as a function of population size, which are referred to as *empirical scaling laws*; are of great interest to economists and social scientists as they may provide insight into the factors that influence the value of the exponent and point to more sustainable economic and policy-decision issues. Moreover, these scaling laws are indicators of general organizational and dynamic principles that can be observed across different spatial and temporal scales (West, 1999). Concurrent with the effort on scaling the social dimensions of cities, significant research has been put forth by urban geographers and economists to contextualize urbanization in terms of spatial forms and growth patterns of urban clusters (Bettencourt et al., 2008). Viewed from this perspective, urban development can take many distinct forms based on the geographical attributes of the built environment and the layout of transportation networks resulting in a more compact or sprawling urban form. One of the initial attempts in theorizing the spatial distribution of urbanization was the Central Places Theory (CPT), put forward by Christaller in the 1930s. CPT, despite its limitations, provides a useful explanation of the existence of hierarchy in urban centers from an economic perspective (Eaton and Lipsey, 1982; Fujita et al., 1999). In addition, the CPT has been extended in conjunction with Zipf's Law to estimate the city size based on fractal dimensions and self-organizing criticality (Beckman, 1958; Chen and Zhou, 2006). Recent research in this area have primarily focused on the complexity and spatial distribution of urban areas furthering the concepts of fractal dimensions and self-organizing criticality (Batty, 2008; Batty and Longley, 1986). Understanding how the urban areas grow would provide critical insight in planning and designing UIS that are sustainable and enhance the comfort and wealth of the residents.

A metabolic scaling law for biological organisms was first proposed by Kleiber (1947), where he noted that the metabolic rate of an organism (i.e. the minimum rate of energy needed for the sustenance of an organism) can be scaled to the  $\frac{3}{4}$ <sup>th</sup> power of the mass of the organism. This holds over 27 orders of magnitude ranging from the largest mammal (blue whale) to unicellular organisms (West, 1999). These allometric scaling laws in biology were hypothesized to spur from a general model describing the transportation of essential materials through space-filling fractal networks (e.g., blood vessels) (West et al., 1997). However, challenges to this hypothesis have also been put forward, and there may be several, not mutually exclusive, explanations for this pattern (Kozłowski and Konarzewski, 2004; White et al., 2007). Nevertheless, in recent years the law of metabolic scaling has been extended to correlate urbanization with resource use, economic development, knowledge creation and urban dynamics (Bettencourt et al., 2008, 2007; Bettencourt and West, 2010; West, 1999). Bettencourt et al.'s analysis of empirical data across multiple countries reveals that a diverse set of urban attributes can be scaled to the size of the urban population and the scaling exponents can be broadly classified into three categories: (i) *linear*: for attributes typically associated with individual human needs; (ii) *sublinear*: for attributes characterizing economies of scales associated with resource investment for infrastructure, mimicking biological organisms; and (iii) *superlinear* signifying increasing rates of return on social currencies like innovation, information and wealth with increasing

population size (Bettencourt et al., 2008, 2007). While the causality of these observed scaling laws are not adequately developed, a robust theoretical development of the science of *infrastructure ecology* would provide the necessary framework for analyzing these phenomena. As has been observed empirically, bigger cities provide economies of scales in terms of energy and resource investment while providing increased rates of return on social currencies. As the urban area agglomerate globally to create *mega regions*, understanding the causality of these phenomena would allow us to design urban areas to require fewer resources and generate more comfort and wealth. There is also a growing body of research, which predicate these scaling laws analyzing urban infrastructure from a network perspective (Chen and Chen, 2015, 2012; Su et al., 2012).

## 6. Discussion

Infrastructure ecology views urban systems as complex adaptive systems; the sustainability and resilience of which emerge from the complex interactions and co-evolution of a city's interdependent engineering, ecological, and socio-economic infrastructure through time and space. The inclusion of socioeconomics in infrastructure ecology is crucial as socioeconomics acts as the decision driver behind design, operation, and use of urban infrastructure systems. Also, urban infrastructure systems share many commonalities with ecological systems. Both systems:

1. are complex, dynamic and adaptive;
2. are comprised of interconnected components exchanging flows of energy and matter;
3. share some general architectural dynamics across time and space;
4. create novelty; and
5. cannot be evaluated or understood by looking at any component element, but instead must be examined as a system.

The current paradigm of UIS development is not on the most sustainable path. With the massive need for UIS being imminent, a sustainable and resilient trajectory of UIS development is of immediate need. The concept of infrastructure ecology can provide the decision makers with a pathway for sustainable and resilient UIS (re)development. While the concept as presented herein provides a theoretical basis for the science of infrastructure ecology, it does not provide explicit goal statements for urban planners, engineers and other decision-makers. Goal statements are crucial in envisioning the desired outcome, and this discussion provides an excellent groundwork to develop a systematic and comprehensive framework to implement the concept of infrastructure ecology. We prescribe 12 Principles of Infrastructure Ecology (see box), which provide a framework for urban planners, engineers and other decision-makers in an urban system to engage in when planning or designing new urban infrastructure systems or rehabilitating aged ones. Urban infrastructure systems designed from within this framework would lead to better comprehension about the dynamics of the interconnections between different components within the UIS and would allow for adaptive design and holistic optimization that meets growing demands without further stressing the energy and resource base.

### 6.1. The 12 principles of infrastructure ecology

These 12 principles should be considered as parameters in a complex and interconnected system, similar to the 12 Principles of Green Engineering as proposed by Anastas and Zimmerman (2003). Since UIS is an integrated system, it may not be possible to optimize

all of these principles simultaneously. There are instances of synergy, as elucidated through the infrastructural symbiosis, where successful implementation of one principle augments one or more of the other principles. In other instances, where there is a lack of synergy, the goal should be to optimize the system solution.

## 12 Principles of Infrastructure Ecology (12 PIEs)

1. **Interconnected Rather Than Segregated**
2. **Integrate Material, Energy & Water Flows**
3. **Manage the Inherent Complexity**
4. **Consider the Systems Dynamics**
5. **Decentralize to Increase Response Diversity & Modularity**
6. **Maximize Sustainability & Resilience of Material & Energy Investment**
7. **Synergize Engineered & Ecological Systems**
8. **Design to Meet Stakeholder Preference**
9. **Maximize the Creation of Comfort & Wealth**
10. **Socioeconomics is the Decision Driver**
11. **Adaptive Management is a Requisite Policy Strategy**
12. **Utilize 'Renewable Flows' Rather Than 'Depleting Stocks'**

### I Interconnected Rather Than Segregated

Urban infrastructure systems should be designed and optimized as an interconnected entity rather than designing and optimizing individual infrastructure components. This would allow the designers and planners to avoid the unintended consequences of compartmental optimization. The case of electrification of personal automobiles, as discussed above, can be considered as an example. With a microscopic focus on carbon reduction, inadvertently it exerts a surge in the water demand of the region.

### II Integrate Material, Energy and Water Flows

Material, energy and water flows should be integrated and optimized across the urban infrastructure system. Urban infrastructure components mediate the flows of material, energy and water within the urban system, reducing overall waste outflows. Failure to integrate these flows across the urban system would result in tradeoffs between the uses of the capitals, i.e. energy might be, and often is, sacrificed for gain in material flow efficiency. As an example, the case of air-cooled microturbine deployment in a CHP framework may be considered. The total WFE savings by and far outweighs the potential of water savings that can be achieved through the implementation of low-flow fixtures, drip irrigation for personal yards, or other water saving devices.

### III Manage the Inherent Complexity

Urban infrastructure systems are complex adaptive systems. Complexity results from the interaction of urbanites, infrastructure in the socioeconomic environment and quality of life, energy, water and material use emerge from these interactions. By managing complexity, our desire is to create infrastructure that has the right combinations of features that will increase adoption of more sustainable infrastructure. Considering the complexity in design allows integrating synergistic benefits that arise as emergent properties of complex systems, which are non-apparent otherwise. The complexity of social decision making within the urban context can be

assessed by using agent-based models, which are able to predict and evaluate the adoption rate in response to policies (Lu et al., 2013).

#### IV Consider the Systems Dynamics

Urban infrastructure systems are dynamic-adaptive systems operating across multiple spatiotemporal scales. Systems dynamics should be considered to analyze and design urban infrastructure systems. The urban infrastructure system along with its socio-economic and environmental counterparts is interconnected through feedback and query loops. Considering the systems dynamics into design would allow for the inclusion of effects that arise in these systems due to a positive/negative change in another system.

#### V Decentralize to Increase Resilience, Response Diversity and Modularity

Decentralizing the urban infrastructure system increases the response diversity which increases the adaptive capacity and resilience of the system. Response diversity is defined as *the diversity of responses to environmental and demographic changes among infrastructure components that contribute to the same infrastructure function* (Adapted from (Elmqvist et al., 2003)). In addition, decentralization (distribution of smaller components often acting in parallel to centralized systems) improves redundancy and allows gradual development of urban infrastructure to meet the increasing demand rather than speculative building of massive centralized Greenfield infrastructure development.

#### VI Maximize Sustainability and Resilience of Material and Energy Investment

Urban infrastructure systems should be designed to maximize its sustainability and resilience for any material and energy investment. Traditionally systems are designed to maximize the efficiency of investment in terms of benefit-cost analysis. To achieve the goal of sustainable urban development, the sustainability and resilience of capital investment (including assessment of natural capital) must be considered as often the solution that yields the maximum benefit-to-cost ratio might not be the most resilient or sustainable solution.

#### VII Synergize Engineered and Ecological Systems

Engineered systems should be designed to integrate, complement, and where possible, regenerate the natural ecological systems. In addition to restoring and enhancing the ecological services, this would add to the resilience of the urban infrastructure system at a systems level by increasing its capacity to handle unexpected perturbations in the system. For example, as discussed above, implementation of LID technologies throughout the City of Atlanta could control the stormwater runoff from a 100 year storm event with relative ease and lower capital investment when compared to an engineering-only solution of building combined-sewer storage tunnels for runoff regulation.

#### VIII Design to Meet Stakeholder Preference to Manage the Socioeconomic Complexity

Urban infrastructure systems should be designed to meet the stakeholder preference and policies should be designed to increase the adoption of sustainable and resilient infrastructure alternatives. Stakeholders play the most crucial role in adoption of any technology. In the instance where the design does not meet their preference, its adoption is likely to be underwhelming. Strategic

policy decisions that encompass multiple infrastructure regimes should be able to encourage a greater adoption of sustainable and resilient alternatives for urban infrastructure. As an example, the development of the Atlantic Station development in the city of Atlanta, GA can be considered. Once a brownfield left behind by a steel plant which went out of business, it transformed itself into a thriving mixed-use neighborhood as it catered to the need of the local stakeholders.

#### IX Maximize the Creation of Comfort, Well Being and Wealth

Urban infrastructure system design should strive for greater and more equitable creation of comfort and wealth for the residents while improving urban health. Sustainable urban development should focus on all of the three basic tenets of sustainability, environment, society and economics; not only on reduction of environmental impacts. In addition to reducing the environmental impact, sustainable urban development should also focus on maintaining economic prosperity, increasing social equity and improving environmental well-being.

#### X Socioeconomics is the Decision Driver

Urban infrastructure system design is governed by socioeconomic decision making. It is not an absolute technical endeavor. Infrastructure planning and design should explicitly consider the role of socioeconomics and how it influences the when, where and how of infrastructure development. A prime example that can be considered is the effect of gentrification and how it alters the property tax base and other socioeconomic dimensions of a particular neighborhood and its implication on sustainable urban development/redevelopment.

#### XI Adaptive Management is a Requisite Policy Strategy

Considering the uncertainties of the future and the associated risks, adaptive management should form the framework of policy decision making. Since attainment of 'absolute' sustainability is improbable, adaptive management strategies allows for gradual progress towards becoming more sustainable and allows recovering from any unfortunate setbacks that might occur in pursuit of that path. For example, the City of Atlanta experienced a 500 year drought in 2008 followed by a 100 year flood in 2010. With increasing uncertainties, adaptive management plays a key role in sustainable management of the urban infrastructure systems.

#### XII Utilize 'Renewable Flows' Rather Than 'Depleting Stocks'

Material, water and energy investment in new infrastructure development/rehabilitation of aging infrastructure systems should focus on utilizing renewable flows rather than depleting stocks. In an increasingly resource-constrained world, moving from nonrenewable resources to renewable ones is a requisite condition for sustainable development.

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