Developing a Roadmap for Resilient, Innovative, and Sustainable Cities: Toward An Energy, Water, and Food Nexus Approach and Beyond

Joshua B. Sperling, Ph.D.
Urban Futures and Energy-X Nexus Postdoc Fellow
National Renewable Energy Laboratory

&

Philip R. Berke, Ph.D.
Department of Landscape Architecture & Urban Planning
Director, Institute of Sustainable Communities
Texas A&M University

FEW Nexus Workshop on Integrated Science, Engineering, and Policy:
A Multi Stakeholder Dialogue
January 26 -27, 2017, College Station Texas

Developing a Roadmap for Resilient, Innovative, and Sustainable Cities: Toward An Energy, Water, and Food Nexus Approach and Beyond

Summary

In the 21st century, shaping a future of resilient, innovative and sustainable cities through integrated approaches to energy, water, and food (EWF) systems and services poses unique challenges and opportunities (Brugmann et al., 2014). Urban EWF systems approaches are a high priority, especially as urban settings host the majority of the world's population. Cities and their EWF systems will also continue to evolve due to three emerging and not-yet-well-understood dynamics of 1) urbanization (UN-Habitat, 2016), 2) environmental change (Seto and Solecki, 2015), and 3) globalization (World Economic Forum, 2016). Responses to these three transformative forces (among others, e.g. rising living standards, rapidly growing EWF demands, ageing systems) could lead to very different futures. One future may be more urban sprawl, energy-water use, emissions, food insecurity, funding gaps toward infrastructure maintenance, and unhealthy /vulnerable individuals, communities, and cities. Another future may bring multiple benefits, from more choices, larger investments, greater affordability and accessibility, to healthier, more livable and resilient cities, along with less resource use and fewer greenhouse gas emissions. Within this context, this paper offers a synthesis and road map on energy, water and food nexus approaches toward desired futures of sustainable and resilient cities, based on initial literature review and key knowledge gaps identified.

Introduction

The risks that cities are now facing due to multiple stresses (e.g. extreme events, short-falls in high quality basic services, violence, and pollution) can have economic, environmental, and social impacts, and therefore require critical knowledge and opportunities to develop integrated responses. This includes the contexts of trans-boundary energy, water, and food systems and the related services that populations in cities depend on daily. In the next two decades, demands for energy, water, and food are expected to rise 30-50%, while demands for motor vehicles may rise more than 200% (Sperling & Gordon, 2011). If providing for these new demands are managed in an unsustainable manner (especially in cities), and without considering interconnections, outcomes may be increased instability, conflict, and environmental damage (Bizikova et al. 2013; WEF, 2011). While sustainability and resilience plans are underway to address these challenges, with multiple cities and diverse communities investing in definitions and agendas within their own local contexts (100 RC, 2016), few cities have taken an EWF nexus approach to the plans.

For the purposes of this paper, urban resilience is broadly defined here as the capacity of any system, service or entity (e.g. people, institutions) within or across a city or metropolitan region to anticipate and plan for disruptions, to recover from shocks and stresses, and to adapt and achieve transformative revitalization from disruption (NRC 2012). This is a critical concept embedded within and supported by the emerging field of interdisciplinary ‘urban science’, which is expected by 2030, “*to connect thousands of researchers and represent more than $2.5 billion in annual research and development investment to advance sustainable, resilient, and smart urbanization and transfer that knowledge to the public sector” (PCAST, 2016).*

Examining both the disruptions and innovations towards resilient cities by focusing on the provision, management, and interdependencies of life-supporting energy-, water-, food-, and other (e.g. waste, mobility, buildings/housing, communication) (E-W-F+) systems and services can be considered a 21st century grand challenge. For example, understanding recovery patterns, system interdependencies (e.g. as cascading failures from one system/service to another), and trends is critical to identifying optimal resilience strategies (Marcotullio, Sarzynski, Sperling et al. 2016). Simonoff, Restrepo, and Zimmerman (2007) analyzed U.S. electric power outages from a variety of causes and found not only an increasing trend over the years but, since the early 2000s, increasing duration of the outages. As studied by Zimmerman (2014), in the case of Hurricane Sandy, and others within the past decade (US DOE, 2013), such energy sector vulnerabilities and outages can also have impacts on other critical sectors – from food, water, mobility, to communications.

At the same time, opportunities for building community resilience and reliability of basic services extends beyond social, economic, ecological and technological systems for EWF, into other urban systems (land) and governance domains (SEI, 2011; also see Figure 1). Similarly, interdisciplinary nexus science and innovation approaches that develop collaborative efforts across sectors, scales and jurisdictions, can enable new capacities to anticipate changes and effectively respond to emerging risks.to enhance multi-level governance and cross-sector infrastructure management responses to: a) urbanization, in how it shapes affluence, rapidly rising infrastructure and energy-water-food resource demands, and related emissions, risks and vulnerabilities; b) environmental change, specifically in terms of new and not-yet-seen thresholds of stresses and shocks to and from EWF+ urban systems, ; and c) globalization, by harnessing new levels of EWF+ connectivity, while also reducing inequality and risk.

In response to these challenges and opportunities, and building on Brugmann et al. 2014, this paper proposes developing an ‘urban nexus science’ (UNS) roadmap as a means of identifying and exploring synergies, tradeoffs, and co-benefits across EWF+ systems for building 21st century resilient and sustainable cities. UNS, as a strategic approach towards transformations, aims to explore and develop evidence on the co-benefits of increasingly integrated systems design and interdisciplinary evidence for strategic urban planning. This includes development of nexus-friendly methods to urban data, technology and policy, and behavior/decision science. Through a ‘knowledge-towards-action’ or ‘science-towards-solutions’ co-production strategy (Future Earth, 2014), UNS aspires to offer future actors and institutions the knowledge and analytical insights that can inform diffusion of best practices, and new synergistic innovation frameworks that can be leveraged and shared across cities and communities, globally. Applied UNS and data-driven approaches for shaping urban resilience, innovation, and sustainability are critical goals, especially as cities and people increasingly respond to disruptions - both bad and good alike.

1. An EWF+ Nexus Roadmap for Co-Developing Resilient & Sustainable Cities

Key Challenge:
Today, multiple hazard risks and disruptions are re-shaping city functioning and the planning of EWF+ systems and services, due to both chronic stresses (e.g. aging infrastructure, and food and water shortages) and acute shocks (e.g. violent storms, extreme heat/pollution events, cyber-security breaches and disease outbreaks). As a result of natural disasters alone, financial losses have been rising relative to increases in population and gross national product. Indeed, annual average per capita loss has more than tripled in the US over the past 50 years (Gall, 2011), and annual worldwide losses have quadrupled over the prior three decades to nearly $200 billion (World Bank, 2016). In addition, the WEF 2016 Global Risks report highlighted five most pressing risks/issues, all of which relate to the themes of this paper: large-scale involuntary migration, extreme weather events, failure of climate change mitigation and adaptation, interstate conflict, major natural catastrophes.

Key Opportunity:
At the same time, and for the first time in many decades, cities everywhere are experiencing massive innovation. These innovations could lead toward dramatically different futures. One future could be more urban sprawl, energy use, greenhouse gas emissions, cascading infrastructure service failures, and unhealthy cities and individuals. The other future could bring both public and private benefits, including more choices, greater affordability and accessibility, and healthier, more livable cities, along with less resource use, pollution, and greenhouse gas emissions.

Urban Synergies, Co-Benefits, Tradeoffs, and Innovations due to Integration
This roadmap on resilient cities and innovations at the nexus of food-energy-water systems (RC-INFEWS) therefore aims to explore the critical urban nexus science and interdisciplinary strategies that can help to achieve more desirable pathways. By focusing on potential synergies between food, energy, and water systems, and related resilient urban infrastructures and policies that enhance the co-benefits, a roadmap can be developed to identify strategies that best advance pursuit of the public interest. Key research questions include timing (will changes be evolutionary or revolutionary), role of different levels of government influencing the future of cities, and the relative importance of and tradeoffs between different goals.

Urban Nexus Science-Towards-Solutions for Energy, Water, and Food in Cities
This rest of this paper aims to elaborate on and bring clarity to this complex yet important topic through a lens of interdisciplinary research and research questions that can potentially help to catalyze important synergistic strategies, evidence-bases on effectiveness of diverse innovations, and necessary understandings for shaping a future of resilient, innovative, and sustainable cities. With research that looks back on historical urban development (what was), characterizes current system and

service conditions (what is), uses cities as living laboratories for innovation and looks forward towards the future of cities (what could be), applied research can be developed and lessons can be gleaned for delivering resilient cities and food-energy-water services that improve quality of life and catalyze connected urban innovation.

2. An Energy-Water-Food Outcomes Framework and Key Research Questions

While systems approaches and nexus-thinking can advance urban resilience by taking account of the interdependencies across multiple sectors of urban systems, , more integrated planning and policy-making can still be time-consuming and ineffective without the evidence that supports increased coordination. To date, this evidence base is still nascent and remains in early stages, perhaps due to the complexity of setup, coordination, and transaction costs involved. Therefore, research questions are needed that help create a more robust evidence base, specifically identifying the most critical connection points for integration toward resilient and adaptive systems via built-in feedback mechanisms, that can reduce the disruptive effects of environmental change, rapid urbanization and globalization - all of which could undermine resilience.

At the same time, strategic responses need to be crafted through identifying key E-W-F security strategies and outcomes that advance resilience. Therefore, readily available data that can inform single sector and 'nexus'-based indicators, across the spectrum of simple systems (we know the knowns); complicated systems (we know the unknowns); complex systems (we don't know the unknowns) to interconnected (e.g. water for energy and food; energy for water) or chaotic systems (all over the place) are needed (Amadei, 2016).

Figure 1 illustrates the urban nexus concept in the case of the energy, water and food (E-W-F) security nexus and factors that affect the degree to which E-W-F sectors are mutually reinforcing and produce co-benefits. The E-W-F sectors are inextricably linked as the actions in one sector have impacts in one or both of the others. For example, one recent study on the nexus (at a national scale) found that renewable energy could supply 80% of electricity demand in the U.S. by 2050, providing significant reductions in water use (~50%), with gross land-use impacts totaling less than 3% of U.S. land area (Arent et al. 2014). This study also suggested efforts to understand whether land can support expansion of biopower-related land- use without undue competition with food production and other uses would still be necessary. Similarly, and based on literature review, more research is needed on urban EWF systems and their nexus, considering the interdisciplinary, multi-scalar, transboundary, and cross-sectoral opportunities for integration (Ahamed, Sperling et al. 2017).

Within this context, and as additional society-relevant E-W-F security outcomes, Figure 1 identifies: 1) resilient economic development through transition toward green economy and greater resource use efficiency; 2) equity in access to each EWF sector among all population groups; and 3) healthy ecosystems that offer critical life support services for human settlements. Additional outcomes of concern to cities, desirable characteristics of energy (or water or food) systems/services can be identified through an urban nexus innovation process, described in Figures 2 and 3.

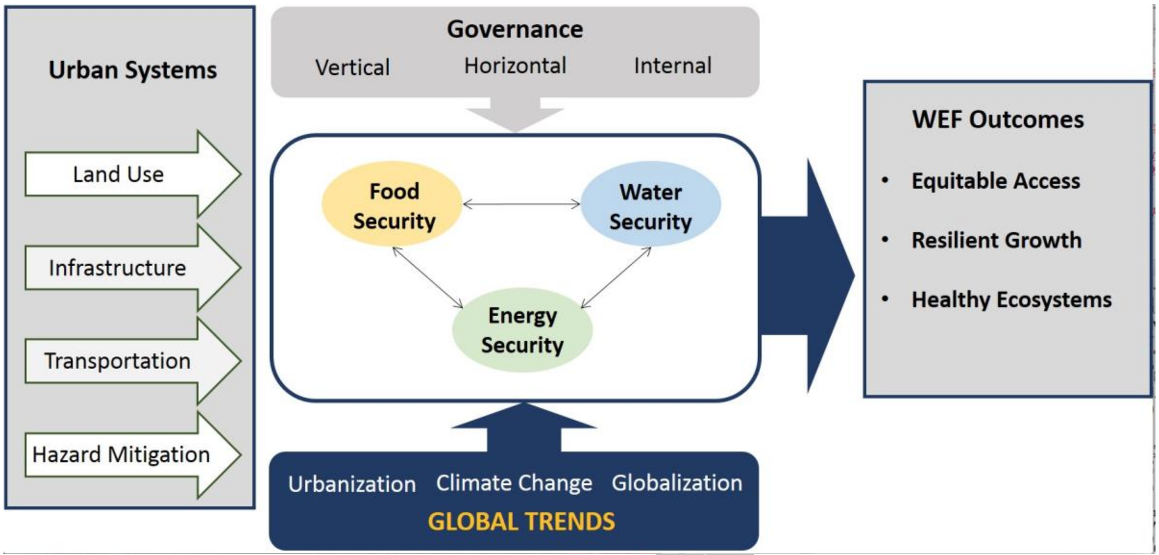

Figure 1: Factors Influencing Water-Energy-Food Security Outcomes [Source: Adapted from SEI (2011) by Phil Berke).

To achieve E-W-F security, the urban nexus innovation approach supports improved integration and coordination of governance and planning across multiple urban systems and across scales. These systems include, for example, planning for infrastructure, land uses, transportation, and mitigation of environmental hazards; alternatively (as shown in Figure 2 and 3), they can include social, economic, technological, ecological, and governance systems that E-W-F systems are embedded in. In both cases, conventional "silos" of data and governance approaches to technology, planning, policy, behavior change, and finance strategies, needs to give way to approaches that build synergies across systems, scales and contexts.

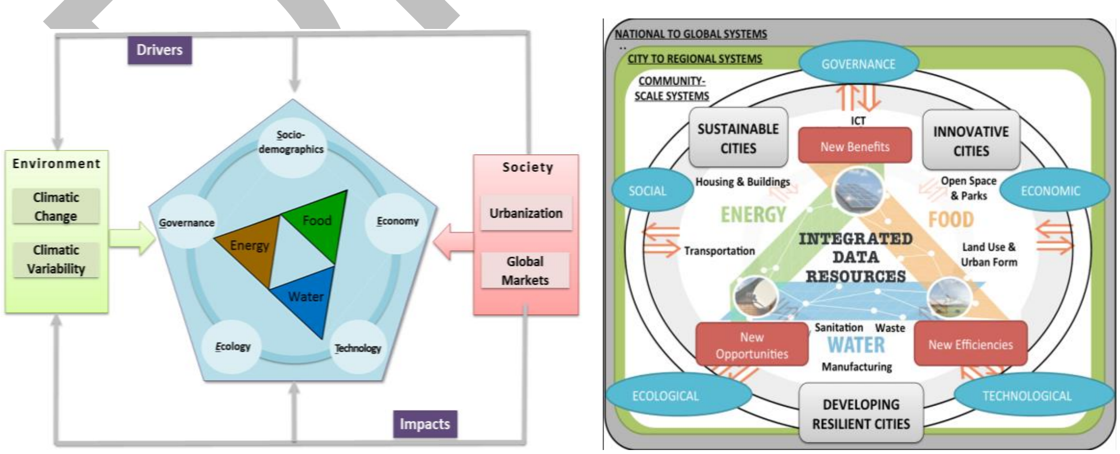

Figure 2. Urban FEW Security Nexus Frameworks: Addressing Drivers, Impacts, & Systems/Services Across Scales (left: Romero-Lankao & Gnatz 2016; Right: Sperling & Frenzl)

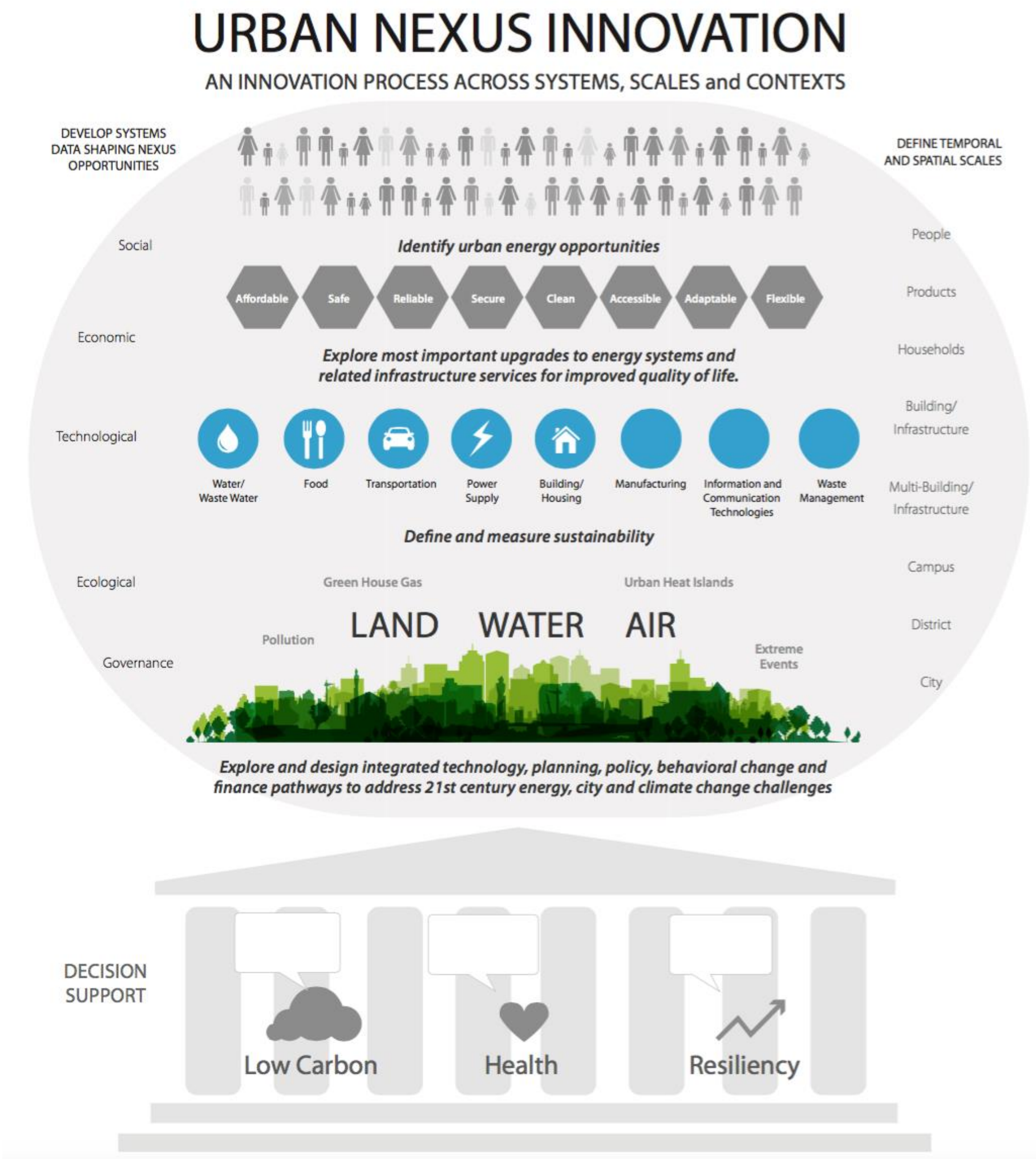

Figure 3. Urban Nexus Innovation & Knowledge Co-Production: A Human-Centered, Interdisciplinary, and Systems-Oriented Approach (Source: Sperling and Gillies)

3. An Interdisciplinary Research Agenda: Mega-Trends of Disruptive Forces and Fragmented Policy Making

Whether they are called disruptive forces, drivers of change, and/or megatrends, cities during the 21st century will be presented with two unique sets of challenges and opportunities: 1) urbanization, environmental change and globalization; and 2) fragmentation of governance systems aimed at urban planning and policy-making (Rodin 2014). The following section further explores these driving forces of change, as it relates to resilient cities and innovation at the nexus of food-energy-water systems. We first elaborate on each challenge, then develop initial research questions that could help to inform an interdisciplinary research agenda for 'UNS' , co-production of useful/useable knowledge/analytical insights, and innovation.

Disruptive Global Forces

I. Urbanization: The reality of the world's population urbanizing more rapidly than at any time in human history, and related exposures to extreme hazard risks for growing populations, is making the complex task of defining appropriate levels of density and urban service provision increasingly challenging (UN SDG 11.3, 2016). This is not only due to increasing vulnerability as municipal governments struggle to keep pace with management of growth pressures, yet also a result of increasing affluence in cities leading to rising resource demands/ pollution. Example urbanization opportunities and strategies to counteract hazards include: adequate land use controls to steer new development away from hazardous areas; providing smart, connected, critical infrastructure to meet rising demands efficiently; ensuring FEW-related infrastructure systems and health care systems are reducing risks associated air pollution (Sperling, 2014), or disease outbreaks related to water, sanitation, and overcrowded sleeping conditions (Agarwal, 2008).

Key Research Questions:

- What are appropriate urban densities for reducing resource consumption, emissions, exposures to poor quality services, and extreme events, while also increasing community characteristics of livability, efficiency, and inclusivity?
- Why and how are urban citizens, infrastructure designers and operators, and diverse people/institutions (across systems and scales) innovating with respect to urbanization and the nexus of urban FEW systems/services?
- What is optimal balance of centralized versus decentralized/off-grid food-energy-water systems for increasing human security in urbanizing regions?
- Are integrated, yet distributed, FEW-service delivery models best when considering informal/refugee/disadvantaged/vulnerable settlements?

The *trends* unfolding on urban areas and nexus issues critically motivate the design, planning, and implementation of integrated urban systems, infrastructure services, and governance for resilient urbanization and urban-regional development in cities globally. To understand the interdependencies, synergies, tradeoffs, and co-benefits of our urban transitions, international cooperative research on urban NEXUS science will be essential. Just this century:

- By 2030: food demand will grow by 35%, water demand by 40%, energy by 50% (with a majority of this new demand coming from populations living in cities)
- By 2050: this planet is expected to host double the number of urban dwellers

- By 2100: projections for ~ 9 billion urban residents, with urban population split unevenly - 1.2 billion living in cities that we now think of as developed countries and 7.8 billion in cities of developing world (Fuller, 2014)

Within this context, additional key questions could include:
- What will future demands look like for cities and which risks to urban energy-water-food systems and local populations are highest priority, especially under rapid growth conditions and a changing climate where increased frequency and intensity of extreme events impact FEW systems and people?
- For best managing natural/FEWL resources, what are the human/behavioral, and information/data systems required for effective investments and incentives for ensuring reliable/resilient service operations when considering human behavior?

II. Environmental change and extreme weather events: have emerged as another major contributor to the severity and extent of disruptions. Cities face threats like sea level rise, dramatic fluctuations in rainfall, increases is storm intensity, longer periods of intense heat, and disturbance of ecosystems that provide critical life support services to cities. The threats degrade infrastructure, economic activity, and social cohesion. Climate trends are already believed to be diminishing global crop yields like wheat and corn (Lobell and Gourdji 2012). Some areas are so affected by chronic drought that people become "climate refugees" leaving their homes to urbanizing areas (World Economic Forum 2016).

Key research questions:

- How and why are cities introducing technology, planning, policy and behavioral change approaches to both mitigate and adapt to climate change?
- How and why are risks communicated and proactively addressed with respect to urban FEW security and extreme hazard risks?
- What are the extreme event thresholds, optimal spatial/temporal-scales, and transformative levers/breakthrough ICT technologies for motivating and developing sustainable-resilient-healthy-smart- resource-effficient-connected infrastructure systems, and related quality of life services?

III. Globalization, including various global institutional (e.g. business-education-regulatory-communication) integration processes, can involve external events that impact the resilience of cities, their people and institutions. For example, external disruptions on cities can range from worldwide integration of supply chains that support regional economies to large-scale involuntary migrations/urban refugee settlements of displaced people from across geographic borders due to economic dislocation, conflict and famine. Globalization has accelerated the pace of change, and increased economic interdependencies and volatility. Transport of products to distant markets rather than local ones increases use fossil fuels and greenhouse gas emissions. In emerging economies, the pressure on farmers to enter global markets may increase food insecurity as less food is available for local populations.

Key questions:

- Where are the co-produced FEW+ (+ indicating transportation, ICT, etc) nexus scientific studies and globalization innovations with insights that are scalable, replicable, transferable, especially when considering/comparing integration approaches, interdependencies, diverse local/cultural contexts?
- What are the transformative globalization levers/breakthrough technologies for motivating and developing resilient-healthy-connected infrastructure systems, and related quality of life services for people in cities?
- What are the interdependencies and cascading failures of FEW systems and their related supply chains for global business continuity under extremes?

Fragmented Governance

Integrated and coordinated governance across urban systems is critical facet for building urban resiliency and specifically for achieving water, energy and food security. This includes the ability of public and private actors to bring together disparate plans for land use, hazard mitigation, and capital improvement for infrastructure, work collaboratively across urban systems, develop integrated solutions, and coordinated implementation actions. Coordinated governance involves sharing of information across decision-making entities, including: **internal** integration across different types of urban systems supported by individual local agencies like public works, planning, emergency management, and stormwater utilities; **horizontal** integration with adjacent and nearby communities that make plans and policies that have cross-boundary effects; and **vertical** integration involving compliance with regional, state and national plans to be eligible for funds and technical assistance, and international agreements involving, most notably climate change and disaster mitigation.

However, governance and policymaking aimed at coordination of the different water-energy-food sectors is often fragmented. For example, compared to compact forms of development, an urban land use plan that encourages low-density sprawl increases the potential to consume larger amounts of prime agricultural lands, and require more energy and infrastructure investments for transport between spread out land uses and for transfer of potable water over greater distances (Brugmann et al., 2014). As a consequence of dysfunctional and isolated decision-making, there has been a decline in urban resilience regarding water, energy and food security (Brugmann et al., 2014), that is likely accelerate due to climate change, rapid urbanization and globalization. To address this concern, the World Economic Forum (WEF 2011) produced a consensus document concluding that a grand challenge of the 21st century is to improve the reactive and disjointed approach that currently dominates policy making. The World Economic Forum stated that,

> "Shortages [in one or more W-E-F sectors] could cause social and political instability, geopolitical conflict and irreparable environmental damage. Any strategy that focuses on one part of the water-food-energy nexus without considering its interconnections risks serious unintended consequences" WEF 2011, p. i)

The reactive and disjointed approach is characterized by decision-making that is fragmented across policy arenas internal to a local jurisdiction (e.g., emergency management, transportation, and land use). Further, the narrow objectives of individual state, national and international initiatives often hinder local efforts aimed at plan integration. In this context, planning and policy across urban systems serves to weaken linkages in the water-energy-food nexus. Failure to integrate multiple plan making activities has become a international policy concern; ICLEI (2014) maintained that cities are where we must address global and local resource constraints, as they offer enormous opportunity to de-silo urban systems that separately address water, energy and food sectors.

Key questions to improve governance and planning:

- What tools should be developed to identify the congruencies, conflicts, and opportunities for co-benefits across different plans and policies that guide management of different urban systems?
- What new technologies are available to engage stakeholders to analyze future scenarios of urbanization, and to assess tradeoffs that create alternative W-E-F impacts?
- What performance measures should be developed to evaluate water-energy-food outcomes aimed at equity, efficiencies, and environmental protection?
- How can organizational capacity and commitment be improved to enable system-wide cooperation in planning and implementation action?
- What mix of incentives and sanctions can be used to persuade internal, horizontal and vertical cooperation?

While additional critical research questions exist, these initial questions bring to light that the three disruptive forces are intertwined and affect one another within what can be defined as a social- economic-technological-ecological-governance (SETEG) systems context [see Figure 2 - Romero-Lanko, Gnatz et al., 2016.] A single disruption frequently triggers another, which exacerbates the impacts of the first, so that the original shock cascades and culminates to multiple extreme events. For example, a major hurricane strikes that causes failure of the electricity supply grid, that leads to the shut down of water treatment infrastructure that, in turn, causes a public health problem and a widespread shutdown of local businesses, which can lead to further degrading of basic services, additional health problems, and even conflict and unrest. Survivors experience unforeseen hardships and suffering.

4. Defining a SETEG Systems Data Framework : An Overarching Perspective

For the first time in decades, the integration of interdisciplinary research and innovation on urban resilience, sustainability, and various 'nexus' topics are experiencing significant investment and attention - from special issues to research awards to business and city summits, globally. With multiple risks and benefits posed by three critical 21st century transformative dynamics: (1) urbanization, (2) environmental change, and (3) globalization, future cities will need to avoid more urban sprawl, resource use, emissions, and unhealthy cities and individuals, and design pathways toward substantial benefits, ranging from more energy choices, water and food security, to building resilience to multiple stresses and shocks. This will require an understanding of a systems of systems perspective, across social, economic, technological, environmental, and governance (SETEG) system domains that shape communities, cities, regions, national and global contexts.

Using a social, economic, technological, ecological, and governance (SETEG) systems framework (Figure 2), research could integrate diverse data streams that can inform development of a suite of tools by interdisciplinary teams to facilitate the building of resilient cities. Below are examples of such data for Delhi, India as relates to an energy entry point to the nexus, with some emphasis on water, and the availability of cooking fuels for preparing food:

- Social: The National Capital Territory of Delhi, India which hosts a population over 18 million, is projected to soon reach 24 million by 2021 and 28 million by 2026. Currently, 55% of households live within 500 meters of roads with high levels of air pollution (putting residents at risk of cardiac and respiratory problems), 16% of households in Delhi lack access to drinking water taps (putting residents at risk of waterborne illnesses), 6% lack access to latrines, and 8% are using wood, dung and charcoal for cooking. Current mortality statistics and other health data as correlated to provision and upgrading of specific infrastructures, including energy, water, sanitation, food, transport, and housing within the city's geographic areas can be described and evaluated (Sperling and Ramaswami, 2013), with confounding factors for infrastructure-related health outcomes also identified (Sperling, 2014).
- Economic: With rising incomes and affluence between 2005 and 2013, peak electricity demand in the NCT of Delhi grew at a compound annual growth rate of 7%, and peak demand deficit in the state increased from 2% to 5% over that same period, often resulting in daily power cuts, that also affected water and food production. According to the Delhi Statistical Handbook, the number of Delhi electricity consumers increased from 2,565,000 in 2003 to 4,301,000 in 2012, including nearly 3,465,000 domestic consumers.
- Technological: In 2011, the Central Electric Authority of India projected that Delhi's power requirements would nearly double over a five-year period (2009-2014) from an average requirement of 4500 MW to 8700 MW and therefore began planning ahead. As of April 2013, the North Capital Territory of Delhi was estimated to have installed electricity generation capacity of 7163 MW, with central, state, and private sector constituting 75%, 23%, and 2% of total capacity, respectively; with renewable power (including small hydro) representing 10% of the mix. At the state level, total system power capacity reached 18007 MW by 2012, with roughly 70% of power from coal, 8% from natural gas, 19% hydro, and 3% nuclear.

- Ecological: Current energy infrastructure conditions in Delhi are poor with unscheduled power cuts, 8% still using solid fuels for cooking, many lacking access to reliable/affordable electricity, and average pollutant concentrates up to four times higher than national outdoor air quality standards. Actions adopted by the Delhi government exhibit the importance of managing energy infrastructure systems given multiple environmental health risks that can be driven by urbanization, air pollution, and climate-related extreme weather (e.g. the rolling blackouts and over 2000 deaths in North India heat wave this summer).
- Governance: Local government and utility operators have proactively planned for a number of activities contributing to improved management of energy systems, including conversion of coal based to gas based power plants, use of CNG for transportation, and reductions in supply losses. Stand-by loss reduction (Prakash, 2014) can have significant impacts, especially as these power losses make up 25% of total Delhi electricity produced. On the demand-side, efficiency standards for appliances and lighting that make-up the bulk of Delhi's residential energy demand have also been a focus; as well as Delhi's Transportation Department vision aiming to implement a comprehensive multi-modal system of ~500 km of metro rail, bus priority lanes, and CNG across the entire bus fleet. However, the SHR goals of reduced emissions and risks to people and infrastructures remain critical challenges – this includes poorly maintained transmission lines, extreme heat and overloaded grids due to struggles to meet rapidly rising demand. Government plans for climate-proof transmission and distribution systems are key to reliable electricity and the 'Heat Action Plans' under development should consider use of cooling centers by transit stations during extreme heat events. New policies under consideration reducing supply losses, and achieving air pollution and GHG mitigation co-benefits are critical.

These examples of challenges and opportunities, and relevant data using and integrating key aspects of SETEG systems, provide an initial framework to explore how, why, and where are energy-water-food systems integration, urban infrastructure services provision and governance interventions helping to achieve co-benefits toward resilient, sustainable cities. How and why are growing cities such as Delhi introducing technology, planning, policy and behavioral change approaches to both mitigate and adapt to climate change? What will future EWF demands look like and which risks to urban systems and local populations are highest priority, especially under rapid growth conditions and a changing climate where increased frequency and intensity of extreme events impact EWF systems and people?

Using this context of Delhi, India, and Table 1 below, another key question could be: What systems and subsystems at the nexus of EWF+ are most important to building resilience in cities? What are the roles of policy actors, to infrastructure managers, to researchers, to service users in understanding interactions and synergies of EWF systems for building resilient , sustainable, and innovative cities in the 21st century?

Table 1 –SETEG systems and related global drivers shaping energy-water-food systems and resilient, sustainable, and innovative cities (based on literature review).

[redacted]			
Social Systems	- Energy access inequality - Population growth - Urbanization - Valued Goods & Services	- Unequal access - Population growth - Urbanization - Water insecurity	- Hunger/malnutrition - Changing Diet - Protests/instability - Pop growth/urbz.
Economic Systems	- Growth driving demands - Price volatility / shocks - Market speculation - Willingness to Pay	- Growth driving increased demands - Price and utilization by Economic Sector	- Food price - Globalization - Market speculation - Energy prices
Technological/Built Infrastructure Systems	- Energy efficiency - Production/Storage - Rebound Effects - Renewable Technologies	- Water efficiency - Supply & Treatment - Distribution - Reuse/Desalination	- Crop and Livestock Breeding - AgTech Productivity - GMOs
Ecological Systems	- Pollution/externalities - Fossil fuel production - Weather/Climate	- Pollution; Biodiversity/Climate - Quantity/ quality	- Land/Soils - Weather/Climate - Ecosystem Pollution
Governance Systems	- Resource conflicts - Policies & Regulations - Financing & Investment	- Resource conflicts - Virtual water - Policies/Distribution	- Export/Trade Policy - Foreign Direct Investment

Conclusions

Developing resilient and sustainable cities and urban nexus science-towards-solutions must become a worldwide priority. However, significant knowledge gaps on the most effective points of interdependency pose a serious challenge to moving forward efficiently, with useful knowledge and rich analytical insights. Technical, planning, governance, and finance solutions are needed to improve the process of urbanization and capacity across scales to support city-regions in anticipating and pro-actively planning for disruptions in advance of shocks and for chronic stresses that can wear down capacity and reduce reliable and affordable access to high quality energy, water and food. Cities need new technologies that will prevent or limit disruptions that can be identified and predicted, better data monitoring systems, and better knowledge of interactions among crucial infrastructure systems. Of equal importance, cities need to strengthen and improve governance approaches by integrating fragmented planning among interconnected sectors of urban systems, better public engagement and awareness, and improved plan implementation, monitoring of outcomes, and adaptation. Resilience will require a combination of social, economic, technical, ecological and governance system-based solutions.

References

Amadei, B., 2014. Food-Water-Energy-Land Approach to Community Development. Mortenson Center in Engineering for Developing Communities. University of CO.

Ahamed, S., Sperling, J., Cohen, E., Stephens, J, Galford, G. and D. Arent. 2017. The Urban Food-Energy-Water Nexus in a Growing US Metropolitan Region: Exploring Spatial Data Integration and City-Relevant Visualization in Denver, Colorado. Environmental Research Letters: (in review). Special Issue: Focus on Urban Food-Energy-Water Systems: Interdisciplinary, Multi-Scalar and Cross-Sectoral Perspectives. Ramaswami, A. and J. Newell, eds.

Arent, D., et al. 2014. Implications of high renewable electricity penetration on water use, greenhouse gas emissions, land-use, and materials supply. Applied Energy 123: 368-377.

Gall, M, Borden, K, Emrich, C, and Cutter, S. The Unsustainable Trend of Natural Hazard Losses in the United States. *Sustainability* 2011: 3: 2157-2181 doi:10.3390/su3112157

Bizikova, L., Roy, D., Swanson, D., Venema, H., and M. McCandless. 2013. The Water-Energy-Food Security Nexus: Towards a practical planning and decision-support framework for landscape investment and risk management. IISD. http://www.iisd.org/pdf/2013/wef_nexus_2013.pdf

Brugmann, J., Brekke, K., Price, L., Vogt, C., et al. 2014. Operationalizing the Urban Nexus: Towards resource-efficient and integrated cities and metropolitan regions. [http://www.iclei.org/urbannexus.html]

U.S. Department of Energy. 2013. U.S. energy sector vulnerabilities to climate change and extreme weather. USDOE.

Lobell, DB. and S.M. Gourdji, SM. The Influence of Climate Change on Global Crop Productivity. *Plant Physiology* 2012: 160: 1686–97

Marcotullio, P. J., Sarzynski, A. Sperling, J., Chavez, A., Estiri, H., Pathak, M., and Zimmerman, R. (2016). Energy transformation in cities. In C. Rosenzweig, W. Solecki, P. Romero-Lankao, S. Mehrotra, S. Dhakal, and S. Ali Ibrahim (eds.), Climate Change and Cities: Second Assessment Report of the Urban Climate Change Research Network. Cambridge University Press.

National Research Council (NRC). *Disaster resilience: A national imperative.* Washington, DC: National Academies Press, 2012.

President's Council of Advisors on Science and Technology (PCAST). 2016. Report to the President: Technology and the Future of Cities. Executive Office of the President.

Rodin, J. *Being strong in a world where things go wrong: The resilience dividend*. New York: The Rockefeller Foundation, 2014.

Romero-Lankao, P., Gnatz, D., Wilhelmi, O., and M. Hayden. 2016. Urban Sustainability and Resilience: From Theory to Practice. Sustainability 2016, 8, 1224.

Seto K. and Solecki W. eds. 2015. Handbook in Urbanization and Global Environmental Change. Routledge Press.

Simonoff, J. S., Restrepo, C. E., and Zimmerman, R. (2007). Risk management and risk analysis-based decision tools for attacks on electric power. Risk Analysis 27, 547–570.

Sperling, J. (2014). Exploring the nexus of infrastructures, environment and health in Indian cities: Integrating multiple infrastructures and social factors with health risks. Doctoral dissertation, University of Colorado, Denver.

Sperling, D. and D. Gordon. 2009. Two Billion Cars: Driving Toward Sustainability.

Stockholm Environment Institute (SEI). 2011. *In Focus: Water Energy, Food Nexus Report* [https://climatecommercial.wordpress.com/2011/11/09/in-focus-water-energy-food-nexus-report/]

UN-Habitat. 2016. World Cities Report. Urbanization and Development: Emerging Futures. Chapter 2: Urbanization as a Transformative Force. http://wcr.unhabitat.org/

World Bank. *Disaster Risk Management*. 2016. http://www.worldbank.org/en/topic/disasterriskmanagement/overview

World Economic Forum . 2011. *Water Security: The Water-Food-Energy-Climate Nexus*. [https://www.weforum.org/reports/water-security-water-energy-food-climate-nexus]

World Economic Forum. *The Global Risks Report*, 11th edition. 2016 http://www3.weforum.org/docs/Media/

World Economic Forum. *The Global Enabling Trade Report. 2016. http://reports.weforum.org/global-enabling-trade-report-2016/*

Zimmerman, R. (2014). Planning restoration of vital infrastructure services following Hurricane Sandy: Lessons learned for energy and transportation. Journal

of Extreme Events 1. Accessed:
http://www.worldscientific.com/doi/pdf/10.1142/S2345737614500043