Resilient urban energy: making city systems energy efficient, low carbon, and resilient in a changing climate

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Abstract

How can urban energy systems be energy efficient, low carbon, and resilient in a changing climate? This question is analyzed from a systems perspective, considering how climate change impacts both energy supply and energy demand in cities. Temporally, this analysis considers both climate *stresses*, e.g. rising temperatures, shifts in precipitation patterns, and climate *shocks*, e.g., storm events, disruptions from cold snaps or heat waves. Using this dynamic systems perspective, this paper draws upon a range of emerging literature and practice on climate action, resilience and adaptation. This ranges from utility reliability and emergency risk management, to end-use energy efficiency and urban infrastructure planning. Case studies of three cities are included – Washington DC, USA; Copenhagen, Denmark, EU; and Shenzhen, Guangdong, China – to illuminate how cities are making their energy systems efficient, low-carbon, and resilient. The analysis finds wide variation in the methods and areas of focus, as well as varying degrees of connection the cities are making between low-carbon efforts and resilience efforts related to urban energy. While institutional coordination is challenging, cities are finding that it leads to better energy and climate change strategies. Beneficial strategies across the cities include: distributed energy resources (such as microgrids, and district heating and cooling), passive and efficient energy systems in buildings, and partnerships across government agencies, businesses, and communities.

Introduction

In the realm of urban energy and climate, cities are undertaking at least three inter-related efforts: (1) energy-focused initiatives (efficiency, clean and renewable energy), (2) initiatives focused on greenhouse gas (GHG) reduction (low-carbon development, climate change mitigation), and (3) climate resilience or adaptation plans. The same urban infrastructure is targeted in these different plans and actions, including: supply systems for energy, water, and food; transport systems; buildings; waste and wastewater management systems. The same urban infrastructure must meet multiple performance criteria, as well as equitably serve a mix of users, be ecologically sound, consider the aesthetics of the urban landscape, be efficient in economic and energy terms, be low-carbon, and be resilient to the shocks and stresses of climate change. For example, resilience planning for heat waves must ensure that cooling is accessible to populations most susceptible to heat-related illness. At the same time, city energy and climate action plans must consider the energy efficiency of the urban building stock, as well as low-carbon cooling options such as passive cooling, district cooling, or solar PV plus storage.

This paper examines three questions:

1. What are the stresses and shocks on urban energy systems – on energy end-use as well as energy supply – in a changing climate?
2. What initiatives are cities undertaking to make their energy-related infrastructure energy efficient, low-carbon and/or resilient?
3. To what extent are cities coordinating or integrating these initiatives, and how has that influenced their strategies for urban energy systems?

This analysis utilizes a dynamic systems perspective (Meadows 2008) to examine how urban energy systems can be energy efficient, low-carbon, and resilient in a changing climate, considering energy end-use as well as supply, and considering climate impacts over different time scales. Climate *stresses* refers to shifting trends and long-term challenges such as rising temperatures and shifts in precipitation patterns. Climate *shocks* include disruptions from storm events, cold snaps, or intense heat waves (Arup 2014). Urban energy systems, refers to assets and operations that supply or utilize energy for services that provide public health and safety, public security, economic functioning, and overall well-being of the people.[1] The term low carbon, means reducing emissions of greenhouse gasses, especially energy-related carbon dioxide (CO_2) and methane (CH_4). The term *carbon* is used as short-hand for these carbon-based GHGs throughout the paper.

We examine these questions with short highlights of frameworks from the literature, and with case studies of three cities: Washington DC, USA; Copenhagen, Denmark, EU; and Shenzhen, Guangdong, China. These cities were chosen because each one is making notable efforts in city energy management, carbon reduction, and climate resilience. The geographic range offers perspective on how cities with different economic structures, governance, and cultures can tackle common problems of climate change. In addition, each of these cities is situated in one of the top GHG-emitting regions of the world, thereby providing important examples for climate action.

Analysis frameworks

Analysis frameworks for climate change impacts on urban energy systems include frameworks that focus on hazards, sectors, risk, resilience, physical infrastructure, ecological systems, people – and frameworks that integrate some or all of those foci. Reviews of emerging frameworks and metrics have been conducted by Hammer et al. (2011), Leichenko (2011), Cutter et al. (2014), Evans and Fox-Penner (2014), Seto et al. (2014), Molyneaux et al. (2016), and Sharifi et al. (2016), among others. As of yet, there is no standard framework used to analyse the climate resilience of urban energy systems.

SECTOR- AND RISK-FOCUSED FRAMEWORKS

One example of a single hazard-focused framework is the Bay Conservation and Development Commission (BCDC 2011) *Adapting to Rising Tides*, which analyses the impacts of sea-level rise on infrastructure assets around the San Francisco Bay Area. The BCDC framework includes detailed quantitative risk assessment of energy assets (generation facilities, substations, etc.) that could be impacted by sea-level rise. Other climate impacts are acknowledged but not analysed in depth.

One example of a sector-focused framework is an adaptation guide for the energy and utility industry prepared by a global sustainability non-profit (BSR 2009), based on analysis of utility industry reporting under the Carbon Disclosure Project. The BSR utility guide highlights opportunities as well as risks for the industry, and it summarizes good practices and company examples. To protect value, energy utilities are preparing disaster plans and investing in climate resilient assets (such as smart grids and improved water recycling). Utilities are also diversifying locations and operations, so that if drought decreases hydropower resources in one location, generation in other locations can compensate. Utilities are creating value by developing new and improved energy storage techniques (compressed air, large-scale batteries, hydrogen) and by forming strategic partnerships with communities and clean tech consortia.

Another example of sector-focused framework with a more integrated and urban focus is a handbook for climate adaptation of urban water systems. This helpful international guide, prepared by ICLEI EU with UNESCO and partners (Loftus et al. 2011), has a framework that considers multiple climate hazards, vulnerability and risk, people and ecological systems, as well as infrastructure and the economy. The handbook also includes examples of good practice from cities around the world. The handbook highlights the non-linear and unprecedented nature of man-made climate change, and it emphasizes that adaptation and resilience efforts must be future-oriented and flexible, decentralized as well as integrated. Although focused on the urban water sector, this framework offers insights for the urban energy sector.

Following ICLEI EU framework on urban water systems, and in answer to the first question posed in this paper, Table 1[2] provides examples of climate stresses and shocks on urban energy systems, along with potential impacts on the city. The table is not comprehensive, but includes climate impacts that appear in the case studies.

CITY RESILIENCE FRAMEWORKS

The Arup (2014) *City Resilience Framework* comes from a relatively new initiative of the Rockefeller Foundation and partners that shifts the focus from "adaptation" to "resilience." In preparation for funding action plans and Chief Resilience Officers (CRO) in the *100 Resilient Cities* (100 RC) program, Rockefeller turned commissioned consultancy firm Arup to research and develop a city resilience framework. The framework emphasizes a systems-oriented definition of resilience:

> Resilience focuses on enhancing the performance of a system in the face of multiple hazards, rather than preventing or mitigating the loss of assets due to specific events.

Surveying the literature, delving into desktop case studies, and interviewing stakeholders in six cities globally, Arup devised the framework summarized in Table 2 (Arup 2014). The literature review highlighted seven qualities of city resilience: Reflective, Robust, Redundant, Flexible, Resourceful, Inclusive, and Integrated. Some of these qualities were also utilized in the ICLEI urban water adaptation framework mentioned above, namely the flexible and integrated qualities. Missing from the Rockefeller and Arup framework is attention to the non-linear nature of climate change and the need to be future-

1. The definition used in this paper builds on the definition of infrastructure by Cutter et al. (2014) in the U.S. *Third National Climate Assessment*, as well as Seto et al. (2014) in the 5th IPCC Assessment Report, and Hammer et al. (2011) in the 1st Urban Climate Change Resource Network (UCCRN) Assessment Report.

2. Decreased precipitation >> decline in water flow or quality, Potential Impacts on the City: During droughts and heat waves, limited water supply and higher water temperatures lead to reduced capacity of cooling water for thermal power generation, as well as the more obvious loss of hydropower due to reduced water flows. In the 2003 heat wave in Europe, France had to curtail some nuclear power generation because of insufficient cooling water.

Table 1. Examples of Climate Impacts on Urban Energy Systems.

Climate Hazard & Effects	Energy System Affected (end-use or supply)	Impact on Energy System (Stress or Shock)	Potential Impacts on the City
Higher temperatures >> heat waves, hotter nights	Building cooling systems (end-use)	Higher demand for cooling, overload on power grid (stress, shock)	Power disruptions; heat-related illness for those without sufficient/affordable cooling; possibly increased GHGs
	Thermal power generation from fossil fuel or nuclear (supply)	Insufficient cooling, decrease in generation (stress, shock)	Reduced electricity supply; greater expense for alternate supply on spot market
More severe or frequent storms >> high winds, heavy rains, coastal storm surge, inland flooding	Building energy systems for space heating and hot water (end-use)	Efficient boilers damaged in flooded basements (shock)	Residents/workers/customers without heat; potential loss of home or business for the poor
	Building envelope and fabric for energy efficiency (end-use)	Damage to roofs, floors, walls and insulation (shock)	Increased energy demand and GHGs or cost of repairs
	Distribution or transmission lines (electricity supply)	Damaged power lines (shock)	Loss of electric power
Decreased precipitation >> decline in water flow or quality	Thermal power generation; hydropower (supply)	Impairment of cooling processes or decline in hydropower (stress)	Decline or loss of electric power
Sea-level rise	Electricity supply infrastructure (generation, transmission, distribution)	Inundation, more frequently or permanently (stress + shock)	Disruption or prolonged loss of electric power due to damage to underground or low-lying assets
	Liquid fuel refining or distribution systems	Inundation, more frequently or permanently (stress, shock)	Disruption to transport system; increased cost in supply chain
	Water pumping stations (end-use)	Higher energy demand (stress)	Possibly increased GHGs

Source: Authors, drawing on: Loftus et al. 2011; Hammer et al. 2011; Seto et al. 2014 (IPCC AR5); Arup 2014.

oriented, to recognize that the future climate may be dramatically different from the past climate. The ICLEI framework gives more attention de-centralized strategies, whereas the Rockefeller and Arup framework highlight the related but somewhat different qualities of redundancy (which could be multiple centralized infrastructure components) and inclusiveness (which may have a more centralized, top-down perspective).

Synthesis of desktop case studies led Arup to common functions of a resilient city:

> delivers basic needs; safeguards human life; protects, maintains and enhances assets; facilitates human relationships and identity; promotes knowledge; defends the rule of law, justice and equity; supports livelihoods; stimulates economic prosperity.

Folding in the results of stakeholder interviews, Arup developed twelve indicators informed by the functions and qualities of a resilient city. These broadly-defined indicators range from essential needs and livelihood support, to critical infrastructure management, environmental management, and urban strategy and planning. The twelve indicators are grouped into four categories: "the health and wellbeing of individuals (people); infrastructure & environment (place); economy and society (organisation); and … leadership and strategy (knowledge)." The Place-based Infrastructure & Environment indicators most directly connect to urban energy systems. For example, *Indicator 8. Continuity of critical services*, encompasses strategies for maintaining electric power supply during storms for crucial operations such as hospitals and cooling centres and water treatment. The Knowledge-based Leadership & Strategy indicators also have bearing on urban energy systems. *Indicator 8. Integrated development planning* fits well with the main questions of this paper, regarding the connections among energy planning, GHG mitigation, and climate resilience.

Case studies in the next section examine two cities that joined the *100 Resilient Cities* (*100 RC*) program after they developed climate adaptation plans using their own methodologies. The case studies also examine one city that is grappling with climate resilience outside of the *100 RC* framework.

Case Studies

Three cities – Washington DC, USA; Copenhagen, Denmark, EU; and Shenzhen, Guangdong, China – are used as case studies to examine how cities are making their energy systems efficient, resilient, and low-carbon. The three case studies provide a short characterization of each city, its climate, energy demands, energy efficiency measures, climate change mitigation and resilience efforts underway. Efforts to integrate energy efficiency, low-carbon development, and climate resilience are highlighted.

Table 2. Twelve Indicators of a Resilient City.

People: Health & Wellbeing	Place: Infrastructure & Environment
1. Minimal human vulnerability	7. Reduced physical exposure and vulnerability
2. Diverse livelihoods and employment	8. Continuity of critical services
3. Adequate safeguards to human life and health	9. Reliable communications and mobility
Organization: Economy & Society	**Knowledge: Leadership & Strategy**
4. Collective identity and mutual support	10. Effective leadership and management
5. Social stability and security	11. Empowered stakeholders
6. Availability of financial resources, contingency funds	12. Integrated development planning

Source: Arup 2014.

WASHINGTON DC, USA

In June 2012, Washington, DC was struck by a severe storm involving a line of thunderstorms sweeping across the Midwest, known as a *derecho*. The derecho's powerful winds and heavy rains severely damaged the electric grid in DC and the surrounding area. The prolonged power outage that followed exacerbated the dangerous effects of a record-breaking heatwave that lasted 11 days. The storm highlighted the fragility of DC electricity infrastructure and demonstrated the potential for cascading impacts to other critical services including water and health care should the grid fail.

Immediately following the storm, the city launched an effort to place power lines underground in areas of the city at greatest risk to outages. In the years since, climate mitigation and adaptation plans have expanded the focus to include solutions that maximize both resilience and greenhouse gas emissions reductions. In 2016, the District of Columbia released two complementary plans, *Clean Energy DC* (DOEE 2016a) and *Climate Ready DC* (DOEE 2016b), to address how the District will mitigate greenhouse gas emissions and prepare for the impacts of climate change. By incorporating resilience into their mitigation plan, and energy efficiency and distributed generation into their adaptation plan, the District was able to think holistically about addressing climate change. The holistic approach to energy resilience yielded actions and strategies that might not have been prioritized had the two been considered separately. Each of the plans is summarized briefly below.

Energy Efficiency in Climate Ready DC

In order to develop its climate adaptation plan, the District conducted a comprehensive assessment of the vulnerability of its infrastructure, public facilities, and residents to climate change related hazards. This sector-based approach to assess vulnerability incorporated both the likelihood of impact from heat or flooding, the District's primary climate hazards, and the potential consequences of an impact. A multidisciplinary advisory group comprised of local government agencies, regional planning organizations, and private utilities, helped to assess the relative consequence of potential impacts, which allowed for risk-based prioritization of assets and infrastructure systems. The criteria used to score each system and asset is summarized in Table 3. Energy infrastructure was found to be particularly vulnerable due to the combination of exposure to more extreme heat events, severe storms, and flooding, and the potential consequences of disruption to the dependence of critical water, transportation, and health and safety services on the electric grid in particular (Kleinfelder 2016 in DOEE 2016c).

In order to address these risks, *Climate Ready DC* identifies several actions to flood proof and harden the city's physical electricity distribution infrastructure. Looking beyond the existing infrastructure, the plan also calls for continued and expanded investments in energy efficiency, renewable energy, and energy storage in order to reduce peak demand and lessen dependence on the regional electric grid. The following list summarizes key actions related to energy resilience.

- *Conduct distribution system planning in order to identify the best strategies for stabilizing the power grid with distributed energy resources including storage, renewable energy and micro-grids capable of islanding.*
- *Ensure that climate risks are considered in utility rate cases for investments in new and upgraded infrastructure. Flood proof and/or elevate electric infrastructure.*
- *Provide back-up power for emergencies at all identified critical facilities. Ensure that existing back-up power systems are located above projected flood elevations.*
- *Continue to pursue energy efficiency for all commercial and residential buildings through incentive programs, building codes, and financing to increase grid stability by reducing energy demand at peak periods and during extreme events.*

As the city moves to implement *Climate Ready DC,* they are working through existing programs, policies, and partnerships to advance each of the actions. For example, the District is looking to its existing building energy and green construction codes to strengthen requirements for thermal efficiency that will both reduce building energy u se and improve resilience in the event of an energy outage.

Energy Resilience in Clean Energy DC

Clean Energy DC is the District's strategy to meet its medium-term goal of reducing GHG emissions by 50 % below 2006 levels by 2032. It identifies specific policies and programs that would allow the District to surpass this goal, and put it on a path to achieving its long-term goal of 80 % reduction in emissions by 2050. As building energy use accounts for nearly three quarters of the District's GHG emissions, energy efficiency and distributed renewable energy are critical components of the strategy. The contributions of each of the strategies to achieving the GHG emissions goal are shown in Table 4.

While it is not shown in Table 4, *Clean Energy DC* identifies grid modernization and energy resilience as critical to enabling the deep penetration of renewable energy, neighbourhood scale

Table 3. Vulnerability Assessment Consequence Scoring Criteria.

Score	Area of Service Loss	Duration of Service Loss	Cost of Damage	Impact on Public Safety Services	Impacts on Economic Activities	Impacts to Public Health/ Environment	Impacts on Vulnerable Populations
3 (Most Severe)	Two or more Wards	>7 days	>$1 m	High	High	High	High
2 (Moderate Severe)	One Ward	1–7 days	$100 k–$1 m	Moderate	Moderate	Moderate	Moderate
3 (Least Severe)	Neighbourhood	<1 day	<$100 k	Low	Low	Low	Low

Table 4. GHG Reduction Projections by Strategy, Washington DC.

GHG Reduction Strategy	Percent GHG Reduced from Total 2032 Business as Usual Scenario
Federal Fuel Efficiency Regulations – Corporate Average Fuel Economy (CAFE) Standard	5.8 %
Walking, Cycling and Public Transit (mode share change)	6.4 %
Electric Vehicle Adoption	0.4 %
Getting to "Net-Zero" in New Construction	5.2 %
Energy Efficiency in Existing Buildings	6.6 %
Neighborhood-Scale Energy Systems	0.5 %
Prioritizing low carbon energy in electrical Standard Offer Service (Power Purchase Agreements for Standard Offer Service)	6.6 %
Mandating electricity suppliers to Procure Renewable Energy (Renewable Portfolio Standard)	7.1 %
Renewable Portfolio Standard's Local Solar Requirement	1.2 %
Total GHGs Avoided vs. 2032 BAU	39.8 %
Total GHGs Reduced vs. 2006 Baseline	51 %

Source: DOEE 2016a.

energy, and net-zero energy buildings. The recommendations identified are based on the three stages of grid modernization identified by Di Martini and Kristov (2015): 1) Grid Modernization, 2) Distributed Energy Resources (DER) Integration, 3) Distributed Markets. Most U.S. grids, including the District's, are in Stage 1. Specific actions identified by Clean Energy DC include:

- *Adopt a framework for valuing distributed energy resource costs and benefits.*
- *Support the collaborative development of an integrated distribution plan.*
- *Outline a path to overcome legislative and regulatory barriers to grid modernization.*

The District's complementary planning efforts have led to tangible next steps, including conducting feasibility assessments of microgrids and district energy (Urban Ingenuity 2015), the exploration of strategies to combine distributed solar with battery storage, and distribution system planning efforts.

COPENHAGEN, DENMARK

Copenhagen is a European city that strives to be low-carbon, climate resilient, and sustainable in multiple ways. As a capital city and port city with a population of near 800,000, Copenhagen has embraced inter alia wind power, bicycling, and public-private partnerships to enhance the urban quality of life as well as the economy. Beginning with its 2009 Climate Plan, the city followed with a pledge to become carbon neutral by 2025 in its *CPH 2025 Climate Plan* (2012). Copenhagen's efforts were recognized with a City Climate Leadership award from the C40 Cities Climate Leadership Group and Siemens in 2013.[3] The entire country of Denmark has goals for 100 % renewable heat and power by 2030, and 100 % renewable energy in all sectors by 2050 (Go 100 %).

Prominent features of the *Climate Plan* are: an interconnected heat and power system, shifting to 100 % renewable electricity with wind and other sources, shifting to carbon neutral district heating and cooling systems, expanding walking, bicycling and public transit to 75 % of trips, and promoting energy saving in buildings (Copenhagen 2012). Figure 1 illustrates how the strategies are expected to contribute to the city's total carbon reduction, with additional detail on de-carbonization of energy production.

In 2005, roughly half of Copenhagen's 2.5 million tonnes of CO_2 emissions were from electricity consumption in buildings

3. Copenhagen, C40 award winner, 2013: http://www.c40.org/profiles/2013-copenhagen and http://blogs.worldbank.org/sustainablecities/insights-urban-oscars.

and business, with the other quarters from district heating and mobile sources (Copenhagen 2012). As the city invests in wind power, and more district heating with captured heat and renewable energy, emissions are declining. Further efforts will help Copenhagen to get closer to its goal of carbon neutrality. These efforts include (Sustainia n.d., Guide to Copenhagen 2025, pp. 95–96):

- Rooftop Solar Collectors provide solar thermal water heating.
- Rooftop Solar PV provides building electricity.
- District heating from Combined Heat and Power (CHP) systems supplies 98 % of city's heat demand.
- District cooling for commercial and public buildings comes from a network of pipes partly chilled with cold seawater.
- Heat Storage in 300,000 m^3 capacity hot water tanks in former dry dock in Nordhavn, part of district CHP.
- Geothermal energy for hot water and electricity generation.
- Smart Grid enables two-way flow of electricity to manage loads in line with fluctuating supply by renewables.
- Non-recycled waste is incinerated for energy, in district heating system.
- Off-shore wind farms are cooperatively owned by a partnership of residents of Copenhagen and energy companies, engaging the public to support renewable energy and leveraging financing for the city.
- International Grid Connections allow Denmark to sell excess electricity to other countries, so that wind power isn't wasted and the wind companies do well economically.

Energy Resilience Efforts

Climate change adaptation and resilience planning in Copenhagen began in 2009 (Leonardsen 2015), in parallel with climate change mitigation planning, and as part of Copenhagen's overall sustainability efforts. Planning quickly shifted into action in 2011 after a cloudburst event caused rapid flooding and washouts, sewage surge, and massive infrastructure damage costing nearly €1 billion (Kabell 2016). Copenhagen's *Climate Adaptation Plan* (2011) emphasizes blue-green infrastructure – such as rain gardens, bio-swales as stormwater channels, and parks as water detention ponds – that serves multiple purposes: stormwater management to protect people and infrastructure, natural cooling of the urban heat island effect, and public amenities that add to the everyday quality of life in the city. For other climate hazards, such as sea-level rise and storm surge, the city found that a centralized approach and utilization of grey infrastructure will be more effective and less costly; the Adaptation Plan calls for a centralized a concrete storm surge barrier. Copenhagen's adaptation efforts were recognized by another C40 award in 2016 (Scruggs 2016). Copenhagen's approach is also representative of growing efforts to make emergency preparedness part of everyday infrastructure (Humphries 2016).

Copenhagen's *Climate Adaptation Plan* focuses on management of storm-related flooding and sea-level rise, some of which could impact energy infrastructure. The city is also preparing to manage higher temperatures with passive cooling techniques in buildings (solar orientation, shading, cool facades and roofs) and district cooling systems utilizing seawater. The *Guide to Copenhagen 2025* (Sustania n.d.) notes that resilience is inherent in the city's integrated heat and power system. The system allows fluctuating wind power to be stored as heat or in electric vehicle batteries. With a mix of energy supply (wind, geothermal, biomass, CHP, district heating and cooling) at multiple scales (from roof-top to district to off-shore wind), Copenhagen is less prone to energy disruptions from climate change stresses or shocks. Thus even though Copenhagen's resilience plan focuses on the management of stormwater and rising seas, energy supply and demand is considered in the planning.

Networks and partnerships figure prominently in Copenhagen climate change mitigation and adaptation, and the city is making strong connections between sustainability and the economy. The city was already part of the Danish "Water in Cities" network, involving cooperation among universities, public institutions, and private business. City government is enhancing dialogue among its own offices, such as the Technical and Environmental Administration (TMF) and the Economic Administration (ØF), as well as cooperating with the Copenhagen Cleantech Cluster and other business networks.

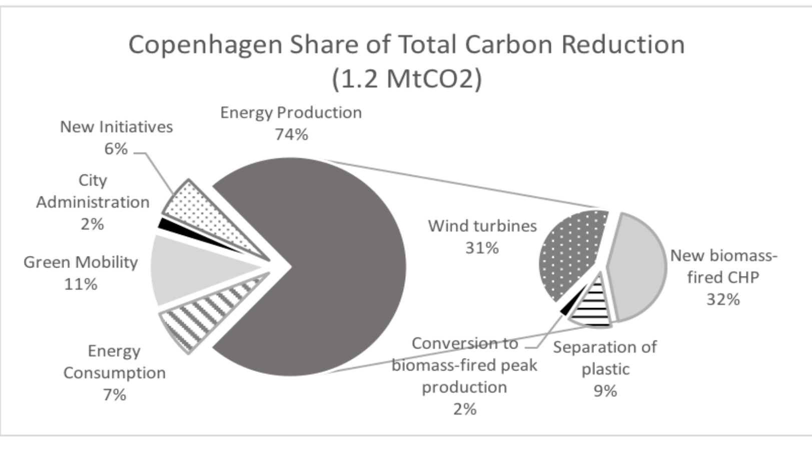

Figure 1. Copenhagen Strategies for Total Carbon Reduction, and for Energy Production Initiatives. Source: Based on Copenhagen 2012.

SHENZHEN, GUANGDONG, CHINA

Shenzhen, a mega-city in China's Pearl River Delta in Guangdong province, grew rapidly from an agricultural city of 58,000 people in the 1980s to the nearly 15 million-person metropolis it is today. Located between Hong Kong and the provincial capital of Guangzhou (see Figure 2), Shenzhen was one of China's first Special Economic Zones, and it still retains a robust manufacturing base and export trade. The city is making efforts to enhance the service sector of its economy (Rutledge 2016), yet Industrial energy demand is still high, and energy demand in Buildings and Transport is growing. Coal-fired electricity is dominant in Guangdong province, accounting for 76 % of electricity, even as the province began investing $23 billion in non-fossil power (nuclear, wind, and solar) in 2014 (Schneider 2015).

Low-Carbon Development

Shenzhen, like most Chinese cities, is focusing its climate change efforts on low-carbon development. These efforts include: reducing energy-related carbon emissions through energy efficiency in industry and buildings, shifting economic structure away from heavy industry, improving urban form and public transit, and pursuing non-fossil energy supply (Khanna et al. 2014; Price et al. 2015). The focus on low-carbon development has direct benefits for air quality and public health, as well the economy.

Shenzhen is one of 36 low-carbon pilot cities and provinces in China, having joined the national pilot program during the 12th Five-Year Plan period (2011–2015) (Ohshita et al. 2015). Shenzhen subsequently joined the Alliance of Peaking Pioneer Cities (APPC) of China in 2015, and participates in the US-China Climate Smart/Low-Carbon cities initiative, part of bi-lateral cooperation between the world's two largest energy consumer and GHG emitters.[4] Because many Chinese cities are still building new infrastructure to accommodate the surge of urbanization, carbon emissions are still rising. But the APPC cities are committing to early peaking of GHG emissions, then to level-off and decrease emissions, to support China's national goal and international pledge for peaking its emissions by 2030. To meet this commitment, Shenzhen and other cities are developing their peaking pathways (akin to climate action or mitigation plans elsewhere), which include investment in low-carbon urban infrastructure (e.g. public transit and non-motorized transport infrastructure), pursuing greater improvement in industrial energy efficiency, enhancing energy efficiency in buildings, and de-carbonizing energy supply (APPC Secretariat, 2016). Shenzhen was the first Chinese city to pilot a municipal carbon trading program beginning in 2013, which has led to the formation of a national carbon trading system starting in 2017. With over 600 companies in the Shenzhen program, they achieved a 17 % reduction in GHG emissions (Scruggs 2016) while growing GDP nearly 9 % year-on-year (NBS 2016).

With dense urban development in a sub-tropical climate, Shenzhen is beset by hot summers and the urban heat island effect. In response, the city has established energy efficiency standards for residential buildings and requires energy performance contracting for public buildings (Layke 2015). The Shenzhen Institute for Building Research has been actively developing and implementing energy efficient and green building design, including its own headquarters (Diamond et al. 2013). Yet more effort is needed to have low-carbon – and resilient – building widely implemented across the city. Developers are still pursuing expensive high-rise buildings surrounded by multi-lane roadways, while affordable housing clustered around daily amenities – an ideal form of low-carbon urban development – languishes or is demolished (Rutledge 2016).

Figure 2. Shenzhen, Pearl River Delta, Guangdong province, China. Source: Circle of Blue and Wilson Center (Schneider 2015).

Climate Change Impacts and Early Resilience Efforts

Shenzhen and other cities of the Pearl River Delta face multiple threats from climate change: intensified storms from inland areas and from typhoons, resultant flooding and coastal storm surge, severe heat waves (which will likely have the largest public health impact), saltwater intrusion, worsening problems with urban drainage (stormwater management), and inundation of important infrastructure (docks, embankments, power plants, industrial facilities), not to mention damage to coastal ecosystems (Du et al. 2013). In addition, the Pearl Rive Delta region is experiencing significant land subsidence, due to intense urban development on top of unstable alluvial soils, exacerbating the problem of sea level rise (Chan et al. 2012; Ghosh 2016).

Despite the increasing impacts of climate change, Chinese cities have paid less attention to efforts termed *climate change adaptation* or *resilience*. There is, however, widespread recognition of increased droughts, desertification, storms, floods, 'airpocalypse' smog events, cold snaps, and heat waves due in some part to climate change.[5] With China's long history of inland riparian flooding and coastal typhoons, along with other natural and human-intensified disasters (earthquakes, sand storms), Chinese cities are unfortunately familiar with

4. For information on the 2015 US-China climate leaders summit, and the launch of the Alliance of Pioneer Peaking Cities in China, see: https://obamawhitehouse.archives.gov/the-press-office/2015/09/15/fact-sheet-us-%E2%80%93-china-climate-leaders-summit.

5. See, for example: http://www.huffingtonpost.com/entry/smog-smothers-beijing-during-cop21-climate-talks_us_565d6a04e4b072e9d1c3180f.

the emerging impacts of climate change. The evacuation of the coastal city of Xia'men, in Fujian province, during the October 2016 Typhoon Meranti is one example of a Chinese city with some emergency response strategies in place (Fan 2016). As another example, the city of Taichung is conducting vulnerability studies and risk assessments, and developing monitoring and warning systems, to prepare for typhoons (climate impact) and earthquakes (non-climate impact) (Guangzhou Awards 2015). The mega-city of Guangzhou, up-river from Shenzhen, set up an emergency on-site operation centre and public shelters for over 100,000 people stranded at a major train station during an unusual cold snap from the North that disrupted rail travel (Guangzhou Awards 2015).

Besieged by more frequent and intense storms, and with the unprecedented pace of urbanization, typical grey infrastructure of concrete street gutters and storm sewers is insufficient and ineffective. Shenzhen is one of 30 cities that have joined China's pilot "sponge city" program for flood management, an approach that utilizes blue-green infrastructure, such as use of permeable pavement, rain gardens as catchment basins, and wetlands as buffers against storm surge (Sheperd 2016). Each pilot city receives US$ 60 to 90 million (RMB 400 to 600 million). After a terrible flood in 2008, Shenzhen turned the plaza surrounding its Mass Sports Centre into a showcase for resilient urban infrastructure, with permeable pavement, rain gardens, and a large rainwater cistern that stores the stormwater for later use (Liu 2015).

Shenzhen's experience with the plaza, and experience in other pilot "sponge cities," highlights the importance of partnerships and integration of resilience with regular city planning. In Shenzhen, the Urban Planning and Design Institute helped to make connections across the city (Liu 2015). The city of Changde worked with a German firm (Wasser Hannover GmbH) on sustainable water management, to develop a detailed plan that went beyond the technical guidance issued by the central government. In Beijing, a technology company working with the national capital city noted the need to develop a skilled workforce and technical know-how, as well as gain the support of the public. Retro-fit projects for resilient infrastructure not only cost more than in new developments; they also inconvenience the public during construction. In the city of Zhenjiang, near Shanghai, the local Urban Planning and Design Institute encountered public animosity – until the rain came. Then residents realized the benefits of the resilience retro-fits, as their streets and businesses and homes stayed dry (Liu 2015).

To develop more comprehensive strategies, a few Chinese cities have joined international networks on climate resilience, such as the four Chinese cities in the Rockefeller *100 Resilient Cities* network (Deyang, Haiyan, Huangshi, and Yiwu). But for most Chinese cities, responses to a range of climate change impacts aren't yet gathered under one plan or even denoted as adaptation or resilience. Rather, local Environmental Protection Bureaus and public health agencies respond to smog pollution episodes, water agencies respond to drought, urban planners and building experts consider the urban heat island effect, and so on. Although Shenzhen is undertaking a number of programs to address different climate hazards, it has not yet developed a comprehensive climate resilience plan, nor has it focused on resilience of its urban energy systems.

Discussion and Conclusions

In all three cities, severe impacts of intense storms pushed the cities from analysis and planning to action and implementation of more resilient infrastructure. In the case of Copenhagen, efforts began with de-carbonization commitments, and with hazard analysis of potential climate impacts on the city, including flooding from a cloudburst storm event. To turn that hazard analysis into an actionable plan, partnerships were formed, the public involved, and financing planned. And, unfortunately, it was the occurrence of a terrible cloudburst event in 2011 that moved the legislative and legal processes forward rapidly. In Shenzhen, which has been giving attention to low-carbon efforts such as carbon trading and green building, severe flooding led to implementation of blue-green infrastructure, and worsening heat waves are leading the city to further enhance its building codes and urban planning to better utilize wind and water flows for cooling. And in Washington DC, the city was pushed to take action by the direct impacts of an intense storm on urban electricity supply.

While institutional coordination is challenging, all three case study cities are finding that it leads to better energy and climate change strategies. If resilience efforts are led by disaster management teams or by public works departments in isolation, they may be missing beneficial and economical strategies. As the experience of Washington DC shows, when disaster management alone was considered in infrastructure choices, it led to a more expensive and less optimal outcome (undergrounding power lines). When multiple perspectives informed choices about electricity supply and use, the strategy of distributed systems with storage and islanding capability emerged as the better choice. The coordination process needs to be managed carefully, however, to avoid stalled decision-making under the weight of an overwhelming number of criteria. In the Washington DC example, clean energy plans and climate readiness plans were prepared separately, keeping the scope of each effort focused and manageable. At the same time, coordination and consultation helped to inform each one. Thus it is a combination of intersecting processes – climate change mitigation plans, disaster management, urban infrastructure planning, community needs and priorities, and climate change resilience planning – that informs decisions about urban infrastructure.

Even with the variation in focus and frameworks across the cities, the analysis identified some common beneficial strategies for urban energy systems: distributed energy resources (such as microgrids, and district heating and cooling), passive and efficient energy systems in buildings, and partnerships across government agencies, businesses, and communities. More research and knowledge sharing is needed to characterize and quantify the co-benefits of these urban energy resilience strategies – and to identify others. Further development of analysis frameworks and cooperation are also needed, such that urban energy systems are energy efficient, low-carbon, and climate resilient – and meet other priorities for the cities they serve.

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