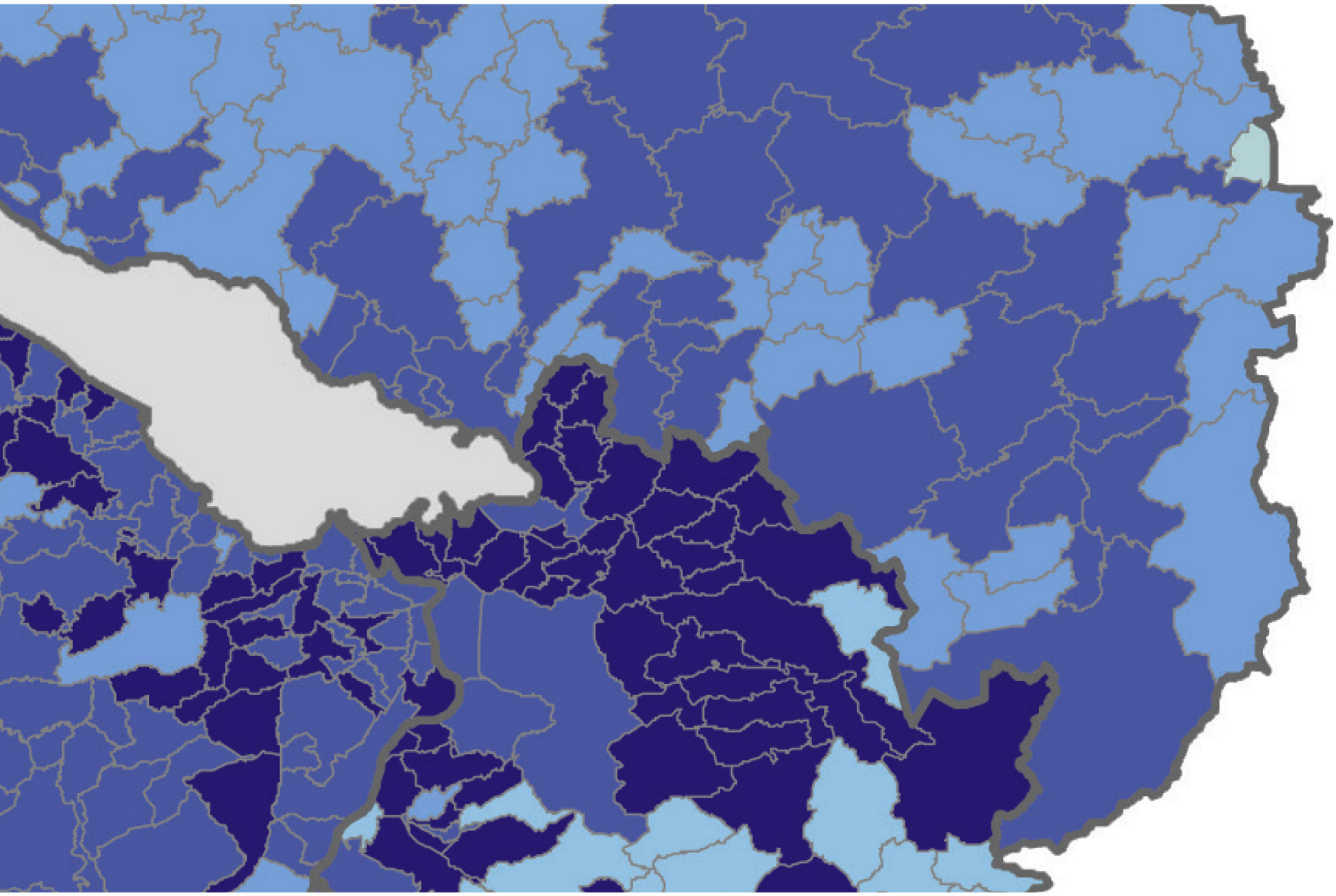
Second Edition

Urban Energy Transition

Renewable Strategies for Cities and Regions



Edited by Peter Droege

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SECOND EDITION

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Utilizing the Urban Fabric as the Solar Power Plant of the Future

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INTRODUCTION

The 21st century presents fundamental challenges and opportunities to the urban fabric, leading some to proclaim it as the "century of the city" (Facchini et al., 2017). Already, the cities of the world house the majority of the global population, and ongoing urbanization processes further stress the deepening commitment to the urban project (Seto et al., 2014; United Nations, 2015). Particularly emblematic of this direction is the growth of so-called "mega-cities"—agglomerations of urban life totaling more than 10 million people and stretching out over many square kilometers. The prevalence of mega-cities has grown from only seven in the early 1960s to 27 in 2010 (Kennedy et al., 2014). By 2020, the world is expected to be home to 37 mega-cities (Kennedy et al., 2014).

This recognition raises the critical question of *how* cities will help shape 21st century development and what opportunities are available to arrive at a sustainable technology, environment, and society relationship. One essential part of the puzzle facing cities is energy generation and use—powering daily life in the world's largest cities requires vast amounts of energy, and these energy use patterns have negative social and environmental consequences (Facchini et al., 2017; Kennedy et al., 2015; Seto et al., 2014).

To explore the question of *how* cities around the world can address the negative social and environmental consequences associated with energy use and generation (mostly focusing on electricity), a useful initial breakdown is to distinguish between action potential within the city boundary and outside the city boundary. For example, focusing on energy generation patterns currently occurring outside of city boundaries, decision-makers can apply pressure on the ex-urban component of the energy system in order to motivate change toward the increased use of clean energy. Cities represent a substantial procurement channel of energy, water, materials, and so forth that could motivate system-wide change. For example, consumption-based carbon accounting strategies can be implemented to internalize the

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environmental consequences of operating various city functions.

As a group of possible policy instruments and options, however, this approach limits the in-city changes by focusing on the modification of the ex-urban energy supply flow. Consider, for example, the ex-urban energy supply dependence established throughout the 20th century: modern energy systems typically consist of large-scale, centralized systems of electricity generation that move vast amounts of electrons into the city to reliably and consistently meet urban energy demand. In other words, the approach seeks to substitute far-away coal and other fossil fuel power stations with equally distant large-scale renewable energy installations. Within such an approach, cities continue their currently passive role as hubs of energy demand, and minimal in-city changes or control are required (Rutter and Keirstead, 2012).

With continuing advancements in sophisticated methods using advanced software options, it has become increasingly clear that the in-city socio-technical potential and design opportunities are plentiful, and range from design changes in transportation (Valdez et al., 2017) and energy efficiency (Shahrokni et al., 2014) to green roofs (Santamouris, 2014) and geothermal energy (Schiel et al., 2016). Examples include: an analysis of Stockholm's electricity consumption, which found opportunities to reduce consumption levels by at least 33% (Shahrokni et al., 2014); up to 62% reduction in CO_2 emissions, and a 50% reduction in diesel consumption (against business-as-usual) in cities such as Mexico City, Guangzhou, and Bogotá by means of smart transportation options such as Bus Rapid Transit (Vincent et al., 2012); and a 29.7% CO_2 emission reduction potential through the use of geothermal energy in an urban area in Germany (Schiel et al., 2016). These observations raise the clear question of how cities can capitalize on this in-city potential to advance their energy sustainability—essentially, how cities can generate and use their own power in a sustainable way.

The question of urban sustainability, however, is accompanied by a question of urban energy governance. Here, a breakdown between two available pathways is offered to provide guidance in terms of the practical pursuit of sustainable energy deployment within the city boundary. Specifically, a first conceptual pathway maintains an operational strategy that reduces the problem at hand to a technical conundrum that can be solved through expert-led technical design and engineering. In a way, this strategy mimics 20th century design principles by focusing on the technical design of the energy system without reconsidering energy governance structures—a pursuit limited to the realization of urban sustainability without explicit consideration of broader factors. A second conceptual pathway perceives the need for a broader transformation where the problem is not simply technical, but includes the involvement of the urban polity and offers a new energy governance strategy. This strategy foresees an era of "prosumer" and "energy citizen" dynamics that allow governance of energy and climate policy in a manner that directly addresses the need for a future that is not only sustainable, but also just (see, e.g., Agyeman and Evans, 2004).

The question of how cities can achieve urban sustainability *and* justice is the central focus of this chapter. The exploration of city options is conducted here by using the concept of the "solar city"—a term that captures the in-city energy system design opportunities (particularly for solar energy), but also allows city residents to generate and conserve energy on behalf of the twin principles of sustainability and justice. The value of the "solar city" concept has been broadly established through scientific investigation of technical potential, financial feasibility, and policy strategy (Byrne et al., 2017b). For example, research efforts frequently find that even mega-cities with more than 10 million people have considerable in-city potential to deploy solar energy technology on their rooftops at a scale that could fundamentally transform urban energy structure (see, e.g., Byrne et al., 2015, 2016, 2017a,b).

The chapter explores the question of urban sustainability and justice by first outlining the 20th century urban energy generation and use patterns with a brief emphasis on the sustainability and justice limitations associated with the model of passive urban energy demand supplied by external, centralized energy ("20th Century Urban Energy Use Patterns and Its Sustainability and Justice Limitations" section). Next, the chapter more thoroughly introduces the in-city energy generation capacity by focusing particularly on the potential contribution of solar energy ("The Urban Role in Moving Energy Use Into the 21st Century" section). This is followed by a discussion of the two available pathways where the case is made that a path that incorporates sustainability and justice delivers greater benefit to urban communities ("Planning a 21st Century Solar City: Available Conceptual Pathways" section). The remainder of the chapter explores the design parameters of this pathway ("Considering the Practicality of the Solar City Concept" section) and applies it to a case study analysis of New York City ("Imagining a Solar City: 21st Century Urban Energy Development in New York City" section).

20TH CENTURY URBAN ENERGY USE PATTERNS AND THEIR SUSTAINABILITY AND JUSTICE LIMITATIONS

Urban energy systems are highly complex and involve many sectors and energy users. Modeling the flow of energy through such a system is a complex undertaking where, for example, variations in temporal or spatial scales needs to be considered (Keirstead et al., 2012). In addition, cities exhibit a wide range of possible energy use profiles dependent on, for instance, geography or urban morphology. Compare, as a case in point, the per capita energy consumption of New York City at around 130 gigajoules (GJ) per person, per year, to other mega-cities such as Mumbai, Karachi, or Kolkata where total energy use per person is around 20 GJ per person, per year (Facchini et al., 2017). Temporally, substantial changes in urban use profiles also take place such as is illustrated in an analysis of New York City from the 17th to the late 20th century (Swaney et al., 2012).

However, in terms of urban energy use, a simplified model can be extracted in which the urban hub functions as a center of passive demand, supplied by ex-urban energy sources (see, e.g., Barragan and Terrados, 2017). An example of such ex-urban energy dependence is Seoul, South Korea, where, before implementation of experimental strategies to address energy self-sufficiency, about 97% of energy service needs were met with imported energy sources (Lee et al., 2014). The simplified model of urban energy use is provided in Fig. 1.

A series of sustainability and justice limitations accompany this model of urban energy use. In particular, estimates of the urban share of global greenhouse gas emissions range from 70% to 75%, and reveal city-level responsibility in the global sustainability shortcoming of the modern energy system (Seto et al., 2014). In part, the sustainability deficit occurs due to the conversion and transmission losses that can account for significant inefficiencies in urban energy use (particularly when including embodied energy in products and materials): an analysis of Beijing found energy loss rates of as high as 71% to fulfill certain city functions (Chen and Chen, 2015). This dynamic is captured under the "asymmetry principle," which describes how energy use patterns at the end-user side reverberate throughout the supply chain as they are dependent on early-stage, ex-urban activities such as mining, transportation, conversion, and transmission processes (Tertzakian and Hollihan, 2009).

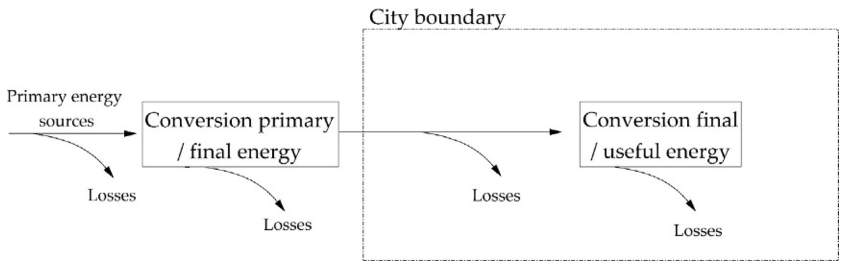

FIG. 1 Simplified urban energy use and generation. *Courtesy of WIT Press from International Journal of Sustainable Development and Planning, Volume (12), No. (3), 2017, page 416–424.*

The supply-dominated focus of the 20th century energy system also engenders a justice deficit, as illustrated by the following observations:

- The world's largest cities together represent about 6.7% of the global population, but are, among others, responsible for 9.3% of electricity use, 12.6% of waste generated, and 9.9% of gasoline use (Kennedy et al., 2015);
- New risks due to hydraulic fracturing extraction of natural gas to power daily life impact predominantly rural communities, as approximately 7 million people in mostly rural areas are now exposed to the increased prevalence of man-made earthquakes (Petersen et al., 2017);
- Urban communities benefit from centralized power generation, but often do not share the same risk profile. Seoul, Korea is a case in point: representing about 20% of the country's population, the city yields the benefits of nuclear electricity generation (which provides about 30% of Korea's electricity), but the city's location in the northwest shields it from the risks of this generation, as all nuclear power plants are located in the east and south of the country (Lee et al., 2014).

THE URBAN ROLE IN MOVING ENERGY USE INTO THE 21ST CENTURY

Changes in the composition of the primary energy supply that fuels this simplified model represented in Fig. 1 have taken place over time (see, e.g., Haberl et al., 2011; Rutter and Keirstead, 2012). While these energy transitions are influenced by and affect society as a whole, cities play an important role in the process of change: energy transitions "always work at least partly through urban processes, urban practices, and urban change, and that, concomitantly, the urban experience and condition (in their inherent diversity) are constantly reconfigured by energy and by the evolving and contested ways in which they are connected" (Rutherford and Coutard, 2014).

To effect change and advance sustainability, cities can apply pressure on both ex-urban and in-city processes. The ongoing effort to create advanced inventories of urban energy use and greenhouse gas accounting will likely help shape these options—especially as more data becomes available. For example, greenhouse gas inventory efforts revealed that 92% of Beijing's 2014 greenhouse gas emissions can be traced back to energy consumption (Li et al., 2017).

Options to apply pressure on ex-urban energy generation and conversion processes would essentially seek to modify the primary energy source material visualized in the left side of Fig. 1. Such an approach could help address sustainability concerns. However, a continued reliance on long supply chains and multiple conversion moments maintains an overall grid system vulnerable to disruption (Bakke, 2016). As a case in point, on August 14, 2003, a sagging power line in Ohio short-circuited after hitting a tree branch, and represented the starting point for a rolling blackout that crippled the energy system all the way from Detroit to Toronto to New York City, and left more than 50 million people without power (Wald, 2013). Another example of vulnerability is the disruptive effect of Hurricane Sandy, which left 2 million people in New York City without power, and is accompanied with estimated reparation costs of $41.9 billion (Henry et al., 2013). System-wide vulnerability is further evident from the disruptive effect of the Fukushima Daiichi nuclear power plant disaster: in the immediate aftermath of the accident, about 15.8 GW of thermal power had to be shut down throughout Japan (Hayashi and Hughes, 2013). This problem appears to be an endemic character trait of modern energy systems as stress tests of energy systems unaffected by "Fukushima" nevertheless revealed substantial weaknesses. To illustrate, the cost of necessary post-Fukushima safety upgrades of the French nuclear power fleet is estimated at 10 billion Euro (IEA, 2017).

Therefore, strategies that focus on the in-city dynamics of energy use can claim promising potential. Increasingly advanced understanding of the urban energy potential has been made possible through the use of, among others, sophisticated modeling techniques. City-wide installation potential of solar photovoltaic (PV) technology on cities' rooftops, for example, has been estimated for cities across the United States, Europe, Asia, and beyond (Adam et al., 2016; Byrne et al., 2015, 2016, 2017a,b; Gagnon et al., 2016; Miranda et al., 2015; Scheer, 2008; Wong et al., 2016). These studies consistently find significant solar energy generation potential: a review of recent research compared 52 cities across the world and found that technical solar electricity generation potential could account for at least 30% of annual electricity consumption in most cities (Byrne et al., 2017a,b). For example, the city of Seoul can cover about 30% of its annual electricity consumption, 66% of its electricity consumption during daylight hours, and more than 95% of its electricity needs during mid-day summer days using solar energy (Byrne et al., 2015).

Similarly, a recent publication by Project Sunroof, a project developed and operated by Google, confirmed this observation, as it notes that about 79% of all US rooftops have suitable rooftop space available for solar energy installation, ranging from 90% of buildings in Hawaii, Arizona, Nevada, and New Mexico to 60% of homes in Pennsylvania, Maine, and Minnesota (Conkling, 2017). Urban morphology restructuring could expand the potential: changes in the urban morphology could improve solar irradiation of rooftops and façades by as much as 9% and 45%, respectively (Sarralde et al., 2015).

A global survey of the technical potential for rooftop solar photovoltaic by the International Energy Agency (IEA) arrived at a global estimate of 5400 gigawatt (GWp) of installation potential, equivalent to an annual generation of 9100 terawatt-hours (TWh) (IEA, 2016). Based on IEA modeling assumptions, such a level of generation could cover up to 32% of global urban electricity demand by 2050, or about 17% of global total electricity demand by 2050 (IEA, 2016). In today's terms, 9100 TWh would be sufficient to cover about 37% of global annual electricity use for all functions and services (BP, 2017).

PLANNING A 21ST CENTURY SOLAR CITY: AVAILABLE CONCEPTUAL PATHWAYS

The findings of in-city potential and the need to address sustainability and justice concerns associated with an ex-urban supply-dominated model suggest that the next energy transition will need to include a decidedly urban component. As such, it helps to distill essential characteristics of previous urban energy transitions. Investigation into the urban dynamic as it relates to energy transitions reveals five common features that can be associated with past energy use changes (Rutter and Keirstead, 2012):

(a) each transition is accompanied by an intensification of energy use;

(b) each transition made the urban energy system increasingly organizationally and technologically complex;
(c) government and private-sector actors were, through policy and other interventions, drivers of these transitions;
(d) all urban energy system transitions occurred in parallel with broader societal and technological transformation; and
(e) shorter and shorter intervals between transitions can be observed.

Based on these characteristics, a critical distinction between two conceptual pathways can be drawn in efforts to plan for a 21st century "solar city." Both pathways benefit from existing trends with strong downward price projections, such as is the case for renewable energy options such as solar energy technology (Barbose and Darghouth, 2016), advanced data gathering and analytics (Rogers et al., 2015), and battery energy storage developments for electric vehicles and stationary applications (Nykvist and Nilsson, 2015).

First, a pathway consisting of policy instruments and design parameters that are aligned with the principles and processes that have supported previous energy transitions can be called "20th century energy development principles." At its core, this approach reduces the notion of in-city energy generation and use to a problem statement that is technical in nature and, as such, requires no particular changes to energy governance structures. Such a pathway would therefore likely deliver an energy transition that retains the five common features of the preceding past energy transitions. A review of the modern energy system reveals what this pathway would likely yield: an urban energy system of standardized, real-time, city-level management of energy use and generation managed by experts in bureaucratic bodies of administration.

A second pathway is available that recognizes the twin challenge of "just sustainability" (Agyeman and Evans, 2004) and emphasizes the justice complications with ever rising levels of energy intensity or increasingly complex organizational structure and technological requirements. By restoring energy governance to the urban polity, the second pathway emphasizes that the pursuit of sustainability is not simply technical, and requires consideration of justice principles in design and planning. Effectively, this second pathway allows for the use of new design principles—what could become 21st century energy development principles—to help shape what it means to be the 21st century solar city.

Planning a 21st Century City With 20th Century Principles

The 20th century energy system was created along six historic guiding principles, the combined functioning of which can be captured as an unrelenting focus on providing affordable and abundant energy through large-scale, centralized systems with an emphasis on growing energy supply to meet forecasted demand, and deference to technical experts to make technology selection decisions (Sovacool, 2011). The resulting society-energy relationship positions end-users firmly as consumers without much agency over the energy system that provides the social utility of energy services (Sovacool, 2011).

Application of this mind-set to the challenge of implementing a solar city would likely produce familiar energy system dynamics. In simplified terms, this pathway would position the broad diversity of energy development opportunities represented within city boundaries as an ill-defined, multidimensional, and dynamic problem (Cajot et al., 2017) best approached with the tool of standardization and aggregation resembling the 20th century effort to construct single, large-scale, centralized power plants. In other words, the impulse under this pathway is to pursue integration and standardization in order to redefine the problem statement into one that can be managed through technical, expert-based systems. Such an approach would rely on the integration of various administrative scales, departments, and actors, turning away from the current "parallel" or silo-based approach, which relies on compartmentalized and distinct urban planning (Sperling et al., 2011).

The in-city sustainable energy potential, under this pathway, is effectively positioned as a complementary extension to the 20th century model in which additional functions are added to allow for the further growth of the system. Such an energy vision could include the following features:

(a) Integration between energy sources, generation options, and advanced information and communications technology to monitor, verify, and control energy flows;
(b) Interactive interfaces between energy system governing bodies and markets to efficiently manage and deploy energy generation functions;
(c) Optimization between economic, energy, environmental performance, and a strong focus on reliability and availability of energy;
(d) A resilient energy system capable of withstanding various forms of disruption;
(e) Adaptive to (rapidly) changing conditions; and
(f) Prediction of loads, energy generation, market trading, grid conditions including maintenance, and other operations (Manfren et al., 2011).

Such an energy vision can be conceptually simplified to an approach that places renewable energy generation and demand-side reduction activity within the city boundary, but maintains dependence on the outside energy grid (Fig. 2). Important benefits would be derived from such an approach. For example, in line with the asymmetric principle, energy losses stemming from ex-urban supply chains are reduced by means of integrated in-city energy efficiency, energy storage, and renewable energy generation measures (including many sectors such as the built environment, mobility, manufacturing, transit, etc.). Similarly, as illustrated in Fig. 2, the city's relationship to the overall energy grid could be modified to a bi-directional interaction.

Planning a 21st Century Solar City Using 21st Century Principles

The focus on extending the modern energy grid into the city by adding additional generation functions and other services, however, also

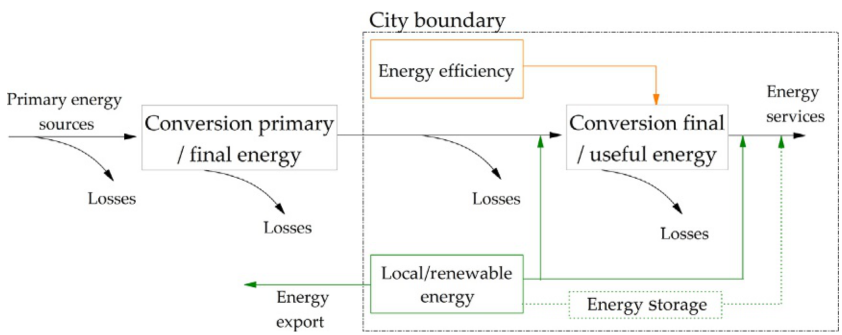

FIG. 2 Conceptual overview of urban energy use and generation. *Courtesy of WIT Press from International Journal of Sustainable Development and Planning, Volume (12), No. (3), 2017, page 416–424.*

faces its limitations. For example, ongoing intensification of energy use is typically accompanied by environmental and social damages, even when this energy supply is more sustainable. Similarly, increasing the level of organizational and technological complexity requires expert oversight at all times, and limits citizen participation. Citizen participation under this model is limited to the role of energy consumption as expert-based bureaucratic logics of control determine the roll-out of the city-wide system. The standardization effort would further likely demonstrate limited flexibility to the different contexts facing urban communities around the world.

Another option that seeks to overcome the justice and sustainability limitations associated with 20th century energy development is available—a model using 21st century principles. The combined pursuit of sustainability and justice likely benefits from the deployment of a variety of experiments and efforts in order to meet the broad diversity in geographies, urban morphologies, cultures, and so forth. As such, the 21st century model combines the promising potential of in-city energy generation analyses with the emerging evidence of creative experimentation exhibited by urban communities all around the world (see, e.g., Jordan et al., 2015). A rapidly growing movement of city ambition and on-the-ground action illustrates the practical feasibility of this second strategy. For example, motivated in part by the newly adopted provisions in the Paris Climate Change Agreement—which represents global commitment to reducing society's effects on the climate but enables additional authority at the city and region level—many cities have positioned themselves as hubs of creativity and experimentation (see, e.g., Bulkeley and Castán Broto, 2013; Byrne et al., 2017a,b; Castán Broto and Bulkeley, 2013). The heterogeneous landscape shaped by city-level action and ambition across the world enables leadership opportunities, where the second option can be envisioned, drafted, and implemented.

Indeed, the early evidence of on-the-ground performance suggests that creative urban-level policy design and energy system planning can play a major role in addressing not only energy sustainability, but also mitigate energy justice complications that have continuously plagued the 20th century system. Initial evidence of urban-level greenhouse gas mitigation activity shows cities and municipalities reducing their emissions (Kennedy et al., 2012; Kona et al., 2016). For example, analysis of early evidence from urban participants within the network-based European Covenant of Mayors found a 23% emission reduction, most of which occurred throughout the 2012–14 timeframe (Kona et al., 2016). In addition, analysis of urban interventions regarding climate change illustrates how city politics and practices "are constantly engaging with and refracting the idea of justice" (Bulkeley et al., 2014). Importantly, evidence of the functioning of inclusive urban energy and climate planning processes suggests a higher realization of equity and justice outcomes (Anguelovski et al., 2014; Chu et al., 2016). These efforts to frame urban justice dimensions benefit from experimental approaches to urban research and decision-making, such as is performed by "living laboratories" (Voytenko et al., 2016), urban (sustainability) transition labs as well as "real-world" laboratories (see, e.g., Voytenko et al. 2016; Wiek, Kay, & Forrest, 2017). These experimental strategies reveal a potential for community engagement and interaction that can accelerate societal change toward sustainability *and* apply transformational solutions that maintain climate justice objectives.

The in-city sustainable energy potential, under this pathway, is positioned as a new dynamic system to which the 20th century, ex-urban energy system would need to adapt. Energy services, such as resiliency and others, are integrated into the community fabric, where appropriate, with consideration of context. Such an energy vision could include the following features:

(a) Application of a diversity of energy sources, generation options, and use of monitoring and verification techniques to deliver energy services to energy customers and prosumers (as opposed to the more passive role of energy consumers);
(b) Interactive interfaces between energy customers and energy markets to translate complexity to easy-to-understand control systems available for use by end-users;
(c) In-city communication between independent energy systems (such as micro- or nano-grids) to enable customer preference alignment;
(d) Deployment of resilient energy systems capable of withstanding various forms of disruption and capable of continued operation, even under cases of external supply cancellation; and
(e) Adaptive to (rapidly) changing conditions.

Such an energy vision can be conceptually simplified to a model in which the in-city condition consists of interconnected, but independent, parts that each rely on context-appropriate technologies and measures, and that can continue operation, even when in-city connections fail, or when connection to the larger grid fails (Fig. 3). Conceptually, the independent parts are designed, at least in part, through citizen participation; and are reflective of the energy needs of the constituents each part serves. This yields important energy justice benefits such as alignment with actual energy service needs (as opposed to planning for potential demand increases) and an opportunity to reduce the energy intensity of the overall system (Byrne and Taminiau, 2016).

CONSIDERING THE PRACTICALITY OF THE SOLAR CITY CONCEPT

The preceding findings of in-city sustainable energy technical potential for a broad range of technology options raise the question of practicality of implementation. The conceptual

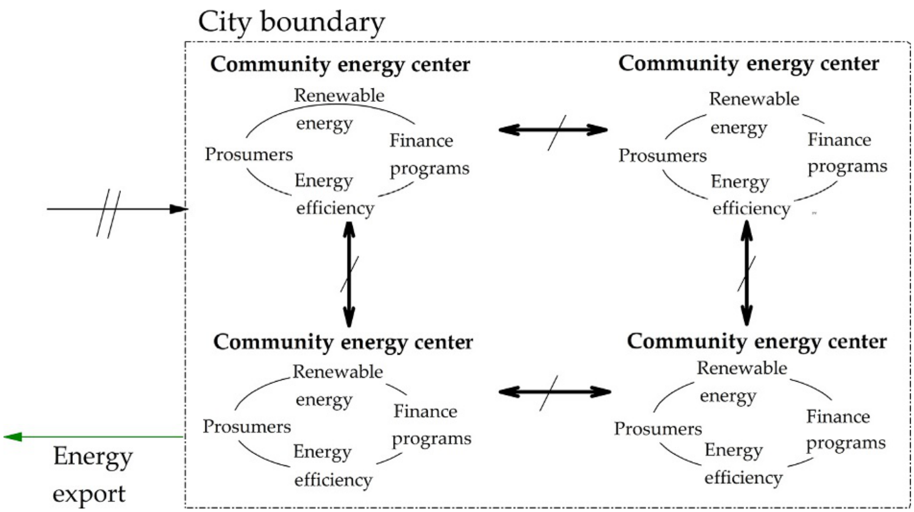

FIG. 3 Simplified model of city design. *Crosslines* illustrate option to disconnect components from each other or from the outside energy grid without disruption to function.

distinction between the two pathways, meanwhile, suggests that the second pathway is perhaps more capable of addressing any energy justice complications that the first pathway might have difficulty avoiding. As such, this chapter now briefly turns to the question of solar city implementation under such second pathway conditions.

In a general sense, implementation of solar cities likely requires positioning of in-city sustainable energy technology as essential components of city infrastructure—integral to the function of what it is to be a city in the 21st century. This position is in sharp contrast to the current positioning of sustainable energy as a form of "add-on" technology option that is procured by those with sufficient resources. Limitations of the "add-on" approach include socio-economic barriers that prevent sustainable energy technology uptake such as income, education, environmental consciousness, or building stock ownership (Gooding et al., 2013; Kwan, 2012).

A strategic reconsideration to *sustainable energy as infrastructure* could help accelerate deployment. In this context, a pooled transaction model has been proposed as a practical pathway toward solar city realization (Byrne et al., 2016). Operating at the infrastructure scale, this pooled transaction model brings together the community's potential for sustainable energy installation and uses its value to attract low-cost investment. Essentially, the approach recognizes the public benefits associated with city-wide sustainable energy implementation and applies private capital to secure these benefits (Byrne and Taminiau, 2016). Such portfolio-based development of sustainable energy, where the portfolio can consist of different technologies in different quantities, depending on community decision-making and context (i.e., the offering can be tailored to program participants), is accompanied by benefits such as better risk distribution and mitigation, increased predictive accuracy regarding performance, and a resulting lower cost of investment (Hyde and Komor, 2014; Lowder and Mendelsohn, 2013; Mendelsohn and Feldman, 2013).

The strategy's feasibility has been tested for six cities across the world. Investigation of a pooled transaction approach—keeping in mind financial, market, and policy conditions—revealed the practicality of the approach for New York City, London, Seoul, Tokyo, Amsterdam, and Munich (Byrne et al., 2016), even under a wide range of starting circumstances (Byrne et al., 2017a,b). The investigation showed that all six cities are able to feasibly deploy city-wide solar electricity within 10–15 year financing timeframes (Byrne et al., 2017a,b). The securitization approach can be extended to other sustainable energy technology options and measures, as demonstrated by its use for energy efficiency (Byrne and Taminiau, 2016).

This pooled transaction model differs substantially from the "add-on" model of sustainable energy development. To illustrate the mind-switch that this re-positioning represents, consider the use of "solar maps"—advanced visualization options that show urban energy potential for, in this case, solar energy throughout the city. The use of such "solar maps" is increasingly common (Freitas et al., 2015; Santos et al., 2014). For example, cities such as San Francisco, New York City, Boston, and Seoul have put these kinds of maps in operation (Byrne et al., 2015). These maps can be used in two different ways, one of which illustrates the current "add-on" approach, and the other could be a component of the "sustainable energy as infrastructure" approach.

First, when applied as a "front-end" tool, the visualization informs individuals about the solar potential of their rooftops, and enables procurement and installation decisions (Kanters et al., 2014). This represents the "add-on" mindset, where individuals make buying decisions based on available information, and their own financial resources.

A separate approach is to use such visualization and decision-making analysis options as "back-end" tools to assist in community-, city- or district-scale urban energy system development (Kanters et al., 2014). In this manner, context-specific technology portfolios that meet community needs can be devised, allowing for a broad deployment of technology and measures across the community (as opposed to only where individuals can afford individual purchase) (Byrne et al., 2017a,b). Positioning sustainable energy as *infrastructure*, in this way, mimics the installation process for other components of infrastructure such as water, communication, transportation, and so forth, but enables consideration of community-specific needs and wants due to the broad diversity of the makeup of possible sustainable energy technology portfolios and their specific financing and lifetime characteristics.

The sustainable energy as infrastructure approach can be broken down into a variety of process steps that are mapped here in Table 1. The process mapped out in Table 1 is inclusive, considers a broad variety of technology options and measures (including energy efficiency), and ultimately accelerates deployment of sustainable energy.

IMAGINING A SOLAR CITY: 21ST CENTURY URBAN ENERGY DEVELOPMENT IN NEW YORK CITY

In 1882, the world's first centralized electric generation and distribution system was developed and installed in New York City. Edison's Pearl Street Station serviced a one-square mile area in the heart of Manhattan's business district. As the birthplace of the centralized electric grid, New York offers a useful case example of what a solar city could represent, and how it could be realized.

Now, 135 years after the installation of Pearl Street Station, the city's electricity system serves more than 3 million customers that together represent more than 8.3 million people and 250,000 businesses (City of New York, 2013). A recent article by the New York Times documented that New York City is responsible for about 60% of New York State's overall electricity consumption, while only generating about 40% of the state's electricity (Rueb, 2017). With the planned closing of the nuclear power plant Indian Point in 2021, responsible for about 25% of New York City power consumption, the need to move new sources of power generation closer to the city is even more urgent (Rueb, 2017).

The city's electric grid experiences summer peak electric loads of more than 11 GW, double that of the next largest US city (Los Angeles) (City of New York, 2013). To cope with this high level of peak demand, 24 power plants located either within the city, or directly connected to the city (together, the "in-city fleet"), can generate up to 9.6 GW of power (City of New York, 2013). The in-city fleet lies dormant most of the year, as the city relies on cheaper electricity from upstate New York or New Jersey. Fueled predominantly by natural gas, two-thirds of the in-city fleet is more than 40 years old, and is of lower efficiency than modern plants (City of New York, 2013). Within New York City, the generation and use of electricity is among the largest source of greenhouse gas emissions attributable to human activities, responsible for 14.9 million tons of CO_2 equivalent (tCO_2eq) out of a total 46.2 tCO_2eq or over 32% (Pasion et al., 2016). In addition, much of the in-city critical energy infrastructure is located in highly vulnerable floodplains (which became especially evident during hurricane Sandy), and storm surge risks will become worse over time (City of New York, 2013).

Bringing a new in-city fleet of sustainable energy online could help alleviate some of the problems the city is currently facing. For example, New York City's 3 p.m. electricity demand peak (Rueb, 2017) could be alleviated by solar energy, as this is right around the time when a solar PV system is most productive. New York, furthermore, provides valuable and advanced data regarding city operations that could help advance the development of in-city sustainable energy. Such data yields interesting insight into, for example, the city's detailed building-to-building shading patterns (Bui and White, 2016), or even a full 3D representation of

TABLE 1 Preliminary Map of the Strategy to Position Sustainable Energy as a Component of Infrastructure

Sustainable Energy as a Component of Infrastructure Process		Possible Actors Involved
Map solar energy potential	Use visualization tools such as Geographic Information Systems (GIS) software to determine community-level potential	Community members GIS/solar map expert Urban planner Energy planner
Policy direction	Enable portfolio development and portfolio-based financing (e.g., provide a reserve fund for overcollateralization or allow use of sovereign credit rating)	Financial institutions Policy-makers Advisers NGOs
Prepare portfolios of sustainable energy options	Build integrated portfolio of differing opportunities based on, for example, building characteristics and community energy service needs	Community members Engineers Building permission dept. Architects Urban planner Energy planner
Financing	Enable a pooled transaction of many buildings and multiple energy technologies and measures with wide variety of characteristics	Financial institutions Policy-makers Advisers

more than 1.1 million of the city's buildings (Cesium, 2017).

At an installed capacity of 160 MW, distributed renewable generation in New York is currently small, but growing rapidly. Technical potential estimates routinely underscore the promise of distributed generation in New York. For example, a recent analysis by the National Renewable Energy Laboratory (NREL), investigating 47 cities across the United States, put New York City's technical potential for solar energy at 8.6 GWp, or about 10.7 TWh of annual electricity generation potential (Gagnon et al., 2016). Similarly, a previous analysis by the authors arrived at around 9 GWp and 11 TWh (Byrne et al., 2016). The recent Google Sunroof Project estimate put New York City's electricity generation potential at about 9.1 TWh (Conkling, 2017).[1] Making use of the techniques developed in the literature (Byrne et al., 2016), supported by advanced and publically available datasets, the spatial solar electricity generation potential across the five boroughs of New York City can be mapped out (Fig. 4).

In total, the city of New York could provide about 23% of its annual electricity consumption from solar electricity.[2] For example, as covered in Fig. 4, Queens can generate about 42% of its

[1] Estimates are sensitive to assumptions and underlying data. Differences in size and quality of PV technology, tilt of system deployment, data discrepancies, boundary setting, etc. likely explain much of the differences in final estimates.

[2] Our finding is slightly higher than the Gagnon et al. (2016) estimate of 18% of annual electricity consumption. A comparison of annual electricity generation shows two very close numbers: 10,742 GWh/year (Gagnon et al., 2016) versus our 11,372 GWh/year. The difference in the contribution share of annual electricity consumption lies with the use of two different data points: Gagnon et al. (2016) compare their electricity generation finding against annual consumption of 59,678 GWh while we use the 2013 electricity consumption estimate of 49,515 GWh. When our estimate of generation potential is compared against the electricity consumption level used by Gagnon et al. (2016), it represents a share of about 19%, very close to the 2016 NREL estimate. The 2013 data point is used as it allows for a detailed, hour-by-hour breakdown of borough-level consumption patterns.

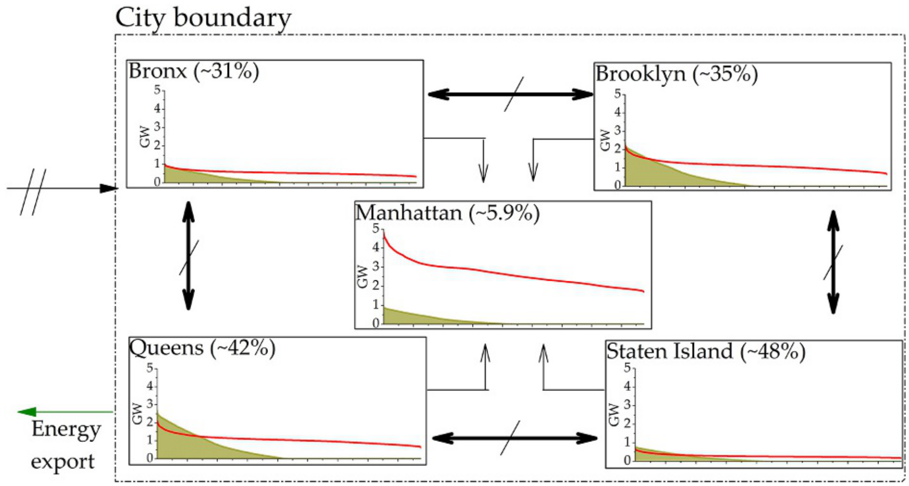

FIG. 4 Overview of the spatial solar city potential of New York City. The *red line* provides hourly electricity consumption value for 1 year sorted from largest to smallest (by borough). The *dark yellow line* with *shaded area* is hourly electricity generation from solar energy technology under a full deployment scenario sorted from largest to smallest. *X*-axis represents one full year in hours. Note: the electricity consumption and solar electricity generation data points do not occur in the same hour, as they are both sorted based on their own load profile. An hour-by-hour breakdown of consumption and generation that does allow for direct comparison is illustrated in Fig. A1 in Appendix A.

annual electricity consumption with solar power, and the Bronx can meet about 31%. The illustration also shows how some of the boroughs could generate much larger shares of their annual electricity use from solar power than others—in particular, Manhattan, with its dense and vertical building morphology and high levels of energy use, would only be able to achieve about 6% of its annual electricity use. In contrast, the smaller and less dense Staten Island could produce close to 48% of its electricity from solar power on an annual basis.

The solar electricity contribution to *daylight* (as opposed to annual) electricity consumption is significantly higher (as solar power is only operational during the day). For example, the maximum hourly solar electricity contribution as a share of electricity consumption in the Bronx is 210% (see also Appendix A). In other words, under full deployment of its technical potential, the Bronx can, for certain times of the day during certain days of the year, generate more than double the electricity consumption taking place at that hour. The maximum value for Manhattan is 39.6%.[3] As illustrated in Fig. 4, these dynamics likely result in electricity flow from the other boroughs into Manhattan under a solar city implementation. In other words, New York City could become its own power plant, providing renewable energy from borough to borough when needed—this becomes especially true when incorporating additional energy technologies such as energy storage or energy efficiency.

A strategy that pursues solar city implementation would accelerate the already strong

[3] In some ways, this makes Manhattan an attractive target as increased in-city solar production is less likely to encounter grid limitations (Anderson et al., 2010). However, based on ConEdison numbers of grid capability, solar electricity potential in the other boroughs is unlikely to exceed grid capabilities especially when solar city implementation is considered for a wide variety of technologies with different profiles—for instance, a city-wide energy efficiency program in conjunction with solar PV installation could help alleviate grid conditions.

performance of the city (Byrne et al., 2017a,b; Kennedy et al., 2012). From an infrastructure-scale development perspective, financial and policy assessment of the potential could help inform policy- and decision-makers and the city's communities about the viability of large-scale financing to support the roll-out of a solar city program. As mentioned, such an analysis has been conducted for six cities across the world (Amsterdam, London, Munich, New York City, Seoul, and Tokyo), and found a reasonable financial feasibility of large-scale solar deployment in these urban contexts (Byrne et al., 2016), even when including quantitative risk assessment of different starting conditions (Byrne et al., 2017a,b). A representation of the findings for New York City is provided here, including changes in input parameters (Table 2). In particular, considering the length of financing is often a key dimension to city government and financiers alike (Mendelsohn et al., 2015), the table shows how policy decisions can shorten the maturity of the securitization. The selection presented here shows policy regimes that can shorten city-wide financing to maturity lengths of 11 years when one policy action is considered and 10 years when the combined use of policy actions is deployed.

Table 2 shows how, using Monte Carlo analysis methods, a quantitative risk assessment of current conditions suggests a 12-year financing of a New York solar city is feasible. Feasibility, here, is defined as 80% of the 30,000 Monte Carlo simulation per maturity providing a positive cumulative benefit-cost ratio across the lifetime of the debt service (for more information see Byrne et al., 2017a,b). As provided in Table 2, policy changes could influence the "soft cost" profile of photovoltaic system installation and operation (e.g., permitting, inspection, customer acquisition, planning, etc.), which is a key strategic target, especially in the United States (Ardani et al., 2013; Byrne et al., 2017a,b; Seel et al., 2014). Policy options include standardization and streamlining of application processes and other paperwork, additional equipment standardization and classification, general business practice efficiency improvements, and so forth. Various levels of aggressiveness in these policy options can be deployed. Another policy option captured in Table 2 is the reduction of the cost-of-capital, which can be achieved through a variety of mechanisms such as guarantees, overcollateralization, reserve funds, and so forth (Mendelsohn and Feldman, 2013). Table 2 captures the improvement contribution by lowering soft costs by 5%, financing costs by 10%, and both soft costs and financing costs by 15%. These improvements can shorten the required financing lifetime to 11 years or 10 years, depending on the level of policy support. Input parameter changes such as these can inform policy-makers and urban and energy planners about the range of possibilities in terms of financing a solar city option.

TABLE 2 Overview of Model Results Under Different Policy Regimes for a New York City Solar City Strategy

Quantitative Risk Assessment (QRA) Share of 30,000 Simulations That Show Cumulative Positive Cash Flow Throughout Project Lifetime Under Different Input Conditions (%)	Maturity (Years)					
	8	9	10	11	12	13
Current risk assessment	5.4%	18.3%	46.9%	74.7%	88.2%	94.2%
Soft cost reduction (-5%)	7.3%	24.2%	57.0%	80.5%	90.8%	95.5%
Cost of capital reduction (-10%)	6.3%	21.6%	54.4%	80.0%	90.4%	95.5%
Soft cost and cost of capital reduction (-15%)	16.5%	51.2%	81.2%	91.1%	96.6%	98.6%

Possible policy regimes selected based on typical municipal authority. *Shaded area* represents feasibility.

CONCLUDING REMARKS

Urban centers have positioned themselves as active participants in the climate change and energy narrative. This emerging paradigm of "polycentric" climate change governance enables the serious consideration of city-wide transformation and its potential contribution to global environmental and social improvement. The potential for cities and regions to advance on climate change has become especially important in the wake of the announcement by the US Administration to withdraw from the Paris Agreement regarding the country's climate change commitments. Cities and regions in the United States have since come forward to announce their continued resolve to address climate change and, in some cases, their commitment to redouble their efforts (Bulkeley and Betsill, 2013; Byrne et al., 2017a,b; Tabuchi and Fountain, 2017). The solar city option introduced here is in line with such ambitions.

The solar city option is offered here as a transformative, but practical, strategy that the cities of the world could pursue to deliver on international goals of sustainability and justice. In particular, an infrastructure-scale focus is provided here as a potential path forward. The infrastructure-scale strategy enables a portfolio-based capitalization design capable of attracting large investment from the private market in order to spur the deployment of solar energy (and other sustainable energy technologies such as energy efficiency, mobility, etc.) throughout the urban fabric while retaining the benefits of decentralization and context-specific deployment. The portfolio-based approach sketched here enables a series of capitalization offerings to the private market that could begin to unlock the potential. This is especially a viable option for large cities that frequently tap into the capital markets for debt financing, like New York.

Case study analysis of New York City provided here and supporting analysis documented in the extant literature (Byrne et al., 2015, 2016, 2017a,b) suggests the practical feasibility of the strategy when market, finance, and policy conditions are evaluated. Furthermore, the quantitative risk assessment model deployed in the case study analysis offers decision-makers, energy planners, and urban planners the insight necessary to evaluate the level of policy support required to meet predefined thresholds of program viability.

The solar city option can address the substantial social and environmental dilemmas associated with conventional, centralized energy production, as the model enables higher levels of resiliency and energy security by capturing the benefits of distributed generation and modular technology components such as solar power, but at a transformative scale. Established commitments to the climate change narrative, combined with scientific documentation of the severity and urgency of the global environmental change process, make the solar city strategy an option worth deploying in the near term.

APPENDIX A

The illustration provided in Fig. 4 indicates the spatial electricity consumption and solar electricity generation across one full year for each of the five boroughs of New York City. However, as captured in the note in the caption of Fig. 4, the data is visualized by sorting both hourly electricity consumption and electricity generation from largest to smallest. As such, data points represented by the line for electricity consumption can no longer be directly compared with data from the electricity generation curve—they occur at different times of the year. To provide insight into the relationship between consumption and generation, the following illustration shows the sorted electricity consumption data per borough, but does not sort the hourly solar electricity generation data (Fig. A1). The illustration shows that solar electricity generation levels commonly surpass the consumption level, sometimes by a large margin.

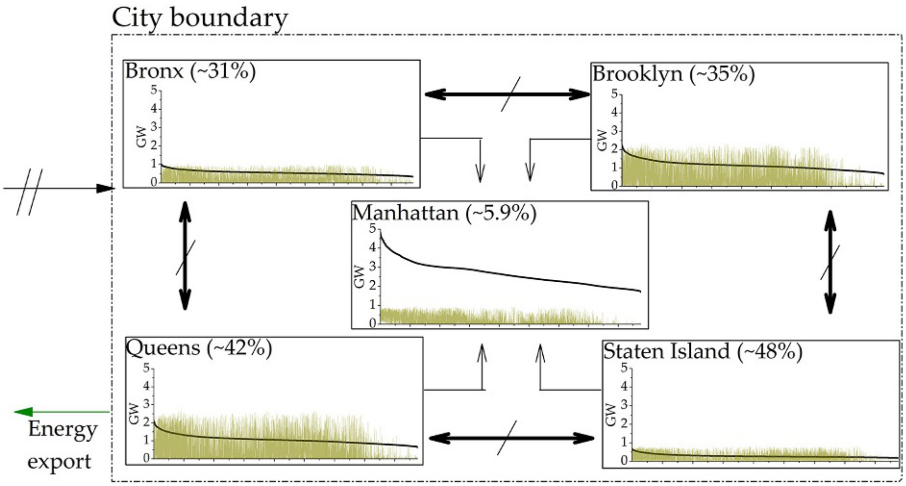

FIG. A1 Overview of the spatial solar city potential of New York City. The *black line* provides hourly electricity consumption value for 1 year sorted from largest to smallest (by borough). The *dark yellow line* represents the corresponding hourly electricity generation from solar energy technology under a full deployment scenario. *X*-axis represents one full year in hours. Note: for electricity consumption, the load profile is sorted from largest to smallest to create a load curve. The associated value for solar electricity generation in that hour is illustrated to allow for direct comparison between the two curves.

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