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Are solar cities feasible? A review of current research

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ABSTRACT
Urban 'polycentric' experimentation is enabling a new understanding of the sustainability potential of cities across the world. Coupled with the rising prominence of 'grid parity' conditions for solar energy, it is becoming clear that cities have abundant opportunities to reconfigure urban energy economies on platforms fuelled mainly and, in a few more years, entirely on energy conservation and renewable (especially solar) energy. Early evidence of the practical application of 'solar cities' models suggests the financial feasibility of city-wide development of electricity infrastructures based on conservation and renewables. The results of technical and economic potential investigations capture the promise of the model. But a question remains: how can we realize the investment needed to implement solar cities. We examine three pathways: 'project-based solar development'; 'strategic solar development'; and 'infrastructure-scale solar city development', focusing in each case on solar electricity development since much of the conservation potential in cities is capable of self-financing (Byrne, J., & Taminiau, J. (2016). A review of sustainable energy utility and energy service utility concepts and applications: Realizing ecological and social sustainability with a community utility. *Wiley Interdisciplinary Reviews: Energy and Environment*, *5*(2), 136–154. doi10.1002/wene.171). After review of some of the advantages and disadvantages of each approach, we recommend infrastructure-scale development as the most promising means to attracting city-wide, cost-effective, sustainable energy investment.

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Introduction

Urban life defines much of humanity's environmental, economic, and social relations and conditions. As Lewis Mumford long ago reminded us (Mumford, 1961, p. 571):

> The chief function of the city is to convert power into form, energy into culture, dead matter into the living symbols of art, biological reproduction into social creativity.

Modern conversions have often fallen well short of the standards of sustainability that Mumford and others demanded. Among the more challenging patterns created by contemporary urban life are the following: cities and their metropolitan rings are responsible for 71%–76% of carbon dioxide emissions (CO_2) from commercial energy use while only representing about 54% of the world's population (Seto et al., 2014; United Nations, 2015).

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The materiality of the corresponding nature-society relationship extends beyond the emblematic issue of global climate change as it includes local air pollution, ozone layer degradation, acid rain, and many other obstacles. For example, for urban areas where frequent air pollution monitoring takes place, over 80% of people are exposed to air containing fine particulate matter and sulfur dioxide (SO_2) concentrations beyond World Health Organization (WHO) limits. For cities in low- and middle-income countries with more than 100,000 inhabitants, 98% of the population is exposed to damaging concentrations of these pollutants (Osseiran & Chriscaden, 2016). These numbers are sobering. After more than 40 years of policy efforts and technology innovations directed at this problem, we still suffer from it. Modernization, it appears, is unable to reverse direction on pollution, leading some to ask if modernity itself, and its principal means of organizing human activity – urbanization – could be the problem (Byrne, Hughes, Toly, & Wang, 2006). The environmental and social conditions produced representations of modernity and progress: our pursuit for urban-centered economic growth.

This imagery of cities as icons of unsustainability is often challenged by the vibrant and innovative character ascribed to the world's cities. Deep social relations, intertwined through networks of urban life, nurtured through the vanguard of knowledge development by urban universities and schools, and expressed through urban culture, cuisine, and care represent a high level of diversity and creativity that should be well-suited to address these environmental, social, and economic trials.

Conventional proposals to address environmental challenges risk neglecting the value of cities' diversity and homegrown potential. Proposed energy solutions to address climate change, for instance, commonly argue for the continued reliance on external energy sources through large-scale power plants, whether they are revived fossil fuel technology components such as 'clean coal' or 'dash for gas' approaches, or 'giant power' in the form of nuclear energy, or mega applications of renewable energy (so-called 'green titans') (Byrne & Toly, 2006). The challenge presented to the urbanism of the twenty-first century is to approach environmental conflicts, not by discounting their domestic value, but by embracing it. One of the authors of this paper framed this challenge in the form of a question over ten years ago: 'can cities sustain life in the greenhouse?' (Byrne et al., 2006). The answer to such a question cannot be merely technical and economic; social conditions and relationships will have to be reconsidered and, where necessary, reconfigured.

An innovative approach to the question is taking shape as cities across the world embark on integrated climate change mitigation and adaptation strategies at the local level and through transnational networks (see, e.g. Aylett, 2014). Combined, the effort displayed by these cities has become a significant driver of global emission reductions. For example, the commitment set by 228 cities around the world, home to only 436 million of the seven billion people on earth, equals a cumulative emission reduction target of 2.8 Gt CO_2-eq. by 2020, 6.1 Gt CO_2-eq. by 2030, and 13 Gt CO_2-eq. by 2050 (ARUP, 2014). The 2050 cumulative commitment is equal to the current combined annual emissions of China and India and will likely strengthen as additional cities formulate 2030 and 2050 targets (ARUP, 2014). Stated ambition is being matched by performance-on-the-ground as, for instance, the European Covenant of Mayors found a 23% reduction in overall emissions across their database of 315 urban greenhouse gas inventories (which cover primarily the 2012–2014 timeframe (Kona et al., 2016). These urban-scale efforts are an example of cities taking action to shape the climate change narrative.

The experimentalist city

Creative experimentation and learning are key processes within this urban-led narrative. Cities transfer effective policies across jurisdictions through network-based transmission, embark on creative projects, and mobilize thought leaders and gain popular support for transformative applications (see, e.g. Aylett, 2014; Bulkeley & Castán Broto, 2013; Castán Broto & Bulkeley, 2013). This experimentalist foundation of the new climate governance movement, commonly labelled 'polycentric governance' (see, e.g. Ostrom, 2010), has facilitated the origination of urban 'laboratories' that reorient cultural relationships, social dynamics, and energy economies. These experimental strategies address urban-level priorities but have global ramifications (ARUP, 2014).

Urban experimentation and investigation is facilitating a shift in the scientific effort past its descriptive analytic preoccupation and towards the integration of society at large using interdisciplinary and participatory research methods (Lele & Norgaard, 2005). Such research is conducted in a range of 'social lab' settings, captured under concepts like the urban transition lab (Nevens, Frantzeskaki, Gorissen, & Loorbach, 2013; Wiek & Kay, 2015); 'urban living labs' (Voytenko, McCormick, Evans, & Schliwa, 2016); or 'real-world' laboratories (Luederitz et al., 2016). Common characteristics of successful experiments in the urban setting are their emphasis on geographical embeddedness, learning, participation (especially energy and water end-user involvement), and leadership (especially, the presence of local champions) (see Bos, Brown, & Farrelly, 2013; Luederitz et al., 2016; Voytenko et al., 2016). Critically, urban experimentation and research of this kind contributes to social learning that can help accelerate socio-technical system change by strengthening the society-science interface (Bos et al., 2013).

Cities that embark on such a trajectory, furthermore, will be held to account both by an internal citizenry but also by the global community (Gordon, 2016). As cities increasingly commit themselves to transnational networks of urban governance, their performance and identity are increasingly defined in global terms. One way to illustrate the pronounced level of commitment is to compare several large global cities to their national counterpart (Figure 1). Assuming a linear annual reduction pathway to the stated target, Figure 1 reports that London, New York City, Tokyo, and Seoul have set aggressive emission reduction objectives that outpace national commitments and efforts. This pattern has been noted by several research teams (see, e.g. Cerutti et al., 2013; Kona et al., 2016; Reckien et al., 2014). To illustrate, an analysis of Italian municipalities found that all 36 cities and towns under investigation pledged action beyond national targets (Lombardi, Rana, Pazienza, & Tricase, 2014). At a larger scale, cities associated with the European Covenant of Mayors have formulated an average 29% emission reduction target by 2020, thus voluntarily exceeding the European Union (EU) wide commitment of a 20% reduction by 2020 (Climate Alliance, 2014). Similarly, an assessment of 200 large and medium-scale urban areas across 11 European countries found that the combined urban-led target of all cities per country of 26.7% reductions exceeds the 20% reduction target set across the EU (Reckien et al., 2014). Not only are the ambitions of cities often greater than national or regional intentions, recent performance is higher too. Thus, Figure 2 depicts the actual savings rate of New York City, London, Seoul, and Tokyo, showing that urban performance tops national contributions to lowering climate risk.

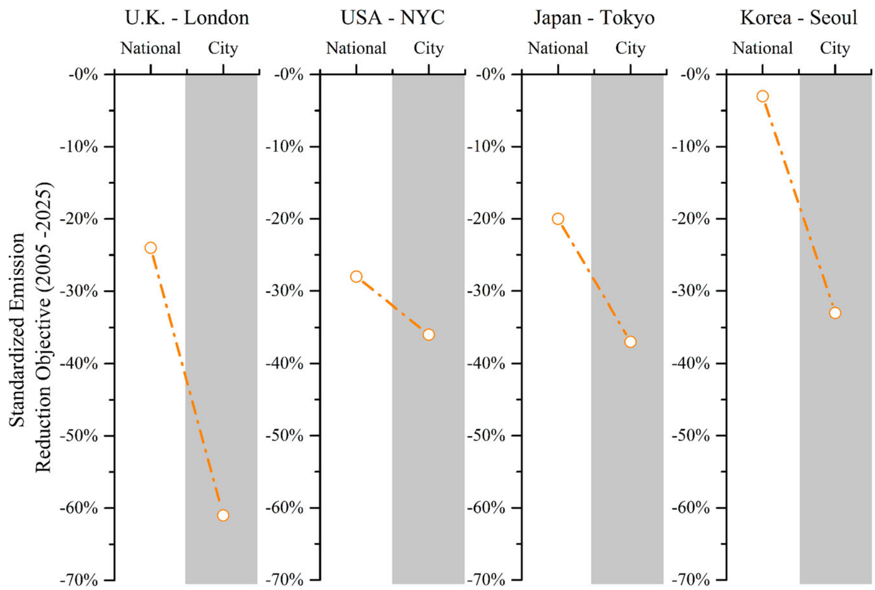

Figure 1. Slope graph of national-level (left of each panel) and city-level (right of each panel) commitments to emission reductions. Source: Authors.

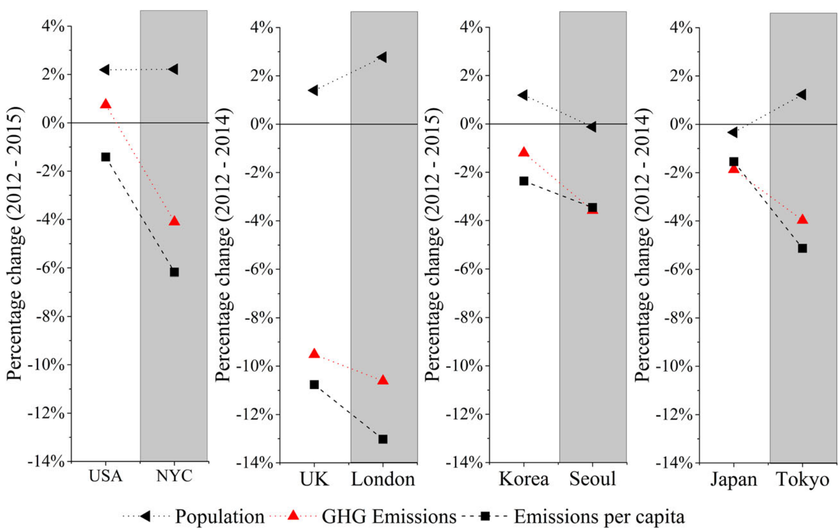

Figure 2. Population, greenhouse gas emissions, and emission per capita changes for the cities of New York city, London, Seoul, and Tokyo and their national counterpart. Source: Authors, data derived from city and national greenhouse gas inventories.

The solar city

The experimental approach to urban sustainability has motivated creative urban science efforts. For instance, as part of an 'energy lab' experimentation drive, cities are beginning to realize their sustainable energy potential as a key means to abate climate change. This understanding is facilitated by increasingly advanced analysis of, for example, the solar energy potential in the built environment (see, e.g. Denholm & Margolis, 2008; Gagnon, Margolis, Melius, Phillips, & Elmore, 2016), city-wide energy saving opportunities (Shahrokni, Levihn, & Brandt, 2014), urban geothermal energy capabilities (Schiel, Baume, Caruso, & Leopold, 2016) or a city's option to develop city-wide green and/or cool roofs (Santamouris, 2014). Deployment of such energy technologies and measures are accompanied by valuable improvements in environmental sustainability (Perez, Zweibel, & Hoff, 2011; Sener & Fthenakis, 2014).

These investigations commonly find significant potential for city-wide sustainability efforts. For example, investigating the energy saving potential of Stockholm using big data analysis, Shahrokni et al. (2014) found that city-wide energy use could be reduced by 33%. Findings of this magnitude have spurred the development of web applications that visualize district or city-scale opportunities (see, e.g. Hong, Chen, Lee, & Piette, 2016). The combined potential of all city-wide sustainable energy options and technologies has been captured by some observers under the aggregate heading of the 'Solar City' (Byrne, Taminiau, Kim, Lee, & Seo, 2017; Byrne, Taminiau, Kim, Seo, & Lee, 2016; Byrne, Taminiau, Kurdgelashvili, & Kim, 2015).

An attempt to illustrate the engagement of science in facilitating solar cities is provided in Figure 3. Capturing the available literature on the topic of solar electricity in the urban environment over 1995–2017, the bar chart shows that an increasing amount of research attention is directed at the question of solar energy in urban contexts. For instance, while there are exceptions, the majority of the available research captured in Figure 3 has been published since 2008. Globally, at least 190 investigations into city-level solar energy applications or assessments have been performed.

Increasingly, advanced methods and software are being deployed to investigate larger and larger datasets of buildings (Freitas, Catita, Redweik, & Brito, 2015; Melius, Margolis, & Ong, 2013). The U.S.-wide analysis of municipal solar energy potential, for instance, used advanced geographic information system (GIS) software and light detection and ranging (LIDAR) technology to investigate energy insolation and shading throughout

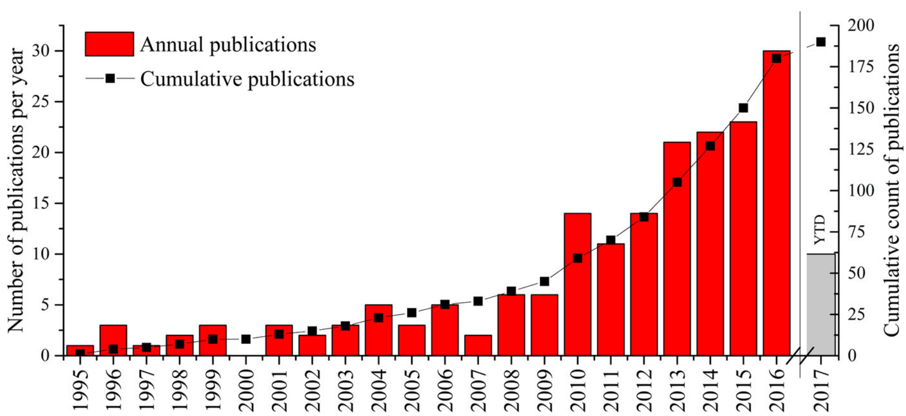

Figure 3. Overview of the development of urban solar energy research (1995–2017).

Note: Selection of literature was conducted using a combination of a 4-level systematic literature review using SCOPUS supplemented by snowball literature gathering using additional search databases. 2017 data is year-to-date as of February 2017.

the year drawing from a database of over 26.9 million buildings, equivalent to about 122 million people or 40% of the total U.S. population (Gagnon et al., 2016). Likewise, a 2014 investigation estimated the technical potential for solar energy across 11,593 municipalities in Germany (Mainzer et al., 2014) while a 2016 analysis reviewed 6794 sites across the U.K. city of Leeds (Adam et al., 2016).

The pursuit of the solar city: technical potential

The investigation of city-wide solar electricity potential has been conducted for a broad range of cities with varying conditions. For example, investigations into solar energy potential include mega-cities like Hong Kong (Peng & Lu, 2013; Wong et al., 2016), Seoul (Byrne et al., 2015), Dhaka (Kabir, Endlicher, & Jägermeyr, 2010), and Mumbai (Singh & Banerjee, 2015). The authors of this paper estimated the technical potential for six cities across different countries, including Amsterdam, London, Munich, New York City, Seoul, and Tokyo (Byrne et al., 2016, 2017).

Technical potential assessment methods typically involve at least three steps: (a) identifying the total rooftop area of the buildings within the scope of the study; (b) calculating the rooftop area suitable for solar energy deployment; and (c) estimating the photovoltaic (PV) capacity and electricity generation potential when solar energy is deployed on all suitable rooftop area (Figure 4). For example, the investigation of city-wide solar energy potential for the city of Seoul, as conducted by Byrne et al. (2015), used publically available building-based datasets to account for, among others, the number of floors and building sizes to estimate the total rooftop area at 187 million square metres. Validation using advanced computer aided drawing software confirmed the full-census estimate. Using so-called suitability or utilization factors to discount unfavourable conditions such as building-to-building shading or rooftop obstructions, the study found 94 million square metres of suitable rooftop area. Factoring in technical and physical characteristics unique to photovoltaic installation, such as panel-to-panel shading effects and maintenance requirements, an estimated 56 million square metres was considered technically available for solar energy deployment. Based on the study's assumptions regarding technological and installation characteristics such as module efficiency, this estimate

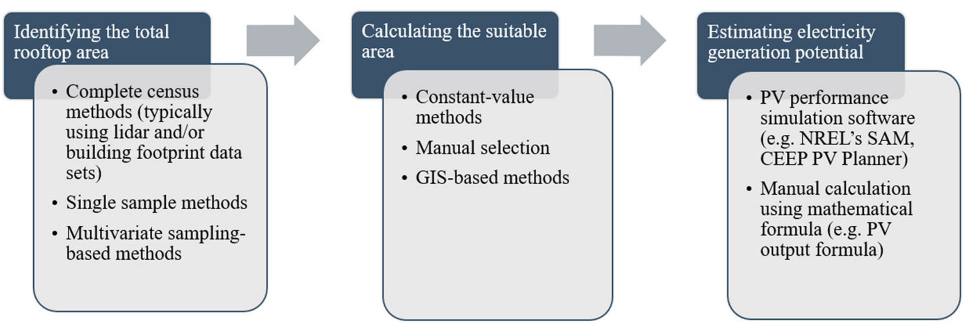

Figure 4. Overview of the three steps used in the assessment of city-wide solar electricity technical potential.

Note: For each step, several methodological approaches are available. For more details about these methodological options, Byrne et al. (2015), Melius et al. (2013), and Freitas et al. (2015) are useful starting points.

corresponds to about an 11 gigawatt (GWp) installation capable of generating roughly 14 terawatt-hours (TWh) of electricity per year (Byrne et al., 2015).

The technical potential estimates captured in the available literature suggest substantial sustainability improvement opportunities across cities of various sizes and locations. Drawing from several studies, the contribution to urban energy supply of a theoretical solar city application is captured in Figures 5 and 6 for 52 cities in the United States, European Union, and in Asia. The graphs show that most cities can meet more than 30% of annual electricity demand through a solar city project.

Combined, the 52 cities represented in the two graphs are home to about 72 million people and represent an estimated 109.4 GWp technical potential. At a 2015 global installation of 227 GWp, the technical potential of the sample represented here is equal to about 48% of the installed global solar energy capacity (REN21, 2016). As indicated by the bubble size in Figures 5 and 6, large and mega-cities account for the majority of this potential. For instance, the cities over 1 million inhabitants in the 52 city sample, together account for about 55% of the 109.4 GWp potential.

Solar cities could dramatically alter urban energy economies. For instance, Seoul could cover about 30% of its annual electricity consumption with solar electricity and about 66% of its electricity consumption during daylight hours (Byrne et al., 2015). During peak electricity generation moments, which typically occur during mid-day in the summer, Seoul could provide well over 95% of its electricity needs with the distributed rooftop solar plant (Byrne et al., 2015). City-wide deployment of rooftop solar could further cover about 60%, 50%, and 38% of Los Angeles, San Francisco, and Portland's annual electricity consumption, respectively (Gagnon et al., 2016). Our analysis of Amsterdam, Munich,

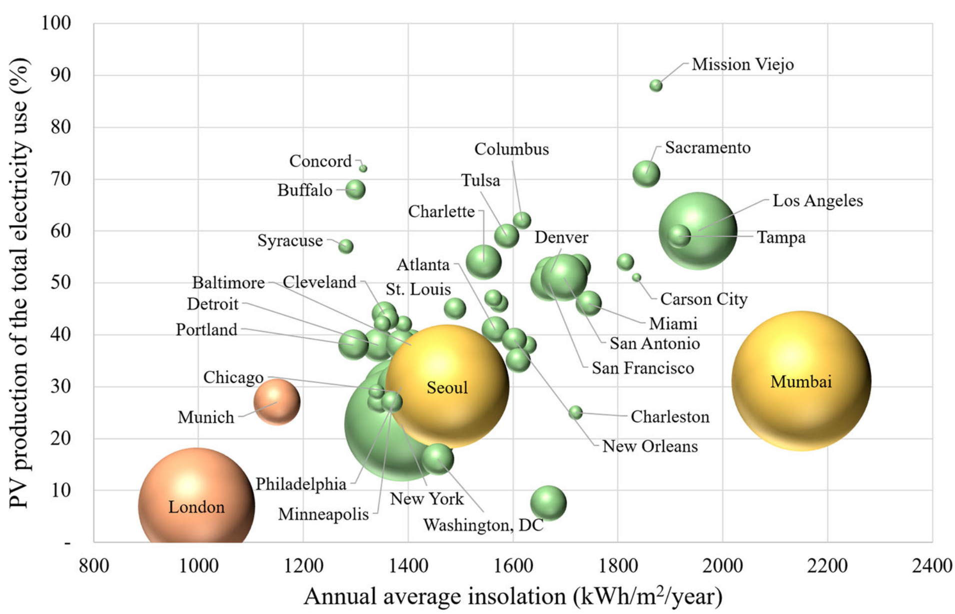

Figure 5. Bubble graph illustrating the potential rate of solar PV electricity generation to the total annual electricity consumption for 52 cities.

Note: Bubble size of each city represents the city's population and the colour identifies the location of the city: red (Europe), yellow (Asia), and green (the United States) (Colour online).

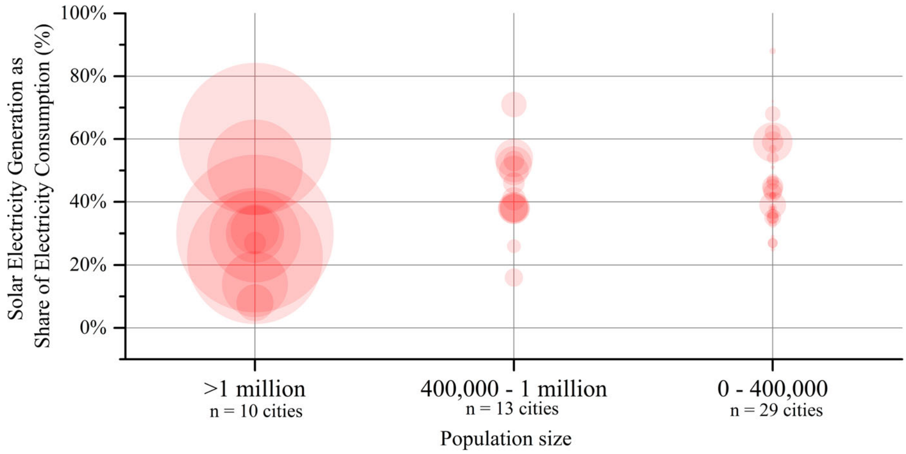

Figure 6. Technical potential estimate for a selection of cities across the world.
Note: Bubble size determined by annual electricity generation of the solar city PV system.

London, New York City, Seoul, and Tokyo, furthermore, found an estimated total potential of 35.5 GWp across these cities, greater than the 25.6 GWp currently installed in the United States (Byrne et al., 2016). Similarly, a global assessment by the International Energy Agency (IEA) compiled information on about 1600 predominantly German cities and extrapolated the resulting potential to population-density relationship to arrive at a global technical potential estimate of 9100 TWh or 5400 GWp (IEA, 2016). Based on their modelling assumptions, such an installation level could cover up to 32% of global urban electricity demand by 2050, equivalent to about 17% of global total electricity demand by 2050 (IEA, 2016). In current terms, this estimate is about 24 times the global installed capacity of PV in all forms (i.e. utility-scale, commercial, and residential).

Integrated energy planning strategies, where solar PV is combined with other sustainable energy technologies, could further underscore solar city potential (Lund, Mikkola, & Ypyä, 2015; Wegertseder, Lund, Mikkola, & García Alvarado, 2016). In addition, solar energy deployment could make use of other underutilized assets such as parking lot canopies or building facades. For instance, a Singapore-wide analysis of urban solar energy potential estimated that the overall PV-suitable area could be increased by 10% when incorporating façade-integrated PV (Luther et al., 2013).

Weighing the practicality of the solar city model: investment assessment approaches and findings

Urban science efforts, as detailed above, have revealed a significant technical potential for the deployment of solar energy within municipal jurisdictions. The successful roll-out of a solar city project along these lines and scales could have profound implications for the design and dynamics of urban energy economies and energy infrastructures. This raises the question of the practicality of solar cities: infrastructure-scale solar PV planning requires significant investment far beyond current levels.

A first consideration is the economic competitiveness of solar PV. Costs of the technology have fallen materially over the past several years. For instance, in the United States, median installed prices have come down 56%, 61%, and 67% since 2007 for the residential, non-residential ≤500 kW, and non-residential ≥500 kW markets respectively (Barbose & Darghouth, 2016). A similar 60% drop in prices has been observed in the U.S. utility-scale solar PV market since the 2007–2009 period (Bolinger & Seel, 2016). These major declines in installed prices have substantially changed the landscape of the global solar PV market. Analysis of unsubsidized levelized cost of energy (LCOE) suggests that (large-scale) PV is already an economically attractive source of U.S. power generation, competing directly with new natural gas power plants (Lazard, 2016). Grid parity (also called socket parity) conditions have now been established in at least 30 countries around the world, including countries in Europe, Japan, Australia, Mexico, and parts of the United States (Shah & Booream-Phelps, 2015). Continuing technological, policy, and other economic advancements are expected to spread the prevalence of grid parity conditions to other countries and locations (Bolinger, Weaver, & Zuboy, 2015; Breyer & Gerlach, 2013). For example, key factors that influence economic viability of PV projects are the compensation level for the generated electricity, initial investment cost, discount rate, and PV system turn-key prices (Audenaert, De Boeck, De Cleyn, Lizin, & Adam, 2010; Bernal-Agustín & Dufo-López, 2006; Byrne et al., 2017; Mitscher & Rüther, 2012).

Project-based solar development

Broadly, a selection of three approaches are available that can determine the investment feasibility and overall practicality of city-wide solar energy. First, there is the conventional approach, labelled here 'project-based solar development'. With this approach, national, regional, and local policy-makers set the enabling conditions for solar PV deployment to occur and project developers (including individual home-owners) decide whether or not to install solar PV. Investment is typically in the form of small to modest size bank loans (i.e. from less than $25,000 to $10 million). The enabling conditions can be influenced through conventional and typical policy tools such as subsidies, tariffs, tax credits, rebates, etc. The approach, at its core, is incremental and relies on a project-to-project cycle of individual developers and project promoters identifying suitable project opportunities, incorporating all relevant project dynamics (such as customer acquisition, applying for rebates, setting up equity-debt balances, etc.), and finding usually local investors. This approach has been successful in a range of countries and settings. Germany (40 GWp) has always stood out in this regard but has recently been overtaken by China (44 GWp) in terms of absolute PV capacity deployment (REN21, 2016). On a per capita basis, Germany (1.1 kW/capita) still ranks highest followed by Spain (0.7) and Italy (0.5) (REN21, 2016).

Complications with the strategy include high transaction costs, high procurement and installation costs, slower development rates, and high borrowing costs. These have prompted redesign of policy and investment strategies in, for example, Germany (Auer & Anatolitis, 2014; Rodrigues et al., 2016), the U.K. (Cherrington, Goodship, Longfield, & Kirwan, 2013; Muhammad-Sukki et al., 2013) and Japan (Ministry of Economy, Trade and Industry, 2017). To illustrate, Germany's second iteration of its energy policy rethink (labelled Energiewende 2.0) gradually lowers policy support in an effort to rein in costs (Auer & Anatolitis, 2014; Rodrigues et al., 2016). German policy support rates decreased from $0.61 to 0.16 $/kWh between 2007 and 2013 (Rodrigues et al., 2016).

Strategic solar city development

To accelerate solar city development, a second approach has emerged where advanced understanding of city-wide potential is used to facilitate larger project development. This second 'strategic solar development' approach, utilizes insights provided by, for example, GIS investigations to identify the most profitable or best-suited PV projects. For example, a common iteration of GIS derived tools is the 'solar map' (Freitas et al., 2015; Kanters, Wall, & Kjellsson, 2014; Santos et al., 2014). Used as a front-end tool, the solar map informs citizens and investors of a municipality about the solar potential of their rooftops which could help motivate PV installation decisions (Kanters et al., 2014). The city of Basel, Switzerland is offered as an example of this approach where a solar map informs building owners of PV installation opportunities supported by city-level subsidies (Kanters et al., 2014). A particular advantage of this approach is that it helps reduce several 'soft' costs associated with PV deployment. Importantly, while the 'hard' costs (e.g. the modules themselves) of PV installation have come down substantially, significant cost reduction potential remains in the 'soft' costs of PV deployment such as permitting, inspection and interconnection costs (PII) or installation labour (see, e.g. Ardani et al., 2013; Burkhardt, Wiser, Darghouth, Dong, & Huneycutt, 2015; Dong & Wiser, 2013; Seel, Barbose, & Wiser, 2014). Customer acquisition costs in the United States, for instance, represent a substantial 'soft' cost at $0.67/W in 2010 (Ardani et al., 2013). The 'strategic solar development' approach can deploy sophisticated visualization and decision-analysis tools, like solar maps, to help identify the most profitable or best-suited PV locations and they can be used to identify market size and possible impacts of standardization all of which can lower acquisition and installation costs. For instance, using advanced GIS methods, rapid financial feasibility identification for 6794 buildings across the U.K. city of Leeds was conducted which helped to prioritize PV installation sites (Adam et al., 2016).

Infrastructure-scale solar development

Finally, a third approach reconsiders PV deployment paradigmatically by positioning the solar city as an infrastructure-scale strategy as opposed to project-to-project development. This pathway likewise makes use of sophisticated GIS and other methods but frames the development opportunity as a question for urban energy planning. For example, solar maps, under this approach, are used as a back-end tool for urban decision-makers in which investment attractiveness and community aspiration are the drivers. It is this third approach that we consider to have substantial potential to drive solar city adoption. Efforts to research the financial, policy, and market dynamics of this approach have been conducted by the authors (Byrne et al., 2016, 2017). Infrastructure-scale solar development combines the energy generation potential of the available and suitable rooftop area to develop pooled offerings for debt investment by capital markets as well as bank syndicated investments (Byrne et al., 2016). Such a portfolio-based approach could unlock substantial benefits (Hyde & Komor, 2014; Lowder & Mendelsohn, 2013; Mendelsohn & Feldman, 2013) as cities learned throughout the twentieth century when water, communications, transportation, education, and other networks were built into the urban metabolism. An important benefit of infrastructure-scale deployment of PV in the urban fabric is the capture of available economies of scale (Barbose & Darghouth, 2016). Such economies of scale extend beyond simple technology component procurement and include elements such as lower financing cost, lower installation costs through for instance by city block building deployment, and energy design based on community aspirations and preferences (Hyde & Komor, 2014; Lowder & Mendelsohn, 2013; Mendelsohn & Feldman, 2013). Such an urban-led initiative could perhaps also circumvent socio-economic and other limitations that prevent PV uptake within a project-to-project pathway. For instance, socio-economic factors such as income, education, and environmental consciousness circumscribe PV deployment while building stock ownership models further limits PV implementation under the other two approaches (Gooding, Edwards, Giesekam, & Crook, 2013; Kwan, 2012).

The new market conditions in which PV finds itself offer opportunities to the solar city concept under this strategy. With grid parity conditions available now in many cities, deployment at the city-scale is now feasible. In particular, urban-led initiatives that utilize the socket price of electricity to fulfil programme and other costs could deliver solar energy services to end-users without increasing their electricity bill.

Investigations of the financial feasibility of urban solar energy at city-wide levels of deployment are somewhat scarce compared to the depth of knowledge regarding the technology's technical potential in urban settings. Nevertheless, the available evidence suggests positive profitability of infrastructure solar development in the urban fabric (Adam et al., 2016; Audenaert et al., 2010; Byrne et al., 2016, 2017; Halder, 2016; Mitscher & Rüther, 2012; Mondal & Sadrul Islam, 2011; Muhammad-Sukki et al., 2013; Rodrigues et al., 2016; Sun et al., 2013). For instance, a test of the economic viability of landscape-scale PV electricity generation for nine prefecture-level cities in Fujian province in China found that particularly the southeastern coastal region, including cities like Zhangzhou (4.8 million people), Xiamen (3.5 million), and Quanzhou (8.1 million), could viably develop rooftop-solar projects under the right policy conditions (Sun et al., 2013). A study of 6794 sites across Leeds (U.K.) found that 6408 rooftops could support PV deployment of which over 75% could deliver positive net present value (Adam et al., 2016). Finally, the authors of this paper analyzed the financeability of city-wide solar energy

Table 1. Overview of economic assessments considering project solar development of rooftop PV in urban settings.

Source	City/Region	Description	Relevant metrics	Policy conditions included	Economic feasibility
Bernal-Agustín and Dufo-López (2006)	Zaragoza, Spain	1 kWp grid-connected system	NPV, PBP	Varying subsidy level(0%, 20%, 40%)	Profitable but policy-responsive
Mitscher and Rüther (2012)	5 state-capitals, Brazil	2 kWp grid-connected system	LCOE, NPV	Net metering	Economically competitive with residential tariffs
Cherrington et al. (2013)	Cornwall, UK	2 kWp system on residential buildings	ROI, PBP, Net Profit	FIT	ROI ranging between 6 and 8%
Muhammad-Sukki et al. (2013)	UK, Germany, France, Italy, Spain, Czech	2.6 kWp residential system	Total Profit, ROI, PBP	FIT	ROI: 2%–3.6%

Note: NPV = net present value, FIT = feed-in tariff, PBP = payback period, LCOE = levelized cost of energy, ROI = return on investment.

Table 2. Overview of economic assessments considering strategic solar development of rooftop PV in urban settings.

Source	City/Region	Description	Relevant metrics	Policy conditions included	Economic feasibility
Adam et al. (2016)	Leeds, UK	A total of 101.4 MW with varying system sizes (4, 10, 50, 100, 150, 250 kW) on 6408 rooftops	NPV, ROI	FIT	Positive NPV for over 75% of sites
Miranda, Szklo, and Schaeffer (2015)	5570 municipalities, Brazil	A total of 40.16 GWp residential rooftop PV with various sizes based on socio-economic criteria	LCOE	None	Feasible in sites where residential tariffs are high
Sun et al. (2013)	9 cities in Fujian province, China	Rooftop PV in built environment that can generate 6.37 TWh annually (approx.. 3.8 GWp)	Electricity production cost, NPV, Simple PBP	FIT (assumption)	Economically viable when FIT applied
Mondal and Sadrul Islam (2011)	14 locations, Bangladesh	1 MW grid-connected systems in 14 locations	IRR, NPV, BC ratio, cost of energy production, simple PBP	None	Cost-competitive under favourable conditions
Audenaert et al. (2010)	Flander, Belgium	3 MWp commercial projects	NPV, IRR, PBP, PI, etc.	Tax credits, FIT-type policy, net-metering	Feasible under favourable policy conditions

Note: NPV = net present value, FIT = feed-in tariff, BC = benefit-cost, IRR = internal rate of return, PBP = payback period, LCOE = levelized cost of energy, ROI = return on investment, PI = profitability index.

deployment in Amsterdam, Munich, New York City, London, Seoul, and Tokyo and, using Monte Carlo simulation, determined that these six cities have a reasonable risk-return profile to warrant consideration of infrastructure-scale installation of solar energy (Byrne et al., 2016, 2017).[1] For these six cities, a \$9.9 billion investment in 3.2 GWp could be repaid from electricity bill savings within 10–15 years while reducing city carbon emissions, creating jobs, and deriving system benefits roughly valued at \$25 billion (Byrne et al., 2016, 2017).

Table 3. Infrastructure-scale assessment of financial feasibility of city-wide PV deployment.

Source	City/Region	Description	Relevant metrics	Policy conditions included	Economic feasibility
Byrne et al. (2016)	Amsterdam, London, Munich, New York, Seoul, Tokyo	City-wide assessment of rooftop PV determined total technical potential (35.5 GWp) and economic potential (10.64 GWp). Financial assessment conducted	BC ratio	FIT, tax credits, rebates, SREC	Feasible in most cities (except London and Seoul due to irregular cash flow)
Byrne et al. (2017)		city-by-city for: Amsterdam:110 MW London: 330 MW Munich: 180 MW NYC: 800 MW Seoul: 860 MW Tokyo: 920 MW			Feasible in all cities when allowing for 10–15 year financing

Note: BC = benefit-cost, SREC = solar renewable energy credit, FIT = feed-in tariff.

Research findings consistent with project-based solar development, strategic solar development, and infrastructure-scale solar development are provided in, respectively, Tables 1–3.

Concluding remarks

Ongoing investigations into municipal options suggests urban-led initiatives that use homegrown potential and diversity can lead the much needed sustainability transition. Through experimentation, partnerships, and reconfiguration of sustainable energy strategies, urban laboratories around the world are exploring new ground for nature-society relationships (Byrne & Taminiau, 2016). This research activity has given rise to city-wide planning models of sustainable energy potential, including technologies such as solar PV, geothermal, energy efficiency, wind energy, etc. Grouped under the heading of 'solar city', this large-scale potential could be practically approached through three investment strategies: 'project development', 'strategic development', and 'infrastructure-scale development'.

Recent research on the feasibility of applying infrastructure-scale solar city development strategies shows the transformative power of the model when combined with well-designed policy incentives and financing instruments (Byrne et al., 2016). Cities finding more than 60% of their daylight electricity need and over 30% of their all-hours demand from a distributed, rooftop solar plant thrusts them into the forefront of the deep decarbonization initiative sought worldwide by the 2016 Paris Accord. Incorporating uncertainty profiles of design and financing parameters shows robust economic feasibility in six cities across the world for a wide range of starting conditions (Byrne et al., 2017). In other words, practical implementation of the solar city concept is within reach even for the world's mega-cities.

With increasing sophistication of mapping and visualization technologies, urban planners and decision-makers are faced with a choice on how to use these tools. Applying these tools as 'front-end' options to inform project developers or individuals looking to install sustainable energy technology measures can be very helpful. But this use alone might neglect some of the inherent capability that city-wide insights and data provide. Drafting and designing city-wide strategies that reposition sustainable energy as a component of infrastructure, as opposed to an 'add-on' project component, provides valuable visioning of the transformation of urban life we need to realize genuine sustainable development. The combined transformative application of the solar city, coupled with the experimentation and innovation currently taking place in many cities across the world, signals that, indeed, cities can not only sustain life in the greenhouse but can thrive in the new paradigm. A *sustainable* urban metabolism is within our grasp.

Note

1. The economic feasibility of solar PV projects depends on technical, market, and policy factors that affect costs and benefits generated from system installation through operation stages (Byrne et al., 2016). Variables commonly factored in economic analysis of distributed power generation include system type, size, and cost, financing method, profit potential, and policy incentives. Using over two million simulations of variable input profiles, the Monte Carlo analysis of the six case study cities identified solar city opportunities as

reasonable when 80% of simulations demonstrated a positive cumulative benefit-to-cost ratio (Byrne et al., 2017). Depending on the duration of financing, all six cities demonstrated a reasonable profile under these terms. Benefit-cost assessment of city-wide solar PV projects in this manner provides a comprehensive and systematic comparison across different project scenarios (Allan, Eromenko, Gilmartin, Kockar, & McGregor, 2015; Drury, Denholm, & Margolis, 2011; Sun et al., 2013).

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References

Adam, K., Hoolohan, V., Gooding, J., Knowland, T., Bale, C. S. E., & Tomlin, A. S. (2016). Methodologies for city-scale assessment of renewable energy generation potential to inform strategic energy infrastructure investment. *Cities (London, England)*, *54*, 45–56. doi:10.1016/j.cities.2015.10.015

Allan, G., Eromenko, I., Gilmartin, M., Kockar, I., & McGregor, P. (2015). The economics of distributed energy generation: A literature review. *Renewable and Sustainable Energy Reviews*, *42*, 543–556. doi:10.1016/j.rser.2014.07.064

Ardani, K., Seif, D., Margolis, R., Morris, J., Davidson, C., Truitt, S., & Torbert, R. (2013). *Non-hardware ("soft") cost reduction roadmap for residential and small commercial solar photovoltaics, 2013–2020* (No. NREL/TP-7A40-59155). Golden, CO: National Renewable Energy Laboratory (NREL).

ARUP. (2014). *Working together: Global aggregation of city climate commitments* (Arup and C40).

Audenaert, A., De Boeck, L., De Cleyn, S., Lizin, S., & Adam, J. (2010). An economic evaluation of photovoltaic grid connected systems (PVGCS) in flanders for companies: A generic model. *Renewable Energy*, *35*(12), 2674–2682. doi:10.1016/j.renene.2010.04.013

Auer, J., & Anatolitis, V. (2014). *The changing energy mix in Germany*. Frankfurt am Main: Deutsche Bank Research.

Aylett, A. (2014). *Progress and challenges in urban governance of climate change - results of a global survey*. Cambridge, MA: MIT.

Barbose, G. L., & Darghouth, N. (2016). *Tracking the sun IX: The installed price of residential and non-residential photovoltaic systems in the United States* (No. LBNL-1006036). Lawrence Berkeley National Laboratory (LBNL).

Bernal-Agustín, J. L., & Dufo-López, R. (2006). Economical and environmental analysis of grid connected photovoltaic systems in Spain. *Renewable Energy*, *31*(8), 1107–1128. doi:10.1016/j.renene.2005.06.004

Bolinger, M., & Seel, J. (2016). *Utility-scale solar 2015: An empirical analysis of project cost, performance, and pricing trends in the United States*.

Bolinger, M., Weaver, S., & Zuboy, J. (2015). Is $50/MWh solar for real? Falling project prices and rising capacity factors drive utility-scale PV toward economic competitiveness. *Progress in Photovoltaics: Research and Applications*, *23*(12), 1847–1856. doi:10.1002/pip.2630

Bos, J. J., Brown, R. R., & Farrelly, M. A. (2013). A design framework for creating social learning situations. *Global Environmental Change*, *23*(2), 398–412. doi:10.1016/j.gloenvcha.2012.12.003

Breyer, C., & Gerlach, A. (2013). Global overview on grid-parity. *Progress in Photovoltaics: Research and Applications*, *21*(1), 121–136. doi:10.1002/pip.1254

Bulkeley, H., & Castán Broto, V. (2013). Government by experiment? Global cities and the governing of climate change. *Transactions of the Institute of British Geographers*, *38*(3), 361–375. doi:10.1111/j.1475-5661.2012.00535.x

Burkhardt, J., Wiser, R., Darghouth, N., Dong, C. G., & Huneycutt, J. (2015). Exploring the impact of permitting and local regulatory processes on residential solar prices in the United States. *Energy Policy*, *78*, 102–112. doi:10.1016/j.enpol.2014.12.020

Byrne, J., Hughes, K., Toly, N., & Wang, Y. (2006). Can cities sustain life in the greenhouse? *Bulletin of Science, Technology & Society*, *26*(2), 84–95. doi:10.1177/0270467606287532

Byrne, J., & Taminiau, J. (2016). A review of sustainable energy utility and energy service utility concepts and applications: Realizing ecological and social sustainability with a community utility. *Wiley Interdisciplinary Reviews: Energy and Environment*, *5*(2), 136–154. doi:10.1002/wene.171

Byrne, J., Taminiau, J., Kim, K. N., Lee, J., & Seo, J. (2017). Multivariate analysis of solar city economics: Impact of energy prices, policy, finance, and cost on urban photovoltaic power plant implementation. *Wiley Interdisciplinary Reviews: Energy and Environment*, e241–n/a. doi:10.1002/wene.241

Byrne, J., Taminiau, J., Kim, K. N., Seo, J., & Lee, J. (2016). A solar city strategy applied to six municipalities: Integrating market, finance, and policy factors for infrastructure-scale photovoltaic development in Amsterdam, London, Munich, New York, Seoul, and Tokyo. *Wiley Interdisciplinary Reviews: Energy and Environment*, *5*(1), 68–88. doi:10.1002/wene.182

Byrne, J., Taminiau, J., Kurdgelashvili, L., & Kim, K. N. (2015). A review of the solar city concept and methods to assess rooftop solar electric potential, with an illustrative application to the city of Seoul. *Renewable and Sustainable Energy Reviews*, *41*, 830–844. doi:10.1016/j.rser.2014.08.023

Byrne, J., & Toly, N. (2006). Energy as a social project: Recovering a discourse. In J. Byrne, N. Toly, & L. Glover (Eds.), *Transforming power: Energy, environment, and society in conflict* (Energy and Environmental Policy Series, 9th ed., p. 1). New Brunswick, NJ: Transaction Publishers.

Castán Broto, V., & Bulkeley, H. (2013). A survey of urban climate change experiments in 100 cities. *Global Environmental Change*, *23*(1), 92–102. doi:10.1016/j.gloenvcha.2012.07.005

Cerutti, A., Iancu, A., Janssens-Maenhout, G., Melica, G., Paina, F., & Bertoldi, P. (2013). Covenant of mayors in figures 5–years assessment. Joint Research Centre, European Commission. doi:10.2788/1062.

Cherrington, R., Goodship, V., Longfield, A., & Kirwan, K. (2013). The feed-in tariff in the UK: A case study focus on domestic photovoltaic systems. *Renewable Energy*, *50*, 421–426. doi:10.1016/j.renene.2012.06.055

Climate Alliance. (2014). *Climate alliance 2013/2014 - annual report and planning*. Frankfurt: Climate Alliance.

Denholm, P., & Margolis, R. (2008). *Supply curves for rooftop solar PV-generated electricity for the United States*.

Dong, C., & Wiser, R. (2013). The impact of city-level permitting processes on residential photovoltaic installation prices and development times: An empirical analysis of solar systems in California cities. *Energy Policy*, *63*, 531–542. doi:10.1016/j.enpol.2013.08.054

Drury, E., Denholm, P., & Margolis, R. (2011). *The impact of different economic performance metrics on the perceived value of solar photovoltaics* (No. NREL/TP-6A20-52197). Golden, CO: National Renewable Energy Laboratory (NREL).

Freitas, S., Catita, C., Redweik, P., & Brito, M. C. (2015). Modelling solar potential in the urban environment: State-of-the-art review. *Renewable and Sustainable Energy Reviews*, *41*, 915–931. doi:10.1016/j.rser.2014.08.060

Gagnon, P., Margolis, R., Melius, J., Phillips, C., & Elmore, R. (2016). *Rooftop solar photovoltaic technical potential in the United States: A detailed assessment* (Technical Report). National Renewable Energy Laboratory (NREL).

Gooding, J., Edwards, H., Giesekam, J., & Crook, R. (2013). Solar city indicator: A methodology to predict city level PV installed capacity by combining physical capacity and socio-economic factors. *Solar Energy*, *95*, 325–335. doi:10.1016/j.solener.2013.06.027

Gordon, D. J. (2016). The politics of accountability in networked urban climate governance. *Global Environmental Politics*, *16*(2), 82–100. doi:10.1162/GLEP_a_00357

Halder, P. K. (2016). Potential and economic feasibility of solar home systems implementation in Bangladesh. *Renewable and Sustainable Energy Reviews*, *65*, 568–576. doi:10.1016/j.rser.2016.07.062

Hong, T., Chen, Y., Lee, S. H., & Piette, M. A. (2016). CityBES: A web-based platform to support city-scale building energy efficiency. *Urban Computing*. doi:10.1145/12345.67890

Hyde, D., & Komor, P. (2014). Distributed PV and securitization: Made for each other? *The Electricity Journal*, *27*(5), 63–70. doi:10.1016/j.tej.2014.05.002
IEA. (2016). *Energy technology perspectives – toward sustainable urban energy systems*. Paris: International Energy Agency.
Kabir, M. H., Endlicher, W., & Jägermeyr, J. (2010). Calculation of bright roof-tops for solar PV applications in Dhaka megacity, Bangladesh. *Renewable Energy*, *35*(8), 1760–1764. doi:10.1016/j.renene.2009.11.016
Kanters, J., Wall, M., & Kjellsson, E. (2014). *The solar map as a knowledge base for solar energy use*. doi:10.1016/j.egypro.2014.02.180
Kona, A., Melica, G., Koffi, B., Iancu, A., Zancanella, P., Calvete, S. R., … Monforti-Ferrario, F. (2016). *Covenant of mayors: Greenhouse gas emissions achievements and projections*.
Kwan, C. L. (2012). Influence of local environmental, social, economic and political variables on the spatial distribution of residential solar PV arrays across the United States. *Energy Policy*, *47*, 332–344. doi:10.1016/j.enpol.2012.04.074
Lazard. (2016). *Lazard's levelized cost of energy analysis - version 10.0*. Author. Retrieved from https://www.lazard.com/perspective/levelized-cost-of-energy-analysis-100/
Lele, S., & Norgaard, R. B. (2005). Practicing interdisciplinarity. *Bioscience*, *55*(11), 967–975. doi:10.1641/0006-3568(2005)055[0967:PI]2.0.CO;2
Lombardi, M., Rana, R., Pazienza, P., & Tricase, C. (2014). The European policy for the sustainability of urban areas and the covenant of mayors initiative: A case study. In R. Salomone & G. Saija (Eds.), *Pathways to environmental sustainability: Methodologies and experiences* (pp. 183–192). Cham: Springer International Publishing. doi:10.1007/978-3-319-03826-1_18
Lowder, T., & Mendelsohn, M. (2013). *The potential of securitization in solar PV finance*. Report by the National Renewable Energy Laboratory (NREL). Retrieved from Www.Nrel.Gov/Docs/fy14osti/60230.Pdf
Luederitz, C., Schäpke, N., Wiek, A., Lang, D. J., Bergmann, M., Bos, J. J., … Westley, F. R. (2016). Learning through evaluation – A tentative evaluative scheme for sustainability transition experiments. *Journal of Cleaner Production*, In press. doi:10.1016/j.jclepro.2016.09.005
Lund, P. D., Mikkola, J., & Ypyä, J. (2015). Smart energy system design for large clean power schemes in urban areas. *Journal of Cleaner Production*, *103*, 437–445. doi:10.1016/j.jclepro.2014.06.005
Luther, J., Reindl, T., Wang, D. K. S., Aberle, A., Walsh, W., Nobre, A., & Yao, G. G. (2013). *Solar photovoltaic (PV) roadmap for Singapore (A summary)*. Singapore: Solar Energy Research Institute of Singapore (SERIS).
Mainzer, K., Fath, K., McKenna, R., Stengel, J., Fichtner, W., & Schultmann, F. (2014). A high-resolution determination of the technical potential for residential-roof-mounted photovoltaic systems in Germany. *Solar Energy*, *105*, 715–731. doi:10.1016/j.solener.2014.04.015
Melius, J., Margolis, R., & Ong, S. (2013). *Estimating rooftop suitability for PV: A review of methods, patents, and validation techniques; sponsor org.: USDOE office of energy efficiency and renewable energy policy and analysis*. United States. doi:10.2172/1117057
Mendelsohn, M., & Feldman, D. (2013). *Financing US renewable energy projects through public capital vehicles: Qualitative and quantitative benefits* (No. Technical Report NREL/TP-6A20-58315). National Renewable Energy Laboratory.
Ministry of Economy, Trade and Industry. (2017). *Changes in the feed-in tariffs from April 2017*. Retrieved from http://www.enecho.meti.go.jp/category/saving_and_new/saiene/kaitori/dl/kaisei/2017_fit.pdf
Miranda, R. F. C., Szklo, A., & Schaeffer, R. (2015). Technical-economic potential of PV systems on Brazilian rooftops. *Renewable Energy*, *75*, 694–713. doi:10.1016/j.renene.2014.10.037
Mitscher, M., & Rüther, R. (2012). Economic performance and policies for grid-connected residential solar photovoltaic systems in Brazil. *Energy Policy*, *49*, 688–694. doi:10.1016/j.enpol.2012.07.009
Mondal, A. H., & Sadrul Islam, A. K. M. (2011). Potential and viability of grid-connected solar PV system in Bangladesh. *Renewable Energy*, *36*(6), 1869–1874. doi:10.1016/j.renene.2010.11.033

Muhammad-Sukki, F., Ramirez-Iniguez, R., Munir, A. B., Mohd Yasin, S. H., Abu-Bakar, S. H., McMeekin, S. G., & Stewart, B. G. (2013). Revised feed-in tariff for solar photovoltaic in the United Kingdom: A cloudy future ahead? *Energy Policy*, *52*, 832–838. doi:10.1016/j.enpol.2012.09.062

Mumford, L. (1961). *The city in history: Its origins, its transformations, and its prospects*. New York: Houghton Mifflin Harcourt.

Nevens, F., Frantzeskaki, N., Gorissen, L., & Loorbach, D. (2013). Urban transition labs: Co-creating transformative action for sustainable cities. *Journal of Cleaner Production*, *50*, 111–122. doi:10.1016/j.jclepro.2012.12.001

Osseiran, N., & Chriscaden, K. (2016). *Air pollution levels rising in many of the world's poorest cities*. Retrieved from http://www.who.int/mediacentre/news/releases/2016/air-pollution-rising/en/

Ostrom, E. (2010). Polycentric systems for coping with collective action and global environmental change. *Global Environmental Change*, *20*(4), 550–557. doi:10.1016/j.gloenvcha.2010.07.004

Peng, J., & Lu, L. (2013). Investigation on the development potential of rooftop PV system in Hong Kong and its environmental benefits. *Renewable and Sustainable Energy Reviews*, *27*, 149–162. doi:10.1016/j.rser.2013.06.030

Perez, R., Zweibel, K., & Hoff, T. E. (2011). Solar power generation in the US: Too expensive, or a bargain? *Energy Policy*, *39*(11), 7290–7297. doi:10.1016/j.enpol.2011.08.052

Reckien, D., Flacke, J., Dawson, R. J., Heidrich, O., Olazabal, M., Foley, A., … Pietrapertosa, F. (2014). Climate change response in Europe: What's the reality? Analysis of adaptation and mitigation plans from 200 urban areas in 11 countries. *Climatic Change*, *122*(1), 331–340. doi:10.1007/s10584-013-0989-8

REN21. (2016). *Renewables 2016 global status report*. Renewable Energy Policy Network for the 21st Century (REN21).

Rodrigues, S., Torabikalaki, R., Faria, F., Cafôfo, N., Chen, X., Ivaki, A. R., … Morgado-Dias, F. (2016). Economic feasibility analysis of small scale PV systems in different countries. *Solar Energy*, *131*, 81–95. doi:10.1016/j.solener.2016.02.019

Santamouris, M. (2014). Cooling the cities - A review of reflective and green roof mitigation technologies to fight heat island and improve comfort in urban environments. *Solar Energy*, *103*, 682–703. doi:10.1016/j.solener.2012.07.003

Santos, T., Gomes, N., Freire, S., Brito, M. C., Santos, L., & Tenedório, J. A. (2014). Applications of solar mapping in the urban environment. *Applied Geography*, *51*, 48–57. doi:10.1016/j.apgeog.2014.03.008

Schiel, K., Baume, O., Caruso, G., & Leopold, U. (2016). GIS-based modelling of shallow geothermal energy potential for CO_2 emission mitigation in urban areas. *Renewable Energy*, *86*, 1023–1036. doi:10.1016/j.renene.2015.09.017

Seel, J., Barbose, G. L., & Wiser, R. H. (2014). An analysis of residential PV system price differences between the United States and Germany. *Energy Policy*, *69*, 216–226. doi:10.1016/j.enpol.2014.02.022

Sener, C., & Fthenakis, V. (2014). Energy policy and financing options to achieve solar energy grid penetration targets: Accounting for external costs. *Renewable and Sustainable Energy Reviews*, *32*, 854–868. doi:10.1016/j.rser.2014.01.030

Seto, K. C., Dhakal, S., Bigio, A., Blanco, H., Delgado, G. C., Dewar, D., … Ramaswami, A. (2014). 2014: human settlements, infrastructure and spatial planning. In O. Edenhofer, R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, … J. C. Minx (Eds.), *Climate change 2014: Mitigation of climate change. Contribution of working group III to the fifth assessment report of the intergovernmental panel on climate change*. New York, NY: Cambridge University Press.

Shah, V., & Booream-Phelps, J. (2015). *F.I.T.T. for investors. Crossing the chasm - solar grid parity in a low oil price era*. Frankfurt: Deutsche Bank Market Research.

Shahrokni, H., Levihn, F., & Brandt, N. (2014). Big meter data analysis of the energy efficiency potential in Stockholm's building stock. *Energy and Buildings*, *78*, 153–164. doi:10.1016/j.enbuild.2014.04.017

Singh, R., & Banerjee, R. (2015). Estimation of rooftop solar photovoltaic potential of a city. *Solar Energy*, *115*, 589–602. doi:10.1016/j.solener.2015.03.016

Sun, Y., Hof, A., Wang, R., Liu, J., Lin, Y., & Yang, D. (2013). GIS-based approach for potential analysis of solar PV generation at the regional scale: A case study of Fujian province. *Energy Policy*, *58*, 248–259. doi:10.1016/j.enpol.2013.03.002

United Nations. (2015). *World urbanization prospects. The 2014 revision* (No. ST/ESA/SER.A/366). New York, NY, USA: United Nations Department of Economic and Social Affairs, Population Division.

Voytenko, Y., McCormick, K., Evans, J., & Schliwa, G. (2016). Urban living labs for sustainability and low carbon cities in Europe: Towards a research agenda. *Journal of Cleaner Production*, *123*, 45–54. doi:10.1016/j.jclepro.2015.08.053

Wegertseder, P., Lund, P., Mikkola, J., & García Alvarado, R. (2016). Combining solar resource mapping and energy system integration methods for realistic valuation of urban solar energy potential. *Solar Energy*, *135*, 325–336. doi:10.1016/j.solener.2016.05.061

Wiek, A., & Kay, B. (2015). Learning while transforming: Solution-oriented learning for urban sustainability in phoenix, arizona. *Current Opinion in Environmental Sustainability*, *16*, 29–36. doi:10.1016/j.cosust.2015.07.001

Wong, M. S., Zhu, R., Liu, Z., Lu, L., Peng, J., Tang, Z., … Chan, W. K. (2016). Estimation of Hong Kong's solar energy potential using GIS and remote sensing technologies. *Renewable Energy*, *99*, 325–335. doi:10.1016/j.renene.2016.07.003