Renewable and Sustainable Energy Reviews 41 (2015) 830–844

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

A review of the solar city concept and methods to assess rooftop solar electric potential, with an illustrative application to the city of Seoul

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ARTICLE INFO

Article history:
Received 3 March 2014
Received in revised form
29 May 2014
Accepted 8 August 2014

Keywords:
Solar city
Photovoltaics
Built environment
Solar energy
Peak shaving
Urban solar potential
Solar rooftop potential

ABSTRACT

Energy economy restructuring at the city level is an essential prong in any strategy that aims to address the dual energy and climate change challenges. Cities form hubs of human activity that are accompanied by high levels of energy consumption and emissions but also contain existing resources and infrastructure to transition to a greener energy economy. This paper reviews efforts to date to define the 'solar city' concept and assessment methods for estimating the solar electric potential of an often neglected but vital city resource in energy matters – its rooftop real estate. From this review, an application of the solar city concept is formulated and an assessment method is offered for its investigation. An illustrative case study is provided, using the City of Seoul, South Korea. Representing nearly one-quarter of South Korea's population and a one-third of its economic activity, the application of the solar city concept to the city can have significant consequences for the future energy development pathway of the municipality and the country (the metropolitan area of Seoul encompasses nearly one-half of the national population). The research demonstrates that a technical potential equivalent to almost 30% of the city's annual electricity consumption can be supplied by widespread deployment of rooftop-based distributed photovoltaic systems. Using the methodology developed in the paper, we estimate that sixty-six percent of the annual daylight-hours electricity needs of the City of Seoul can be served by distributed solar power systems on a typical day. It is additionally found that considerable peak shaving is possible, lessening the pressure on the city's electricity grid. These findings can be expected to extend to other large cities when the solar city concept is thoughtfully applied.

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http://dx.doi.org/10.1016/j.rser.2014.08.023
1364-0321/

1. The idea of a solar city

Mega-cities are cited by some researchers as icons of unsustainability [1,2]. Others believe that large urban centers contain strategic resources such as research and development (R&D) institutions, universities, sophisticated business sectors and populations accustomed to rapid change and these resources could be used to produce resilient and ecologically sensitive economies [3]. A new cohort of researchers are exploring urban life as an agent of change towards renewables-based, low-carbon communities [4–6]. Recently, cities have banded together to address common challenges and share solutions by forming 'polycentric' [7,8] partnerships such as the C40 Climate Leadership Group and the International Council on Local Environmental Initiatives (ICLEI) to assist in the formulation of city-level measures and solutions [9]. These initiatives challenge standard energy development models based on centralized supply, and suggest greater attention to decentralized energy [10,11]. Urban deployment of such strategies are often amalgamated under concepts such as the 'eco-city', 'sustainable city', or 'solar city' and have found widespread local, regional, and national acceptance [12–17]. This confirms that urban centers can have a significant role in addressing the 21st century challenge to sustainably realize climate, energy and economic objectives [4,18]. Likewise, international organizations such as the World Bank [19], the Organization for Economic Co-Operation and Development (OECD) [20,21], and the United Nations Environment Program (UNEP) [22] have embraced city energy economy restructuring as a key tool to meet low-carbon development goals [23]. Of particular interest for energy economy restructuring is the unused 'rooftop real estate' that might be usefully capitalized through photovoltaic (PV) energy technology deployment. Often captured under the concept of the 'Solar City' [10,18,24], many investigations have focused on widespread deployment of PV energy technology in urban environments [25,26–29]. Application of the solar city concept draws its power from the realization that solar PV energy technology has significantly matured over the last four decades, represented by dramatically falling prices and rapidly increasing global penetration rates [30]. Also supported by the realization that solar radiation levels, even in places with modest solar resources, nevertheless provide significant energy potential, proponents of solar cities have urged greater research attention to the idea's promise [1,3,18,31].

Computations to determine rooftop PV potential have been performed across various scales and regions ranging from supranational assessments such as ones prepared for the European Union [32,33] to local, small-scale assessment of neighborhoods or city blocks [34,35]. At the national level, efforts to identify technical rooftop PV potential find significant value for urban PV application. For instance, studies of the U.S. [36,37], European Union [32], Israel [38], Canada [39], and Spain [40] find that widespread urban PV deployment could cover 15–45% of national electricity consumption. Similarly, these findings are accompanied by substantial estimates of potential PV capacity such as 664 gigawatt (GW_p)[1] for the U.S. [36], 951 GW_p for the European Union [32], and 73 GW_p for Canada [39].

Investigations have also been performed at the regional level. For instance, Lopez et al. [41] provide a GIS-based overview of all the U.S. states and their technical rooftop potential. Following the lead of Lopez et al. [41], Wiginton et al. [42] calculate a population density-PV potential relationship for a region within the province of Ontario (Canada) and find that there is 70 m^2 of roof area available per capita ($\pm$ 6.2%) or 25 million m^2 on which 5.74 GWp of PV capacity can be installed throughout the province. Ranging from a potential 2.5% share of electricity consumption for Kaua'i (Hawai'i) [43,44] to almost 7% for Los Angeles County [45,46] up to 47% for San Diego County [47] and 41% for California as a whole [41], regional calculations underscore the existence of significant generation potential from a decentralized solar approach to meeting energy needs. Moreover, despite the fact that other energy technologies, such as large, utility-scale wind or concentrated solar power find are estimated to have even larger technical potentials [41], decentralized, rooftop PV are seen as offering benefits which centralized 'clean energy' systems lack [48–50].

As momentum for distributed solar power grows, sophisticated tools are being deployed to track and assist the realization of solar communities. Fig. 1 depicts the results of important efforts to record PV utilization in four cities. These 'solar maps' document PV installations, promoting to visitors to the sites the fact that PV is a tangible, valuable option. One city (New York) has invented a planning tool – 'Solar Empowerment Zones' – to assist businesses and residents in each of the city's five boroughs to design and implement ambitious installation goals. Several visualization tools empower members of the public to investigate the potential of PV energy technology for their specific situation. One prominent example is PVWatts (http://pvwatts.nrel.gov), developed by the National Renewable Energy Laboratory (NREL), which provides easy access to estimates of solar energy production potential from grid-connected PV systems.

Many investigations have been published at the city-wide or city block level [25–29,34,35,38,51–55]. These research efforts seek to estimate PV potential for small-scale cities or neighborhoods. For the 30,000 residents of Newark (Delaware, USA), the Center for Energy and Environmental Policy (CEEP) calculated a technical potential to generate 124.86 GWh from the installation of 96.4 MW_p which would satisfy over 75% of annual daylight electricity needs while being competitive with existing electricity prices [56]. Similarly, for the small town of Bardejov (Slovakia – 3000 population), Hofierka and Kanuk [57] calculate the potential to generate 25.15 GWh. For the Canadian municipality of Calgary (approximately 1.0 million), Pelland and Poissant [39] project the potential to generate solar electricity at 5.8 TWh. An estimate by Bergamasco and Asinari [26] suggests a 719–858 GWh potential for Turin (Italy – 900,000 inhabitants).

For New York City (8 million), Plunkett et al. [25] determined technical, economic, and achievable potentials of rooftop PV deployment. In terms of technical potential, the team estimates a maximum technical total of 8.1 GW_p of which 4.3 GW_p (6.7 TWh) can be placed on industrial and commercial roof area, parking lots, and exclusion zones and 3.8 GW_p (5.6 TWh) on residential roof area. A more recent estimate was performed by the Center for Advanced Research of Spatial Information (CARSI) in cooperation with the U.S. Department of Energy Sustainable Cities Initiative and New York City Solar City Program. Through the use of advanced data derived from Light Detection and Ranging (LIDAR) datasets, CARSI was able to map all one million buildings in the city and determine their available rooftop area. CARSI estimates 57 million m^2 of available rooftop area which could allow for the installation of 5.8 GW_p of PV systems, equivalent to 40% of NYC's peak demand [58,59]. Another U.S. city designated by the Department of Energy as a 'Solar America City' – San Francisco (more than 800,000 residents), in calculations done to establish the Solar Map of the city, found a technical PV rooftop potential of 400 MW_p (440 GWh) [60]. This estimate was based on a citywide assessment of solar resource and rooftop shade analysis.

[1] Unlike conventional energy capacity descriptions of fossil fuel power plants, weather variability and other factors influence solar energy's performance. For this reason, the capacity of a PV panel is measured as its maximum output under standard test conditions. This capacity measurement is reported with a subscript 'p' to designate its peak output.

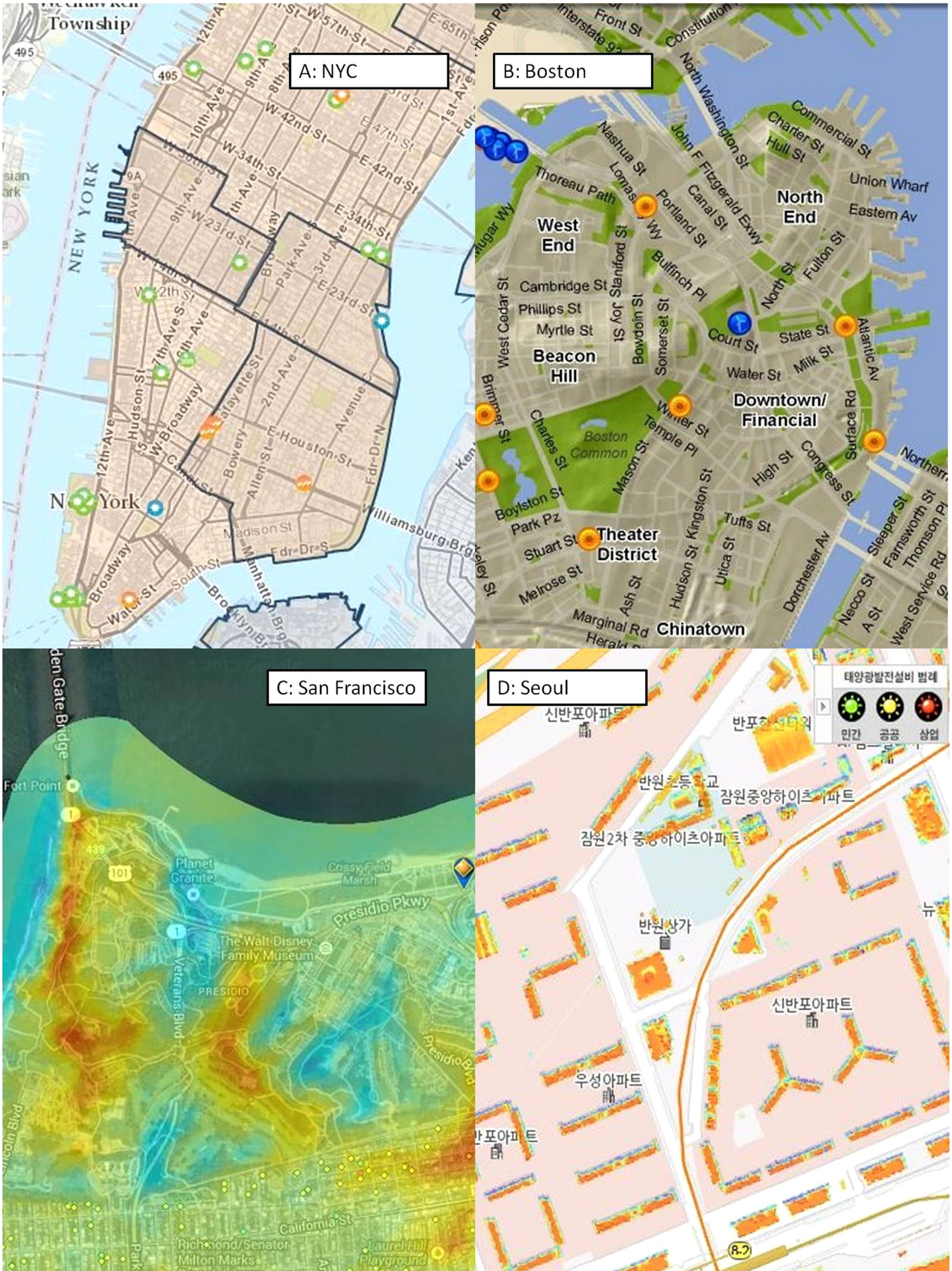

Fig. 1. City solar maps of New York City (A), Boston (B), San Francisco (C), and Seoul (D).

For Hong Kong (over 7 million residents), Peng and Lu [27] determine the technical potential of rooftop PV as well as its environmental benefits. The authors estimate a technical potential of 5.97 GW_p (5981 GWh) which can account for 14.2% of the city's 2011 electricity use. According to the authors, this corresponds to avoiding the emissions of 3.73 million tons of greenhouse gas

Table 1
Overview of a selection of cities solar PV technical potential estimates.

City	Population (millions)	Rooftop PV (GW_p)	Rooftop PV (TWh/year)	Land area (km^2)	MW_p on suitable rooftop/(km^2)	GWh from suitable rooftop/km^2/year	Electricity Consumption (TWh)	Share of electricity consumption
NYC (USA) [25] [a]	8.3 [62]	8.1	12.3	302.64	26.8	40.6	2011: 54.1 [64]	22.75%
San Francisco (USA) [60]	0.83 [62]	0.4	0.44	121.4	3.3	3.6	2012: 5.9 [46]	7.49%
Hong Kong [27]	7.2 [63]	5.97	5.98	78	76.5	76.7	2012: 43.1 [64]	13.88%
Turin (Italy) [26]·[61] [b]	0.9 [63]	-	0.86	130.17	–	6.6	2011: 10.7 [65] [c]	8.02% [c]

[a] The authors calculated technical potential against a 2022 target year and a 2003 space availability.
[b] The authors develop several scenarios based on different solar PV energy technologies (mono-crystalline, mixed, and thin-film) which hugely influence the estimated potential. Here, the estimate for widespread deployment of mono-crystalline solar PV panels is documented.
[c] The electricity consumption value given is for the Province of Turin rather than for the city of Turin. As such, the share of electricity consumption given here reflects the share of the electricity consumption in the province of Turin if an urban PV strategy for the city of Turin is deployed.

(GHG) against an energy payback time from 1.9 to 3.0 years [27]. Similarly, calculated energy yield ratios range from 10 to 15.8, demonstrating that the city's large-scale rooftop PV deployment could yield at least 10 times its energy requirement throughout the course of the system's lifetime [27].

An overview of these four cities is provided in Table 1.

There are good, practical reasons for encouraging the adoption and dissemination of strategies to enhance urban environmental quality and livability. Cities are economic powerhouses, major energy consumers, and key contributors to environmental degradation [21,66]. China´s 35 largest cities representing about 18% of the population, for instance, account for 40% of the country´s energy use and carbon dioxide (CO_2) emissions [67]. In fact, the world's cities account for approximately 67% of global energy use and 71% of global energy-related carbon dioxide emissions [21] reserving for them a major role in the fight against climate change through measures such as mixed-use developments, low-carbon/low-energy transportation, renewable energy generation, and energy conservation. Considering that the Asian continent will continue to experience rapid urbanization – the continent will see its urban population increase by about 1.4 billion people by 2050 [68] – new strategies for urban livability and energy economy restructuring are necessary to restrain energy use and associated environmental degradation. The realization that China annually adds about 1.7 billion m^2 of new floor space [69] elevates the urgency to deliver such new strategies.

Benefits from an urban-focused action strategy are substantial. The implications of one mega-city adopting a new development pathway grows far beyond its own municipal borders as such cities' purchasing power, influence, and leverage extends to many corners of the economy [70]. A successful strategy of local and distributed applications of energy can capture associated technical, economic, and environmental advantages [31,48,56,71]. An immediately identifiable technical advantage of energy localization is the prevention of transmission and distribution losses that occur over long distances. Additional energy benefits are the lower infrastructural construction and maintenance requirements of the grid system, a displacement of the need for additional centralized energy facilities, and an advantage known as 'peak shaving' [72,73] where PV output lessens peak demand impacts. The modular nature of PV, furthermore, makes it an especially attractive technology for small-scale urban applications as it is economically scalable and structurally adaptable to meet the energy user's needs [54]. Local and global environmental benefits can be accrued with urban PV deployment as such strategies capitalize on existing structures (thus avoiding the requirement of additional dedicated space) and use a renewable energy resource. Finally, socio-economic benefits in the form of enhanced (energy) security, local job creation, and isolation from price volatility and grid instability can be delivered through a solar city strategy.

2. Methodological options to determine rooftop PV potential

Estimating the PV potential of an urban landscape is a complex task. Building elevations, urban densities and varying urban morphologies combined with a lack of advanced data complicate assessment. While many methodologies to overcome such complications have been proposed, these can be grouped into three primary categories [74]. Driven by data availability and considerations of scale of the study area, these categories can be described as follows:

1. Sample methodology. Sampling techniques can be used to provide a reliable estimate of available roof surface which can then be extrapolated to the total area. The methodology finds its basis in a study by Izquierdo et al. [40,75] and, as Schallenberg-Rodriguez [74] notes, this method is suitable for large regional assessments of rooftop power potential. While sampling will be less accurate than a census of all rooftops of the study area, it has been shown to provide a reliable estimate.
2. Multivariate sampling-based methodology. This methodology seeks to draw correlations between population density and available roof area (e.g., [42]). The methodology includes additional variables to advance specificity compared to the previous method. Considering that the methodology retains a sample-based approach, the method is generally seen as relatively inexpensive but, due to the inclusion of additional variables, can be seen as more time consuming.
3. Complete census methodology. This method relies on the computing of the entire rooftop area in the study region. This can be performed either through existing statistical data sets that contain building-based information such as floor area, number of floors, and the total number of buildings, or through the use of advanced cartographic data sets that offer a digitized model of the study region. Such cartographic data sets allow for the computation of the rooftop area of the study region and are often processed through state-of-the-art software packages. Schallenberg-Rodriguez [74] notes the rising popularity of this method and attributes it, in part, to the increased computing power made available through such software packages such as Geographic Information System (GIS) applications. Whether deployed through building-based data sets or cartographic data sets, this methodology category is expected to produce high-accuracy results but can be considerably more time consuming and expensive compared to the previous two methods, especially when procurement of up-to-date cartographic information is required [74].

The review of methodologies performed by Schallenberg-Rodriguez [74] shows that a differentiation can be made between

Table 2
Comparison of three primary methodologies to estimate PV-suitable roof area for large cities. Source: [74].

Methodology	Source of data	Data requirements	Analytical rigor	Accuracy
Single sample methodology	Sample-based	Low	Modest	Relatively inaccurate
Multi-variate methodology	Sample-based	Medium	High	Reliable estimate
Complete census methodology	Full census	High	Highest	Most accurate

the three categories, where complete census assessments are expected to produce the most accurate estimate provided data requirements are met (see Table 2). This article continues with a discussion of this third estimation technique and develops a census assessment methodology for large-scale cities like the City of Seoul. At the heart of any methodology are two key steps that need to be navigated in order to arrive at an estimate for urban rooftop PV potential. First, an estimate of the total roof area in the study region needs to be computed. The second step is to determine what area of the total roof area is actually suitable for PV implementation.

2.1. *Estimation of building stock roof area*

Building-based data sets can contain a variety of information regarding the study region. For instance, data sets can contain information on the total floor area of the city, on ground floor area, on the number of floors per building, building height, lot coverage, floor area ratio, etc. However, these inputs need to be converted to an estimate of the total roof area that is available in the study region. A common process of arriving at an estimate for overall rooftop area using such data sources is to apply a 'rule of thumb' ratio that describes the relationship between gross ground floor area to rooftop area [27,32,36,41,76]. This rule of thumb assumes a particular multiplication factor to calculate rooftop area from floor area and is often differentiated based on building type.

Others (e.g., [26,38,57,61]) rely on advanced cartographic information and high-resolution images derived from remote sensing technologies such Light Detection and Ranging (LiDAR) [59]. Software applications such as, for instance, GIS-based Feature Analyst (FA) can also be used to compute the overall rooftop area [42].

2.2. *Estimation of PV-suitable rooftop area*

For cities where advanced data sets are available, complex computations can be performed for each building of the city to determine their rooftop area available for PV installation – this is the case for CARSI's assessment of NYC [58]. Such building-specific, detailed assessments were also performed by researchers for other jurisdictions [57,77–79]. Another method relies on samples of typical urban morphologies in a study area in order to determine shading and construction limitations; sample findings are then extrapolated to the study region or city [80]. A common approach, spanning across many methodological approaches, is to use reducing coefficients derived from literature to account for shading and other limitations [42,52,81,82]. But extrapolation of this kind has risks. Studies have found widely ranging utilization factors by neighborhood and even city block. In Greece, for instance, a study focusing on multifamily, multi-story buildings found utilization factors ranging from 0.25 to 0.5 depending on the duration of insolation time [34]. A New Zealand study of five residential blocks found individual utilization factors ranging from 0.22 to 0.47 [35]. A study on Delhi's (India) PV potential used separate utilization factors for residential (0.2), commercial (0.2–0.3), industrial (0.4), government (0.3), transport (0.2) and public and semi-public (0.4) buildings [51]. A Canary Islands study found high utilization factors for industrial (0.9) and services (0.6) buildings but relatively low utilization potential for residential flat roofs (0.35–0.48) and pitched roofs (<0.11) [74]. Similarly, a Switzerland study of three different sites finds considerably different utilization factors (0.49–0.73–0.95) [53]. A GIS-based study of Israel, also, finds a high industrial and services utilization factor of 0.9, but limits residential flat roofs (0.5–0.7) and pitched roofs (0.2) [38]. Finally, a study in Germany that looked at sites that were predefined as solar-suitable, found a high utilization factor of 0.9 [52]. In Table 3, the utilization factors for a selection of studies are given to demonstrate the used utilization factors at the larger scale.

Table 3
Overview of reduction factors used in a selection of the literature.

Location	Overall utilization factor	Source
Spain	0.34	[40,75]
India	0.30	[81]
Hong Kong	Architectural suitability: 0.7 Solar suitability: 0.55 Overall utilization: 0.39	[27]
EU-27	Architectural suitability: 0.6 Solar suitability: 0.55 Overall utilization: 0.33	[32]
California	Residential: 0.10 Commercial: 0.30	[45]
USA	Residential: 0.22–0.27[a] Commercial: 0.6–0.65[a]	[36,41]
IEA (PVPS)	Architectural suitability: 0.6 Solar suitability: 0.55 Overall utilization: 0.33	[76]

[a] Factor differentiated based on warm (residential: 0.27, commercial: 0.65) and cool (residential: 0.22, commercial: 0.6) climates.

3. A methodology to estimate rooftop PV potential of large-scale Cities: Seoul as a case study city

In 2008, Korea announced its plan to pursue a 'Low-Carbon, Green Growth' development pathway for the next 60 years [83,84]. This announcement was followed in 2009 with the Green New Deal, a $38.5 billion investment in green and environmental projects, and the *National Strategy for Green Growth up to 2050* which would shift the country's planning from an emphasis on quantitative to qualitative growth. The strategy was supported by the introduction of the *Five-Year Green Growth Implementation Plan for 2009–2013*, an $83.6 billion strategy (representing 2% of national GDP) that contains the following objectives [85]:

a) Reducing the country's greenhouse gas emissions by 30% by 2020 against a 2005 baseline;
b) increasing the country's new and renewable energy to 11% of energy supplies by 2030;
c) constructing 1 million green homes by 2020 and refurbish 1 million existing houses using new and renewable energy; and
d) developing the world's first nationwide smart grid system by 2030.

To realize these objectives, Korea has implemented a range of national policies. In 2012, Korea introduced its Renewable Portfolio Standard (RPS) to obligate utility companies to produce electricity from renewable energy to certain rate in their total power production. Applicable renewables in the RPS include PV, wind, hydro, fuel cell, ocean energy, bio energy and other energy prescribed by Korea government. It applies to 13 utility companies producing electricity with a capacity above 500 MW per year [86]. These companies have to source 2% of their total power generation in 2012 from renewables. The share is planned to grow to 10% in 2022.

3.1. *Justifications for Seoul city as a case study*

Like the rest of the country, the city of Seoul underwent a similarly rapid industrialization process, growing from about 2.5 million people in 1960 to over 10 million people in 2011 (about 20% of the country's population) and now accounts for 22.6% of the country's total GDP [87–89]. 2011 electricity consumption was 47.2 TWh (the vast majority is used by the city's residential, commercial and public/educational sectors) [89]. Seoul generates a modest amount of electricity through renewable energy sources; in 2011, the city installed about 4 MW_p of solar PV (about 5.3% of the country's 78.8 MW_p installed renewable energy capacity) generating about 20.9 GWh (about 2.3% of the nation's 917 GWh of renewable electricity) [89]. Thanks to the city's relatively strong policies on energy and environment, Seoul's carbon dioxide equivalent (CO_2-eq.) per capita is lower than many other large cities in the world. However, Seoul's air quality remains poor as it emits almost 18 times the national average air pollutants per km^2 and the levels of NO_2, SO_2, and PM10 are almost double those of Paris [89]. Moreover, Seoul's average concentration of particulate matter (55 micrograms per cubic meter) is well above the guidelines set by the World Health Organization (WHO) (20 micrograms per cubic meter) [90].

Pioneering in green energy development, Seoul was the first Korean city to announce long-term policies with the objective to transform itself into a 'green city'. In its 2007 Master Plan for Green Growth, Seoul laid out the following objectives:

a) Reduce greenhouse gas emissions by 40% by 2030 compared to the 1990 baseline;
b) reduce energy consumption by 20% by 2030 compared to 2000 level;
c) increase new and renewable energy use by 20% by 2030;
d) create 1 million green jobs through the promotion of ten major green technologies that can be considered suitable for Seoul. The national *Ten-Year Basic Plan* can be seen as a guideline for these ten major technologies as it selected three high-priority areas for investment: fuel cells, photovoltaic technology, and wind power [84]; and
e) create 10,000 green buildings.

Its most recent effort is a comprehensive strategy to 'mine' energy efficiency and renewable energy (especially solar thermal and PV) as indigenous resources of the city. To support the new direction, Seoul began in 2013 to host its own annual International Energy Conference, formed the Seoul International Energy Advisory Council to help the city learn about 'best practices' from around the world, has become active in C40 urban sustainability initiatives, launched a transportation eco-mileage policy measure, [2] and its mayor was elected to head the World Mayors Council on Climate Change [91]. Under the direction of the Mayor's Office, the City enlists citizens and businesses to join specific programs intended to reduce energy demand by 2 million tons of oil equivalent (TOE) by 2014 (equal to the capacity of one nuclear reactor) and reduce CO_2 emissions by 6.06 million tons [92]. The campaign has quickly garnered public support and enthusiasm, with broad segments of the city's population involved in the aggressive effort to shift to green energy options.

Similar to the country as a whole, Seoul faces energy security concerns as it annually consumes 46.9 TWh of electricity but only generates about 1.38 TWh. Seoul can thus contribute to the alleviation of the nation's and its own dependence on external energy resources through a strategy that deploys domestic energy technology at the site of use. In fact, as South Korea's energy insecurity deepens with rising energy consumption, the value of an urban PV strategy becomes more apparent. Post-Fukushima uncertainties are affecting East Asian energy policy [93], and a Seoul Solar City could lessen the dependence of its residents and the country on fossil fuel imports and Korea's nuclear power plant fleet which has had performance problems, grapples with waste disposal issues, and faces persisting environmental challenges (including those arising from coastal pollution and hazards) [94,95, p. 109].

At the same time, a Seoul Solar City program would be consistent with the desire of its public and leaders to provide a positive urban model in the areas of climate change response, environmental sustainability and green economy development. To date, growth in renewable energy capacity in Korea has been meager, rising only from 2.3% of the energy mix in 2003 to 2.8% in 2011. Seoul's record is no better.

3.2. *Estimating building stock roof area*

Due to the unavailability of up-to-date cartographic information for the case study, total roof area is derived from literature-informed steps. Where other studies have adopted a 'rule of thumb' ratio (gross ground floor area to rooftop area) to calculate rooftop area [27,32,36,41,76], the proposed methodology allows for the calculation of rooftop area in the case that ground floor area estimates are unavailable but total floor area estimates can be accessed.

Total floor space numbers from the Korea Statistical Information Service (KOSIS) form the foundation of the estimate of rooftop PV potential. Floor space estimates are given in Table 4 per building type and a total floor space of 605 million m^2 is obtained. To determine rooftop area, the methodology needs to account for the vertical nature of the city of Seoul and Table 5 presents an overview of the city's building stock by floor. From this data, an estimate of the total number of floors can be calculated (Table 5) which is then used to derive an average area per floor, allowing us to reach an estimate of 187 million m^2 of total rooftop area (Table 6).

This calculation provides a gross estimate of the city's rooftop real estate which could be refined using GIS software or other advanced cartographic information. However, this study could not obtain up-to-date data sets of this nature. As an alternative, a triangulation of the estimated 187 million m^2 was pursued using a 2002 GIS data set (see section 3.3).

3.3. *Cartographic cross-check of estimate*

As described by Schallenberg-Rodriguez [74], studies that realize a census of all available buildings through the use of such advanced cartographic data sets are, at least in principle, errorless. Many research efforts rely on such data sets (e.g., [26,38,57,61]) to produce their estimates. However, up-to-date cartographic information for the City of Seoul was unavailable. In light of the expensive nature of advanced GIS information, the proposed methodology crosschecks the estimate derived from building-based data sets with those of an older cartographic map of the

[2] Initial results appear encouraging as 560,000 households participate in the eco-mileage system, saving an estimated 40,000 t of oil equivalent (TOE) and 110,000 t of carbon dioxide each year [91].

Table 4
Seoul number of buildings and floor space. 2012 data from KOSIS. *Source*: [92].

	Total	Dwellings	Commercial	Factory	Educational/social	Other
Number of buildings	646,891 (100%)	494,704 (76.5%)	129,391 (20%)	3117 (0.5%)	15,562 (2.4%)	4117 (0.6%)
Floor space (m^2)	605,444,189 (100%)	277,017,527 (45.8%)	157,170,562 (26.0%)	9,457,290 (1.6%)	51,180,728 (8.5%)	110,618,082 (18.3%)

Table 5
Number of floors in the city of Seoul. 2012 Data from KOSIS. *Source*: [92].

	Total	1 floor	2–4 floors	5 floors	6–10 floors	11–20 floors	21–30 floors	≥ 31 floors
Number of buildings	646,891 (100%)	143,924 (22.2%)	414,488 (64.1%)	50,039 (7.7%)	21,124 (3.3%)	13,390 (2.1%)	2973 (0.5%)	242 (0.04%)
Calculation to get floor space	Sum	× 1	× 3	× 5	× 8	× 15	× 25	× 50
Number of floors	2,093,850 (100%)	143,924 (6.9%)	1,243,464 (59.4%)	250,195 (11.9%)	168,992 (8.1%)	200,850 (9.6%)	74,325 (3.5%)	12,100 (0.6%)

Table 6
Estimated rooftop area for the city of Seoul.

Total area of all buildings (m^2)	Total floors of all buildings (est.)	Average area per unit floor (m^2/floor)	Total rooftop area (m^2)
605,444,189	2,093,850	289	187,050,838

City of Seoul. A crosscheck with such a data set that produces a similar estimate as the estimation methodology can be used to validate the accuracy of the estimate.

The total rooftop estimate of 187 million m^2 was derived from 2012 KOSIS data. The study gained access to cartographic information from 2002 which covers the entire area of Seoul in that year and can thus be used to compute a full 2002 census estimate of the city of Seoul. Fig. 2 depicts one section of the city with an enlarged illustration of buildings captured in the cartographic data set. Data extraction from these vector files through automated computer aided design software (Autodesk AutoCAD 2013) yields a rooftop area result for the 2002 census of city buildings of 147 million m^2. One way to evaluate the accuracy of the 187 million m^2 estimate is to compare the 2002 vector file finding with a rooftop area estimate derived from the outlined methodology but using 2002 KOSIS data. The result is given in Table 7. The cross-check method produces a 153.6 million m^2 estimate, or a deviation in expected rooftop area of just over 4 percent. We conclude from this analysis that 187 million m^2 is a reasonable base estimate and can be used to initiate the next step in the investigation of Seoul's PV potential.

3.4. *From total rooftop area to suitable area*

The discussion of the literature demonstrates that a wide range of utilization factors are in use. Here, in line with Denholm and Margolis [36] and Lopez et al. [41], a 60% availability factor was used for the commercial, industrial, education/social, and public/agro-fishery building types of Seoul. Residential buildings typically have a slightly less attractive rooftop real estate for PV deployment due to their smaller scale and architectural obstructions. For residential buildings, a 39% availability factor was used in line with Peng and Lu [27] who corroborated their utilization factor with empirical support from the city of Hong Kong. Hong Kong is a nearby mega-city with a similar high-rise architecture as Seoul. In addition, Hong Kong is a vertical mega-city with a modest industrial base, features also found in the case of Seoul. Peng and Lu's [27] study of Hong Kong refined previous literature-based estimates of utilization factors for International Energy Agency (IEA) member countries [76] to account for specific building characteristics through an on-site feasibility study of selected areas in the city. This method cross-checked two of Hong Kong's building types through detailed measurements and visual inspection and the authors concluded that previously adopted architectural suitability reduction factors required modification to account for the case study of Hong Kong. In particular, the 0.6 architectural suitability factor was refined to 0.7, leading to an overall utilization factor of 0.39 (see Table 3) [27].This assumption yields an area suitable for PV deployment of about 94 million m^2 (Table 8).

Seoul-specific restrictions exist that further hinder the suitable area for PV deployment. Of particular importance is the legal requirement for a rooftop set aside for heliports. Korean Construction Law stipulates that every building which is both higher than 11 stories and has a total floor area of all stories above the 11th floor that is greater than 10,000 m^2 needs to have a heliport installed on the roof. Table 5 shows that about 2.6% of Seoul's 2012 building stock is 11 floors or higher. Using the average area per floor of 289 m^2, this corresponds to a potential heliport set aside of about 4.86 million m^2. However, high-rise buildings that exceed 11 floors are likely to be larger than the citywide floor area average of 289 m^2 and, for this reason, use of a set aside value based on 2.6% of total rooftop area is likely an underestimate. Because the building-based data available from KOSIS does not offer further discrimination across the categorizations given in Table 5, and because other potential factors specific to the situation of Seoul are also neglected in the literature-based utilization factors, this case study has doubled the set aside area in an effort to assure sufficient consideration of this important rooftop use. Table 8 records the results, finding that the suitable area for PV system configurations is 89.5 million m^2.

3.5. *From suitable area to PV system installment*

To realize actual technical potential, panel-to-panel shading effects and service and maintenance requirements need to be taken into account. This is a component of the analysis often neglected in other studies of urban rooftop PV potential. While a PV system realizes higher output when deployed at a specific angle to the sun, a tilted PV panel will cast a shadow that reduces performance of any panel behind it. In their assessment, Peng and Lu [27] first calculate an optimal angle for PV deployment of 23°, using Hong Kong specific meteorological data and the Perez model for diffuse solar irradiance incidence on tilted surfaces [96]. They follow their assessment with a calculation of the space required for PV at that angle when accounting for Ground Coverage Ratio (GCR) [97]. However, while a 23° angle might be optimal from the perspective of the individual PV panel, a PV system might deliver a lower performance due to the higher tilt leading to the

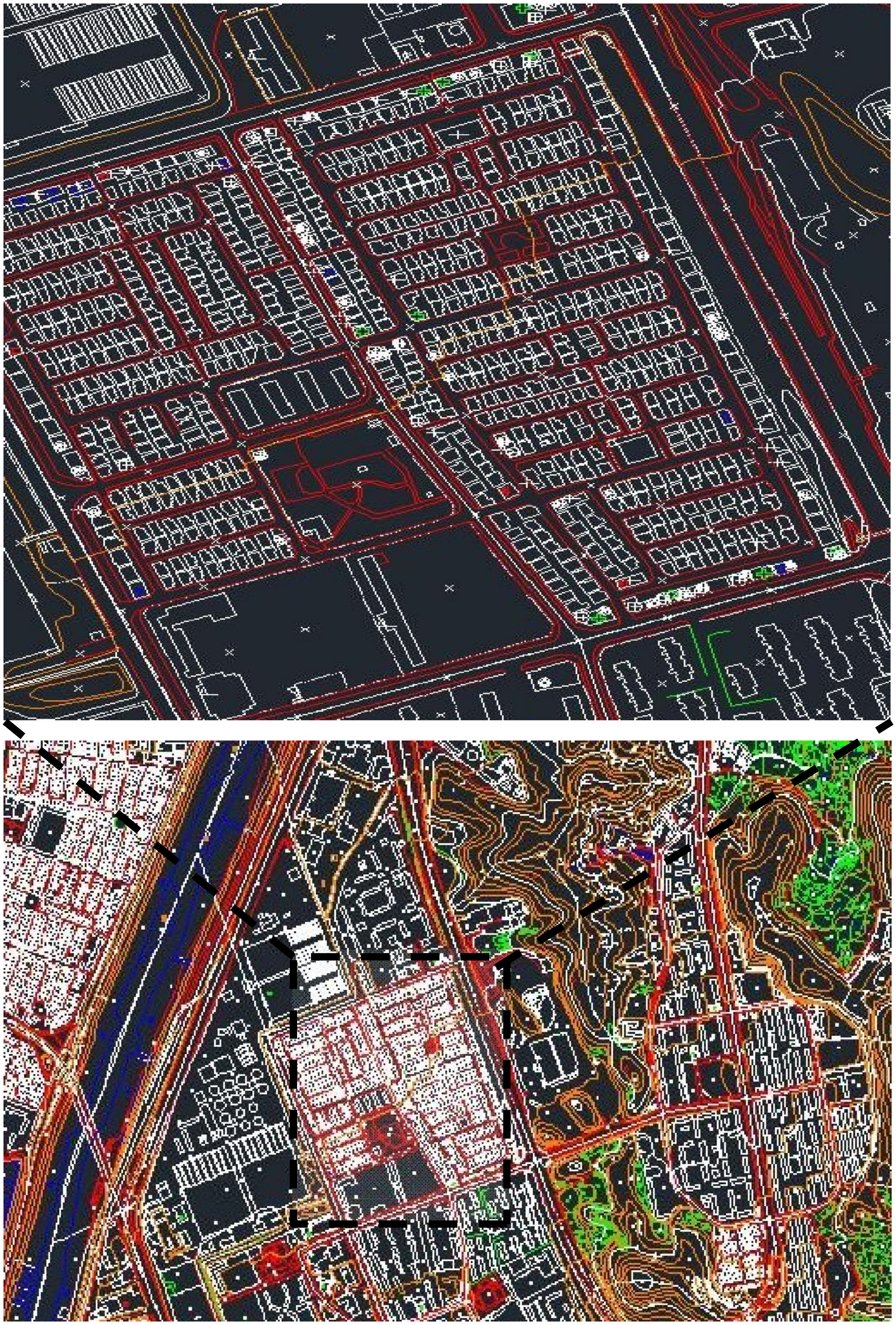

Fig. 2. Illustration of the cartographic vector files. On the left hand side, a vector file for a portion of Seoul is given to show how the vector files contain a variety of metadata. On the right, a section of the left-hand side illustration is magnified to show how all buildings of Seoul are captured in the vector files. Cartographic vector files were provided by Dr. Sehil Byeon of the Korea Research Institute for Human Settlements (KRIHS).

Table 7
Estimated rooftop area for the city of Seoul for the year 2002.

Total number of buildings	Total area of all buildings (m^2)	Total floors of all buildings (est.)	Average area per unit floor (m^2/floor)	Total rooftop area (m^2)
702,345	396,282,631	1,812,433	219	153,565,469

deployment of fewer PV panels. [3] In fact, GCR is significant at high angles (Formula 1) [97]. A 23° tilt angle, under Formula 1, allows

[3] Another consideration in vertical cities, where PV systems might be deployed on (very) high buildings is that of maintaining structural integrity when confronted with prevailing strong winds which might make a steep angle – such as the 23° finding by Peng and Lu [27] – economically unsuitable due to expensive structural mooring actions.

Table 8
Suitable rooftop area by building type. [a] a.

	Residential	Commercial	Industrial	Education /social	Public/other	Total
Total area of buildings (m^2)	277,017,527 (45.8%)	157,170,562 (26%)	9,457,290 (1.6%)	51,180,728 (8.5%)	110,618,082 (18.3%)	605,444,189 (100%)
Total rooftop area (m^2)	85,584,041 (45.8%)	48,557,548 (26%)	2,921,812 (1.6%)	15,812,189 (8.5%)	34,175,247 (18.3%)	187,050,083 (100%)
Suitability factor (%)	39%	60%	60%	60%	60%	50%
Suitability area (m^2)	33,377,776 (35.4%)	29,134,529 (30.9%)	1,753,087 (1.9%)	9,487,314 (10.1%)	20,505,148 (21.8%)	94,267,854 (100%)
Suitable area after heliport set aside (5%)	NA	NA	NA	NA	NA	89,544,961 (100%)

[a] Building types are those developed by the Korean government and reported by KOSIS. Education/social category includes schools, universities, hospitals, etc. Public/other includes indoor markets for fishery products, vegetables and fruits, and forest products.

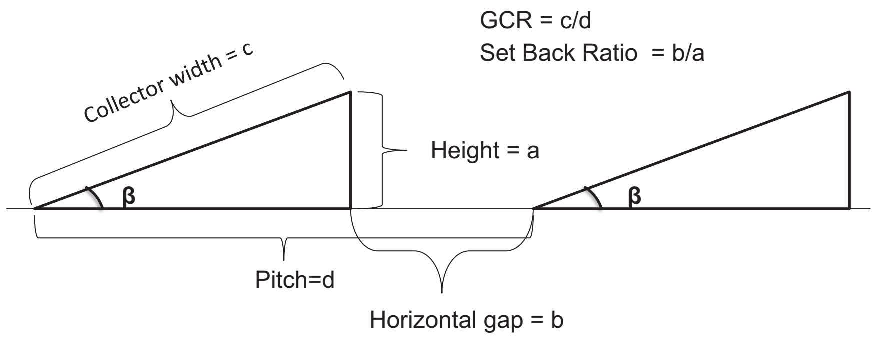

Fig. 3. Ground Coverage Ratio (GCR) calculations and dimensions [98].

Table 9
Overview of GCR and SA effects on available rooftop estimates.

Tilt	GCR (%)	SA (%)	Available rooftop space (%)
0	100	20	80
5	80	17	63
10	66	13	53
15	57	10	47
20	51	7	44
25	46	3	43
30	42	0	42

PV installation only on 48% of the roof area.

$$GCR = \frac{c}{d} = (\cos(\beta) + SBR \times \sin(\beta))^{-1} \quad (1)$$

where (Fig. 3) c=collector width, d=pitch, β=panel angle, SBR=set back ratio=the horizontal gap between PV panel rows, divided by the height of the PV panel.

The methodology proposed here specifically accounts for GCR and Table 9 presents an overview of the fractions of rooftop available at various angles. In addition to GCR, solar PV installations require a service area (SA) for maintenance and access. At higher angles, space freed up due to the spacing between the PV panels can be used for maintenance and access but lower angles need to specifically account for walkthrough space needs. Thus, while Table 9 depicts a 100% availability ratio for PV panels, a reduction of the available rooftop area should still be processed to account for SA.

Considerations for the proper design of access and maintenance pathways are addressed in the International Fire Code (IFC) 2012 [98] which was drafted with input from the Solar Energy Industries Association (SEIA) Codes & Standards Working Group. The guidelines established in the IFC 2012 serve as the basis for local ordinance development, and in most cases have been adopted as the industry standard. Roof access, pathways, and spacing requirements are discussed in detail in Sections 605.11.3.1 through 605.11.3.3.3 of the IFC. The SEIA Working Group also collaborated with the California Department of Forestry and Fire Protection to publish its Solar Photovoltaic Installation Guide [99] which establishes guidelines on the same specifications as those provided in the IFC 2012. Based on these guidelines, the percentage of available space can be calculated in a manner which is consistent with IFC standards. In the case that there are no obstructions or other design constraints, the average minimum roof space required for access and maintenance pathways, depending on building type, ranges from about 11% to 19%, with large commercial installations typically requiring less space for maintenance and access compared to smaller building types. Fig. 4 depicts a schematic example of how access and maintenance pathways take up a portion of the available rooftop space for a large commercial installation. However, the calculation shown in Fig. 4 neglects the space needed for maintenance and service access around obstructions such as skylights and roof hatches.

The combined interaction between GCR and SA is given in Table 9. When all panels of the installation are installed at no tilt, no space needs to be reserved for panel-to-panel shading effects. However, as shown in Table 9, a certain amount of space needs to be reserved for maintenance and (emergency) service access requirements. Obstructions (e.g., heating, ventilation, and cooling structures) and other architectural features such as cross gables for tilted roofs require additional space, resulting in an estimated 20% SA requirement at no-tilt deployment of solar panels. SA requirements under circumstances of PV installation at higher tilts are here assumed to be linear.

To arrive at an estimate of technical potential for the entire city of Seoul for PV deployment, GCR and SA space needs must be deducted from the PV suitable rooftop area. In addition, a final assumption needs to be made about the efficiency of the solar PV system. Table 10 presents the results for the GCR+SA calculations for various tilts for each building category.

Unlike other studies [27], the calculations here do not draw on a specific PV module but rather rely on a generic high-end efficiency PV system. Current module efficiencies sold in the market vary between 14% and 23% [100–102]. The obvious purpose of preparing a technical potential estimate for rooftop PV for the city is to enable

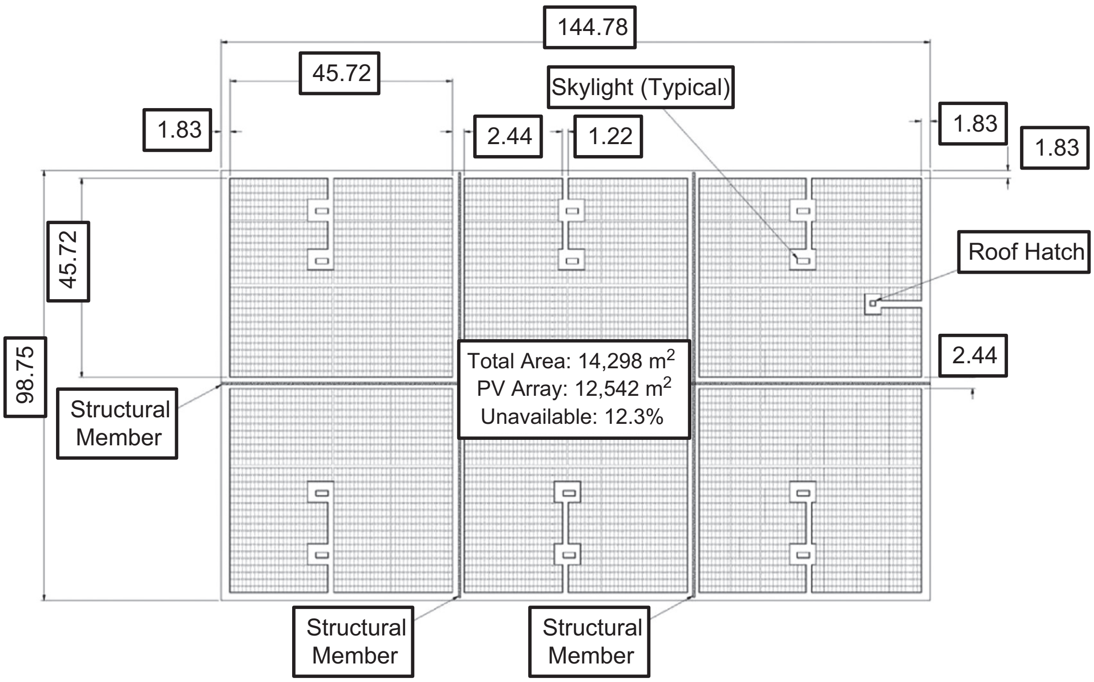

Fig. 4. Schematic illustration of a no-tilt PV system on a large commercial rooftop. Units in meters. Adapted from [98].

Table 10
Rooftop area available by use after accounting for GCR and SA.

Tilt	GCR (%)	SA (%)	Available roof space (m^2)					
			Residential	Commercial	Industrial	Education/social	Public/other	Total
0	100	20	25,367,110	22,142,242	1,332,346	7,210,358	15,583,913	71,635,969
5	80	17	19,927,754	17,394,380	1,046,657	5,664,273	12,242,324	56,275,388
10	66	13	16,830,650	14,691,005	883,989	4,783,951	10,339,664	47,529,259
15	57	10	15,027,686	13,117,248	789,293	4,271,476	9,232,039	42,437,743
20	51	7	14,016,731	12,234,813	736,195	3,984,122	8,610,973	39,582,834
25	46	3	13,527,451	11,807,734	710,497	3,845,049	8,310,392	38,201,123
30	42	0	13,401,753	11,698,016	703,895	3,809,320	8,233,171	37,846,154

Table 11
Technical potential for PV deployment in the city of Seoul at 20% module efficiency.

Tilt	Generation (MWh/MWp)[a]	Residential MWp (GWh)	Commercial MWp (GWh)	Industrial MWp (GWh)	Education/social MWp (GWh)	Public/other MWp (GWh)	Total MWp (GWh)
0	1228.61	5073 (6233)	4428 (5441)	266 (327)	1442 (1772)	3117 (3829)	14,327 (17,603)
5	1267.31	3986 (5051)	3479 (4409)	209 (265)	1133 (1436)	2448 (3103)	11,255 (14,264)
10	1299.13	3366 (4373)	2938 (3817)	177 (230)	957 (1243)	2068 (2687)	9506 (12,349)
15	1326.07	3006 (3986)	2623 (3479)	158 (209)	854 (1133)	1846 (2448)	8488 (11,255)
20	1346.65	2803 (3775)	2447 (3295)	147 (198)	797 (1073)	1722 (2319)	7917 (10,661)
25	1360.77	2705 (3682)	2362 (3214)	142 (193)	769 (1046)	1662 (2262)	7640 (10,397)
30	1368.34	2680 (3668)	2340 (3201)	141 (193)	762 (1042)	1647 (2253)	7569 (10,357)

[a] Conversion parameter derived from Seoul meteorological data and calculated with PV Planner software [103].

analytical consideration of large-scale deployments.[4] If the city embarked on a strategic plan to make best use of its PV-available roof area, PV module manufacturers and vendors would likely lower bid prices in order to participate in large-volume market opportunities.[5] Therefore, we have used a module efficiency at the upper end of the current market – 20%. Table 11 reports the generation and peak capacity (by building type and typical tilt angles) resulting from the assessment method developed in this paper.[6]

[4] Different technologies exist to convert sunlight to electricity. Two options have relevance for this study: flat plate photovoltaic (PV) and concentrating PV (CPV). To increase the electricity generated from a given roof area, one could consider the use of CPV. However, as Wang et al. [104] note, important limitations exist with CPV technology. Especially, additional cost due to, among others, high-accuracy tracking requirements, material specifications, and direct beam dependency lead to our focus on PV flat panel for the present analysis. Wang et al. [104] demonstrate that module costs for CPV need to be considerably lower compared to flat plate PV for the same target Levelized Cost of Electricity (LCOE).

[5] The case study assumes deployments would occur annually for a part of the available roof area. It is likely the plan would need to be 10 years in length – the same length of time currently used by the national government to plan thermal and nuclear power plant additions [105].

[6] To enable estimates by building type – a valuable tool for strategic planning, we have assumed the set aside for heliports to be evenly distributed by building type.

For a fixed unit area, PV systems installed at zero tilt will naturally create the largest electricity conversion area. But in the case of Seoul, this will not result in the largest level of electricity generation. Additionally, there are wind loading considerations as mentioned earlier. Thus, tradeoffs exist between conversion area, output (and the revenue it provides) and safety (including the cost it can represent) For this case study, after considering the tradeoffs involved, we have selected a 5° tilt angle in order to reach a technical potential estimate for rooftop PV in Seoul.

3.6. Overview of the proposed methodology

In short, this paper proposes a methodological approach that improves an existing methodology [74] and advances a workable strategy to estimate megacity rooftop PV potential, uniquely accounting for additional factors such as GCR and SA. The methodological approach is visualized in Fig. 5.

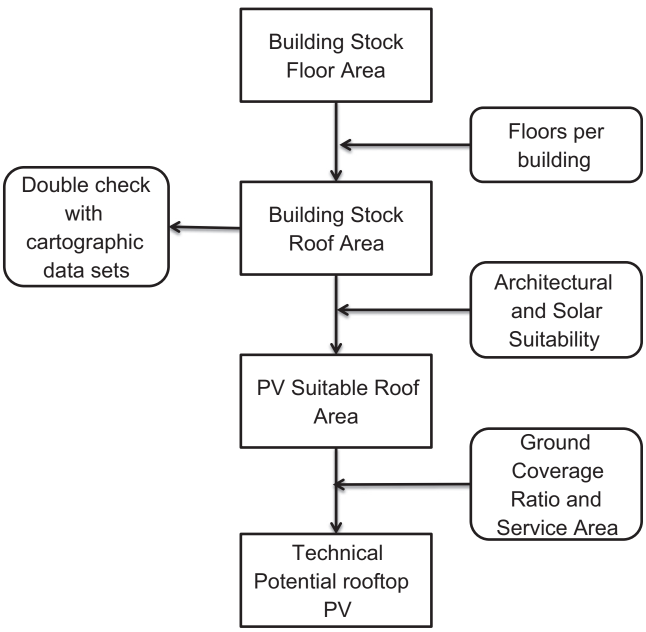

Fig. 5. Step-by-step overview of the proposed methodology.

4. Pursuing a Seoul solar city

Fig. 6 visualizes the steps taken to methodically arrive at an assessment of technical potential for rooftop PV for Seoul. At a five degree tilt, the city could install 11,255 MW_p of PV (14.26 TWh). It shows that about 30% of the total rooftop area can ultimately be technically useful for solar PV installations with the majority share on residential and commercial rooftops.

The technical potential assessment demonstrates the significant promise of the Solar City concept for the city of Seoul. At a 2012 electricity use of 47.23 TWh [106], the 14.26 TWh solar electricity generated under a five degree regime for Seoul Solar City is estimated to be 14.26 which is equivalent to 30% of the city's electricity consumption and allow the city to power 66% of its daylight needs from 9 am to 6 pm (Table 12). The 11.255 GW_p distributed solar power plant would correspond to over 110% of the peak load demand of Seoul (KEPCO furnished an estimate of 10.1 GW peak demand to CEEP for 2012). Naturally, socio-economic factors and policy context will constrain the realization of all of this potential.

Peak shaving during daylight hours would be an important contribution of Seoul Solar City. To illustrate this point, data from the Korea Electric Power Corporation (KEPCO) was used to calculate peak shaving potential for the city of Korea. However, the available electricity demand data from KEPCO was grouped in three blocks – 9 am–6 pm, 6 pm–11 pm, and 11 pm–9 am – complicating the assessment of peak shaving benefits due to averaging of electricity demand. Also, the load profile of the city during these hours would need to be defined, raising another complication in determining the peak shaving effect. An attempt was made to approximate Seoul city's daylight load curve from 10 am to 5 pm to demonstrate the potential contribution of PV for peak shaving purposes (Fig. 7). The analysis in Fig. 7 is based on the assumption that the city's load profile resembles that of a large hotel, a conservative approach to a complex question which requires

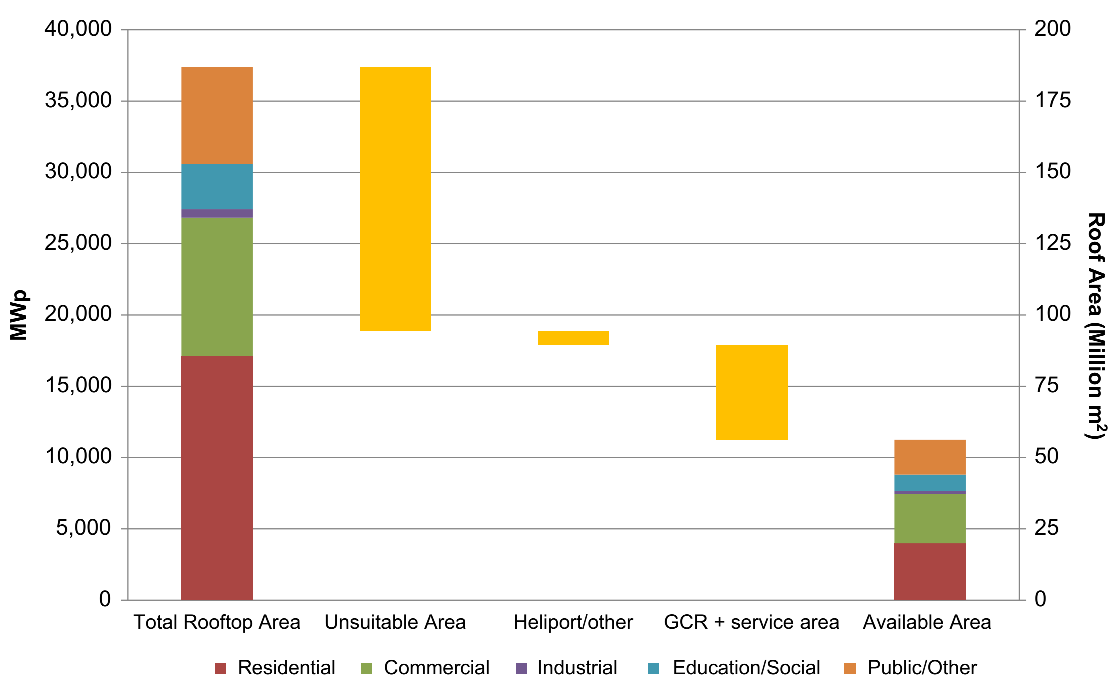

Fig. 6. Visualization of the methodological steps to arrive at an estimate of rooftop PV technical potential for Seoul.

Table 12
Summary of study findings.

2012 Population (Millions)[a]	10.5
2012 City electricity use (TWh)[a]	47.23
2012 City peak demand (GW) [b]	10.1
Solar potential electricity supply (TWh)	14.26
Potential of rooftop solar supply as a % of city total electricity use (all hours)	30%
Potential of rooftop solar supply as a % of city total electricity use (daylight hours)	65.7%
Solar potential total capacity (GW_p)	11.255
(Seoul rooftop solar potential in GW_p) ÷ (Seoul Peak Demand)	1.11
Solar potential peak shaving during noon – 2 pm for typical August weather	> 50%
Seoul solar supply during noon – 2 pm for typical May weather	> 95%

[a] Source: [106]
[b] Source: Korea Energy Power Corporation (KEPCO). The estimate was prepared at the request of CEEP. It is based on readings for each substation in the City of Seoul and may have an error of ±5%. The peak in 2012 occurred at approximately 2 pm on August 6, 2012.

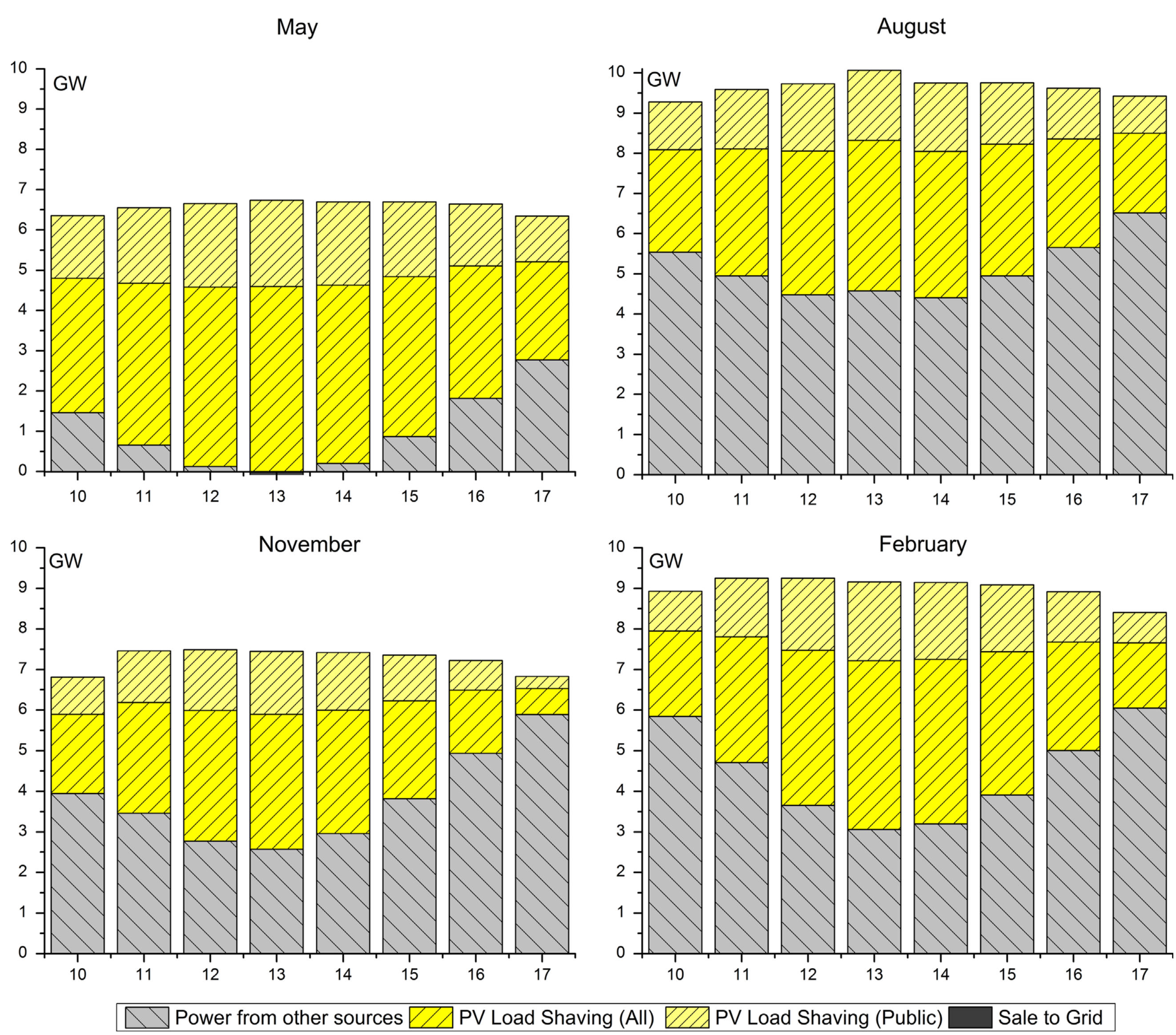

Fig. 7. Visualization of potential electricity service from Seoul's available PV rooftop area during peak demand periods for selected months.

detailed spatio-temporal data to properly determine impact. Still, the elementary analysis is instructive. The temperature, solar radiation and other data used to perform the analysis rely on typical-meteorological-year methods using Korean data. The graphs were created using PV Planner, a software tool invented at the Center for Energy and Environmental Policy [103].

For a typical May in Seoul, three-quarters of all hourly electricity needs of this busy city between 9 am and 4 pm, and over 90% of consumer needs between noon and 2 pm could be serviced by Seoul Solar City. More than one-half of its hourly needs between noon and 2 pm during typical weather for the months of February, August and November could be furnished by the distributed solar plant located on a portion of the city's rooftops.

Because August is often the peak month for electricity use, this finding of rooftop PV's potential has special significance. Most of the power plants serving Seoul are located nearly 1000 km south of the city. Seoul Solar City could materially decongest the transmission and distribution (T&D) system during peak hours of the peak month, thereby improving performance of the electric grid, extending the life of key T&D equipment, and improving reliability during one of the most vulnerable periods of grid service. When monetized, these system benefits could greatly enhance the cost-effectiveness of Seoul Solar City. Early work on the topic suggested that system benefits alone could offset initial capital costs by more than 30% [107,108].

The city experienced rolling blackouts in summer 2011 due to high temperatures driving electricity demand above the national grid's supply reserves [109]. In 2013, the problem persists as the city struggles to reduce summertime electricity consumption [110]. These recent difficulties during peak hours underscore the value of a load-following renewable energy system.

Fig. 7 also depicts the service potential if only the city's public buildings are used. The purpose in offering this visualization is to enable city planners to consider pilot-scale projects from which they can learn the actual operational features of distributed solar systems.

A summary of findings is provided in Table 12.

5. Concluding remarks

Rapid urbanization is expected to continue throughout the 21st century [68]. Energy-intensive urban development along the lines pursued for the last 100 years will aggravate environmental risks (in particular thoses associated with urban air quality and global climate change), and attentuate city economic vulnerabilities.

Lessons learned from cities which have applied the 'solar city' concept are reviewed in the paper to inform research on how they might restructure their energy economies in the face of looming environmental and economic risks. A method to assess the technical potential for urban rooftop PV is developed and illustrated using a city (Seoul) in the most rapidly growing economic region in the world in order to facilitate research on alternative energy models for urban development. We believe the case study of Seoul has particular value by highlighting the significant role mega-cities can play in a polycentric approach to resolving energy problems.

Assessment of technical potential is only a first step. Integration of a decentralized solar generation system into a system designed over the last century on the basis of principles of centralization and uninterrupted supply will need to be addressed [11,111,112].

And there is the question of economic potential. Capitalizing the technical potential of PV is costly and must be weighed against its benefits. While we cannot in one paper address technical and economic potential, we wish to briefly note the findings of Lazard Investment Bank (which includes a leading global financial advisory unit focused on energy investment) showing that PV already competes favorably in applications which replace peak electricity generation [113]. The bank's energy advisory unit also projects grid parity throughout the U.S. by 2016 for applications competing against retail electricity prices (Seoul's retail electricity prices fall in the mid-range of American rates). Their analysis also consistently shows that energy efficiency is considerably more cost-effective than PV.[7]

Nonetheless, assessment of technical potential is an essential component of research focusing on energy options for the dominant mode of human settlement – cities. Assessment of PV's potential is likewise essential – it is the only indigenous supply resource which all cities possess.

Acknowledgments

The authors acknowledge with appreciation the financial support of the National Research Foundation of Korea (MSIP, University-Institute Cooperation Program).

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