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Estimation of rooftop solar photovoltaic potential using geo-spatial techniques: A perspective from planned neighborhood of Karachi – Pakistan

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ABSTRACT

With an ever increasing population and significant solar resource availability throughout the whole year, Karachi metropolis hold a promising rooftop solar photovoltaic (PV) potential considering its millions of urban households. This research work highlights techniques to combine geographic information systems (GIS) and object-based image recognition approach to identify the available rooftop area for PV deployment in a small scale region of DHA Phase 7 Karachi. A six step methodology has been adopted for the estimation of rooftop PV potential which involves geographic division of high resolution satellite imagery; sampling and rooftop feature extraction using FE tool of ENVI EX software; extrapolation of rooftop areas for the entire ROI using roof area-population relationship; visual inspection to analyze different rooftop factors such as building orientation, shading effect from trees and nearby buildings and other roof uses; a comparison of extracted rooftops to the physically measured sample rooftops, reduction for shading and other uses; and finally conversion to energy and power outputs. A relationship of total roof area and population of 13 m^2/capita ±5% has been found. With higher efficiency rooftop PV panels, 12.24 MW of solar power can be generated which is 122.4% of peak power demand of DHA Phase 7.

1. Introduction

Pakistan is an energy deficient country and has been under severe energy crisis since last two decades. Ko et al. [17], mentioned that energy is a consequential parameter of production input during a country's economic development. In spite of significant solar resource availability throughout the whole year, electricity production in Pakistan is not sustainable and it is mainly dependent on conventional sources of energy. Consequently, environmental hazards along with energy security have become the major concerns in the current energy scenario of the country. Dependence on conventional sources of energy for electricity generation also leads towards impacts on climate change and depletion of fossil fuels resources. Jamal et al. [14] highlighted that renewable energy provides an alternate solution to sustainable electricity production by replacing hydrocarbon based fossil fuels. Jamal et al. [37] mentioned that renewable energy has a higher cost disadvantage when compared with fossil fuels but their environmental friendliness as well as round the clock availability make them a preferred source of energy. Nevertheless, the role of renewable energy in the current energy mix of the country is almost negligible. Although, the Pakistani Government has taken some initiatives in form of development of Quaid-e-Azam Solar Park in Punjab, Pakistan but there is a severe need to replicate such steps throughout the whole country to overcome long prevailing energy crisis in the country. Thus, the role of renewable energy in general and solar energy in particular for sustainable electricity generation in the country is of the utmost importance.

Karachi – the globalized complex and the mega city of Pakistan with an ever increasing energy consumption profile has an installed power generation capacity of 2341 MW which is mainly dependent

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on fossil fuels. The Intensive use of fossils fuels for electricity generation has resulted in environmental degradation of economic hub of the country. In particular Naz and Ahmed [24] highlighted the fact that the demand and supply gap of energy associated with malfunctioning in power distribution results in hours of load shedding in Karachi which varies by districts, income group and gender. Awan and Khan [3] emphasized that utilizing PV system is one of the efficient ways of direct conversion of solar energy into electricity. The mega city of Karachi has been through intense urbanization during last two decades. Thus, due to an ever increasing population and significant solar resource availability throughout the whole year Karachi metropolis holds a great potential for solar photovoltaic (PV) installations for its millions of urban households. Consequently, there is a severe need to identify and assess rooftop PV potential of Karachi that could be utilized for sustainable power generation to cater daily electricity requirements.

Geographic Information System (GIS) has now become a mature technology and it has been readily used for renewable energy analysis by many researchers such as Singh and Banerjee [33], Jamal et al. [14], Sun et al. [35], Latif et al. [18], Liu et al. [20], Ordóñez et al. [26], Wiginton et al. [39], and Izquierdo et al. [13] to name a few. However, use of GIS tools for rooftop PV potential assessment is also associated with cost constraints such as an availability of commercial software tools, high resolution satellite imagery and sophisticated data such as LIDAR which are not usually available in public domain. The main objective of this research work is to propose a methodology that utilizes freely available satellite imagery with geospatial techniques thus highlighting its significance for extracting rooftop PV potential without encountering cost barriers and other associated complexities. Moreover, none of the studies has been conducted yet for the estimation of rooftop PV potential of Karachi. Therefore, this preliminary research work is a first of its kind initiative to highlight an immense solar energy potential of Karachi which can be utilized as a sustainable solution to power crisis in the city.

Through this research work an initiative has been taken to overcome challenges of electricity shortfall in Karachi. In this article, geographic sampling has been merged with object-based approach to classify imagery to determine available rooftop area for the assessment of rooftop PV potential of DHA Phase 7 Karachi. Feature Extraction Module of ENVI EX software has been applied to the region of interest (ROI) to produce object-based supervised classification algorithms to extract rooftop features from freely available high resolution satellite imagery. Limitations of the software tool utilized for extracting rooftops has been discussed. From this rooftop extraction process, a relationship has been developed between population density and rooftop area and it has been extrapolated to the entire region. Understanding the relation between rooftop area and population density is significant not only for the potential assessment of rooftop PV potential but it also helpful for urban sustainability studies and planning.

Field validation of sample rooftops has been performed in ROI. In physical measurement process of sample rooftops, each sample rooftop has been assessed for the availability of rooftop area. A survey of ROI has also been performed to analyze the effect of shading from nearby buildings and trees. From total roof area, an estimate of available rooftop area has been produced by considering factors such as shading, other uses and orientation of rooftops. Energy modeling of a sample rooftop building has been performed using Hybrid Optimization Model for Electric Renewable (HOMER) software and yielded rooftop PV energy output has been compared with the electrical load of the building. An estimate of rooftop PV potential of ROI has been made by considering available rooftop area, PV panel efficiencies and insolation in the region. Solar power output has been compared with local peak power demands. Limitations of the research work has been discussed and future research directions have also been indicated.

The findings of this research article could be beneficial for both government and private sector policy makers and urban planners. It would also highlight the immense need for long-term renewable energy policy for the mega city of Karachi.

2. Background

2.1. Related work

There has been many studies conducted by different researchers around the globe which demonstrated the use of GIS tools and techniques for the estimation of rooftop PV potential employing different algorithms and models. It is evident from the published literature that image recognition technique, both object-based and spectral-based, have been a vital tool for study of urban fabric and determination of roof area as identified by Akbari et al. [1], Guindon et al. [12], Ratti and Richens [29], Richens [30] and Taubenböck et al. [36]. This strengthens the usage of object-based image classification technique in the present research work. Table 1 characterizes the identified relevant literature of rooftop PV potential estimation.

It is pertinent to mention that none of the studies has been found in published literature addressing the use of GIS tools and techniques for rooftop PV potential estimation of Karachi, Pakistan. With millions of urban households and scarcity of electric power for its inhabitants, the mega city of Karachi holds a great potential for rooftop PV installations in the city.

2.2. Renewable energy scenario of Karachi

Alternate Energy Development Board (AEDB), Government of Pakistan has already introduced Pakistan Renewable Energy Policy in 2006 but unfortunately its implementation has been quite slow and no stimulated progress has been observed during last few years. According to NASA's Surface Meteorology and Solar Energy (SSE) database, Karachi has an annual average Direct Normal Irradiance (DNI) of 6.20 kWh/m^2/day. Fig. 1 shows the monthly averaged direct normal irradiation at Karachi.

However with such a significant solar power potential, use of naturally available solar energy is limited to small scale applications only such as solar street lights, solar heater etc. Karachi – with an ever increasing energy profile is governed by K-Electric [15] (hereafter referred to as KE) for its electricity requirements. KE with an installed generation capacity of 2341 MW produces 52% of the required electricity through its own system while remaining energy is purchased from different local sources. Due to demand-supply gaps and power distribution losses, long prevailing power outages are common in the city. Due to rapidly increasing estimated population of over 24 million and tremendous solar resource availability throughout the whole year, the mega city of Karachi has significant potential for rooftop PV installations for the millions of urban households of the city. In particular, Karachi also an advantage of having privately-run power utility and it can be easier to initiate a process to integrate solar energy in the grid system (Tribune: Karachi has the potential, [38]). Thus there is a need to explore and demonstrate the potential for rooftop PV systems for urban households of Karachi.

2.3. Description of study area

Defence Officers Housing Authority (DHA) is an upscale real estate and property development organization administered and

Table 1
Characterization of GIS based rooftop PV potential studies from published literature.

Reference	Location	Criteria used	Key findings	Data and GIS technique used	Renewable energy tool used
Rhythm and Banerjee (2015) [33]	Mumbai (India)	Combination of land-use data and GIS based image analysis of sample satellite images for the estimation of rooftop PV potential of Mumbai	Estimated rooftop PV potential may provide 12.8–20% of average daily demand and 31–60% of morning peak demand	Google Earth™ satellite imagery and Quantum GIS (QGIS) software tool	Rooftop PV simulation tool PVsyst
Jamal et al., [14]	Dhaka (Bangladesh)	Use of Quickbird imagery to compute bright rooftop of Dhaka city and estimation of rooftop PV generation potential through HOMER analysis	An optimized use of fossil fuels was ensured since electricity production used both PV and fossil fuels, PV generation potential may meet 15% of local grid electricity demands	Quickbird imagery of Dhaka city, ArcGIS software	HOMER energy modeling tool
Sun et al., [35]	Fujian (China)	Use of high resolution grid map of solar radiation combined with other restriction factors to assess solar PV generation at regional scale	PV technology provides high flexibility for rooftop PV applications and large-scale PV plants	SRTM 90 m DEM, Global land cover products with ArcGIS software	None
Stoll et al., [34]	Tokyo (Japan)	Use of Google maps and 34 years average daily irradiance data to analyze the potential of available roof area for rooftop PV installations to replace nuclear capacity	The estimated PV potential coupled with local electricity provider would be sufficient to replace nuclear capacity	Google maps have been used to analyze rooftop space	None
Liu et al., [20]	Jiangsu (China)	Use of land use map, meteorological data and aerial maps to analyze the potential of roof mounted PV system	Estimated PV potential may meet 40% of the local electricity demands	Google Earth™ images with land use map, ArcGIS software	None
Wiginton et al., [39]	Ontario (Canada)	Combination of census data and digital orthophotos for automated rooftop feature extraction to analyze PV potential of Ontario	Province-wide rooftop PV deployment may be helpful in meeting 30% of Ontario's electricity requirements	DRAPE orthophotos, Feature Analyst Extension of ArcGIS software	None
Ordóñez et al., [26]	Andalusia (Spain)	Use of statistical construction data with Google Earth™ imagery to evaluate the useful surface area of sample representative buildings for rooftop PV installations	Estimated rooftop PV power may meet 78.89% of energy demands of Andalusia (Spain) thus representing an external energy dependence of 21.02% only	Google Earth™ imagery and AutoCAD software (non-GIS based tool)	None
Izquierdo et al., [13]	Spain	Methodology is based on land use maps, population and building densities data with stratified sample of vectorial GIS maps of urban areas to estimate available rooftop area for large scale rooftop PV deployment in different provinces of Spain	The total and per capita available area on roofs of different provinces of Spain was estimated for rooftop PV installations	Google Earth™ imagery, GIS tools and Linux scripts for processing of data	None

run by the Pakistan Army. It lies in the southern part of Karachi metropolis having geographic coordinates 24^0 48′ 19″ N and 67^0 04′ 10″ E. DHA is spread over an area of 35.82 Km^2 and some parts of its area are still under development due to an extension process of residential plots. Its estimated population contains 660,931 number of residents (Source: Wikipedia [40]). DHA reflects the growth oriented high-class living values (Source: Global Security [9]). It is one of the well-planned and well-managed areas of Karachi metropolis.

DHA comprises eight residential phases with some of its part being commercial as well. DHA Phase 7 (hereafter referred to as Phase 7) has been selected as the ROI for this research work since majority of this part contains residential houses. There are two small commercial settlements as well i.e., Sehar Commercial and Jami Commercial Area. Phase 7 has an area of 2.608 Km^2 with an estimated population of 12,102 inhabitants. There are 2630 buildings in Phase 7 containing residential houses, commercial buildings, mosque, educational institutes etc. Sehar Commercial Area contains 106 buildings while Jami Commercial Area comprises 125 buildings. There are 2 mosques and 3 recreational parks as well. Thus, there are around 2300 residential houses in Phase 7.

In particular, electricity is supplied in Phase 7 by KE. Electrical load data of ROI has been acquired from centralized Load Dispatch Centre (LDC) facility owned and operated by KE in DHA, Karachi. LDC monitors the consumption and maintenance of load requirements throughout the whole city. KE supplies electricity to whole DHA area through the network of 31 sub-stations (feeders) each of 11 KV. There are three grids i.e., Defence grid station, DHA-1 grid station and Creek City grid station each of 132/11 KV, which circulates electricity to their 11 KV sub-stations. This circulated power is further distributed to the Phase 7 service area consumers through the network of Pole Mounter Transformers (PMTs) each of 0.4 KV. Electrical load varies from 1 MW to 2.5 MW on each sub-station. The service area of Phase 7 has a range of customers starting from domestic 0.4 KV to 11 KV bulk customers. Fig. 2 shows the region of interest and its location in Karachi.

3. Methodology

A six step procedure has been used in this paper to analyze available rooftop PV potential of Phase 7. Rooftop PV potential assessment is associated with an availability of commercially available data and software tools. Nevertheless, in the Pakistani

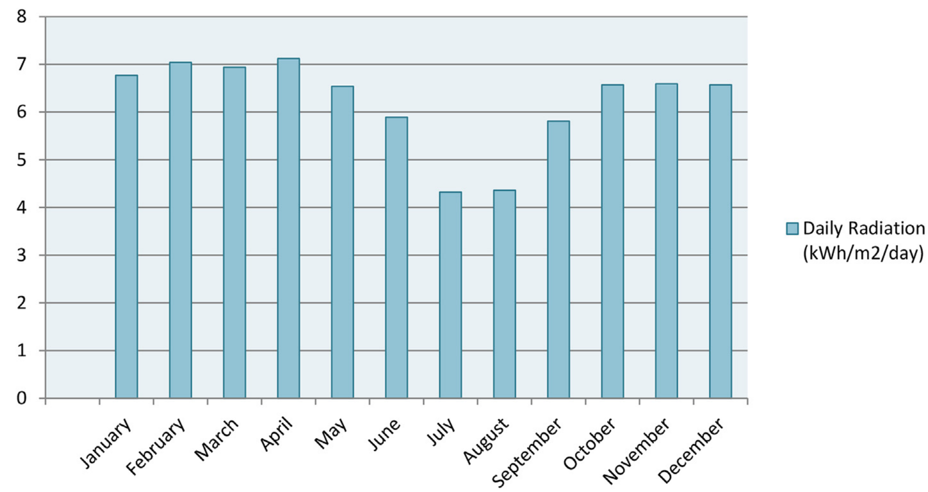

Fig. 1. 22-year monthly averaged DNI at Karachi (Source: NASA [21]).

context data availability and lack of resources is a major issue. Thus, a methodology has been proposed through this research work which utilizes satellite imagery available in public domain to estimate the rooftop PV potential of region of interest. Fig. 3 shows the block diagram of the proposed methodology.

A similar kind of approach for rooftop PV quantification has been adopted as demonstrated by Wiginton et al. [39]. Nevertheless, in this research work physical measurement of sample rooftops and a rigorous field survey of ROI has also been performed. First, Google Earth™ satellite imagery of ROI has been segmented into small geographic units so that land area and population density information can be easily extracted for smaller units. The extracted information has been used for sampling process in which rooftop areas of Phase 7 have been obtained through automated feature extraction technique. In third step, sample information of roof areas has been extrapolated to entire Phase 7 area. In the fourth step, a rigorous field validation process has been performed. Next, total rooftop area has been reduced to analyze available roof area for PV deployment through the physical measurement of sample rooftops and survey of ROI. Energy modeling of a representative sample building has been performed and energy output has been compared to the electrical load of the building. In the last step, an estimate of total output power through deployments of PV system has been obtained and energy output has been compared to local electricity demand of ROI.

3.1. Geographic division

To perform the rooftop area analysis of ROI with more accuracy, it was necessary to divide the entire region into small geographic sub-divisions (GSDs) containing 25–35 building rooftops. Wiginton et al. [39] also used the same technique by dividing the entire region of Ontario, Canada into smaller units based on census subdivisions administrative boundaries. For this research work, scan maps of administrative boundaries of Phase 7 have been obtained. These maps were fully digitized in ArcGIS environment to obtain administrative boundaries of Phase 7 in vector shapefile format. This vector data of administrative boundaries facilitated the division of ROI into GSDs. Similarly, Izquierdo at al. [13], also chose municipal geographical unit in their study of rooftop PV potential of Spain. In the present study, there are 115 non-overlapping GSDs in ROI which together make the entire region.

3.2. Sampling

All 115 GSDs have been sampled on the basis of population density to analyze the relationship of corresponding roof area. With reference to the published literature, it is pertinent to mention here that rooftop extraction process of this research study involving the use of ENVI EX Feature Extraction tool, has not been adopted previously for rooftop PV potential estimation. Sampling has been done as follows.

3.2.1. Roof print area

It was necessary to perform sampling of GSDs to acquire roof print data of ROI. Unfortunately, such required data was not available in public domain. Thus, rooftops of ROI were hand-digitized using high resolution imagery in ArcGIS software to obtain roof print area of ROI. However, as pointed out by Wiginton et al. [39], that this technique of information gathering is not reliable and a more innovative procedure must be used.

3.2.2. Feature Extraction module and input data

Feature Extraction (FE) tool is a module for the extraction of information through panchromatic and multispectral satellite imagery in ENVI EX software. As discussed previously, FE has not been used previously for studies pertaining to quantification of rooftop PV potential. FE has been selected for this research work due to its user-friendly interface where a researcher can interpret more results in less processing time. Behind simple and easy-to-learn interface of FE, there lies a complex object-based image classification algorithm. FE utilizes the machine learning approach where a researcher can “train” the program by assigning objects of unknown identity to one or more feature based on their spatial, spectral and texture characteristics. Similar to Feature Analyst extension of ArcGIS software, FE tool is capable of classifying batches of images simultaneously. Through this research work, an applicability of FE tool has also been assessed for quantification of rooftop PV potential.

Satellite imagery used in this research work has been acquired from Google Earth™. Google Incorporation has readily made available its satellite imagery for scholarly and educational activities under “fair usage” clause of Google permission guidelines (Source: Google Inc. [10], Permission guidelines). As mentioned earlier, Google Earth™ imagery of Phase 7 has been divided into 115 GSDs each having spatial resolution of 0.5 m.

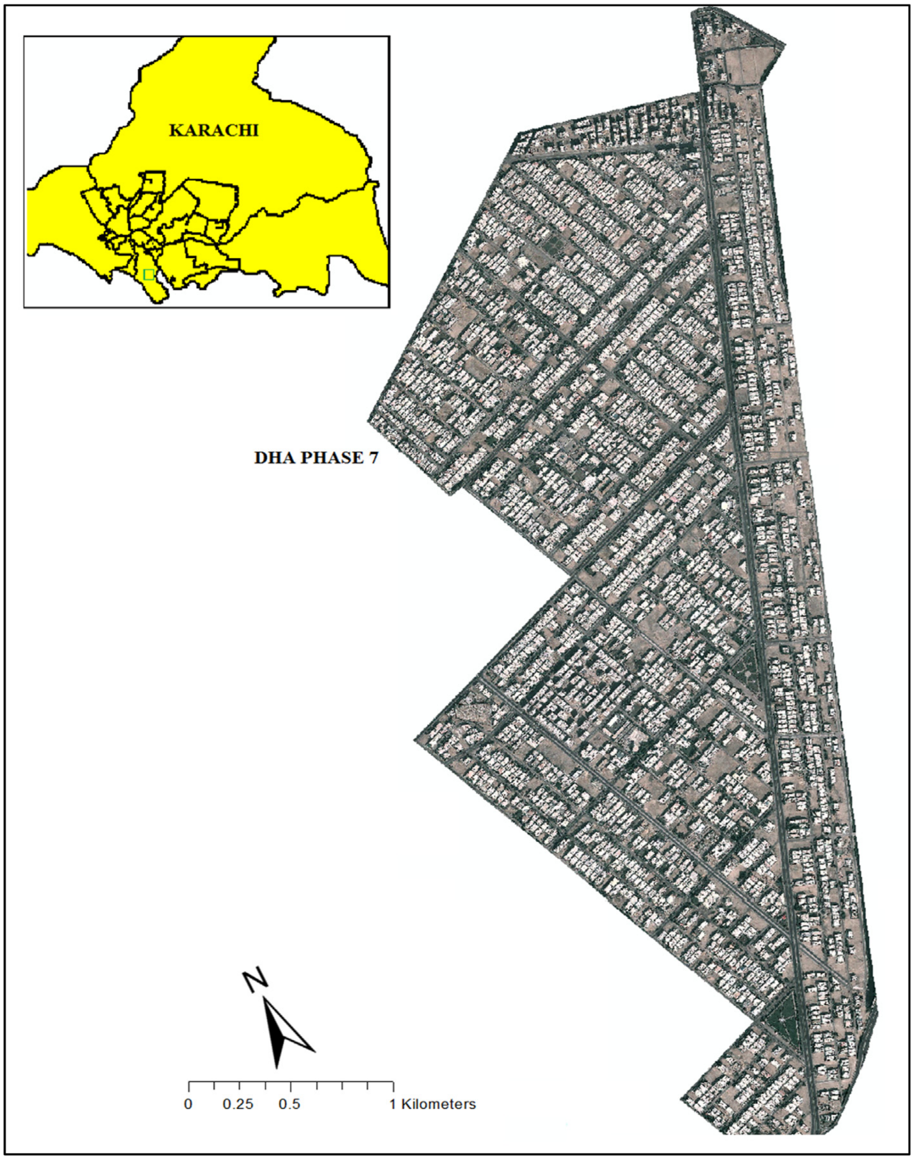

Fig. 2. Google Earth™ satellite imagery of DHA Phase 7 Karachi (ROI).

3.2.3. Selection of samples

Sample selection of GSDs has been done on the basis of population density of ROI. This is evident from the published literature as many researchers such as Wiginton et al. [39], Izquierdo et al. [13], Taubenbock et al. [36], Lehmann and Peter [19], Pratt [28], and Naroll [23] have identified a strong relationship between population density and roof area of the region of interest. Thus, investigating the trend of population density and roof area for both densely populated and sparsely populated is of the utmost importance not only for the rooftop PV quantification but also for the urban sustainability studies. Based on population density information, GSDs have been categorized into three respective classes: low (0–100 persons/hectare), medium (101–500 persons/hectare) and high (above 500 persons/hectare). As discussed previously in Section 2.3 that DHA is an upscale housing development containing sparsely dense area with usually big houses. However, some of its parts are quite dense due to commercial and other settlements. Out of 115 GSDs, 19 were found to be of low population density, 49 were identified having medium population density while 47 were found to be of high population density. A characterization for 10 randomly selected representative samples has been done in following Table 2. Settlement typology has also been addresses in Table 2 which has been illustrated through Google Earth™ imagery and field validation process of Phase 7.

3.2.4. Urban feature extraction process

FE tool has been used in this research work for the identification of urban rooftops in Phase 7. In the context of Karachi, the word “urban” is associated with areas having well-developed infrastructure as well as residential and commercial buildings. FE tool has found to be significantly effective in identifying building rooftops including both residential and commercial settlements. Nevertheless, rooftops which were missed by the tool (flat, gray buildings) have been added through manual digitization process. FE utilizes object-based image analysis technique to extract features of interests from high resolution satellite imagery. Traditional

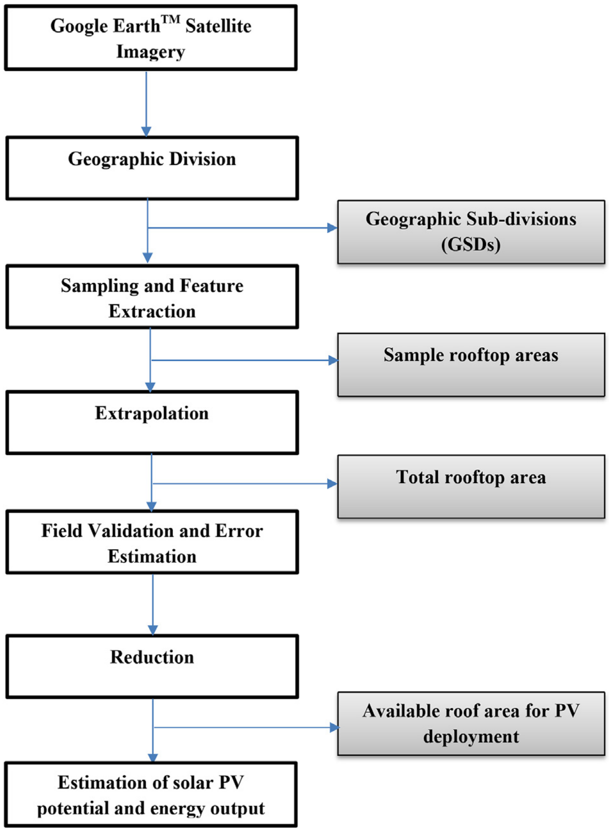

Fig. 3. Block diagram of the proposed methodology for rooftop PV potential assessment.

showing the results of segmentation process where each segment is assigned the mean band values of all the pixels belonging to that specific region. After segmentation, the researcher then merges the segments to combine similar adjacent segments by re-assembling over segmented or highly textured results. User may apply a different combination of segmentation and merging levels to obtain clear boundaries around features of interest as the results of segmenting and merging pixels may be viewed in preview panel all the time. Nevertheless, due to highly similar spectral or texture characteristics of nearby features some misleading features such as vegetation and open space may be regarded as rooftop so a researcher must use a combination of segment and merge level where satisfactory results are obtained. Values of 30 for Segment level and 90 for Merge level effectively delineates the boundaries around impervious surfaces such as roads, sidewalks and rooftops (Source: Digital Globe). Next step is the optional Refinement step where a user has an option to further refine the segmented image by applying the Thresholding technique. Thresholding is suitable for extracting point objects having high contrast values with respect to the background such as bright aircraft against a dark tarmac. FE tool then computes the spatial, spectral and texture attributes which will be used in supervised classification.

In the next step, researcher has an option to classify an input image using rule-based or example based supervised classification technique. In the rule-based classification technique, a researcher applies certain rules on computed attributes to extract impervious surface features from the satellite imagery. However, in this research work supervised classification technique has been employed to extract rooftop features from the input image. Example based or supervised classification technique is the process of utilizing training samples to assign objects of unknown identity to one or more known features.

Table 2
Representative samples of GSDs of ROI with their characteristics.

Geographic subdivision (GSDs)	Population density (persons/hectare)	Population density classification	Settlement typology
Jami commercial area	750	High	Commercial, institutions
Khyaban-e-Badar	630	High	Residential
Khyaban-e-Badbaan	910	High	Residential
Sehar commercial area	840	High	Commercial, institutes
Khyaban-e-Sehar	470	Medium	Residential
Khyaban-e-Abbasi	98	Low	Residential, open space
Khyaban-e-Rizwan	399	Medium	Residential, sparse open space
Khyaban-e-Muhafiz	70	Low	Residential, open pace
Creek Lane	80	Low	Residential, open space
Khyaban-e-Rahat	400	Medium	Residential

classification methods are based on pixel-based approach while object-based method offers more flexibility in the types of features to extract (Source: Exelis Visual Information Solutions [7]). Following sections describe the steps involved in feature extraction process of FE tool. The workflow used to extract building rooftops have been illustrated in following Fig. 4.

In the feature extraction process, a user first segments the input image into regions of pixels based on their similar spatial, spectral and texture based characteristics. For the present case, the input image was Google Earth™ satellite imagery. Segmentation is the process in which a researcher divides the image into segments corresponding to real world features. Segmentation results may be viewed in the preview panel on-the-fly of feature extraction process. FE tool creates a Region Means image which is a raster file

Before performing supervised classification, the researcher must collect the training samples by creating new classes, selecting representative samples of different features and assigning them to various classes such as rooftop, grass, roads etc. When segmentation is complete, the Example-based Classification panel appears with one undefined class. The researcher may rename this class as rooftop and must select segments that corresponds to rooftops in the input image as the training samples of rooftops. Similarly, features which are not rooftops are chosen. The more the training samples a researcher selects, the more chances of better classification results. After selection of training samples for different features, supervised classification is performed. FE offers three methods of supervised classification: K-Nearest Neighborhood (KNN), Support Vector Machine (SVM), and Principal Component

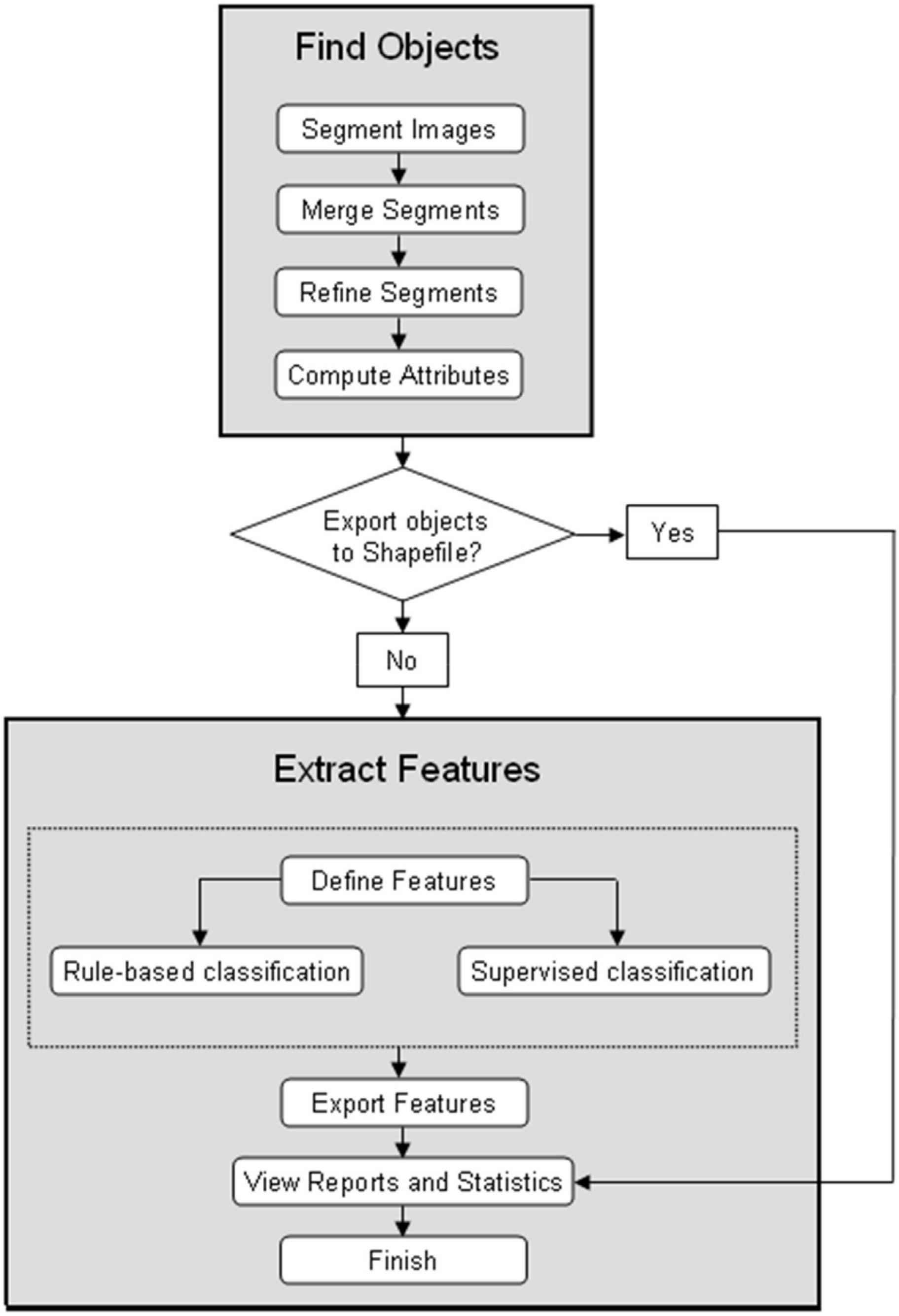

Fig. 4. General rooftop extraction workflow using Feature Extraction tool of ENVI EX software. This method has been repeated for each GSD.

Analysis (PCA). KNN supervised classification method is more rigorous than other two methods and it accurately distinguishes similar classes as it classifies segments based on their proximity to neighboring training regions [7]. Therefore, KNN supervised classification technique has been employed in this research work. The researcher may adjust the KNN settings, collect more training samples or define a new class for unclassified data unless satisfactory classification results are obtained. Through the output panel, the researcher exports the classification results into a raster image or polygon shapefiles of each feature. In the present study, only rooftop features' vector shapefile of each GSD was exported and was overlain to Google Earth™ satellite image of Phase 7 to analyze FE rooftops extraction process. Following Fig. 5 demonstrates the output of an automated feature extraction run in the GSD of Khayaban-e-Rahat where FE rooftop have been shown as orange, while some missing rooftops were hand-digitized and have been shown as yellow polygon features overlain to respective buildings.

In order to reduce the features extraction time, batch classification of all GSD images have been performed after the creation of an automated feature extraction file. Although, FE demonstrate the high level of suitability for rooftop extraction process but some

Fig. 5. Sample automated feature extraction results using FE tool of ENVI EX software. FE rooftops are orange while yellow rooftops are hand-digitized additions. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

difficulties have also been faced by authors during this process. As mentioned previously, some areas in DHA are newly developed or under development and their rooftop feature differs significantly from those previously developed. Second difficulty faced was of spectral similarity among different nearby features. Such difficulties lead toward classification inaccuracies containing false features. In order to overcome this difficulty, a manual cleanup was performed where an inclusion of building shades, spaces between neighboring buildings and other features identified as rooftops were traced and eliminated. In particular, some missing buildings have also been added in final rooftop shapefile of Phase 7. Although, cleanup and manual addition of missing buildings is the part of rooftop extraction workflow but these associated steps have not been shown in Fig. 4.

3.3. Extrapolation

Rooftop extraction has been extrapolated to the entire ROI by relating the roof-area to the corresponding population for each GSD. It is has been demonstrated previously by many researchers such as Wiginton et al. [39], Izquierdo et al. [13], Pillai and Banerjee [27], Ghisi [8], and Kumar [16] that roof area has a strong correlation with population. The relationship of roof area and population in each sample GSD is significant for the determination of roof-area per capita ($A_{roof\text{-}area/cap}$). Then, using the values of $A_{roof\text{-}area/cap}$ and population (p) gross roof area ($A_{roof\text{-}gross}$) for the entire ROI can be extrapolated as demonstrated by Wiginton et al. [39].

$$A_{roof\ (gross)} = A_{roof\text{-}area/cap} * p \quad (1)$$

3.4. Field validation of sample rooftops

Having extrapolated the gross roof-area for ROI, it was necessary to perform field survey of Phase 7. The purpose of field survey was twofold: first, to assess the accuracy of extracted rooftop features as compared to actual measured rooftops and second, to analyze the factors of shading, other uses on rooftops as well as the study of building orientations of ROI. Thus, for the accuracy assessment of extracted rooftops a rigorous field validation survey has been performed in Phase 7 where 10 sample rooftops have been accessed to take physical measurements of rooftop areas. These measurements have been compared to the extracted rooftop areas yielded from satellite imagery feature extraction process. Fig. 6 shows the sample rooftop of GSD Khyaban-e-Ittehad whose extracted rooftop area through FE tool was found to be 200 m^2.

The sample building is a 500 yards bungalow in Sadi Lane 9, DHA Phase 7, Khyaban-e-Ittehad, Karachi having geographic coordinates 24.813422^0 N and 67.076825^0 E. The FE tool during automated feature extraction process yielded its extracted rooftop area as 200 m^2. During field validation work, a rooftop map was developed using AutoCAD® software. Fig. 7 shows the map of sample building rooftop.

The field validation work of sample building rooftop revealed that the actual rooftop area is found to be 19.2 m × 12.2 m = 234.11 m^2. An overhead water tank, open space, roof entrance stairs, and some other uses were also found on sample rooftop. The overhead water tank was of 12.7 m^2, rooftop entrance was of 14.8 m^2, open space was of 16.46 m^2 while other uses were of 6.1 m^2. Total area reserved for different uses on sample rooftop was found to be 50 m^2. Consequently, actual available rooftop area of sample building was found to be 184 m^2. A similar kind of approach was also used by Oka et al. [25] for estimation of potential space for rooftop greening in Tokyo metropolitan region. Following Fig. 8 shows the oblique view of sample rooftop building showing different rooftop uses.

A database of 10 sample rooftops has been created to compare the actually measured rooftop areas and extracted rooftops areas through FE tool. Table 3 summarizes the comparison of actual and extracted rooftops of ROI.

Thus, an average accuracy of 92% has been achieved when extracted rooftops were compared with actual measured sample rooftops. This comparison showed that FE module has proven to be a powerful tool for rooftop PV potential estimation pertaining to any region of interest. During the field validation process, a survey of buildings of ROI has also been performed to analyze the building orientation and shading effect. This has been explained in detail in next section.

3.5. Reduction

Once the gross rooftop area has been computed, reduction must be made in the roof area considering the different kinds of rooftop uses such as shading effect, overhead water tank, chimneys and other uses. Building orientation is of the utmost importance and must also be accounted for reduction to obtain actual available rooftop area for PV installations. Field survey of ROI revealed that 95% of the total roof area contains small and large but flat buildings

Fig. 6. One of sample rooftops of DHA Phase 7 Karachi for field validation work. Location of above sample rooftop (GSD: Khayaban-e-Ittehad, DHA Phase 7, Karachi) has also been mentioned in figure.

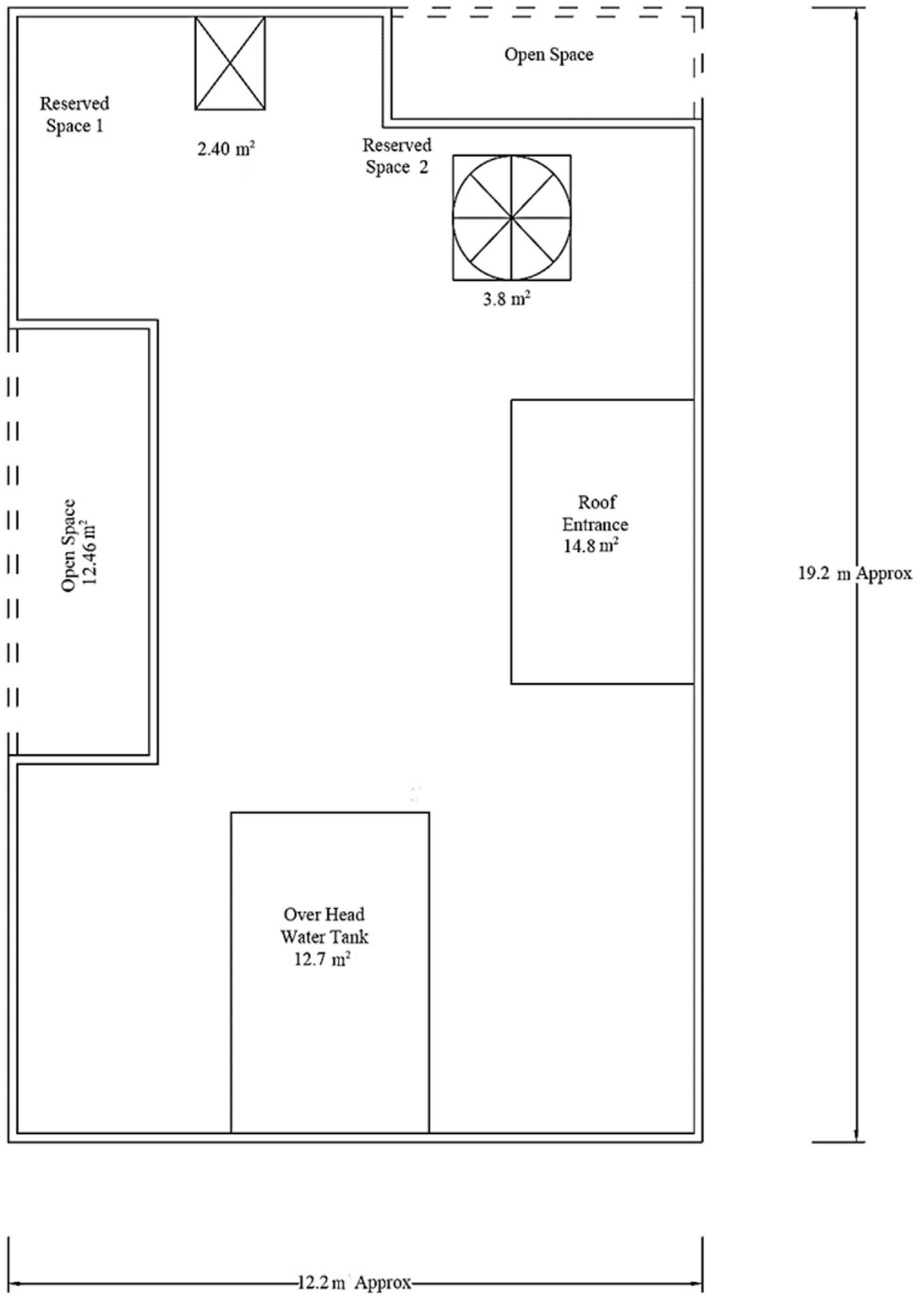

Fig. 7. Map of sample rooftop 1 located in ROI Khyaban-e-Ittehad (refer to Table 3) for calculation of actual rooftop area.

($R_{\boldsymbol{flat}} = 0.95$). Flat buildings do not undergo for the reduction in area and are unaffected by building orientation ($B_{\boldsymbol{flat}} = 1$). Only 5% of the total buildings in ROI have been identified as peaked buildings ($R_{\boldsymbol{peaked}} = 0.05$). Buildings with peaked rooftops are considered to have 50% south-facing area suitable for rooftop PV installations ($B_{\boldsymbol{peaked}} = 0.5$). Thus, considering the building orientations the fraction of properly oriented roof area (ROF) may be computed as follows using the approach of [39]:

$$ROF = R_{flat} * B_{flat} + R_{peaked} * B_{peaked} \tag{2}$$

$$ROF = 0.95 * 1 + 0.05 * 0.5 = 0.975 \tag{3}$$

The next factor that must be accounted for the reduction in roof area is shading, rooftop other uses and PV installations and servicing. Factors of unshaded area and building orientation together yield the fraction of available rooftop area that may be utilized for PV installations. Different researchers used different values of fraction of available roof areas in their research initiatives such as Wiginton et al. [39] used the value of 0.30 while Izquierdo et al. [13], used the available roof area fraction as 0.34. Lehmann and Peter [19] used the value of 0.90 while Scartezzini et al. [31] utilized available fraction of roof area as 0.95. For the case of present research work, it is evident from the field survey of sample rooftops that approximately 20–25% of total roof area is reserved for water tank and other uses and considering the effect of shading from nearby trees and buildings, the fraction for shading and other rooftop uses is taken as:

$$R_{\boldsymbol{shading}} = 0.35 \tag{4}$$

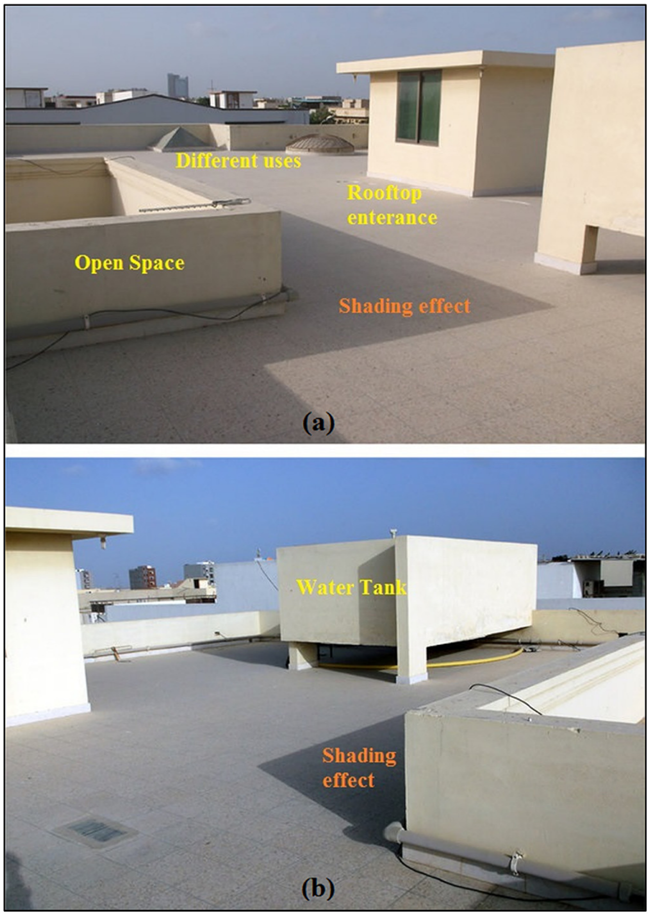

Fig. 8. Above image (a) presents an oblique view of sample rooftop 1 (ROI: Khyaban-e-Ittehad) showing different rooftop uses and shading effect while image (b) shows another oblique view of the same sample rooftop 1 showing water tank etc.

3.6. Estimation of rooftop PV potential

3.6.1. Rooftop PV power potential and energy output

Having obtained the available roof-area for PV deployment for the entire ROI, the solar power potential and energy output for Phase 7 area may be computed. Rooftop PV potential is mainly dependent on the efficiency of PV module utilized for generating solar electricity. Thus, selecting the high efficiency and best performance solar panel is of the utmost importance. Efficiency and performance factors of different types of PV panels vary according to their manufacturing technology and material used. Table 4 summarizes the efficiencies and characteristics of different types of PV panels to exhibit various scenarios of solar power generation for ROI.

Estimation of rooftop PV potential power also depends on solar global insolation (I_g) measured under global AM 1.5 spectrum of 1000 W/m^2 and available rooftop area for PV deployment i.e., $A_{(PV)}$. Considering all the factors, solar power potential (P) may be computed as:

$$P = I_g \times eff \times A_{(PV)} \tag{7}$$

For an annual energy output, the mean daily global insolation on a horizontal link (I_{mdh}) must be considered. According to NASA Surface meteorology and solar energy database, I_{mdh} for Karachi is 5.448 kWh/m^2/day. Thus, the annual energy output may also be computed as:

$$E = I_{mdh} \times 365 \times eff \times A_{(PV)} \tag{8}$$

3.6.2. Energy modeling for sample building

Prior to the estimation of rooftop PV potential and energy output for the entire region at macro-scale, the real-time analysis of solar energy output for the sample building of ROI has been performed to analyze the energy yield at micro-scale and its comparison with building's real time electrical load. The main objective of

Table 3
Comparison of extracted and actually measured rooftops. Note that map of sample rooftop 1 has been shown in Fig. 7 for actual measurements performed.

Sample	Location in ROI	Actual measured rooftop area after the elimination of roof uses (m^2)	Extracted rooftop area (m^2)	Percentage of accuracy
Rooftop 1	Khyaban-e-Ittehad	184	175	95%
Rooftop 2	Khayaban-e-Badar	240	219	91%
Rooftop 3	Jami Commercial Area	280	262	94%
Rooftop 4	Khyaban-e-Sehar	220	192	87%
Rooftop 5	Khyaban-e-Abbasi	175	163	93%
Rooftop 6	Khyaban-e-Rizwan	170	151	88%
Rooftop 7	Sehar Commercial Area	290	268	92%
Rooftop 8	Khayaben-e-Sehar	135	122	90%
Rooftop 9	Khyaban-e-Badbaan	270	260	96%
Rooftop 10	Creek Lane	260	242	93%

Thus the available roof area for PV installations (A_{PV}) is the total roof area reduced by shading and building orientation factors:

$$A_{(PV/capita)} = A_{roof\text{-}area/cap} * ROF * R_{shading} = A_{roof\text{-}area/cap} * 0.34 \tag{5}$$

And it may be extrapolated for the entire ROI using its population:

$$A_{(PV)} = A_{(PV/capita)} * p \tag{6}$$

Table 4
Overview and comparison of four different types of PV technologies.

PV technology	Module efficiency	Panel output (W/m^2)
Mono-crystalline Si (c-Si)	22.9%	229
Poly-crystalline Si (p-Si)	18.5%	185
Amorphous Si (a-Si)	12.2%	122
Cadmium-Telluride Cells (CdTe)	17.5%	175

Source: Efficiencies of PV panels have been taken from Green et al. [11] measured under global air mass (AM) 1.5 spectrum (1000 W/m^2)

energy modeling for the sample building was to analyze energy yield at micro-scale only and analyses have not been replicated for whole Phase 7 area. Energy modeling tool HOMER has been used for micro-scale solar energy analysis. HOMER has been developed by National Renewable Energy Laboratory (NREL) [22]. Brown and Rowlands [4] highlighted the capability of HOMER as a powerful tool containing optimization algorithms, sensitivity analysis algorithms as well as economic optimization model. It is capable of yielding hourly power output which is based on input parameters for solar PV applications. According to NREL's HOMER User Guide 2011, HOMER performs simulations of PV systems by making energy balance calculation for each of 8766 h of a year. HOMER has been used by many researchers for urban solar energy modeling and renewable energy optimization analysis such as Akella et al. [2], Simic and Mikulicic [32], Dalton et al. [6], Chow et al. [5], and Jamal et al. [14]. The sample building has been shown in Fig. 6. Monthly electrical load data of the sample building has been acquired and it has been shown in following Fig. 9.

Incident solar radiation is a critical factor for the efficient performance of PV modules. HOMER uses insolation data from NASA's Surface Meteorology and Solar Energy Database, which provides 22 years monthly averages of solar radiations data for any location around the globe. The data set consists of Monthly Averaged Direct Normal Irradiation (DNI) (kWh/m^2/day) and is based on location's latitude. Using the Graham algorithm, HOMER then generates hourly synthetic data of solar radiations for full 8766 h of a year. Hence, analysis performed with this data will not necessarily represent actual characteristics of the insolation for any specific location and thus highlights a limitation of this research work. To perform solar energy modeling for both grid-connected or off grid system, HOMER needs some basic information such as the system configuration, load profiles, components specification and resource data such as insolation data, economics and environmental parameters. However, the main objective of energy modeling at micro-scale was to compare the yearly solar power production with real-time electrical load of the building and economic as well as environmental analysis was beyond the scope of the paper. Sample building for energy modeling lies in GSD Khyaban-e-Ittehad area which is served by 132/11KV DEFENCE grid station. The load profile of June 01, 2015 has been acquired for DEFENCE grid station from KE Load Dispatch Centre (LDC), Karachi. May and June are usually the hottest months in this region thus receiving higher solar radiations. Fig. 10 shows the average daily load profile of DEFENCE 132/11 KV grid station.

To integrate the effect of seasonal variations on load curve, user needs to provide different load profiles for different months or day types. However, for the case of present research work lack of availability of electrical load data for the whole year represented a difficulty for seasonal variations analysis of load curve. However, HOMER computed the seasonal profile of load curve based on average daily load profile and has been shown in following Fig. 11.

PV system can be with or without battery backup. Excess electricity can be stored in battery storage. In the present study, the whole PV system has been designed to be the grid-tied system without battery backup since electricity will be supplied from both sources i.e., from PV system during day time and from KE grid at night thus optimizing the efficient use of naturally available solar energy to cater daily electricity requirements. The system comprised of PV panel, Converter and Grid. System parameters have been selected from market survey. Following Fig. 12 shows the model of the grid-tied PV system.

Simulations in HOMER shows that due to tremendous amount of solar resource available throughout the whole year, deployment of rooftop PV systems would be most beneficial to cater daily electricity requirements for the inhabitants of DHA in particular and Karachi in general. Simulation results have been tabulated in following Table 5.

HOMER simulation results in Table 5 shows that the annual AC load consumption is found to be 881 kWh/year while PV array energy production for the sample building will be 979 kWh/year. The annual AC load consumption has been computed by HOMER based on average daily load profile input data and is associated with lack of availability of data constraints. However, results show that there will be a significant energy production through rooftop PV system in the day time and electricity load burden on feeder will almost be negligible. Consequently, the excess electricity generated could also be stored with the help of battery backup to utilize solar electricity throughout the whole day. Thus, the amount of energy yield through the utilization of naturally available solar energy would be sufficient to cater the electricity requirements of sample building throughout the whole year. The surplus electricity can also be fed back to the main grid thus ensuring an incentive of feed-in-tariff (FIT) for the consumer. However, in case of grid connected PV system without battery backup, the electricity will be supplied from feeder at the night time. In particular, utilization of solar energy for daily electricity requirements would be helpful to

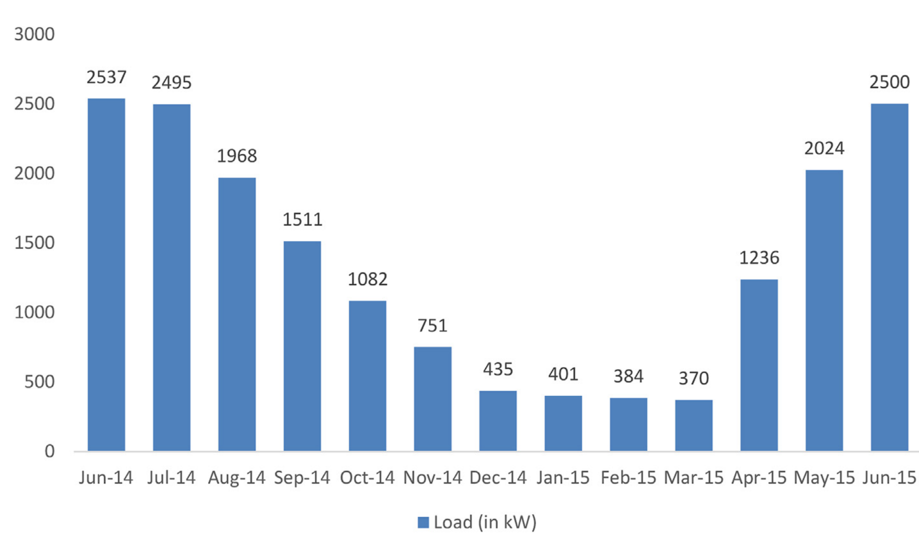

Fig. 9. Monthly electrical load requirement data of the sample building.

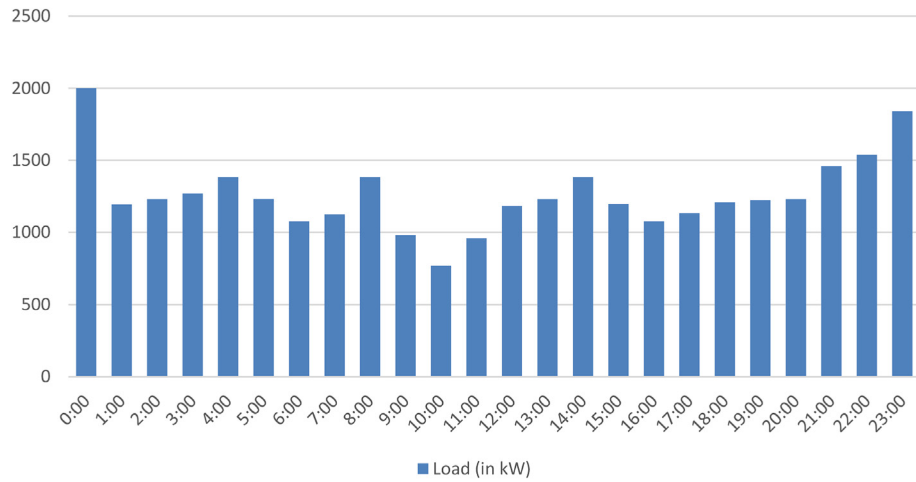

Fig. 10. Average daily load profile of 132/11 KV DEFENCE grid station. Source: LDC, KE.

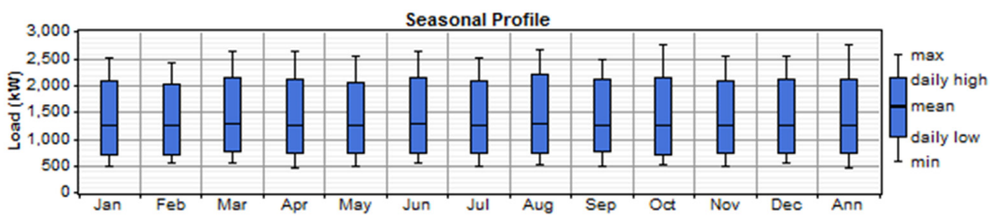

Fig. 11. Seasonal profile of load curve.

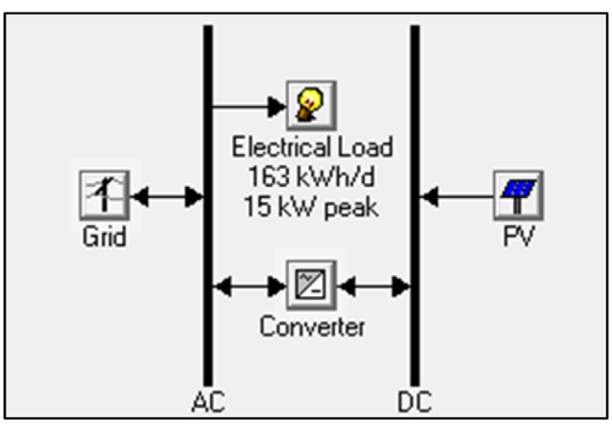

Fig. 12. Model of the grid-connected PV system (without battery backup) for sample building.

Table 5
Simulations results of solar power production from rooftop PV system.

Production	
PV array	979 kWh/year
Consumption	
AC primary load	881 kWh/year

minimize power distribution losses and an awareness to promote green energy in the region could be created. It is also worthwhile to mention that if rooftop PV systems are installed on all buildings of Phase 7 area, the enough amount of electricity could be generated to fulfill the electricity requirements of this region only utilizing freely available solar energy.

4. Results

4.1. Key findings

After geographic division and sampling of GSDs, roof area has been plotted against population to acquire their relationship required for the extrapolation process. The relationship of roof-area and population is significant for the estimation of roof-area per capita. In a set of 10 sample GSDs selected for these analysis, a constant linear relationship has been observed between total roof area and the population of each GSD as shown in following Fig. 13. The linear relationship having an R-squared value of 0.978, shows a strong positive correlation across both small and large GSDs of ROI. The relationship in Fig. 6 also indicates a total roof area of 13m^2/capita ±5% which is to be used in equations (1) and (5) as well as a base value (b) of 1,038 m^2 for ROI. The value of intercept may be explained due to the sparsely developed infrastructure of Phase 7 containing large vacant spaces and under development areas with very less number of inhabitants. Nevertheless, the value 1038 m^2 is well within the error and it will be disregarded in the further analysis.

A comparison of roof-area per capita of this research work with previous research initiatives reveals that 13 m^2/capita is a reasonable estimate of roof area per person considering the context of DHA Phase 7 Karachi due to the following reasons:

- Phase 7 is a smaller area of DHA, Karachi approximately expanding to 2.608 Km^2
- Phase 7 is well developed area of Karachi with sparsely dense buildings as compare to other areas of Karachi
- Some of the land is under development phase for new houses

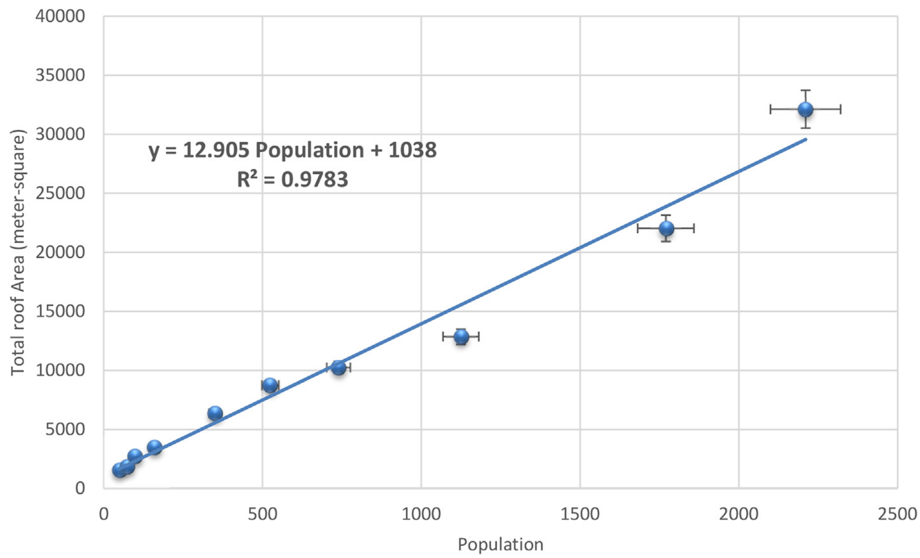

Fig. 13. Total roof area as a function of population. Error bars represent a 5% error on each data point.

- Large vacant spaces

It is worthwhile to mention that in this research work, roof area per capita has been estimated after reduction of building orientation factors, shading effect and other roof uses as depicted in Fig. 8. On the contrary Izquierdo et al. [13], reported a range of 24.4–180.5 m^2/capita for Spain before the reduction of shading and other factors. However Wiginton et al. [39], reported a roof area per capita of 70 m^2 for the region of Ontario, Canada after reduction of constraint factors. Building density and urban sprawl are the consequential parameters having a direct influence on variation of roof area per capita in different regions. This is evident from research work conducted by Ghisi [8] who reported a range of 17.6–21.2 m^2/capita for Brazil. While Pratt [28], even reported a range of 10.6–30.7 m^2/capita in the United Kingdom.

It is pertinent to mention here that the value of 13 m^2/capita $\pm$5% of the total roof area is of the utmost importance as it is not only significant for the estimation of rooftop PV potential but also for urban sustainability studies of the region. Nevertheless, the relationship analyzed between population and roof area is an overall approximation for the combination of different land uses as GSDs contained different types of settlements such as residential buildings, commercial buildings, educational institutes and other land uses. In addition to the relationship of population and roof area, a fairly complex relationship of population density and roof area per capita also exists for the smaller scale. Researchers such as Wiginton et al. [39], Izquierdo et al. [13], Lehmann and Peter [19], Taubenbock et al. [36] and Pratt [28] have investigated this relationship in their research work. Lehmann and Peter [19] reported that for non-residential buildings, roof area per capita decrements with a cubic function as population density increases while for residential buildings it decreases with a quadratic function.

The roof area per capita has been extrapolated to entire ROI using equation (1), yielding a value of 157,326 m^2/capita $\pm$5%. This value is significant as it can be used for the urban solar planning of DHA Phase 7, Karachi. This computed value of roof area per capita must be reduced by considering all constraint factors for solar PV applications. Using equation (5), the area available for PV per capita, $A_{(PV/capita)}$, has been calculated to 4.42 m^2/capita $\pm$5%. Next, this available roof area for PV per capita has been extrapolated to the entire ROI using equation (6), thus yielding a value of 53,491 m^2 $\pm$ 5%. This value depicts an available rooftop area of Phase 7 which is suitable for PV deployment as it addresses building orientation factors, shading effect and is free from other rooftop uses.

Finally, equations (7) and (8) have been used to approximate the solar power potential and annual energy outputs utilizing available roof area for PV installations. Results have been summarized in following Table 6. Different scenarios according to PV panels' efficiencies have been presented for Phase 7 area.

It is clear from Table 6 that solar potential power of 12.24 MW and an annual energy output of 24.35 MWh will be significant for Phase 7 area to cater daily electricity requirements with large scale deployment of crystalline-silicon PV panels. Thus, a considerable contribution could be made through the installations of rooftop PV systems to DHA Phase 7 grids. Following Table 7 summarizes the ability of rooftop PV systems to meet the peak power demand of ROI.

It is evident from Table 7 that rooftop PV systems could play a vital role in meeting power demands in DHA Phase 7 Karachi. If rooftop PV panels are utilized for solar power production, then mono-crystalline Si based PV systems can provide 122.4% times the peak power demands of Phase 7 area, while poly-crystalline PV systems can achieve 98.9% of the power demands. Similarly, amorphous silicon and cadmium-telluride based PV systems can meet 65.2% and 93.6% of the peak power demands of ROI respectively. This shows the immense potential for the deployment of rooftop PV systems for sustainable solar power generation in DHA Phase 7 Karachi.

4.2. Comparison with previous research initiatives

The present research work is a first of its kind research initiative for the estimation of rooftop PV potential of this region as no earlier estimate has been found in published literature addressing rooftop PV potential of Karachi. However considering the global scenario, many researchers have conducted studies for different regions across the globe for rooftop PV potential estimation. In this section, comparison of present research work with most relevant previous research initiatives has been done. Recently Rhythm and Banerjee (2015) [33], estimated rooftop PV potential of Mumbai (India) utilizing Google Earth™ satellite imagery similar to the present study while rooftop PV simulation software *PVsyst* has been used for

Table 6
Solar power and energy outputs for DHA Phase 7 Karachi based on four PV panel scenarios.

Solar PV panel type	Module efficiency	Power output for ROI (MW)	Annual energy output for ROI (MWh)
Mono-crystalline Si (c-Si)	22.9%	12.24	24.35
Poly-crystalline Si (p-Si)	18.5%	9.89	19.67
Amorphous Si (a-Si)	12.2%	6.52	12.97
Cadmium-Telluride Cells (CdTe)	17.5%	9.36	18.61

Table 7
Significance of rooftop PV systems to meet peak power demand of DHA Phase 7 Karachi.

Solar PV panel type	Power output for ROI (MW)	Percentage of Phase 7 peak power demand (10 MW)
Mono-crystalline Si (c-Si)	12.24	122.4%
Poly-crystalline Si (p-Si)	9.89	98.9%
Amorphous Si (a-Si)	6.52	65.2%
Cadmium-Telluride Cells (CdTe)	9.36	93.6%

Source: Power demand has been obtained from K-Electric [15].

modeling purpose. Similar to this research article Jamal et al. [14], have also used HOMER for energy modeling and rooftop potential mapping for Dhaka city, Bangladesh. Chow et al. [5], also used HOMER energy modeling tool for urban solar energy modeling. In this research work, although a similar kind of methodological approach has been used as Wiginton et al. [39], but field validation of extracted rooftops has been performed and Feature Extraction module of ENVI EX has been used in contrast to the research work conducted by Wiginton et al. [39]. While validation process of extracted and physically, a similar approach has been used as Oka et al. [25], to analyze the available space for rooftop PV deployment however, analyses have been performed through physical measurements and visual inspection of buildings.

4.3. Limitations and errors

Few limitations in this research work have also been identified which have been discussed in this section one by one. For the sampling purpose, roof print area of Phase 7 was required which was not available in public domain. However, hand-digitization technique was used to generate roof print area of ROI for sampling purpose of GSDs. In particular considering the human error, it represented a limitation of this research work. Thus, a more rigorous method of information gathering must be used to analyze roof print area of region of interest. Lack of availability of weather ground observatories data highlighted another limitation of research work. To perform the HOMER simulations that would reflect real characteristics of insolation of DHA and its nearby areas, weather data from ground observatories is indispensable. However, lack of measurement facilities at these weather observatories is also one of the limitations in real time analysis of insolation scenario of DHA. For this reason, 22-years insolation data of DHA, Karachi from NASA's SSE database has been acquired. In HOMER analysis, another limitation was identified in form of lack of availability of electrical load profile for different days and months of the year. Dataset from KE indicating load curve variations of different seasons must be used for more in-depth analysis of energy modeling.

During the analysis, some sources of error have also been identified in this study. The errors occurred during rooftop extraction process using FE tool when many of the buildings i.e., large, flat and gray buildings were missing in the extraction results and were outlined by manual digitization and therefore presented an error due to missing buildings in the feature extraction process which was less than 5%. Although, FE tool workflow has been shown in Fig. 4 but manual cleanup was also performed for each GSD's rooftop feature extraction process. Reason being due to spectral similarities many of the features were identified as rooftops such as nearby grass, gaps between consecutive buildings and open spaces etc. so a manual cleanup has been performed to minimize these feature extraction inaccuracies. In particular, some missing rooftops have also been added manually. However, the overall average absolute error in rooftop extraction on Google Earth™ satellite imagery was less than 10%. This occurrence of error is directly dependent on the number of samples selected for the analysis and for large number of sample GSDs the identified error could be minimized. Moreover, ±5% error has been reported in roof area per capita values. In particular, the linear relationship of total roof area and population is based on an overall approximation of sample GSDs and contains 5% error.

The main focus of this research work was on the estimation of rooftop PV potential. Thus, a basic approach has been used to estimate PV power and energy output for small scale regional analysis. It is pertinent to mention that such an analysis might have been associated with some additional error considering the basic approach of analysis performed.

5. Discussion and conclusion

The annual energy output from the deployment of rooftop PV systems in Phase 7 area as shown in Table 7, exhibits an important role that solar power technologies can play for sustainable power generation. Such an enormous amount of annual energy yield can have a direct influence on local electricity infrastructure by minimizing line losses and consumers can be benefited through the incentive of FIT. This will also promote diffusion of PV to cater local electricity demands thereby preventing the depletion of fossil fuel reserves. Recently, due to “heat wave” a drastic change in local air temperature of Karachi has been observed due to an excessive amount of carbon dioxide and other hazardous gases in the environment. Rooftop PV systems with its environmental friendly nature may be an alternative and sustainable solution to meet daily energy requirements of Karachi metropolis. It is pertinent to mention here that the mega city of Karachi with its millions of urban households has a great potential for the deployment of rooftop PV systems. However, lack of government's interest and implementation policies has been a real hindrance in an adoption of solar power technologies for sustainable power generation.

Ever since the inception of Pakistan's renewable energy policy in 2006, there has been no real progress in this field. Although, government agencies such as Alternate Energy Development Board

(AEDB) and Pakistan Council of Renewable Energy Technologies (PCRET) have been in operation even before the inception of national renewable energy policy but there has not been a major development in this field with an exception of Quaid-e-Azam Solar Park recently established by the Government of Punjab, Pakistan. Unfortunately, the progress of national renewable energy policy has been slow. Although, solar PV technologies have been used in the mega city of Karachi but their usage is limited to small scale applications only. The role of solar energy to bridge the gap of energy demand and supply in Karachi in particular and in Pakistan in general is significant. Solar power technologies has the tendency to bring energy security, provide socio-economic benefits to the people and most importantly to mitigate climate change. Thus, this research work highlights an immense need of policy framework by concerned government agencies that would promote diffusion of PV in Karachi metropolis for rooftop solar PV applications.

In this research article, geospatial tools and techniques have been combined with feature extraction algorithms to develop an understanding of solar energy potential of DHA Phase 7 Karachi through the deployment of rooftop PV systems. Since no earlier estimates of this region have been found in published literature so initially a small area of Phase 7 has been selected as ROI for more specific estimation of rooftop PV potential. Whole area of DHA, Karachi could be explored in future to analyze solar power potential of this upscale residential settlement of Karachi with well-developed infrastructure. A six step methodology has been adopted for the estimation of rooftop PV potential of Phase 7 Karachi which involves geographic division of high resolution satellite imagery; sampling and rooftop feature extraction using FE tool of ENVI EX software; extrapolation of rooftop areas for the entire ROI using roof area-population relationship; visual inspection to compare extracted rooftops with actual physical measured rooftops and also to analyze rooftop factors such as building orientation, shading effect from trees and nearby buildings and other roof uses; reduction for shading, building orientation etc. based on visual assessment of buildings; and finally conversion to energy and power outputs. It is worthwhile to highlight here that the adopted methodology contains a broad set of parameters and techniques that may be modified to estimate rooftop PV potential for any region in general.

This research work has also demonstrated the applicability of Feature Extraction module of ENVI EX software for quantification of PV potential for the region of interest. Analysis shows that FE tool works well for rooftop feature extraction with an acceptable limit of errors which could be minimized through the selection of large number of samples. FE tool also facilitated in investigating the relationship of roof area and population and constant roof area of 13 m^2/capita has been computed for DHA Phase 7 Karachi. This value of roof area per capita is of the immense importance and it is not suitable for rooftop PV quantification studies but it is also highly suitable for urban sustainability related work such as rooftop greening applications, rainwater runoff, urban solar planning and land use planning to name a few. Solar power potential and annual energy outputs for different scenarios of PV technologies have been computed. It has been realized that mono-crystalline Si based rooftop PV systems could provide 122.4% of the DHA Phase 7 peak power demands. Through this first of its kind research initiative, an understanding of roof area with PV potential and energy outputs has been developed which has an immense significance for policy framework to shift Karachi metropolis towards sustainability path.

6. Future work

During the analysis of this research work, many future directions have been identified to further expand and strengthen the key findings shown here. First, increasing the area of region of interest and number of samples used for sampling purpose would definitely further minimize the error estimates. The collection of more roof area-population points across whole DHA and the mega city of Karachi would facilitate in confirming the roof area-population relationship identified in this research work. Considering the scenario of Karachi metropolis in contrast to DHA, there are very densely populated areas with slums and Katchi Abadis having diversified rooftop structures thus roof area-population relationship could be explored with more in-depth analysis. Administrator Karachi and management of district municipalities of Karachi should be encouraged to make available roof print area of all districts of Karachi as this data is critical for rooftop PV potential analyses. To improve the accuracy of shading and building orientation conversion factors, a more detailed analysis for shading and other roof uses for DHA and whole Karachi would be performed. These analyses could be further refined by considering solar panels tilt and azimuth angles. Finally, a more in-depth analysis of the ability of rooftop solar panels to meet the electricity demands of DHA and Karachi by considering seasonal variations and spatial distribution of insolation across whole city of Karachi.

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