Implementation of Open Source GIS Tools to Identify Bright Rooftops for Solar Photovoltaic Applications – A Case Study of Creek Lanes, DHA, Karachi

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Abstract: The mega city of Karachi is still mainly dependent on conventional sources of energy to cater its daily electricity requirements. Dependence on conventional sources of energy for power production results in environmental degradation and depletion of fossil fuel resources. In particular, it also highlights an immense need of alternate sustainable solution for current electricity generation scenario. In this research work, an innovative methodology has been proposed to identify bright rooftops using open source geographic information system (GIS) tools which may be utilized for sustainable power generation in Karachi metropolis. First, bright rooftops have been extracted using open source Quantum GIS (QGIS) software. Edge extraction technique using gradient filter; an open source algorithm of QGIS has been utilized. Furthermore, image processing techniques have been used to extract and refine building rooftops. Then, rooftops have been polygonized and their area has been calculated using Measure Area function of QGIS. To assess the accuracy of the extracted rooftops, field validation work has been performed and sample rooftops have been physically measured. A comparison of extracted and physically measured sample rooftops yielded 90.45% accuracy. Reduction in total roof area has been made considering different roof uses and shading effect from nearby trees and buildings. Then, unshaded bright rooftops area of 4,626 m^2 has been calculated which can be used for solar photovoltaic (PV) applications in Creek Lanes, DHA Phase 7 Karachi. An annual energy output of 2.1 MWh has been estimated using Crystalline Silicon (c-Si) solar PV panel and available rooftop area. The methodology adopted can be extrapolated to macro-scale as well. However, challenges and limitations for extrapolation of methodology have also been highlighted. Solar radiation studies that demonstrate the use of open source GIS tools for sustainable power generation for this region have been scarce. Thus, this study is a preliminary research work to highlight an immense solar electricity potential that exists for Karachi metropolis.

Keywords: Solar PV, QGIS, Karachi, electricity generation, rooftops.

INTRODUCTION

Energy is the driving parameter that plays a vital role in a nation's economic development. Without a sufficient provision of energy, economic prosperity is badly affected [1]. The mega city of Karachi with an installed power generation capacity of 2341 MW has been under long prevailing energy crisis. Electricity generation in Karachi is mainly dependent on fossil fuels and the role of renewable energy in current energy mix of the mega city is almost negligible. Relying on only conventional sources of energy to meet daily electricity requirements leads towards environmental degradation in form of hazardous gas emissions as well as depletion of fossil fuel resources. In particular, Naz and Ahmed [2] highlighted the fact that due to energy demand and supply gap associated with malfunctioning in power generation and distribution, hours of power outage has become a routine in Karachi metropolis which varies by income groups, districts and towns. The mega city of Karachi is blessed with its geographic location and it has an annual average Direct Normal Irradiance (DNI) of 6.20 kWh/m^2/day [3]. With such a significant availability of solar energy throughout the whole year, the millions of urban houses hold a promising potential for rooftop PV systems which could be utilized for the sustainable electricity generation in Karachi metropolis.

Researchers across the globe have been using different tools and techniques to utilize the significant potential of renewable energy for sustainable power generation these days. Among such tools, GIS has now become a mature technology and it has been used by many researchers to estimate rooftop PV potential in different regions of the world. However, it is worthwhile to mention that use of GIS tools is associated with an availability of commercial software and data thus highlighting its cost constraints. Therefore, the main objective of this research work is twofold – first, an identification of bright available rooftops' area for solar PV applications in the region of interest and second, the use of open source GIS tools to analyze their capability for rooftop PV potential

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estimation studies. Open source GIS tools have already been used by many scientists for rooftop PV assessment studies. Recently, Liang *et al*., [4] used an open source 3D GIS model to assess PV potential in urban areas. Ames *et al*., [5] designed and developed an open source map based software i.e., PV Mapper for the analysis of large scale PV systems. Similarly, Nguyen and Pearce [6] utilized *r.sun* module of an open source software GRASS GIS to integrate the effect of shading losses in rooftop PV potential assessment as well as for rooftop PV potential yield [7]. Hofierka and Kanuk [8] also used *r.sun* module of GRASS GIS and PVGIS web based open source solar radiation database to estimate rooftop PV potential in urban settlements. Suri *et al*., [9] developed PV-GIS which is a free and an open source web-based solar radiation database to estimate PV potential yield across entire Europe. Recently, PV-GIS has been expanded to cover the areas of Africa [10] and Asia as well. At this juncture, it is pertinent to mention that studies pertaining to rooftop PV potential estimation using open source GIS tools for Pakistan in particular and for Asia in general have been scarce.

In this research work, publicly available open source GIS tools have been utilized to identify bright rooftops for solar PV applications in a small residential area of Karachi, Pakistan. Bright rooftops have been extracted using QGIS software and digital image processing techniques. Field validation of sample rooftops has been performed to analyze the accuracy of extracted rooftops. A comparison of extracted and physically measured rooftops has been made. Different factors of shading and other roof uses must be accounted to obtain rooftops' usable area thus, a reduction has been made in extracted rooftop area based on field survey and published literature. Bright available rooftop area has been calculated which can be further utilized for solar PV applications such as the installations of rooftop PV systems to generate sustainable electricity. Bright rooftops identified at micro-scale can be extrapolated to macro-scale of whole DHA area with some limitations to assess the rooftop PV potential for the entire region of interest. Rooftop PV potential studies of this region have been scarce so this research work is a preliminary research work to highlight a significant potential of rooftop PV systems utilizing open source GIS tools and techniques.

Study Area and Data

Defence Officers Housing Authority (DHA) is an upscale residential enterprise having an area of 35.82 Km^2. Its lies in southern part of Karachi having geographic coordinates as $24^0 49'16"$ N and $67^0 04'23"$

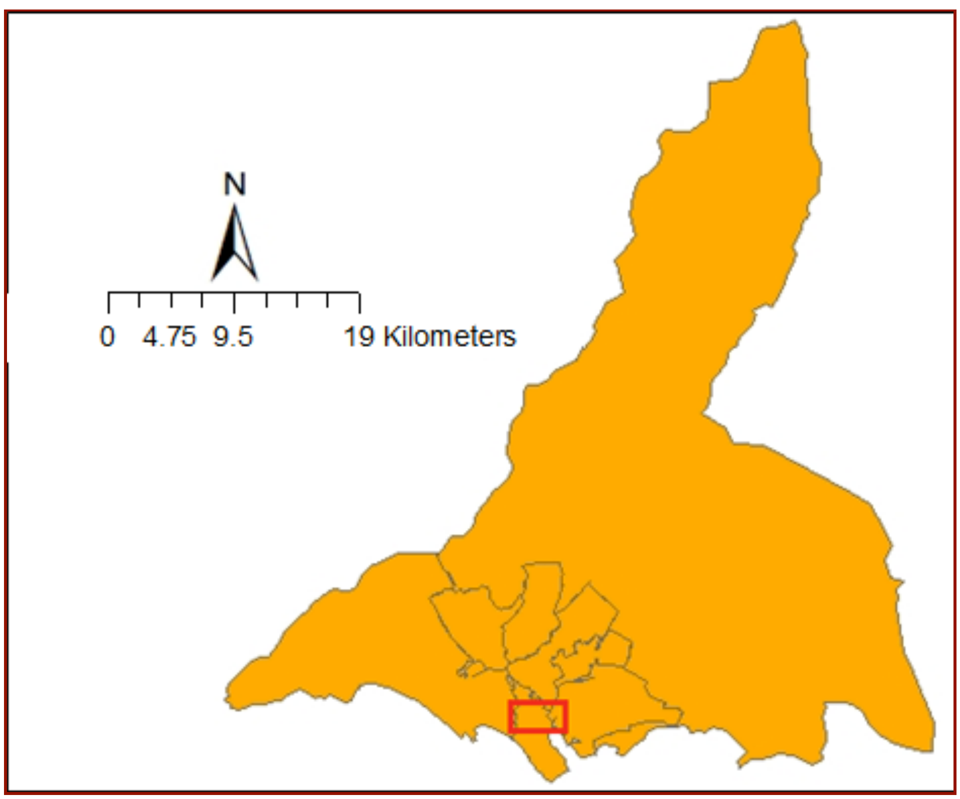

Figure 1: Location of DHA in Karachi.

E. Figure **1** shows the location of DHA in the mega city of Karachi.

DHA contains different types of residential and commercial settlements. Creek Lanes, a small residential area of DHA Phase 7 Karachi has been selected as the area of interest (AOI) in this research work. DHA Phase 7 contains majority of the buildings as residential houses thus it is a potential area for the possible deployment of rooftop PV systems. Moreover, this area may also not represent the whole picture of complex urban pattern of Karachi metropolis which contains small and large congested settlements as well.

An open source satellite imagery of Google Earth^{TM} of March 14, 2014, freely available in public domain has been acquired to identify bright rooftops in the area of interest. Google Earth^{TM} imagery has a spatial resolution of 0.5m and has been pre-processed for radiometric correction and noise minimization. Use of available satellite imagery in public domain also highlights the significance of this research work which is free from cost constraints of commercially available sophisticated datasets. Figure **2** shows the sample satellite image of AOI.

METHODOLOGY

An easy-to-use methodology has been used in this research work to analyze the capability of open source GIS tools to identify rooftops' area for solar PV applications for the region of interest. Figure **3** shows the overall workflow of methodology.

Freely available Google Earth^{TM} satellite imagery of March 14, 2014 for AOI has been acquired for this research work having spatial resolution of 0.5m. Google Earth^{TM} sample satellite imagery was pre-processed for radiometric correction and noise minimization before extraction of rooftops. Then, rooftop features of AOI have been extracted using open source QGIS software. The Orfeo Toolbox (OTB) in QGIS software provides open source edge extraction algorithm using Sobel, Touzi and Gradient filter. In this research work, edge extraction has been implemented on the input image using gradient filter which computes edge features (impervious surfaces such as roads, sideways, building rooftops, vegetation etc.) on every pixel. After the detection of impervious surfaces, digital image processing techniques have been employed and a simple thresholding filter was applied to extract rooftop features. The extracted rooftop features were

Figure 2: Sample Google Earth^{TM} satellite imagery of Creek Lanes (AOI), a small residential block in DHA Phase 7 Karachi.

converted to building polygons in form of a vector shapefile through careful manual digitization and their area was computed using 'Measure Area' function of QGIS software. Only outer edges were hand-digitized to acquire an estimated area of rooftops of AOI.

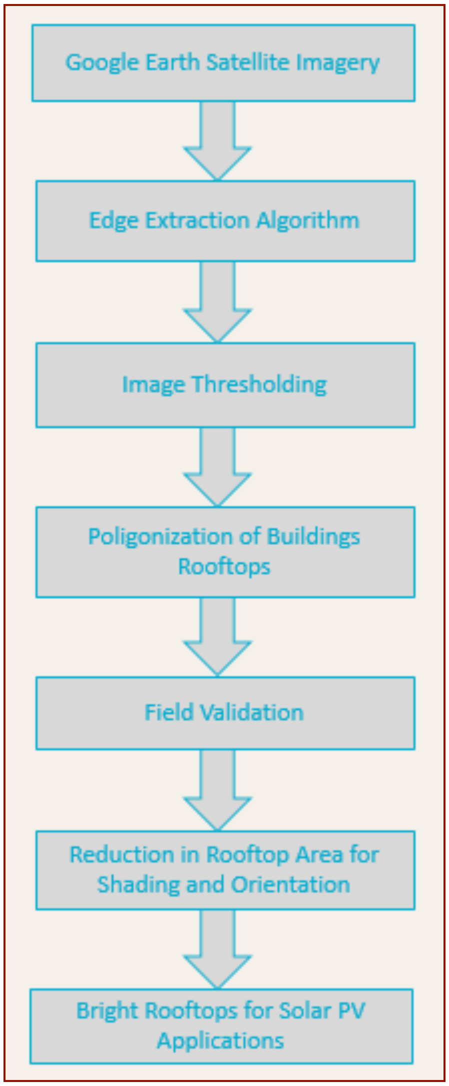

Figure 3: An overall workflow of the methodology.

Then, field validation to assess the accuracy of extracted rooftops was performed and 10 sample rooftops were physically measured to analyze the accuracy of extracted rooftops' area as well as to analyze different rooftop uses such as water tank etc. In this research work, however, field validation of only one sample rooftop has been shown. To analyze the shading effect from nearby trees and buildings, a field survey of sample rooftops in AOI was also performed to assess the availability of rooftop area for possible rooftop PV installations. Considering the influence of shading effect pertaining to rooftop PV potential estimation studies, a fraction of available rooftop area has been adopted based on the field survey assessment. This crude estimation was sufficient for the case of present AOI due to their uniform rooftop structures. However, it is pertinent to mention that this adopted fraction of available rooftop area can be utilized for solar PV applications for the case of present research work only and must be evaluated further for future rooftop PV potential estimation of small and congested houses in other areas Karachi having non-uniform rooftop patterns. Therefore, for this specific case of Creek Lanes, DHA Phase 7, Karachi a fraction of 0.60 has been adopted which represents an available percentage of rooftop area i.e., bright rooftop area free from shading and other roof uses such as water tank etc. for rooftop solar PV installation. Adopting this similar kind of technique is evident from published literature as it has been used by many researchers such as Izquierdo *et al*., [11], Pillai and Banerjee [12] and Scartezzini *et al*., [13]. Although, a small residential block has been selected to analyze the applicability of open source GIS for solar PV applications, nevertheless the methodology can be extrapolated, with some limitations, for whole DHA area as well to assess the significance of open source GIS tools for the estimation of rooftop PV potential. Moreover, considering the complex pattern of urban households in the mega city of Karachi, the proposed method may not be applicable to small and congested settlements having more dense and irregular household patterns consequently showing the limitations of this research work.

RESULTS AND DISCUSSION

The Edge Extraction algorithm of QGIS software computes edge features on every pixel of the mono-band input image. For the case of present research work, Google Earth^{TM} satellite imagery contains three channels i.e., Red, Green and Blue. The blue noise is easier to minimize through the process of smoothing [14] thus the blue channel of Google Earth^{TM} satellite imagery was selected for edge extraction algorithm. Following Figure **4** shows the result of edge extraction algorithm applied on Google Earth^{TM} imagery.

For the case of present research work, only rooftops were of the interest among other impervious surfaces extracted in Figure **4**. Thus, digital image processing techniques have been employed and a simple thresholding filter was applied to extract clear rooftops boundaries. Image thresholding has been an effective technique in remote sensing applications and it has been used by many researchers such as Balaji and

Figure 4: The implementation of edge extraction algorithm on sample satellite imagery to compute edge features. Note that edges of impervious surfaces such as residential building rooftops, roads, sideways, open spaces etc. have been extracted.

Sumathi [15], Patra *et al*., [16] and Rosin *et al*., [17] to extract features of interest. Image pixels less than 135 and greater than 170 have been filtered out using QGIS software to extract rooftop features for this case. However, it is worthwhile to highlight that this thresholding limit may significantly differ for the case of other areas of Karachi having small, congested houses with irregular patterns and larger house density. The user must first determine the thresholding limit through careful visual assessment in a GIS based software before implementation of image thresholding technique to obtain clear boundaries of rooftops in the region of interest. Figure **5** shows the output of image thresholding to obtain clear rooftop boundaries.

Nevertheless, during the process of image thresholding many unwanted impervious surfaces having similar texture and spectral characteristics as rooftops were also obtained. The spectral and texture characteristics of old buildings and newly constructed buildings may differ significantly and it may lead towards inaccuracies in rooftop extraction process using image thresholding techniques. To minimize this source of error and unwanted impervious features, a manual cleanup in QGIS was performed to remove unwanted impervious features.

After extraction of rooftop features, a careful hand digitization was performed to obtain polygon boundaries of extracted rooftops and their area was calculated using Measure Area function of QGIS. It may be noted that manual digitization may not be accurate method and may be time-consuming for the case of greater spatial coverage of region of interest. For such large regions, automated rooftop features extraction method may be more preferable. Figure **6** shows the extracted rooftop polygons overlain to building rooftops in Google Earth™ satellite imagery.

Rooftop extraction results yielded a total roof area of 7,710 m^2 in sample satellite imagery of Google Earth™. However for rooftop PV potential estimation studies, other factors such as shading, water tanks etc. should also be considered. Thus, a field survey was performed to analyze the effect of rooftop constraint factors and also to assess the accuracy of extracted rooftops. 10 sample rooftops were physically accessed and their area was physically measured and compared

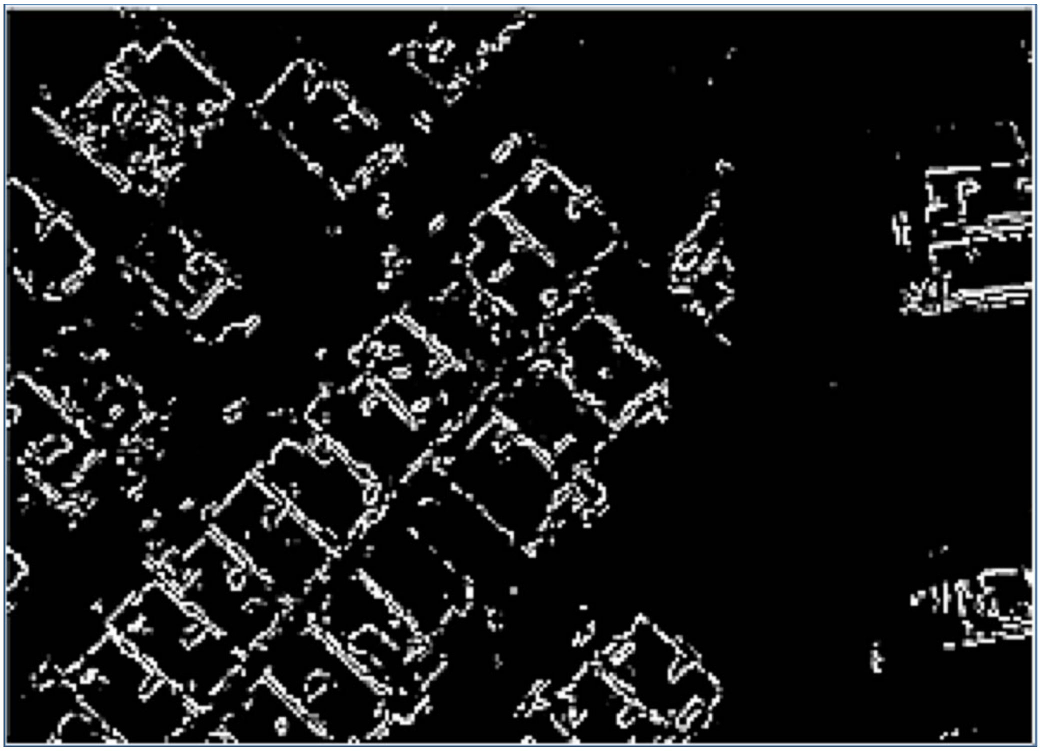

Figure 5: The output of image thresholding technique to extract rooftop features. White boundaries show the extracted rooftops. Some unwanted impervious surfaces having same spectral and texture characteristics as rooftops have also been identified.

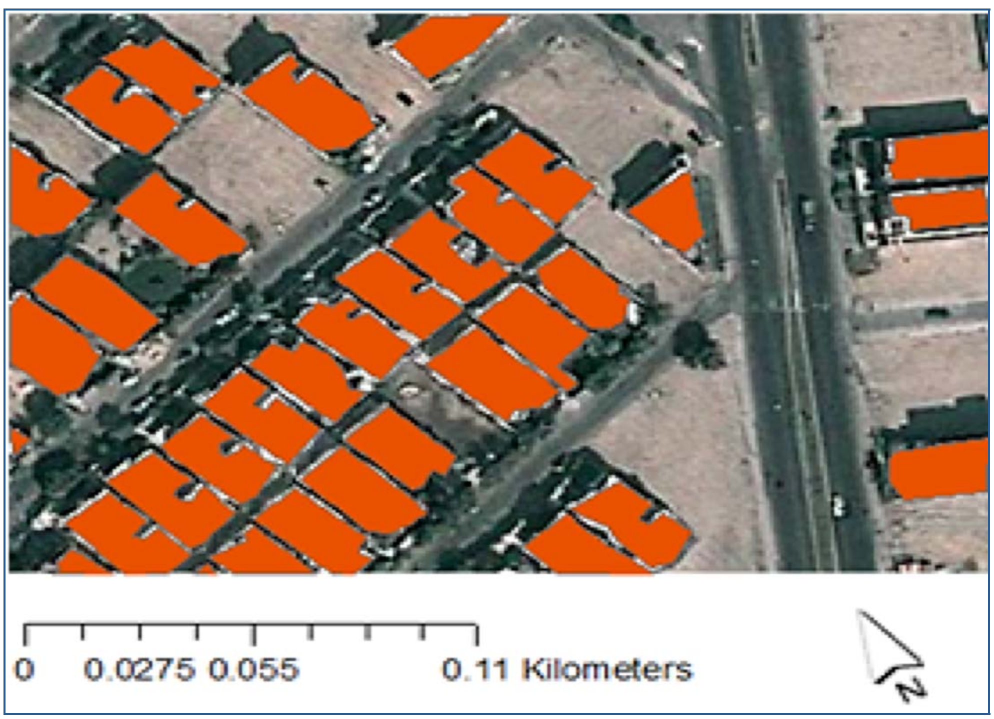

Figure 6: Extracted rooftop features overlain to residential buildings in Creek Lanes, DHA Phase 7 Karachi.

to the estimated rooftops' area. However, field validation of one of the sample rooftops only has been shown in this research article. Figure **7** shows the oblique view of one of the sample rooftops accessed for physical measurement.

The extracted rooftop area of one of the sample rooftops shown in Figure **7** is found to be 95m^2 while the physically measured rooftop area after the reduction of miscellaneous roof uses such as water tank, roof entrance and other uses was found to be

Figure 7: An oblique view of one of the sample rooftops. Shading effect and other roof uses have been highlighted.

105m^2. Thus, the extracted rooftop area was found to be 90.45% accurate. The comparison showed the ± 10% error in rooftops' area extraction using satellite imagery of AOI in comparison to the physically measured rooftops. These errors may be identification of impervious surfaces such as nearby shadows, vegetation etc. identified as rooftop boundaries. It may also be also noted that this percentage of error may significantly increase for the case of other largely dense areas of Karachi. Nevertheless, the proposed methodology demonstrated a fair amount of potential to identify bright rooftops for solar PV applications in DHA in particular with some limitations. After the reduction of influences from shading and other roof uses, the available bright rooftop area has been computed as 4,626 m^2. These identified bright rooftops and their computed area is of the utmost importance as it can be used for different kind of solar PV applications such as solar water heating, solar air conditioning, rooftop PV systems for electricity generation etc. For this available rooftop area for possible solar PV panel installations, the annual energy output (E) may be computed as follows:

$E = GSR \times N \times Eff. \times A_{PV}$ (1)

Where;

E = Annual energy output (in MWh)

GSR = Mean global solar radiations; 5.448 kWh/m^2/day for Karachi

N = number of days in a year; 365

A_{PV} = Available rooftop area of AOI for solar PV installations; 4626 m^2

Annual energy output for AOI considering different PV panel scenarios due to their varying efficiencies have been summarized in Table **1**.

Thus, using c-Si PV panel, annual energy output of 2.10 MWh can be produced which is sufficient to cater the annual electricity requirements of AOI. In particular, the proposed solar PV installations can be used in parallel to the input electricity from main grid thereby reducing electricity load on local grid stations. Although, a small residential area of Creek Lanes, DHA Phase 7 has been taken into the analysis but the adopted methodology can be extrapolated to whole DHA area due to the planned nature of its residential and commercial settlements and uniform rooftop structures with fair amount of accuracy and some limitations. However, to extrapolate the proposed methodology to whole Karachi metropolis, challenges such as varying rooftop structures, small and congested houses, shading effect from adjacent

Table 1: Annual Energy Output for DHA Phase 7 Karachi Based on Four PV Panel Scenarios

Solar PV panel type	Module efficiency (Eff.)	Annual energy output (E) for AOI (MWh)
Mono-crystalline Si (c-Si)	22.9%	2.10
Poly-crystalline Si (p-Si)	18.5%	1.70
Amorphous Si (a-Si)	12.2%	1.1
Cadmium-Telluride Cells (CdTe)	17.5%	1.6

Source: Efficiencies of PV panels have been taken from Green et al., (2015) measured under global air mass (AM) 1.5 spectrum (1000W/m^2).

houses, multiple rooftop uses and varying house density need to be addressed first.

CONCLUSION

In this research work, an applicability of open source GIS tools for the identification of bright rooftops has been demonstrated for Creek Lanes, a small residential block of DHA Phase 7 Karachi. An easy-to-use methodology has been proposed to identify bright rooftops which include extraction of rooftop features using QGIS software; implementation of image processing and GIS techniques to further refine the results to obtain clear boundaries of rooftops; field validation of sample rooftops to assess the accuracy of extracted rooftops; reduction from total rooftop area to obtain available bright rooftop area for possible solar PV installations in Creek Lanes, DHA Phase 7 Karachi. On comparison of estimated rooftops' area with physically measured sample rooftops' area, an accuracy of 94.45% has been achieved. Total area of extracted rooftops was found to be 7,710 m^2 while the effective available area of 4,626 m^2 has been identified which can be utilized for different types of rooftop solar PV installations. Moreover, an annual energy output using different scenarios of PV panels has been presented for AOI. It has been realized that using c-Si PV panel, an annual energy output of 2.10 MWh can be generated which is sufficient to cater the electricity requirements of AOI. The proposed methodology can be extrapolated to whole DHA area due to nearly uniform rooftop structures of its buildings with some limitations. However, for the extrapolation of the adopted methodology to the whole mega city of Karachi, major challenges which need to be addressed first have been highlighted. This study highlights the immense potential of solar PV applications for urban rooftops of Karachi metropolis. It is pertinent to mention here that none of the studies has been conducted yet employing the open source GIS tools specifically for this region to identify bright rooftops for solar PV applications thus this research is a first of its kind research initiative to address this research gap. This research work can be helpful for policy makers and concerned government agencies to highlight the immense potential of millions of urban households of mega city of Karachi for solar PV applications for sustainable electricity generation in the city.

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