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Investigating solar energy potential in tropical urban environment: A case study of Dar es Salaam, Tanzania

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ABSTRACT

Solar energy is considered to be an alternative sustainable energy source in the urban environment. The potential of using solar energy in urban areas is highly dependent on urban morphology which affects the level of solar irradiance received by individual buildings. Many studies focus on solar energy potential of building form in urban areas but relatively few studies examine how urban morphology affects solar energy potential of urban neighbourhoods. It leads to inefficient design of neighbourhoods in terms of solar energy potential. The present study investigates the potential of exploiting solar energy in Dar es Salaam, Tanzania by using numerical modelling of solar irradiance on building roofs and façades. It is shown that there is substantial solar irradiance received by building roofs in all four study neighbourhoods and urban morphology has considerable effects on annual solar irradiance. Solar irradiance of different orientations of tilted roofs and façades is subject to seasonality of the solar azimuth angle. It is suggested that such abundant solar energy sources would provide solutions to accommodate the increasing energy demand and to improve living quality in urban areas due to the rapid urbanization of the city.

1. Introduction

Solar energy is widely considered to be a sustainable and readily available energy source in the urban environment. As about 54% of the world's population being resided in urban areas, enormous amount of energy is used and a large proportion of the greenhouse gases are released at the same time. In particular, urban population in developing countries is expected to vastly increase in the next few decades (United Nations, 2014). In Africa, it was estimated that a 1% increase in urbanization leads to a 14% increase in charcoal consumption, in turn leading to increased air pollution and emissions of greenhouse gases and thus a contribution to global warming (World Bank, 2009). It results in the urgent need for the exploitation of solar energy in order to mitigate the impacts of fossil-fuel consumption and improve the living quality of urban areas (Pearce, 2002).

In developing countries in Africa, the use of electricity has been increasing in the last decade. For example, in urban areas of Tanzania, the proportion of urban population having access to electricity has increased 39% in 2005–52% in 2009 (Shkaratan, 2012). In particular, the annual electricity consumption of high-income households is over 360 kW h and is expected to increase due to the rapid economic development in Tanzania (Hosier & Kipondya, 1993). Half of Tanzanian's charcoal is used in Dar es Salaam, mostly for urban household energy, with an increase of 70% in 2009. On the other hand, the limited access to grid electricity in rural areas leads to an overall 6% of the total population having access to grid electricity in Tanzania (Bauner, Sundell, Senyagwa, & Doyle, 2012). Tanzania's electricity generation, which is mainly based on hydropower and natural gas, is however sensitive to variations in precipitation rate and fossil fuel prices and consequently power failures are common. To cope with this, many industries, hotels, shops and private households have installed their own diesel-driven generators, especially in Dar es Salaam (Bauner et al., 2012). This leads to increased emissions of toxic and greenhouse gases and the cost to install and operate these generators is a large burden on the economy. There is thus an enormous demand for more reliable electricity generation which can potentially be accommodated by the exploitation of solar energy in the urban environment.

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One of the problems associated with the exploitation of solar energy in urban areas is the high-rise and compacted urban form which prevents solar radiation from reaching building surfaces (Yun and Steemers, 2009). It reduces solar energy potential since solar irradiance is the most crucial parameter to photovoltaic (PV) systems. Several studies have previously examined the relationship between solar energy potential and urban morphology. Compagnon (2004) quantified the potential of façades and roofs for PV electricity production in Switzerland by numerical simulations of solar irradiance. It was shown that different building layouts with the same density exhibit large variations of solar energy potential on buildings facades, suggesting that solar availability can be increased even for dense urban areas. Cheng et al. (2006) analyzed the effect of urban form and density (in terms of plot ratio) on the PV potential of the building envelope. Vertical randomness in building height is found to be more favourable at lower site coverage since it provides better solar access to building façades. Sarralde et al. (2015) further used a number of descriptors of urban morphology to describe various urban forms which are parametrically analyzed for their corresponding solar energy potential. By modifying specific descriptors of an existing neighbourhood, they found that the availability of solar irradiance of building façades can be increased by 45%. Therefore, careful design of urban neighbourhood is very important to optimizing solar energy potential in urban areas.

A wide range of tools have been developed to simulate solar irradiance at both building and urban scales (Compagnon, 2004; Lindberg, Holmer, & Thorsson, 2008; Šúri et al., 2005, 2007). High-resolution digital surface models (DSM) are used to estimate the availability of solar radiation for extensive areas due to the computational efficiency using 2.5-dimensional raster-based calculations. These models have been widely used to determine solar energy potential for roofs with various geometries (Hofierka & Kanuk, 2009; Nguyen & Pearce, 2012). The recent model developed by Redweik et al. (2013) provides estimations of wall irradiances by calculating diffuse and direct irradiances on ground, roofs and walls for individual hours on a high-resolution DSM.

The present study aims to examine the solar energy potential of different urban settings in Dar es Salaam, Tanzania. Four typical urban settings with different building geometries (buildings height and coverage) are chosen to compare the effect of various urban morphological parameters on the availability of solar radiation on both roofs and façades of buildings. Findings of the present study form a part of the project entitled “Efficient use of land and energy in Dar es Salaam, Tanzania – Urban planning and climate adaptation”, which aims to develop a set of planning recommendations for a sustainable, climate-sensitive urban planning in Dar es Salaam, Tanzania.

2. Methodology

2.1. Study area – Dar es Salaam, Tanzania

Dar es Salaam (6.8°S, 39.3°E), located on the eastern coast of the country, is the largest city of Tanzania. The city is situated on a relatively flat coastal plain which has a gentle slope towards the Indian Ocean. The general climatic conditions in Dar es Salaam are shown in Fig. 1. It has a tropical savanna climate according to the Köppen climate classification with annual mean temperature of 26.0 °C and annual rainfall of about 1000 mm. Pronounced dry period is observed from June to October and rain season is generally in April and May. Dar es Salaam has a population of over four millions in the metropolitan area. The city has experienced rapid urbanization which leading to a nearly doubled population in the last two decades (Brennan & Burton, 2007; Ndetto & Matzarakis, 2015). The annual growth of 4.4% is one of the highest in the world (Ndetto & Matzarakis 2013) and partly due to this an estimated 70% of the city's population live in informal (unplanned) neighbourhoods (UN-Habitat, 2010a).

Dar es Salaam is characterized by a radial structure with settlements along four major roads which all originate from the City Centre. Informal settlements have emerged in between the main roads and in the periphery in a pattern of compact, low-density residential areas. They are settlements developed in unsecure land tenure by organic subdivision of customary land and built outside urban norms. Diversity on dwellers income from middle to very poor is characteristic and in some neighbourhoods formal dwellers live next door to informal dwellers (Rasmussen, 2013). These settlements are mainly as one-storey houses, contributing to urban sprawl and inefficient use of land (Lupala, 2002). High-quality housing is found in the coastal areas north of the City Centre where low-rise and low-density development dominates with higher coverage of vegetation.

Representative study areas of 400 × 400 m from four neigbourhoods with characteristic urban morphology and building types are

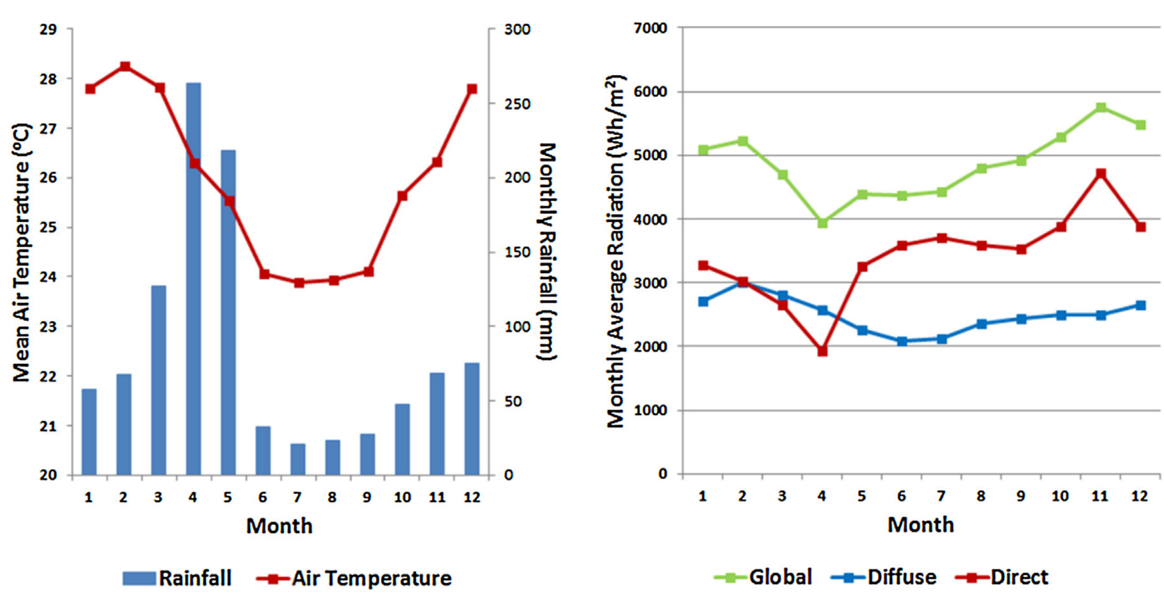

Fig. 1. Monthly distribution of mean air temperature and rainfall (left) and three radiation components (right) of Dar es Salaam.

Table 1
Summary statistics of building parameters of the four study areas.

	Building Coverage (%)	Average Bldg Height (m)	Max Building Height (m)	Min Building Height (m)	Total Building Volume (m^3)
City Centre	41.2	16.6	55.1	3.7	1096025
Kariakoo	53.5	15.2	50.1	2.3	1302945
Upanga	16.2	7.9	28.5	2.1	206072
Manzese	49.6	3.7	11.3	1.9	291715

chosen in order to examine the solar energy potential of different urban settings in Dar es Salaam. Details of the urban morphological information are documented in Table 1. The chosen neigbourhoods are the City Centre, Kariakoo, Upanga being formal settlements and Manzese as informal settlement (Fig. 2). The City Centre and Kariakoo are situated in the administrative and commercial areas characterized by medium- to high-rise buildings while Upanga is a residential district and Manzese is characterized by compact urban form with one- to two-storey Swahili houses (Fig. 3) (Directorate of Human Settlements Development, 2002; Lupala, 2002; UN-Habitat, 2010b).

2.2. Meteorological data

Hourly meteorological data, including air temperature, relative humidity, three components (global, diffuse and direct) of solar radiation, are obtained from the solar radiation database and software Meteonorm 7. The data period is one whole calendar year. The software provides long-term meteorological data from stations over the world, supplemented by surface data from five geostationary satellites (Remund and Müller, 2011; Remund et al., 2014). For areas not covered by meteorological stations or missing data due to instrumental failure, the data are spatially interpolated from different stations. The hourly data are calculated from monthly values by using a stochastic model in order to produce a resultant time series corresponding to “typical years” for photovoltaic, solar thermal or building simulation studies.

2.3. The development of digital surface model

Since gridded spatial data like LiDAR data are limited in Dar es Salaam, field measurements were conducted in order to obtain information about building height, roof structures and dimensions. Satellite images were acquired from WorldView-2 at 50cm-resolution and first used to determine building footprint and identify possible roof structures. The height of roof vertices was measured on the field using Nikon® Laser 550 Rangefinder. Roof geometry was determined by the Feature Manipulation Engine (FME) software developed by Safe Software® and subsequently converted into 2.5D raster-based building DSM at a resolution of 0.5 m (for both horizontal and vertical scales), as shown in Fig. 3. In addition, tree height and size of tree crowns in the study areas is measured and provides information for the vegetation DSM which also forms the input of the numerical modelling of solar radiation.

2.4. Numerical modelling

Solar irradiance on roofs and facades is calculated using a 2D solar radiation model, Solar Energy on Building Structures (SEBE; Lindberg, Jonsson, Honjo, & Wästberg, 2015). By making use of DSMs including height information it could also be referred to as a 2.5D calculation scheme. The main DSM consists of building and ground heights. Two optional DSMs of the same size as the ground and building DSM can be used to represent 3D vegetation of trees and bushes. The two vegetation DSMs account for: (1) the canopy and for (2) the trunk zone. For the vegetation pixels, the canopy

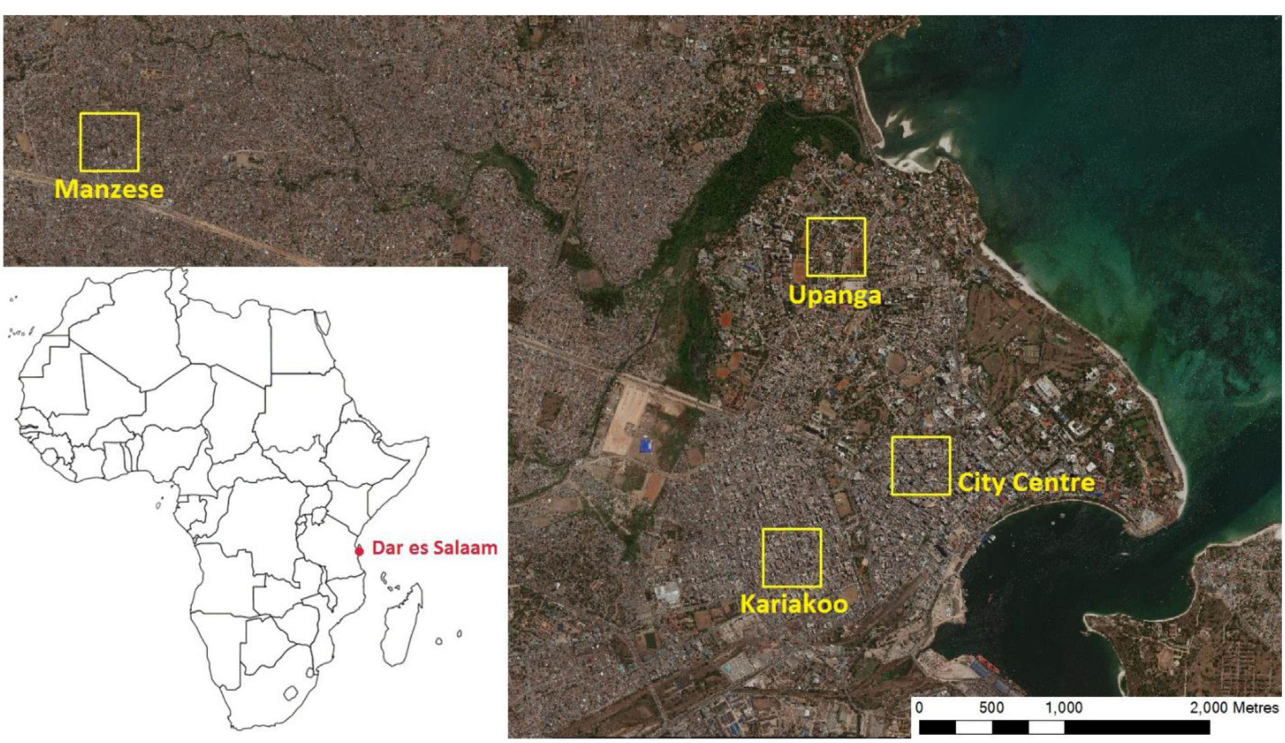

Fig. 2. Location of Dar es Salaam and the four study areas.

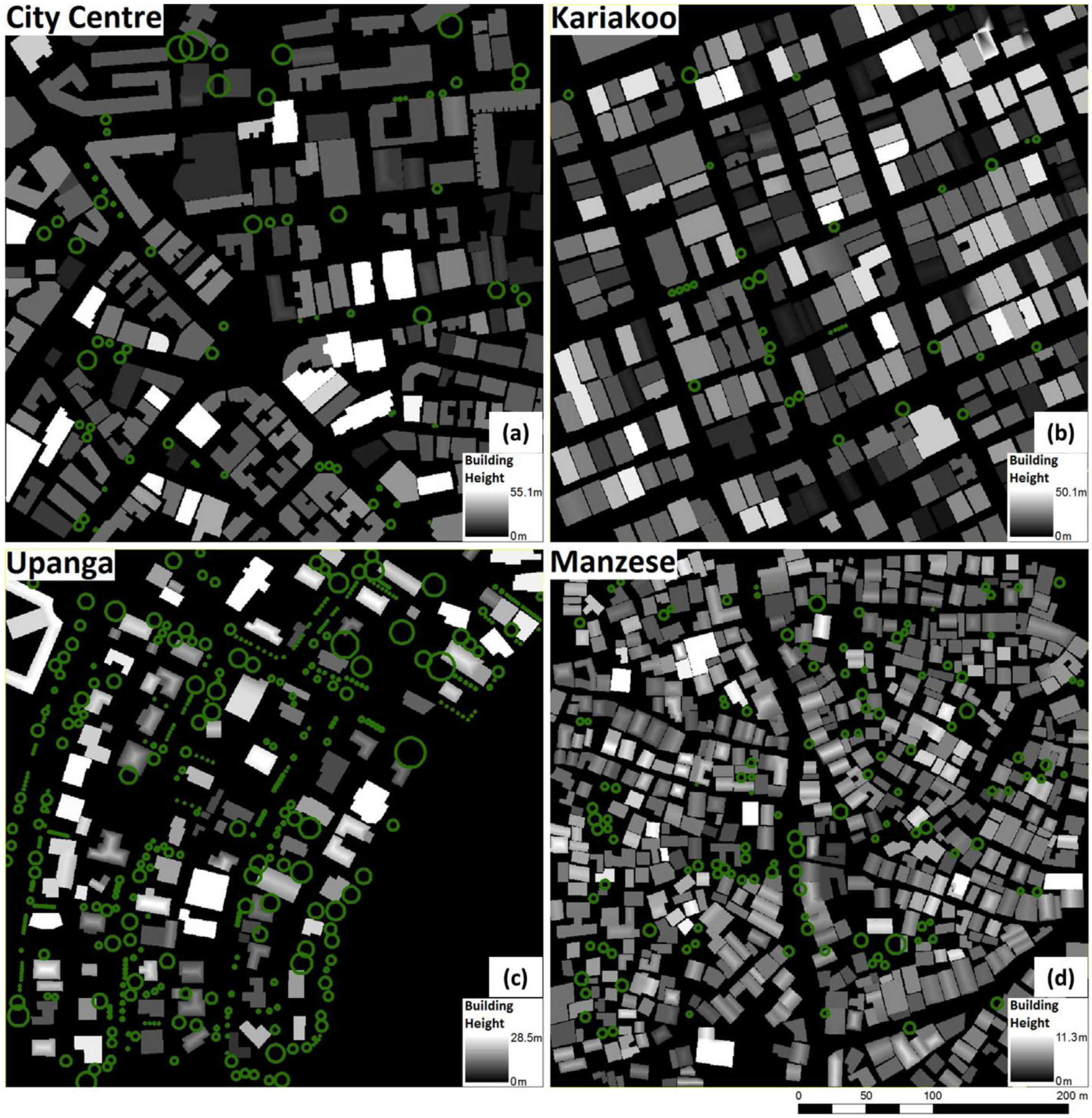

Fig. 3. Digital surface model of the four study areas. Green circles indicate the location of trees in the study areas. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

DSM (CDSM) has the height of bushes and/or trees (meter over ground), whereas the trunk zone DEM has the height of the base of the canopy (see Fig. 2 in Lindberg & Grimmond, 2011). Thus, each tree has its own shape which is dependent on the spatial resolution of the DSMs.

Essential for estimating solar radiation in urban areas in a correct way is to generate accurate shadow patterns from buildings and vegetation as well as ground topography within the model domain. To cast a shadow, the altitude and azimuth of a distant light source (the Sun) are specified. Following Ratti and Richens (1999), 'shadow volumes' are computed by sequentially moving the raster DSM at the azimuth angle of the Sun, reducing the height at each iteration based on sun elevation angle. To derive sunlit fractions on walls, a modified version of the shadow casting algorithm is used. The algorithm is relatively straightforward to obtain the height of the shadow when it hits a building wall using an ordinary edge detecting filter to identify wall pixels. Note that a wall section is considered to be shadowed if the sun beam falls oblique to that section.

SEBE makes use of observed hourly meteorological data as input. The unobstructed three components of shortwave radiation are used as primary input data: direct radiation perpendicular to the Sun (I), diffuse (D) and global (G). Instead of iterating the model for each hourly time step, the meteorological data is pre-processed and redistributed into 145 patches of similar solid angles throughout the sky vault according to the well-known approach presented by Tregenza and Sharples (1993). To redistribute the direct radiation component, as iterating through the meteorological data, the position of the Sun is derived and added to the centroid of the closest of the 145 patches on the sky vault. The diffuse radiation component is redistributed for the patches based on the all-weather model of sky luminance developed by Perez et al. (1993).

The total irradiance for a roof pixel (R) on a DSM is calculated by summing the direct, diffuse and reflected radiation such as:

$$R = \sum_{i=1}^{p} [(I\omega S + DS + G(1 - S)\alpha)]_i \quad (1)$$

where p is i th patch on the hemisphere. I is the incidence direct radiation, D is diffuse radiation and G is the global radiation origi-

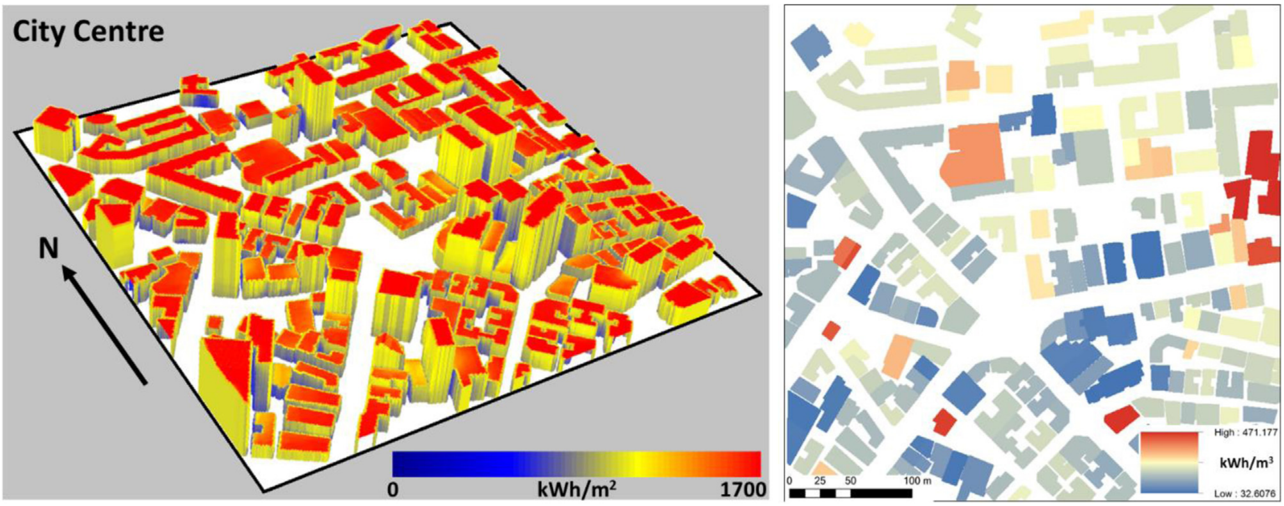

Fig. 4. Annual solar irradiance in kW h for horizontal and vertical pixels in City Centre (left). Annual roof irradiance per unit building volume (kW h m^{-3}) of individual buildings (right).

nating from the i th patch. α is the surface albedo and ω is the sun incidence angle. The first and second term represents the direct and diffuse irradiance, respectively whereas the third term accounts for reflected irradiance.

S is the shadow calculated for each pixel:

$$S = S_b - (1 - S_v)(1 - \tau) \quad (2)$$

where S_b and S_v are shadows from buildings and vegetation, respectively represented by a Boolean value (presence = 0 or absence = 1) and τ is the transmissivity of shortwave radiation through vegetation.

The walls pixels are identified on the DSM using an edge detecting filter and divided into a number, 1 m segments based on the wall height for every pixel identified as a wall. The shadow volume approach described in Section 2.1 is applied and each wall segment is divided into 3 classes; segments shadowed by buildings, shadowed by vegetation or sunlit. Then, shortwave irradiance is calculated using the same sets of equations as presented above. For a wall pixel, the reflection term is only considered for half of the hemisphere, i.e. the visible part. However, added is a reflected part originating from the ground such as:

$$Ground_{reflected} = (G\alpha)/2 \quad (3)$$

For tilted roofs, the reflection from the ground is not considered. However, this component is usually very small and would have a minor effect on the total irradiance because view factor from the tilted roofs to the ground is very small.

3. Results

3.1. Urban form and solar irradiance

Solar irradiance of the roofs and building façades is compared between the four study areas in order to examine the effect of urban form on solar energy potential. Over 95% of the roof pixels in all study areas received over 1500 kW h of solar radiation in a year, suggesting that the solar energy potential is extremely high in the city. However, only 46–77% of the wall pixels reach the threshold of 800 kW h for PV panels on vertical surface. It is probably due to the high solar elevation (up to 88° at local solar noon in February and March). In addition, the density of urban structures also affects the

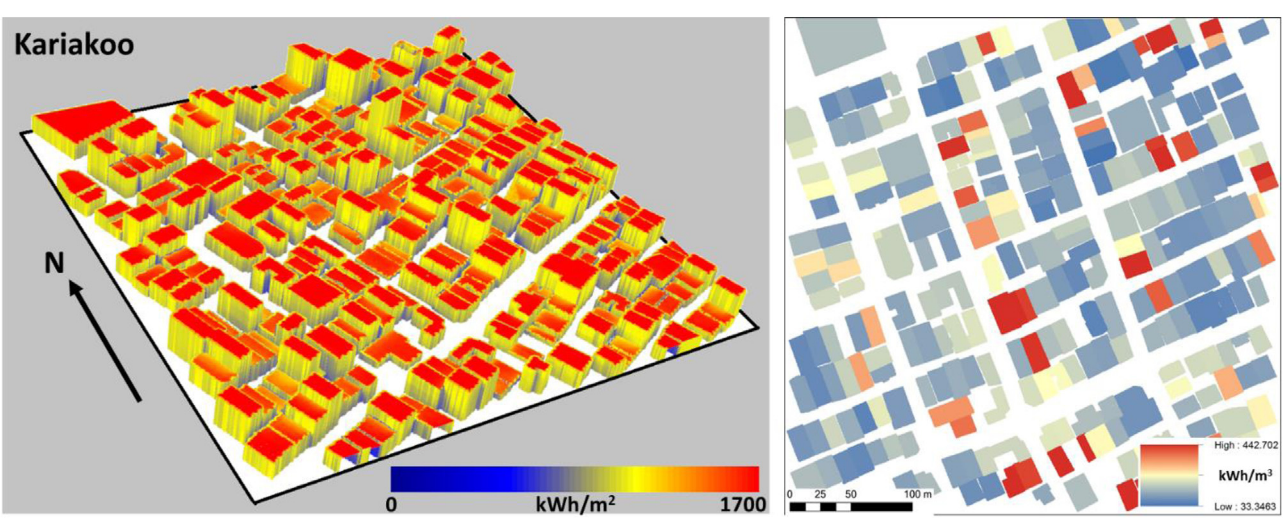

Fig. 5. Annual solar irradiance in kW h for horizontal and vertical pixels in Kariakoo (left). Annual roof irradiance per unit building volume (kW h m^{-3}) of individual buildings (right).

Table 2
Solar irradiance of the four study areas.

	Total Solar Irradiance (GW h)	Total Roof Irradiance (GW h)	Total Wall Irradiance (GW h)	Average Roof Irradiance (MW h m^{-2})	Average Wall Irradiance (kW h m^{-2})
City Centre	232.8	109.5	123.3	1.39	580.9
Kariakoo	269.8	134.1	135.7	1.34	535.5
Upanga	74.0	45.3	28.7	1.38	704.0
Manzese	187.2	143.7	43.5	1.42	655.5

solar energy potential on building façades since substantial amount of solar irradiance is observed in areas with relatively higher building coverage.

3.1.1. City Centre and Kariakoo

The spatial distribution of solar irradiance differs in different parts of the city. In City Centre (Fig. 4) and Kariakoo (Fig. 5), there is an abundant amount of solar radiation received by individual buildings (over 100 GW h per year for both roofs and façades; Table 2). In particular, the total amount received by building roofs in Kariakoo is higher than that in City Centre due to its high building coverage. In both areas, the solar potential of buildings situated between high-rise apartments is considerably lower, indicating that solar irradiance is influenced by the shadow pattern of individual pixels. Building façades shaded by trees also generally exhibit the lowest solar irradiance. In addition, the amount of solar radiation per cubic metre of building volume is much lower in these two areas, ranging from 30 to 470 kW h m^{-3}. It suggests that the solar energy available to individual occupants is lower in dense urban areas despite of the high total available solar irradiance.

3.1.2. Upanga

In Upanga, the lowest total roof irradiance (about 45 GW h) is observed here due to the low building coverage (Fig. 6). The majority of the roofs receive high level of solar irradiance. However, it is also evident that certain amount of lower roofs and building walls exhibits lower solar irradiance as there are considerable amount of trees in Upanga. Sun exposure of roofs becomes very important in such a densely vegetated area. Moreover, solar irradiance per cubic metre is moderate in Upanga with about 60% of the households receiving 300–600 kW h m^{-3}.

3.1.3. Manzese

The high potential of solar irradiance on building roofs is further reiterated in Manzese. Having a total roof area of near 100,000m^2, it has the highest total roof irradiance among the four study areas (>140 GW h per year). Due to its compacted urban form, building walls are generally shaded by surrounding buildings, resulting in much lower wall irradiance (about 43 GW h per year) in the area (Fig. 7). Moderate wall irradiance can be observed in open building walls along major roads and pedestrian paths. The majority of buildings receive 500–800 kW h m^{-3} in Manzese. It has considerably higher solar potential than City Centre and Kariakoo. In informal settlements like Manzese, solar energy can provide a self-sustainable energy source in order to increase the use of more advanced electrical devices.

3.2. Seasonal variation of solar irradiance on buildings

3.2.1. Roof irradiance

Monthly variations in solar irradiance on building surfaces are evident although there is generally no significant seasonality in the climate of Dar es Salaam. Fig. 8 shows the monthly solar irradiance on different roof and wall orientations in the parametric setup. Solar irradiance of flat and tilted roofs is compared for five inclination angles (from 10° to 50°). It is clearly shown that the monthly variation of solar irradiance resembles that of the direct radiation for 10° and 20° inclination angles. The less inclined roofs have similar pattern as the flat roof although the flat roof receives higher amount of solar radiation than tilted roofs facing any of the four cardinal directions from October to March when the solar elevation is high (74.3°–88.8°). However, the solar irradiance in February and March is approximately 30 kW h lower than the peak in November due to regional cloudiness. As inclination angle increases, the solar irradiance received by tilted roofs drops substantially since the energy from incoming solar radiation is dissipated on a larger surface.

The lower solar elevation (<70°) results in smaller differences in solar irradiance between flat and tilted roofs from May to August. The north-facing roof receives slightly higher level of solar radiation

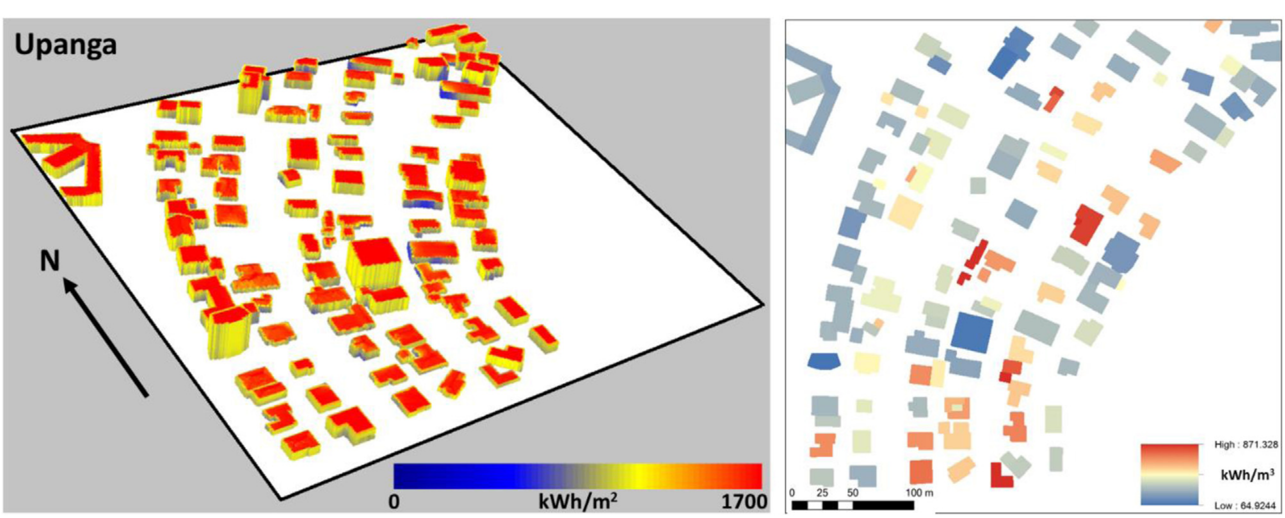

Fig. 6. Annual solar irradiance in kW h for horizontal and vertical pixels in Manzese (left). Annual roof irradiance per unit building volume (kW h m^{-3}) of individual buildings (right).

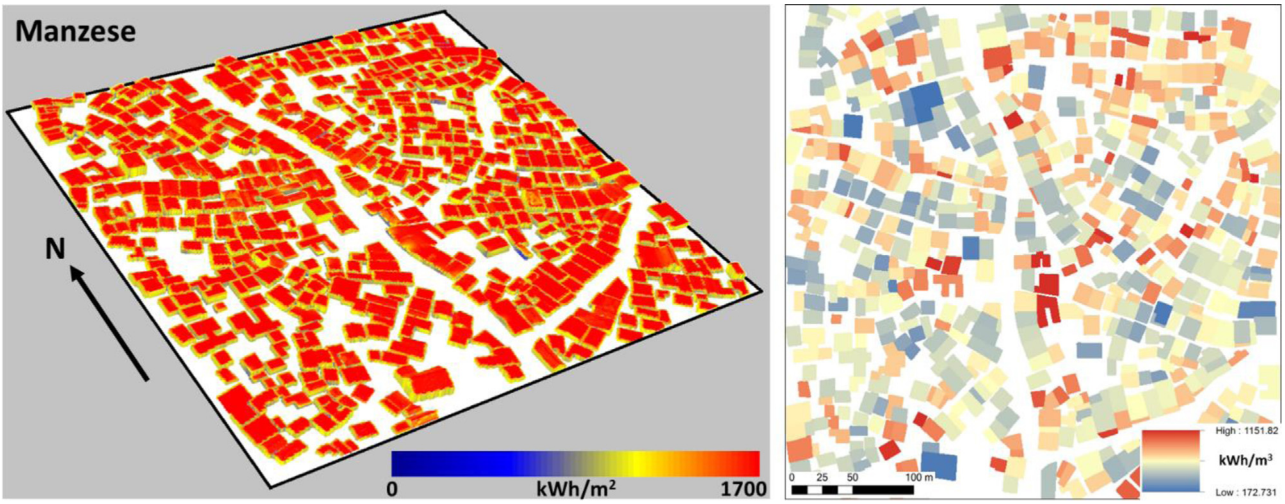

Fig. 7. Annual solar irradiance in kW h for horizontal and vertical pixels in Upanga (left). Annual roof irradiance per unit building volume (kW h m^{-3}) of individual buildings (right).

since the sun is in the north during this period. Under these conditions, solar radiation received by steeper roofs facing the north are considerably higher than the south-facing counterpart and such difference increases with higher inclination angles. However, the amount of solar radiation received by the steepest roof (50°) is about 25% to 30% less than the roof with 10° inclination during this period. Furthermore, considerable reduction in solar irradiance is observed across inclination angles in April when the city experiences high level of precipitation.

3.2.2. Wall irradiance

Wall irradiance of the four cardinal directions in the parametric setup is compared. The monthly variation is highly dependent on the solar azimuth angle and it is best shown by the peaks in solar irradiance on the north- and south-facing façades (Fig. 8). Direct radiation peaks in November so the highest solar irradiance (near 120 kW h) is observed on the south-facing façade. However, the prolonged period of clear-sky conditions from May to August results in the high annual solar irradiance on the north-facing façade (over 800 kW h). Solar irradiance on the east- and west-facing façades is relatively more stable throughout the year. However, the east-facing façade receives higher level of solar radiation than the west-facing façade (200 kW h higher) and it also exhibits similar monthly variation to direct radiation in Dar es Salaam.

4. Discussion

4.1. Physical potential of using solar energy in Dar es Salaam

The findings of the present study show a substantial solar energy potential in the city of Dar es Salaam. Most of the roofs in the study areas receive more than 1500 kW h m^{-2} of solar irradiance annually. Given the relatively low electricity consumption per capita (about 100 kW h per year), the abundant solar irradiance provides an alternative energy source to household and local electricity usage (Kovac, 2012). Urban morphology predominantly influences solar irradiance in the areas. In City Centre and Kariakoo, the presence of high-rise buildings cause considerable overshadowing, particularly to building façades, which have a large potential in exploiting solar energy. Lower area average in annual roof and wall irradiance is observed in both areas due to the higher building coverage. Cheng et al. (2006) suggested that the effect of tall buildings on PV potential is more prominent in areas with high building coverage due to the overshadowing, which is the case in these two areas. Martins et al. (2014) also reported that spacing between buildings has a direct effect on solar irradiation due to the level of sun and sky obstruction. It implies that, with growing urbanization in the city of Dar es Salaam, high-rise buildings may have a negative effect on solar energy potential due to the increasing building coverage. Careful design of building and urban form is therefore required with regard to maximizing solar energy potential in the city.

In contrast, the relatively low-rise settings in Manzese produce the highest solar energy potential due to its high building coverage which maximizes the exposure to solar radiation. Košir et al. (2014) found that increasing layout density does not reduce PV potential when building height is low. Extensive roof areas are certainly suitable for the establishment of PV panels and result in substantial electricity production. This would contribute to wider use of electricity with renewable energy sources and improve living quality in such informal settlements.

Annual solar irradiance shows substantial intra-annual variations for different orientations of both tilted roofs and building façades. Flat roofs receive higher annual solar irradiance than any of the tilted roofs. However, the optical loss due to the presence of dust on a horizontal surface may reduce the electricity generated by individual PV modules (Catita, Redweik, Pereira, & Brito, 2014). North- and south-facing tilted roofs exhibit higher solar energy potential among the four cardinal orientations despite of having about 100 kW h of annual irradiance less than the flat roof. They are therefore considered to be appropriate locations for the establishment of PV panels.

Substantial variations in solar irradiance are observed on building façades due to the effect of solar azimuth angle. Although the annual solar irradiance on building façades is generally half of the roof irradiance, its high values (about 800 kW h m^{-2} per year) are still considered to have considerable solar energy potential. As the city continues to grow and high-rise buildings will be more common, extending the exploitation of solar energy to building façades will provide a solution to the increasing energy demand in urban areas.

In rapidly growing developing cities like Dar es Salaam, energy demand is expected to grow in the future and high dependence on traditional energy sources like fossil fuels will have negative environmental impacts. Renewable energy sources like solar power provide a solution to accommodate such enormous demand on energy without causing detrimental effects on the environment.

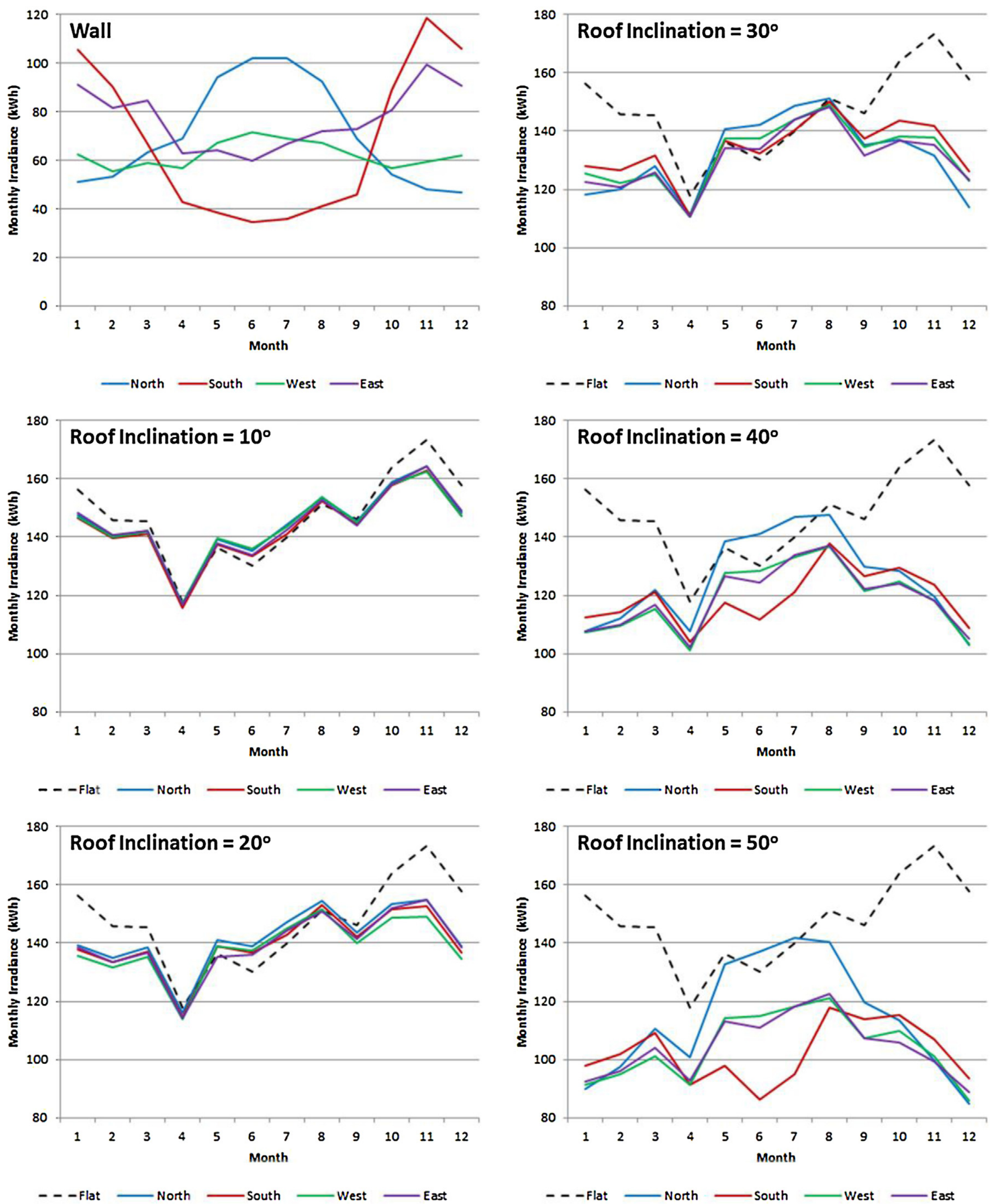

Fig. 8. Monthly solar irradiance of building façades and titled roofs with inclinations from 10° to 50° of four orientations.

However, as stated in Kichonge et al. (2014), the projected future shares of renewable energy sources (excluding hydro power) in Tanzania accounts for only 10% in 2035. It implies that there is still room for better utilization of solar energy potential in Tanzania. In additional, distribution and transmission losses account for about 20% of the energy production (Kihwele, Hur, & Kyaruzi, 2012). Therefore, solar energy offers an on-site production of energy for electricity generation and water heating, which greatly reduces the distribution cost. It also allows wider access to electricity in the city's outskirt where infrastructure is generally limited.

4.2. Socio-economic challenges of the development of solar PV electricity generation

According to Karekezi and Kithyoma (2003), it is important to provide reliable and affordable electricity to citizens for lighting and other domestic purposes. These are also the major challenges of the development of solar electricity generation in the country. The use of solar energy in Tanzania is still in its infancy and solar PV systems are limited to projects implemented by non-governmental organizations for dispensaries, hospitals, offices and communication technology (2012). It is likely due to the lack of established government policies which are crucial to creating a framework for disseminating renewable energy technology and encouraging private sector investment (Sampa, 1994). Karekezi (2002, p.1066) suggested that policy programmes related to the promotion of renewable energy should "demonstrate the economic and environmental benefits of renewables technologies to Africa's poor and propose short and medium-term policy initiatives that would engender large-scale dissemination of renewables". As the communities are more concerned about the immediate and tangible benefits such as job creation and income generation, the policy programme should be able to address such deliverables at both macro- and micro-levels.

The high establishment and maintenance cost of solar PV systems hinders the implementation of solar PV electricity generation in Tanzania (Ahlborg and Hammar, 2014). The financing conventionally relies on government subsidies and local capital, complemented by private loan component (Holland, Perera, Sanchez, & Wilkinson, 2001). However, according to Alzola et al. (2009), the monthly fee of a 10-year loan for complete financing of the solar PV systems for 350 inhabitants can be up to 2200 US Dollars. It is virtually impossible for rural areas or informal settlements to have electricity generated by solar PV systems without a comprehensive financing plan. This could be provided through public-private partnership with participation of the local community.

Theft of the PV systems is another barrier to the implementation of solar PV electricity generation (Mulugetta, Nhete, & Jackson, 2000). PV panels are perceived as expensive commodities and a stolen panel generates considerable financial rewards for those engaged in these activities. It was reported that there are about 10% of the 6000 PV systems installed in South Africa being stolen, which greatly discourages people to install PV systems for modern lighting and other domestic uses in their households (Ellegård, Arvidson, Nordström, Kalumiana, & Mwanza, 2004).

While high potential of solar irradiance on building roofs is reiterated in Manzese, issues such as affordability, access to reliable and safe energy technology, also in the long term, and land use efficiency are important and need to be considered. Moreover, the roof structure of the houses may not be appropriate for adding the weight of PV panels. Therefore, energy solutions for informal areas should be guided by collectiveness and governmental responsibility rather than individual solutions. Collective PV panels with good and proper infrastructure could be developed and strategically placed in Manseze, where they could deliver electricity not only for individual householders but also at neigbourhood level. Streets and common space lighting could be provided as well, contributing to the safety of the dwellers, especially young women. A collective solution would also facilitate maintenance and reduce the risk of theft of PV panels.

5. Conclusions

The present study employs numerical modelling of solar irradiance on building roofs and façades in order to investigate the effect of urban morphology on the solar energy potential of four urban neighbourhoods in Dar es Salaam, Tanzania. Due to the high solar elevation angle, the city is generally abundant with solar irradiance which allows extensive exploitation of solar energy for domestic use. Despite of such high solar energy potential, urban morphology has considerable effects on solar irradiance, which may hinder or contribute to the exploitation of solar energy. High-rise apartments reduce solar irradiance on the roofs of surrounding low-rise houses, particularly in areas with high building coverage. However, north- and south-facing building façades of such high-rise buildings are found to have considerable potential for the establishment of PV panels, suggesting that a careful design of both buildings and the surrounding neighbourhood is crucial in the exploitation of solar energy. In contrast, low-rise compacted informal settlements are found to receive the highest roof irradiance due to the absence of overshadowing caused by high-rise buildings. Due to the fact that such settlements are generally located either in between main roads or on the outskirts of the urban areas and that the infrastructure is so poor, the use of solar energy would improve their access to electricity and reduce the dependence of traditional energy sources which cause environmental problems. Further work will include the examination of how different urban morphology and building forms affect solar irradiance as well as the use of scenario-based approach to quantify the effect of different planning proposals on the solar energy potential in the city.

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