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Beyond costs: How urban form could limit the uptake of residential solar PV systems in low-income neighborhoods in Ghana

Mark M. Akrofi *, Mahesti Okitasari

United Nations University, Institute for the Advanced Study of Sustainability, 5–53–70 Jingumae, Shibuya-ku, Tokyo 150-8925, Japan

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A B S T R A C T

This paper examines the relationship between urban form, residential rooftop solar PV potential, and levelized cost of electricity (LCOE) in high-income, middle-class, and low-income neighborhoods in Accra, Ghana. Using building footprint data, ArcGIS Pro, and linear regression analysis, we find a statistically significant association between urban form parameters (building density, neighborhood compactness, building footprint area, suitable rooftop area, and near distance between buildings) and the rooftop solar PV potential in all the three types of neighborhoods. However, the well-planned high-income neighborhood exhibited the highest rooftop solar PV potential with low LCOE values for most houses, while the lowest rooftop PV potential and highest LCOE values were found in the largely unplanned low-income neighborhood. The low-income neighborhood exhibited higher density with clustered building patterns and, consequently, lower rooftop PV potential. The LCOE ranged between \$0.02/kWh-\$0.19/kWh for most buildings, with 92 %, 74 %, and 51 % of houses in the high-income, middle-class, and low-income neighborhoods falling within this range, respectively. We conclude that while capital subsidies for residential solar PV can boost their uptake by urbanites, their effectiveness could be limited in low-income neighborhoods due to the limitations imposed by their urban form. It may be more appropriate for policy interventions to target such neighborhoods with community solar schemes while targeting high-income neighborhoods with building integrated solar photovoltaics.

Introduction

Energy use in buildings accounts for 17.5 % of global greenhouse gas emissions (GHG) (Ritchie & Roser, 2020), making it one of the crucial sectors for decarbonization toward achieving the global GHG emission targets by 2030 (Feng et al., 2023; Huang et al., 2022a). Much of the energy used in buildings occurs in cities, which currently account for over two-thirds of global emissions (United Nations, 2018). Nevertheless, buildings provide an opportunity to reduce energy-related greenhouse gas (GHG) emissions through the installation of renewable energy technologies such as solar photovoltaics (PV) on their facades and roofs (Pandey et al., 2022; Wang et al., 2022). According to the International Energy Agency (IEA, 2014), installing solar PV systems on buildings could generate more than half of the global solar capacity by 2050. To this end, numerous studies have explored the feasibility and strategies for effectively integrating solar PV into the built environment (Akrofi et al., 2022; Garabitos Lara et al., 2023; Lundgren & Dahlberg, 2018; Mangiante et al., 2020; Nateghi et al., 2023; Xu et al., 2020). A consensus arising from these studies is that while solar PV systems are now widely economically viable, their expansion depends on the extent to which they can be integrated into the built environment (Akrofi & Okitasari, 2022; Lobaccaro et al., 2017a; Lobaccaro et al., 2019; Lundgren & Dahlberg, 2018; Wall et al., 2017).

The perspective above emerged from the findings that a city's urban form—the physical characteristics of the built environment such as neighborhood layouts, building types and shapes, building density, and building heights (Živković, 2019) — significantly influences the feasibility and performance of building integrated solar PV (BIPV) systems. Kanters et al. (2013) recount that where these urban form parameters are not checked in the early design phase of the neighborhood, suboptimal outcomes are obtained from the solar PV systems, and this outcome tends to discourage their uptake by homeowners (Kanters et al., 2013). However, Asaporter and Nadin (2020) noted that cities' spatial and urban form characteristics are sparsely addressed in the energy policies/strategies of many countries. In an attempt to address this gap, this article aims to examine the relationship between urban form attributes and residential rooftop solar PV potential in diverse socio-economic classes (high, middle, and low-income) of

* Corresponding author.
E-mail address: akrofi@student.unu.edu (M.M. Akrofi).

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neighborhoods in Ghana. In doing so, the study further examines how the levelized cost of electricity (LCOE) varies across the different neighborhood types. LCOE is a commonly used economic metric for making investment decisions on solar PV systems, and it refers to the average cost per kilowatt hour of electricity produced over the lifespan of the solar PV system (Putranto et al., 2022). The article draws implications from the findings for urban planning and residential solar PV policies in Ghana.

This study is necessitated by the fact that the cost of residential solar PV systems is often cited as a preeminent barrier to their uptake by homeowners, especially in developing regions such as Ghana (Brunet et al., 2018; Kizilcec & Parikh, 2020; Scott, 2017). Upon synthesizing the literature on the adoption of residential solar PV systems in sub-Sahara Africa, Kizilcec and Parikh (2020) noted that challenges regarding financial viability are dominant. The issue of affordability, in particular, is prevalent with low-income levels, and high up-front costs of the solar PV system often cited as the primary reason (Brunet et al., 2018; Scott, 2017). Consequently, the most recommended policy solutions include making residential solar PV systems more affordable through subsidies, tax and tariff reductions, and import duty and value-added tax exemptions (Hansen et al., 2015; Nygaard et al., 2017; Zhang, 2014). Such measures are observed in Ghana, where the government seeks to increase the share of renewable energy in the energy mix from 42.5 MW in 2015 to 1363.63 MW by 2030 (Energy Commission, 2019). One of the primary policy efforts toward this goal is the national rooftop solar program, a capital subsidy program aimed at lowering costs and encouraging the uptake of residential solar PV systems in the country.

Drawing from the connections between urban form and rooftop solar PV potential, this article questions whether policy interventions that seek to lower the cost of residential PV systems alone can facilitate their rapid and broader diffusion. The article is organized as follows. The ensuing section frames this study by setting out the key analytical framework through which we explore the interrelationships between urban form and rooftop solar PV potential. It is followed by an overview of residential solar PV policies in Ghana. The next section describes the methods used and the study area. In the section that follows, we present key findings in Accra. Drawing on these findings, we discuss the critical implications of contemporary issues and policies on solar PV. Finally, we offer recommendations for future studies based on our findings and limitations.

Analytical framework

Why urban form matters for urban energy transitions

Huang and Castan Broto (2018) contend that while clean energy technologies are now widely technically and economically viable, "their expansion depends on the process that embeds technologies within spatial configurations" (p.37). Bridge et al. (2013) referred to this process as socio-spatial embeddedness, defined as the degree to which renewable energy technologies can be infused into the urban fabric or built environment. Huang and Castán Broto (2018) noted that the physical characteristics of the built environment could facilitate or hinder the integration of clean energy technologies such as solar in cities. Thus, the successful integration of solar PV systems into buildings, for example, could influence and be influenced by the urban area's physical characteristics (urban form), such as building density, neighborhood layouts, building shapes, and heights. Gosens et al. (2015) assert that incorporating the spatial or urban form dimension into sustainable energy transition theories would bolster their analytical strength. In line with this view, Truffer and Coenen (2012) opined that unearthing the theoretical underpinnings of sustainability transitions requires an understanding of *transition spaces* which they define as "a synthesis of locally embedded contexts of events, objects and actions coupled with the wider socio-political, institutional and cultural context" (Truffer & Coenen, 2012, pg.11).

In the seminal diffusion of innovations theory, Rodgers (2003) pinpoints how the social system is a key determinant of how innovations are adopted. Rodgers (2003) argues that the diffusion of innovations occurs within a social system and is, thus, shaped by the social structure. This system could shape individuals' innovativeness as well as their adoption behavior. Elements of the social system include socio-economic status, education, gender, age, cultural norms, social supports, institutions, laws, and regulations, which could all influence an individual's access to and perception of an innovation (Rogers, 2003). Several studies (Schulte et al., 2022; Simpson & Clifton, 2017; Thomas et al., 2021) on the diffusion of residential solar PV systems have focused on these social factors. In Ghana, for example, existing studies on residential solar PV adoption have shown that elements of the social system, such as education, income levels, housing tenure arrangements, and prestige, significantly influenced the adoption of solar home systems (Boamah & Rothfuß, 2018; Mensah & McWilson, 2021). Studies dealing with the social system in terms of the urban form characteristics of the neighborhoods in which different social groups live are hard to come by. Thus, this study attempts to address a critical gap by focusing on different social systems in high-income, middle-class, and low-income neighborhoods with specific reference to how the urban form of such neighborhoods could impact the uptake of residential rooftop solar PV systems.

Urban form effects on rooftop solar PV potential in cities

Several studies have shown that urban form significantly affects the solar energy potential that can be harnessed in cities, particularly on the roofs and facades of buildings (Boccalatte et al., 2022; Morganti et al., 2017; Sarralde et al., 2015; Zhang et al., 2019). Kanters and Wall (2014) noted that density is the most influential factor affecting solar energy potential on buildings, while Lobacarro et al. (2017b) recount that if elements of urban morphology such as building heights, the distance between buildings, and building materials are optimized, the realizable solar energy potential could be increased by 25 % in Trondheim, Norway (Lobaccaro et al., 2017b). Similarly, Saralde et al. (2015) found that solar energy potential in London's neighborhoods could be raised by 9 % and 45 % on buildings' rooftops and facades by optimizing a combination of up to eight elements of the urban form. These factors range from land use characteristics to buildings' geometric features, such as perimeter, volume, floor area, and site coverage.

When buildings' heights are unchecked, overshadowing effects may occur from high-rise buildings, thus reducing the amount of solar irradiance that reaches neighboring low-rise buildings (Lau et al., 2017). Apart from shading effects, factors such as the façade-to-site ratio, gross space index, and sky factor equally influence how much solar irradiance is received by buildings which in turn affects the overall solar potential that can be realized from their rooftops and facades (Morganti et al., 2017). Mohajeri et al. (2016) found an inverse relationship between urban compactness and solar energy potential in that solar potential tends to decrease as urban compactness increases. According to Lobaccaro and Frontini (2014), overshadowing effects from neighboring buildings are more significant in compact neighborhoods, which is why they receive less solar irradiance. Similarly, Lobaccaro and Frontini (2014) studied how urban densification affects solar PV potential on buildings' rooftops and facades in Lugano, Switzerland. Their results also indicate that buildings' height, location, and orientation create overshadowing effects that affect the solar energy potential. Zhang et al. (2019) concluded that urban design significantly affects solar energy potential and energy efficiency in buildings, noting that solar energy potential could be increased by 200 % by appropriately designing urban block typologies.

In Africa, several studies explore rooftop solar PV potentials in cities (Alrawi & Al-Ghamdi, 2020; Ayodele et al., 2021; Mukisa et al., 2019; Zawilska & Brooks, 2011). However, the effects of urban form on solar energy potentials in the built environment have not been widely studied (Bensehla et al., 2021). A few studies have identified building shapes, type of house, urban density, building heights, and building material as significant determinants of rooftop solar PV potential in African cities (Bensehla et al., 2021; Lau et al., 2017; Mahaya et al., 2022). The neighborhood selection was based on the building types in all the studies outlined. Thus, in addition to the building types, this study takes into account the socio-economic classification of neighborhoods (high, middle, and low-income), given that such neighborhood types are often distinct in terms of their physical characteristics such as building types, neighborhood layouts, and conformity to planning and building standards. In Ghana, existing studies have focused on socio-economic and demographic factors affecting residential solar PV adoption (Boamah & Rothfuß, 2018; Boamah & Rothfuß, 2020; Opoku et al., 2020) without much attention to the interrelationships between urban form and rooftop solar PV in the broader context of urban planning.

This article will focus on the experience of Accra in unsettling the influence of these critical urban form characteristics. Examining the intersection between the built environment and solar PV diffusion is paramount to developing a grounded understanding of urban energy transition and highlighting efficiency and effectiveness issues regarding policies to promote residential solar PV uptake. Until the barriers to installing solar PV systems can be empirically grounded in the local context of urban form and its socio-spatial dimensions, the broader adoption of solar PV for urban energy transition may not be fully understood.

Policies to promote residential solar PV systems in Ghana

The Renewable Energy Act 2011 (382)

Enacted in 2011, Ghana's Renewable Energy Act (382) seeks to increase the share of renewable energy in Ghana's energy mix by creating an enabling environment for developing, managing and utilizing renewable energy resources sustainably (Energy Commission, 2019; Hagan, 2015). A range of national initiatives was launched to facilitate the implementation of the Renewable Energy Act. One initiative that is directly linked to residential solar PV systems is the Scaling-up Renewable Energy Program in Ghana Investment Plan (SREP-Ghana IP). As part of this initiative, a solar PV-based net metering with battery storage project was developed. The project sought to provide a net metering scheme to reduce the economic cost of rooftop solar PV systems for households and small and medium-sized enterprises (SMEs) (Energy Commission, 2019). Some 15,000 units of rooftop solar PV were planned under this project to increase the share of renewable energy in the electricity generation mix by 25-30 MW (Hagan, 2015). The net metering scheme presented a billing mechanism through which owners of solar PV systems receive credit for the electricity their systems supply to the grid, and this credit is set off against the electricity they purchase from the distribution utility (Energy Commission, 2015).

The scheme was piloted between 2015 and 2017 with planned expansion alongside the national rooftop solar PV program (see next section) launched by the government. However, the program was grounded to a halt not long after the start of its implementation. Adobea-Oduro et al. (2020) assert that the net metering program failed due to technical and financial challenges. Boamah and Rothfuß (2020) also noted that the program attracted significant public interest, with many customers seeking to trade solar power and off-set their tariffs, a situation that threatened the revenue accruing to Ghana's major utility and electricity distributor—the Electricity Company of Ghana (ECG). Consequently, the program was halted and would be resumed if only strategies to prevent ECG revenue losses were established and implemented (Boamah & Rothfuß, 2020). This situation highlights the conflict between national utilities and private electricity generation in Ghana and other African countries, where electricity generation and distribution are typically done through a centralized government agency or utility (Akrofi & Akanbang, 2021).

The national rooftop solar PV program

In 2015, the government of Ghana, through its Ministry of Power, launched the national rooftop solar program to reduce the peak load on the national grid by 200 MW. The program comes as a capital subsidy given to beneficiaries either as a cash payment or through the supply of 500 W solar panels. To receive these incentives, beneficiaries must first buy and install the requisite Balance of System (BoS) components of the solar home system. These include inverters, charge controllers, and batteries (Energy Commission, 2017). In addition to buying the BoS, prospective beneficiaries must use only LED lamps, install deep cycle batteries for PV systems, and use only solar PV installers licensed by the Energy Commission (Energy Commission, 2017). Once all these prerequisites are met, prospective beneficiaries must apply to the energy commission to receive the incentives. If the application is approved, the applicant receives the solar panels for free, or cash payment is made to a licensed residential solar PV installer to do the installation for the beneficiary. The licensed solar installer is paid directly by the energy commission, a sum of about GHS 1900 (Boamah & Rothfuß, 2018).

Since the start of its implementation, about 2449 people have applied to the program, and the Energy Commission has approved purchasing the BoS components for 1273, of which 727 applicants have received solar panels as of 2017 (Appiah, 2017). While this capital subsidy reduces the cost of the SHS for homeowners, it must be noted that the cost borne by the homeowners is still relatively too high for low-income households. Even with the subsidy, beneficiaries must bear about 60 % to 70 % of the cost (Appiah, 2017). Also, the 500 W solar panels provided are insufficient to meet all households' electricity needs. Homeowners who intend to expand the capacity of their SHS tend to do so at their own cost (Boamah & Rothfuß, 2018). To ease this financial strain, a number of commercial banks have collaborated to provide loans to interested beneficiaries. However, Boamah and Rothfuß (2018) noted that these loans come with high-interest rates of 29–35 %, often discouraging homeowners from taking them.

Apart from the financial challenge, Appiah (2017) adds that critical challenges facing the national rooftop solar program include logistical challenges. This challenge delays the inspection of the prerequisites for approval of beneficiaries' applications. Other challenges include erroneous application forms and the lack of understanding of the terms and conditions of the program by some of the SHS installation companies (Appiah, 2017). The challenges above relate more to the programs' administration and strategy. Other vital aspects regarding the influence of external factors, such as the physical characteristics and suitability of buildings for solar PV installation, which can affect the feasibility and effectiveness of solar PV systems, have not been explored. More broadly, no studies explore the program in the broader context of urban planning, where the effects of urban form are considered. Our study sheds some light on this research gap and attempts to address it.

Materials and methods

Description of the study area

The study area for this research is the city of Accra in Ghana. Accra is Ghana's capital city, with a population of about 4 million people (Ghana Statistical Services, 2020). It is located between latitudes 5.556°N and longitude 0.169°W and falls within the dry equatorial climatic zone, with an average annual rainfall of about 730 mm and an average daily temperature between 20 and 30 degrees Celsius (Ghana Statistical Service, 2014). The city has an average Direct Normal Irradiation (DNI) of 3.174 kWh/m^2 per day and 1158.5 kWh/m^2 per year, with monthly DNI ranging between 70.2 kWh/m^2 in January to 137.3 kWh/m^2 in October (World Bank, 2022). Like many African cities, the cityscape of Accra is characterized by older and often poorly planned inner-city areas that low-income urban dwellers occupy, while well-planned, high-income neighborhoods (mostly gated estates) could be found on the urban fringes. In this study, three neighborhoods, namely Regimanuel Gray Estate (high-income), Dansoman (mostly middle-class/income), and Alajo (low-income), have been selected.

Regimanuel Gray estate is a well-planned neighborhood along the Spintex road in Accra. It is characterized by exceptionally planned layouts and consists predominantly of detached and semi-detached houses. The building designs are almost uniform, with identical shapes, roofing types, and heights. Dansoman, on the other hand, is a planned neighborhood comprised of mostly middle to upper-income dwellers, with a mix of housing types such as detached, semi-detached, and condominiums (Ehwi et al., 2020). Alajo is an informal neighborhood characterized by mostly unplanned development and low-income dwellers. Some physical characteristics of these study areas can be seen in Fig. 1. The aerial images of the study areas show a more coherent and uniform neighborhood layout and the same building designs in the Regimanuel Gray estate. The layout in Dansoman is also clear; however, the building types are mixed and not as distinct as in the case of the Regimanuel Gray estate. On the other hand, no clear layouts can be observed in Alajo. The buildings in Alajo are more clustered with no distinct layouts compared to Dansoman and Regimanuel Gray Estate. Other characteristics of these neighborhood types, including the suitable rooftop area, building footprint area, and degree of compactness, are discussed in the results section.

Data and methods

Estimating the rooftop solar PV potential

Generally, the parameters needed to determine the rooftop solar PV potential are 1) the suitable rooftop area for solar PV installation, 2) the solar irradiance, 3) the solar panel's efficiency, and 4) the performance ratio of the solar panels. The annual electricity yield (solar energy potential) from a solar PV system is given by the formula (Huang et al., 2022b; Tian et al., 2021):

$$Eyr = A^{*} r^{*} H^{*} Pr. \tag{1}$$

where *A* denotes suitable rooftop area, *r* denotes solar panel efficiency, *H* denotes average annual solar irradiance on tilted panels, and *Pr* denotes the performance ratio of the solar panels (Huang et al., 2022b; Tian et al., 2021). In this study, the estimated electricity produced by the photovoltaic system is referred to as PV output (hereafter known as PV_{Out}) computed in kWh. Thus, Eq. (1) is rewritten as

$$PV_{Out} = A^{*}r^{*}H^{*} Pr \tag{2}$$

Data on each parameter in Eq. (2) are already available from various secondary sources (see Table 1). For our computations, we used building footprint data and suitable rooftop area data from the World Bank's *energydata.info* database (Fang et al., 2020). The annual average solar

Table 1
Parameters and data sources used for solar PV potential calculation.

Parameter	Value	Remarks	Source
Building footprint (Residential)	N/A (polygons)	Building polygons (shapefile)	Fang et al. (2020). World Bank *energydata.info*
Suitable rooftop area *(A)*	Varies	The rooftop angle, obstruction, and shading were taken into account during the suitable area calculation.	Fang et al. (2020). World Bank *energydata.info*
Solar panel efficiency *(r)*	17.52 %	Manufacturer's specification (From previous studies)	Quansah et al. (2020), Odoi-Yorke & Woenagnon (2021)
Annual average solar irradiance on tilted panels *(H)*	1158.5 kWh/m^2	For the greater Accra metropolitan area	World Bank Global Solar Atlas (World Bank, 2022)
Performance ratio of solar panels *(Pr)*	75 %	Based on previous Studies	Abdul-Ganiyu et al. (2020); Sekyere et al. (2021)

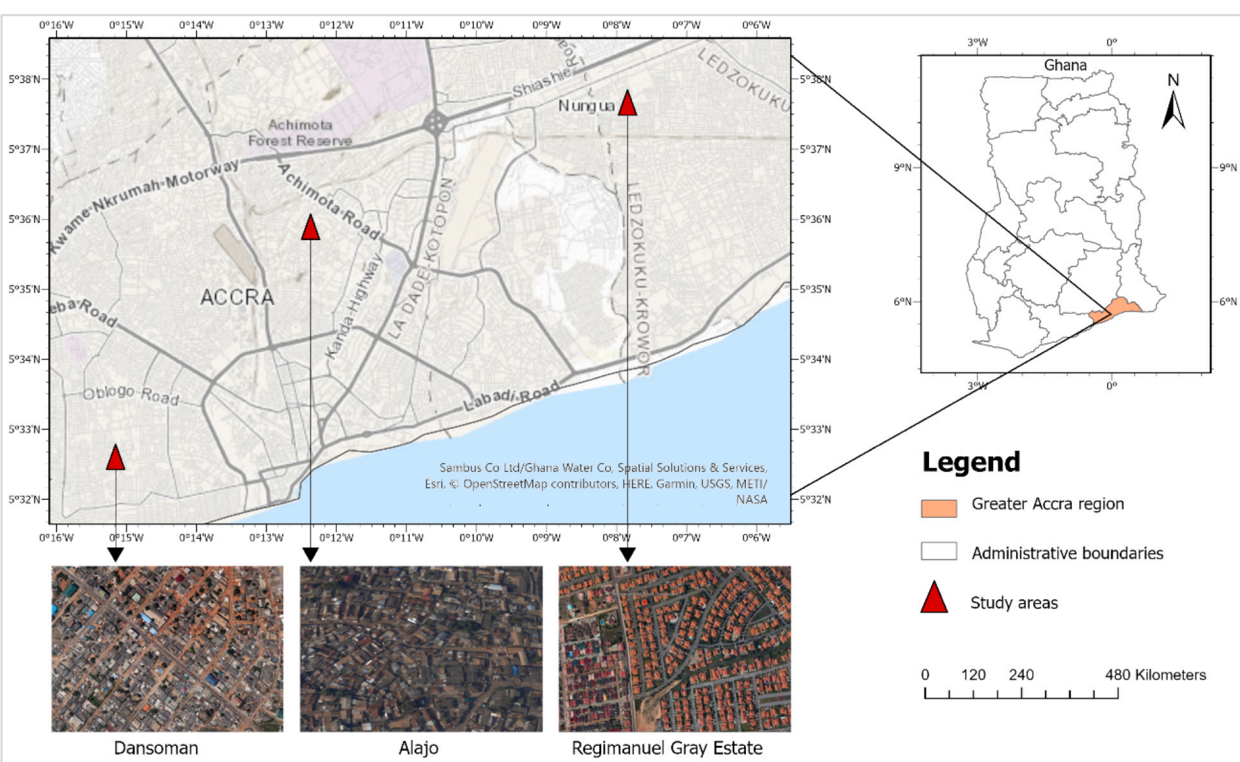

Fig. 1. Map showing the study areas.

irradiance value for the city of Accra was obtained from the World Bank's Global Solar Atlas (World Bank, 2022), while the performance ratio and solar panel efficiency were obtained from previous studies on solar PV systems in Ghana (Abdul-Ganiyu et al., 2020; Nocheski Solar, 2019; Sekyere et al., 2021). These data sources are summarized in Table 1.

Data on all the parameters listed in table one were accessed in July 2022. The building footprint data and associated metadata on suitable rooftop areas for Accra were downloaded in shapefile format from the World Bank's *energydata.info* database and imported into ArcGIS Pro software for analysis. Data specific to the three neighborhoods of interest (Regimanuel Gray Estate, Dansoman, and Alajo) were extracted. Also, since we focus on residential buildings/houses, other building types, such as commercial and public buildings, were removed from the dataset.

Estimating the levelized cost of electricity (LCOE)

The formula for calculating LCOE is specified in Eq. (3) as:

$$LCOE = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{Et}{(1+r)^t}} \tag{3}$$

where I_t is the investment cost, M_t is the operation and maintenance cost, F_t is the fuel cost, Et is the electricity produced, all in year t, r is the discount rate, and n is the system's lifetime. The fuel cost is omitted in this study, given that solar PV systems do not require fuel to operate (Putranto et al., 2022). Hence the final formula applied is given in Eq. (4) as:

$$LCOE = \frac{\sum_{t=1}^{n} \frac{I_t + M_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{Et}{(1+r)^t}} \tag{4}$$

For the cost components, data were obtained from a major residential solar PV system supply company in Ghana—Nocheski Solar (2022). In this study, a mini off-grid residential solar system package was considered. This system costs \$2099.99 (including installation) and can provide backup electricity for 8 h (Nocheski Solar, 2022). The package comprises a 500 W solar panel capacity, 2.4 kWh battery storage capacity, and a Victron Phoenix inverter with a capacity of 800 VA. It can power 10 LED bulbs, 5 fans, and two 32-inch LED TVs (Nocheski Solar, 2022), typical appliances Ghanaian households own. The annual operation and maintenance cost was set at \$8, with a system lifespan of 25 years based on previous studies in Ghana (Odoi-Yorke & Woenagnon, 2021; Quansah et al., 2020). A discount rate (As of July 13, 2022) of 18.86 % (Bank of Ghana, 2022) was applied, while the annual electricity generated (E_t) corresponds with the PV potential (PV_{Out}) computed in Eq. (2).

Key assumptions

In reality, the solar irradiance of each rooftop will be influenced by site-specific factors such as location, orientation, and height. However, since such data is unavailable for each house, we use the average solar irradiance for the city of Accra. Hence, we assume that the average annual solar irradiance on tilted panels is 1158 kWh/m^2 (World Bank, 2022) for each building in the study. Also, the investment cost of the residential solar PV system will differ depending on the system size that each household chooses. However, since obtaining such data at the time of this study is impossible, we use the mini off-grid residential solar system described above. Hence, it is assumed that the investment cost will be \$2099.99 for all houses. It is worth pointing out that these assumptions are not exclusive to our study, as other studies on the LCOE of PV systems (e.g., (Odoi-Yorke & Woenagnon, 2021; Putranto et al., 2022; Quansah et al., 2020)) have used a similar approach. Since economic and weather conditions are not static, it is plausible that the investment cost and solar irradiance will keep changing, thus highlighting the future uncertainties inherent in our assumptions. Again, such uncertainties are typical of LCOE estimations for solar PV systems (Vaderobli et al., 2020). We acknowledge this as a limitation in conclusion section and provide recommendations for future research.

Estimating the urban form parameters

After importing the shapefile containing the building polygon and suitable area data for the three neighborhoods, their attribute tables were exported in comma-separated values (CSV) format using ArcGIS Pro's *Table to Excel* tool. Data on the parameters in Table 1 and the cost parameters were added to each respective study area's attribute table. We used Microsoft Excel to compute the rooftop solar potential of houses in each study area and the LCOE. The results were then imported into ArcGIS pro, which was used then to create visualizations in the form of maps. In analyzing the data, to begin with, we examined the relationship between the solar PV potential (PV_{Out}) and building density. In doing so, the building footprint polygons were converted to points using the *Polygon to Point* tool in ArcGIS Pro. Next, the building density was computed using the *Kernel Density* function, and the results were overlaid with the PV_{Out} layer to ascertain the relationship between the two variables. The Kernel Density is given by the formula in Eq. (5).

$$Density = \frac{1}{(radius)^2} \sum_{i=1}^{n} \left[\frac{3}{\pi} .pop_i \left(1 - \left(\frac{distance_i}{radius} \right)^2 \right)^2 \right] \text{ for } disti < \text{radius.} \tag{5}$$

where $i = 1, \ldots, n$ are the input points, pop_i is the population field value of point i, which is an optional parameter, and $dist_i$ is the distance between point i and the (x,y) location (see (Esri, 2022) for more information on the kernel density function).

The *Aspect*[1] tool in ArcGIS pro was used to examine the *Aspect* (slope direction) in the study area. The building footprint area was computed using the *Add geometry*[2] tool in ArcGIS Pro. Building footprint area is the size of the building as measured by the perimeter of its outer walls and shape. The neighborhoods' compactness level was also examined to determine whether the buildings were clustered or dispersed. This analysis was done using the *Average Nearest Neighbor* tool in ArcGIS pro. The nearest neighbor tool measures the distance between a building's centroid and the centroid of its nearest neighbor (Mitchel, 2005). It then computes an average of all the nearest distances to produce a ratio for the entire neighborhood. If the ratio is >1, the distribution of buildings is considered dispersed, and if it is <1, the distribution is considered clustered (Mitchel, 2005). The Average Nearest Neighbor ratio is given by the formula in Eq. (6).

$$ANN = \frac{\overline{D}_o}{\overline{D}_E} \tag{6}$$

where $\overline{D}_o$ is the observed mean distance between each feature and its nearest neighbor while $\overline{D}_E$ is the observed mean distance for the feature given in a random pattern (see Mitchel, 2005 for details). The *Near*[3] tool in ArcGIS pro was used to estimate the near distance between buildings in all study neighborhoods. Near Distance measures the average distance between one building and the closest building to it. This metric is different from the nearest-neighbor ratio in that it generates a near-distance value for each building in the neighborhood, while the nearest neighbor provides a ratio for the entire neighborhood based on the distance between each building's centroid and that of its nearest neighbor.

[1] For how it works, see https://pro.arcgis.com/en/pro-app/latest/tool-reference/spatial-analyst/aspect.htm.

[2] https://pro.arcgis.com/en/pro-app/latest/tool-reference/data-management/add-geometry-attributes.htm.

[3] For how it works see https://pro.arcgis.com/en/pro-app/latest/tool-reference/analysis/near.htm.

Establishing the association between urban form and rooftop solar PV potential

The relationship between urban form attributes (footprint area, suitable rooftop area, near distance, and nearest neighbor ratio) and the rooftop solar PV potential (PV_{Out}) was examined using linear regression models in Eqs. (7) and (8). The model is given as follows:

$$PVout_i = \alpha_i + \beta Dep_i + NearestNeighbour + \varepsilon_i \tag{7}$$

where Dep_i denotes suitable rooftop area, building footprint area, and near distance between buildings. To control for the differences between neighborhoods, we estimate Eq. (8) with neighborhood dummies. This equation is given as follows:

$$PVout_i = \alpha_i + \beta \mathrm{D}ep_i + Reg + Dan + \varepsilon_i \tag{8}$$

where *Dan* and *Reg* are dummy variables for Dansoman and Regimanuel Gray Estate, respectively, and Alajo is the base.

Results

Urban form characteristics of the study areas

The pattern of buildings' layout in a neighborhood is one of the indicators of its urban form. This pattern can either be clustered or dispersed, and the extent of clustering or dispersion is measured using the average nearest-neighbor analysis. The results yielded average nearest neighbor values of 1.08, 1.11, and 0.90 for the Regimanuel Gray Estate, Dansoman, and Alajo, respectively. These results imply that the spatial pattern of buildings in Regimanuel Gray Estate and Dansoman is dispersed, while the pattern is clustered in Alajo. Table 2 summarizes the results of the average nearest-neighbor analysis.

The p values in Table 2 indicate a statistically significant dispersion of buildings in Regimanuel Gray Estate and Dansoman, while a statistically significant clustering is observed in Alajo. Whether the observed clustering or dispersion is random or not is determined by the Z-score. A very high or very low (negative) z-score value associated with a lower p value indicates that the distribution is not random (Mitchel, 2005). Hence, it can be deduced that the buildings in all three neighborhoods were not randomly sited. This situation is understandable because, in the case of Dansoman and Regimanuel Gray Estate, the neighborhoods have been well-planned and highly adhere to the planned layouts. The result of this adherence is visible in the layouts of these neighborhoods, as seen from their aerial images in Fig. 1.

On the other hand, even though Alajo exhibits no proper planning and, thus, no clearly visible layout patterns, the siting of buildings is not necessarily random as people will naturally choose the most suitable sites or at least the less dangerous sites (e.g., disaster-prone areas, marshy or steep areas) to build. For example, the *Aspect* (ground slope and its direction) analysis of the three neighborhoods shows that buildings are generally not sited in areas with very steep slopes even though a few buildings could be found in such areas. Figs. 2, 3, and 4 show an overlay of the building layouts in the three study areas and the *Aspect* on which the buildings are cited.

In all three study areas, the steepest slopes are facing west, northwest, and north, with directions ranging from 247.5° to 360°. However, areas lying within 0–22.5° north and 22.5–67.5° northeast were relatively gentle sloping. Observably, the steepest points in the study areas are not populated, even though few buildings are present in some areas. This is understandable since such hilly areas are typically unsuitable for buildings as they could be prone to flood-induced landslides. The results of the *Aspect* analysis highlight the degree of adherence to building regulations/standards in the study communities. In the gated estate, it can be observed that the steepest points are generally avoided, as very few buildings can be found in such areas. However, in Dansoman and Alajo, clusters of buildings could be found on the steep slopes. Alajo, in particular, is known to suffer severe flooding almost every year during the rainy season in Accra (Twum & Abubakari, 2019).

In terms of building characteristics in the three neighborhoods, the mean suitable rooftop area for solar PV installation and the mean building footprint area were higher in the Regimanuel Gray Estate and lowest in Alajo. A suitable rooftop area for solar PV installation is the area in square meters on the building's rooftop that receives adequate solar irradiance taking into account the shading factor, the tilt angle of the roof, and obstructions such as trees, chimneys, or poles (Huang et al., 2022b; Vulkan et al., 2018). Descriptive statistics on the suitable rooftop area and building footprint area are summarized in Table 3.

Table 2
Average nearest-neighbor ratios in the study areas.

Neighborhood	Parameters				
	Observed mean distance	Expected mean distance	Nearest neighbor ratio	Z-score	p value
Regimanuel Gray Estate	21.49	19.95	1.08	5.61	0.00
Dansoman	16.53	14.78	1.11	15.13	0.00
Alajo	13.05	14.53	0.90	−9.14	0.00

Rooftop solar PV potential in the different neighborhood types

The potential annual electricity that can be generated from rooftop solar PV (PV_{Out}) ranged from 312.0 kWh/yr-118,984.2 kWh/yr in Alajo, 239.3 kWhr/yr-133,158.6 kWh/yr in Dansoman, and 239.3 kWh/yr -126,977.7 kWh/yr in Regimanuel Gray Estate. The mean annual potential was highest in the Regimanuel Gray Estate (35,598.6 kWh/yr) and lowest in Alajo (13,688.4 kWh/yr), with Dansoman having a mean of 22,386.7 kWh/yr. However, the standard deviation indicates that the rooftop solar PV potential of most buildings in these communities is below the mean. The standard deviation was highest for Regimanuel Gray Estate (18,515.5 kWh/yr), followed by Dansoman (16,532.2 kWh/yr) and Alajo (11,453.9 kWh/yr). The high-income neighborhood (Regimanuel Gray Estate) exhibits greater potential on buildings' rooftops than the middle-class (Dansoman) and low-income (Alajo) ones. Fig. 5 shows that the proportion of buildings with the highest rooftop solar PV is more significant in Regimanuel Gray Estate and Dansoman compared to Alajo.

Association between urban form attributes and rooftop solar PV potential

The results from the regression analysis affirm that the suitable rooftop area, building footprint area, nearest neighbor ratio, and near distance between buildings have statistically significant relationships with the rooftop solar PV potential. These results are summarized in Table 4.

The significant association between the urban form attributes and the rooftop solar PV potential is due to the susceptibility of the urban form attributes to external factors such as shading and obstructions, which affects the amount of solar irradiance received by buildings (Boccalatte et al., 2022; Lobaccaro & Frontini, 2014). Boccalatte et al. (2022) noted that large buildings with big surfaces (rooftop area) appear less shaded, even if they are low-rise, compared to high-rise buildings with small surfaces. Thus, neighborhoods with a majority of buildings having larger building footprints and suitable rooftop areas are expected to have higher solar PV potential and vice versa. This assertion is affirmed by the results in Table 3, where it is apparent that the mean suitable rooftop area and building footprint area, for example, are higher in Regimanuel Gray Estate and Dansoman as compared to Alajo.

Controlling for all other differences between the neighborhoods while using Alajo as the base, regressions 4, 5, and 6 affirm that the rooftop PV potential is higher in Regimanuel Gray Estate and Dansoman than in Alajo. The level clustering/dispersion of buildings in each

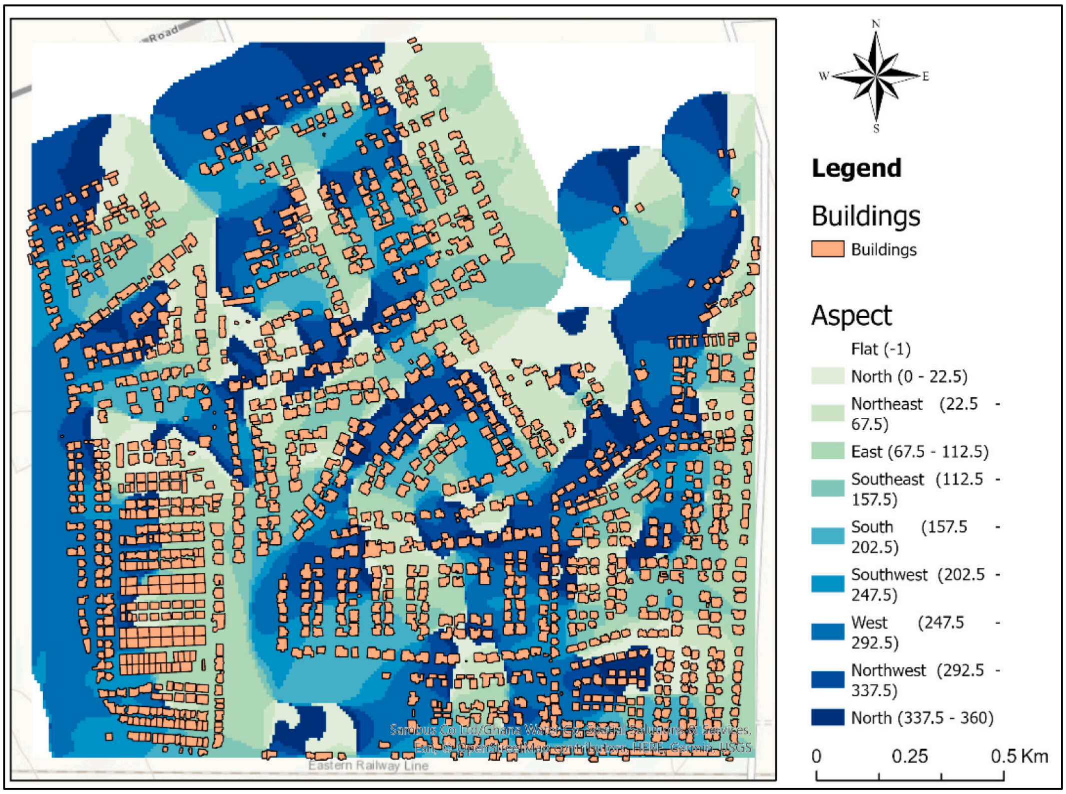

Fig. 2. Aspect and building layouts in Regimanuel Gray Estate.

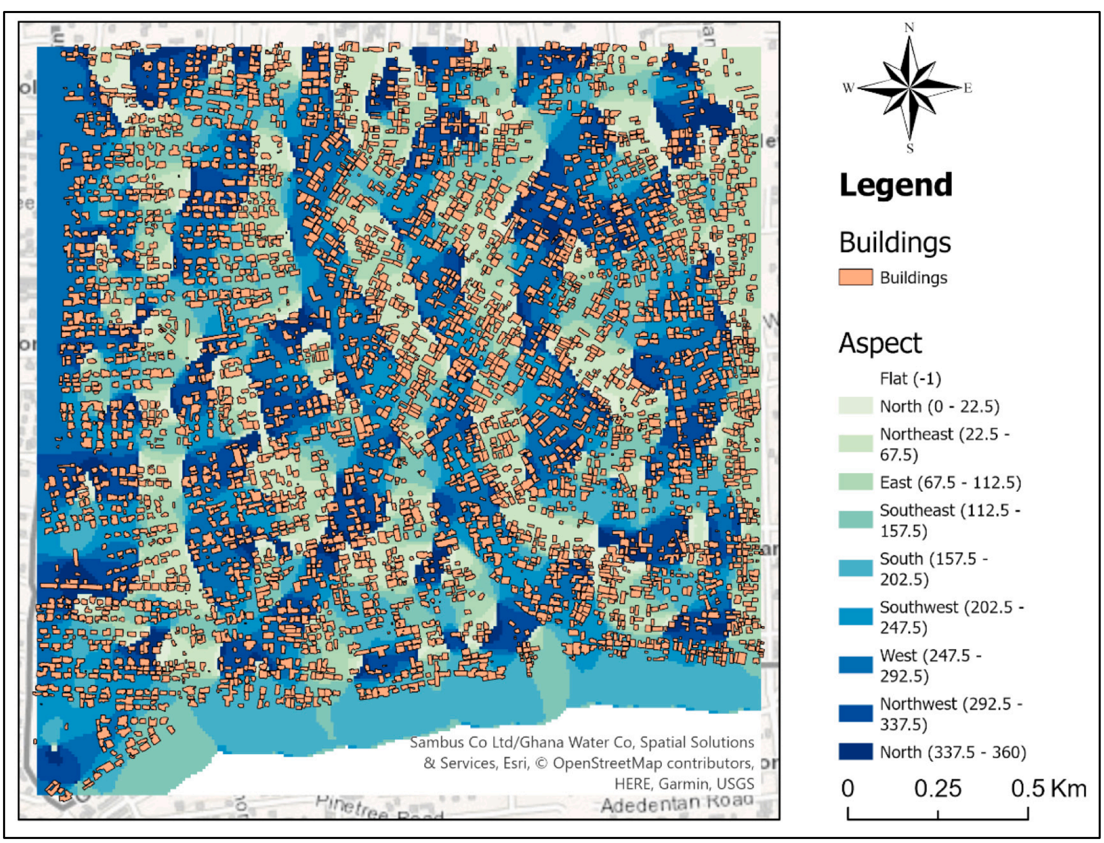

Fig. 3. Aspect and building layout in Dansoman.

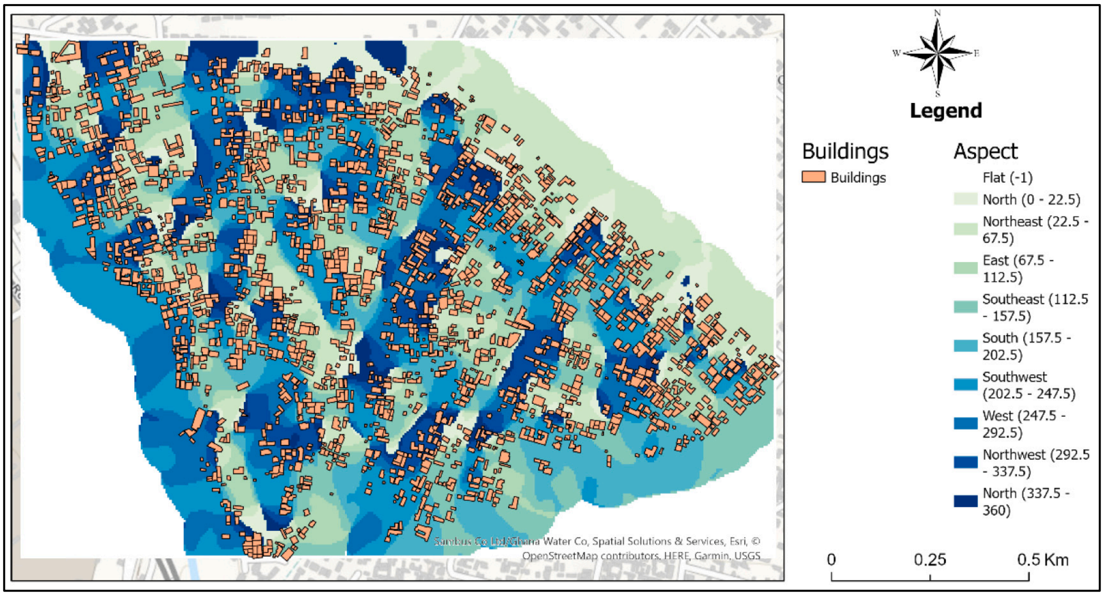

Fig. 4. Aspect and building layout in Alajo.

Table 3
Descriptive statistics on suitable rooftop area and building footprint area.

	N	Minimum	Maximum	Mean	Std. deviation
Suitable rooftop area (m^2)					
Alajo	2222	2.05	782.5	90.02	75.33
Regimanuel Gray Estate	1465	1.57	835.1	234.1	121.8
Dansoman	4419	1.57	875.7	147.2	108.7
Building footprint area (m^2)					
Alajo	2222	11.02	1367	143.3	102.5
Regimanuel Gray Estate	1465	6.14	1094	329	154.2
Dansoman	4419	6.75	1202	221.8	142.8

neighborhood turned out to have the most significant correlation with the rooftop solar PV potential. This finding is consistent with those made by Mohajeri et al. (2016), who noted that dispersed neighborhoods have higher rooftop PV potentials because they receive higher solar irradiance as compared to compact ones. Overall, it is apparent that the high-income neighborhood exhibits greater potential for rooftops than the middle-class and low-income neighborhoods due to their urban form characteristics. Previous studies (Bensehla et al., 2021; Boccalatte et al., 2022; Mahaya et al., 2022) show that neighborhoods with consistent building features like heights, detached configurations, and shapes have higher rooftop solar PV potentials. This is the case of the Regimanuel Gray Estate, characterized by primarily detached and semi-detached houses with consistent building designs, shapes, heights, and configurations.

On the other hand, neighborhoods such as Dansoman and Alajo are characterized by different housing types ranging from detached configurations to condominiums and compound houses of different shapes and sizes. Compound houses are typically single or multi-story houses with several rooms (averaging 10–15) and an open courtyard. Thus, they occupy a large square area and have larger rooftops. This finding explains why the maximum suitable rooftop area (Dansoman = 875.7 m^2, Alajo = 782.5 m^2) and building footprint area (Dansoman = 1202 m^2, Alajo = 1367 m^2) are higher in Dansoman and Alajo as compared to Regimanuel Gray Estate even though the estate has higher mean for values for the suitable rooftop area and building footprint area than Dansoman and Alajo. Compound houses are usually multi-occupancy (mostly renters or extended families), where several households share the same roof. This situation presents a challenge to residential rooftop solar PV adoption as it raises the question of who has access to the rooftop (Barau et al., 2020). A few gated estates in Ghana also have multi-story condominiums. No such condominiums were present in the Regimanuel Gray Estate. However, the same issue of access rights to the rooftop could arise in areas where there are multi-occupant high-rise condominiums.

Relationship between building density and rooftop solar PV potential

Similar to the findings made by previous studies (Bensehla et al., 2021; Kanters & Wall, 2014; Lobaccaro & Frontini, 2014), we found variations in the rooftop solar PV potential based on the building density in each study area. The building density was much higher in Dansoman and Alajo, with observable clusters of buildings with low rooftop solar energy potential in the denser parts of each community. On the other hand, the Regimanuel Gray Estate exhibits less density and higher rooftop solar PV potential. Lobaccaro and Frontini (2014) noted that denser neighborhoods have lower rooftop solar PV potential due to overshadowing effects from the ground and neighboring buildings. Several outliers are visible in each community where high-potential buildings are spotted in denser areas (see Figs. 6, 7, and 8).

In Fig. 6, for example, buildings with high rooftop solar PV potential are found in the southwestern part of the Regimanuel Gray Estate, where the building density is higher than in other parts of the neighborhood. One reason for this variation is that the buildings in question have larger suitable rooftop areas than their neighboring counterparts. By clicking on these buildings on the map (in ArcGIS Pro), the metadata showed that the suitable rooftop area for most of them is above 330 m^2 compared to their neighboring buildings, whose suitable rooftop areas were mostly below 200 m^2. These variations are also visible in terms of the size of the building polygons on the map. A second factor that could explain these outliers is the height of the buildings. Generally, higher buildings receive more solar insolation than buildings with lower heights, especially if they are located on the same site (Lobaccaro et al., 2017b).

However, since data on building heights for the study areas were unavailable, we could not verify if the height of the buildings influenced the variations in the rooftop solar PV potential. Some previous studies also suggest that density may not significantly influence rooftop solar PV

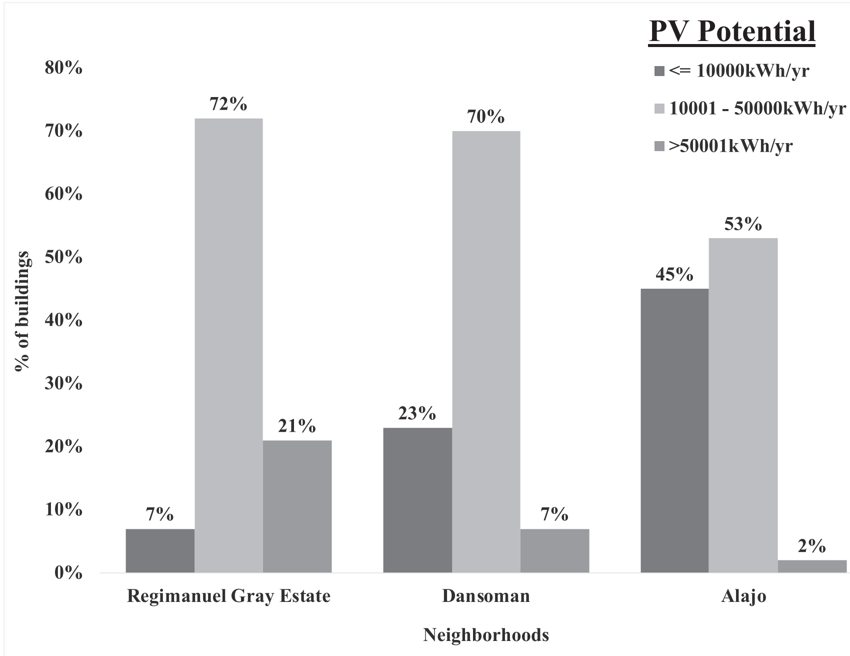

Fig. 5. Proportion of buildings by rooftop solar energy potential for each neighborhood.

Table 4
Association between urban form parameters and rooftop solar PV potential.

Variables	(1) lnPVOut	(2) lnPVOut	(3) lnPVOut	(4) lnPVOut	(5) lnPVOut	(6) lnPVOut
SuitARea	0.00699*** (4.76e-05)			0.00703*** (5.04e-05)		
BFA		0.00547*** (3.47e-05)			0.00548*** (3.66e-05)	
NearD			0.0302*** (0.00314)			0.0378*** (0.00303)
NNR.	0.530*** (0.0595)	0.405*** (0.0566)	2.957*** (0.109)			
Regi. Gray				0.0667*** (0.0174)	0.0627*** (0.0165)	1.115*** (0.0290)
Dansoman				0.113*** (0.0125)	0.0858*** (0.0119)	0.523*** (0.0223)
Constant	8.085*** (0.0609)	8.045*** (0.0578)	6.627*** (0.114)	8.561*** (0.0109)	8.408*** (0.0108)	9.250*** (0.0187)
Observations	8106	8106	8106	8106	8106	8106
R-squared	0.749	0.773	0.091	0.749	0.773	0.163

Standard errors are in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.
Note: Alajo neighborhood is used as the base.

potential. Mohajeri et al. (2016) noted that urban compactness (which is influenced by building density) had less influence on solar PV potential on buildings' rooftops than on their facades. However, dispersed neighborhoods receive higher solar irradiance than compact neighborhoods (Mohajeri et al., 2016). It is apparent in Fig. 7 that the building density in the eastern part of Dansoman is much higher than in the western part. Observably, buildings with higher rooftop solar potential can be seen in the western part, while several clusters of lower potential buildings are concentrated in the denser eastern part. On the other hand, Alajo is characterized by higher building density across all areas of the neighborhood. Consequently, it has very few buildings with higher rooftop solar PV potential and a higher concentration of buildings with lower potential. These findings align with those made by Mahaya et al. (2022), who also found that neighborhoods with low density have higher solar energy potential than those with higher density.

LCOE of rooftop solar PV in the different neighborhood types

LCOE is one of the important metrics considered when investing in solar PV systems. It refers to the average cost of electricity produced over the lifetime of the solar PV system. Generally, a lower LCOE value is preferable since it indicates that the PV system owner will pay less for the electricity produced over the system's lifetime. A recent report by Lazard, a US-based financial firm, puts the LCOE of residential solar PV systems at \$0.147–\$0.221/kWh (Lazard, 2021). Estimates from the IRENA equally put the LCOE of residential solar PV systems well below \$1/kWh (IRENA, 2017). Consistent with these figures, the LCOE of rooftop solar PV for the majority of the residential buildings we analyzed have LCOEs between \$0.02/kWh-\$0.19/kWh. The proportion of buildings with LCOEs within this range was highest in Regimanuel Gray Estate (92 %), followed by Dansoman (74 %) and Alajo (51 %). Fig. 9 presents a summary of the proportion of buildings in each LCOE range for the three study areas.

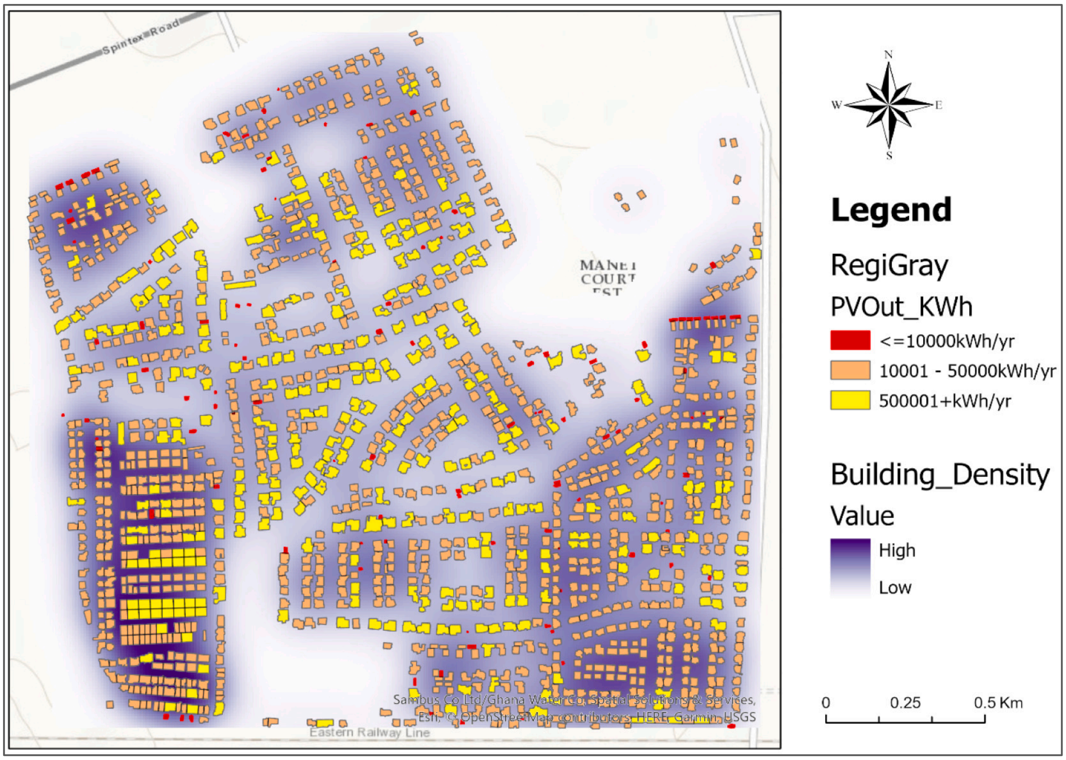

Fig. 6. Building density and rooftop solar potential in Regimanuel Gray Estate. Note: Building density is in square kilometers (km^2).

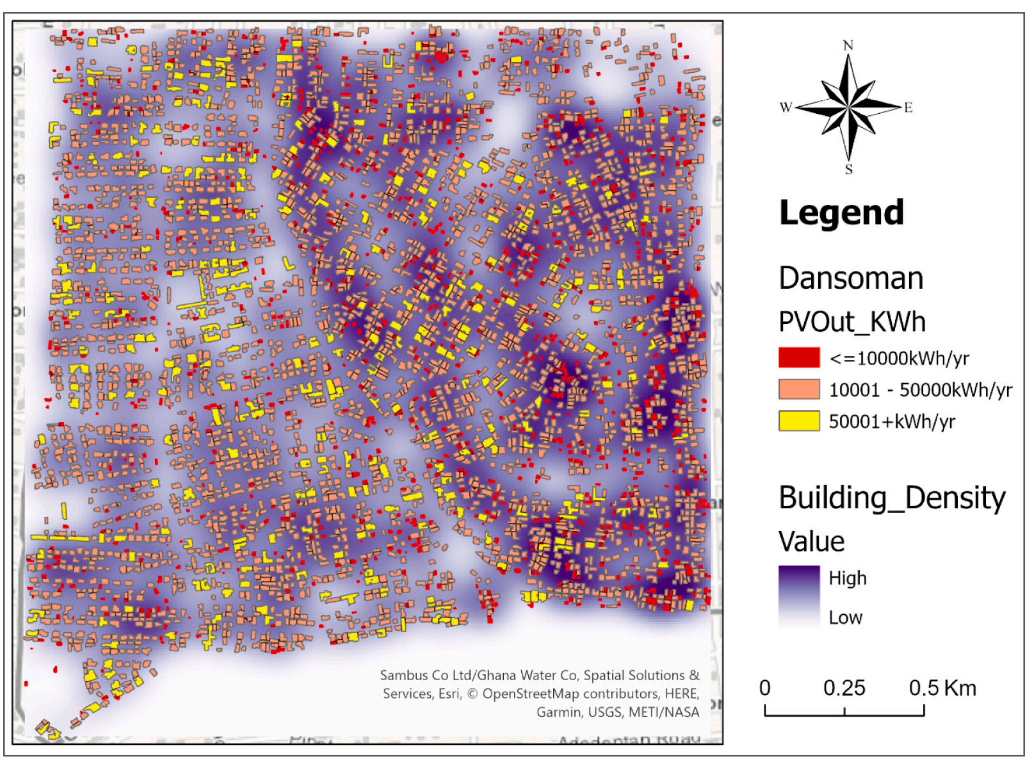

Fig. 7. Building density and rooftop solar potential in Dansoman.

It is apparent from Fig. 9 that the economic viability of rooftop solar PV is higher in high-income neighborhoods and lowest in low-income ones. This finding highlights the argument that some urban dwellers, especially those in informal and unplanned areas, may face limited choices in adopting residential rooftop solar PV systems due to urban informality (Barau et al., 2020). Nonetheless, with >50 % of buildings in the low-income having an LCOE of $0.02/kWh-$0.19/kWh, it can be deduced that the economic potential for adopting residential solar PV systems is moderate for low-income dwellers.

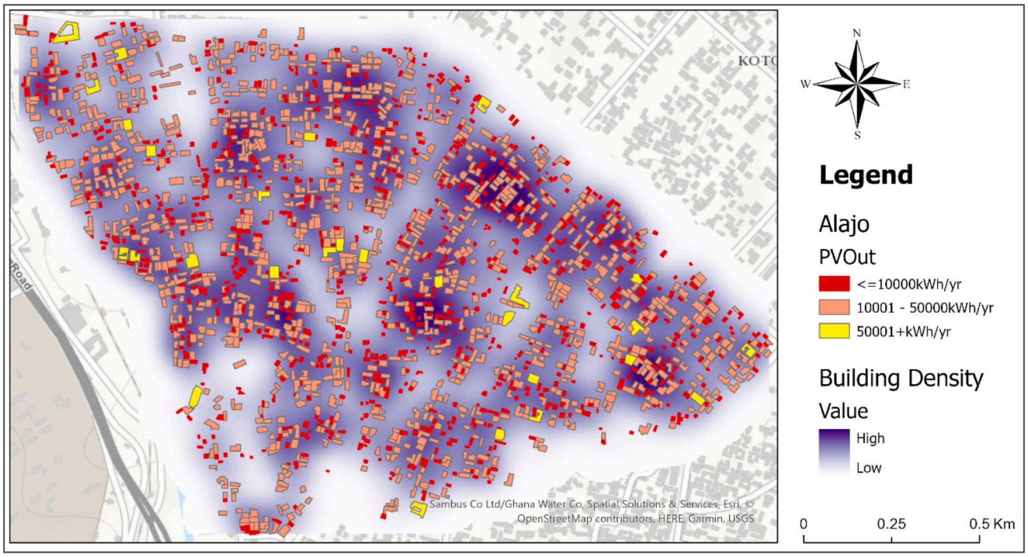

Fig. 8. Building density and rooftop solar potential in Alajo.

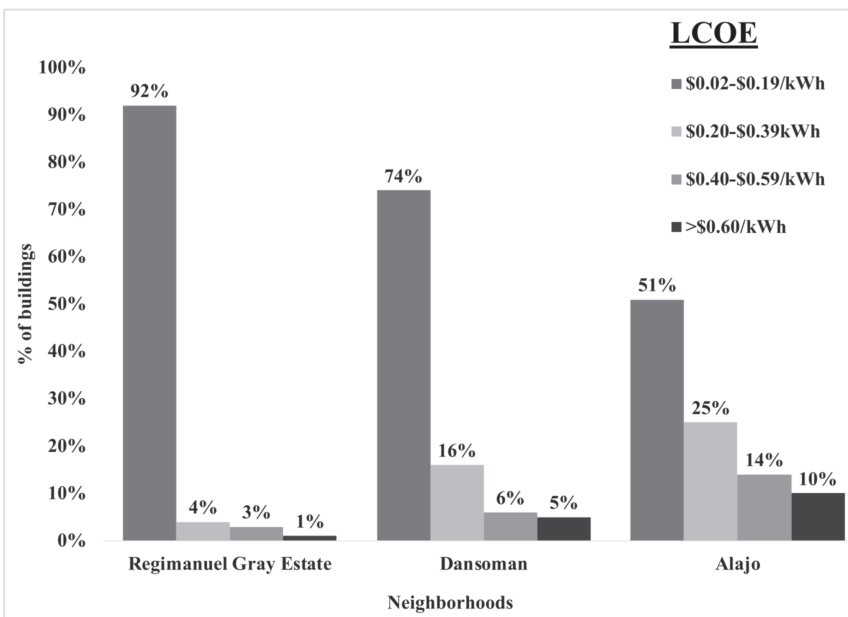

Fig. 9. Proportion of buildings by LCOE of rooftop solar PV.

Discussion

The main findings drawn from the results of this study is that urban form characteristics not only affect rooftop solar PV potential but could also limit the uptake of solar PV systems in poorly planned and often low-income neighborhoods. A summary of the main results is presented in Fig. 10.

This paper demonstrates that the potential for residential rooftop solar PV is higher in well-planned high-income neighborhoods than in middle-class and low-income ones due to the nature of their urban form. The level of compactness and building density, in particular, tend to have the most significant effects where neighborhoods with compact layouts and higher building density, such as Dansoman (middle-class) and Alajo (low-income), yielded lower rooftop solar PV potential as compared to Regimanuel Gray Estate (high-income), which has a lower building density. Most houses in the high-income neighborhood also had lower LCOE values compared to the middle-class and low-income neighborhoods. Studies on the uptake of residential solar PV systems, especially in the global South, have often centered on socio-demographic determinants such as educational attainment, knowledge of solar PV systems, willingness to adopt, and income levels, among others (Groenewoudt et al., 2020; Kizilcec & Parikh, 2020; Thomas et al., 2021).

While these factors are essential for urban energy transitions, our findings imply that even where such socio-demographic and economic factors favor the adoption of residential PV systems, the options for adoption could be limited by the urban form characteristics of different neighborhood types. Dwellers in poorly planned and mostly informal areas of the city are at a particular disadvantage. These findings, therefore, have important implications for policies that aim to lower the costs of solar PV systems for homeowners.

Take the case of Ghana's capital subsidy program, for example. It can be deduced that even if the program substantially reduces the cost of residential solar PV systems for urbanites in low-income neighborhoods

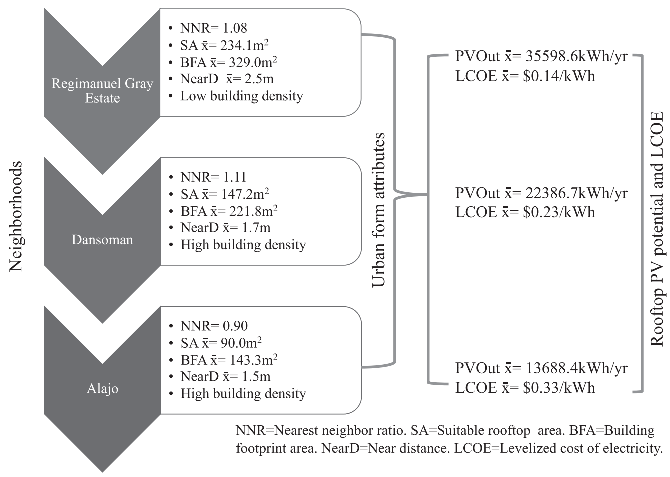

Fig. 10. A summary of the main results of the study.

such as Alajo, they may not obtain optimum outcomes from the PV systems due to the limitations imposed by the urban form characteristics of the neighborhood. Previous studies of this capital subsidy program have critiqued it for favoring high-income households who can afford the balance of system components and, thus, question its inclusiveness (Boamah & Rothfuß, 2018). Our findings also suggest that urbanites in low-income neighborhoods may lose out on the program because the urban form of their neighborhoods is not as favorable for rooftop solar PV systems as compared to the high-income neighborhoods. Given this circumstance, one would easily assume that there is an inherent bias against low-income urbanites since they do not stand an equal chance of reaping the benefits of the rooftop solar program. However, we argue that the question of *who pays for the clean energy transition* should be an important consideration. Given that high-income neighborhoods have more favorable conditions for residential solar PV uptake, could it not be mandatory for housing in such neighborhoods to have residential solar PV systems? Such a mandate will require real estate developers, for instance, to incorporate solar PV systems into their properties.

Countries like Japan are already taking steps for such mandates. For example, the Tokyo Metropolitan Government is seeking to make solar panels compulsory for all new homes developed by housing companies (The Japan Times, 2022). The wealthiest 10 % of people globally produce 52 % of cumulative carbon emissions (Gore, 2020). In Ghana, ownership of backup diesel generators is common among wealthier households in high-income neighborhoods such as gated estates (Silver, 2016). Such generators cause emissions, noise, and air pollution. Clean energy interventions such as Ghana's capital subsidy program could target these wealthier groups who socio-economically have the needed pre-conditions to adopt and pay for clean energy technologies. Community solar schemes may be more appropriate for low-income neighborhoods than solar home systems due to the urban form limitations in such neighborhoods. A previous study on Ghana's capital subsidy program for rooftop solar PV reached a similar conclusion that that visions of a just energy future must be "set in relation to how and why practical solutions to the energy 'needs' and 'visions' of socially and spatially differentiated groups could be realized" (Boamah & Rothfuß, 2020, pg.1). Such an approach opens up many questions for further research. We outline some of these questions alongside the limitations of our study in the next section.

Conclusion and future research recommendations

The article highlights an often-neglected dimension in the urban energy transition discourse by reiterating the importance of spatial features of the built environment in the transition process as put forward by Huang and Castan Broto (2018), Gosens et al. (2015), and Truffer and Coenen (2012). Gosens et al. (2015) and Truffer and Coenen (2012) contend that the analytical ability of sustainability transition theories could be strengthened if they incorporate the spatial dimension. Such considerations will add to the theory and spell out more practical implications for strategies toward integrated solar energy and urban planning for city administrators and urban planners. Thus, we recommend that future studies go beyond the usual demographic and socio-economic determinants of the diffusion of solar PV applications in the urban environment and incorporate the effects of the morphological characteristics of the urban area.

Further studies need to explore the prospects of supplying solar homes by real estate developers in Ghana. If residential solar PV systems are to be made an integral part of their properties, the willingness of prospective homeowners to buy such properties is crucial and needs to be researched as well. Our results affirm a significant correlation between urban form and rooftop solar PV potential. This calls for incorporating solar considerations into the early stages of urban planning/design as well as the design of houses. However, hardly any studies explore the extent to which key actors such as urban planning authorities, real estate developers, and homeowners are aware of urban form effects on solar PV potentials and its implications for integrating solar energy into urban planning. Further research is needed to address this gap.

Finally, we would like to highlight some limitations of this study. The investment, operation, and maintenance costs (which significantly influence the LCOE) used in calculating the LCOE were fixed for all the houses based on the existing data and information on residential solar PV systems in Ghana. In reality, the investment cost will vary for each house/building depending on specific characteristics such as the user's needs, income level, and housing type. However, data on investment and operation, maintenance costs, and other metrics for computing the LCOE are not available for each of the houses analyzed in this study; hence an assumed, but realistic estimate had to be used for the calculations. Future studies could gather actual investment costs through household surveys to better reflect the LCOE values and compute other economic metrics, such as the payback period of the solar PV systems.

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CRediT authorship contribution statement

Mark M. Akrofi: Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Visualization, Writing – original draft. **Mahesti Okitasari:** Conceptualization, Supervision, Writing – review & editing, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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