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Research Paper

Are households willing to adopt solar home systems also likely to use electricity more efficiently? Empirical insights from Accra, Ghana

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ABSTRACT

The diffusion of renewable energy technology, such as solar home systems (SHS), has great potential to reduce GHG emissions. However, households' energy efficiency (EE) and curtailment behavior (CB) play a crucial role in this process. This study examines the rooftop solar PV potential, households' willingness to adopt SHS, and their EE/CB implications for mitigating CO_2 emissions through SHS adoption. A survey of 216 households was carried out alongside rooftop solar PV potential analysis in a high-income gated estate and a middle-class neighborhood using secondary data. First, we find that rooftop solar PV has the potential to offset all grid electricity and its associated CO_2 emissions for at least 63.5% of households. Secondly, the willingness to adopt SHS is lower in the high-income neighborhood than the middle-class ones. This dynamic is explained by the occupancy status, where most of those in the high-income neighborhood tend to be renters – a group known to have a low willingness to adopt SHS. Thirdly, our results affirm that energy-saving behavior is more common in a middle-class neighborhood where the propensity to adopt SHS is also high. Our results suggest that households willing to adopt SHS are more likely to engage in EE/CB. However, this tendency is common among middle-class households, who, in practice, may not be able to afford the SHS. Our findings underscore the need for more targeted policy interventions for SHS, and EE and CB among homeowners, high-income neighborhoods, and real estate developers.

1. Introduction

About 40% of the global carbon emission reductions needed to reach net zero by 2050 can be achieved through energy efficiency (IEA, 2021). In emerging economies such as Ghana, it is widely expected that economic growth and a burgeoning middle class will lead to more electricity consumption due to households' ability to purchase more electric appliances (Never et al., 2022; Xu et al., 2021). An increase in electricity consumption potentially raises households' electricity-related carbon dioxide (CO_2) emissions (Okuyama et al., 2022; Qiu et al., 2019). As such, how energy efficiency improvement can perform a mediating role in neutralizing the energy-sustainability-inhibiting effects of economic growth becomes a key factor (Murshed et al., 2022; Qudrat-Ullah and Nevo, 2021). On the other hand, a growing middle class with increased purchasing power also provides an opportunity for investing in renewable energy technologies such as residential solar photovoltaics (PV) systems (Akrofi et al., 2022). However, while clean energy technologies such as solar SHS provide immense opportunities for lowering carbon emissions, their mitigative potential is tied to households' energy efficiency and curtailment behavior (Okuyama et al., 2022; Shahsavari and Akbari, 2018).

There is mixed evidence of whether adopting residential solar PV systems mitigates households' carbon emissions. On the one hand, some studies suggest that the adoption of residential solar PV systems mitigates household electricity-related carbon emissions (Havas et al., 2015; Shahsavari and Akbari, 2018). On the other hand, the adoption of residential solar PV systems has been found to increase households' electricity consumption and related carbon emissions (Okuyama et al., 2022; Qiu et al., 2019). The latter is described as the *solar rebound effect,* which refers to the amount of energy savings that is lost due to increased consumption of energy services attributable to behavioral responses to residential solar PV installation/ownership (Beppler et al., 2021; Deng and Newton, 2017; Frondel et al., 2020; Toroghi and Oliver, 2019). When residential solar PV complements rather than substitutes electricity from the grid, households tend to consume more electricity, thinking that having solar PV gives them room to do so (Okuyama et al.,

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Table 1
Comparison of this study with existing studies.

Authors	Study features	Our study
Mensah and McWilson (2021)	Focuses on households' willingness to adopt SHS with emphasis on socio-demographic factors influencing such willingness	Estimates the rooftop solar PV potential, potential CO_2 emission reduction, households' willingness to adopt SHS, EE, and CB, and draws implications of households' EE and CB for SHS adoption
Tetteh and Kebir (2022)	Focuses on the determinants of grid-connected solar PV adoption among households	Focuses on rooftop solar PV systems without connection to the grid
Boamah and Rothfuß (2018)	Examines factors driving SHS adoption among urban households	Examines rooftop solar PV potential, households' willingness to adopt, and their EE and CB.
Owusu-Manu et al. (2022) Twerefou and Abeney (2020) Adjei-Mantey and Adusah-Poku (2021) Amoah et al. (2018) Never et al. (2022).	Focus on energy efficiency and conservation/ curtailment behavior of households	Goes beyond EE and CB of households to examine the potential of rooftop solar PV to meet households' energy needs, and households' willingness to adopt SHS
Beppler et al. (2021) Deng and Newton (2017) Frondel et al. (2020) Toroghi and Oliver (2019)	Examines the solar rebound effects from solar PV adopters	Focuses on prospective adopters and so it does not examine the rebound effects but provides possible implications for that.

2022) . This behavior consequently increases their carbon footprint from electricity consumption. Havas et al. (2015) observed a 15% rebound effect in electricity consumption by solar PV adopters, while Beppler et al. (2021) observed a 28.5% rebound effect, noting that nearly one-third of the electricity generated from solar PV is used for increased energy services rather than reducing electricity consumption from the grid. Similar solar rebound effects were observed in Germany (Frondel et al., 2020), Australia (Deng and Newton, 2017), and the Netherlands (Aydin et al., 2022), amongst others.

Solar rebound effects do not only have implications for the mitigative potential of solar PV adoption regarding carbon emissions but also for the kind of policies that are implemented to boost solar PV uptake. The most commonly cited policy measures are feed-in-tariffs (FiTs) and net metering schemes (Boccard and Gautier, 2021; Deng and Newton, 2017). For instance, Boccard and Gautier (2021) noted that a net metering initiative and subsidies for residential solar PV in Belgium led to the oversizing of PV systems by households, consequently creating a solar rebound effect. Oliver et al. (2019) also found that introducing rebates for residential solar PV increases the rebound effect. Similar subsidization policy efforts are currently observed in Ghana, where the government, through the Ghana Energy Commission, is rolling out capital subsidies, FiTs, and net metering schemes to boost residential solar PV uptake (Akrofi and Okitasari, 2023). Nonetheless, at the time of writing this paper, no documented evidence of the solar rebound effect was observed in Ghana. Given the rapid advancement in clean energy technologies, middle-income countries such as Ghana are widely expected to leapfrog from fossil-based energy systems to cleaner energy sources. While the continuous decline in residential solar prices is expected to spur their uptake in developing countries, the extent to which such uptake can mitigate CO_2 emissions remains unclear. Mitigating emissions from the residential sector is particularly important given that the sector accounts for about 11% of greenhouse gas (GHG) emissions (direct + indirect) globally (Dhakal Nepal et al., 2022).

Against this background, the objective of this study is to assess the implications of households' EE and CB for electricity-related CO_2 emission reduction regarding the adoption of residential solar PV systems in Ghana. The study focuses on high-income and middle-class neighborhoods known for high electricity consumption but also possess significant opportunities (e.g., high-income and high levels of educational attainment) for residential solar PV adoption (Akrofi et al., 2022; Never et al., 2022). The analysis begins with estimating the residential rooftop solar PV potential and related CO_2 emission reduction regarding grid-based electricity consumption. This estimation is followed by analyzing households' self-reported willingness to adopt SHS and their EE and CB. We then analyze the implications of households' EE and CB for CO_2 emission reductions through the adoption of SHS. The article is structured as follows. Section 2 sets the context for the study, providing related literature and contributions. In Section 3, the methods used for the analysis are explained, while a presentation of the results and a discussion of findings are presented in Section 4. Finally, the policy implications and conclusion are presented in Sections 5 and 6, respectively.

2. Background of the study

2.1. Residential solar PV adoption in Ghana

Residential rooftop solar PV systems are gradually gaining popularity among Ghanaian households, thanks in part to policy efforts being made by successive governments to raise awareness and provide incentives, such as capital subsidies for rooftop solar PV (Energy Commission, 2017). On the other hand, high grid electricity tariffs, intermittent power supply from the grid, and increasing awareness of the benefits of residential rooftop solar PV systems are compelling more households to invest in SHS (Boamah and Rothfuß, 2018; Mensah and McWilson, 2021; Tetteh and Kebir, 2022). In 2015, the government of Ghana launched a capital subsidy scheme through its national rooftop solar PV program under which households, upon meeting a set criterion, receive 500Watts solar PV panels or an installation service from a licensed SHS installer who is paid by the energy commission (Energy Commission, 2017). Despite these policy efforts and some financial institutions offering loans for residential rooftop solar PV systems, their adoption rate has been slow, prompting a few studies to examine the adoption behavior of households (Mensah and McWilson, 2021; Tetteh and Kebir, 2022).

The most common factors influencing households' willingness to install SHS in Ghana are their income levels, educational attainment, occupancy status, and perceived benefits from the SHS (Mensah and McWilson, 2021; Tetteh and Kebir, 2022). Income and educational attainment levels correlate positively with the willingness to adopt SHS. Homeowners and individuals who perceive SHS to be beneficial in terms of the reliability of electricity supply and decrease in expenses on grid electricity tend to be more willing to adopt SHS (Mensah and McWilson, 2021; Tetteh and Kebir, 2022). In addition to these factors, Tetteh and Kebir (2022) noted that individuals who are aware of the capital subsidy of the national rooftop PV program are more willing to adopt SHS. Presently, only very few studies (e.g. (Boamah and Rothfuß, 2018; Mensah and McWilson, 2021; Tetteh and Kebir, 2022)) focused on the adoption of SHS in Ghana. Hence, a broader understanding of the dynamics of residential PV adoption in the country is yet to be uncovered. More so, while the EE and CB of households have been widely studied, its implications for residential solar PV adoption with regard to sustainability goals of reducing CO_2 emission have received virtually no scholarly attention yet in Ghana. In a related study, Opoku et al. (2020) studied the cost-saving potential of solar energy and EE in Ghana; however, this was for a tertiary institution and not households. This is one of the critical gaps we address in this article.

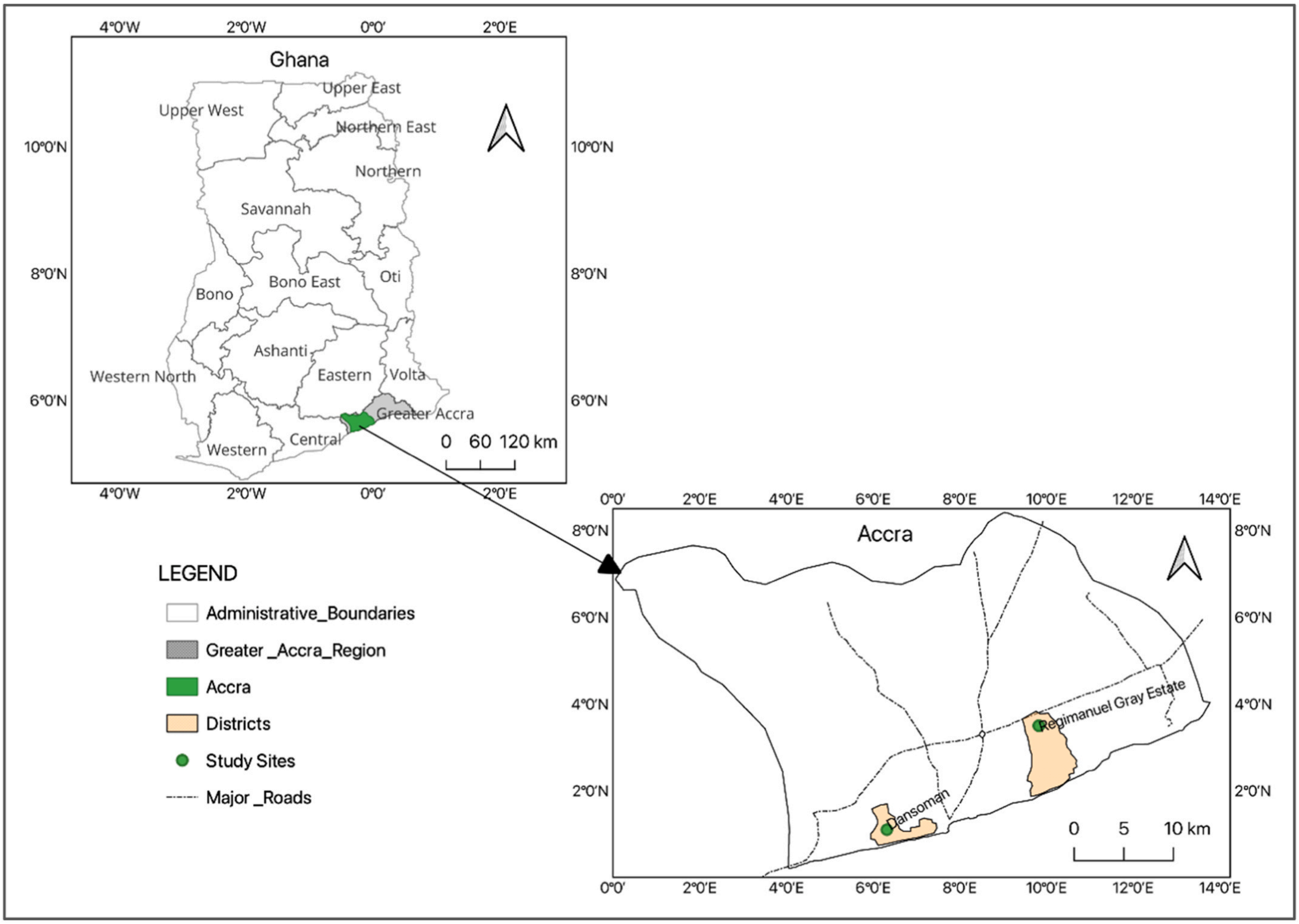

Fig. 1. Location of the selected study areas.
Source: Author's construct.

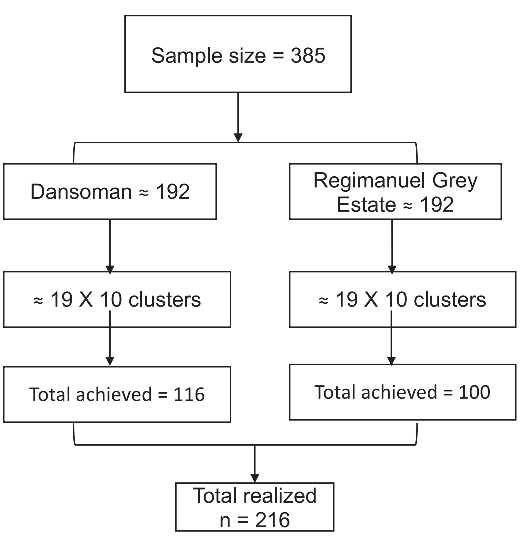

Fig. 2. Process of selecting households.

2.2. Residential energy efficiency in Ghana

The residential sector in Ghana accounts for nearly half (47%) of electricity consumption in the country. However, around 30% of wastage of electricity occurs due to inefficiency in end-use electricity (Energy Commission, 2020). Most notable efforts to promote energy efficiency in Ghana date far back to 2005 when the country first started implementing its Appliance Efficiency Programme. A number of legislative instruments— LI 1815 Energy Efficiency Standards and Labelling Regulations, LI 1932 Energy Efficiency Regulations, and LI 1958 Energy Efficiency Standards and Labelling (Household Refrigerating Appliances) Regulations were also enacted in 2005, 2008, and 2009, respectively. These initiatives, notably the Appliance Efficiency Program, which saw a massive replacement of incandescent lamps with compact fluorescent lamps, resulted in energy savings that reduced the peak load electricity demand in the country by 200–240 megawatts (MW) (Adobea Oduro et al., 2020). Nonetheless, efficient use of electricity remains a major challenge among households in Ghana (Gyamfi et al., 2018).

While the government, through the Energy Commission, continues to promote initiatives such as energy-efficient labeling and restricting the importation of sub-standard/inefficient refrigerators (Energy Commission, 2014), studies show that adherence to these measures is associated with the EE and CB of households (Owusu-Manu et al., 2022; Twerefou and Abeney, 2020). EE behavior refers to households' tendency to invest in more energy-efficient appliances or renewable energy – e.g., solar – while CB refers to the tendency to reduce energy use by turning off or putting appliances on standby when they are not in use (Never et al., 2022). In the Ghanaian context, past studies show that low-income households are less likely to engage in EE behavior often due to the cost involved in purchasing modern energy-efficient appliances or

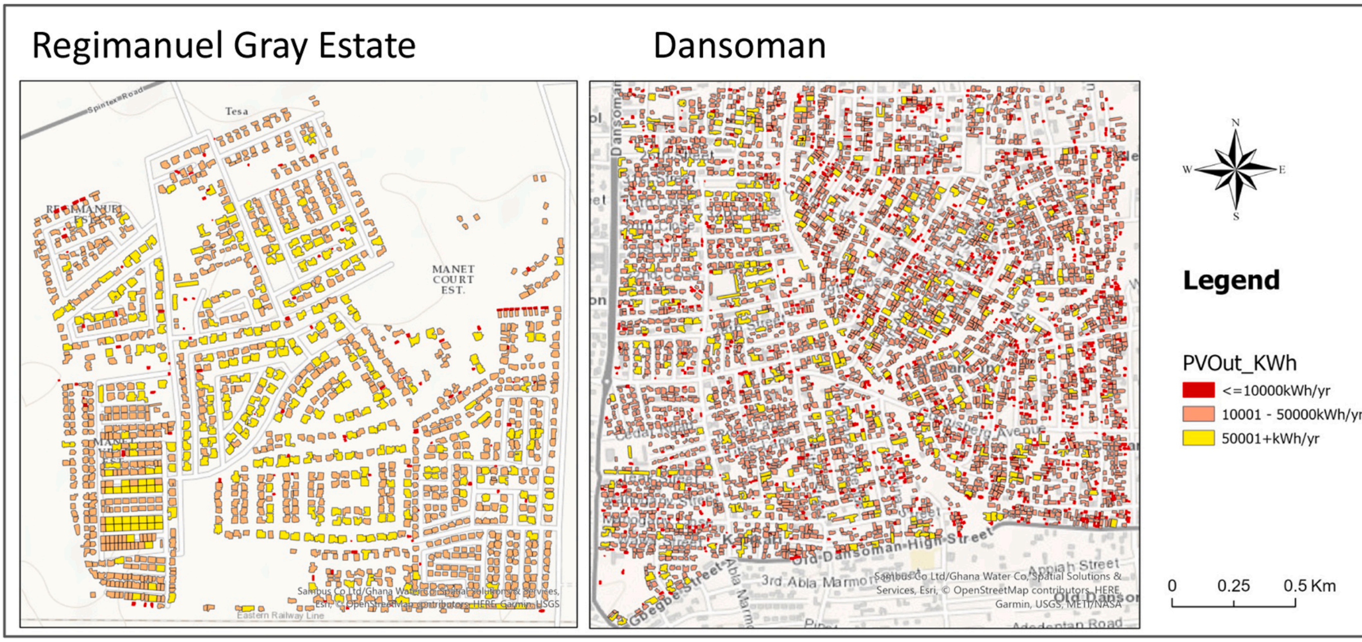

Fig. 3. Map showing the rooftop solar PV potential in the neighborhoods (scenario 1).

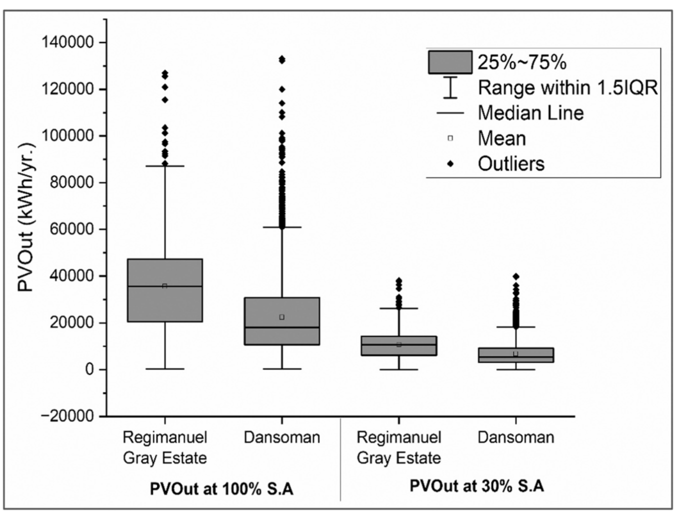

Fig. 4. Annual rooftop solar PV potential distribution in the study neighborhoods. Note: S.A denotes suitable rooftop area.

renewable energy systems (Adjei-Mantey and Adusah-Poku, 2021; Amoah et al., 2018; Never et al., 2022).

On the other hand, Ghanaian high-income and highly educated households generally have a higher propensity towards EE and are more likely to invest in it (Amoah et al., 2018; Never et al., 2022). In contrast, Adjei-Mantey et al. (2021) noted that this may not always be the case since they found an inverse relationship between the level of education attained and households' likelihood to use energy-efficient light bulbs. Low environmental consciousness was cited as a possible reason why highly educated households could be less likely to use such light bulbs (Adjei-Mantey and Adusah-Poku, 2021). However, Never et al. (2022) found that Ghanaian households' level of environmental concern is uncorrelated with their EE investments. Instead, they noted that younger and highly educated households have a higher propensity towards EE investments. Adjei-Mantey et al. (2021) further noted that risk-averse and female-headed households are more likely to engage in EE behavior in Ghana.

Regarding CB, all the aforementioned socio-demographic factors correlating positively with EE behavior in Ghana, except income, correlate positively with CB. In contrast to its positive correlation with EE behavior, income has an inverse relationship with CB (Never et al., 2022; Twerefou and Abeney, 2020). Low-income households are more inclined to exercise CB, such as turning off electrical appliances or putting them on standby when not in active use. In contrast, high-income households are less likely to do the same (Never et al., 2022). Umit et al. (2019) explained that little effort and no up-front financial investment are needed for CB, which is why it is easier for low-income households to undertake CB. Hence, for CB, socio-psychological factors are more significant than financial and technological factors (Trotta, 2018). For example, in the case of Ghana, Never et al. (2022) found that age, gender, educational attainment, and level of environmental concern correlate positively with CB. Table 1 provides a summary of how our study compares with existing studies and the specific contributions that this paper makes.

Table 2
Households' CO_2 emissions from grid electricity.

Monthly electricity expense (GHS)	Annual consumption (MWh)	CO_2 emissions (tCO_2/MWh)	% of households in Regimanuel Gray Estate	% of households in Dansoman	% of the total sample
< 50	< 1.62	< 0.97	0.0%	0.9%	0.5%
50–100	1.62–3.24	0.97–1.94	2.0%	35.5%	19.9%
101–200	3.28–6.49	1.96–3.89	46.5%	40.2%	43.1%
> 200	> 6.49	> 3.89	51.5%	23.9%	36.5%

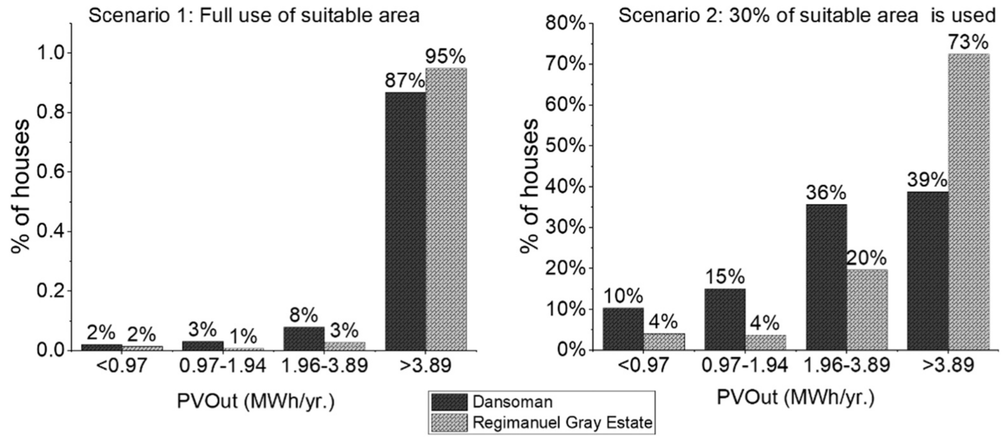

Fig. 5. Annual rooftop solar PV potential by the proportion of houses in each neighborhood.

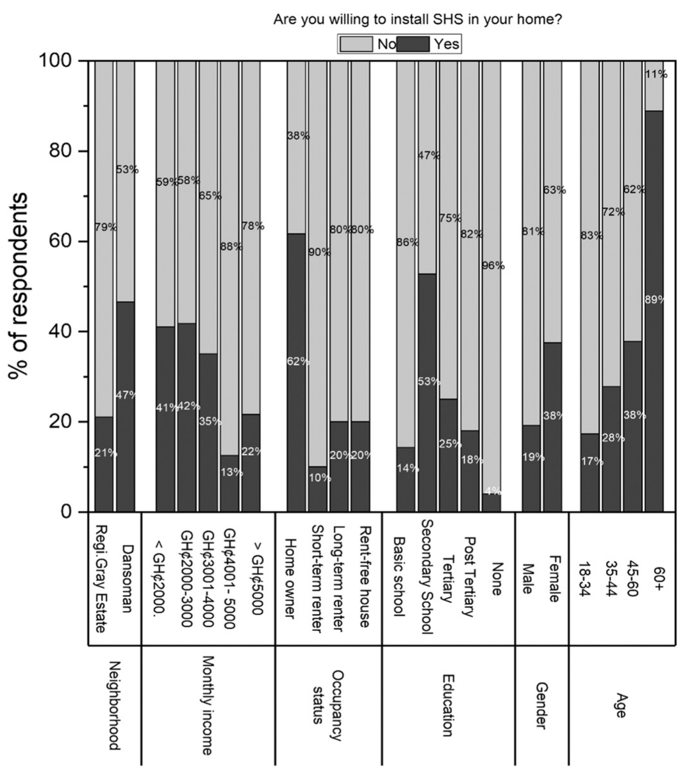

Fig. 6. Households' willingness to adopt SHS.

3. Materials and methods

3.1. Description of the study area

The study area for this research is the city of Accra in the Greater Accra Region of Ghana. It is located between latitudes 5.556°N and longitude 0.169°W and shares boundaries with the Eastern, Central, and Volta regions and the Gulf of Guinea to the North, West, East, and South, respectively. The city lies 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). It has an average Direct Normal Irradiation (DNI) of 3.174kWh/m^2 per day and 1158.5 kWh/m^2 per year, with monthly DNI ranging between 70.2kWh/m^2 in January to 137.3kWh/m^2 in October (World Bank, 2022). Two neighborhoods, namely, Regimanuel Gray Estate (high-income, gated estate) and Dansoman (mostly middle-class neighborhood), are the primary study sites for this research. These neighborhoods were selected based on their socioeconomic characteristics.

Regimanuel Gray Estate is a well-planned, high-income 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). These neighborhoods' distinct physical and socio-demographic characteristics allow for a more comprehensive analysis of rooftop solar PV potential, adoption behavior, and EE and CB patterns in different neighborhood types. With the similarities shared between Ghana and other sub-Saharan African countries regarding socio-demographic and urban form characteristics and policies for residential solar PV, results obtained from this study can be fairly generalized to other countries in the region. We provide policy implications of our findings for policymakers in Section 5. The study areas for this research are illustrated in Fig. 1.

3.2. Estimating the rooftop solar PV potential

To estimate the rooftop solar PV potential, we use Accra's average annual DNI of 1158.5 kWh/m^2 alongside a solar panel efficiency of 17.5% (Nocheski Solar, 2019) and a performance ratio of 75% based on figures reported by previous studies on the performance of solar PV systems in Ghana (Abdul-Ganiyu et al., 2020; Sekyere et al., 2021). These parameters were used to derive the annual rooftop electricity yield. The annual energy produced by a PV system (Eyr) is given by

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

where *A* denotes suitable rooftop area, *r* denotes solar panel efficiency, *H* denotes average annual solar radiation on tilted panels, and *Pr* denotes the performance ratio of the solar panels (Tian et al., 2021). In this study, the estimated electricity produced by the PV system is referred to as PV output (hereafter known as PV_{Out}) computed in kWh. Thus, Eyr from Eq. (1) is written as PV_{Out} in the subsequent sections of this paper. Our estimation is based on two assumptions: first, we assume a scenario where the total suitable rooftop area of each building is fully used for solar PV installation, and second, a scenario where only 30% of the suitable area is used. The suitable rooftop area is defined as the area (in square meters) on a building's rooftop that receives adequate solar irradiance considering the shading factor, tilt angle of the roof, and hindrances such as trees, chimneys, or poles (Huang et al., 2022; Vulkan et al., 2018). The first assumption is consistent with those made by related studies such as Huang et al. (Huang et al., 2022), Ayodele et al.

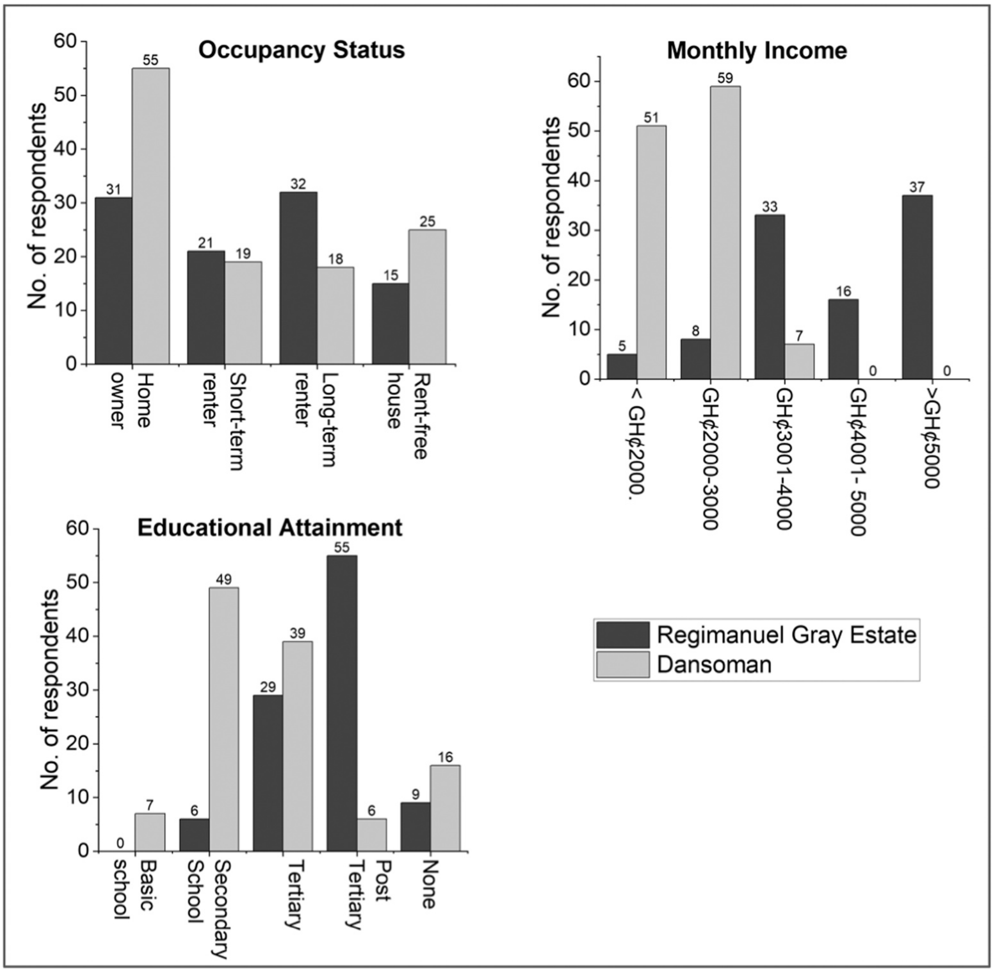

Fig. 7. Selected demographic characteristics of households in the study areas.

Table 3
Households' EE and CB behavior by neighborhood types.

Variables		Community					
		Regimanuel Gray Estate		Dansoman		Total	
		Count	Row N %	Count	Row N %	Count	Row N %
How often do you turn off your electrical appliances when not at home or when they are not in use?	Always	2	4.3%	44	95.7%	46	100.0%
	Sometimes/ occasionally	97	58.1%	70	41.9%	167	100.0%
	Never	1	33.3%	2	66.7%	3	100.0%
How often do you keep your electronic devices on standby when not in use?	Always	5	20.8%	19	79.2%	24	100.0%
	Sometimes/ occasionally	90	60.8%	58	39.2%	148	100.0%
	Never	5	11.4%	39	88.6%	44	100.0%
Do you consider energy efficiency labels/ratings when purchasing electrical appliances?	Always	7	16.3%	36	83.7%	43	100.0%
	Sometimes/ occasionally	90	61.6%	56	38.4%	146	100.0%
	Never	3	11.1%	24	88.9%	27	100.0%

(2021), and Wang et al. (2022), while the second assumption is derived from other studies where between 20% and 40% of the rooftop area is often considered for solar PV installation (Toroghi and Oliver, 2019).

Data on the suitable rooftop area (A) was obtained from the World Bank's *energydata.info* database[1] (Fang et al., 2020). These data comprised building footprints and their associated suitable rooftop areas for Accra. The data were downloaded in shapefile format and imported into ArcGIS Pro software for analysis. Data specific to the two neighborhoods of interest (Regimanuel Gray Estate and Dansoman) were extracted. Since we focus on residential buildings, other building types, such as commercial and public buildings, were removed from the dataset. Only single-family and multi-family residential buildings were analyzed. In total, 1465 and 4419 residential buildings were analyzed in

[1] https://energydata.info/ (accessed July 19, 2022).

Table 4
Association between demographic factors and household's EE and CB.

		How often do you turn off your electrical appliances when not in use?	How often do you keep your electronic devices on standby when not in use?	Do you consider energy efficiency labels/ratings when purchasing electrical appliances?
VARIABLES				
Neighborhood Type	Chi-square	43.476	40.395	42.859
	df	3	2	2
	Sig.	.000*	.000*	.000*
Age	Chi-square	26.672	26.247	11.268
	df	9	6	6
	Sig.	.002*	.000*	0.08
Gender	Chi-square	3.409	4.286	7.588
	df	3	2	2
	Sig.	.333	0.117	.023*
Educational Attainment	Chi-square	39.996	22.901	32.249
	df	12	8	8
	Sig.	.000*	.003*	.000*
Sector of Occupation	Chi-square	41.322	41.327	60.308
	df	24	16	16
	Sig.	.015*	.000*	.000*
Monthly Income	Chi-square	34.168	34.418	40.165
	df	12	8	8
	Sig.	.001*	.000*	.000*
Occupancy status	Chi-square	36.284	36.204	46.374
	df	9	6	6
	Sig.	.000*	.000*	.000*
House Type	Chi-square	6.138	8.411	9.95
	df	9	6	6
	Sig.	0.726	0.209	0.127
SHS Willingness	Chi-square	65.435	67.77	94.149
	df	3	2	2
	Sig.	.000*	.000*	.000*

* The Chi-square statistic is significant at the.05 level.

Regimanuel Gray Estate and Dansoman, respectively.

3.3. Estimating households' grid-related carbon footprint

The carbon footprint from grid electricity is the amount of CO_2 emitted per unit of electricity consumed from the grid. This emission can be derived by simply multiplying the amount of electricity consumed by the grid emission factor. Available data shows Ghana's average grid emission factor is 0.6 tCO_2/MWh (Takahashi and Louhisuo, 2022). Households' monthly spending on electricity bills (obtained during the household survey) was divided by the electricity price for households in Ghana to get their monthly electricity consumption. The amount of electricity consumed was then multiplied by the grid emission factor to derive households' grid-related CO_2 emissions. The household electricity price in Ghana at the time of this research was GHS 0.37/kWh (Global Petrol Prices, 2022). The results of this analysis can be found in Section 4.2.

3.4. Household survey protocols

Households in Dansoman and Regimanuel Gray Estate were the target population for this study. Data on the specific number of households in these neighborhoods could not be obtained at the time of this research. The latest government statistical survey in 2020 indicates that Regimanuel Gray Estate – located in the Ledzokuku Municipal District which has 72,382 households, and Dansoman – situated in the Ablekuma West District which has 49,031 households (Ghana Statistical Services, 2020). Since the specific number of households in the two study neighborhoods is unknown, the following formula was used to derive the sample size. This formula is used when the sample frame or sample population is unknown and is given by

$$N = \frac{(Z-score)^2 X \quad StdDev \quad X(1-StdDev)}{(marging \quad of \quad error)^2} \tag{2}$$

with a confidence level of 95%, standard deviation of 0.5, a 5% margin of error, and a corresponding Z-score of 1.96, where N is the sample size (Smith, 2013). The resultant sample size is 384.5. According to Smith (2013) and Israel (1992), a sample of at least 200 is generally adequate for statistical analysis. Regarding the selection of participants for the household survey, the sample size was first split into approximately 192 each for Dansoman and Regimanuel Gray Estate. Each neighborhood was then divided into 10 clusters of houses based on physical landmarks such as roads. Approximately 19 houses were expected to be selected from each cluster to realize the total sample size. A visual summary of this process is provided in Fig. 2.

In each cluster, convenience sampling was used to select households for questionnaire administration by trained field enumerators. This selection was based on the availability of a suitable respondent for the survey in each household. Household heads were the main targets for the survey. However, in the absence of the household head, any adult household member (aged 18 years and above) with adequate knowledge to answer the survey questions was recruited. To ensure that respondents were suitable for the survey, the field enumerators first presented an informed consent form and explained the purpose, nature, and objectives of the survey, including specific information needed. If the participants acknowledge that they can provide the required information, enumerators ask for their consent to participate in the survey. If agreed, the participants must sign the informed consent form before the questionnaire is administered. Since the questionnaires were preloaded on iPads, a check box was provided next to the informed consent text for participants to tick, indicating that they consented to participate. In the event that no consent is given or a suitable respondent is not found, the enumerators skip that household and select another until the desired number of households per cluster is reached. Enumerators received training before the primary data collection to ensure they were familiar with the survey protocols, objectives, and their roles and duties. This was done through a joint effort between the researchers and the survey firm[2] to ensure the quality of the data collected. The training was also to ensure that the selection of households is dispersed across each neighborhood. The research instruments were pre-tested for validity and reliability from September 5th to 9th, 2022, while the main data collection exercise was carried out over one month, from September 12th, 2022, to October 10th, 2022.

4. Results and discussion

4.1. Rooftop solar PV potential in the study areas

Considering the first scenario, that the entire suitable rooftop area of each building is used for PV installation, the average amount of electricity that can be generated from rooftop solar PV is 35,598.6kWh/yr. and 22,386.7kWh/yr. in Regimanuel Gray Estate and Dansoman, respectively. Under the second scenario where only 30% of the suitable

[2] The field data collection was subcontracted to Think Data Services Limited, a registered data collection firm in Ghana. https://www.thinkdataservices.com/.

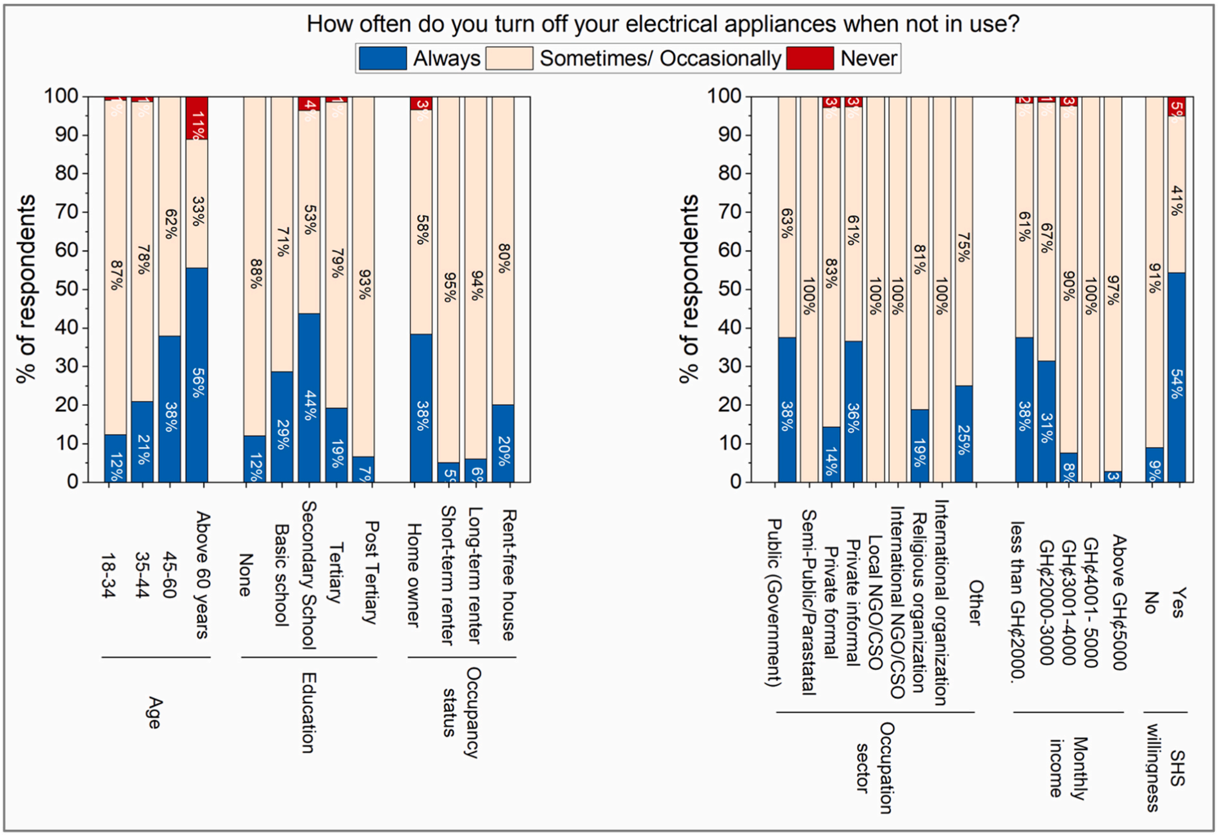

Fig. 8. Household's tendency to turn off appliances when not in use.

rooftop area is used; these averages are 10,680.0kWh/yr. and 6716.0kWh/yr. for Regimanuel Gray Estate and Dansoman, respectively. In a preceding study (see (Akrofi and Okitasari, 2023)), we found that the urban form characteristics (e.g., building density, building footprint area, the near distance between buildings, etc.) of these neighborhoods accounted for the differences in solar PV electricity potential realized. Owing to its well-planned nature and dominance of detached and semi-detached buildings with low density, Regimanuel Gray Estate has a higher rooftop solar PV potential than Dansoman (Akrofi and Okitasari, 2023). Fig. 3 visually represents the rooftop PV potential for the first scenario where the entire rooftop area is used. Fig. 4 provides the distributional characteristics of the rooftop solar PV potential in the two neighborhoods under the two scenarios. It is apparent from both figures that the rooftop solar PV potential is higher in Regimanuel Gray Estate. The next section compares these results with households' grid-electricity consumption and CO_2 emissions.

4.2. Households' CO_2 emissions from grid-electricity

The annual electricity consumption of households and its related CO_2 emissions are computed in categories based on defined ranges used during the survey. The results of this analysis are presented in Table 2.

From Table 2, it can be deduced that overall, most households (63.5%) consume not more than 6,486.5kWh (6.49MWh) of electricity per year, with their CO_2 emissions ranging from 0.97 tCO_2/MWh to 3.89 tCO_2/MWh per year. The proportion of households with higher electricity consumption and CO_2 emissions is larger in Regimanuel Gray Estate compared to Dansoman. This is a finding that is not surprising given that Regimanuel Gray Estate is a high-income neighborhood while Dansoman is a middle-class neighborhood. From the rooftop solar PV potential analysis, we found that 95% and 87% of houses in Regimanuel Grey Estate and Dansoman, respectively, have an annual rooftop solar PV potential of more than 6.49MWh/yr. if the entire suitable rooftop area is used for PV installations (scenario 1). On the other hand, if 30% of the suitable rooftop is used (scenario 2), these proportions decrease to 73% for Regimanuel Gray Estate and 39% for Dansoman, as shown in Fig. 5.

These results imply that in both scenarios, rooftop solar PV has the potential to offset all the grid electricity consumed and its associated CO_2 emissions for most households in Regimanuel Gray Estate, *all things being equal*. On the contrary, this is not the case for Dansoman in the second scenario, where 30% of the suitable rooftop is used. Nonetheless, significant proportions of grid offsets and emission reductions can be achieved in both neighborhoods through rooftop solar PV installations. According to estimates by the United States National Renewable Energy Laboratory (NREL, 2012), carbon emissions from solar PV systems are around 40gCO_2/kWh over the lifetime (typically 25 years) of the PV system. This estimate is a near-zero figure when converted into tCO_2/MWh annually. Thus, our results provide indicative evidence that rooftop solar PV has the potential to reduce households' CO_2 emissions from electricity consumption significantly.

Kuşkaya (2022) reached a similar conclusion upon examining the emission reductions from residential solar energy consumption in the USA, noting that solar energy strongly mitigates CO_2 emissions. On the contrary, Okuyama et al. (2022) found that Japanese households who adopted residential solar PV increased their electricity consumption and CO_2 emissions by 3.02% and 1.75%, respectively. The subsequent sections examine the dynamics of households' energy use behavior regarding EE and CB in Regimanuel Gray Estate and Dansoman. The potential for rooftop solar PV is high, but are households willing to invest in SHS? We address this question first before delving into households' EE and CB.

4.3. Households' willingness to adopt solar home systems

Overall, 34.7% of respondents indicated a willingness to install SHS

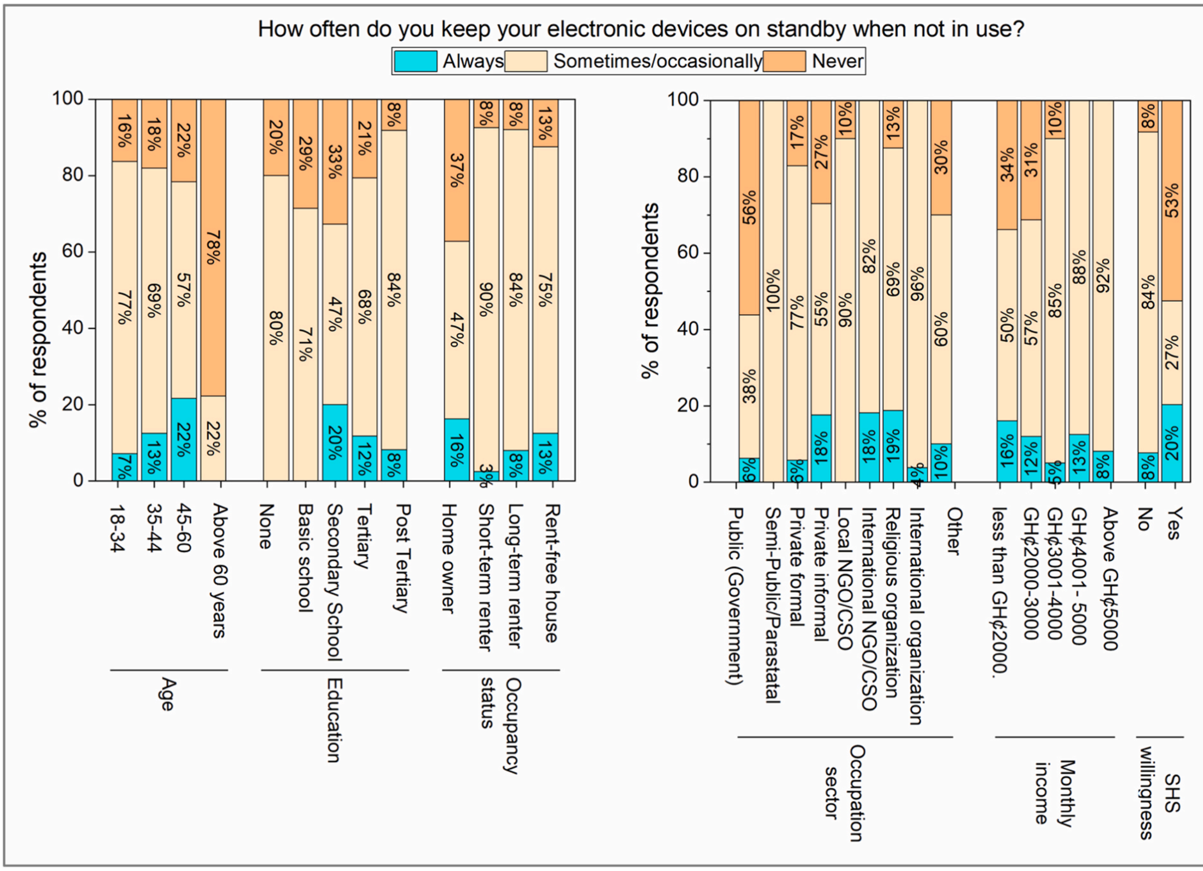

Fig. 9. Households' tendency to put appliances on standby when not in use.

in their homes. The proportion of respondents willing to adopt SHS is higher among households in Dansoman (47%) and homeowners (62%) compared to households in Regimanuel Gray Estate (21%) and renters (30%), respectively. It can also be observed from Fig. 6 that the proportion of households willing to install SHS is higher among low-income groups and respondents who have attained secondary education than high-income groups and those who have attained tertiary/post-tertiary education, respectively.

Our results on income and education contradict previous studies (Mensah and McWilson, 2021; Tetteh and Kebir, 2022), which found that willingness to adopt SHS is higher among highly educated and higher-income households. This contradiction can be explained by the occupancy status of the households. Our results and those of Mensah and McWilson (2021) show that willingness to adopt SHS is particularly low among renters. These results explain why the willingness to adopt SHS is lower in Regimanuel Gray Estate than in Dansoman, even though the Estate consists of predominantly high-income and highly educated households (see Fig. 7).

Most households in Regimanuel Gray Estate are renters, while homeowners constitute the majority in Dansoman. Renting complicates SHS adoption because making changes to the structure of the house, such as installing renewable energy systems or any installations that require alterations to the housing structure, can only be done by the homeowner. Secondly, many renters do not consider installing SHS because of the challenge of relocating the system if they move to a different accommodation (Boamah and Rothfuß, 2018). Hence, while some studies (Matthies and Merten, 2022; Ramos et al., 2016) have found that highly educated and high-income households are more likely to invest in renewable energy technology such as SHS, we find that the occupancy status of households could play a mediating role in making such investments. The policy implications of this finding are discussed in Section 5.

4.4. *Energy efficiency and curtailment behavior in the two study neighborhoods*

The previous section has shown that a moderate proportion (34.7%) of households are willing to adopt SHS. In this section, we examine whether adopting SHS can reduce households' CO_2 emissions from grid electricity, taking into account their EE and CB. Past studies distinguish between curtailment behavior (e.g., turning off or putting appliances on standby) and efficiency behavior (e.g., investing in energy efficiency), noting that the former correlates positively with low-income groups while the latter correlates with high-income groups (Kumar et al., 2023; Matthies and Merten, 2022; Ramos et al., 2016). High income, for example, enables households to purchase more efficient heating technologies, invest in renewable energy or purchase modern energy-efficient appliances (Matthies and Merten, 2022). However, while high-income groups are more likely to make such investments, it does not translate into their energy-saving habits (CB), such as turning off or putting appliances on standby (Bruderer Enzler and Diekmann, 2019; Matthies and Merten, 2022; Ramos et al., 2016).

Out of 44 of our survey respondents who indicated that they always turn off their electrical appliances when they are not in use, only 4.3% of them live in the Regimanuel Gray Estate as compared to the remaining 95.7% who live in the Dansoman. A similar pattern is observed for households who put their appliances on standby when they are not actively using them. The majority of households who do so live in Dansoman, while only 20.8% of them reside in Regimanuel Gray Estate. Nonetheless, the number of households that turn off or put their appliance on standby and always consider EE labels/ratings when purchasing electrical appliances is low (see Table 3).

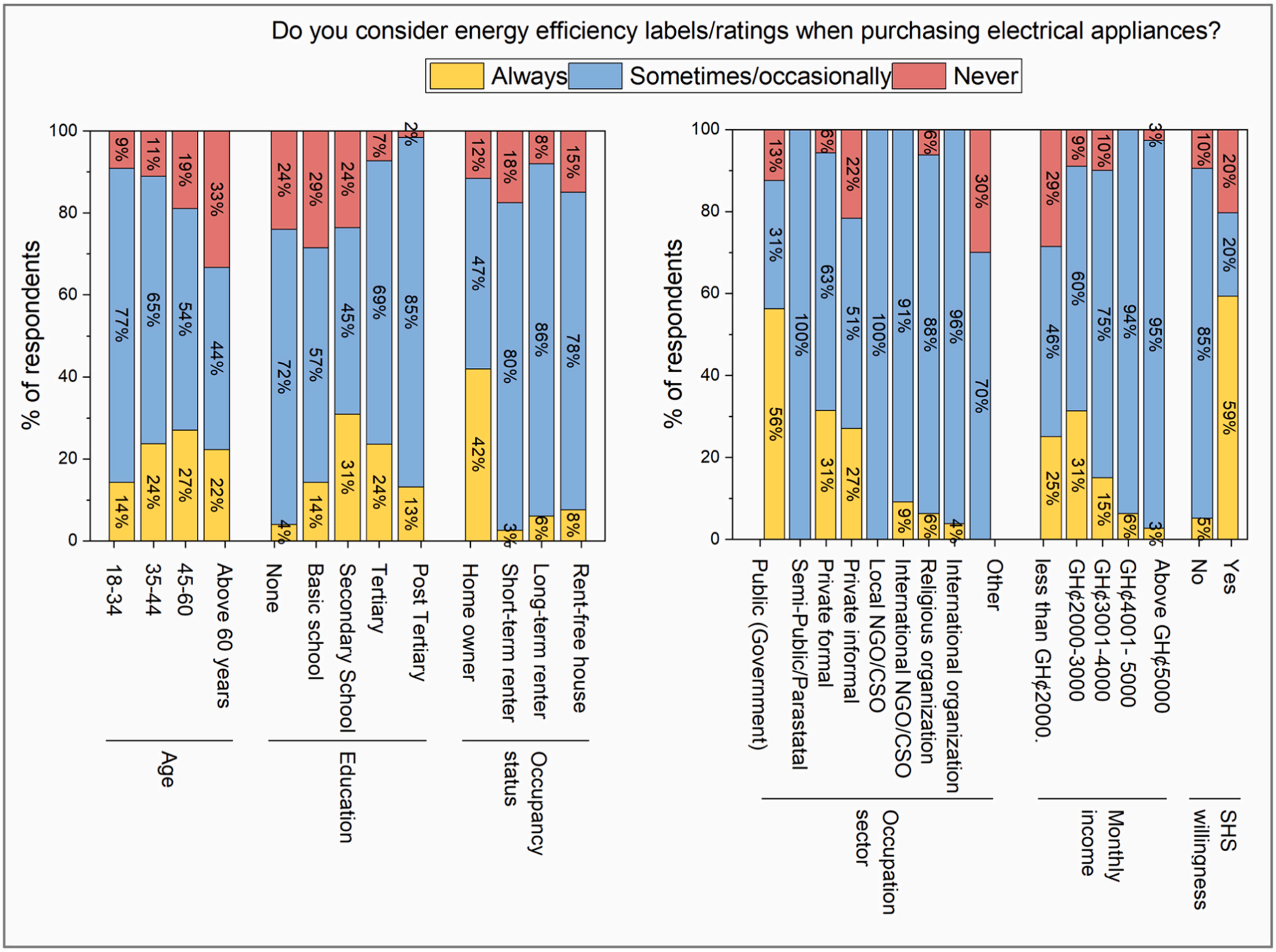

Fig. 10. Households' likelihood to consider EE labels/ratings.

A Chi-square test of independence analysis further revealed a significant association between households' socio-demographic attributes and their EE and CB, except for gender and the type of house they live in. The results of this analysis are presented in Table 4.

Past studies have identified age, gender, and educational attainment as common predictors of households' EE and CB (Never et al., 2022; Ramos et al., 2016; Trotta, 2018). In the Ghanaian context, Never et al. (2022) identified age and educational attainment as positive correlates of households' likelihood to purchase energy-efficient appliances. They noted that younger and highly educated residents were more likely to buy energy-efficient appliances. All three variables also correlated positively with households' CB, where older people, females, and highly educated individuals were more likely to curtail (Never et al., 2022). In addition to age and educational attainment, Twerefou and Abeney (2020) found a significant correlation between households' EE/CB, the type of house in which they live, and the sector in which they are employed. They noted that households residing in compound houses are more cautious of energy efficiency. On the other hand, public sector workers are less cautious of their energy use behavior and efficiency (Twerefou and Abeney, 2020).

Our results from Table 3 affirm most of the findings from the studies outlined above. However, contrary to the findings of Twerefou and Abeney (2020), we find no significant association between the household's EE/CB and the type of house they live in. The same result was obtained for gender. Notably, a statistically significant association was found between households' willingness to adopt SHS and their EE and CB. However, while the chi-square tests show the degree of association between the variables, they tell little about the nature of the relationships and do not imply any causation. Hence, cross-tabulations were carried out for the variables to understand better these relationships, and the results were visualized using grouped stack bar charts. We explore these relationships further in Section 4.5.

4.5. Descriptive analysis of households' energy efficiency and curtailment behavior

Similar to the findings of Never et al. (2022), this study shows that older people are more likely to curtail their energy use than younger ones. However, our educational attainment findings contradict Never et al. (2022), who noted that highly educated people are more likely to curtail. The proportion of people who turn off their household appliances when not in use tends to decrease for people who have attained Tertiary (Bachelor, HND, Specialized Training) and Post Tertiary (Master and Doctoral) education. On the other hand, the proportion of people who turn off their appliances continuously rises from 12% to 56% as the age groups increase from 18 to 34 to Above 60 years. The results further suggest that homeowners, public sector (government) workers, low-income groups, and people willing to adopt SHS are more likely always to turn off their appliances when not using them. The findings for income affirm the assertion that low-income groups are more likely to curtail than high-income ones (Matthies and Merten, 2022; Ramos et al., 2016), while that of the sector of employment/occupation contradicts the findings of Twerefou and Abeney (2020) that public sector workers are less cautious of their curtailment behavior. A similar trend is found regarding the likelihood of putting appliances on standby when not in active use. However, some slight variations exist, as seen in Figs. 8 and 9.

The proportion of households who put their appliances on standby when not in use is higher among those willing to adopt SHS than those unwilling to adopt SHS. Further, the proportion of people who put their appliances on standby increases as age increases up to 60 years. It decreases as the level of education attained increases from secondary school (high school and vocational/technical school) to post-tertiary (Master's, PhD, etc.). Nonetheless, people who have attained at least secondary education are more likely to put their appliances on standby than those who have attained only basic or no formal education. Homeowners are also more likely to put their appliances on standby than renters and rent-free dwellers. The findings from age, educational attainment, and occupancy status regarding households' tendency to put their electrical appliances on standby align with the results for groups putting their appliances off when not in use. Inferring from the findings in Figs. 8 and 9, it can be fairly drawn that a household's CB is linked with their age, educational attainment, occupancy status, and income level, as found by previous studies (Matthies and Merten, 2022; Never et al., 2022; Ramos et al., 2016; Trotta, 2018; Twerefou and Abeney, 2020).

Our EE behavior results slightly differ from CB. Most homeowners, public sector workers, and people willing to adopt solar home systems are likely to always consider the EE ratings of appliances before purchasing them. While this proportion is lower in high-income groups compared to the low-income ones, it is observable that the proportion of those who never consider EE ratings when buying electrical appliances is higher among the low-income groups. Also, the cumulative proportion of people who always or sometimes consider energy efficiency ratings when purchasing appliances is higher among high-income households (e.g., 100% of those earning GHS 4000–5000 and 98% of those earning above GHS 5000 per month) than low-income ones (e.g., 71% of that earning below GHS 2000). Hence, the propensity to engage in EE behavior, such as purchasing more efficient appliances, is higher among high-income groups. This finding affirms that EE behavior is more common among high-income households, while CB is more common among low-income households (Matthies and Merten, 2022; Ramos et al., 2016). Fig. 10 presents the likelihood of households considering EE ratings/labels on appliances before purchasing them.

5. Policy implications

In light of the above results and discussions, we draw two main findings from this study. First, in higher-income neighborhoods such as Regimanuel Gray Estate, which tend to have higher solar PV potential, the tendency for SHS adoption is low due to the occupancy status of the residents who are mostly renters. Second, while our results suggest that households willing to adopt SHS are also more likely to engage in EE and CB, these behaviors are common among middle and low-income households who, in practice, may not be able to afford the SHS. Our findings have four significant policy implications for residential solar PV diffusion.

First, with most households in the high-income neighborhood being renters, it could be less beneficial for policy interventions to target such households since most of them are unwilling to install SHS. Available data shows that the majority of residents in Accra are renters, with only 18.3% of households in the city owning their homes, while the national homeownership average is around 42.1% (Ghana Statistical Service, 2019). Policy interventions such as the national rooftop solar PV program in Ghana may be more appropriate and effective to target real estate developers who develop and rent/sell houses in high-income gated neighborhoods like Regimanuel Gray Estate. SHS interventions in middle-class neighborhoods like Dansoman need to target homeowners since, unlike the Regimanuel Gray Estate, homeowners typically make all the housing decisions (from design to construction).

Second, utility-scale solar could be a viable option to overcome the challenges associated with residential solar, such as SHS. In addition to the challenge posed by the occupancy status of the household, our previous study (Akrofi and Okitasari, 2023) also found that urban form characteristics of neighborhoods could pose challenges to adopting rooftop solar PV systems. Community solar schemes with ground-mounted PV arrays and utility-scale solar projects would be appropriate for renter-dominated contexts and low-income neighborhoods where the characteristics of the built environment pose restrictions to solar PV installation and performance (Akrofi and Okitasari, 2023; Boccalatte et al., 2022).

Third, it is essential to address the solar rebound effect to realize the full potential of rooftop solar PV in terms of offsetting electricity consumed from the grid and its associated CO_2 emissions. To mitigate this effect, policy interventions for solar PV must be accompanied by energy efficiency and curtailment measures to develop a 'double dividend', where adopters not only generate energy but also engage in curtailment (Truelove et al., 2014) or sufficiency behavior (Seidl et al., 2017). A good example is Ghana's national rooftop solar PV program, which requires all prospective beneficiaries to install only LED bulbs in their homes to be eligible for the capital subsidy granted through the program.

Lastly, given the numerous barriers to adoption by low and middle-income households, equitable policy interventions and business models are necessary to accelerate solar PV diffusion and close the gap between the achievable and technical potential for solar PV in urban areas. These policy recommendations are not only applicable to Ghana. They could also suit the context of many other sub-Saharan African countries such as Kenya, Uganda, Cote d'Ivoire, Tanzania, Nigeria, South Africa, and Senegal. Like Ghana, these countries have large proportions of renters and are characterized by gated estates (especially in South Africa), as well as similar policy frameworks and interventions for residential solar PV (Barau et al., 2020; Hansen et al., 2015; Kizilcec and Parikh, 2020; Rahut et al., 2018; Statista, 2023).

6. Conclusion

Energy efficiency and curtailment behavior remain key if the goal of solar PV adoption to curtail carbon emissions related to electricity consumption in the residential sector is to be achieved. This study demonstrated that rooftop solar PV has the potential to reduce households' CO_2 emissions from electricity consumption significantly in rapidly developing cities like Accra. Furthermore, in the high-income neighborhood (Regimanuel Gray Estate), where it is generally expected that households' income levels and educational attainment will favor the adoption of SHS, the willingness to adopt SHS is relatively low compared to the primarily middle-class neighborhood (Dansoman). However, this dynamic is explained by the occupancy status of the households, where most of those in the high-income neighborhood tend to be renters. Our results also affirm that energy-saving behavior, such as turning off or putting appliances on standby, is more common among middle-class groups. Nonetheless, such behavior is higher among households willing to adopt SHS both in gated and non-gated neighborhoods. It must, however, be emphasized that willingness to adopt SHS does not signify the ability to do so. Hence, in practice, even though the willingness to adopt SHS is higher among the middle-class and low-income groups, they may not have the requisite finance to purchase them.

While this study provided some empirical insights into SHS adoption and the implications of EE and CB for CO_2 emissions, we would like to emphasize that our results must be interpreted cautiously. First, "willingness to adopt" SHS, as used in this study, is based on households' self-reported willingness to adopt based on their existing knowledge of SHS. Thus, we did not provide any SHS-related information, such as the upsides and downsides of SHS, during the survey. We believe that such information could influence their responses. However, our main aim was not on the mediating role of knowledge nor value-belief-norm on the households' willingness to adopt SHS or their energy-saving behavior as done by previous studies (Abdullah et al., 2017; Appiah et al., 2023; Fornara et al., 2016). Secondly, given that the occupancy status tends to be the most significant factor regarding households' willingness to adopt SHS, it is essential to note that renters who indicated an unwillingness to adopt might have only done so because of their occupancy status and not based on their true intentions. Further studies are necessary to understand the interaction between these determinants (households' occupancy status, energy efficiency, curtailment behavior, environmental concern, and SHS knowledge) and policy interventions to better explain solar PV transitions or, rather, the slow diffusion of SHS among households in developing countries.

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CRediT authorship contribution statement

Mark M. Akrofi: Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Writing – original draft. **Mahesti Okitasari:** Supervision, Writing – review & editing. **Hassan Qudrat-Ullah:** Writing – review & editing.

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.

Data availability

Data will be made available on request.

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