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Abstract. This paper examines the potential for PV to improve the performance of primary schools in London. Disaggregate data including energy use is compared with modelled PV generation, showing that electricity demand could theoretically be met in 59% of the schools investigated. The impact of several key factors is then considered, including architectural heritage, building age and form. The results show that the greatest PV potential exists in newer schools, as well as those that are shorter and with less dense forms.
Keywords. Schools, education, renewables, photovoltaics, heritage.

1. Introduction

The UK is committed to achieving net zero carbon emissions by 2050. Accounting for 40% of national emissions, considerable improvement to the building stock will be required to meet this target [1]. Education represents an important building sector, both in terms of current performance as well as improvement potential. Schools make up around 15% of public sector emissions and 2% of the overall national emissions [1]. They are also important societally: Integrating renewable technologies into schools has been identified as an opportunity both for major emissions reductions as well as engaging young people in issues around climate change and sustainability [2].

Alongside retrofit measures to reduce energy demand, an increased use of renewables, such as PV (photovoltaics), will be an important part of the UK's future. London for example aims to install 1GW of panels by 2030 and 2GW by 2050 (the 2030 target represents a 10-fold rise from current levels) [3]. How such a large expansion of PV should occur requires a better understanding of the characteristics of the building stock as well as how those characteristics relate to PV potential. A recent study estimated that 14% of the UK's electricity use could be met by rooftop PV, but only 2% might be cost-competitive with the grid [4]. The paper identified deployment in the public-sector as providing opportunities for "economies of scale, replicability and […] mobilis[ing] the local PV markets." While some studies have analysed PV in specific sectors, including schools in South Korea [5], others have modelled potential across large urban areas in increasing detail. A 2015 study of London showed that PV potential can be estimated at a local scale from aggregate morphological variables [6] while, more recently, models have been developed to estimate performance at the individual building scale [7,8].

This paper explores the opportunity for rooftop PV in 802 gas-heated primary schools in London (44% of the city's primary schools [9]). Analysis was undertaken using modelling of PV generation, alongside empirical data on energy consumption and the condition of the school buildings.

2. Methodology

The study used establishment-level data on the school stock from the following three sources:

- 3DStock: 3DStock is a GIS-based model of the built environment [10]. Constructed from a number of sources, the model holds buildings data at the level of each individual property. At the time of writing, 3DStock covers London plus a few other urban areas across England and has been used to explore the characteristics and performance of the stock [11,12].
- Unified Schools Database: This is a database of the English school stock, produced by combining data from a 2012-15 national survey of school buildings (the Property Data Survey Programme [13]), with the Display Energy Certificates database, which provides energy data for public non-domestic buildings since 2008 [14]. This database has been used to examine the performance of the school stock, and for building energy modelling [15,16].
- London Solar Opportunity Map (LSOM): This is a model of solar potential for London [8,17]. Annual irradiation has been calculated for most rooftops and land area in the city, using high resolution LiDAR data converted into a 3D triangular mesh. Direct and diffuse irradiation received by each triangle were calculated, considering solar angles and sky view factors. The model accounts for built form, roof type (e.g. pitched/flat), roof clutter (e.g. HVAC plant and chimneys), and surrounding elements (e.g. shading from neighbouring buildings and trees). An overall efficiency of 15% was used to convert predicted irradiation into electricity generation. Figure 1 shows the LSOM results for two example schools, alongside photos.

Figure 1. Predicted PV generation (kWh/m^2) for two example schools (photos: www.bing.com/maps).

Combining the above sources, the data collected for each school is detailed in Table 1. Checks were carried out to ensure consistency between datasets where appropriate. For example, ground floor areas in the schools database were compared with the building footprints in 3DStock. Following this matching and processing, schools with incomplete or inconsistent data were excluded, and the study was limited to gas-heated primary schools. The final sample was 802 schools.

Table 1. Summary of data collected for each school for the study.

Source	Variable	Detail
3DStock	Built form	Building form and footprint
	Site	Site shape, area (m^2) and location (including conservation area)
Schools Database	Energy use	Annual electricity and fossil-thermal use (kWh).
	School size	Total floor area and ground floor area (m^2)
	Construction	Construction era (pre-1919; interwar; 1954-66; 1967-76; post 1976)
	Roof condition	Roof condition (grade A-D) based on visual inspection (% of total)
	Heating fuel	Main heating fuel (gas, electricity, other)
	Heritage	Listed status
LSOM	Viable roof	Roof area (m^2) and form (orientation, tilt angle, etc.)
	Solar irradiation	Annual predicted irradiation across viable roof area (kWh)

3. Results and Discussion

3.1. What is the PV potential for schools in London?

As Figure 1 shows, the predicted irradiation varies considerably, even across single roofs. Since the economic and environmental suitability of any given section of roof will depend on its generation, the total potential for each school will be driven by the minimum acceptable level: Covering the entire roof with panels may be technically feasible but would include areas expected to produce very little electricity. Figure 2 shows how PV potential varies with such a threshold, from 700-1,150kWh/m^2 per year. At 15% efficiency and 140Wp/m^2, this corresponds with 105-173kWh/m^2 of electricity generated and load factors of 8.6-14.1%. Figure 2a shows the viable roof area as a proportion of total school roof in red, and the predicted annual generation as a proportion of the school's recent electricity use in green (the bands are the quartiles). In the sample, the median electricity use is 48 kWh/m^2 (slightly higher than the national average [16]), with an interquartile range of 39-58 kWh/m^2. Figure 2b shows the breakdown of viable roof area, in terms of orientation and tilt, against the same threshold range.

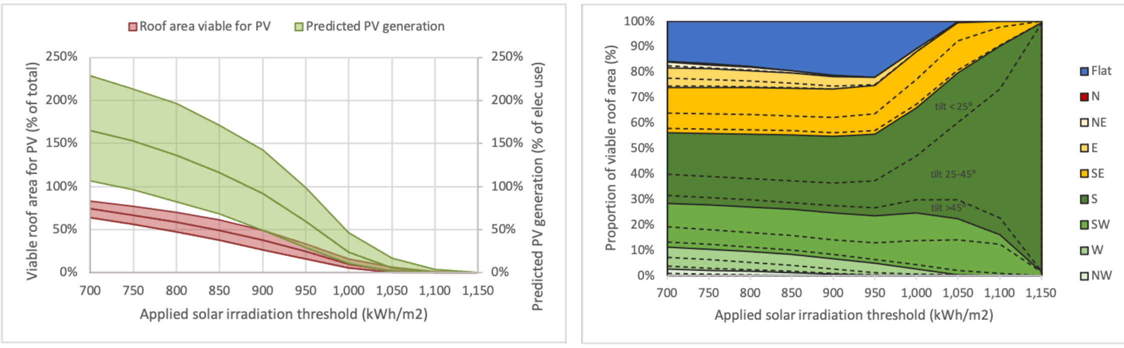

Figure 2. Predicted (a) PV generation, roof area, and (b) orientation with minimum solar irradiation.

The results reveal a high potential for PV across London primary schools. At the lower limit, a median of 74% of roof area per school is predicted to receive at least 700kWh/m^2, and panels covering this space would cover the school's annual electricity in three-quarters of the sample. As expected, the level of irradiation is strongly dependent on roof form. Four-fifths of the roof space that will receive at least 700kWh/m^2 irradiation is southeast-to-southwest facing (63%) or flat (16%). This trend remains steady to 950kWh/m^2, above which the southeast-to-southwest roof space forms an increasing share of the total, particularly where tilted 25-45°. It should be noted that, where a school's predicted PV generation exceeds it's current energy use, this is a *net* balance; the level of export & import from the grid will depend on the relationship between PV generation variability and the academic timetable, as well as the installed systems. However, temporal factors are outside the scope of the present study.

3.2. How does PV potential vary with building characteristics?

Next, the impact of building characteristics on PV potential has been examined. These analyses were carried out using an irradiation threshold of 850kWh/m^2, in line with typical performance in the UK [20]. Figure 3 presents the distributions of viable roof area and PV generation for five construction age bands. These bands correspond with 'distinct eras within school building programmes' [13] and have been used in archetype modelling to identify schools with similar built forms and envelope and systems characteristics [15]. (In Figure 1, the left and right images are examples of older (pre 1919) and more modern (post 1976) schools respectively). As before, viable roof area and PV generation are presented as proportions of the total roof area and current electricity use respectively. The graphs show the mean, 25th, 50th and 75th percentiles values, and sample sizes are shown in brackets.

On average, 49% of primary school roof space in London is viable for PV. However, this varies considerably, with 1.3% of the schools predicted to have *no* suitable area while 1.6% have over 80% suitable roof area. Considering age, mean viable area rises between pre-1919 and 1967-76 schools (31-

58%), before dropping to 54% for the most recent schools. All 3 quartiles follow the same trend. As expected, the predicted annual PV generation closely follows the roof area trend. Accordingly, the results suggest that 59% of the schools could meet or exceed their annual electricity consumption using on-site PV. The age-PV trends reflect differences in the typical building & urban characteristics between construction eras. For example, across London primaries, older schools tend to be taller, more likely to have pitched roofs, and are more likely to be located in Inner London: The first two variables drives the ratio of roof space-to-usable floor area and the proportion of viable roof space respectively, while Inner London typically has higher densities and taller buildings than Outer London [11].

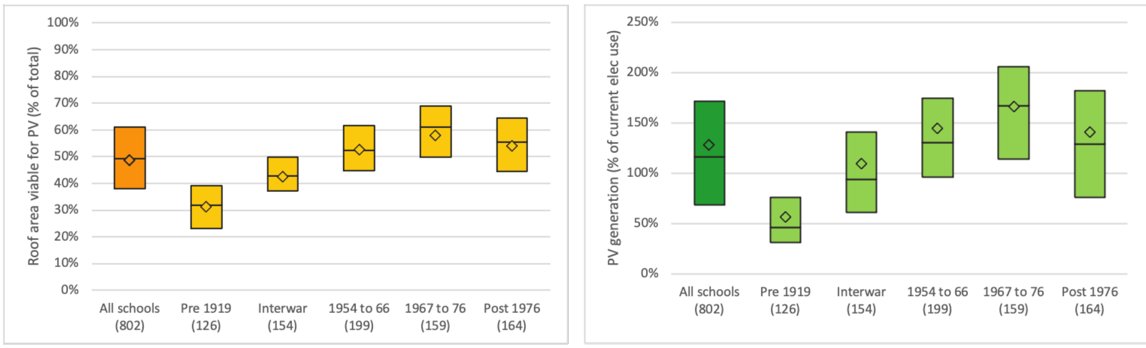

Figure 3. Predictions of (a) suitable roof area and (b) PV generation for London schools.

Since this study focusses on gas-heated schools, electricity accounts for 20-30% of the total energy in the sample. Assuming typical efficiencies of the existing boilers of 80% and COPs of replacement heat pumps of 2.0, electrification of heating might be expected to raise mean electricity use by a factor of ~2.2. On such a basis, across the sample, the same level of PV would cover the annual electricity use for only 10.4% of the schools, if rolled out in conjunction with a conversion to electric-heating.

While the results above show the theoretical potential for PV, practical factors may limit how much is achievable. For example, listed buildings or those in conservation areas can have limitations on installing PV [18,19]. Figure 4 shows the heritage and roof condition data for the sample.

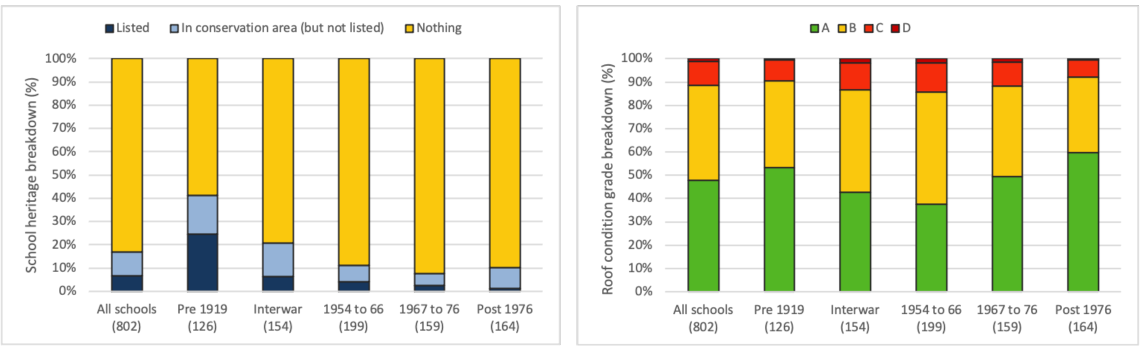

Figure 4. Distribution of (a) schools with heritage status and (b) current roof condition.

Unsurprisingly, heritage is strongly linked to building age, with 41% of pre 1919 schools listed or in conservation areas, compared with 10% of post 1954. The precise impact of heritage status on the potential for PV is not clear cut: While energy improvement guidance exists, the implementation is decided by each Local Authority and so varies geographically [18]. Conservatively, however, the 17% of schools in the sample listed or in conservation areas may be unlikely to be allowed PV installations. Figure 4b presents the distribution of roof condition across the stock, determined by surveyors using the following criteria: grade A is ‘performing as intended and operating efficiently’, B is ‘performing as intended but exhibiting minor deterioration’, C is ‘exhibiting major defects and/or not operating as intended’ and D is ‘life-expired and/or serious risk of imminent failure’ [13]. While these are qualitative assessments made solely from visual inspection, they may be proxies for the suitability of the roofs for PV. Grade A roofs might be more likely to be structurally sound, for example. Conversely, while grade C and D roofs are unlikely to be *currently* suitable for PV, they will be the building elements in most immediate need for renovation, and so the added cost of PV as part of such work may be reduced compared with a standalone PV installation works. For the overall sample, 12% of roof area is grade C or D, compared with 48% and 41% A and B respectively.

3.3. How does PV potential vary with urban & building form?

A key factor in driving PV potential is the form of a building and its relationship to the surrounding urban environment. To examine this further, the PV results have been integrated into 'Spacemate' plots. These are graphs with Floor Space Index (FSI, total floor area ÷ site area) and Ground Space Index (GSI, ground floor area ÷ site area) on the y- and x-axes respectively. Each school is located on Spacemate, based on it's form and size. FSI:GSI ratio equals mean building height, and this is represented in Spacemate by radial lines. Of course, FSI and GSI are not inextricably connected to the urban context; buildings that fill their site (GSI ~1) exist in low and high density areas for example, as do tall buildings (high FSI/GSI ratio). However, they are strongly linked through factors such as land price. The interquartile range for FSI for Outer London schools is 0.15-0.35, compared with 0.34-0.76 for Inner London, and for GSI these are 0.13-0.27 for Outer and 0.24-0.34 for Inner London. Consequently, different areas of Spacemate have been shown to correspond with different built forms and energy use [11], and FSI has previously been shown to be a strong indicator of PV potential [6].

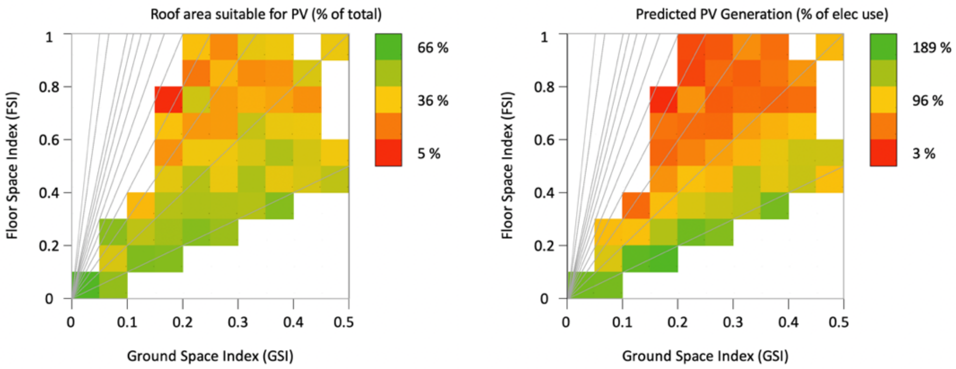

Figure 5. Distribution of (a) suitable roof area and (b) PV generation across Spacemate.

Figure 5 presents mean roof area and PV generation on Spacemate histogram plots. (These are limited to FSI 1 and GSI 0.5 for legibility, since the proportion of schools outside of this range is very small [<4%]). The links between PV and ground coverage (GSI), building density (FSI), and height (FSI/GSI) can be seen by looking along the x-axis, y-axis, and radially. The results illustrate strong links between PV and morphology. Viable roof area falls with rising ground coverage (54% for GSI <0.1 to 25% for GSI >0.5) and density (57% for FSI <0.2 to 30% for FSI >1), and PV generation exhibits the same trends. Increased height is also inversely correlated to roof area and PV generation. The latter may be expected due to geometry (all-else-being-equal each additional storey represents a factor reduction in roof area per m^2 of occupied floor space). However, one might expect height to be associated with a reduced risk of overshading. The fact that the proportion of viable roof area also falls with increasing height may be because taller schools are more likely to be located in areas with taller buildings and, since much of the stock is not vertically uniform, there will be self-overshading.

4. Conclusion

This paper presents an analysis of the potential for PV in primary schools in London, using modelled estimates of solar irradiation and empirical data on energy performance and building characteristics. The results suggest that almost half of the roof area could receive annual irradiation of 850kWh/m^2 or more, and panels covering this space could cover the current annual electricity use for 59% of the schools assessed. Considering the characteristics of the stock reduces the proportion of this theoretical potential that may be practically achievable. For example, almost one-fifth of the schools examined include listed buildings or are located in conservation areas, and therefore may have restrictions on the installation of solar panels. This illustrates an issue that may need to be examined as the UK moves towards its emissions reduction targets; how do you balance the desire to improve building performance, alongside the need to preserve architectural heritage. Nonetheless, the results are promising in the context of London's desire "to see more public buildings, like schools, hospitals, universities and government buildings at the forefront of the move to solar energy generation." [3]

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