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Solar energy and urban morphology: Scenarios for increasing the renewable energy potential of neighbourhoods in London

Juan José Sarralde [a, d, *], David James Quinn [b], Daniel Wiesmann [c], Koen Steemers [a]

[a] Energy Efficient Cities initiative, Department of Architecture, University of Cambridge, 1–5 Scroope Terrace, Cambridge CB2 1PX, UK
[b] Architecture Department, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA 02139, USA
[c] Instituto Superior Técnico, Technical University of Lisbon, Avenida Rovisco Pais 1, 1049-001 Lisbon, Portugal
[d] Instituto de Arquitectura y Urbanismo, Universidad Austral de Chile, Edificio Ernst Kasper, Campus Isla Teja, Valdivia, Chile

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ABSTRACT

Amongst academics and practitioners working in the fields of urban planning and design, there has been an on-going discussion regarding the relationships between urban morphology and environmental sustainability. A main focus of analysis has been to investigate whether the form of cities and neighbourhoods can be related to their energy efficiency, especially regarding the energy intensity of buildings and transportation. However, to analyse the overall energy performance of urban systems, both the consumption and the generation of resources need to be assessed. In terms of urban environmental sustainability, the potential to generate renewable energy within the city boundaries is a research topic of growing interest, being solar energy one of the main resources available.

This study uses neighbourhood-scale statistical models to explore the relationships between aggregated urban form descriptors and the potential to harvest solar energy within the city. Different possible scenarios of urban morphology in Greater London are analysed and variables of urban form are tested with the aim of increasing the solar energy potential of neighbourhoods. Results show that by optimising combinations of up to eight variables of urban form the solar irradiation of roofs could be increased by ca. 9%, while that of façades could increase by up to 45%. Furthermore, based on these results, a series of trade-offs needed for the optimisation of conflicting variables is unveiled. Finally, some recommendations for design strategies are offered with the aim of helping urban planners and designers improve the solar energy potential of new or existing urban areas.

1. Introduction

It is widely accepted that generating energy within the city boundaries can bring many advantages, a main one being the increase in efficiency due to the reduction of energy transmission losses. Amongst all possible sources of renewable energy available in the urban context, such as wind, geothermal and solar energy, the latter is probably the most popular and has been studied to great lengths. This paper reports on the results of a collaborative research effort aimed at developing a methodology of urban modelling for evaluating the solar renewable energy potential (REP) of cities, based on their urban morphology.

1.1. Urban morphology and renewable energy potential of cities

In the last decades there have been many examples of research looking at the solar potential of cities, including both passive solar gains and the potential of harvesting solar energy to heat water and to generate electricity. Back in 1997, Project ZED [1] used the RADIANCE ray-tracing software to investigate the solar exposure of cities and the environmental contributions from solar penetration in an urban area. Some years later the PRECis project [2] built upon the experience of Project ZED to assess the potential for renewable energy generation in cities, by exploring the relationships between urban form and the energy and environmental performances of buildings. Furthermore, Yun and Steemers [3] analysed the impact of urban settings on the potential for energy generation using façade-integrated photovoltaic (PV) panels.

Further on the relationship between urban morphology and solar potential, the SOLURBAN project [4] used the extraction of urban form descriptors from 3D models and built upon the results

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* Corresponding author. Instituto de Arquitectura y Urbanismo, Universidad Austral de Chile, Edificio Ernst Kasper, Campus Isla Teja, Valdivia, Chile. Tel.: +56 63 229 3464.

E-mail address: jjsarralde@gmail.com (J.J. Sarralde).

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of previous research [5,6] to evaluate the solar potential of three Swiss cities with different levels of building density. By comparing the results of the three cases, an inverse relationship was found between urban density (measured as plot ratio) and the potential for façade and roof mounted PV and solar thermal collectors. Other studies [7,8] followed up on these results and looked into more detail at the efficacy of using aggregated measures of urban form such as the height-to-width ratio of street canyons, site coverage, plot ratio, horizontal distribution, and vertical uniformity of buildings, amongst others, for calculating irradiation availability at district level. Meanwhile, more recently, further tools to perform neighbourhood-scale analysis of solar availability have been developed. SUNtool [9] and CitySIM [10] utilise complex computer modelling techniques to predict the performance of various energy generation technologies, including solar, within the city boundaries.

This paper builds upon the existing body of research to further expand the understanding of how this knowledge could influence urban planning and design to increase the solar potential of cities.

1.2. *Aims of this study*

The aim of this analysis is to test whether the knowledge obtained on the relationships between urban morphology and solar potential can help create cities that are more suited for harvesting solar energy. This is done by optimising certain parameters of urban morphology in order to increase the solar potential of buildings' roofs and façades. It is acknowledged that the variables of urban form involved in this analysis are not easily modified in the case of existing neighbourhoods. Hence, this parametrical exploration should be primarily considered as a theoretical exercise. However, it is expected that the insights gained through this research will be useful when briefing and designing new neighbourhoods or towns and to help guide planning policy in order to increase the solar REP of cities.

2. Methodology

This section offers a brief summary of the data and methods used in this study.

First, spatial data was used to characterise the urban morphology of neighbourhoods in London, UK, by computing a variety of aggregated urban form descriptors. The same data was then used to model the solar irradiation of building envelopes by means of computer simulation. The next step was to perform a statistical analysis to explore the interrelations between the aggregated descriptors of urban morphology and the solar irradiation of building envelopes. The outcome of this analysis was the creation of two separate models capable of predicting (to different degrees) the solar irradiation of roofs and facades, based on the urban form of a neighbourhood. These models are named *Roof-SolREP* and *Façade-SolREP*, respectively. Finally, the two models were used to test different scenarios of urban form. The aim of this was to explore whether the solar potential of building envelopes could be optimised by introducing changes to the urban morphology of neighbourhoods.

2.1. *Urban form characterisation*

Table 1
Data sources for the calculation of urban form descriptors.

Data set	Data source
UK census (2001), generalised land use database (GLUD, 2005)	Neighbourhood statistics: http://www.neighbourhood.statistics.gov.uk/
Ordnance survey mastermap: building heights & footprints	University of Edinburgh's EDINA, Digimap collections: http://edina.ac.uk/

Table 2
Data sources for the calculation of urban morphology descriptors.

Group	Descriptor	Units
Building typology	1) Share of detached houses	%
	2) Share of semi-detached houses	%
	3) Share of terraced houses	%
	4) Share of apartment blocks	%
Vertical & horizontal distribution	5) Average building height	m
	6) Standard deviation of building heights	m
	7) Average distance between buildings (nearest neighbours from centroids)	m
Land use	8) Share of area covered by domestic buildings	%
	9) Share of area covered by roads	%
	10) Share of area covered by private gardens	%
Building geometry	11) Average building volume	m^3
	12) Average building perimeter	m
	13) Average building orientation (variation between the main longitudinal angle of building footprint and due north)	°
Building density	14) Plot ratio (total floor area divided by total area of neighbourhood)	
	15) Site coverage (share of total built area)	%
	16) Total floor area	m^2
	17) Total area covered by buildings	m^2
	18) Total area of neighbourhood	1 K m^2

Table 1 presents the data sources used for the calculation of 18 different aggregated descriptors of urban form. These were extracted from spatial data using computer code written in the Python programming language and linked to a Geographical Information Systems (GIS) platform (using the ArcGIS ArcMap 10.0 software). The 18 descriptors used were categorised in 5 groups and are listed in Table 2. Furthermore, all data was aggregated to the UK Census geographical division of Lower Layer Super Output Area (LSOA), which is the unit of analysis in this study and is assumed to represent a typical neighbourhood of Greater London, as illustrated in Fig. 1. By definition, each LSOA contains a population of ca. 1500 inhabitants. Therefore, different LSOA can show great variations in terms of area, building typologies, building use, and urban morphology.

2.2. *Modelling solar irradiation of buildings*

The data on solar irradiation was obtained using computer simulations. For roofs, the analysis was carried out using the ‘Area Solar Radiation’ tool form the ArcGIS ArcMap 10.0 software package. This tool derives solar radiation from a raster surface, in this case from digital elevation models (DEM) based on the buildings of a LSOA, and produces an output raster showing radiation values in watts hours per square metre (Wh/m^2). The simulation was carried out on a dataset containing 4718 LSOA samples, which represent 77.8% of all LSOA in Greater London. The analysis of solar irradiation of façades was computed using the ‘Solar Access Analysis’ tool of the widely used Autodesk Ecotect Analysis 2011 software. This tool computes detailed shading masks for each building within a LSOA and simulates the solar irradiation of all vertical elements. The solar radiation was calculated using average daily values for each month of the year, using historic weather data for London. Because this analysis was much more computing intensive than the simulation of roofs, it was carried out for a smaller sample of 93 LSOA in the London Borough of Camden.

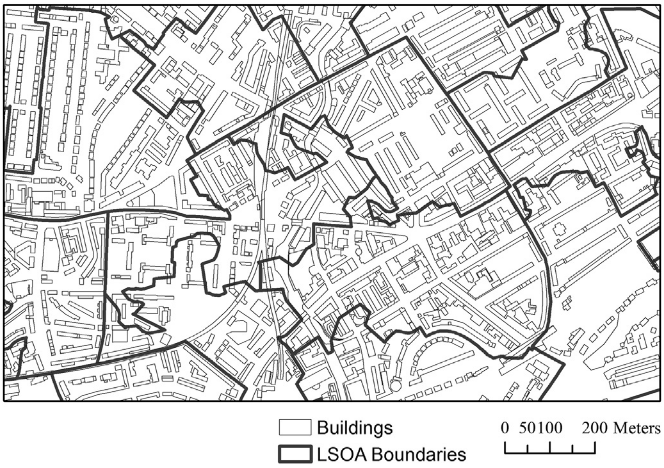

Fig. 1. Examples of LSOA divisions in Greater London.

Table 3
Descriptors of urban morphology used to predict the solar irradiation of roofs and façades.

Roof-SolREP	*Façade-SolREP*
1) Share of semi-detached houses	1) Average building height
2) Share of area covered by private gardens	2) Site coverage
3) Average building perimeter	3) Average distance between buildings
4) Standard deviation of building heights	
5) Plot ratio	
6) Average distance between buildings	

2.3. *Statistical models for predicting solar irradiation*

The statistical models used to predict solar radiation falling on roofs and façades were written with the R software using multiple regression models with spatial error correction. For each LSOA, the independent variables tested were the 18 urban form descriptors presented in section 2.1, while the simulated values of solar radiation described in section 2.2 were used as the dependent variable. The observations in the regression models are spatially allocated through the division of LSOA boundaries and can therefore not be assumed to be independent of each other. Hence, a spatial weights matrix of 11 nearest neighbour connections was introduced as an error term. After a careful process of model specification based on the *spatial error* model presented in equation (1), the *Roof-SolREP* model finally selected produced a Nagelkerke pseudo R-squared value of 0.74, based on six descriptors of urban morphology. On the other hand, the *Façade-SolREP* model specified obtained a pseudo R-squared value of 0.58 based on just 3 descriptors of urban form. The descriptors used in both models are listed in Table 3. As an illustration of the results obtained from these models, Fig. 2 shows the distribution of predicted solar radiation falling on roofs (in Wh/m^2 per LSOA per annum) for the whole of the Greater London sample, obtained using the *Roof-SolREP* model.

Equation (1). Formula for the *spatial error* model specification

$$y = X\beta + u;\ u = \lambda W u + \varepsilon$$

where: y is the dependent variable; X is the matrix of co-variates; β is a vector parameter; u is an error term; W is the spatial weights matrix; λ is a scalar parameter; and ε is an independently and identically distributed normal error term.

Finally, the models were validated by contrasting the predicted results with the original data obtained from computer simulations, as explained previously in 2.2. For the *Roof-SolREP* model, the percentage of error showed a relatively high accuracy in the prediction of solar radiation, with a mean error percentage (calculated from the residuals between original and predicted data) of 0.84% and a standard deviation of just 0.83%. In the case of the *Façade-SolREP* model, the mean percentage of error was much larger at

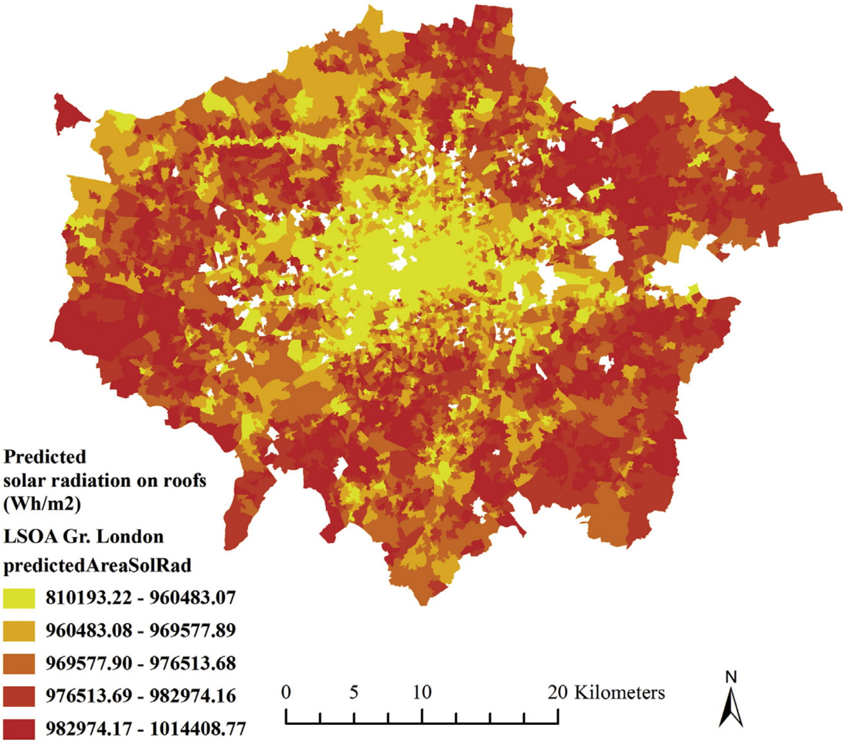

Fig. 2. Spatial distribution of predicted data for solar radiation incident on roofs for the Greater London sample, expressed in Wh/m^2 per LSOA per annum.

8.05% with a standard deviation of 9.43%. This difference could be expected considering that the sample size for the *Façade-SolREP* model was just 93 observations, compared with a sample of 4577 observations for the *Roof-SolREP* model.

3. Scenarios for optimising the solar potential of neighbourhoods

The *SolREP* models previously presented were used to test different possible scenarios of urban morphology that could help increase the solar irradiation of building envelopes.

3.1. Comparing neighbourhoods with similar predicted solar irradiation

First, an analysis was carried out to explore the scale of the influence that each urban form descriptor used in the *SolREP* models might have on the results of solar irradiation. For this, three samples of neighbourhoods with similar predicted values of solar irradiation were compared, for roofs and façades respectively. The samples selected illustrate the high variability of urban form in neighbourhoods with a similar solar REP, showing the complexity of combining different urban form variables to increase the potential for harvesting solar energy in neighbourhoods. This exercise is illustrated with the results for roofs, which showed an overall higher variability than in the case of façades. Figs. 3–5 present three LSOA (samples A, B and C, respectively) that obtained very similar values for predicted solar irradiation of roofs (represented by variable *Y*, expressed in Wh/m^2) using the *Roof-SolREP* model. Their *Y* values were the closest to 970,574 Wh/m^2, which is the mean annual value of *Y* amongst all samples.

With a simple visual check it can be observed that samples A, B and C display very different urban configurations. This is supported by the data presented in Table 4, which shows large variations between their respective urban form descriptors. Of all six variables examined, the share of area covered by private gardens shows the largest variation. Sample C has the largest share of garden area, which is 53% larger than sample A and 15.8% larger than sample B. This is followed by the share of semi-detached houses, where sample B presents the largest share with a difference of 43% over sample A and 34.1% over sample C. The average building perimeter also shows a relatively large variation of up to 31% between samples C and B (highest and lowest respectively), while the variable of plot ratio presents a maximum variation of 27.9% between the densest sample C and the least dense, sample A. On the other hand, two other descriptors of urban morphology show relatively small percentages of variation between samples. The maximum variation in the average distance between buildings is 11.1%. Finally, in the standard deviation of building heights, the highest-ranking sample B and the lowest-ranking sample A show a variation of just 10.1%. This means that all three samples show a relatively uniform skyline, with standard deviation values of just over 2 m in building height.

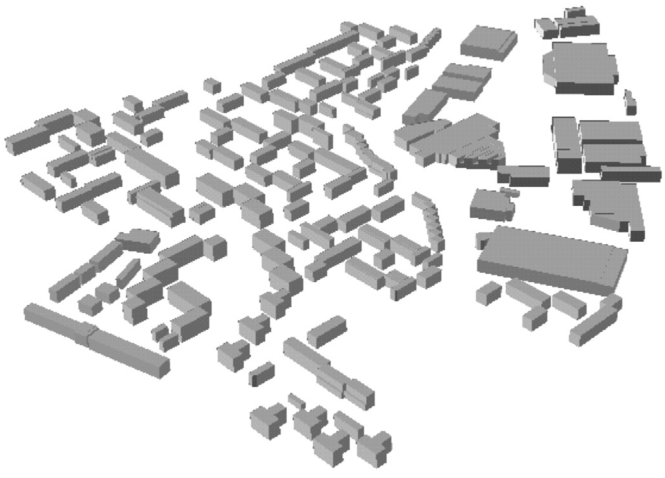

Fig. 3. Sample A: LSOA representing the mean value for predicted solar irradiation of roofs.

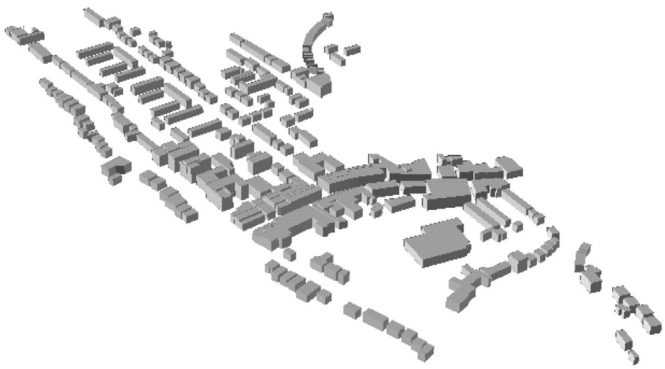

Fig. 4. Sample B: LSOA representing the mean value for predicted solar irradiation of roofs.

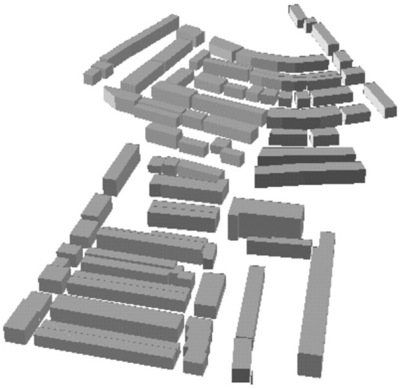

Fig. 5. Sample C: LSOA representing the mean value for predicted solar irradiation of roofs.

This analysis shows that, while it might be sometimes difficult to strike a balance between the different variables of urban form to maximise solar REP, it is still possible to have a very diverse range of neighbourhood patterns that yield similarly high results in terms of solar potential.

Table 4
Comparison of values for the descriptors of urban form used in the *Roof-SolREP* model; based on three samples with similar predicted solar irradiation.

Urban form variable	Units	A	B	C	Max. variation
1) Share of semi-detached houses	Fraction	0.07	0.12	0.08	43.1%
2) Share of area covered by private gardens	Fraction	0.17	0.31	0.37	53.0%
3) Average building perimeter	m	86.36	74.68	108.30	31.1%
4) Standard deviation of building heights	m	2.13	2.37	2.19	10.1%
5) Plot ratio	–	0.92	0.93	1.28	27.9%
6) Average distance between buildings	m	21.86	19.68	22.09	11.1%
Predicted irradiation of roofs (*Y*)	**Wh/m^2**	**970,580**	**970,564**	**970,587**	**0.002%**

3.2. *Scenarios for the optimisation of solar irradiation of roofs*

Different scenarios of urban morphology are tested in order to optimise the amount of solar radiation that can be harvested on building roofs. The optimisation is carried out by increasing those variables that are in a direct relationship to solar REP, while at the same time decreasing the variables that are detrimental to it. The results of these scenarios are then compared by quantifying the increase in the solar irradiation of typical neighbourhoods as a result of varying the urban form parameters of the different variables involved.

The first step for testing different scenarios was to define a base-case scenario against which the improvements could be compared. The chosen sample was the LSOA previously presented in Fig. 3 (sample A), as it has the predicted solar irradiation value that is closest to the mean. As presented in Table 5, a total of eight scenarios for increasing solar REP on roofs are analysed. Of these, scenarios 1, 2 and 3 are aimed at simultaneously modifying the values of all six independent variables. The optimisation is performed to different degrees, introducing variations to the values of the urban from descriptors that reflect an increase or decrease of 10%, 20% or 50% of their value, as well as the maximum variation. It is important to note that for the maximum variation, the values used are the minimum or maximum values of each descriptor as found within the whole sample of LSOA, rather than the theoretical extreme values for each variable.

On the other hand, scenarios 4, 5 and 6 are not based on modifying all variables, but on changing the value of one specific variable that has shown to have a higher impact on the prediction of Y, while leaving all other variables at their base-case values. From the analysis presented in 3.1, the variables with lowest variability and therefore with largest influence in the case of roofs are plot ratio, average distance between buildings and the standard deviation of building heights. Hence, these three descriptors were chosen. Finally, the last two scenarios (7 and 8) are intended to maximise a combination of variables. The combinations chosen are those most likely to feature in the design of some new developments, such as a new neighbourhood of semi-detached houses or a low-density 'green' suburban neighbourhood.

3.3. *Scenarios for the optimisation of solar irradiation of façades*

After analysing scenarios for optimising the solar potential of roofs, the same was done for façades based on the three independent variables included in the *Façade-SolREP* model. The base-case scenario selected was the LSOA illustrated in Fig. 6, which presented the Y value closest to the mean solar irradiation of façades of the Camden borough sample. The results of five scenarios for optimising solar irradiation of façades are presented in Table 6. Scenarios 1, 2 and 3 are aimed at modifying all three urban form descriptors used in the statistical model. The fourth scenario is based on the maximum value of just one variable: the average building height. Meanwhile, scenario 5 is based on the combination of the two variables with largest influence on the prediction of Y, which were the site coverage and average distance between buildings. The discussion of the results of all scenarios, for both roofs and façades, is presented in the next section.

Table 5
Comparison of the results of eight scenarios for optimising solar REP of roofs (where: Y = predicted solar irradiation; ΔY = percentage increase in Y over base-case; values used are based on the Greater London sample).

Scenario	Description	Y (Wh/m^2)	ΔY (%)
Base-case scenario	Sample A, Fig. 3	970,580.18	
1) Variation 20%	All modified by 20%	981,501.47	1.12%
2) Variation 50%	All modified by 50%	997,883.40	2.81%
3) Max. variation	All modified to max. value	1,055,870.18	8.78%
4) Low density	Plot ratio at min. value	980,245.41	0.99%
5) Dispersed neighbours	Avg. distance between buildings at max. value	1,018,167.97	4.90%
6) Even skyline	Std. dev. of building heights at min. value	974,901.60	0.44%
7) Uniform development	Share of semi-detached houses at max. value	984,923.48	1.47%
8) Green suburbia	Share of area covered by gardens, plot ratio and avg. distance between buildings at max. values	1,039,866.60	7.13%

Table 6
Comparison of the results of five scenarios for optimising solar REP of façades (where: Y = predicted solar irradiation; ΔY = percentage increase in Y over base-case; values used are based on the Camden borough sample).

Scenarios	Description	Y (Wh/m^2)	ΔY (%)
Base-case scenario	LSOA in Fig. 6	163,840.32	
1) Variation 20%	All modified by 20%	186,586.48	13.88%
2) Variation 50%	All modified by 50%	220,705.72	34.7%
3) Max. variation	All modified to max. value	238,413.56	45.51%
4) Low rise	Avg. building height at min. value	172,402.44	5.22%
5) Dispersed low density	Site coverage at min. value; avg. distance between buildings at max. value	229,851.44	40.28%

4. Discussion of results

After comparing the results of the various scenarios presented earlier, possible conflicts or trade-offs between the variables involved in each statistical model are analysed. This is followed by a discussion on the variables that should be prioritised when trying to optimise the solar irradiation of roofs and façades. Finally, a brief analysis of possible design strategies for the applicability of the models is presented.

4.1. *Comparison of scenarios for roofs*

For the analysis of solar radiation falling on roofs, a total of eight optimisation scenarios were tested against a base-case scenario. Fig. 7 shows a graph with the comparison of results. First, it can be observed that the variation between different scenarios is relatively small. As could be expected, the scenario that performs best is number 3: 'Maximum Variation'. However, its ΔY value (the difference between this scenario and the base-case) is just 8.78%. Moreover, the second best-performing scenario is number 8: 'Green Suburbia', with a ΔY of 7.13%. This confirms the relatively much larger impact of the three variables optimised in scenario 8, as seen in Table 5. Even though this scenario is based on the maximum variation of just three out of the six variables involved in the statistical model, there is a small difference of just over 1.75% between the ΔY of scenarios 3 and 8. With this, scenario 8 is probably the most efficient way of optimising the solar irradiation of roofs without having to modify all six variables involved. Furthermore, in third place is scenario 5: 'Dispersed Neighbours', which achieves a ΔY of 4.9% by only modifying the descriptor of the mean distance between neighbouring buildings. Finally, on the other end of the spectrum, scenarios 4: 'Low Density' and 6: 'Even Skyline' only help increase Y by less than 1%, with ΔY of 0.99% and 0.44% respectively.

The overall outcome of this analysis shows that the potential for increasing the solar irradiation of roofs by modifying the urban morphology of neighbourhoods is relatively small, ranging from 0.44% to 8.78% of increase in Y over the base-case scenario. However, considering that the difference between the mean and maximum values of Y in the whole Greater London sample is just 4.32%, all three best-performing scenarios (3, 8 and 5) are producing better results than the maximum observed in the sample. Moreover, considering that this analysis uses the mean value of the whole sample as a base-case scenario, a much greater increase could be expected when trying to optimise the performance of other samples that are under the mean. With this, it can be said that there is an overall good scope for improving the solar REP of roofs by introducing modifications in the built form of neighbourhoods.

4.2. Comparison of scenarios for façades

Fig. 8 presents a comparison of the results obtained for the five scenarios analysed for the optimisation of the solar irradiation of façades. A much larger variation can be observed here than in the case of roofs, with the best-performing scenario 3: ‘Maximum Variation’ showing a ΔY of 45.51% over the base-case. Furthermore, scenario 5: ‘Dispersed Low Density’ presents an important ΔY of 40.28% over the base-case scenario, achieved by modifying two of the three variables involved in the statistical model, as seen in Table 6. In third place is scenario 2: ‘Variation 50%’, with a Y 34.7% larger than the base-case scenario, while the scenario with the lowest ΔY is number 4: ‘Low Rise’, with a result for Y just 5.22% larger than the base-case scenario.

The large ΔY values observed in the case of façades show the relatively high impact of the different independent variables on the prediction of Y. Considering that the difference between the mean and maximum values of Y within the Camden sample is 14.74%, four out of the five scenarios tested here can significantly outperform the best sample analysed. Thus, the results exposed here show that there is a great scope for improving the solar irradiation of façades by modifying the urban form of neighbourhoods. However, it is worth noting that, while the results for façades seem much more auspicious than the results of the scenarios for roofs, the absolute solar REP of roofs is much larger than that of façades. Hence, while there is more room for improvement in increasing the amount of solar radiation received on façades, this is still a small portion of what can be achieved on roofs. In fact, the best-performing scenario for façades receives just under a quarter of the amount of solar radiation per squared metre received in the base-case scenario for roofs.

5. Applicability of the models

Thus far, the analysis of optimisation strategies for solar REP has been performed separately for roofs and façades. This section offers a discussion on the possible conflicts and trade-offs involved in the model applicability, in terms of developing design strategies to optimise the solar REP on whole building envelopes.

5.1. Possible design strategies and trade-offs involved

The optimisation of the solar irradiation of roofs and façades was based on increasing or decreasing the values of the variables involved in the statistical models used to predict the solar REP. As explained previously, the variables that are in a direct relationship to Y would be increased, while those in an inverse relationship to Y would be decreased. Furthermore, the models for roofs and façades have a different number of variables (6 and 3, respectively) and only one variable is repeated in both models, namely the average distance between buildings. Since this variable is in both cases in a direct relationship to Y, there is no conflict involved and the intention of both models would be to increase the value of that variable. However, there might be some conflicts when trying to maximise other variables that are detrimental to each other.

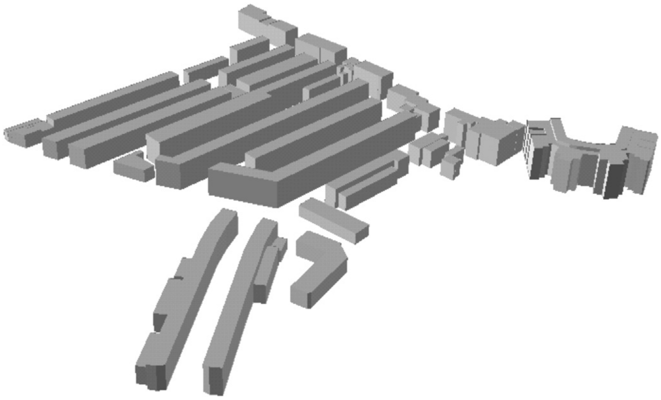

Fig. 6. LSOA representing the mean value for predicted for predicted solar irradiation of façades.

Moreover, in order to analyse how the findings of this study can be interpreted or utilised in the design or retrofit of new and existing urban developments, it is important to have some understanding of typical requirements faced by designers and planners. When confronted with a brief for the design of a new development or the re-design of an existing one, such as an urban master plan for a neighbourhood or town, practitioners will usually be confronted with multiple restrictions and requirements. Typical examples of these are a fixed size of the plot to intervene, maximum building heights or density targets, maximum and minimum areas of ground that can be built, and a target of floor area to be built in order to make the development economically viable. Trying to balance all those requirements can already be difficult. To design the urban form in order to maximise the solar potential can make it even more challenging.

In order to simplify the process, design strategies that use a rationale based on prioritising certain urban form variables over others can be developed, according to the impact of each variable on the overall solar REP of a neighbourhood. For this to work it is also necessary to include some boundary parameters or basic conditions that help set optimisation targets. Even in the case of more liberal design briefs there will be at least two basic requirements, which are likely to be a fixed plot size and a target of floor area to be built. Hence, these two boundary conditions are set for the analysis of possible conflicts between variables. So, when trying to adjust all eight variables of urban morphology involved in both, the models for roofs and façades, an order of priority as presented in Table 7 could help guide the decision-making process.

This order is given according to the individual or combined impact of descriptors of urban form on the overall result, as explained below:

a) The first priority should be given to modifying the variables included in the model of roofs, since the amount of solar radiation that can be harvested on roofs is usually much larger than that on façades. Also, by prioritising the variables of one model over the other, possible conflicts between variables of different models are avoided. An example of this would be the case of trying to modify both, the average building height (which needs to be reduced to optimise irradiation of façades) and the average building perimeter (which needs to be reduced to optimise the solar irradiation of roofs). When constricted by boundary conditions such as a set target of floor area and a limited plot size, a conflict

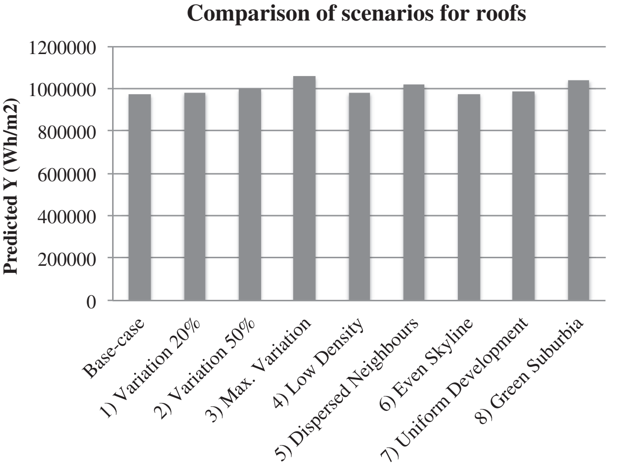

Fig. 7. Comparison of the results of scenarios for optimising solar irradiation of roofs (where: Y = predicted solar irradiation in Wh/m^2).

Table 7
Order of priority for the modification of variables to optimise the overall solar REP of neighbourhoods

Variables in order of priority	
1	All variables in the *Roof-SolREP* model
2	Variables in 'Green Suburbia' scenario
3	Average distance between buildings
4	Plot ratio
5	Standard deviation of building heights
6	Average building perimeter
7	Share of area covered by private gardens
8	Share of semi-detached houses
9	All variables in the *Façade-SolREP* model
10	Variables in 'Dispersed Low Density' scenario
11	Site coverage
12	Average building height

between these two variables can arise. This is because reducing building height can lead to an increase in average building perimeter and vice-versa.

b) The next priority would be to modify combinations of variables that are very effective together, such as scenario 8 for roofs: 'Green Suburbia'.

c) The variable of average distance between buildings has the largest impact on Y and is included in both models. Hence it should be the most important single variable to maximise.

d) When trying to modify the rest of the variables in the *Façade-SolREP* model, combinations of variables such as scenario 5: 'Dispersed Low Density' should be prioritised over the modification of single variables.

e) Finally, there might be a conflict between the average building height and site coverage. The aim in the model for façades would be to reduce both variables. However, this is not possible with the boundary conditions mentioned earlier, since decreasing one will inevitably lead to increasing the other. In this case a trade-off has to be considered. Even though the average building height has a larger impact than site coverage on the results of the *Façade-SolREP* model, the priority should be given to reducing the site coverage because it is complementary to increasing the average distance between buildings.

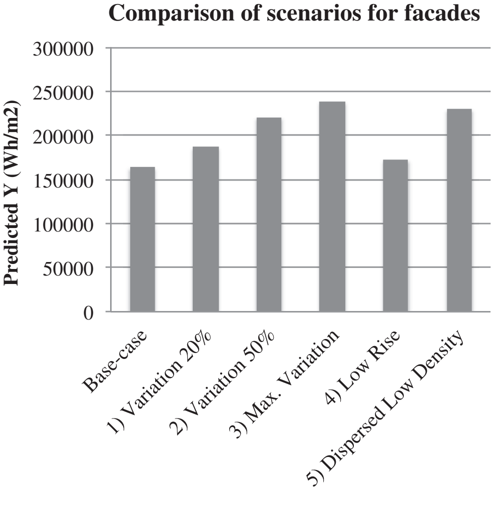

Fig. 8. Comparison of the results of scenarios for optimising solar irradiation of façades (where: Y = predicted solar irradiation in Wh/m^2).

5.2. Limitations and further research

Although the primary objectives of this study are theoretical, aiming at exploring and quantifying the relationships between urban form and solar REP, it is acknowledged that the models developed and the findings obtained might have some further applicability in the fields of urban planning and design. Due to the top-down, large-scale nature of this study, it is assumed that the applicability of the models developed will lay in the early stages of the design process, as an effective diagnosis tool to test whether the parameters of urban form utilised can be modified to improve solar REP. Moreover, the findings presented here could be used to inform planning policy and briefs of urban design to help maximise the solar potential of new and existing developments.

However, a limitation to be considered is that the recommendations presented here are purely intended to increasing the solar irradiation of building envelopes, rather than as a holistic strategy for increasing energy efficiency of neighbourhoods. For that, many other variables need to be considered, such as a wider mix of technologies for energy generation and the energy demand of buildings and transportation. Finally, it is worth noting that although the idea of testing the applicability of the models and findings in realistic design scenarios or case studies is beyond the scope of this analysis, this is one of the immediate next steps that should be taken in future research in order to further test the usefulness of these findings.

6. Conclusions

The study presented here demonstrated the applicability of research carried out to investigate the relationships between urban morphology and the solar renewable energy potential (REP) of neighbourhoods in London, UK. Using statistical models developed to predict the solar irradiation of roofs and façades, a total of 13 scenarios for the optimisation of solar REP were tested. Results show that by introducing changes in aggregated descriptors of urban form, the solar irradiation of roofs could be increased by around 9%, while that of façades could grow by up to 45%. Furthermore, possible strategies for the applicability of the findings were presented, where some variable combinations are prioritised over others in order to increase the overall solar REP performance of neighbourhoods.

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