A STUDY OF THE INFLUENCE OF HOUSING UNIT FORM AND DENSITY ON SOLAR POTENTIAL

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Synopsis

The paper presents a study of solar potential of different shapes of single family housing units, and of the response of some configurations of assemblages of such units in a neighbourhood pattern. Both the shapes of individual units and the compactness of their assemblage are crucial for the design of affordable energy efficient housings. Seven shapes are studied as well as some variations of L shape. The results show that irregular building shapes obtained by rotation of some facades can present several advantages. Judicious manipulation of unit shapes and their positioning on a given site can lead to optimization of solar radiation and its time distribution over the assemblage. This may provide better potential for solar electricity generation through building integrated photovoltaics that completely cover near-equatorial facing roofs, as well as passive solar gains through optimally located window areas.

1. Introduction

Affordable energy efficient housing development relies on building design, site planning and the interaction between them. Building shape plays a key role in governing energy consumption in buildings [1] and can provide advantages in capturing of solar energy. Land use and infrastructure have significant impact on energy per capita associated with the development and maintenance of this infrastructure [2]. Compact development enables efficient low cost public transport, offsetting part of the housing costs. On the other hand, high density may reduce the accessibility of building to solar radiation [2] and consequently its solar energy utilization potential.

The current paper investigates the effects of various design parameters of single-family housing units on radiation incident on equatorial –facing façades and radiation transmitted by the fenestration of these façades, on the one hand, and on electricity generating potential of PV systems integrated in the roofs of these units, on the other hand. These design parameters include: the shape and orientation of individual units; the orientation of surfaces within a unit, the modes of joining units (e.g. in triplex, quadruplex, and row configurations) and of the housing density of the site.

2. Approach

The study is divided into two main parts. The first part provides a comparison of solar irradiation that strikes different housing unit shapes. Seven plan layouts of housing units - square, rectangle, trapezoid, L shape, U shape, H shape and T shape, are considered in this study (Fig.1). The units are designed as two-storey single family houses in a northern climate (Montreal, Canada – latitude 45 N).

Variations of some parameters governing certain shapes are explored to identify design possibilities that enhance solar radiation capture potential on near-south facing roofs and facades. The rectangle, with aspect ratio of 1.3 is generally considered as an optimal shape for passive solar design for the given climate [3], and is therefore adopted as a reference case for assessing shape effects on irradiation. These shapes are illustrated in Figures1a.

In the second part of the study several combinations of groups of three and four units of a given shape are studied. The solar irradiation of each unit in a group is then compared to the reference unit, thus indicating the effect of increased density. Comparison of this effect among groups then provides information on the influence of shape and orientation on solar irradiation.

2.1 Plan designs

The basic design of plans relies on passive solar design principles [4] and rules of thumb [5]. The design ensures that the overall east-west dimension of the house – the solar façade, is larger than the perpendicular dimension (north-south), to maximize passive solar gains in winter. For non-convex shapes, an additional parameter should be taken into consideration. This parameter is the ratio of the shading to shaded façade widths, termed the depth ratio – a/b, in Figure 1. The shaded façade width and the depth ratio are determined so as to maintain a functional interior space.

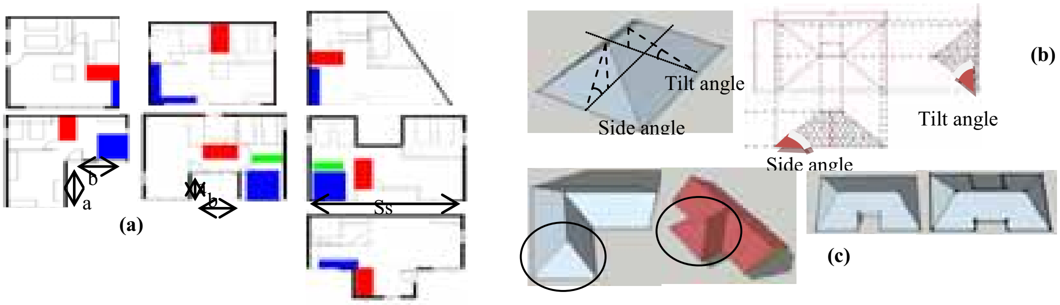

Figure 1 (a), Ground floor plan layouts of basic shape, b) Single ridge roof designs; c) Double ridge designs in L, T, U and H shapes.

2.2 Facades and Windows

The ceiling height of the ground floor is set at 3 m to enhance daylight penetration [6]. Double pane, low-emissivity argon filled windows are selected. All windows are composed of units having an area of about 2 m^2. The area of south-facing ground floor windows, consisting of three units, is 10% of the floor area of the ground floor. Due to the different areas of south facing façades of different shapes, the south window constitutes different percentage of these facades.

For non-convex shapes, except for T shape, a single window unit (2 m^2), corresponding to a third of the total south window area is located on the shaded façade. The dimensions of the T shape allow a single window unit to be fitted on each of the 3 south facades.

2.3 Roofs

The basic roof design in this study is a hip roof (Fig. 1b) with tilt and side angles of 45º. The roofs of all shapes, except L and T shapes are designed with their ridge running east-west at the centre of the plan area, with recesses cut out where appropriate (U and H shapes) –Fig 1c. In the case of L and T shapes the ridge of each wing runs along its centre, with a triangular south facing hip at the south end, and the north wing roof ends with gables (Fig. 2b). The total area of near south facing roof is used to integrate the photovoltaic system. This includes the triangular portions of hip roofs in L and T shapes.

An additional roof, used as reference case for comparative evaluation of the electricity generation potential by the south facing building integrated photovoltaic (BIPV) systems of all other roofs, is a gable roof with 45º tilt angle covering the rectangular shape of aspect ratio of 1.3 (Fig. 1). This roof is termed "optimal" in what follows.

3. Parametric Investigation

3.1 Shape parameters

The study investigates the effects of a number of parameters on two major response variables –solar radiation incident on near-south facing facades, solar radiation transmitted by ground floor windows in these facades and PV electricity production potential.

The parameters whose effects on the response variable are investigated include, in addition to the basic shapes, several variations to the geometry of the L shape. Shape variations include varying values of the depth ratios – a/b and variations to the angle enclosed by the wings of the layout. Two values of the depth ratio, in addition to the basic value of 1, are 1/2 and 3/2. In the design of units with varying depth ratios, the floor area is kept constant (around $60m^2$), while maintaining the total width of the south facade (as far as possible) and the functionality of the interior partitions.

Variations to the angles between the wings of L shape consist of changing the magnitude of the angles β – rotation of the southern wing, and θ – rotation of the northern wing; β and θ take three values each, 15º, 30º and 45 º (Figure 2).

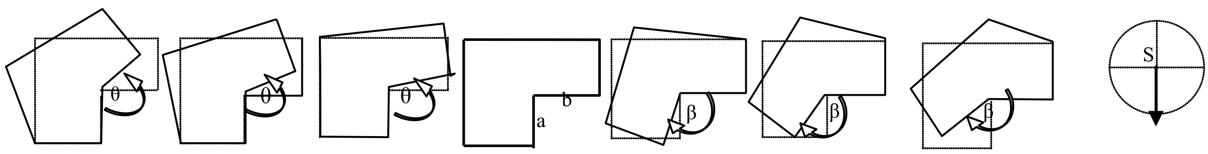

Figure 2, Shape variations in L units.

3.2. Site parameters

Site parameters consist of unit shape, unit density and site layout. In this presentation only L shape and some variations of this shape are included. A depth ratio of ½ is adopted for L shape. Two magnitudes of the angles θ and β are adopted – 30º and 60º. Two types of density effects are analysed. Spacing effect is assessed by comparing attached units in triplex or quadruplex with detached units. The effect of obstructing the south facades of the selected assemblage of units by a row of similar housing configurations is assessed by what is termed hereunder as row analysis. Three distances between rows are studied: 5m, 10 m and 20m.

Two site layouts are presented in this paper. The first site is characterized by a straight road (Fig.3 (I, a) and (I, b)). The other layout incorporates a semi -circular road ((Fig.3 (II, a) and (II, b)). The units are positioned with respect to the shape of the roads, in the two sites. The circular road is selected to represent an extreme case of curved road. Only two configurations are presented in this paper for each site (see Fig. 3). In the row study, assemblages of attached and detached L variation (β=30 º), are analyzed.

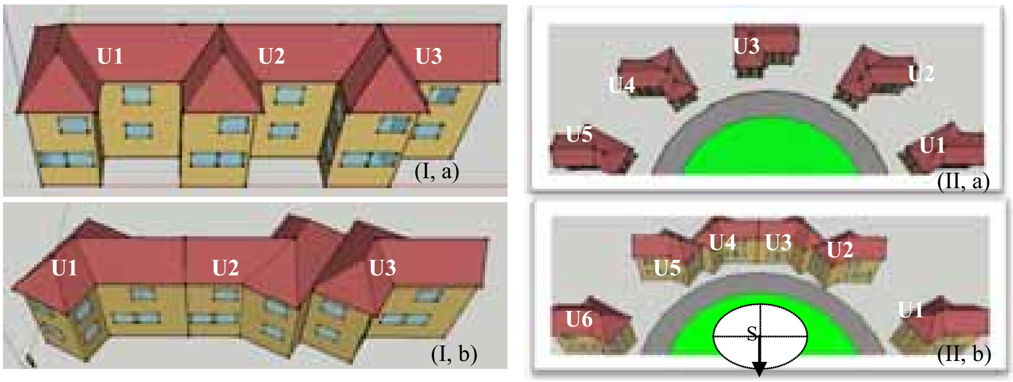

Figure 3, configurations of site I and site II, (I, a) attached L shape, (I, b) attached L variation, (II, a), detached L variations, (II, b) attached L variations

3.3. Simulation modelling

Montreal, Canada (45º N Latitude) is adopted as the pilot location for this study. Two design days, a sunny and cold winter day (in January), and a sunny and warm summer design day (in July) are used to represent two extreme sunny days, to study the incident solar radiation on the facades and roofs of all configurations. Additionally, a whole year weather data set is used to estimate the annual electricity production of the building-integrated photovoltaic system, designed to cover the total area of near south-facing roof surfaces. The weather files of the building simulation program EnergyPlus are used for the simulations [7]. The hourly direct solar radiation is computed using Energy Plus. The computation is based on the ASHRAE solar radiation model of [8] and accounts for the shadow cast on surfaces. The shading algorithm accounts for self-shading geometries, such as L shape. ASHRAE model yields values that are representative of conditions on cloudless days for a relatively dry and clear atmosphere. The clearness numbers are usually used as correction factors to apply this model to locations with clear, dry skies or locations with hazy and humid conditions [8].

A simple model of roof-integrated PV system with constant electrical conversion efficiency of 12% is employed throughout the study. Shading of the PV array by other surfaces, in non-convex shapes, is considered in the computation.

4. Simulations and Results

4.1. Shape study

Solar radiation

The results of the first stage highlight the significance of the building shape on solar radiation, due to the effect of mutual shading of facades. The Total radiation is compared to the radiation of the rectangular shape, which serves as reference. The H shape has the largest south-facing façade, possessing an area that is 25% larger than that of the rectangle shape, resulting in 19% increase in solar radiation incident on this facade. Depending on the depth of the shadow receiving facade and the number of shadow projecting facades, solar radiation can significantly decrease (up to 50%, for a U shape).

Following are the main observations of the effect of the depth ratio and L shape variations:

• The radiation incident on the shaded south facade of L shape is reduced by 12%, 22 %and 26%, as compared to the radiation on the exposed south facade, for depth ratio values of 1/2, 1 and 3/2, respectively.

• The reduction in transmitted radiation by the window of the shadow receiving south façade, compared to that of the non shaded window, is 3%, 27% and 34 % for a/b values of 1/2, 1 and 3/2 , respectively.

• The transmitted radiation by the shaded facade window decreases with increasing values of the angle θ. Increasing the angle β reduces the transmitted radiation by the exposed facade window while increasing that of the shaded facade window (Fig 4).

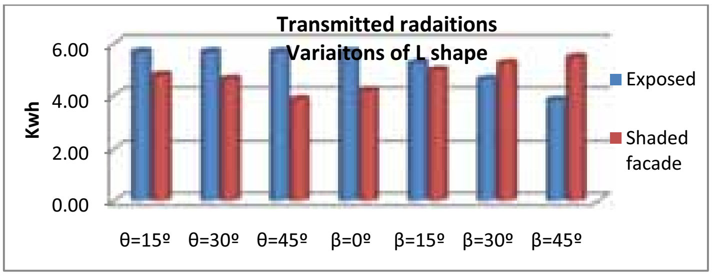

Figure 4, radiation transmitted by the shaded and exposed facades of L variations

Electricity generation

The rectangular layout with gable roof has a total south facing area of around 40 m^2, a peak electricity generation for the winter design day of 4.32 kW and annual generation of 8000 kWh. The results of comparison of the electricity generation of all considered roofs to the optimum roof indicate that the square shape has the lowest generation ratio (0.53). The roofs of the rectangle and of L shape have comparable ratios (0.62 and 0.63 respectively). Figure 5 illustrate the peak electricity generation for the design days and the annual generation, for the considered roof design.

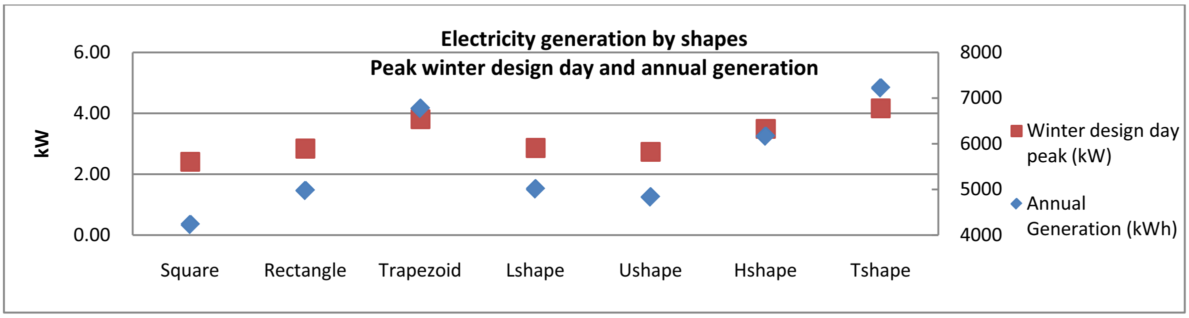

Figure 5 Electricity generation of shapes, peak for winter design day (kW) and annual generations (kWh)

The electricity generation of the basic L shape (with depth ratio =1) is reduced by a maximum of 6% per unit area, on a winter design day, in comparison with the electricity generated by a unit area of a non-shaded south facing roof. The annual electricity generation unit area indicates that the maximum difference between different depth ratios is 4% or less for L shape.

The peak electricity generation for all shapes, both for the south-facing roof and the hip for L shape are presented in Figure 6 together with the annual electricity generation. The normalized data of the total annual electricity generation indicate that the highest electricity generation per m^2 is registered when the angle β or θ are at 15°, reaching about 2% higher than the electricity generation of the basic shape, where β and θ =0°. The total generating potential increases with β and θ due to increased exposed area.

This increase reaches 54% for β =45º, and around 48% for θ=45º as compared to the basic L shape – Fig 6.

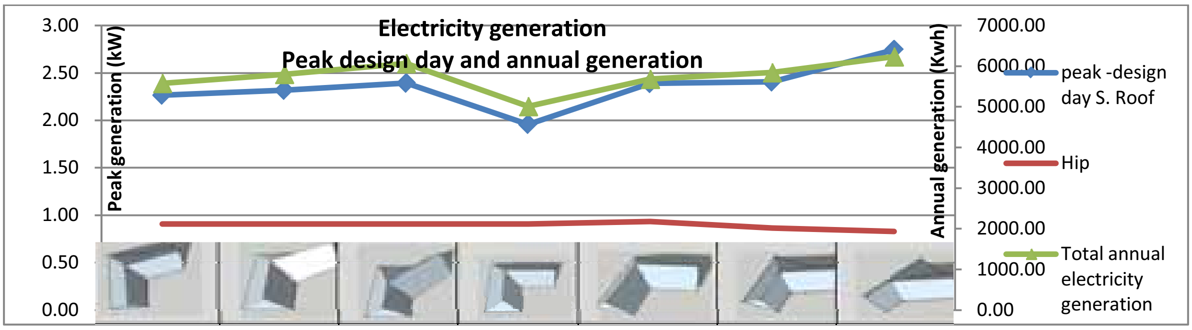

Figure 6 Electricity generations of L shape variations, peak for winter design day and annual generations

The hourly electricity generation during the winter design day indicates that the different variations allow reaching the peak at different times. The peak generation is reached in earlier hours with the variation of the angle θ (rotation of the north wing), while the opposite occurs when the angle β is changed. The implementation of these results is discussed in the next section.

4.2. Site study

Solar radiation

The results of solar radiation incident on the facades of the units for all configurations, in site I and site II (Fig.3), and for the row study are compared to the results of the isolated shape of each configuration. The isolated unit of each configuration serves as reference for this specific configuration. The main results are summarized in the following:

- Using L shape and variation of L shape in assemblage of attached units, as shown in the configurations of site I (Fig.3, (I, a) and (I, b)), has no significant effect on the solar radiation incident on the near south-facing facades and transmitted by the fenestrations of these facades. The maximum reduction of transmitted radiation due the shadow casted by adjacent units is about 4%, as compared to the reference unit of each configuration (i.e. L shape and L shape variation with β =30º) .
- In the detached configuration of site II (Fig. 3(II, a)), the transmitted radiation by the south facing windows of the shaded façade of some units is reduced by up to 33% , in comparison to the isolated L shape variation with β =30º, on the winter design day. This is due to the shadow casted by adjoining units. The transmitted radiation on the exposed south facades of the rotated wing (with β or θ =30º) is about 22 % of the radiation transmitted by the reference unit. For β or θ =60º, the transmitted radiation is reduced by around 50%.
- In configuration (II, b) the transmitted radiation by the shaded south facing windows is reduced by a maximum of 25% in comparison with the 33% in detached configuration, highlighted above. This is due to absence of mutual shading.
- The row study of detached and attached L shape units with β = 30 º (Configuration (I, b) in Fig. 3) shows that obstructing the south facades by a row of units has a highly significant effect on the radiation incident and transmitted by the fenestration of the facades (Figs. 7a and 7b). The results presented in Figures 7a and 7b are associated with three units (U1, U2 and U3) as shown in the example of Figure 3 (I, b) (but for the obstructed row). At 5m row distance the transmitted radiation is reduced by up to 95 % for some units. The triplex configuration is more affected by the south obstructing row of units than the configuration with three detached units.

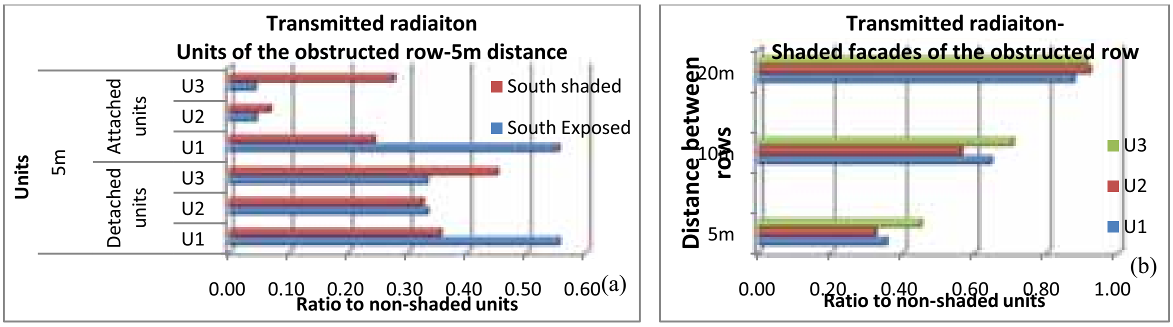

Figure 7, reduction of transmitted radiation associated with each unit, (a) by the south facades of the two configurations at 5m distance, (b) by the shaded facade of the detached configuration

Electricity generation

The results indicate that, in general, there is no significant effect of the density of the studied units, whether these units are placed in rows or assembled in triplex or quadruplex, on the electricity generation of the BIPV of the near south- facing roof. Following are the main observations:

- Maximum reduction of 5% of electricity generation is recorded due to the shadow cast by adjoining units, in configurations a and b of site I (Fig 3).
- The row density, even at 5m distance between units, does not have significant effect on the electricity generation (around 5%).
- A significant shift of the profile of the electricity generation is obtained by the BIPV of different units. The difference in timing of peak electricity is due, in the present study, to the rotation of the south wing of L shape. A difference of peak time of up to 6 hours is observed in the configurations of site II. The graphs of Figure 8 show the effect of different configurations on the electricity generation profile of the south wing of different units.

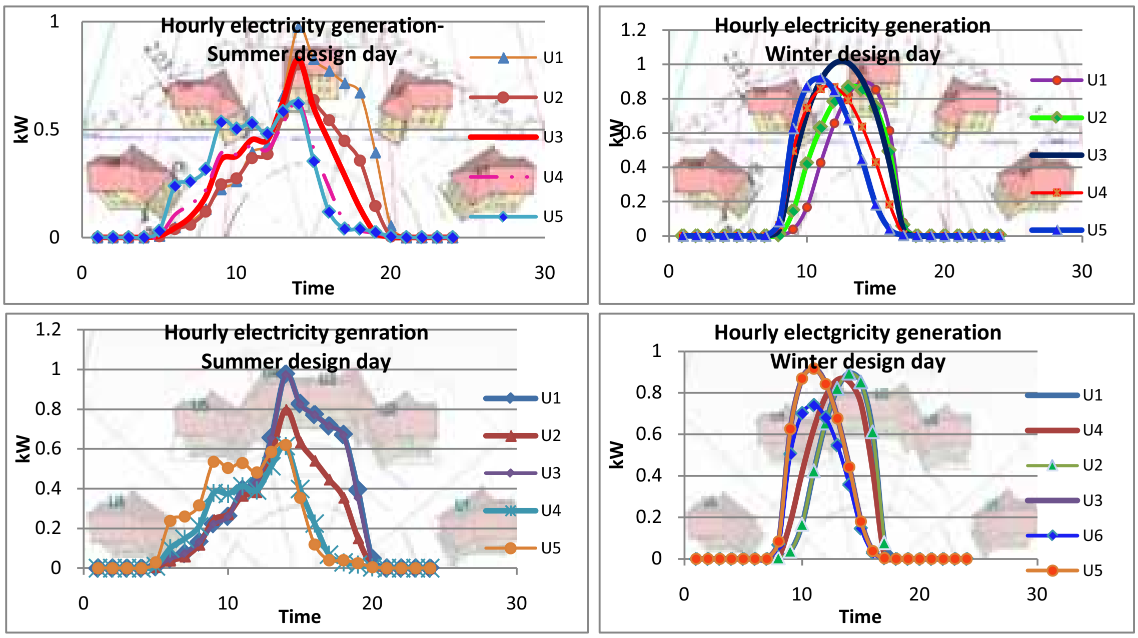

Figure 8, South wing hourly electricity generation by configurations of site II, (a) (II, a) summer design day; (b) (II, b) winter design day; (c) (II, b) winter design day, (d) (II, b) summer design day.

Conclusion

This study investigates the potential of various geometric shapes of housing units to capture solar energy from near-south facing facades and roofs, for conversion to electricity, heat or transmission as daylight. The effect of site layout and density of units on this potential is explored as well.

The results indicate that several parameters should be considered in the optimization of shapes for passive solar design. In rectangular layout, the aspect ratio of the south facing façade to lateral façade width is of primary significance. Non- convex shapes offer a wider flexibility in architectural as well as solar design, but due to their complexity their efficient design is influenced by several parameters. For instance, the solar radiation is significantly affected by the depth ratio (the ratio of shading to shaded façade length). Shape effects, such as shading can be controlled and manipulated by variations of the basic geometry. Increasing the angle enclosed between shading and shaded wings, the shading effect can be mitigated.

The radiation on the tilted roof and therefore the electricity generation per unit area by the BIPV system of the basic L shape (depth ratio of 1) is reduced by 6% in comparison with the reference case. The difference of electricity generation between L shapes with depth ratio of 1 and ½ is about 3%. The rotation of a part of the roof, as studied in L shape variations, can be advantageous in shifting the timing of peak generation. A difference as large as six hours of peak generation of different units can be achieved by the implementation of these variations in a specific site layout. Shift of peak solar radiation at different hours can result in a more even electricity generation profile, thus imposing less demand on the electric grid. Shifting peak generation time towards peak demand time can lower net energy cost and also reduce net peak demand from the grid.

The site study shows that the electricity generation is not significantly affected by assembling the units in triplex or quadruplex layouts. Mutual shading by rows of units has little effect on electricity production (maximum of 7% reduction). However the row configuration has a highly significant effect on the near south facing facades, reducing transmitted solar radiation by as much as 95%.

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