Solar Optimized Neighbourhood Patterns: Evaluation and Guidelines

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Abstract

The current study presents key findings and recommendations related to the solar potential of building integrated photovoltaic (BIPV) and energy demand of two-storey single family housing unit assemblages, located in Montreal, Canada (45ºN). The design parameters studied include geometric shapes of individual units, density of units and site layouts. Shapes include rectangular and L shapes of varying geometry. Density effect is analyzed through different assemblages of detached and attached housing units, as well as of parallel rows of units. Site layouts include a straight road and semi-circular road patterns, with the curve facing south or north.

The analysis employs the EnergyPlus simulation package to simulate configurations consisting of combinations of values of parameters in order to assess the effects of these parameters on the electricity production potential of BIPV systems covering complete near south facing roof surfaces, as well as heating and cooling demand of individual units and neighbourhoods. Effects are evaluated as the change of the energy generation and energy demand, relative to reference configurations. The reference shape is a rectangle, the reference density is detached units and the reference layout is a straight road. Preliminary guidelines for the design of solar optimized neighbourhoods are proposed, based on the effects of the design parameters studied.

1 Introduction

Building shape and spatial characteristics of neighbourhoods can affect solar potential and energy demand of buildings. Geometry of a building and the urban context in which it is situated influence directly its accessibility to solar radiation (Hachem et al, 2011a and 2011b). Solar energy can be exploited passively for heating and daylighting, or actively to generate electricity and provide domestic hot water by means of solar collectors.

Extensive research has been conducted to determine the effects of various parameters on solar access and energy performance of urban areas. These studies are mostly concerned with existing urban areas and therefore are limited in their ability to generalize findings. Some studies employ simplified urban archetypes that can be parameterized, but these run the risk of not representing realistic urban designs. The most frequently assessed archetypes are pavilions (Morello et al., 2009), including shape variations for high-rise buildings (Leung and Steemers, 2009), courtyard configurations (Kämpf and Robinson, 2010), row houses (Jabareen; 2006) and urban street canyons (Ali-Toudert, 2009). Some tools have been and are being developed for specific tasks. One tool is employed in interactive design of street layouts to obtain feedback on energy impact (Christensen and Horowitz, 2008). Another tool can be used to estimate the on-site energy consumption for heating, cooling and lighting for whole districts. (Perez et al. 2011)

A review of the existing literature indicates a lack of systematic design approach for passive solar design, especially at the level of the neighbourhood. Such approach should define the primary parameters in the design of solar optimized neighbourhoods, ranging from the building level to the neighbourhood level, and present a methodology of application of such parameters in the design process.

The focus of this presentation is a summary of the effects of the main design parameters on energy generation and on energy demand. Energy generation is by means of photovoltaic systems integrated in the south and near south facing roof surfaces. Energy demand that is influenced by the design parameters includes heating and cooling of housing units in neighbourhoods. The study presents preliminary guidelines for the design of neighbourhoods for optimized solar potential.

2 Approach

Analysis and results presented in this paper are based on extensive study of some 77 configurations of neighbourhood patterns, and multiple additional scenarios designed to identify the effect of single independent design parameters, that are decoupled from others (e.g orientation, various effects of shape parameters, etc.). The effects of the design parameters are assessed through simulations employing the EnergyPlus software (EnergyPlus, 2010), in conjunction with *Google Scketchup* (to generate geometric data). The weather data for Montreal, Canada (45°N) is employed to represent a northern mid-latitude climate zone.

Neighbourhood characteristics take into account common municipal regulations that determine practical issues, such as minimum distances between detached units and road width. Detailed information about the design and analysis of these patterns can be found in Hachem et al. (2011b). The neighbourhood patterns are characterized by the shapes of housing units, their density and the road layout. The housing units are designed to be highly energy efficient. The main thermal characteristics of these units are presented in Table 1. A geothermal heat pump with a coefficient of performance (COP) of 4 is assumed to supplement the passive and active solar heating. Building integrated photovoltaic systems (BIPV) are assumed to cover the total area of south and near south facing roof surfaces (See Figure 2).

Table 1: Thermal characteristics of housing units

Thermal resistance values:	Exterior wall: 6 RSI Roof: 10 RSI Slab on grade: 1.2 RSI
Thermal mass	20cm concrete slab on ground.
Window type	Triple glazed, low-e, argon filled (SHGC=0.57), 1.08 RSI
Shading Strategy	Interior blind
Occupants	2 adults and 2 children, occupied from 17:00 - 8:00
Set point temperatures	Heating set point 21°, cooling set point 25ºC
Air infiltration rate	0.8ACH @50Pa

The methodology adopted in this paper consists of first presenting each of the design parameters, and then summarizing the effects of these parameters on energy generation by the BIPV systems and on energy consumption for heating and cooling. Energy demand calculations are based on an assumed energy conscious behaviour of occupants (Brandemuehl and Field, 2011).

3 Design Parameters and their Effects

Individual Units

Shape

Two-storey housing option is adopted in this study. 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. The total floor area of the two floors is 120 m^2. South facing window constitute 35 % of the south façade surface.

Rectangular and L shapes are selected in this study because they can be considered as the basic shapes for passive solar design. Other shapes can be derived from combination / variation of these shapes. An important parameter characterizing non-convex shapes such as L shapes, is the relative dimensions of the shading and shaded facades. The ratio of the width of the shading façade (*a*, Fig.1) to that of shaded façade (*b*, Fig.1) is termed the depth ratio – *a/b*, in Figure1. The shaded façade's width and the depth ratio are determined so as to maintain a functional interior space. A depth ratio of ½ is adopted throughout this study. This ratio is selected in order to minimize the shade cast on the main wing (Hachem et al, 2011a). The rectangular shape has an aspect ratio (ratio of south façade to lateral façade width) of 1.3. This ratio is within the optimal range for passive solar design in northern climate (Athienitis and Santamouris, 2002).

Variations of L shape are explored to identify design possibilities that enhance solar radiation capture potential on near-south facing roofs and facades. L variants are characterized by the angle β– the deviation from 90° of the angle enclosed by the wings of the L shape (Fig.1). L variants are denoted by the letter V. The branch of an L or V shape can be attached at either the west end – W configuration, or at the east end – E configuration. It can also be facing south (S) or north (N). Thus the configuration L-WS, for instance, denotes L shape with the branch attached to the west end of the main wing towards the south (Fig.1). In L variants the value of the angle β is added to the notation – e.g. V-WS60 denotes a variant of the L-WS with $\beta=60^o$. An additional shape, termed hereunder Obtuse-angle (O) is an L variant with β =70°. This shape is particularly suitable for sites with curved road.

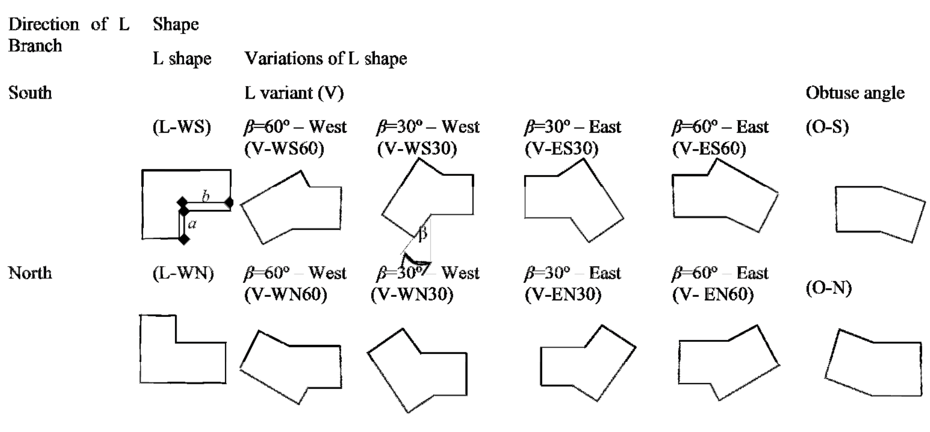


Figure 1: Characteristics and identification of L shapes

Roof design

The basic roof design assumed in this study is a hip roof with tilt and side angles of 45°. Roofs with tilt and side angle variations are studied in Hachem et al. (2011a). The height of the lowest edge of the roof is kept constant at 7m above ground level. In L shape and its variants the ridge of each wing runs along its centre, with a triangular hip at the end of the branch and a gable at the free end of the main wing. Both wings of the obtuse-angle roof end with hips (Fig. 2).

A photovoltaic system is assumed to cover the total area of all south and near-south facing roof surfaces. These surfaces include the triangular portions of hip roofs of L shape and its variants, and the two near south facing surfaces in obtuse-angle roofs. A BIPV system covering a complete roof surface may also be designed to act as the roof weather barrier in addition to producing electricity. Figure 2 illustrates the integration of the PV systems in south and near south facing roof surfaces, in shapes featuring in this study.

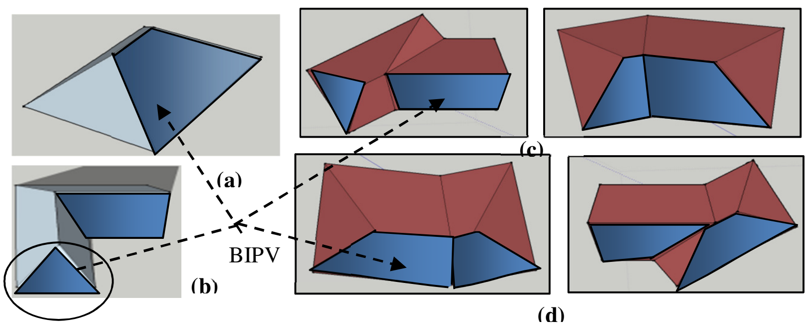


Figure 2: Roof shapes and PV integration. PV integrated surfaces are shown blue. a)Rectangle b)L-shape c)Roofs of V-WS60- variant and obtuse-angle O-S in site II – Fig. 9; d) Corresponding shapes in site III (Fig. 9): V-EN60 and O-N

Design parameters of individual units

The parameters studied in this section are the shape parameters, rectangular and L shape, and the effect of rotation of the wing of L shape. The effect of orientation from due south on the energy generation and energy performance of the rectangular shape is first studied, to decouple this parameter from all other effects in the neighbourhood design. The angle of orientation varies from 0° (due south) to 60° east or west of south.

Main effects

Orientation

Deviation of the orientation of the rectangular housing unit from the south by up to 45° west or east leads to an approximate reduction of 5% of the annual generation of electricity, as compared to a south facing BIPV system. A rotation of the system by 60°, west or east of south, results in a reduction of some 12% of the total annual electricity generation (Hachem et al, 2011c).

The annual heating and cooling loads increase with increased angles of rotation. Heating load is increased by up to 30% with a rotation angle of 60° east or west from south, as compared to the south facing rectangular shape.

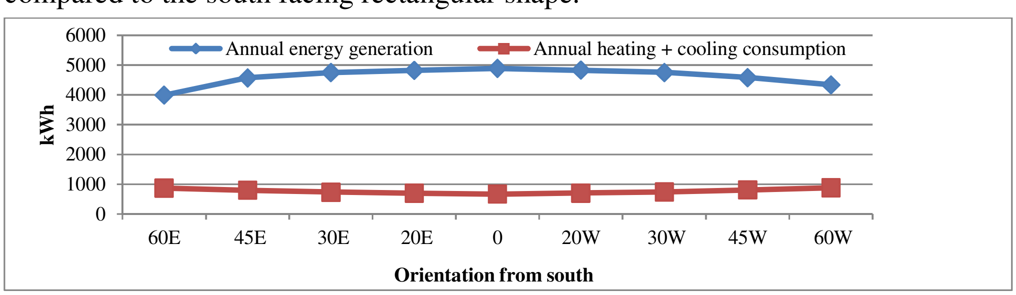


Figure 3: Annual energy generation and cumulative energy demand for heating and cooling of rectangular housing unit, assuming the use of a heat pump

Shape

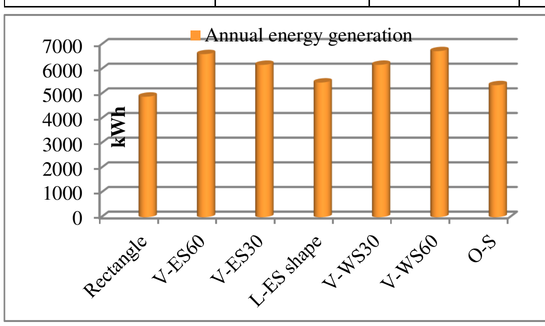
Electricity generation

The two main effects of L and L variant shapes on electricity generation, as compared to the rectangle, are an increase in electricity generation due to the increase in the south facing roof surface area of L variants and a shift of peak generation by different roof surfaces. The increase in annual energy generation of L variants can reach 50%, relative to the reference case (rectangle). A maximum shift of peak generation time by 3 hours is obtained by the BIPV system of L variants with 60° wing rotation. A spread of peak generation of up to 6 hours (associated with an orientation of 60°-70 ° to the west and to the east) can be achieved among different variants of the L shape. Time spread of peak electricity generation among housing units can result in a more even electricity generation profile, thus imposing less demand on the electric grid. This can be economically beneficial, especially in regions where the cost and price of electricity vary with time of day.

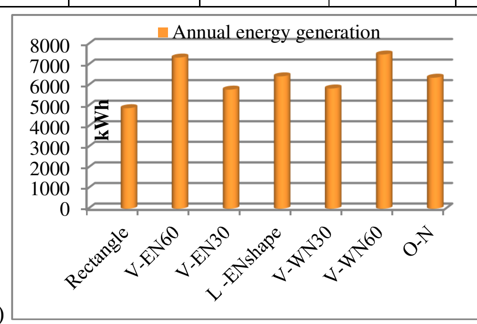
The comparison of energy generation of all unit shapes to the reference case is presented in Table 2. Annual energy generation of all unit shapes is presented in Figure 4.

Table 2: Comparison of annual electricity generation of all housing units to the reference case.

	Rectangle	V-ES60	V-ES30	L-ES	V-WS30	V-WS60	O-S
Comparison to reference	1	1.35	1.26	1.21	1.26	1.38	1.10
		V-EN60	V-EN30	L-EN	V-WN30	V-WN60	O-N
		1.50	1.18	1.32	1.18	1.53	1.30



(a)



(b)

Figure 4, Annual energy production (kWh) of selected L variants (a) South facing branch (V-ES and V-WS), (b) North facing branch (V-EN and V-WN)

L shape and L variations have the additional advantage of increased daylight utilization, an aspect not studied in detail in this paper, but which requires further investigation.

Energy demand

L shape, L variant (V-W30) and obtuse angle shape require 7%, 6% and 2%, respectively, more heating energy than the reference case (rectangle). The cooling load of L variant exceeds that of the reference case by 19% and the obtuse angle and L shape by 8% and 4%, respectively, however, cooling load in northern climate constitutes a small percentage of heating load. Cooling and heating consumption of all Lvariants, is shown in Figure 5.

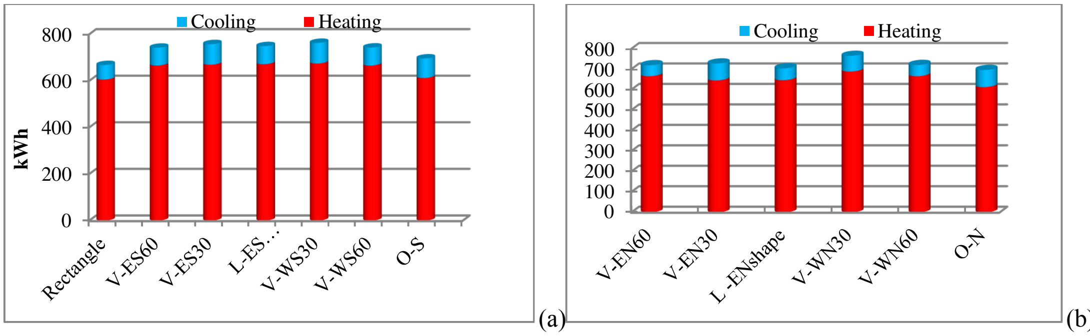


Figure 5: Annual heating and cooling of selected L and L variant shapes (a) South facing, (b) North facing

Neighbourhoods

Planar Obstruction Angle (POA) and distance between units

A major effect on solar potential of neighbourhoods is mutual shading by adjacent units. Two parameters define the relative position of the shaded and shading units: the angle of obstruction and the distance between the units.

Planar Obstruction Angle (POA) is a new concept introduced in this research representing the angle between the center of the south façade of the shaded unit and the closest corner of the shading unit (Fig. 6). Various POA values are studied, in addition to the effect of aligning the units, as shown in Figure 6. The second parameter is distance (*d*) from the center of the south façade of the shaded unit to the closest corner of the obstructing unit. Four values of *d* are investigated in the analysis: 20m, 15m 10m, and 5m. A distance of 5m is unlikely to be applied in practice but it is studied in order to assess the trend. The effects are studied for a single shading unit (Fig. 6a) and two shading units (Fig.6b).

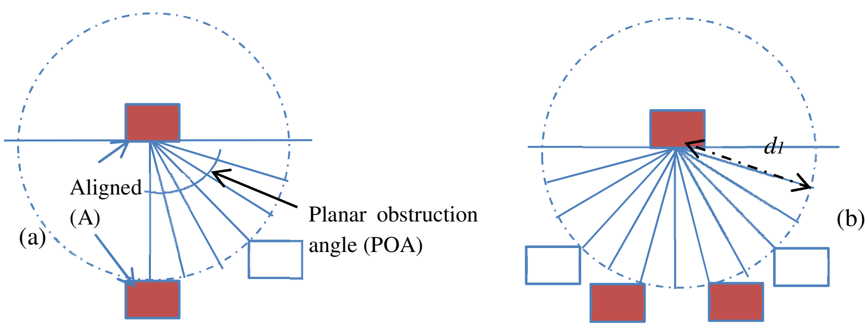


Figure 6: POA concept, shading and shaded units are represented by solid colour; shaded unit is in the centre of the circle; (a) single shading unit, (b) two shading units

Main effects

No Significant effect of POA and distance between units is observed on energy generation of the BIPV system. This is due to the fact that all units have the same height and there is no mutual shading of roofs.

For a distance larger than 10 m the effect of POA is small, when a single obstructing unit is considered. With a distance of 5m heating load increases significantly with decreasing POA. The heating load for a POA of 15° or less is some 35%, higher than the unobstructed unit. The results of the effect of POA and distance on the heating load, associated with one obstructing unit are presented in Figure 7.

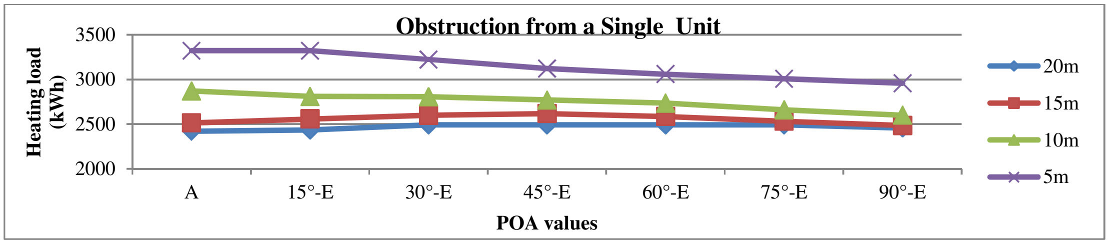


Figure 7: Effect of POA and distance between units on the heating load of a unit shaded by a single unit

For two shading units (Fig. 8) the increase in heating load can reach 70% for a POA of 15°, at a distance of 5m. For a distance of 15 m, the large increase is associated with a POA of 45° and it reaches 35%, as compared to the non-obstructed unit. The results of heating load as a function of POA values and the distance between units are presented in Figure 8.

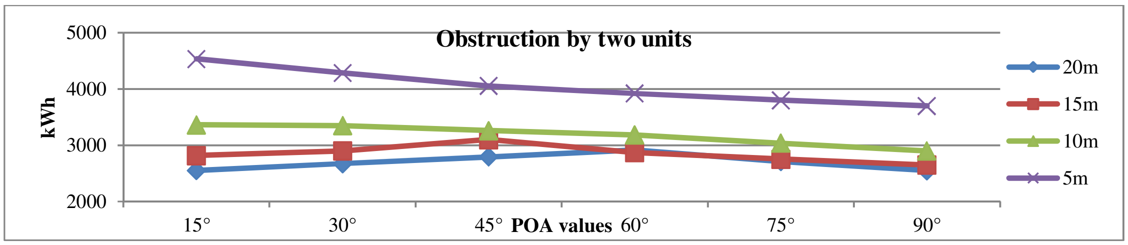


Figure 8: Effect of POA and distance between units on the heating load of a unit shaded by two units

Site layout

Three site layouts are studied, presented in Figure 9a, 9b and 9c. Site I is characterized by a straight road, running in the east-west direction. The other two layouts incorporate semi-circular roads. In site II the curved road is south facing (i.e. the center lies south of the arc), while in site III it is north facing. The circular road is selected to represent an extreme case of curved road design option. The housing units are positioned with respect to the shape of the roads in all sites.

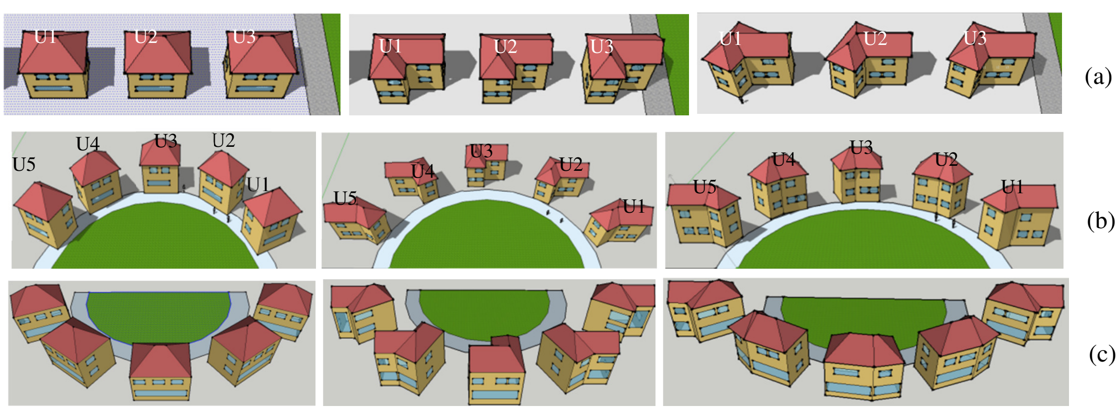


Figure 9: Configurations applied in each site, (a) site I, (b) site II, (c) site III

Main Effects

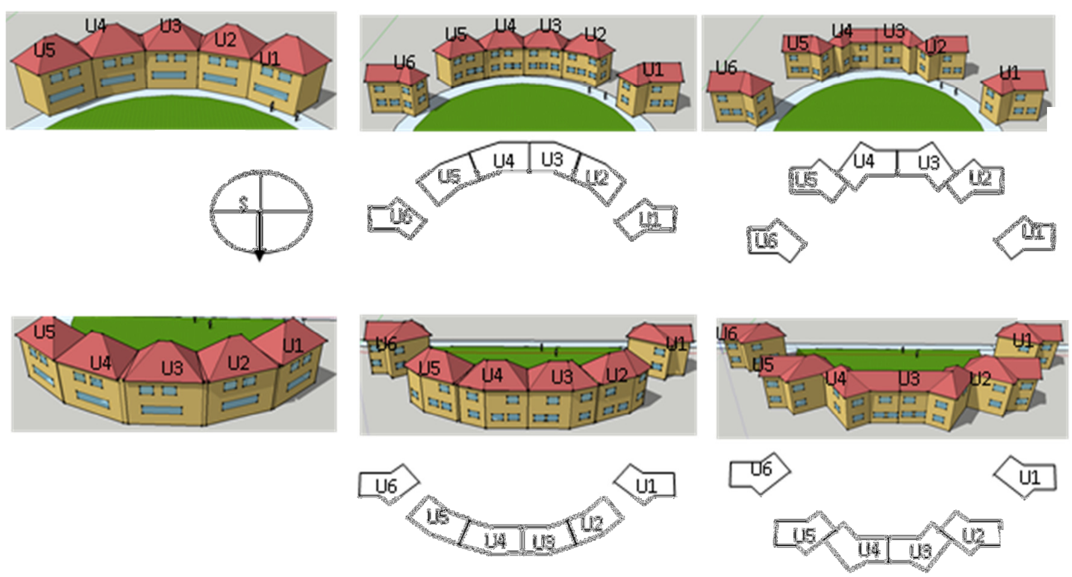
The results indicate that the site layout has no significant overall effect on the average electricity generation per unit area of roof surface. This is mainly due to the fact that, although the units were designed specially to conform to the shape of the road, the orientation of the units and of the roofs covered by the BIPV systems are kept within the optimal range.

Comparison of energy demand of housing units in neighborhoods to the corresponding isolated units indicates, on average, an increase in heating load and a decrease of cooling load. The increase in heating load reaches 12 % and 22% for the rectangular shape in site I and site II, respectively. L shape heating load increases by 15% in site II as compared to 12% in site I. One reason for this effect is the shade cast on the east and west facades, in all configurations, and partially on south facing facades in site II. In site III, the increase in heating load is not significant.

Density

Spacing

The density of a row of housing units is measured by the spacing between units (*s*). Three values of spacing are adopted for each site: *s1*, the basic spacing of detached units, is assumed as 4 m. In order to assess the influence of increased spacing on energy demand, a second spacing *s2*=2*s1* is adopted. The density achieved with the basic spacing is ca. 9 units per acre (u/a), while the s2 is around 5 u/a. The highest density (ca.16 u/a) is obtained by attaching units in triplex, quadruplex or pentuplex configurations, with *s0*=0 (Fig. 10)



(a)

(b)

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Figure 10: Attached configurations applied in sites II and III, (a) site II, (b) site III

Main Effects

No significant difference in electricity generation is observed between attached and detached configurations of a given shape. This is due to the fact that the design of the roof is kept constant through all the study, except for the attached rectangular shape. The rectangular shape is replaced by a trapezoid shape in the attached units of site II and III, to conform to the shape of the roads. This shape modification leads to a decrease of the average electricity generation of 10% in site II, as compared to the rectangular shape in site I, and to an increase of 10% in site III.

Energy demand for heating and cooling of attached units is lower than for the corresponding detached configurations. For instance, heating demand of the attached trapezoids and attached obtuse angle configurations in site II is reduced by 35% and 20% respectively, relative to the detached units. The average values of heating demand for units of each site, corresponding to the spacing values (attached A – *s0*, detached D – *s1*, and 2D – *s2*) are shown in Figure 11. For site I, only configurations of the rectangular shapes and of L variants are show in Figure 11, since obtuse angle is not studied for this site. Doubling the space between the units (from s1 to s2=2s1), does not affect significantly the heating demand. While cooling load increases with larger spacing between units, cooling energy is negligible as compared to heating (ca. 10%).

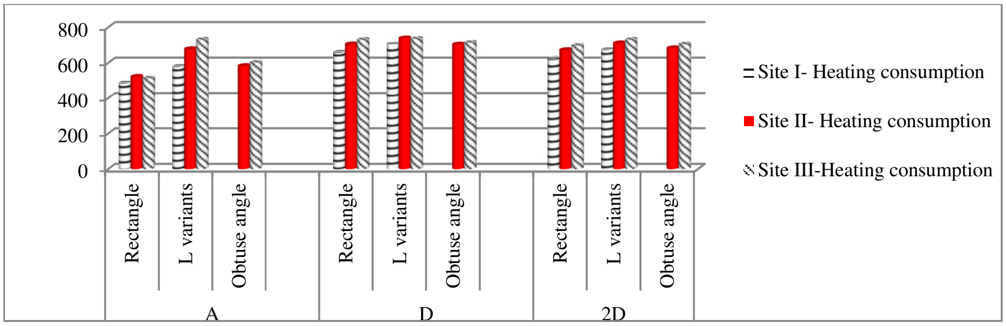


Figure 11: Heating consumption at different spacing between units in site II and site III

Row Configurations

In site I the effect of obstructing the south facades of selected configurations by a row of similar housing configurations is assessed by what is termed hereunder row effect. A maximum practical density of 35 u/a can be reached in the row configurations. Four values of row spacing (*r*) are simulated: 5m, 10 m, 15 m and 20m, corresponding to 20%, 40%, 60% and 80%, respectively, of the minimum spacing between rows to avoid shading (*x*). This minimum distance (*x*), can be estimated based on the shadow length equation (NRC-IRC, 2005):

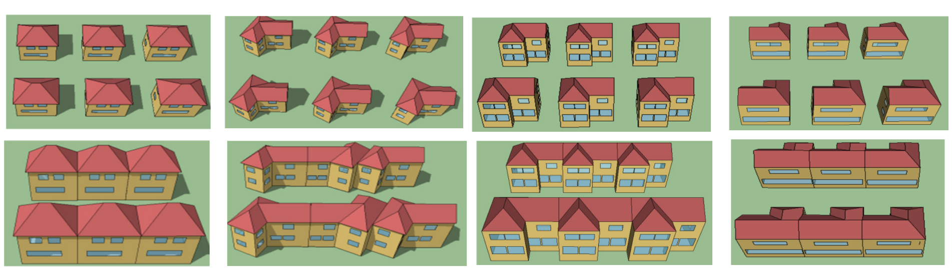
$$SL = \frac{\mathrm{H.cos}(\phi-\psi)}{\tan\alpha} - \frac{W}{2} \qquad \text{(eq. 1)}$$

where, *SL* is the shadow length, *H* is the total height of the shading building, ϕ is the solar azimuth, ψ is the azimuth of the surface, α is the solar altitude, *W* is the width of the shading building .

Using the shadow length equation for the 21st of December, associated with the lowest sun altitude at solar noon, the minimum spacing (*x*) to avoid row shading is ca. 25m.

The studied configurations are the detached and attached rectangular units, the detached and attached L units and the detached and attached configurations of L variant (V-WS30) (see Figure 12). Two configurations of L units are studied, with the branch facing south L-S and the branch facing north L-N.

It should be noted that 5m is unlikely to be employed when the south facing facade is the principal facade and its inclusion in the study is aimed at providing an extreme case in order to assess the trend.



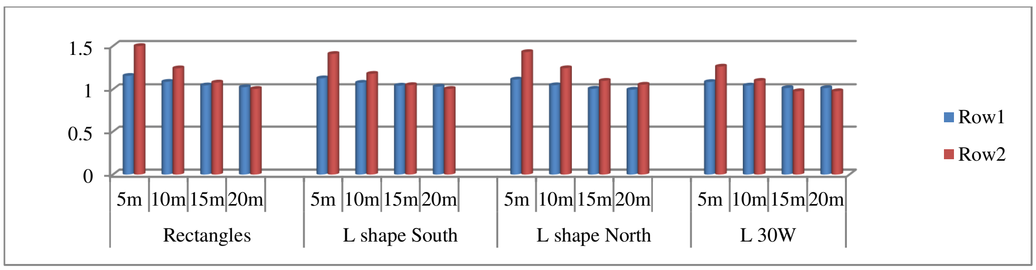
(a)

(b)

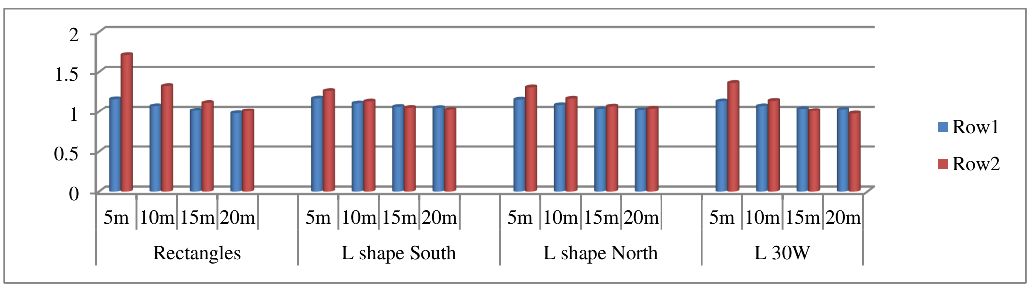
Figure 12: Row configurations, (a) detached units, (b) attached units

Main Effects

The row effect on electricity generation is measured by comparing the electricity generation of the roofs of the obstructed rows (R2) to that of the exposed row (R1). The results show that the yearly generation of all configurations is not significantly affected by the distance (<4%). The row effect on heating and cooling loads is assessed for site I by comparing the loads of obstructed and exposed rows to the corresponding isolated row. The results of this comparison are presented in Figures 13a and 13b for detached and attached units respectively. Generally, the average heating load increases significantly for the units of the obstructed row (R2), while the cooling load decreases. For the exposed row (R1), heating and cooling load are affected for a row spacing of 10m or less. The increase in heating load of R2 can reach 50% for the detached rectangular units configuration at 5m row spacing, and up to 70% for attached units.



(a)



(b)

Figure 13: Heating load of two rows relative to isolated rows (a) detached units, (b) attached units

The comparison of the heating load of the obstructed row (R2) of detached rectangular units to the heating load of the unobstructed row (R1) is presented as function of the minimal distance between rows to avoid shading (x) in Figure 14.

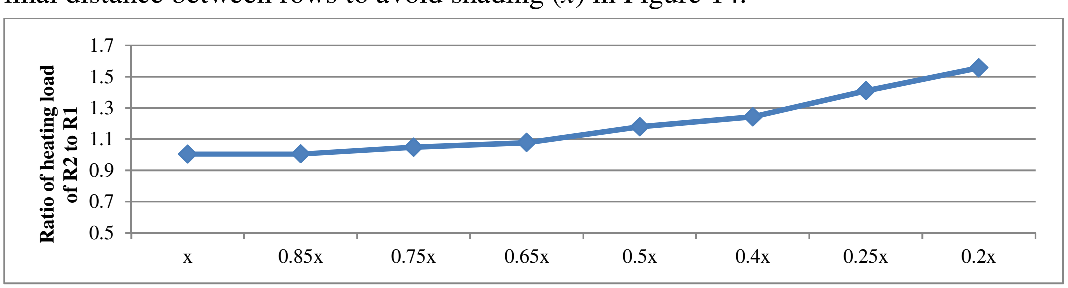


Figure 14: increase of heating load of the obstructed row of detached rectangular units as function of the minimal distance (x)

4 Discussion and Design Guidelines

The study shows that several parameters should be considered in the design process of solar optimized residential neighbourhoods.

This section summarizes these parameters and presents a preliminary methodology for the implementation of a design procedure that incorporates these parameters. The design procedure is expressed in the form of a flowchart in Figure 15.

The design of a neighbourhood starts with specifications about the site layout – road shape (straight or curve road, orientation of the road, etc.) and level of density required (low, medium or high, in terms of number of units per acre), as well as specifications for the dwelling units themselves (floor area, number of storeys etc.). The design process consists in general of a) the development of design alternatives that match housing shapes with the given specifications; b) a procedure for selection among the alternatives and refining the selected design. The main parameters influencing design alternatives are the shape of housing units and their positioning in the given site.

1) Shape of housing units

For a given set of housing units' specifications (number of floors, floor area, etc.), a number of housing shapes may be designed based on:

a) General site considerations – accessibility, functionality, convenience.

b) Minimizing total area for a given functional area (minimizing passages and distributors in the interior space, minimizing wasted spaces etc.).

c) Energy considerations – Passive and Active solar design. In this paper, active solar design refers to generation of electricity using BIPV systems. Potential of combined electrical /thermal systems is considered in Hachem et al (2011c). Daylighting should be considered as well.

The main aspects of shape design, presented in this paper are highlighted below. A detailed study on shape parameters and their effects is presented in Hachem et al. (2012).

General

- Orientation: orientation of units should be within the optimal range (equatorial facing to 30° east or west). Otherwise, trade-offs in shape design should be made (see curved road, below).
- South facing window area: a 35% of the façade represents a good window size option that enables to reduce significantly heating load without a significant increase of cooling load.

Convex shapes:

- Aspect ratio – ratio of south façade to lateral façade. An aspect ratio of 1.3 to 1.6 should be applied to maximize passive solar heat gain without significantly compromising cooling loads (Hachem et al., 2012).

Non-convex shapes

For non –convex shapes (self-shading geometries), there are a few parameters that affect energy performance, such as number of shading facades and ratio of shading to shaded façade widths (depth ratio), as well as the angle enclosed by the wings. In this paper only the angle between the wings is investigated. Details of design of non-convex shapes are presented in Hachem et al. (2012).

- Depth ratio: avoid a depth ratio that is larger than ½. A depth ratio of 1 can reduce the incident solar radiation significantly by ca. 20% (Hachem et al, 2011a).
- By increasing the angle enclosed between shading and shaded facades, self-shading can be controlled and manipulated by variations of the basic geometry.

Roofs:

Only hip roof design with 45° tilt angle is considered in this paper. Two effects are found to influence the energy generation of BIPV systems: surface area and orientation.

- South roof area: enlargement of the south facing roof area can be achieved by manipulating the shape design such as demonstrated in L variations.
- Orientation: roof surfaces can be rotated by up to 45° with a reduction in the annual electricity generation of only up to 5% (for a roof slope of 45°). The integration of PV systems in surfaces with different orientations, as studied in L shape variations, enables shifting the timing of peak generation by up to 3 hours relative to solar noon.

2) Positioning of housing units on a site.

The placement of housing units with respect to each other is mainly governed by the site lay-out and the density. Detached units situated within a neighbourhood generally have higher heating and cooling loads than the same units in isolation (by up to 22%). Attached units however require less heating and cooling than the corresponding isolated units.

a) Straight road (east west direction)

Low density- Detached units

- Apply passive solar design for shapes (convex and non-convex) as detailed above
- Minimum distance between adjacent units, as required by bylaws can be applied; this distance (on the east west axis) does not affect significantly the performance of the units.

High density- Attached units

- Attached units are recommended for increased density. Heating and cooling loads are significantly less for attached than for detached units (by up to 35%).
- For non-convex shapes (or self-shading configurations), the depth ratio and number of shading facades should be considered. A ratio of ½ or less is advisable (especially with more than one shading façade).

b) Curved Road

Low density- Detached units

- Planar obstruction angle (POA): a small POA (≤ 60°) should be avoided especially with a small distance between units (≤ 10m). The effect of POA is more critical when a unit is shaded by two units.
- Orientation around the curve: In the case of convex shapes or non-convex shapes with orthogonal wings, the whole unit can be oriented along the curve provided that the orientation from south is still within the optimal range. Beyond certain angle of orientation (30°), it is recommended to design partly oriented units, such as L variant (where only one wing is oriented toward the curve, while the main wing is south facing). For instance a rectangular shape with 45° orientation requires up to 20% more heating energy than an L variant where only the wing is oriented at 45°.

High Density - Attached units

Similar observations as for attached units along a straight road. Additional design issues should be addressed, for instance:

- Rectangular shape is modified to trapezoid. For south facing curve this can lead to reducing the south façade and south facing roof surface areas. Trade-offs can be made with shapes like Obtuse angle (O) in this case.
- Orientation along the curve follows the same design recommendations as for the detached units.

c) Row Configurations

Low density – Detached units

- For row configurations it is recommended keep a distance between rows of at least 85% of the minimum distance required to avoid shading. The minimum distance to avoid shading is a function of the height of the shading building.
- Non convex shapes need less distance in between the rows, due to the fact that the facades are not coplanar.

High density – Attached units

The same design recommendations presented in the design of detached units in a straight road apply to row design with attached units.

The distance between rows is more critical for attached units. Distance between the rows should be at least as much as 2 times the height of the shading buildings.

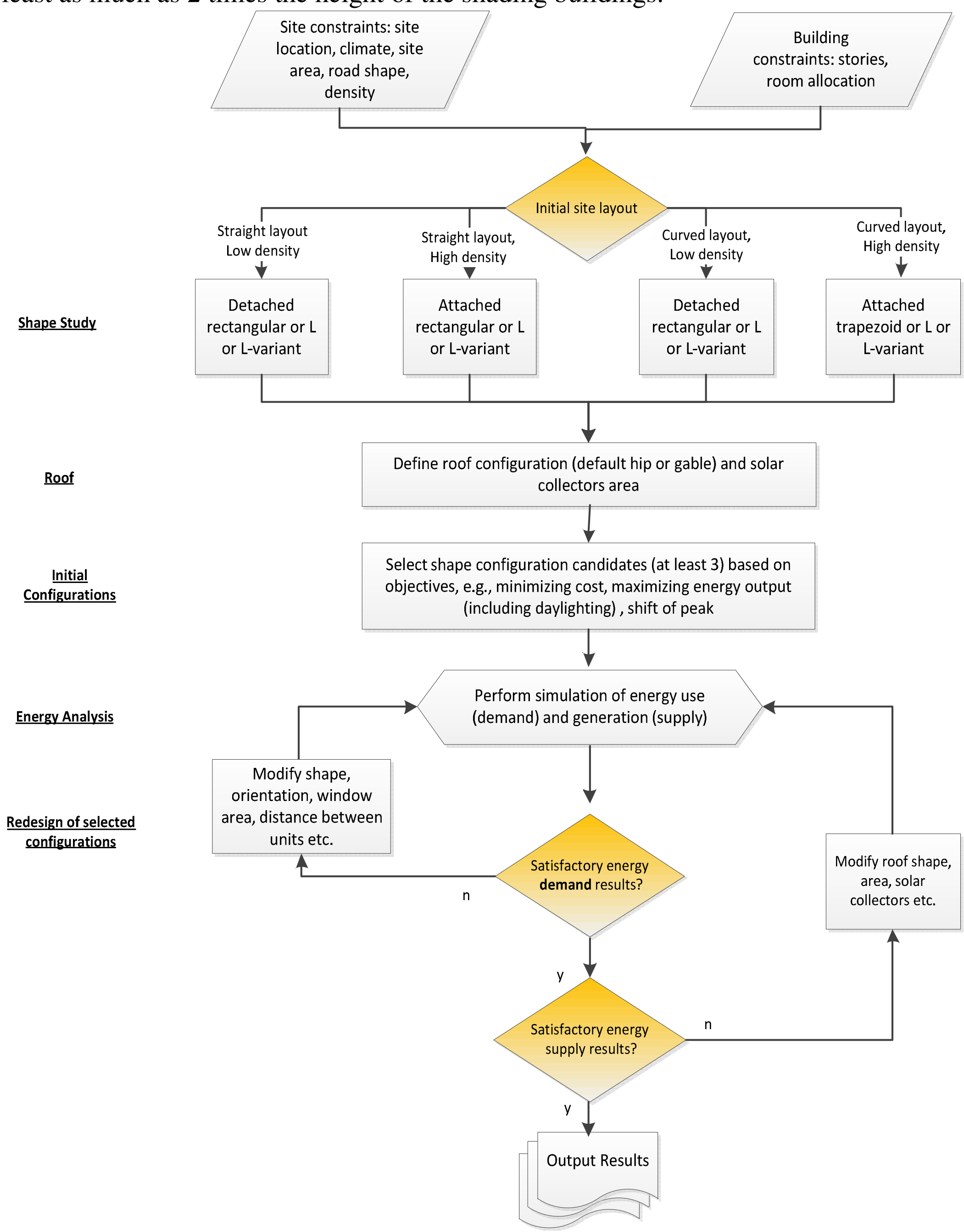


Figure 15: Preliminary flowchart of solar neighbourhood design

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