Solar Potential on Roofs:
An Index for Different Urban Layouts

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ABSTRACT: Volumetric distribution of the built form really affects the capability of an urban environment to integrate renewable energy, with specific regard to active and passive use of solar radiation collected by the building envelope. The solar potential of a generic surface does not directly correspond to the energy received, but is related to the effective possibilities for exploitation.

This study deals with defining an index of horizontal solar collection which expresses the amount of direct solar radiation received by roofs compared to the corresponding overall gross floor area of an urban block. This parameter represents a significant tool in assessing the efficiency of different types of buildings with regard to technical use of solar gains.

The proportion between height and the plan of a building assumes a crucial role. The comparative analysis presented here seeks to examine the relationship between slenderness and potential of an urban block to match its overall domestic hot water through solar gains. The results allow formulation of early considerations about the most appropriate distribution of horizontal and vertical exposure surfaces and about the combination of active and passive use of solar energy.

Keywords: index of horizontal solar collection, domestic hot water demand, urban block, slenderness

INTRODUCTION

On the one hand, rapid increase of urban population and scarcity of available land sources are progressively leading to high density living settlements and to concentration of energy consumption in small areas [1]. On the other hand, forthcoming depletion of fossil fuels and the pressure to reduce CO_2 emissions requires exploitation of alternatives renewable sources. Energy provided by the sun offers great opportunities for both passive use and active applications, such as photovoltaic and thermal conversion systems. Nevertheless, a frequent problem in dense urban areas is the lack of surface area available and suitable for installing appropriate technical devices to convert solar radiation into thermal and electrical energy [2], i.e. the roofs. Within the urban fabric, buildings are often not able to meet their own energy requirements only through solar contribution and additional mechanical installations are therefore required to achieve recommended comfort conditions.

In fact, the real **solar potential** of a generic urban surface (a façade, a roof, a public space) does not directly correspond to the solar gain amounts, but it should be related to effective possibilities for exploiting energy received to satisfy energy demand: it is not simply a matter of quantity, but also of *quality*. In other words, when evaluating the solar potential of an urban block, energy balance between consumption and collection has to be taken into account.

Morphological structure of the urban fabric is recognized as one of the key factors in determining overall energy performance [3,4,5]. For a given building density, volumetric distribution and geometric properties of the built form can change significantly and affect capacity to gain and lose energy in very different ways [6]. Several previous studies focused attention on urban canyon geometry with regard to daylight and sunlight access on façades [7], while less interest has been paid to urban form with regard to possible exploitation of solar energy on roofs. An interesting research study by Cheng et al. relates *vertical randomness* and site coverage in a building cluster to solar potential [8]. This study indicates further investigation issues concerning vertical and horizontal proportions of an urban block and energy performance.

High or Low-Rise Buildings?

The problem of "best height" of an urban building has been a matter of discussion throughout the entire twentieth century and continues being a subject of debate to this day. Although at the beginning, economic, social and hygiene needs represented the most importance issues [9], over the last decades, attention shifted to environmental and energy implications of a vertical development. On the one hand, multi-storey blocks disperse less energy per square meter of floor area than a detached lower building [10], since they have less exposed wall area and roof heat-loss [11]. On the other hand, additional energy is required by higher buildings to run lifts and mechanical conditioning systems providing internal comfort [12].

What, therefore, is the "best height" for an urban block? This topic is quite complex, due to several interacting variables to consider and the debate remains open. Both high and low-rise developments, in fact, provide benefits and disadvantages in terms of energy performance and land occupation. The capacity of a building to match energy needs and solar gains represents an important aspect to consider in providing a more exhaustive answer. In other words, it is not simply a problem of height and relative consumption, but rather concerns volumetric proportions of the block with regard to overall energy balance. Therefore, the previous question could be reformulated as follows: "Which **type** of building would potentially be able to satisfy energy demand by means of its own solar gains?". According to Lynch, the **type** is understood as the relationship between height and footprint of a building [13].

This work deals with study of volumetric proportions of an urban block with regard to its potential to satisfy thermal energy consumption for domestic hot water through solar energy collected on roofs. The main purpose is to evaluate the performance of different urban layouts, by comparing their **index of roof solar potential** to predicted demand, in order to define the most energy efficient volumetric distribution for an urban block. The concept of **slenderness** is introduced as a useful parameter to define the proportion between height and plan of the built mass with regard to horizontal and vertical surfaces available for solar exposure.

METHODOLOGY

This paper is based on analysis of existing urban case studies. All input data used (geometrical characteristics of built volumes, population density, domestic hot water demand, solar gains) refer, as far as possible, to the real state with a very small approximation. Proceeding from the singular and unique aspects of each specific situation, a progressive process of abstraction permits discovering and understanding general common trends, without discarding the importance of specifics in a real urban context.

The research implementation is expressed in 4 main steps which are indicated and explained in the following subsections.

Selection of Case Studies and Calculation of *Slenderness*

Adequate samples of 4 different urban patterns within a given FAR (Floor Area Ratio) values range were chosen in the urban area of Barcelona, Spain (Fig. 1): A) *Eixample*, B) *Gracia*, C) *Barri Gotic* and D) *Poble Sec*.

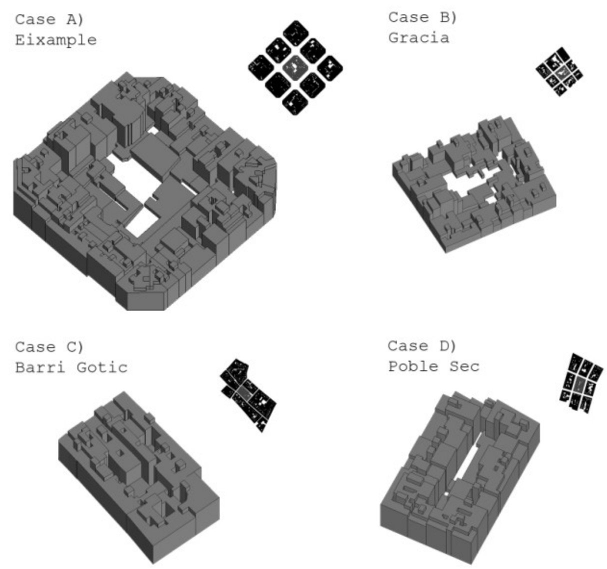

Fig .1: The four selected urban fabric samples and, in evidence, the blocks analysed

As the Fig.1 shows, the analysis always refers to the central block. Table 1 reports basic morphological indicators of selected configurations, defined according to the *Spacecalculator* [14]. For each of them, the **slenderness** coefficient (**S**) is also calculated.

Table 1: Morphological features and slenderness coefficients of the central blocks

		Case A	Case B	Case C	Case D
Floor Area Ratio	FAR	3.12	2.65	3.64	3.05
Height (m)	h	14.64	9.26	14.13	17.41
Floor number	L	5	3	5	6
Average plan surface area (m^2)	S_0	10857	3304	3252	3606
Overall floor surface area (m^2)	F	54285	9912	16260	21636
Slenderness	**S**	**0.24**	**0.27**	**0.40**	**0.45**

Slenderness is one of the main parameters that describe the form of the building, providing an idea of general volumetric proportions, with specific regard to vertical and horizontal development. More specifically, it is defined as the ratio of height (h) to the average surface area of the plan (S_0) of a building, the latter being expressed as the radius of an equivalent circular surface area that is a linear magnitude [15]. The slenderness coefficient is, therefore, an a-dimensional value calculated using the following formula:

$$S = h/(S_0/\pi+h^2)½ \quad (1)$$

The lighting and thermal effects concerning this formal property can seriously affect the global solar potential of a building or an urban block. In principle, for the same built volume, higher values of slenderness should provide better conditions for passive use of daylight and sunlight, thanks to great extension of façades and to minimization of the central floor areas with no direct radiation. On the contrary, lower values of S should enhance active exploitation of solar energy, as a result of the larger collection surface on roofs.

Assessment of Roof Solar Potential

Roof solar potential refers to the month of December which has the lowest level of irradiation in the entire year. Solar analysis is implemented by means of *Heliodon2* [16], a simulation software which provides data about cumulative distribution of solar energy collected by the building envelope, taking into account the influence of surrounding obstructions. The *Heliodon2* calculation model is relatively simple as it assumes isotropic sky conditions and reflections and emissions from other surfaces are not considered. This means that data input and calculation costs are significantly reduced and information provided by the program is not totally diagnostic, but contains potential values that are very useful for comparative and qualitative analysis. Nevertheless, it is possible to obtain more realistic information by adjusting the theoretical values of horizontal solar radiation with experimental data measured in an open surface [17]. The ratio between these two numbers allows for definition of a correction factor (%) to apply to potential results provided by *Heliodon2*. In this work, the weather database available on the *Energy Plus* web-site were used [18].

The **index of horizontal solar collection (I_h)** of a building expresses the amount of solar radiation potentially available to satisfy overall energy requirements. More precisely, it is defined as the ratio of energy collected by roofs to gross floor area (F). It is important to specify that block height within selected portions of urban texture is relatively constant so that shadows cast by surrounding obstructions on roofs are not remarkable. The values of I_h regarding selected case studies are listed in Table 2.

Table 2: Energy gains and index of horizontal solar collection

		Case A	Case B	Case C	Case D
Solar energy gains (kWh/m^2)	I_p	12.35	13.14	16.19	13.04
Index of horizontal solar potential (kWh/m^2)	$\mathbf{I_h}$	**2.55**	**4.25**	**3.24**	**2.20**

Assessment of Energy Load for Domestic Hot Water

Energy demand for domestic hot water depends on the number of people living in a building, on their habits and on the type of sanitary installations. Estimation of needs is normally approximated considering average daily amount of litres/person at a given temperature. In this research study, data from a national statistical study about Spanish residential habits were taken into account, i.e. daily consumption (c_w) of 46 litres/person with a supply temperature of 45°C [19]. The water is assumed to flow into the public network at 12°C, so that the difference of temperature (δT) to compensate is 33°C.

Firstly, values of c_w and δT led to finding individual daily thermal consumption, namely 1.76 kWh/day/inhab. In order to calculate **monthly thermal energy demand (Q_m)** in the various case studies, it was then necessary to multiply the individual consumption by the days of the month and by the actual number of inhabitants of each block [20].

Table 3:Real population data of the reference urban blocks

		Case A	Case B	Case C	Case D
Inhabitants number	-	687	161	292	445
Population density (inhab/ha)	-	130	158	191	213

Comparison of Potential Thermal Energy Produced by Solar Source and Predicted Consumption

The amount of solar radiation effectively converted into thermal energy mostly depends on technological characteristics and on inclination of the solar collectors installed on roofs. In this research study, different types of thermal panels were analysed with tilt angles of 30° and 60° (Table 4): the first angle provides the highest yearly efficiency, the second is ideal for the winter season. To obtain **unit energy production (E_{30} and E_{60})** associated with each block analysed, the previously calculated values of I_h were corrected by the efficiency (η) of the various systems: **a**) single selective glass covered panels; **b**) double selective glass covered panels; **c**) evacuated-tube heat-pipes.

In order to compare predicted requirements to potential supply, defining **unit thermal energy demand (Q_u)** was necessary, which is obtained simply by dividing overall demand (Q_m) by floor area (F).

Table 4: Comparison between unit energy demand and unit energy production associated with different solar collection systems

	Solar system	η (%)	Case A	Case B	Case C	Case D
Qu (kWh/m^2)	-	-	**0.71**	**0.86**	**1.04**	**1.16**
E_{30} (kWh/m^2)	a	35	**0.75**	**2.32**	**1.07**	**0.71**
	b	44	**0.94**	**2.92**	**1.34**	**0.90**
	c	43	**0.92**	**2.85**	**1.31**	**0.88**
E_{60} (kWh/m^2)	a	40	**0.86**	**1.73**	**1.22**	**0.82**
	b	50	**1.07**	**2.16**	**1.53**	**1.02**
	c	49	**1.05**	**2.12**	**1.50**	**1.00**

RESULTS AND DISCUSSION

Slenderness and Solar Potential

Slenderness coefficients calculated by (1) firstly allow splitting the 4 examples into two groups: A and B, with values of 0.24 and 0.27 respectively, could be considered slenderness cases; C and D with 0.41 and 0.45, are instead classified as medium-high slenderness conditions. Solar performances of cases in the same category are supposedly similar. In principle, for lower slenderness coefficients, higher values of I_h are expected, due to the reasons explained in the previous section.

Actually, the results only partially prove this assumption: the index of horizontal solar collection effectively changes in inverse proportion to slenderness, but with the clear exception of Case A (see the graph in Fig. 2); in fact, although it has the lowest slenderness value, it provides very little roof solar potential. Therefore, contrary to what was supposed, cases A and B in the same slenderness class do not demonstrate analogous behaviour: the I_h of the latter (B) is almost twice that of the first one (A): 4.25 vs. 2.55.

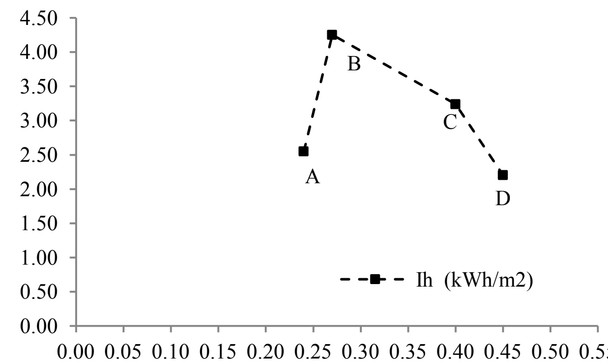

Figure 2: The relationship between index of horizontal solar collection (y axis) and slenderness (x axis)

Further examination of B, C and D makes it evidence that the plans have quite similar average surface areas in all 3 cases (between 3200 and 3600 m^2): variation of solar potential is therefore mainly attributable to the number of levels (L). Parametric verification effectively confirms that the index of horizontal solar collection only depends on height, but it is not definitely affected by average surface area of the plan of the block.

The graph in Fig. 3 relates values of I_h to height of the block. The curve progress can be substantially approximated to a power function: I_h decreases slowlier according to height increase of the building, tending to zero for values of h growing towards infinity.

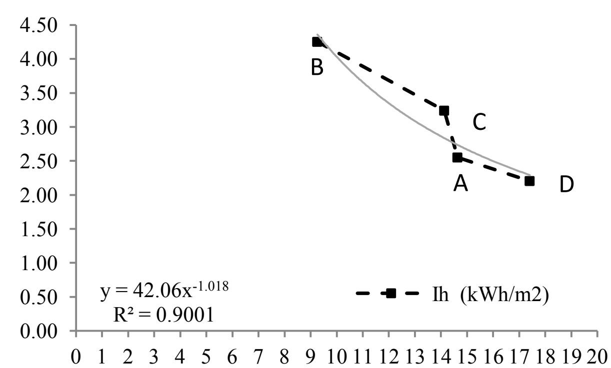

Figure 3: Relationship between index of horizontal solar collection (y axis) and height (x axis) of the urban block

The irregular position of point C in the curve probably depends on roughness of the roof surface: in fact, in a real urban block, the shadows cast by lift and stair towers, chimneys or other technical volumes can truly affect roof solar potential. In case C (*Barri Gotic*), the influence of these obstructions is definitely less considerable than in others, as the 20% increase in the solar gains demonstrates (see Table 2). This performance is ascribable to another general characteristic defining the building form, namely the **compactness**. This parameter effectively concerns the "degree of concentration" of built mass, expressing the relationship between external envelope and volume.

Energy Demand and Energy Production

As predicted, results clearly show that unit thermal energy demand strictly depends on population density of the block, in other words, on capacity to accommodate a certain type of dwellings and a certain number of people. Therefore, the unit thermal energy demand is indirectly related to volumetric configuration of the block. The graph in the Fig. 4 displays a direct proportionality between values of Q_u and both values of P and S.

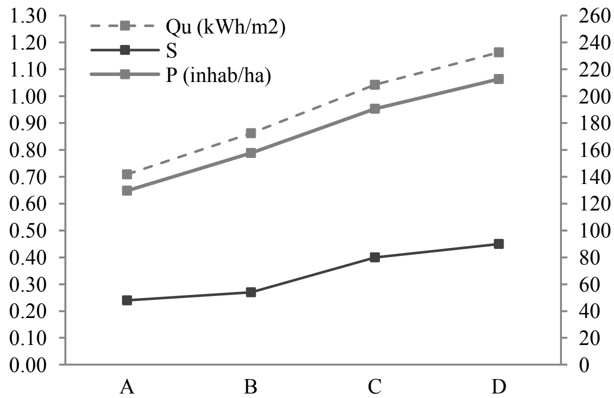

Figure 4: Direct proportionality among index of horizontal solar collection, population density (right y axis) and slenderness (left y axis)

This trend could be explained as follows: a horizontally developed block can potentially accommodate less population density than a vertically developed block. In fact, the larger the occupation of the plan with respect to height, the greater the need to empty volume at certain points (small courtyards, patios and wells), in order to provide natural light and ventilation to interior spaces. The immediate consequence of this mandatory operation is progressive reduction of available effective living surface area. **Porosity**, which is one of the main formal characteristics of a building, seems to be, therefore, related to energy performance as described above; in fact, it essentially defines the ratio between solid and empty parts of its volume. As a tendency, lower population density and lower requirements should correspond to higher porosity values.

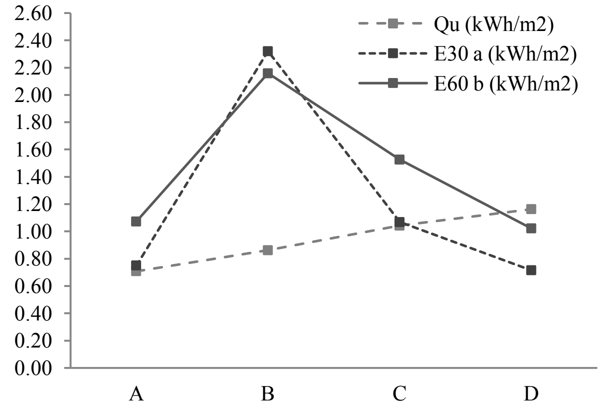

Figure 5: Comparison among unit thermal energi demand and energy produced by single selective glass covered panels (30° tilt angle) and double selective glass covered panels (60° tilt angle)

The graph in the Fig. 5 compares unit energy demand to unit energy produced by 30° tilted plate solar collectors with a single selective glass cover (which currently is one of the most common domestic installations) and by 60° tilted plate solar collectors with a double selective glass cover (which provides the best efficiency in the technical solutions analysed).

In A and C, consumption and supply are completely equilibrated: the potential solar gains on the roof fit the energy needs for domestic hot water of the entire block perfectly. It is important to highlight that, although they belong to different classes of slenderness, these two cases are very similar in height, namely 5 floors. Case B (*Gracia*) performs even better than previous ones: energy production is almost three times greater than predicted demand. The remaining energy is therefore exploitable for other thermal applications, i.e. heating and cooling. Case C (*Poble* Sec) represents, on the other hand, the most unfavourable situation: here the index of horizontal solar collection is able to meet only half of the overall requirement. Of course, the unit energy production could be enhanced by means of more efficient solar collection systems, such as evacuated-tube heat-pipes or double selective glass covered panels and by optimizing the tilted angle (see Table 4). Nevertheless, despite these technological improvements, the energy provided would not completely satisfy overall thermal energy demand in any of the cases; this means that to achieve a minimum balance between solar supply and consumption volumetric proportions of the block need to be adjusted.

Concerning this issue, it is interesting to notice that the *Poble Sec* block (D) has the greatest number of floors in the case studies, i.e., 6. The decrease of only one level would enhance a 20% increase of unit solar potential (from 2.20 to 2.66 kWh/m^2), while the unit energy demand would remain unchanged. Under these initial conditions, an installation of double selective glass covered collectors would provide unit energy production of 1.17 kWh/m^2, representing the least amount required to meet thermal energy needs for domestic hot water of the entire block. The enlargement of the average surface area of the plan would produce a similar qualitative performance, but to achieve equivalent numerical results a substantial modification would be required. In other words, to reach a minimal energy balance, the footprint of the plan of the block should become significantly greater than its current extension.

CONCLUSIONS

This paper sought an optimal combination between volumetric distribution of an urban block and solar performance of its cover regarding thermal energy production. On the one hand, the comparative analysis demonstrated that index of horizontal solar collection is in inverse proportion to the number of floors in the building, but it is not affected by the footprint of the plan. On the other hand, it has been noted that unit thermal energy demand is indirectly related to surface area of the plan or, rather, to the typology of the block and therefore to slenderness. Since the early stages of the design of the building, the thermal energy balance can be improved by means of formal choices which do not only affect potential solar gains, but might also regulate future consumption. Obviously, in the latter case, effects of the designer decisions are much more unpredictable, due to greater influence of subjective factors (e.g. real occupation, habits of users) in determining final demand.

Finally, “What *type* of urban block is therefore able to match solar energy supply to energy demand?” Optimal volumetric proportions cannot be established in absolute terms for an urban block; for every specific value or class of slenderness, several “pairs” of height and surface area of the plan can be associated with different energy performances. The task of architects is to evaluate and select a combination that can provide optimal efficiency in terms of supply and consumption in a given climatic context and specific situation. The four examples selected showed that low and medium-rise buildings are generally more suitable than high-rise buildings to satisfy requirements and work with an autonomous solar supply system for domestic hot water. The threshold of 5 floors might be considered as the upper “limit” to match domestic hot water thermal demand by the solar source; higher buildings tend to be less appropriate for self-reliance, due to the greater extension of gross floor area that requires thermal energy. The influence of the average surface area of the plan, instead, does not appear so remarkable, as it has more to do with population density and the corresponding energy demand, but it is not related to horizontal solar potential of an urban block.

FURTHER DEVELOPMENTS

This research was conducted through the design of 3D virtual models based on original characteristics of the blocks selected, taking into account variations and diversities typical of an existing urban context. If, on the one hand, this kind of approach makes identification of key factors and general trends more complex, on the other hand it allows for evaluation of effective influence of specificities and irregularities. In this case, the influence of formal parameters such as compactness and porosity would probably not have been detected through employment of a generic archetypal model. However, a parametric analysis would be helpful to develop systematic comparisons, for example, among different geographic locations.

Within the European territory, in fact, the index of horizontal solar collection of a block can be substantially different from North to South latitudes, due to the different sun elevation angles. It would be interesting to check if general achievements regarding Barcelona could be extended to other countries. Tendentially, the higher the latitude, the lower should be the values of I_h and *vice versa*. This means that, if the unit thermal energy demand is constant, urban blocks with 5-6 floors are more suitable in Southern countries than in Northern ones, where, low-rise buildings combined with very tilted solar collectors would work more efficiently.

A parametric approach would allow serial assessment of possible active and passive solar potential associated with different types of urban blocks in different locations. This simplified operative process would be useful, in the early stages of the project, to orient designer decisions towards more conscious and efficient settlements. However, methodological arrangements do not have to discard unique features and identity of the specific context of intervention which plays a determinant role, as this paper demonstrated.

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