How street-canyon configurations affect the potential of solar energy

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ABSTRACT: *While the effects of street-canyon configuration on temperature, wind speed and direction, and air quality have received much attention, its impact on solar energy potential has not been much studied. This paper focuses on two aspects of the street-canyon configuration in the city of Geneva in Switzerland: (i) Quantifying its canyon geometric characteristics, including the widths, orientations, and aspect ratios of 1600 street canyons. (ii) Comparing the geometric characteristics with solar irradiation (kWhm^{-2}) of street surface. The results show, first, that the solar irradiation is greatest for the months May to August and that street canyons orientated roughly WNW-ESE, that is, streets facing SSW. Second, street canyons with low aspect ratios (<1.0) and oriented WNW-ESE receive the greatest solar irradiation. In particular, when the aspect ratio reaches 0.5 in May and August, and 1.0 in June and July, the monthly solar irradiation falls below 70 kWhm^{-2}. Third, street canyons of great widths (> 10-30 m) and oriented WNW-ESE receive the greatest solar irradiation. More specifically, the solar irradiation falls below 70 kWhm^{-2} in June and July for streets narrower than 10-15 m, and below the same value in May and August for streets narrower than 20-30 m.*

INTRODUCTION

Solar energy is increasingly important in the energy budget of the world. This importance is likely to increase in the near future. For example, in one forecast, solar photovoltaics (PVs) and solar thermal energy could provide 27% of the world electricity production by 2050, thereby making solar energy the world's largest source of electricity [1, 2].

Urban areas offer great potential for on-site solar energy production. This potential will increase in the near future with continued expansion of urban areas. Urban areas, however, have different configurations in terms of arrangements of streets and buildings in relation to the sun. In particular, two factors related to the urban configuration are of importance. One is the orientation of the streets (and adjacent buildings) in relation to the sun. The other is the aspect ratios of the street canyons, that is, the average height of the buildings adjacent to a street divided by the street width. While these factors have been studied in relation to wind speed and direction and air quality [3, 4], their effects on solar energy potential and accessibility have not received much attention [5, 6].

The main aim of this paper is to show how the canyon configurations including street orientations, street widths, and street-canyon aspect ratios, affect the solar energy potential. While the results are completely general, the data used here are from the city of Geneva in Switzerland (Figure 1).

CASE STUDY

The city of Geneva is located in the southern part of Switzerland, at 46°12'N and 6°09' East (Figure 1). The city is bounded to the northeast by Lake Geneva, where the lake flows back into the river Rhône. Geneva is surrounded by two mountain chains, the Alps and the Jura, and has an average altitude above sea level of 374 m. The city has a population of about 195 thousand (www.bfs.admin.ch) and is the second largest in Switzerland.
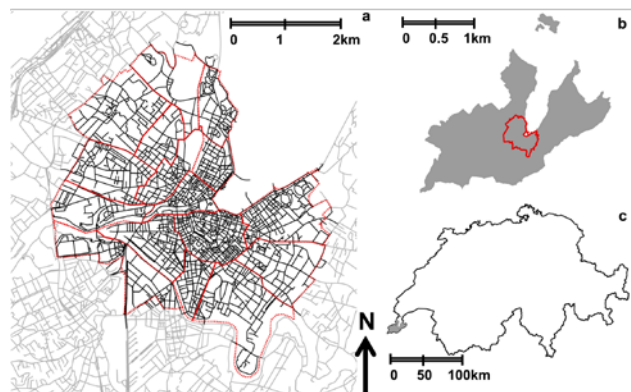

Figure 1: The city of Geneva., showing its location in Switzerland and within the canton of Geneva (red outline) as well as the main street network.

The city is composed of 16 neighborhoods or zones with a total of about 3,400 streets and 11,400 buildings. With a total area of about 16 km^2, the population density

of the city is about 12,000 per km^2. Some 92% of the total land in the city is used for built up area, out of this about 50% are buildings.

METHODS

Of the 3,400 we omitted all cul-de-sacs and park pathways, so that a total of 1600 streets of Geneva were used in this analysis as regards orientation (azimuth), width, and aspect ratio. The azimuths for each street were calculated in ArcGIS and MATLAB program is used for analyzing and visualizing the results, presented as rose diagrams. To quantify street width, we used a Plug-in tool for GIS to create perpendicular line with a fixed size and space in between along street segments. We set 50 meters length for the perpendicular lines (as equal as the widest street segment) and 10 meters distance between them. We choose 10 meters because the length of shortest segment is 10. Then we will have at least one perpendicular line for these segments. The perpendicular lines (a) are cut within the building layer (b). All the perpendicular lines that are not touched by the buildings are erased. Then we obtain a clean layer of perpendicular line, which touches at least one building of each side of the road and cross a street segment. We use *Graph and Shape* tool in GIS to calculate the length of each remaining perpendicular lines. To get the width for each segment, we use spatial join to average the length of all perpendicular lines crossing the segment as street width for that particular segment (Figure 2).
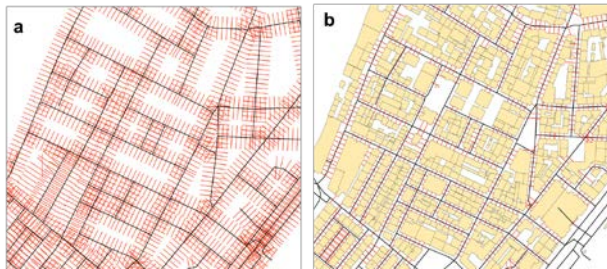

Figure 2: Street segments with their perpendicular lines (a), Perpendicular lines after erasing with building layer (b).

Asymmetric aspect ratios for all the street segments have been calculated. We first calculate the average building heights for each side of the street segment (H1, H2). Then calculate the aspect ratio first for one side, dividing the average building heights by street width (H1/W) and then do the same for the other side of the street segment (H2/W). The aspect ratio for each street segment is calculated based on the average value of the both side of the streets.

ArcGIS tool (Area Solar Radiation) has been used to calculate the monthly street surface solar irradiation. The tool enables to calculate directly the solar irradiance for each point of a given Raster Digital Surface Model

(DSM). The surface model considers the shading on streets from trees. For the street surface irradiation, only the direct and diffuse part of the solar radiation will be taken into account, the reflected part being neglected.

RESULTS

Street widths range from 2 m to 50 m (Figure 3). The size distribution is crudely normal, but somewhat positively or right-skewed. Other things being equal, the width is a measure of the potential for the street itself and the facades of the adjacent buildings to receive solar radiation.

The aspect ratio, that is, the average height of the buildings along a street segment divided by the width of the street, decreases with increasing street width (Figure 4a). This is as expected; the building height ranges from about 2 to 42 m, so that as the street width increases, the aspect ratio should decrease. Generally as the aspect ratio decreases the street canyon becomes more open – its sky-view factor becomes larger – and it has greater potential, for a given orientation, of receiving solar energy.

This is seen in Figure 4b where the modelled solar irradiation (calculated receive solar energy in kWm^{-2}) is given as a function of the aspect ratio. While the coefficient of determination is not very high ($R^2 = 0.35$), the correlation is clear: street canyons with lower aspect ratios, that is, comparatively wide street canyons receive more solar energy, other things being equal, than narrow canyons.
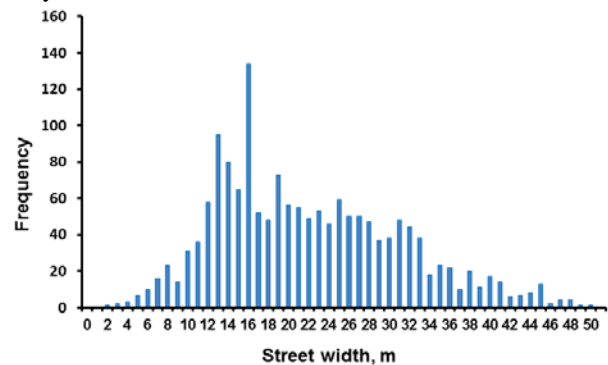

Figure 3: Widths (in meters) of 1600 street canyons in the city of Geneva. The widths range from 2 m to 50 m.

The main reason for the comparatively low correlation coefficient, however, is because the solar irradiation of a street canyon does not depend only on its aspect ratio, but also on its orientation in relation to the sun. Normally, one would expect street-canyons orientated roughly east-west to receive more irradiation than those orientated north-south. This follows because canyons orientated north-south receive strong solar radiation primarily when the sun is almost exactly in the south. And unless the canyons are with an exceptionally low aspect ratio, they are partly or largely (depending on

the time of the year and other factors) in shadow for much of the day. By contrast, street canyons orientated roughly east-west receive much solar radiation during most of the day (except for those with a very large aspect ratio).
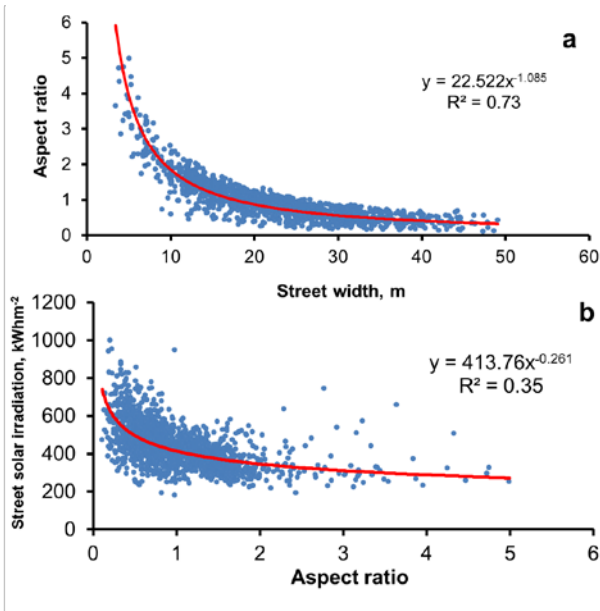

Figure 4: Aspect ratio, width, and solar irradiation of 1600 street canyons in the city of Geneva, Switzerland. (a) Aspect ratio of street canyons as a function of street width in meters. (b) Solar irradiation versus aspect ratio of street canyons. Solar irradiation shown here is that received by the streets themselves; that received by the facades of the adjacent buildings is not included.
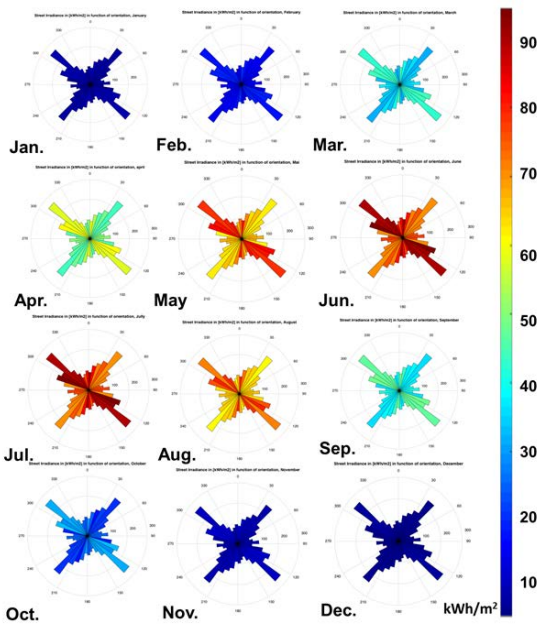

Figure 5. Monthly solar irradiation (in kWhm^{-2}) received by the 1600 analyzed streets of Geneva (that received by the facades of the adjacent buildings is not included here). As expected, the maximum irradiation is received from May to August. Streets orientated WNW-ESE, that is, facing southwest, receive more irradiation than those with other orientations.

The effect of street-canyon orientation on solar irradiation received is seen in Figure 5. Here the monthly solar irradiation through the year is shown in relation to the canyon orientation, presented by rose diagrams.

It is clear that the street canyons oriented WNW-ESE get much more solar irradiation than those with different orientations. This follows because these canyons face southwest, that is, they face the sun during the warmest hours of the day when the sun is high on the horizon and the intensity of the sunlight is close to its maximum. It should be noted, again, that the irradiation of the facades of the buildings adjacent to the streets are not considered here, only the street surfaces themselves.

To explore further the street-canyon configurations in relation to solar-energy potential we analyzed the combined effects of canyon aspect ratio, width, and orientation on the monthly irradiation. The results (Figures 6 and 7) show, first, that most of the irradiation is received during the months May to August, as expected, and, second, that aspect ratio and width have great effects on the solar potential. More specifically, only street canyons with comparatively low aspect ratio show high solar irradiation during these months (May to August, Figure 6). At aspect ratio below 0.5 in May and August, and 1.0 in June and July, the monthly solar irradiation falls below 70 kWhm^{-2}, which compares well with the yearly irradiation results in Figure 4. As regards orientation, the peak in solar irradiation for the WNW-ESE trending streets (cf. Figure 5).
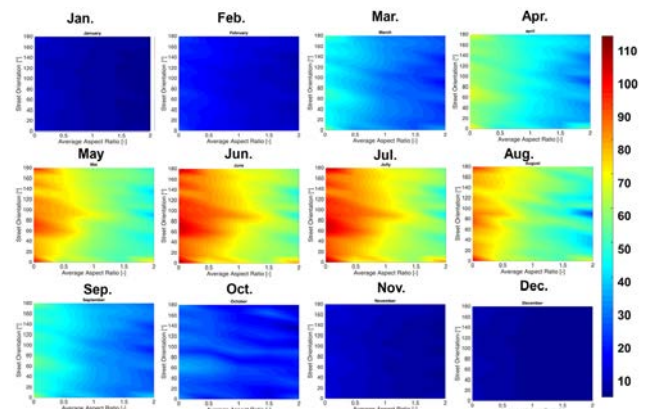

Figure 6: Monthly solar irradiation (color bar in kWhm^{-2}) in relation to street orientation (vertical coordinate axis, 0-180°) and aspect ratio (horizontal coordinate axis, 0-2) for Geneva. Canyons with low aspect ratios (<1.0) and oriented WNW-ESE receive the greatest solar irradiation, particularly during the months May to August.

The solar irradiation received by street canyons of different orientation was also analyzed in relation to street width. The results (Figure 7) agree with, and complement, those obtained for the same factors in relation to aspect ratio. Only wide streets receive considerable solar irradiation. In particular, when the street width is less than 10-15 m, then for June and July the solar irradiation falls below 70 kWhm⁻², which compares well with the irradiation results in Figure 5. For May and August, the solar irradiation falls below 70 kWhm⁻² for streets narrower than 20-30 m. As expected, the peak in solar irradiation for the WNW-ESE trending streets, although less clear than in Figure 5.
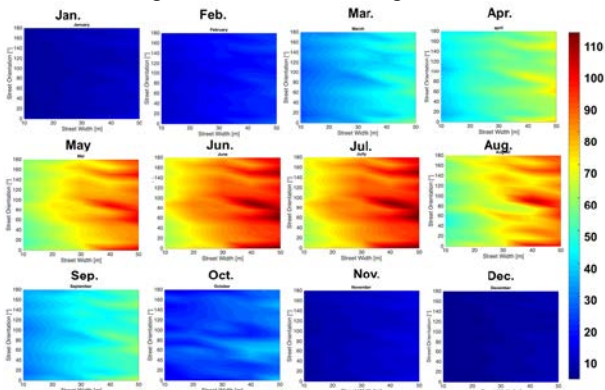

Figure 7: Monthly solar irradiation (color bar in kWhm⁻²) in relation to street-canyon orientation (vertical coordinate axis, 0-180°) and street width (horizontal coordinate axis, 10-50 m) for Geneva. Canyons of great widths (> 10-30 m) and oriented WNW-ESE receive the greatest solar irradiation, particularly during the months May to August.

DISCUSSION

Solar energy is becoming increasingly important energy source with some forecasts suggesting that solar energy may be the world's largest electricity source by 2050 [1,2]. Urban areas are becoming increasingly important sources of solar energy. One of the great advantages of urban areas is that the energy production is on site, thereby minimizing energy transformation (counted as loss) through energy transmission.

The potential of a city for solar energy, however, depends on several factors. These include the location of the area and its climate. For example, cities in dry and sunny areas such as in the northern part of Africa and in the Middle East receive much more solar energy than cities in northern countries, such as in Europe, Asia, and America. In addition, the solar-energy potential of a city or an urban area depends on the internal configuration of the city. In particular, the orientation and geometry of the streets and buildings in relation to the sun may have large effects on the energy potential of a city.

Many previous studies have focused on the effects of canyon configuration on wind speed and wind direction and air quality [3, 4]. By contrast, in the present paper we analyze the effects of street canyon configuration on the accessibility to the solar energy potential. We use the city of Geneva in Switzerland as a case study (Figure 1). Several built form parameters (e.g. building density, orientation) have recently been analyzed in relation to ecological parameters [6] as well as to solar energy potential [7, 8]. Here, by contrast, we focus on the street canyons of Geneva, and their geometric characteristics (e.g. street width, street orientation, and street-canyon aspect ratios) and correlate all these factors with the monthly and yearly solar energy potential (Figures 2-6). The results show that all these configuration factors have great effects on the solar energy potential.

While all the results presented here are from the city of Geneva, the methods of analysis are applicable to any city. Some factors will, of course, be different for cities at different location. In particular, for cities located closer to the equator the sun's height above the horizon during midday increases, and so does the energy received from the sun. How this change in the position (declination) of the sun in relation to street orientation, width, and aspect ratio remains to be explored for cities at different locations.

Another expansion of current work is to model solar irradiation for building facades (canyon depth) and analyze the accessibility of solar potential for building facades in relation to different canyon configurations (e.g. orientation, aspect ratio, canyon width).

CONCLUSION

We measured the orientation, width, and aspect ratio of 1600 street canyons in the city of Geneva in Switzerland with a view of exploring the effects of these factors on the solar-energy potential. The main conclusions of the study may be summarized as follows:

- The street-canyon width ranges from 2 to 50 m, and the heights of the buildings adjacent to the streets from 2 to 42 m.
- The aspect ratios of the street canyons, that is, the heights of the adjacent buildings divided by the widths of the streets, ranges from 0.1 to 10.5, with most values between 0.2 and 5.2. The aspect ratios of the street canyons decrease with increasing street width.
- Solar irradiation (kWhm⁻²) by the street surface - maximum during the months from May to August – is greatest for streets orientated roughly WNW-ESE, that is, for streets facing SSW.
- Street canyons with low aspect ratios (<1.0) and oriented WNW-ESE receive the greatest solar irradiation, particularly during the months May to August. When the aspect ratio reaches 0.5 in May and August, and 1.0 in June and

July, the monthly solar irradiation falls below 70 kWhm[-2].

- Street canyons of great widths (> 10-30 m) and oriented WNW-ESE receive the greatest solar irradiation, particularly during the months May to August. When the street width is less than 10-15 m, then for June and July the solar irradiation falls below 70 kWhm[-2]. For May and August, the solar irradiation falls below 70 kWhm-2 for streets narrower than 20-30 m.

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