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Effects of urban compactness on solar energy potential

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ABSTRACT

Compactness is a major urban form parameter that affects the accessibility of solar energy in the built environment. Here we explore the relation between various compactness indicators and solar potential in the 16 neighbourhoods (11,418 buildings) constituting the city of Geneva (Switzerland). The solar potential is assessed for building integrated photovoltaics (BiPV), solar thermal collectors (STC), and direct gain passive solar systems. The hourly solar irradiation on each of the building surfaces over one year period is calculated using CitySim simulations, while taking the effects of irradiation threshold for roof and facades into account. With increasing compactness, the annual solar irradiation decreases from 816 to 591 kWh m^{-2}. When passing from dispersed to compact neighbourhoods, the BiPV potential (given as percentage of total area) for facades decreases from 20% to 3%, the STC potential from 85% to 49%, and the passive solar heating potential from 21% to 4%, whereas for roofs the BiPV potential decreases from 94% to 79% and the STC potential from 100% to 95%. The solar potential for roofs, therefore, is much less affected than that for facades by the compactness. The results should be of great help for urban-form energy optimisation and building retrofitting interventions.

1. Introduction

Urban areas have expanded enormously in the past decades and are likely to do so in the coming decades. In many countries, they offer great opportunities for on-site energy production and use, thereby minimising the loss or transformation through energy transmission. Solar energy is one of the renewable energy resources with the greatest potential and could be the world's largest source of electricity by 2050 [1]. The rapid increase in the use of solar energy in recent years is highlighting its great development potential at present, and even more so as a future energy source [1,2]. According to the International Energy Agency roadmap 2014, solar photovoltaics and solar thermal energy could contribute to 27% of the global electricity production by 2050 [1], if the expected technological progress and required policy actions will occur. In addition to its being renewable and a carbon-dioxide (CO_2) neutral energy system [3], solar energy has one very obvious benefit, namely that the location of the energy source is commonly the same as the location of the energy use. This applies in particular to solar energy in urban areas, where building envelopes, walls and roofs, are used to capture and transform the solar irradiation into heat and/or thermal energy or electricity.

Quantifying the global solar irradiation reaching building envelopes and assessing their potential for active (photovoltaic electricity production and solar thermal for space/water heating) and passive solar heating have received much attention in the past decade [4–7]. Active solar systems use mechanical and electrical devices to convert solar radiation to heat and electric power. Passive solar systems, by contrast, uses building design (e.g. thermal mass) to capture the sun's heat and to reduce the energy use for space heating and, possibly, for cooling. In particular, there have been several studies on the effects of urban form on the solar energy potential [4,8–12] on scales varying from building and neighbourhood to urban and regional scale [5,13–15] using simulation and statistical methods [7,12]. While these studies have made significant progress in the topics they address, they primarily explore the effects of urban form on solar potential using generic models of urban layouts [10]. Some studies focus on solar potential only in residential buildings [11,16] using a limited number of buildings, while others investigate the effects of urban form on solar potential for new buildings in their early-design phase [11,17]. Also, several methods have been used to improve the design of new

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urban settlements by optimising size and shape of buildings for the utilisation of solar irradiation [18,19].

Urban compactness is one of the most commonly used urban form indicators. The effects of urban compactness on solar potential have, however, rarely been studied in a comprehensive way for the real built environment. Although compactness is used in many studies and assessed in many ways [11,12,20], we still have little information as to how compactness of existing neighbourhoods limits the solar potential of their buildings. In addition, we do not know the most efficient technology for harnessing the solar energy potential for roofs and facades in compact urban areas.

Here we address the effects of urban compactness on solar potential as regards various solar-energy technologies. Our results provide a framework that should be of great help in the decision-making process for assessing and integrating solar potential in dense built environment. The focus is on estimating active and passive solar gains associated with building roofs and facades using CitySim for hourly solar irradiation simulation. Sixteen neighbourhoods in the city of Geneva are used as a case study to evaluate the effects of compactness indicators on the solar potential. A sensitivity analysis is also performed to illustrate the effects of different annual solar irradiation thresholds on the energy potentials of facades and roofs. The results provide guidelines for urban-form optimisation in relation to retrofitting interventions on building envelopes and solar-energy applications in dense urban areas.

2. Data and methods

While the methods introduced and elaborated in this paper are completely general and applicable to other urban areas, all the data used and analysed are from the city of Geneva in Switzerland (Fig. 1). Geneva is located at 46°12′ North, 6°09′ East, at the south-western end of Lake Geneva, where the lake flows back into the Rhône River. It is surrounded by two mountain chains, the Alps and the Jura. The average altitude of Geneva above sea level is 374 m. The city, with a population of about 195 thousand in 2013 (www.bfs.admin.ch), is the second largest in Switzerland and the largest one in the French speaking part of the country. The city is composed of 16 neighbourhoods or zones with a total of 11,400 buildings (Fig. 1). The total area of the city is about 16 km^2 with a population density of 12,000 per km^2. About 92% of the total land in the city is used for built up area, out of this about 50% are buildings.

2.1. Compactness indicators

Several compactness indicators are used to assess the availability of the solar potential in the 16 neighbourhoods. These indicators are (Fig. 2): (a) volume–area ratio, (b) site coverage [5,6,9–12,16,17], (c) plot ratio [5,6,9–12,16,17], (d) building density [15], (e) population density [15], and (f) nearest-neighbour ratio [12]. The indicators are shown schematically in Fig. 2, and explained as follows: (a) Volume–area ratio is the total building volume in a neighbourhood divided by total area of a neighbourhood. (b) Site coverage is the total built area in a neighbourhood divided by total area of a neighbourhood. (c) Plot ratio is the total floor area in a neighbourhood divided by total area of a neighbourhood. (d) Building density is the total number of buildings in a neighbourhood divided by total area of a neighbourhood. (e) Population density is the total number of people living in a neighbourhood divided by total area of a neighbourhood. (f) Nearest-neighbour ratio is the average distance between buildings from centroids normalised by the total area of a neighbourhood. If the ratio is less than 1, the building configuration indicates clustering; if the ratio is greater than 1, the configuration is more uniformly

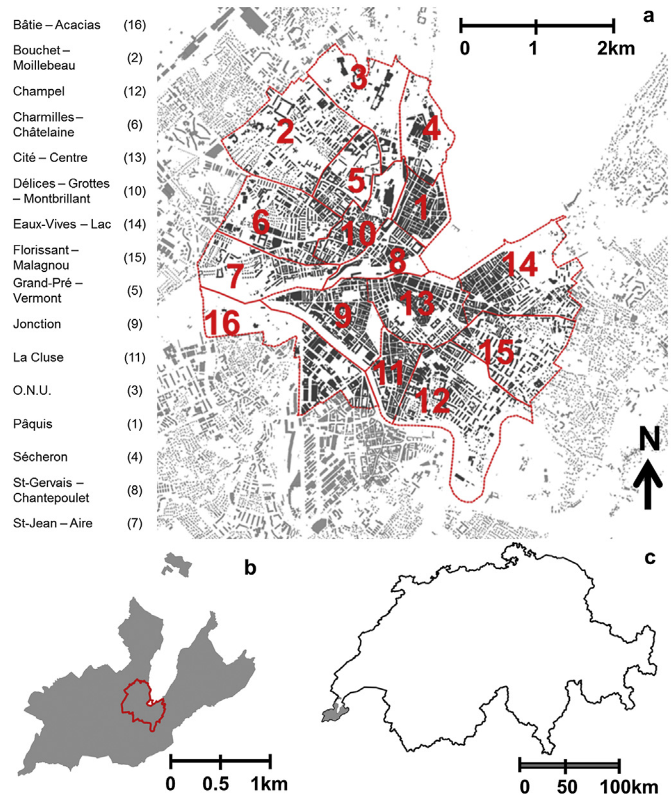

Fig. 1. (a) Building map of the city of Geneva, composed of 16 neighbourhoods, each one marked by broken red line. (b) The location of Geneva city (shown by red, solid and closed curve) in the canton of Geneva. (c) The location of canton of Geneva in Switzerland. (For interpretation of the references to colour in this figure caption, the reader is referred to the web version of this article.)

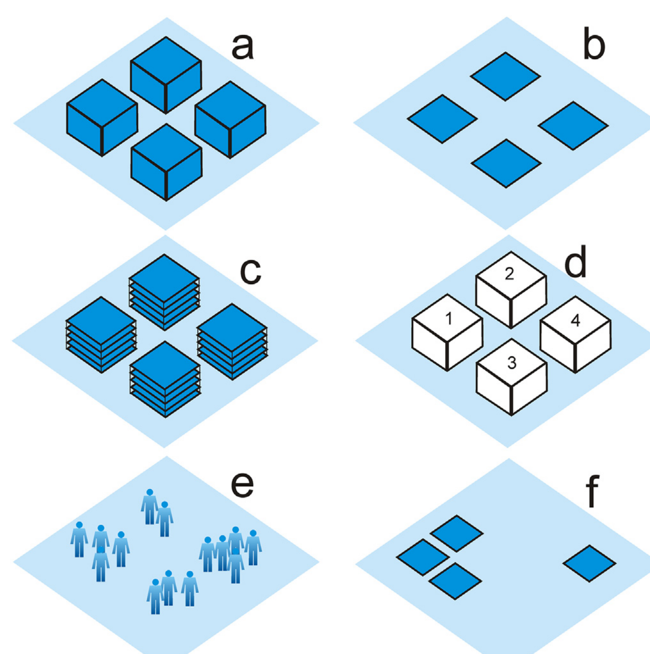

Fig. 2. Schematic presentation of how different indicators of urban compactness are calculated. (a) Volume–area ratio, (b) Site coverage, (c) Plot ratio, and (d) Building density, (e) Population density, (f) Nearest-neighbour ratio.