Renewable Energy 85 (2016) 749–758

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

Feasibility study on the relation between housing density and solar accessibility and potential uses

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ARTICLE INFO

Article history:
Received 28 March 2015
Received in revised form
16 June 2015
Accepted 29 June 2015
Available online xxx

Keywords:
Housing density
Urban area
Solar irradiation
Solar potential and accessibility
Computer simulation

ABSTRACT

This paper aims to address how the solar potential and accessibility of urban housing affects solar energy performance and architectural design. Several simulations were conducted to investigate the relationships between climate conditions and active and passive solar potential by manipulating density-related design factors, including typology, layout, site coverage, floor area ratio (FAR), and number of storeys. The research process consisted of two scenarios: (1) three distinct urban city areas were compared to show the range of solar potential by housing density variation and, (2) 24 generic models of low-rise, mid-rise and high rise housing were analyzed according to changes in density related factors. This research provides a methodology for evaluating solar potential in urban scale and the relationship between housing density and urban design using simulation programs. Based on the outcomes of this research, solar accessibility, the amount of solar irradiation that reaches a building façade and roof, is shown to be related to housing density. The comparison scenarios provide insight into how density and density related factors impact solar potential and, as a consequence, suggest ways to optimize the capacity for solar collection during the initial urban planning phase.

1. Introduction

Today about half of the world's population lives in urban areas and uses about 75% of global resources. As population and environmental concerns increase, the demands for energy efficient housing and urban settlements are becoming increasingly essential [1–5]. In order to promote solar potential and accessibility, studies on passive and active solar energy strategies for urban areas have been conducted in various international locations [6–10], yet little research has been conducted on the effectiveness of design in relation to urban density and energy efficiency. Previous studies have looked at urban energy consumption for differing urban morphologies, and several optimization approaches in urban area have been proposed, based on energy simulations [11–13]. The potential impact of solar energy generation in urban settings or buildings using facade-integrated photovoltaics has also been analyzed [14–16]. Other research has examined details of urban energy consumption related to urban forms including site coverage, plot ratio, and horizontal distribution [17,18]. Recently, urban modeling tools such as CitySIM [19] and SUNtool [20] have been introduced which use computer modeling simulations and techniques to evaluate urban energy performance. However, the effects of urban density on the total energy demand of a city are conflicting and complex [21] since there are a number of entwined energy issues [22] related to density [23]. For example, urban energy consumption is affected by building and urban design patterns, and building energy consumption is related to differences in types of equipment, systems and materials [24,25]. Prior research has primarily focused on energy consumed by transportation on an urban planning scale [26].

To bridge the gap between studies of energy consumption at the transportation urban planning level and current residential energy consumption metrics, it is important to also study solar accessibility related to design both at the building and master plan level. Thus, in this research, we focus on passive and active solar strategies which are particularly important because they require early implementation during the design process, and are typically more influential compared to previous research.

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http://dx.doi.org/10.1016/j.renene.2015.06.070
0960-1481/

A computer simulation was developed to apply quantitative tools to further explore some of the issues extracted from the qualitative research. The simulations applied various measures of solar accessibility to the low-, medium- and high-density sustainable housing developments presented in selected urban areas. The goals of the simulations were: 1) to quantify the effectiveness of the solar technologies used; 2) to compare the effectiveness of particular solar technologies across densities; and 3) to quantify whether solar accessibility was affected by density.

Fundamental design decisions regarding building shape, orientation, and surfaces have to be made at the conceptual design stage of a project when the changes are least expensive [27,28]. Therefore, to increase the effectiveness of various solar applications, it is necessary to have a thorough analysis of solar accessibility. The computer simulations in this study used ray-tracing techniques in order to determine the distribution of solar irradiation on the building envelopes—specifically roofs and facades. In addition, several performance indicators, such as active and passive solar potential, were calculated according to these distributions in order to determine the solar energy utilization strategy for large-scale housing design.

2. Methodology

This section describes the methodology used in this study to find the relationships between climate data and active and passive solar potential, by manipulating density-related design factors including typology, layout, site coverage, and floor area ratio (FAR). The results reveal the interrelations between built forms, density, and solar potential including design criteria such as the potential for photovoltaic, solar thermal collectors, and passive thermal heating.

2.1. Research procedures

The first part of the simulation was conducted on three urban areas. The selection criteria for the cases chosen for the simulation included: unique design qualities, size, representativeness, significance, private and public involvement, and, most important, density. Focusing on density demanded that there be some similarities among the urban areas, such as development scale, site characteristics, comparable attributes, type of development, etc. Because this research focused on completed projects, most of the cases are located in Europe, where sustainable planning was adopted earlier than in other parts of the world. The cases describe (1) Battery Park City, a high-density project in New York City, USA; (2) BO01, a medium-density project in Malmö, Sweden; and (3) solarCity, a low-density project in Linz, Austria. Those three cities were developed and designed by interests in solar utilization. The goal of the comparative analysis was to show the range of solar accessibility levels among the three cases as well as the relationship between solar accessibility and housing density.

The case comparison simulations were conducted using two scenarios. The first scenario calculated solar irradiation using each site's original weather data. (Although Bo01 is located in Malmo, Sweden, weather data from nearby Copenhagen, Denmark was used.) Thus, this scenario considered two variables: density and climatic conditions.

In the second scenario, New York City climatic data was used for all three cases, omitting the weather variable in order to isolate the effects of density on solar irradiation. The building geometry was simplified in order to avoid miscalculation and reduce calculation time.

In the next phase of the simulation, simple generic models of hypothetical low-rise, mid-rise and high-rise housing developments were created. Distinct characteristics of each case were applied to the generic model configurations.

Through the manipulation of density-related design factors, such as height, floor area ratio, lot coverage, and building typology and layout, the relationship between these variables and solar accessibility was demonstrated.

2.2. Computer simulation

The computer simulation was performed using radiation maps and DIVA [29] which was implemented as the GSD in-house plug-in for Rhino, which generates a detailed solar irradiation analysis in the Rhinoceros® program. The radiation maps provided a true measure of the cumulative effects of irradiation on the buildings from the range of unique sky and sun conditions during a set time period. In this three-step process Energyplus annual climate data was obtained; a Perez sky radiance distribution for each hour of interest was generated; and all sky conditions were added together and their value stored in 145 bins. The cumulative sky radiance distribution has been proposed and implemented by several authors, including Mardalejevic [30] and Compagnon [5,6], but this study used Robinson and Stone's [31] approach.

The analysis was done using the ray tracing program Radiance RTrace and RadDisplay [32]. RTrace is designed to support the description of 3D scenes by trace rays in a Radiance scene. RadDisplay is a tool which allows the viewing of Radiance images, luminance and illuminance values, correct exposition, etc.

These purely form-based simulations are directly related to density factors such as built form, building typology, site coverage, floor area ratio, and building height. Detailed attributes of the buildings such as overhangs, canopies, and projections from building facades, were excluded from the simulation as they could have resulted in energy miscalculations and produced inaccurate outcomes.

Although there are a wide range of possible applications for this method of analysis, this particular computer simulation focused on measuring three aspects of solar accessibility. The first was an analysis of the buildings' solar potential. The solar potential of roofs and facades was quantified during a set time period (e.g. annual or winter months) and under specific atmospheric conditions (climate), for active and passive solar heating, photovoltaic electricity production, and day-lighting.

The Radiance Map generates a false-color picture for lighting analysis using input rendered as a Radiance image. The default multiplier of 179 converts radiance or irradiance to luminance or illuminance (kWh/m^2). Illuminance is displayed on a linear scale in specified ranges, where darker areas are represented as blue, and brighter areas move through the spectrum to red. These energetic illuminance maps make it easy to highlight zones for high solar energy collection potential or possible obstacles preventing natural lighting from reaching the exterior envelope of a building (see Fig. 1). Information about the radioactive climate (energy arriving on the site) is taken from the climate database at the meteorological station closest to the site under study. The weather data is in text-based format derived from the Typical Meteorological Year 2 (TMY2) weather format. It is available from EnergyPlus annual climate data provided by the U.S. Department of Energy. The quantity of energy received is cumulated per period (e.g., day, season, and year). Solar irradiation and illuminance values obtained through numerical simulations formed the core part of this approach. Also, the effect of shading and blocking in prototype buildings configuration was automatically applied in simulation programs, which can be varied according to real buildings with exterior ornaments or landscape.