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Evaluation of energy supply and demand in solar neighborhood

Caroline Hachem [a,*], Andreas Athienitis [b], Paul Fazio [c]

[a] Department of Building Civil and Environmental Engineering (BCEE), Concordia University, 1455 de Maisonneuve Blvd., H3G 1M8 West Montreal, Quebec, Canada
[b] Department of Building Civil and Environmental Engineering, Concordia University, West Montreal, Quebec, Canada
[c] Building Envelope Performance Laboratory, Centre for Building Studies, Department of Building Civil and Environmental Engineering, Concordia University, West Montreal, Quebec, Canada

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ABSTRACT

The paper presents a study of solar electricity generation and energy demand for heating and cooling of housing units' assemblages. Two-story single family housing units, located in northern mid-latitude climate are considered in the study. Parameters studied include geometric shapes of individual units, their density in a neighborhood, and the site layout. The plan shapes of the housing units included in this study are rectangles and several variants of L shape. Site layouts studied are characterized by a straight road, a south-facing or a north-facing semi-circular road. Rectangular units and a site layout with straight road serve as reference for evaluating the effect of shape and site parameters. Results indicate that a significant increase in total electricity generation (up to 33%) can be achieved by the building integrated photovoltaic (BIPV) systems of housing units of certain shape-site configurations, as compared to the reference. The energy load of a building is affected by its orientation and shape. Increased heating demand by L variants (by up to 8%) is more than offset by annual electricity production of their BIPV systems (by up to 35%). Heating and cooling loads depend significantly on unit density in a site; Attached units require up to 30% less cooling and 50% less heating than detached configurations of the same site. Variation of surface orientation, particularly in curved site layouts, enables the spread of peak electricity generation over up to 6 h. This effect may be beneficial to grid supply efficiency. Energy balance assessment indicates that some unit shapes generate up to 96% of their total energy use. Neighborhood configurations studied generate between 65% and 85% of their total energy demand.

1. Introduction

The design of net zero energy solar buildings involves a two-fold approach of enhancing energy efficiency while optimizing active solar energy production using photovoltaics and thermal collectors. A net zero energy house (NZEH) generates as much energy as its overall energy consumption, over a typical year [1]. The net zero energy balance can be estimated based on on-site energy consumption or source energy consumption [2]. A successful methodology that may lead to net zero energy status depends upon selecting suitable technical strategies that respond to defined objectives in a specific context [3]. This paper considers the on-site energy consumption.

Coupling energy efficiency measures with active energy production techniques, such as photovoltaic and solar thermal collectors, enables the transformation of buildings into zero-energy systems or even net energy generating systems.

Reduction of energy consumption can be achieved through several measures, such as airtight, well insulated building envelope, implementation of HVAC efficiency measures, including the use of heat pumps, combined with geothermal energy or solar collectors, and finally the use of energy efficient appliances. Window properties and size, especially on the equatorial facade, can maximize passive heating. Solar heat gains can reduce significantly purchased heating energy. A well designed passive-solar building may provide 45–100% of daily heating requirements [4].

Near-equatorial facing roof surfaces are considered optimal for capture of solar energy for electricity and heat generation, and therefore for the integration of photovoltaic/thermal systems. In Canada, building integrated photovoltaic (BIPV) technology is estimated to be potentially capable of providing up to 46% of total energy demand of the residential need [5]. This figure is determined based on a conservative methodology which estimates the available area of roofs and facades for integration of grid connected PV systems, while accounting for architectural and solar constraints [6].

* Corresponding author. Tel.: +1 514 8482424x7080; fax: +1 514 848 7965.
E-mail addresses: c_hachem@encs.concordia.ca, carolinehachem@gmail.com (C. Hachem).

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The performance of a PV system depends mainly on the tilt angle and azimuth of the collectors, local climatic conditions, the collector efficiency, and the operating temperature of the cells. During the winter months, the insolation can be maximized by using a surface tilt angle that exceeds the latitude of the location by 10–15°. In summer an inclination of 10–15° less than the site latitude maximizes the insolation [7]. The PV system is commonly mounted at an angle equal to the latitude of the location, to reach a balance between winter and summer production [8–10].

Building shape plays an important role in governing energy consumption in buildings, as well as having a significant effect on thermal performance and capture of solar energy [11,12]. Rectangular shape is generally considered as optimal for passive solar design and for energy efficiency [13]. However, under certain design conditions in urban context, this shape may not be optimal [12]. For instance, rectangular house plan does not allow uniform penetration of daylight, especially to the north part of the house, where minimum windows are suggested for northern climates. Furthermore, it should be born in mind that shape design is governed by many constraints other than energy efficiency, such as functional demands and quality of life of occupants. For these reasons it is important to explore the penalties, as well as the benefits associated with plan layouts other than rectangular, and with different roof geometries.

Design of solar neighborhoods for exploitation of solar radiation for passive heating, for improved daylight, and for electricity generation, involves consideration of key parameters, including, in addition to building shapes, their density within a site, and the site layout.

Spatial characteristics of neighborhoods and land use regulations can significantly affect solar potential and energy demand of buildings. Land-use patterns influence local temperature distributions [14]. High density development reduces cost and energy use, on one hand while reducing solar accessibility, on the other [15]. Site shape and layout of streets within this site can determine orientation of buildings and thus influence their accessibility to solar radiation [16].

Several studies have focused on investigating the distribution of solar radiation on different surfaces in a built environment, as well as on the availability of solar energy and its optimization, at the urban scale [e.g. 17,18,19]. Compagnon [20] proposed a methodology for estimating the amount of solar energy available to a building of any shape, taking into account obstructions due to the surrounding landscape and associated reflections. Kampf et al. [21] have developed a methodology, employing a multi objective evolutionary algorithm, to minimize energy demand of buildings in an urban area and to maximize incident solar irradiation whilst accounting for thermal losses.

Notwithstanding the interest in the effect of urban development on solar energy, and the various investigations conducted to optimize solar energy, several aspects are not sufficiently addressed. The study presented in this paper forms part of an ongoing research into the effects of certain design parameters of residential neighborhoods on their solar potential and energy performance [11,12,22]. The current study presents an investigation of the electricity generation potential by building-integrated photovoltaic system, and of the energy demand of two-storey single family housing unit assemblages. Climatic data of Montreal, Canada (45°N), serve as input for the analysis. The main objective is the evaluation of alternative patterns of neighborhood to achieve potential net zero energy communities. The main parameters employed in neighborhood design included in this investigation are the shape and orientation of individual units, the density of units in a site, and the site layout.

2. Methodology and design approach

The research presented in this paper is divided into three main parts: (1) the analysis of electricity generation potential by neighborhoods, (2) the analysis of energy performance in terms of heating and cooling consumed by units and neighborhoods, and (3) comparison of energy production and energy consumption of individual units and of whole neighborhoods.

The analysis of electricity generation potential and of energy demand of housing units and neighborhoods is a parametric investigation, in which the effects of three main parameters are assessed. These parameters are the shape of individual units within a neighborhood, the density of units in the neighborhood and the over-all layout of the site in which the neighborhood is located.

The general characteristics of the investigated neighborhoods are based on various sources, including guidelines of urban design, street designs and zoning bylaws [e.g. 23,24,25]. Detailed description of the design of these neighborhoods can be found in Hachem et al. [22]. The design methodology consists of first determining the site layout, followed by design of unit shapes to conform to this layout, and finally combining the shapes in different configurations. For each site, several configurations consisting of combinations of groups of three to six units of a given shape are studied. For each site/shape combination, two densities are considered: medium-low density (around 7 units per acre (u/a)) of detached units [26] and medium-high density (ca. 16 u/a), consisting of attached units. The effect of higher density is studied through configurations of rows of housing units, with varying distance between rows. A maximum practical density of 35 u/a can be reached in some row configurations.

All configurations are subjected to simulations aimed at estimating the BIPV electricity generation and the heating and cooling loads. The simulation employs the EnergyPlus building simulation program [27]. The simulations are followed by a comparative analysis to assess the effect of shape, density and site layout on solar potential and energy performance, relative to a reference case. A rectangle, with aspect ratio of 1.3 and a hip roof serves as the shape reference. The aspect ratio is the ratio of the south-facing facade to the perpendicular facade, and a ratio of 1.3 is considered optimal for passive solar design in northern climate [28]. A site with units arranged along a straight road serves as the site layout reference. Details of the three studied parameters are presented below.

2.1. Characteristics of housing units

The studied housing units are two-storied with constant floor area of 60 m^2 (total livable area of 120 m^2). The two-storey housing option adopted in this study represents one of the most common types of single family homes in Canada [29]. The floor area is based on the need to reduce costs by having a compact design. It should be mentioned that the average floor area for Canadian household, including detached homes, row houses and apartments is 121 m^2, while the average area of single detached house is in the order of 140 m^2 [30].

Two basic shapes are employed – rectangle and L shape. Variations of L shapes are explored to identify design possibilities that enhance solar radiation capture potential on near-south facing roofs and facades. The characteristics of the housing units are detailed in Table 1. The basic design of the units relies on passive solar design principles [13] and rules of thumb [31]. The design ensures that the overall east–west dimension of all units – the solar facade, is larger than the perpendicular dimension (north–south), to maximize passive solar gains in winter. A geothermal heat pump with a coefficient of performance (COP) of 4 is assumed to supplement the passive and active solar heating systems. Ground source heat pumps (GSHPs) can supply heat of up to quadruple the energy