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Study to examine the potential for solar energy utilization based on the relationship between urban morphology and solar radiation gain on building rooftops and wall surfaces

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Abstract

The possibility of solar energy utilization is discussed based on the relationship between urban morphology and solar radiation gain on building rooftops and wall surfaces. It was found that solar radiation on the rooftops of all the buildings in Osaka is reduced to about 86.3% when shadows of surrounding buildings are considered. It is further reduced to about 78.6% when obstacles on the rooftop are added. Power generation is estimated to be 27.3 PJ/year if photovoltaic panels were introduced to all free space on the buildings in Osaka. This corresponds to 1.93 Mt-CO_2/year, with the reduction ratio of primary energy and CO_2 emission being about 12.4% and 8.5% respectively. Solar heat generation is estimated to be 109.1 PJ/year if solar heat collectors were introduced to all free space on the buildings in Osaka. This corresponds to 5.55 Mt-CO_2/year, with the reduction ratio of primary energy and CO_2 emissions being about 49.6% and 24.3% respectively. The relationship between street characteristics and solar radiation on roofs and walls was analyzed for a typical fine summer day. The ratio of solar radiation on wall, roof, and ground surfaces is 17.5%, 25.7%, and 56.8%, respectively, on an average. In residential and industrial areas, there are few buildings, which experience reduced solar radiation on their roofs due to lower building coverage ratio. However, in the city center and in the residential areas, several buildings experience reduced amount of solar radiation on their roofs due to the effect of shadows by surrounding buildings. In the wide north–south and east–west streets, solar radiation on the walls is not reduced, because the heights of the buildings along the main street are aligned. In the narrow north–south streets, solar radiation on the walls is reduced when the opposite building is higher than the building in question. In the narrow east–west streets, solar radiation on the south side walls is not reduced due to the high solar altitude.

Keywords: Urban morphology; Solar radiation gain; Building rooftop; Wall surface

1. Introduction

To promote the use of solar energy, several local governments in Japan have calculated the solar energy potential of the rooftops in their administrative area, with the aim to support private sector introduction of photovoltaic

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panels and solar heat collectors (Tokyo Metropolitan Government, 2014). Previous studies have calculated solar radiation distribution for solar energy utilization with geographic information system (GIS) tools (e.g. Sorensen, 2001). Solar electricity generation potential in the European Union has also been evaluated (Suri et al., 2007; Izquierdo et al., 2008). Solar heating potential has been investigated (Izquierdo et al., 2011), as has the importance of the relationship between urban morphology and solar radiation gain on building rooftops (Robinson, 2006). More detailed studies of solar radiation distribution using GIS tools have been done (Choi et al., 2011; Bergamasco and Asinari, 2011) along with analyses of solar radiation gain on the rooftop and roof shape/area (Wiginton et al., 2010; Bergamasco and Asinari, 2011). Local governments need to identify the potential of solar energy use to prioritize policy. In this study, the potential for solar energy utilization is discussed based on the relationship between urban morphology and solar radiation gain on building rooftops and wall surfaces. In particular, the amount of solar radiation gain on building rooftops is analyzed by focusing on the influence of shadows from surrounding buildings and obstacles, and by surveying rooftop use. As the result, effective knowledge will be derived for future urban planning.

2. Calculation of solar radiation

We calculated solar radiation using the ArcGIS tool. Osaka was chosen as the study site because its land cover is similar to Tokyo 23 wards and Nagoya, and thus it may be considered a typical large city in Japan (see Fig. 1 for land cover types). The city office of Osaka provided data on building shapes, which encompassed 634,228 buildings within an area of 221.3 km^2. The roof area of all the buildings was 70.8 km^2. The mesh size was: 1.0 m on the horizontal side, and 3.5 m on the vertical side. The solar radiation calculation procedure (Rich et al., 1994; Fu and Rich, 2002) is as follows:

i. The visible area of the upper hemisphere is calculated taking into account the influence of the adjacent buildings. The visible area is then overlaid with the sunmap

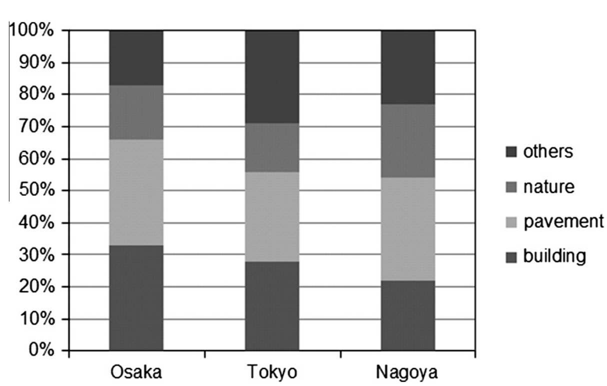

Fig. 1. Types of land cover in Osaka, Tokyo 23 wards, and Nagoya.

and skymap rasters to calculate diffuse and direct solar radiation received from each direction. Examples of overlays of the visible area with the sunmap and skymap are shown in Fig. 2.

ii. Direct solar radiation ($\mathrm{Dir_{tot}}$) is calculated by superimposing the solar orbital diagram for the visible area using following equation.

$$\mathrm{Dir_{tot}} = \Sigma \mathrm{Dir}_{\theta,\alpha} \tag{1}$$

The direct solar radiation from the sunmap sector at zenith angle θ and azimuth angle α is calculated using following equation.

$$\mathrm{Dir}_{\theta,\alpha} = \mathrm{S_{const}} * \beta^{m(\theta)} * \mathrm{SunDur}_{\theta,\alpha} * \mathrm{SunGap}_{\theta,\alpha} * \cos\left(\mathrm{AngIn}_{\theta,\alpha}\right) \tag{2}$$

where $\mathrm{S_{const}}$ is solar constant (=1367 $\mathrm{W/m^2}$), β is the transmissivity of the atmosphere for the shortest path, $m(\theta)$ is the relative optical path length represented by the following equation, $\mathrm{SunDur}_{\theta,\alpha}$ is the time duration, $\mathrm{SunGap}_{\theta,\alpha}$ is the gap fraction, $\mathrm{AngIn}_{\theta,\alpha}$ is the angle of incidence represented by the following equation.

$$m(\theta) = \exp(-0.000118 * \mathrm{Elev} - 1.638 * 10^{-9} * \mathrm{Elev}^2)/\cos(\theta) \tag{3}$$

where θ is the solar zenith angle, Elev is the elevation above sea level.

$$\mathrm{AngIn}_{\theta,\alpha} = a\cos(\cos(\theta) * \cos(G_z) + \sin(\theta) * \sin(G_z) * \cos(\alpha - G_a)) \tag{4}$$

where G_z is the surface zenith angle, G_a is the surface azimuth angle.

iii. Diffuse solar radiation ($\mathrm{Dif_{tot}}$) is calculated by superimposing the whole sky division diagram for the visible area using the following equation.

$$\mathrm{Dif_{tot}} = \Sigma \mathrm{Dif}_{\theta,\alpha} \tag{5}$$

The diffuse solar radiation from the skymap sector at zenith angle θ and azimuth angle α is calculated using following equation.

$$\mathrm{Dif}_{\theta,\alpha} = R_{\mathrm{glb}} * P_{\mathrm{dif}} * \mathrm{Dur} * \mathrm{SkyGap}_{\theta,\alpha} * \mathrm{Weight}_{\theta,\alpha} * \cos(\mathrm{AngIn}_{\theta,\alpha}) \tag{6}$$

where R_{glb} is the global normal radiation represented by the following equation, P_{dif} is the proportion of diffused global normal radiation, Dur is the time interval for analysis, $\mathrm{SkyGap}_{\theta,\alpha}$ is the gap fraction, $\mathrm{Weight}_{\theta,\alpha}$ is the proportion of diffuse radiation represented by the following equation, and $\mathrm{AngIn}_{\theta,\alpha}$ is the angle of incidence.

$$R_{\mathrm{glb}} = \mathrm{S_{const}}\ \Sigma(\beta^{m(\theta)})/(1 - P_{\mathrm{dif}}) \tag{7}$$

$$\mathrm{Weight}_{\theta,\alpha} = (\cos\theta_2 - \cos\theta_1)/\mathrm{Div_{azi}} \tag{8}$$

where θ_1 and θ_2 are the bounding zenith angles, $\mathrm{Div_{azi}}$ is the number of azimuthal divisions.