Calculating potential of solar energy and CO₂ emissions reduction for city-scale buildings based on 3D remote sensing technologies

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ABSTRACT

Solar energy utilization will play an increasingly important role in sustainable urban development because it will help motivate low-carbon development. This study proposed a framework that calculates the solar irradiance on roofs and façades of city-scale buildings, as well as the potential reductions in energy consumption and CO₂ emissions that can be derived from solar energy utilization. This framework consolidates data acquired using 3D remote sensing techniques (e.g., light detection and ranging (LiDAR) data and digital photogrammetry) with existing 3D building vector models from urban planning and building design. To further the economical use of solar energy, the framework provides a new strategy based on three aspects (threshold, structure, and orientation), for a more realistic analysis of the available area of roofs and façades, by combining street view images and point clouds. Nanjing, China, was selected as a study area for validating and analyzing the proposed framework. The experimental area covers approximately 30 km² and 5216 buildings. The reliability of the proposed method was validated by comparing the results with the computation modules of mainstream commercial programs and previous international studies. The following conclusions were drawn from the experimental area. (1) Annual solar energy on the roofs of all buildings was 9647.89 GWh, corresponding to a PV yield of 1447.18 GWh, which equates to reductions of 584.66 kt in standard coal consumption and 1261.94 kt in CO₂ emissions. The annual solar energy on the façades was 5364.63 GWh, corresponding to a PV yield of 804.69 GWh, which equates to reductions of 325.10 kt in standard coal consumption and 701.69 kt in CO₂ emissions. (2) Based on the calculated potential solar energy utilization of the building envelopes, it was shown that the utilization of solar radiation on roofs and façades would promote low-carbon urban development. The utilization of solar energy on the façades of high buildings will contribute to the supply of energy for these buildings and help balance their energy consumption. (3) As the solar incidence angle changes over time, the reductions in energy consumption and CO₂ emissions related to PV power generation are maximal in summer for building roofs, whereas no significant seasonal differences were observed for façades. (4) Incorporating the available area translates the utilization of solar energy and potential CO₂ reductions from theory to practical application by reducing inefficient and invalid areas. The percentages of available area of roof and façade were estimated at 47% and 16% by comprehensive calculations considering three aspects (threshold, structure, and orientation). The corresponding potential of solar energy on the roofs and façades in the validation area B are 167.18 GWh and 53.63 GWh, respectively, compared to the original theoretic values of 316.97 GWh and 237.98 GWh.

1. Introduction

Rapid urban development requires a continually increasing supply of energy. Fossil fuels have provided the primary driving force for socioeconomic development, but the growth of the global economy has come at the expense of the environment (Dennison et al., 2013; Schaefer et al., 2016). Emissions of greenhouse gases (GHGs), e.g., CO₂, CH₄, and N₂O, generated by the burning of fossil fuels and cement
manufacture, the cumulative carbon emissions of which have already exceeded 350 billion tons, have caused global air temperatures to increase noticeably (Boden et al., 2011; Buchwitz et al., 2015). Increases in the global population and in its demand for energy have driven the total primary energy supply (TPES) from $2.55 \times 10^8$ TJ in 1971 to $5.74 \times 10^8$ TJ in 2014, while global electrical power consumption has increased from $1.84 \times 10^7$ to $7.14 \times 10^7$ TJ (fossil fuel power generation accounts for 66.70% of the world's total electrical power generation) in 2014 (IEA, 2016b). The U.S. Energy Information Administration has predicted that global energy consumption will grow by 56% between 2010 and 2040 (U.S. Energy Information Administration, 2013). The average annual growth of renewable energy sources since 1990 has been approximately 2.2%, which is higher than the 1.9% growth rate of the TPES. In particular, global photovoltaic (PV) solar energy generation has an average annual growth of 46.2%, as shown in Fig. 1 (IEA, 2016a). To ensure sustained sociological development, there is urgent need to promote the development of renewable energy technologies and to increase the output of renewable energies; the utilization of solar energy in cities is especially important in achieving these goals (Castro et al., 2013; IPCC, 2011; Kannan and Vakeesan, 2016).

Urban buildings consume large amounts of energy because they constitute primary functional bodies of cities. The energy consumption of buildings accounts for a significant proportion of total energy consumption. For example, the energy consumption of buildings accounts for 40%, 41%, 28%, and 25% of the total energy consumption in Europe, the United States, China, and Japan, respectively. Although the energy consumption of buildings varies by country, the global annual average of the energy consumption of buildings per unit area is approximately 200 kWh/m$^2$ (Blawas et al., 2016; Ma et al., 2017; Yan et al., 2017). To balance the energy consumption and energy supply of buildings, and to reduce environmental pollution, researchers from a wide range of fields are studying methods for increasing the utilization of renewable energies (Foley and Olabi, 2017). Studies have shown that in certain regions, solar electricity generation has greater potential than solar thermal systems, and PV power generation is currently the primary form of solar energy utilization (Si et al., 2016). The surfaces of buildings receive large quantities of solar radiation, and the conversion of this solar energy into electrical power will help supply energy for productive activities and help reduce the consumption of fossil fuels; thus, decreasing the emission of GHGs (Hammer et al., 2003; Luthander et al., 2015). However, unlike conventional power generation facilities, location has considerable effect on the yield of PV power generation systems (Wang et al., 2014). Therefore, accurate calculations of the solar irradiance of building envelopes are necessary for informing the appropriate deployment of PV power generation facilities and the prediction of their yields, as well as informing analyses on the consequent reductions in energy consumption and GHG emissions (Angelis-Dimakis et al., 2011; Fogl and Moudry, 2016). The currently accepted methods for accurate calculations of solar irradiance on building envelopes are based mainly on 3D information of building envelopes and the use of solar radiation models (Li et al., 2016).

People started to investigate solar radiation models in the 1960s. The sky was largely assumed to be isotropic in early studies, i.e., diffuse radiation was assumed to be uniformly received from the sky hemisphere (Kondratyev and Manolova, 1960; Liu and Jordan, 1963). As radiation models became increasingly sophisticated, anisotropic effects and the effects of the atmospheric environment on solar radiation were also taken into consideration. The incident surfaces also developed from simple horizontal surfaces to inclined surfaces (Perez et al., 1986; Gueymard, 1987; Muneer, 1990). Besides, the diffuse component is more complex than direct radiation, as variations in atmospheric parameters such as moisture, aerosols, and large particulate matter concentrations, significantly influence the intensity of diffuse radiation (Zhao et al., 2016). Therefore, we need to consider the geographical environment, data acquisition, and the scale of the study area comprehensively in solar radiation model when calculating solar irradiance. As numerous radiation models of various types are presently available, analyses and comparisons between solar radiation models have been reported (Demain et al., 2013; Muneer and Saluja, 1985; Wattan and Janjai, 2016).

With the development of 3D remote sensing techniques, which are represented by light detection and ranging (LiDAR) and photogrammetry, there is increasing need to incorporate slope, aspect, and shading into building irradiance calculations (Kodysh et al., 2013). Digital surface models (DSM) can be constructed via airborne LiDAR data, stereo images, and image registration (Eckert and Hollands, 2010; Shi et al., 2009; Zhang and Gruen, 2006), and these models can describe surface landscapes in three dimensions, while having simple data structures and high computational efficiencies, widely applied in street- (Wang et al., 2016), city- (Brito et al., 2012), and national-scale (Assouline et al., 2017) solar irradiance studies. Slope, aspect, and shading of buildings provided by DSMs are especially effective for city-scale calculations of direct, diffuse, and global radiation on building roofs (Li et al., 2016). Studies of solar irradiance based on DSM calculations often used the Solar Analysis Tool (SAT) within the ArcGIS software suite and the r.sun model of the GRASS program, and both of two mentioned methods are relatively mature (Kodysh et al., 2013; Fu and Rich, 1999; Hoferka and Suri, 2002; Li et al., 2015; Redweik et al., 2013; Šuri and Hoferka, 2004; Takebayashi et al., 2015). The r.sun model accounts for the effects of terrain, dimensionality, turbidity, and the Clear-Sky Index and the combination of transient and daily modes of the model can calculate the solar radiation at any given time period (Hoferka and Suri, 2002). Especially, the Photovoltaic Geographic Information System (PVGIS) with a resolution of $1 \times 1$ km, calculates solar irradiance for Europe, Africa, and Asia on monthly and yearly time scales based on the r.sun model (Huld et al., 2012).

As building heights in cities continue to increase, the potential of solar radiation incident on building façades will effectively increase the utilization rate of solar energy in urban buildings. 3D building models are used as input data for this task to get detailed information of building façades instead of DSM models with 2.5D character. Calculation methods using 3D models are similar to DSM-based methods. Analysis of building shadows, diffuse coefficient calculation, and solar radiation models selection are still included (Catina et al., 2014). V.sun is already being used to calculate solar irradiance on building façades improved based on r.sun model that is appropriate for 3D vector data (J and M, 2012). In addition, anisotropic sky models,
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