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Energy performance simulation for planning a low carbon neighborhood urban district: A case study in the city of Macau

Zhengwei Li [b, c], Steven J. Quan [a, b], Perry Pei-Ju Yang [a, b, *]

[a] Sino-U.S. Eco Urban Lab, College of Architecture, Georgia Institute of Technology, Atlanta, GA, USA
[b] Sino-U.S. Eco Urban Lab, College of Architecture and Urban Planning, Tongji University, Shanghai, China
[c] College of Mechanical Engineering, Tongji University, Shanghai, China

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ABSTRACT

The concept of a low carbon city has been widely discussed. The research in low carbon city simulation at the community level, however, is still underexplored. A GIS-based simulation model was proposed for testing how urban form and building typology affect energy performance and carbon emissions. Two urban districts in the City of Macau were chosen as sample test cases based on two approaches of carbon emissions analysis, land use-based and building simulation methods. The result shows that the building simulation method is 20% more accurate than the land use based-method in comparison to the actual measurement by including the factor of building shape in the simulations. The analytical results of energy performance, carbon emissions and solar availability were then used to derive urban design guidelines to move the city development toward a low carbon future.

1. Background

Macau as a historical city is well known for its tourism and gambling industry. In recent years, especially after its handover to China in 1999, Macau experienced rapid urban development due to the influx of immigrants from mainland China and the real estate boom related to the dramatic expansion of casino and hotel lands, which resulted from new immigration policies and more liber gambling policies (Pinheiro & Wan, 2008). From 1990 to 2014, Macau's urban area increased from 17.4 km^2 to 30.3 km^2 and the population grew from 339,500 to 636,200, almost doubling in 15 years (Statistics and Census Service, 2015). Over the same period, Macau's economy (measured as GDP in constant US dollars) increased even faster, growing from 5.2 billion to 30.2 billion (World Bank, 2015). In 2006, Macau's gambling and tourism revenue reached 6.95 billion US dollars and surpassed Las Vegas (6.6 billion US dollars) as the premier gambling destination in the world (Pimentel, 2012).

However, such drastic urban development also brought many problems and challenges to the city, including dramatically increased energy consumption. The electricity consumption per capita measured in 1000 kWh/people increased from 2.3 in 1990 to 7.5 in 2014 (Statistics and Census Service, 2015). In 2009, the total carbon emitted from this city was 5,477,762 tons, with an average carbon emissions per capita rate of 9.9 tons/capita and the average carbon emissions per square meter of 181,925 tons/km2. Along with those challenges, Macau also experienced an increase in public disputes over the city government and planning department's unpreparedness and lack of planning (Lee, 2014; Qunli, 2015). For example, some scholars argued that Macau's role as a "growth machine" (Molotch, 1976) led to biased, pro-growth planning that disregarded the need for sustainable development (Chui & Zhao, 1999; Lee, 2014; Pinheiro & Wan, 2008; Tieben, 2009; Yu, 2009). In response to these disputes, Macau's government began to promote a more holistic planning approach geared toward sustainable development: developing several plans such as the "Conceptual Planning on Macau's Urban Development" (CEEDS, (Centro de Estudos Estratégicos para o Desenvolvimento Sustentável), 2010) and the "Environmental Protection Planning of Macao (2010–2020)" (DSPA (Macao Environmental Protection Bureau), 2010), publishing reports on energy efficiency in Macau in 2007, 2011 and 2013 (Office for the Development of the Energy Sector of the Macao Special Administrative Region, 2008, 2012, 2014), and developing guidelines for green buildings in 2009 and

* Corresponding author. College of Architecture, Georgia Institute of Technology, Atlanta, GA, USA.
E-mail address: perry.yang@coa.gatech.edu (P.P.-J. Yang).

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for solar thermal collector devices in 2010 (Office for the Development of the Energy Sector of the Macao Special Administrative Region, 2009, 2010). These new goals were exemplified in the waterfront reclamation project approved in December 2009, which aims to build a "world leading low carbon ecological city".

While these policies have placed a new emphasis on energy efficiency, carbon reduction and sustainable urban development, there has been little discussion as to how much the new district development will contribute to these goals. This research strives to answer this question by investigating the energy and carbon performance of the city through benchmarking two selected existing neighborhood-scale urban districts. The research focuses on energy use in the building sector, as it accounts for a large share of the total energy consumption in cities (Perez-Lombard, Ortiz, & Pout, 2008), as well as the renewable energy potentials in the built environment. In examining these questions, we elucidate a set of low carbon urban design principles to inform the development of the new urban district.

In recent years, Macau's government has begun to explore innovative ways to produce and use new forms of renewable energy. Currently, solar energy is the easiest form of renewable energy to harvest, and Macau has created some guidelines to encourage the growth of solar energy (Office for the Development of the Energy Sector of the Macao Special Administrative Region, 2009, 2010). While Macau has studied other forms of renewable energy, such as Hybrid Solar-Wind Renewable Energy technology (Institute for Entrepreneurship, 2013), this study focuses on solar energy and how urban form can contribute to energy performance of the city. As of yet, Macau has not implemented any solar energy subsidy programs; however, we hope the information in this paper will encourage Macau's government to consider establishing such policies.

This research produces a low carbon urban design framework that will act as a guide for policy makers, planners and citizens in the City of Macau to begin using urban planning and design to implement these principles.

2. Energy and carbon efficiency of urban form: a brief literature review

The idea of low carbon urban design suggests that energy and carbon performance can be changed through urban design, by altering the urban form and building typologies to meet lower carbon emission standards. Low carbon urban design focuses on measuring energy performance and carbon efficiency and how they can be optimized at the level of street blocks, neighborhoods and urban districts. Regarding energy performance, building energy use is of particular interest to planners and designers because it constitutes a large share of the total energy use in cities. Although methods of building energy performance are well documented, measurements of urban-scale building energy performance have yet to be developed (Chingcuanco & Miller, 2012; C. Ratti, Baker, & Steemers, 2005, 2003). Energy flows in cities transcend traditional territories and administrative system boundaries (Grubler & Fisk, 2012). It is difficult for researchers to obtain data at the individual unit-, block-, and district-levels due to problems with data accessibility, confidentiality, etc. As a result, researchers tend to define wider-scale territories, e.g. entire cities or metropolitan areas, as the system boundary and use the system input–output method to investigate the total primary energy supply in territorial analysis or the regional energy statistics of final users (Steinberger & Weisz, 2013). This top-down approach illuminates the distribution of energy supply and demand among a variety of sources, and provides an overall picture of energy consumption and the carbon footprint (Brown, Southworth, & Sarzynski, 2009; Sovacool & Brown, 2010), including in the building sector, which is especially useful in guiding urban or regional level policy and planning. However, the top-down approach fails to illuminate the internal structure of cities and how this affects energy performance. Therefore a bottom-up approach will be necessary to better understand and address this problem (Ishii, Tabushi, Aramaki, & Hanaki, 2010).

To calculate building energy use, different methods have been proposed to scale up from a building system to the block-, district- or neighborhood-level in the building sector using a bottom-up modeling approach. In all of these methods, buildings in the study area are categorized into different groups, each characterized by different features, such as floor area (Jones, Lannon, & Williams, 2001; Shimoda, Fujii, Morikawa, & Mizuno, 2004), window-to-wall ratio (Jones et al., 2001), building age (Jones et al., 2001; Zhao, Martinez-Moyano, & Augenbroe, 2011), household type (single family, aged couple, etc.) (Shimoda et al., 2004), dwelling type (detached house or apartment house) (Shimoda et al., 2004), building functional type (Zhao et al., 2011), climate zone (Zhao et al., 2011), etc. By calculating the energy consumption of a representative building in a category, the energy consumption of that specific category is calculated by aggregating the buildings in that group, and the total energy consumption in the building sector is derived by an aggregation of the results from all categories. However, these methods differ in how they relate building characteristics to energy consumption. While some take into account more detailed input information such as microclimate weather information, thermal properties of building envelopes, occupant behavior, etc. (Shimoda et al., 2004), others are based on artificial calculation procedures that have been validated by numerous cases (Jones et al., 2001; Zhao et al., 2011). Methods that deploy dynamic simulation models vary in how they measure and treat occupant behavior. Some methods assume a static activity schedule for occupant behavior (Shimoda et al., 2004), while other methods use a more realistic probability based occupant behavior approach (Yamaguchi, Shimoda, & Mizuno, 2007).

For renewable energy potential in urban environment, models and tools are available particularly for calculating solar. These models can be differentiated by their principle, suitable application scale, accuracy, etc. Based on the application scale, methods to calculate solar accessibility can be divided into two groups: micro-scale analysis tools (such as Ecotect, Designbuilder, etc.) and macro-scale analysis tools (such as SOLWEIG). Micro-scale analysis tools are typically more accuracy and can be used for modeling the urban environment at the neighborhood-level (Taleghani, Tenpierik, van den Dobbelsteen, & de Dear, 2013), while macro-scale analysis is usually quicker and more cost effective when analyzing the city-scale environment (Thorsson, Lindberg, Björklund, Holmer, & Rayner, 2011). Due to its ability to integrate data from different resources, the Geographic Information System (GIS) is being used more and more often as a platform for solar radiation analysis (Wong, Jusuf, & Tan, 2011).

Regarding to the relationship between urban form and energy performance, researchers have established the link between urban design parameters (density, building typology, layout, etc.), energy production (renewable energy potential) and energy consumption (building energy demand) (C. Ratti et al., 2005; Steemers, 2003; Steinberger & Weisz, 2013). Among the urban design parameters, the geometry of the building is one of the most important factors in determining the building's energy use (Al-Homoud, 2001). Many studies in building energy simulation have attempted to find the optimal shape of an energy-efficient building (Depecker, Menezo, Virgone, & Lepers, 2001; Tuhus-Dubrow & Krarti, 2010); however, the computational time of the synoptic approach that these studies took was far greater than the typology approach, in which the real-world building shape is not a random distribution, but