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Energy self-sufficiency of office buildings in four Asian cities

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Abstract. This paper examines the climatic and technical feasibilities of zero energy buildings in Seoul, Shanghai, Singapore and Riyadh. Annual and seasonal energy demands of office buildings of various scales in the above cities were compared. Using optimally tilted rooftop PV panels, solar energy production potentials of the buildings were estimated. Based on the estimates of onsite renewable energy production and building energy consumption, the energy self-sufficiencies of the test buildings were assessed. The economic feasibilities of the PV systems in the four locations were analyzed. Strategies for achieving zero energy buildings are suggested.

Keywords: zero energy building; solar energy production; climatic variation; Asian cities

1. Introduction

As renewable energy technologies are becoming more efficient and affordable, energy generation from onsite solar, wind or geothermal systems is becoming technically and economically feasible (Weber *et al.* 2006 and Wang *et al.* 2009). Incorporation of energy producing devices in buildings is a normalcy in design practice (Okeil 2010). Building integrated photovoltaics (BIPV) and wind turbines can produce a practically meaningful amount of energy that lessens a building's reliance on the local utility company (Elkinton *et al.* 2009). Going a step further, it is possible to build a building that produces all the energy that it consumes onsite. Small-scale zero energy buildings or homes are no longer an ideal for sustainability, but are a feasible reality. With these advances in renewable energy technologies and ever-growing concerns for the environment, the Architecture 2030 Challenge calls for all new buildings to be carbon-neutral by 2030. The US *Energy Independence and Security Act* requires all new federal buildings and major renovations to comply with the energy performance targets of the Architecture 2030 challenge (US Congress 2007). The European Union *Directive 2010/31 on the Energy Performance of Buildings* mandates to transform all existing or new buildings to be zero energy or near zero energy by 2020 (EU 2010). Are these regulations and public policies for zero energy buildings implementable, or are we targeting for unachievable goals? Are zero energy skyscrapers really possible by 2030? What are technological advances on the horizon that will make zero energy buildings possible by 2020 or 30? These are the questions that motivated this study.

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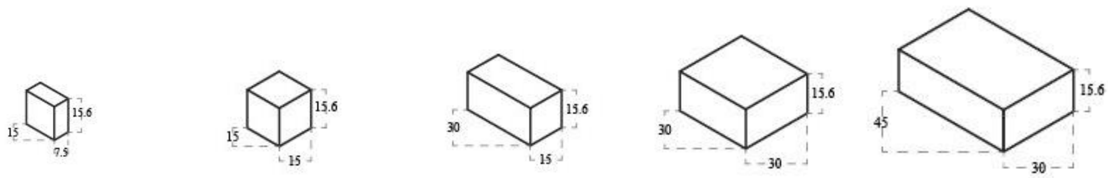
A feasibility study on residential scale zero energy buildings revealed that single family homes equipped with PV panels covering the entire roof surface achieved 100 percent energy self-sufficiency in most regions of the US with an exception in cold climates (Kim and Gerow 2012). Two-story 186 m^2 homes with a 93 m^2 rooftop PV system installed horizontally in Miami (hot and humid climate), Phoenix (hot and arid climate) and San Francisco (marine climate) actually produced surplus energy. The identical home in Detroit (cold climate) was cable of achieving 70% energy self-sufficiency. When additional PV cells are installed on the south façade, net-zero energy homes are achievable in cold climates.

2. Materials & methods

If zero energy residential homes are feasible, is it also possible to achieve nonresidential zero energy buildings? With the current PV efficiency, what is the size limit for achieving zero energy commercial buildings? This study investigates the climatic, technical and economic feasibilities of non-residential zero energy buildings that incorporate a PV system as the onsite renewable energy production technology. Investing the relationship between building size and energy self-sufficiency was the key objective. The feasibilities of small to medium sized office buildings in various climatic contexts were investigated: Seoul, Shanghai, Singapore and Riyadh representing cold, hot and humid, marine coastal, and hot and dry climates respectively.

2.1 Test buildings

The target building type was office. In order to analyze various building geometries in a modular way, a volumetric unit of building, called a voxel, was defined. A voxel is a 15 m wide 15 m deep and 15.6 m high box. The height of the voxel, 3.9 m × 4, is that of typical four-story office building. Using multiplications of this volumetric unit, five test buildings, Buildings A, B, C, D and E, were defined as below (See Fig. 1). The height of the five test buildings was fixed at a constant 3.9 m. The aspect ratios of the test buildings range from 1 to 2. Buildings A, C and E were elongated along the east-west axis exposing their two largest vertical surfaces to south and north, and had aspect ratios ranging from 1.5 to 2 and. Buildings B and D had an aspect ratio of 1 and contained square floor plans. The floor plan of Building-E was 45 m wide and 30 m deep, having an aspect ratio of 1.5, which is approximately the same aspect ratio and floor plan of the Seagram Building in New York. Because of daylight admission and views from interior spaces,



(a) (b) (c) (d) (e)

Fig. 1 Five rest nuildings (a) through (e) (unit: m)

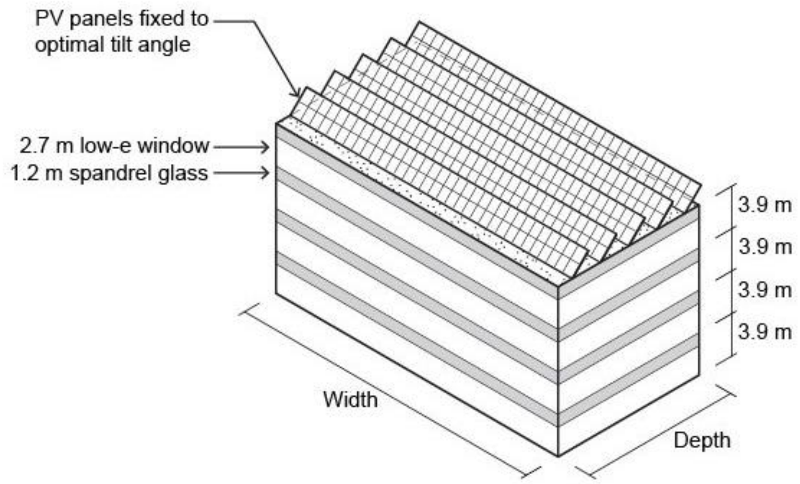


Fig. 2 Building façade dimensions and PV panels of test buildings

the depth of office buildings does typically not exceed 30 m. As such, the 30 m represents a common maximum building depth of office buildings. The wall construction of the test buildings consists of 5 cm × 15 cm metal frame, 60 cm on center, with fiber glass insulation in between studs. The exterior of the walls was finished with spandrel glass and 0.75 cm fiber board sheathing inside.

The test buildings facades consisted of 2.7 m high double-pane argon filled low-emissivity (emissivity = 0.4) windows and 1.2 m high glass spandrel walls (See Fig. 2). The window to wall ratio was 0.69. The U-value of the windows was 2.026 W/m^2-^{0}C, the solar transmittance was 0.63, and the visible transmittance was 0.78. The windows had no overhangs. The U-value of exterior walls was 0.483 W/m^2-^{0}C, the standard insulation value of a typical spandrel glass wall.

The buildings employed water chillers as their cooling source and boilers as their heating source. The air distribution system was a standard variable air volume (VAV) system with a hot water reheat system. The air infiltration rate through exterior enclosures was assumed to be 0.38 cfm/m^2. Internal loads included lighting (7.5 W/m^2) and plug loads (15 W/m^2).

2.2 Onsite energy production system

Photovoltaic cells tilted to an optimal angle on the roof were the energy production technology for the test buildings. PV sizing was based on the assumption that the entire surface of a roof is covered with PV panels. For instance, a building having a 100 m^2 roof surface also has a 100 m^2 PV system. Fig. 3 shows the optimal tilt angles in Seoul, Shanghai, Singapore and Riyadh. It was assumed that PV panels were open to the entire sky and received both direct beam radiation, diffuse sky radiation and ground reflected radiation. The efficiency of the PV systems was assumed to be 18.5%, and their life, 30 years. The capital costs for the PV systems including solar cells, inverters and installation labor was assumed to be \$980/m^2 (Jakubiec and Reinhart 2012). The efficiency of the PV systems, 18.5%, includes the PV cell conversion efficiency and inverter

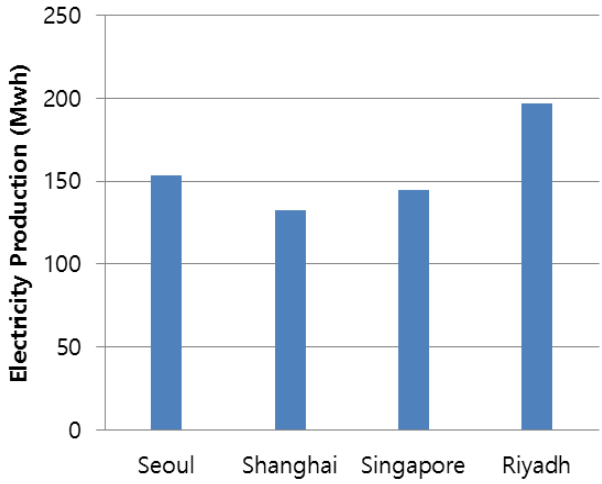


Fig. 4 Electricity production from rooftop PV panels

and other component energy losses. It represents the lifetime average PV system efficiency taking into account temperature variation and dust accumulation.

2.3 Onsite energy production

The amount of solar energy produced is a linear function of the solar irradiance incident on PV panels, I_g, the conversion efficiency of PV cells, η, and the surface area of solar cells, *A*, as

$$E_a = I_g A \eta \tag{1}$$

The optimal tilt angles for solar panels are a function of their latitudes. The solar energy and electricity produced from the PV systems was calculated using the optimal tilt angles and the solar irradiance data published by the National Aeronautics and Space Administration. The optimal tilt angles of solar panels for the four cities are shown in Fig. 3.

Onsite electricity produced from the 450 m^2 rooftop PV panels is shown in Fig. 4. The PV panels in Riyadh produced the highest onsite electricity followed by Seoul, Singapore and Shanghai, which produced the lowest. Buildings in Shanghai can produce approximately 80% and 68% of electricity production in Seoul and Riyadh. Rooftop PV systems in Shanghai and all other Asian cities are a feasible option for onsite renewable energy production.

3. Building energy demands

3.1 Annual energy demands

The influence of different climates on a building's energy demand was compared for identical buildings in four cities. It was found that the test building in Singapore demands the highest amount of energy, while that in Seoul demands the lowest. However, the influence of this climatic variation did not affect the annual energy consumption significantly. Fig. 5 shows the annual energy consumption of Building E, four-story office buildings with a 45 m wide 30 m deep floor plan. The identical office building in Seoul and Shanghai consume similar amounts of energy. The buildings in hot climates, Singapore, hot and humid, and Riyadh, hot and dry, require about 25% more energy than those in Seoul or Shanghai. A majority of the energy demands in the test office buildings are electricity for lighting, cooling and plug loads. In general, gas energy for space and water heating require only a small fraction of the energy consumption of office buildings in the four cities. In Seoul and Shanghai gas energy represents about 15 to 20% of the building's total energy demand. In Singapore and Riyadh, gas energy represents less than 3% of this demand. From this analysis, it can be concluded that onsite renewable systems for zero energy office buildings must be primarily ones geared to produce electricity as opposed to heat.

A detailed breakdown of the energy loads (Fig. 6) for the test office buildings in Seoul reveal that cooling, ventilation fans and pump operations combined represent 32% of the total energy demand, followed by office equipment and lighting. Space heating is responsible for only 15% of office building energy consumption. Cooling and fan operation represent 57%, the largest single

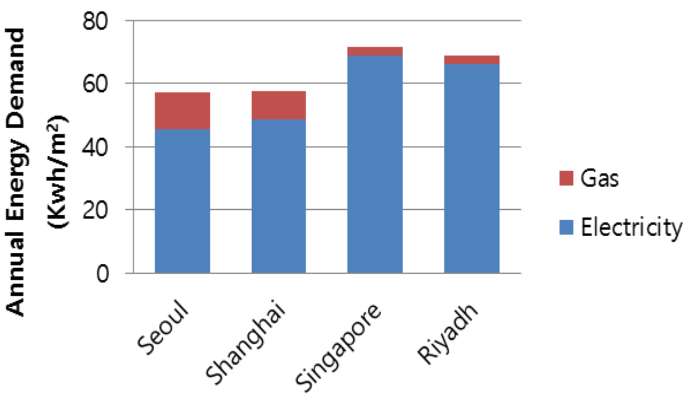


Fig. 5 Annual energy demands of type-E office buildings

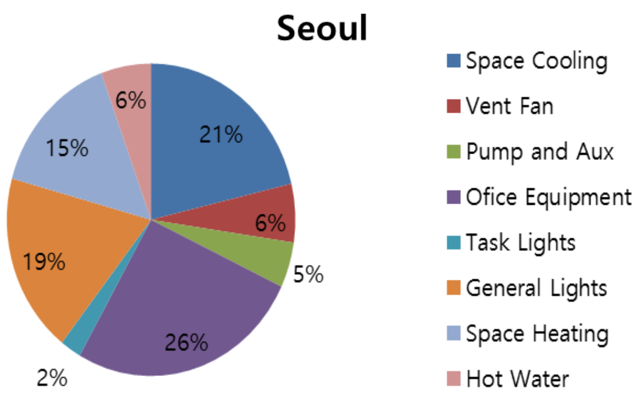


Fig. 6 Energy consumption components of the test building (45 m × 30 m, Seoul)

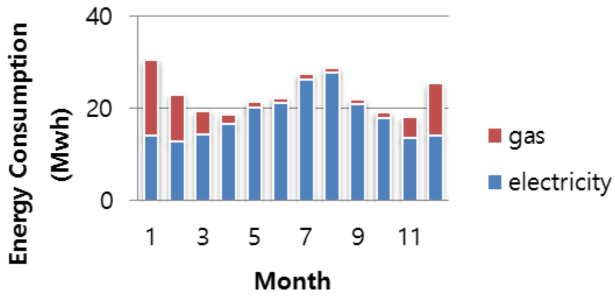


Fig. 7 Monthly energy demands in Seoul

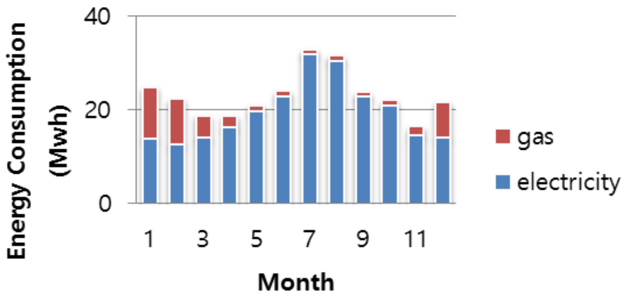


Fig. 8 Monthly energy demands in Shanghai

energy demand, followed by office equipment (22%) and lighting (18%). From this breakdown, it is found that heat gain prevention strategies should be the top strategies for building energy conservation and zero energy design.

3.2 Seasonal energy demands

The seasonal energy demand patterns have implications on several factors in zero energy building systems: (1) renewable energy system sizing; (2) energy storage sizing; and (3) utility buyback connection need.

The monthly energy demands of the four cities reveal different patterns. In Seoul, which has cold winters and hot summers, the peak energy demands of the test buildings occur twice a year: in January ascribing to heating loads and in August to air-conditioning loads. The overall monthly energy demands show a sine-curve distribution. The monthly energy demands in Shanghai have a similar pattern to that of Seoul, i.e., double peaks in a year. However, in Shanghai the summer peak is higher than that of winter.

Singapore shows small seasonal variation in energy demands. Therefore, if a renewable energy system is sized for July demands, it will meet the energy demands for most of the year (zero energy) without having to either store or sell surplus energy to the local utility company. In contrast, the monthly energy demands of the buildings in Riyadh, a hot and dry climate, are highly season-dependent, more specifically solar availability dependent. In Riyadh, the peak energy

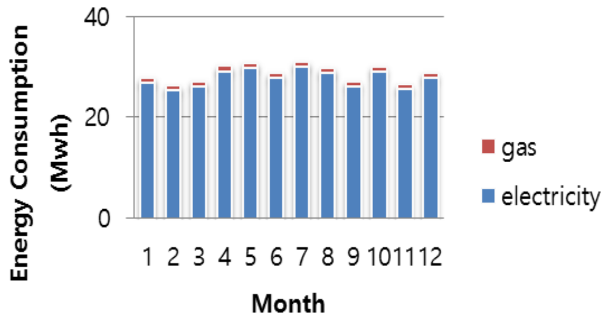


Fig. 9 Monthly energy demands in Singapore

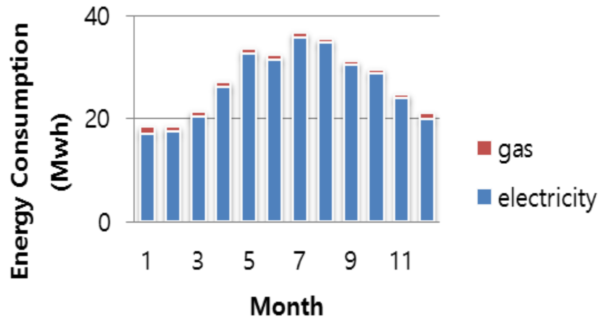


Fig. 10 Monthly energy demands in Riyadh

demand occurs in summer, July, when solar radiation is the highest. Its overall monthly energy demands show a Gaussian distribution peaking in July and bottoming out in January. Thus, a renewable energy system that is sized to meet the spring and fall energy demands will meet the energy demands for most of the year, although it will produce surplus energy in winter and insufficient energy in summer. Because the gas (heat) energy demands are insignificant compared with electricity demands, the renewable systems for zero energy buildings in Singapore and Riyadh can be all electric (PV or wind).

4. Energy self-sufficiency analysis

The feasibility of zero energy office buildings can be analyzed using the energy self-sufficiency index (Kim and Gerow 2012). The energy self-sufficiency is the ratio of the electricity produced from a building's renewable energy system to the energy it demands as

$$S_e = \frac{E_{pv}}{B_e} 100 \tag{2}$$

Where B_e is the energy demand of a building. In this study, PV panels are the only device of energy production. The energy demands of the test buildings were obtained from eQUEST (Hirsh 2007) energy simulations.

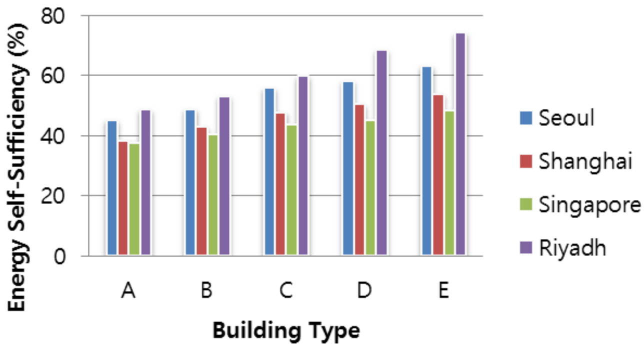


Fig. 11 Energy self-sufficiency of five test buildings

4.1 Energy self-sufficiency

With the current efficiency of PV cells at 18.5% and the rooftop PV panels having areas equal to that of the roof surfaces, approximately 40 to 70% energy self sufficient buildings can be achieved. Fig. 11 shows energy use intensities and the electricity and energy self-sufficiencies of the five test buildings in Seoul, Shanghai, Singapore and Riyadh. The energy self-sufficiency is the lowest in Singapore, where electricity consumption for air conditioning is high and is the highest in Riyadh due to its high solar irradiance. In order to achieve zero energy office buildings, either the size of the roof-top PV panels should be increased or additional PV panels should be installed on the building facades. When higher efficiency PV cells are available and incorporated (US Department of Energy 2011), their energy self sufficiency will further increase. However, the test rooftop PV systems supply significant amounts of the energy demands of the buildings in the four cities.

5. Cost feasibility analysis

The cost of electricity from a solar cell can be determined by the capital (materials and labor) cost, useful life, and the amount of total electricity produced during its useful life. When the operation and maintenance costs are discounted, the cost of electricity from a PV system, C_{elec}, can be calculated as

$$C_{elec} = \frac{C_{inst}}{nE_a} \tag{3}$$

Where, C_{inst} is the capital cost of a PV system per unit area (\$/m^2), *n* is the PV life (in years), and E_a is the annual electricity production from a PV system (kWh). In this study, the capital cost and PV life were assumed to be \$1,046/m^2 (\$97.2/ft^2) and 30 years respectively.

As shown in Eq. (3), the cost of electricity is inversely proportional to its PV life and life time electricity production, which in turn, is proportional to the availability of solar radiation and the conversion efficiency of PV cells. Therefore, the cost feasibility of solar systems will be higher in locations where solar irradiance is high such as in Riyadh. In addition, the cost feasibility of PV

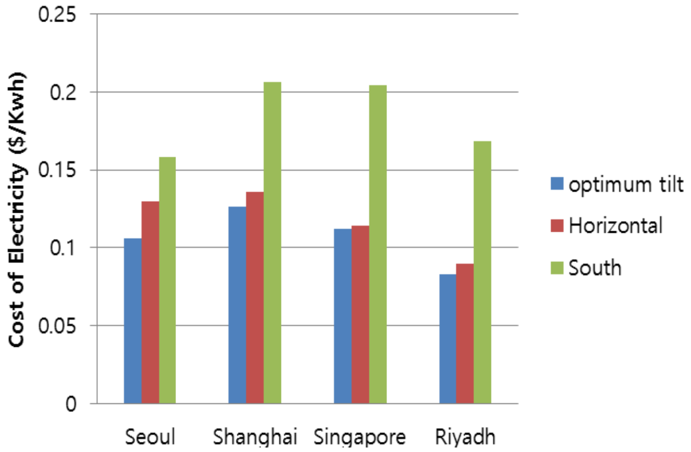


Fig. 12 Costs of Electricity from PV panels

systems varies with the orientation, tilt angle and sun tracking method of solar panels. In this study, the PV systems are assumed to be fixed.

When optimally tilted, electricity produced from PV panels is most economical in Riyadh at $0.08/Kwh, while other cities show costs higher than $0.11/Kwh. Fig. 12 compares the costs of electricity produced by PV panels tilted at three different angles in each city: optimally tilted, horizontal and vertical. Of the three tilt angles, south-facing vertical installations result in the highest costs of electricity (lowest cost feasibility), followed by horizontal installations. When PV panels are optimally tilted, the cost of electricity is lower than or competitive with the typical US residential electricity rate, $0.12/Kwh (EIA 2010). The cost difference between the optimal tilt installation and the horizontal installation is not so significant. However, the difference between the south-facing vertical installations and the optimal tilt is significant. Thus, when possible, tilting solar collectors to the optimal angle is strongly recommended. Otherwise installing panels horizontally would be the next best. Vertical installation of PV panels in Singapore or Shanghai should be avoided.

6. Conclusions

The results from the five buildings examined indicate that with the rooftop PV panels equal to the size of the roof surface area, an energy self sufficiency of approximately 40 to 70% can be fulfilled. Of the four cities studied, Riyadh is the most favorable for zero energy buildings, followed by Seoul, Shanghai and Singapore.

The zero energy building strategies for large scale buildings can be categorized into two main strategies: supply-side and demand-side strategies. Incorporating higher efficiency PV cells is a supply-side strategy for achieving zero energy commercial buildings. At present, PV cells with efficiencies higher than 30% have been developed at various research institutions. When these high efficiency PV technologies become commercially available, it will be possible to produce medium sized zero energy office buildings. By increasing the PV efficiency to 30%, as opposed to the 18.5% assumed in this study, most medium size office buildings tested can become near zero energy buildings. Alternatively, when additional PV panels are integrated with the building's exterior surfaces, zero energy medium sized office buildings will be possible.

On the demand-side, the current levels of building energy demands must be drastically reduced, employing energy conserving building strategies such as high insulation of walls and windows, shading of windows, high efficiency lighting fixtures and HVAC systems. In addition, it should be noted that high-rise buildings consume a significant amount of energy in plug loads including elevators and office appliances. Using high efficiency computers, computer monitors and other peripheral devices are important strategies for large scale zero energy buildings. The pairing of energy demand reduction with onsite renewable technologies is an essential strategy for zero energy buildings.

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