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The operational performance of "net zero energy building": A study in China

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HIGHLIGHTS

- Choose energy efficiency technology in office building to implement "nZEB".
- Simulate its energy consumption.
- Study on the operational performance.
- Optimize its running.

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ABSTRACT

There is no lack of studies on "net zero energy buildings" ("nZEB"). However, the vast majority of these studies focus on theories and simulation. The actual operational performance of "net zero energy building" during occupation has been largely overlooked by previous studies. This study aims to investigate the operational performance of net "zero energy buildings" via the case study of an office building in Tianjin, China. Using simulation, the energy consumption of the building at design phase was estimated and a solar photovoltaic (PV) system was selected. A whole year operation of the occupied building showed that energy consumption of the case building was much higher than the energy generated from the solar PV system. This was mainly due to three issues. Firstly, the equipment was different in terms of category, quantity and running time between operation and design stages, leading to considerable underestimate of energy consumption at the design stage. Secondly, the operational strategies need to be further improved in order to regulate users' behaviors. Thirdly, the efficiency of solar PV system was substantially reduced due to poor atmospheric environment (i.e. haze weather). Therefore, during the design process of "net zero energy buildings", it is imperative to ensure that the energy simulation accurately reflects how the building will actually operate once occupied. The research also revealed other barriers to the design and implementation of "nZEB" in China, such as extra efforts required for effective communicating the capacity of the HVAC design and systems to clients, and the increased cost of "nZEB" (e.g. solar PV system) particularly for public buildings. Finally, the solar radiation intensity of standard year adopted in the simulation needs to be replaced by the most recent meteorological data.

1. Introduction

Energy consumption makes significant contributions to global warming and pollutant emissions. The building sector accounts for a large proportion of the primary energy consumption [1]. In China, buildings represent approximately 28% of the nation's total energy consumption [2,3]. In particular, public buildings account for only 5–6% of the total building area in urban areas [4], yet consume the same amount of electricity as residential buildings with a total floor areas eight times more than that of public buildings [5]. Therefore, it is imperative to improve the energy efficiency of public buildings.

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Nomenclature

c	specific heat capacity, J/(kg °C)
COP	coefficient of performance
$\cos\Phi$	power factor
E_{ds}	simulated energy consumption, MW h
E_o	operational energy consumption, MW h
i	imported energy
I	electric current, A
j	exported energy
m	the amount of the exported energy
n	the amount of the imported energy
$N_{payback}$	the payback period, years
P	cumulative power consumption, kW h
P_e	electric power, kW
P_p	tariff, RMB yuan/kW h
PE_{export}	the annual exported primary energy
PE_{import}	the annual imported primary energy
Q	cumulative cooling/heating capacity of heat pump unit, kW
Q_0	cooling/heating capacity of heat pump unit, kW
$Q_{pv,power}$	total annual electricity production from photovoltaic panels, MW h
Q_s	the annual energy savings, kW h/year
S	total area of photovoltaic panels, m^2
U	voltage, V
V	water flow velocity, m^3/h
$W_{solar,rec}$	solar radiation intensity on the surface of photovoltaic panels, MW h/m^2
ρ	average density of water, kg/m^3
λ	conversion efficiency of photovoltaic system, %
ΔI	capital cost, RMB yuan
Δt	temperature difference between supply and return water, °C
ΔT_Q	the time interval of the accumulated heating/cooling, s
ΔT_P	the time interval of cumulated electricity power, s

Policymakers are embracing the concept of "net zero energy buildings" ("nZEB") as a vital strategy to meet the energy and carbon emission reduction targets [6]. The "nZEB" is a building which generates as much primary energy as its energy consumption over a period of time [7]. In buildings, renewable energy is the only way to generate energy (export energy). Energy consumption (import energy) includes heating, cooling, ventilation, lighting and appliances [8]. The energy balance is achieved when the annual net primary energy is equal or less than zero, shown as Eq. (1) [8].

$$\text{Net primary energy} = \sum_{i}^{n} PE_{import\,i} - \sum_{j}^{m} PE_{export\,j} \leqslant 0 \tag{1}$$

There are two common strategies to achieve "net zero energy" consumption in buildings, i.e. "minimize the energy demand of the building, and supply the remaining energy demand by means of on-site renewable energy resources" [9].

A lot of studies have been conducted to address these two strategies. These include, optimizing building orientation and shape; using insulated materials for the building envelope [10–12]; adopting efficient heating, ventilation and air-conditioning (HVAC) facilities [13–16] and systems [17–21]; using smart control technologies [22]; encouraging energy saving behaviors within occupants [23–28]; and utilizing various types of renewable energy resources [29–33].

For example, previous studies have shown that heating energy could be reduced by more than 35% by means of optimizing the shape and orientation of buildings [34]. Similarly, the total heating and cooling demand could be cut by nearly 26% via proper optimization strategy on building envelop such as window-wall ratio and shading system [35].

Natural ventilation systems also offer an avenue to reduce the energy consumption compared with active cooling methods [36]. In particular, higher ventilation rates are essential for cooling during the summer season [37].

Artificial lighting accounts for around 20% of energy consumption globally [38]. Lighting related energy consumption can be reduced through the use of daylighting. Ihm P's study demonstrated that day-lighting controls can save the lighting energy as much as 77% [39].

Nearly half of energy consumption in commercial buildings is used for heating, cooling and ventilation (HVAC) systems [40,41]. Therefore, the energy savings from the design of HVAC systems can play an important role in achieving "nZEB". These technologies include heat pump systems [42–45], evaporative cooling [46–48] and the heat recovery techniques in fresh air systems. For example, vertical close-loop ground-coupled heat pumps (GCHP) can reduce the annual electrical energy consumption for cooling and heating by as much as 70% compared to air source heat pump systems [49].

Renewable energy plays a crucial role in achieving "nZEB" [2]. Renewable energy resources include wind power, solar photovoltaic (PV) system, biomass energy and geothermal energy [50]. Solar PV system has gained rapid growth where surplus energy can be fed into the local grid. Biogas can be used for cooking and heating in the building, but is mainly used in smallholders in rural areas [51]. The intermittent nature of wind energy has restricted its wide implementation [52]. By contrast, solar power has gained wider implementation in "nZEB" due to its accessibility and easy integration with existing building systems.

Building operation strategy plays a crucial role in the delivery of "nZEB". Various strategies can be adopted for system optimization according to the cooling and heating demands [53]. Energy savings of 17% can be achieved when the system is operated with more appropriate control functions [54]. As a result, the energy production/consumption schedule can be optimized which consequently maximize benefits.

A vast majority of existing studies on "nZEB" focused on the measures of energy savings by means of simulation at the design stage. By contrast, the actual operation of "nZEB" was largely overlooked. As a result, it is difficult to accurately analyze the economy of "nZEB", which prevents its wide implementation. This study examines ways to reduce the energy consumption at the design stage via appropriate energy efficient technologies. According to the annual energy consumption simulation results, a solar photovoltaic system was designed and installed on the building. The energy production and consumption during operation were examined by comparing the simulated results to the actual operation data. The building management systems were then optimized. Finally, the economy of "nZEB" was analyzed.

2. Methodology

2.1. Energy simulation

At the design stage, building energy simulation is often conducted to determine strategies for achieving "net zero energy"