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Evaluating Energy Performance and Improvement Potential of China Office Buildings in the Hot Humid Climate against U.S. Reference Buildings

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Evaluating Energy Performance and Improvement Potential of China Office Buildings in the Hot Humid Climate against US Reference Buildings[1]

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ABSTRACT

This study compares the building code standards for office buildings in hot humid climates of China and the USA. A benchmark office building model is developed for Guangzhou, China that meets China's minimum national and regional building codes with incorporation of common design and construction practices for the area. The Guangzhou office benchmark model is compared to the ASHRAE standard based US model for Houston, Texas which has similar climate conditions. The research further uses a building energy optimization tool to optimize the Chinese benchmark with existing US products to identify the primary areas for potential energy savings. The most significant energy-saving options are then presented as recommendations for potential improvements to current China building codes.

1. INTRODUCTION

China is one of the fastest growing developing countries in the world. As a result, the country's new public building construction is also growing at an alarming rate. With much of the domestic electricity generated from coal, it is not surprising that buildings account for a significant percentage of overall carbon dioxide emissions. In a recent article, Hong (2009) of the Laurence Berkeley National Laboratory pointed out that currently, 18% of China's energy related carbon dioxide emissions are attributed to buildings and that the energy consumed in China's public buildings is expected to rise to 35% of the national total primary energy by 2020. There is obviously a great urgency to raise the energy efficiency standards in buildings to facilitate the country's growth.

Using code-compliant building models along with energy modeling software, building designers can find the necessary measures needed to create high performance buildings that use less energy than typical construction

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methods. This process is more important than ever in the design phase of new public building projects in China as energy efficiency is critical to sustaining the development of this growing country.

This research compares the energy performance of the current building code standards for office buildings in the hot humid climate region of China and the US. In addition, a building energy optimization tool is used to identify key energy design measures that reduce annual end use energy consumption in China's office buildings. The results of the optimization are provided as recommendations for improved office building code standards for this particular climate region of China.

2. OFFICE BENCHMARK: DESIGN STANDARDS AND ENERGY PERFORMANCE

2.1 Benchmark Development

The current benchmarking research for China is an assignment under the Asia-Pacific Partnership (APP) agreement through the National Renewable Energy Laboratory (NREL). As a joint proposal among seven partner countries, the APP aims to accelerate the development and implementation of clean energy technologies and energy efficiency. Furthermore, the Department of Energy's Office of Energy Efficiency and Renewable Energy is working with its Chinese partners to improve the energy efficiency of China's rapidly growing commercial building sector. By using building simulation tools developed by NREL, the APP will make recommendations that will help Chinese authorities form future commercial building energy codes (Zhai and Chen, 2009a).

The Guangzhou, China office benchmark model has been developed in the energy modeling software EnergyPlus to meet regional codes described by Guangdong Design Standard for Energy Efficiency of Public Buildings (DBJ15-51-2007) and the national code (GB 50189-2005) for the hot humid climate region of China. Some features of the building, including aspect ratio, orientation, number of floors, and window-to-wall ratios, are not recognized by either code and are therefore taken from common design practice (Zhai and Chen, 2009b). The US office reference building has also previously been developed in EnergyPlus to comply with the national building code standards described by ANSI/ASHRAE/IESNA Standard 90.1-2004 (DOE, 2010). This model also meets the regional code for Houston, Texas, which has a climate similar to Guangzhou.

2.1 China-US Office Building Comparison

The office building models for Guangzhou and Houston have notable differences. The China office benchmark model is nearly twice the square footage of the US reference building (8,400 m^2 compared to 4,891 m^2). The construction of the China model includes concrete exterior walls and an insulated concrete roof. The US office is constructed of insulated steel-framed exterior walls and an insulated metal decking roof. Both models use a five zone HVAC design layout with four perimeter zones and one core zone but utilize different HVAC equipment. The input parameters for each building are listed in the tables below.

Table 1: Office Envelope and Window Construction Standards

Envelope Construction Standards	**Units**	**China**	**US**
Exterior wall R-value	m^2K/W	1.11	1.42
Roof R-value	m^2K/W	1.39	3.33
Ground floor R-value	m^2K/W	0.56	0.54
Window U-value	W/m^2K	5.33	6.49
Window solar heat gain coefficient	Fraction	0.58	0.36
Window visual transmittance	Fraction	0.29	0.36
Window - to- wall ratios	Fraction	North: 28% South: 33% East/West: 10%	All facades: 47.7%

Table 2: Office Building HVAC Components and Standards

HVAC Component Standards	China	US
Zone equipment type	Four-pipe fan coil units	Packaged multi-zone VAV units
Cooling coil efficiency	None	4.8
Heating coil efficiency	None	0.99
Chiller type (COP)	Electric (4.70)	None
Air conditioners (COP)	None	Electric (3.14)
Boiler type (thermal efficiency)	Electric (0.90)	Natural gas (0.75)
Fan efficiency	0.70	0.60
Fan pressure drop (Pascals)	40	500
Outdoor air flow rate (m^3/s/person)	0.0083	0.01

Table 3: Office Building Loads and Set Points

		Occupied Hours		Unoccupied Hours	
Building Loads and Set Points	Units	China	US	China	US
Occupant density	Occupants/100m^2	25	5.38	0	0
Lighting density	W/m^2	11	10.8	0	0.5
Equipment density	W/m^2	20	8.1	0	3.2
Cooling supply air temperature	^oC	7	14	7	14
Heating supply air temperature	^oC	60	40	60	40
Cooling set point temperature	^oC	26	24	37	30
Heating set point temperature	^oC	20	21	12	15.6

There are six major differences between the models. First, the occupancy density in the Chinese model is nearly four and a half times greater than the US model. The accuracy of this figure is unknown; it may be realistic for the desk space but may not account for lower occupancy areas in corridors, stair cases, and other common areas. Secondly, the zero lighting and equipment power densities during unoccupied hours in the Chinese model are another uncertain assumption. It is very uncommon for all electrical devices to be turned completely off each night, but the assumption will hold until future work can measure these loads directly. Precise measurement of occupant and electricity loads would improve the accuracy of the Chinese model as these components have a significant impact on energy consumption. The other major differences include lower equipment power densities per person and lower roof insulation levels in the Chinese model, HVAC system designs, and heating and cooling set points.

2.2 Energy Performance Comparison

The annual building energy consumption of the China and US models is compared based on floor area and annual occupant-hours. Annual occupant-hours are defined as the sum of the fraction of occupants in the building for each hour of an entire year. Both buildings are simulated using the Guangzhou climate data and location dependent data sets, including ground and water mains temperatures and solar radiation levels. The Chinese office benchmark outperforms the US reference building by a marginal 3% based on floor area. Two reasons for the higher cooling energy in the US model are the lower cooling set points and the greater number of hours that cooling is required.

The Chinese benchmark out performs the US reference building on a per occupant-hour basis as well, but on a much greater scale; the US office model consumes over five times more energy per occupant-hour. This results partly from the US model having about one-fifth as many occupants per square meter but nearly four and a half times the lighting load and nearly twice the equipment load per occupant compared to the Chinese model. Another factor leading to this difference is the operation schedule set; the US model assumes a fraction of the lighting and equipment power densities during non-business hours (most likely attributed to security lighting, computers, printers, luxurious items such as kitchenette refrigerators, and other small loads) whereas the China model assumes these building loads go to zero. As mentioned before, the correctness of this assumption is unknown and direct measurement is necessary to improve the accuracy of the estimation. Cooling energy is about 1.5 times greater in the US model due to the greater number of cooling hours and the lower cooling set points. Finally, the US building operates six days a week compared to five in the Chinese model.

Table 4: Annual End Use Energy Intensity

End Use Category	China % of Total Energy Intensity	US % of Total Energy Intensity
Heating (electricity)	1.20	0.00
Heating (natural gas)	0.00	5.70
Cooling	28.4	42.0
Lighting	21.5	23.0
Electrical Equipment	35.6	26.9
Fans	2.10	2.40
Pumps	9.60	0.02
Heat rejection	2.20	0.00
Total energy per unit floor area [kWh/m^2]	127.9	131.5
Total energy per occupant-hour [kWh/occ.-hour]	0.19	0.99

3. CHINA BENCHMARK OPTIMIZATION

3.1 Optimization Process

The building energy optimization tool used in this research, Opt-E-Plus, was created by the National Renewable Energy Laboratory to help building designers maximize the energy saving potential in new building construction. The user selects a variety of energy design measures (EDMs) corresponding to the project objectives. Then, Opt-E-Plus automatically selects different combinations of EDMs to apply to the baseline model and launches an annual performance simulation in EneryPlus. After analyzing the results of the initial simulations, Opt-E-Plus decides which EDMs to keep and which to change before launching a new set of simulations. The results produce a range of options for building designers to consider (NREL, 2010).

Output from the optimization includes building characteristics and energy savings as well as the economic impacts of each design option (NREL, 2010). Capital cost was chosen over other economic parameters for two reasons. First, specific material types and costs for China are unknown at this point in the research and are difficult to estimate accurately. The material types and costs selected for the optimization are taken from a US database of existing materials and costs. The benchmark building cost is also determined based on the costs of the most similar materials in the US database to accommodate the lack of information. Secondly, appropriate energy costs and other economic data, such as marginal interest rates, are not available and are difficult to assume with confidence. Therefore, a total lifecycle cost analysis is not possible with the amount of information available. It should be emphasized that Opt-E-Plus is primarily used in this study to identify the potential energy savings associated with different EDMs. Future work should include an analysis with accurate material costs and relevant energy and economic data specific to this region of China.

Thirty-four EDMs are selected across twelve categories for the optimization from the US database of existing materials and costs:

- Reduced equipment power density (10% reduction) and lighting power density (10% and 20% reductions)
- Daylighting controls (400 lux set point)
- Skylights (4%, 8%, and 12% of roof area)
- Window-to-wall ratio options (50%, 80%, 120%, and 150% of baseline model on each façade)
- Shading (0.5 south façade overhang projection factor; 0.7 east/west fin projection factor)
- Additional exterior wall insulation (R-2.6, 6.6, and 8.8 m^{2}K/W)
- Additional roof insulation (R-3.4 and 7.1 m^{2}K/W)
- Selective windows with varying U-values and solar heat gain coefficients
- HVAC options (10% and 20% COP increase and/or more efficient fans)
- Ventilation rate options (double outdoor air per person, increase outdoor air per person by half)
- Photovoltaic (PV) application (10%, 30%, and 50% of the roof area)

3.2 Optimization Results

The optimization results are plotted on a graph showing net site energy savings as a function of capital cost percentage difference. A negative capital cost percent difference represents an economic savings. Although the cost data is not specific to China the results do provide some insight into the possible economic trends associated with each building design. Figure 1 is provided as an illustrative example and the specific cost-saving amounts should not be considered as relevant to this region of China.

In general, there are five important points on the figure to consider when choosing a design option. These are identified with circles on Figure 1 and will be addressed from left to right. The first point shows that there are measures which simply reduce capital cost. These include reducing window to wall ratios and reducing the lighting power density. Reducing the lighting power density essentially reduces the number of light fixtures in the space. It does not imply that energy efficient lighting is being installed in place of the standard fixtures. This explains the associated cost reduction; installing more efficient models could increase capital cost. Also, there is no way of knowing if sufficient lighting levels are met after reducing the lighting power density because no information is provided on the illuminance of the fixtures. Therefore, lighting power density must be interpreted with caution. The same is true for equipment power density reductions which occur in other cases.

The second point lies at the bottom of the curve and is considered to be the "optimal" design by definition; this design provides the greatest energy savings at the least capital cost and is important when building owners are concerned with economic saving as well as energy savings. The third point is defined as the cost neutral point. This point shows the maximum possible energy savings achievable with no additional upfront investment. The fourth point shows the potential energy savings after photovoltaics are applied. In this design, PV is applied to 50% of the roof area and the cost significantly increases. The slope of the line between points three and four is directly related to the installed cost of the PV panel. If the designer chose to continue adding PV to the roof without further implementation of other EMDs, the cost would continue to increase at the same rate. Alternatively, the fifth point shows what happens to the cost when additional EDMs are applied in addition to the PV application in case four. The slope increases between these points due to the additional expense induced by the other EDMs. Here, more efficient HVAC equipment and additional insulation is applied. It is important to note that since energy costs are not included in a capital cost analysis, no information is provided on the energy cost savings associated with the each design. However, since the China model uses only electricity as a source of energy, an energy-cost savings calculation could easily be done if the cost of electricity for this region of the country is known.

A net zero energy building cannot be achieved with the application of photovoltaics due to the small roof area compared to the total floor area. Applying PV to 50% of the roof generates approximately 60 MWh of electricity annually, about 5.6% of the annual energy consumption of the benchmark. Applying PV to 95% of the roof area generates approximately 113 MWh of electricity, about 10.5% of the annual benchmark energy consumption. Photovoltaics should be applied only after the building is made as efficient as possible.

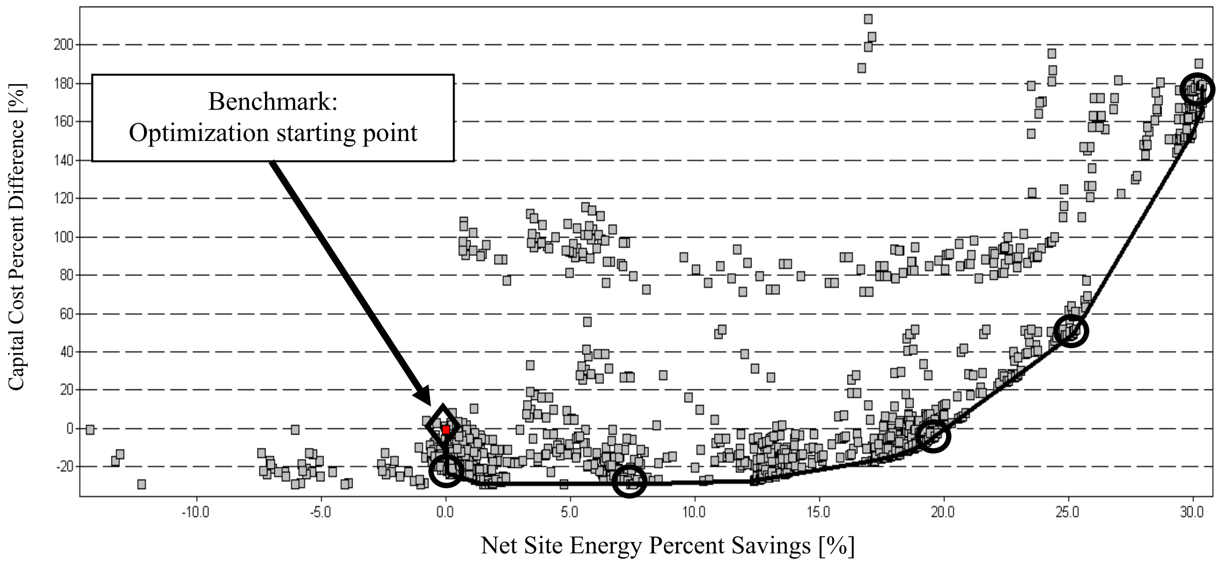

Figure 1: Opt-E-Plus optimization results for the Chinese office building.

4. SENSITIVITY ANALYSIS

The optimization results reveal six categories of energy design measures that have the most significant impact on energy savings. They are equipment and lighting power density (EPD and LPD) reductions, window to wall ratio reductions, increased wall and roof insulation, daylighting controls, skylights, and window shading overhangs. A sensitivity analysis is performed by applying these EDMs individuality to the benchmark model over a range of values. This process identifies which EDMs contribute the most to energy savings.

Four energy design measures are identified as having the greatest energy saving potentials. The first two are equipment and lighting power density reductions, respectively. This is not surprising given that these categories make up the first and third highest percentage of end use energy. The third highest energy saving measure is the use of daylighting controls, which minimize the need for electrical lighting. Reducing the window to wall ratios has the fourth highest impact on energy savings. This helps reduce cooling energy associated with solar gains. All of these measures reduce internal heat gains and thus lower cooling energy, which makes up the second largest percentage of end use energy. Adding shading overhangs to south-facing windows has a much smaller impact on energy savings (1.2% maximum reduction potential). Increasing the wall and roof insulation levels shows insignificant energy savings, which is surprising given the low level of insulation in the benchmark. Skylights have a negative impact on energy savings when applied as a single EDM; adding skylights increase the cooling loads due to increased solar heat gains on the top level. However, skylights help reduce energy consumption when used in combination with daylighting controls and reduced lighting power densities as they allow for more natural light in the top-floor zones.

Figure three shows the energy saving potential associated with three of the top four design measures mentioned above. Daylighting controls are not shown on this plot because of the choice of axis. The energy saving potential associated with daylighting controls falls between lighting power density and window to wall ratio reductions.

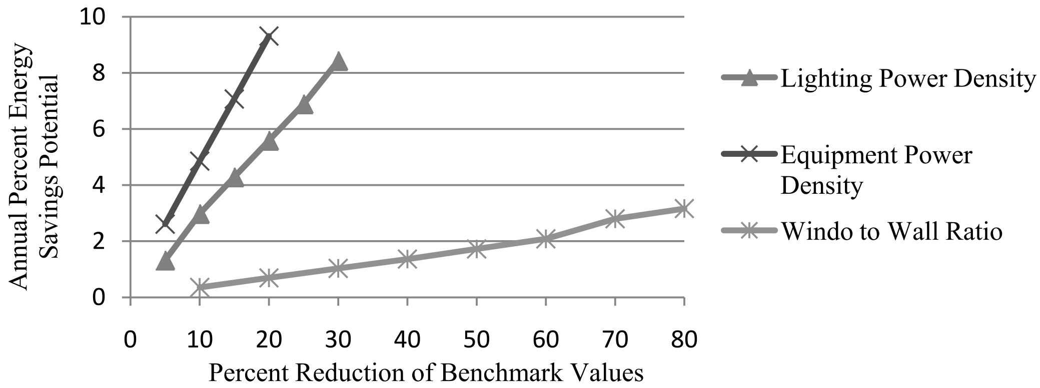

Figure 2: Effects of energy design measures on annual energy consumption.

5. RECOMMENDATIONS

The optimization is performed again by varying the most significant EDMs identified in the sensitivity analysis over a small range of values determined from the sensitivity test before ending at final recommendations for office building code improvements. The second optimization is important because of the interplay between building components. An example of this was mentioned above with the use of skylights. The final recommendations are summarized in Table 5. Table 6 lists the potential energy savings in each end use category with reference to the benchmark. Note that the window to wall ratios have been significantly reduced and are now a very small percentage of the exterior wall area. The sensitivity analysis shows that the incremental energy savings associated with this EDM are small. Therefore, the window to wall ratios could be increased slightly when applied with a package of EDMs without significant energy-saving penalties.

It is important to first reduce the annual energy consumption as much as possible and then apply PV to further offset consumption to keep the size, and therefore cost of the PV system at a minimum. A potential energy savings of 26% can be achieved without the application of PV. A zero energy building is not achievable because of the inadequacy of available roof space. However, about 11% of annual energy can be offset by applying PV to 95% of the roof area. Although the implementation of PV has a high initial cost, its application should be considered as a sustainable method for offsetting electricity demand.

Table 5: Recommended Energy Design Measures

	Wall insulation: R-value (m^2K/W)	Roof insulation: R-value (m^2K/W)	LPD (W/m^2)	EPD (W/m^2)	Skylights % roof area	Window: U-Value (W/m^2K)	South Overhang proj. factor	Window to wall ratios
Benchmark	1.10	1.39	11	20	None	5.33	None	0.24 ave.
Recommended	4.40	6.80	7.7	16	4%	3.86	0.7	0.10 ave.
% +/-	+300	+400	-30	-20	+100	-28	+100	-60

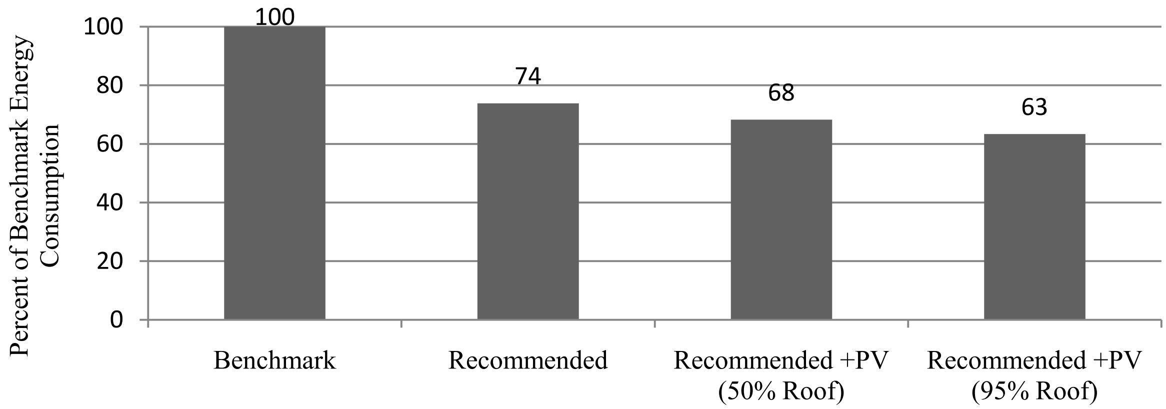

Figure 3: Potential energy savings.

Table 6: End Use Energy Reduction Potential

	Heating	Cooling	Interior Lighting	Interior Equipment	Fans	Pumps	Heat Rejection	Total End Use
% Energy Savings	-37.1	20.08	50.9	20.0	20.0	24.2	22.5	26.1

6. CONCLUSION

A detailed comparison of the design and energy performance differences between the Chinese and US office building models for hot-humid climate regions has been carried out. The major differences are not limited to building materials and HVAC designs but also include building operation schemes and seasonal temperature set points. The most significant differences are the occupancy densities and lighting/equipment power densities; the Chinese model assumes a much higher occupancy density than the US model and zero electricity loads during unoccupied hours. These may be inaccurate estimates and direct measurements of these loads are recommended. Secondly, the heating and cooling set points in the US model are set for what might be considered a more comfortable building, with colder cooling set points and warmer heating set points. Thirdly, the Chinese building has a much lower roof insulation standard, about two-fifths of what is prescribed in the US model. Lastly, the Chinese model has an all water HVAC system for heating and cooling which includes an electric chiller and boiler; the US model uses a natural gas boiler for heating and electric multi-zone air conditioning units for cooling. These design differences lead to energy performance differences.

The energy performance of the Chinese model compares well to the US model on an energy per unit area bases; it uses three percent less than its US counterpart. Interestingly, the Chinese benchmark uses one-fifth the US reference building's annual energy based on occupant-hours. This is partly credited to less extreme temperature settings, lower equipment and lighting loads per occupant, a lower number of annual hours of operation, and a significantly higher occupancy density.

In addition to the comparison, recommendations have been made for improved building code standards for Chinese office buildings in this climate region through the process of building energy optimization. Thousands of annual energy simulations were performed with a building energy optimization tool to identify potential energy savings associated with different energy design measures. After testing the building's sensitivity to these measures, final recommendations were made for office building code standard improvements. These recommendations include increasing the roof and wall insulation levels, reducing equipment and lighting power densities, using daylighting controls, skylights, and south window shading devices, and using higher efficiency windows. Implementing these energy design measures can potentially save 26% of the annual benchmark energy. Applying photovoltaics can offset up to an additional 11% of annual energy use. The economic savings associated with these energy efficiency recommendations have not been analyzed in detail due to the lack of valid material and energy cost data for China.

Therefore, the recommendations made here are based exclusively on potential energy savings. Since electricity is the only source of energy used in the model, the energy cost savings could easily be determined if the cost of electricity is attained for this particular region of China.

With the development of the Chinese benchmarks, energy modeling can be used to identify key energy design measures that lead to potential energy and carbon dioxide emission savings. Given the rapid rate of growth in China, it is critical and urgent that buildings be designed to use less energy. The results presented here can help Chinese authorities develop building codes that achieve this daunting task.

7. FUTURE WORK

Future work will include the optimization of the office and hotel benchmark models for the other climate zones of China, including the severe cold, cold, and hot-summer-cold-winter regions. A Chinese database of materials will also be used in an optimization analysis once this data has been collected. It is recommended that an economic sensitivity test be performed to compare the relative cost savings achievable.

NOMENCLATURE

LPD	lighting power density	(Watts/square meter)
EPD	equipment power density	(Watts/square meter)
EDM	energy design measure	(-)

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