RESEARCH ARTICLE

Passive Design Strategies in Traditional Japanese Architecture: A Case Studies of the Chochikukyo House

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Citation: Pourbakht M. (2025) Passive Design Strategies in Traditional Japanese Architecture: A Case Studies of Chochikukyo House. Open Science Journal 10(1)

Received: 26th August 2024

Accepted: 15th January 2025

Published: 31st March 2025

Funding: The author(s) received no specific funding for this work

Competing Interests: The authors have declared that no competing interests exists.

Abstract:

The Chochikukyo house in Kyoto incorporates traditional Japanese architectural principles while prioritizing ecological design long before sustainability gained widespread attention. This study sought to assess the impact of several architectural elements on the building's energy efficiency, comfort, and environmental sustainability. The author examined building orientation (e.g., southern exposure for optimal sunlight), spatial layout and dimensions (e.g., open floor plan for enhanced airflow), size and height of interior spaces (e.g., compact design for efficient heating), elevation from adjacent ground (e.g., height for improved ventilation), material selection (e.g., insulating materials for energy efficiency), and availability of adequate air circulation. The aim of this experiment was to evaluate the efficacy of these methods in determining whether the building's orientation and layout are optimized for the effective use of passive solar heating and cooling, as well as harnessing solar energy for winter warmth and natural ventilation for summer cooling, thereby reducing dependence on auxiliary heating and cooling systems. He assessed if natural cooling and ventilation techniques, such as cross ventilation and the stack effect, may improve indoor thermal comfort and air quality, so that it may ultimately decrease reliance on mechanical heating and cooling systems. The findings indicate that the strategies implemented in the architectural design of this house, might decrease overall energy usage by 40-50%, illustrating the effectiveness of integrating design elements with modern sustainable construction techniques.

Keywords: Passive Design, Sustainable Architecture, Thermal Comfort, Natural Ventilation, Traditional Japanese Architecture, CFD

Introduction

Koji Fujii, a distinguished architect active from 1888 to 1938, conceived the design of the Chochikukyo House in 1928. This house exemplified a significant advancement in postmodern architecture by attempting to align with the dominant trend of westernizing Japan's traditional society. The house's architectural design was primarily intended to enhance thermal comfort during hot summer months and has since been a good example of environmental considerations in early architectural practices.

The purpose of the current experiment was to measure the effectiveness of these sustainable methods for energy conservation. It is particularly noteworthy that these measures were enacted years prior to the emergence of sustainability as a prevalent concept. Our study of early 20th-century efforts to make sustainability a basic principle of architecture led us to the Chochikukyo house as a perfect example of the passive energy management techniques that are typical of traditional Japanese architecture, which is known for its all-encompassing and interconnected approach (Wanti, 2020; Chung-Camargo et al., 2022; Gaveta, 1991). Other researchers showed that the building's strategic orientation, carefully planned shading features, thermal mass of the walls and roof, and integrated ventilation system all work together to make it a comfortable place to live all year, which reduces the need for energy-intensive mechanical systems (Oluwatayo & Pirisola, 2021).

Furthermore, numerous experts have noted that the alignment of the primary entrances with the prevailing winds in Kyoto facilitates the circulation of fresh air through natural ventilation; however, based on our findings, no precise evaluation has been conducted prior to the current experiment to demonstrate the efficacy of the employed solutions. During our initial visits, we discovered that the dominant breezes could effortlessly traverse the house, facilitating efficient cross-ventilation in the interior areas. This passive cooling approach is essential in Kyoto's hot and humid summers, since it facilitates the removal of heated air and the introduction of cooler air into interior spaces, resulting in a natural reduction in temperature.

The Chochikukyo house utilizes innovative underground cooling pipes as a primary environmental solution alongside various shading techniques to mitigate heat accumulation. Such practices could optimize natural light usage and regulate diffusion and reflection ratios, particularly during hot summer days. The utilization of extensive overhanging eaves and elongated roofing systems is especially significant. It's crystal clear that the presence of these components causes significant shading at the building's entrances by effectively obstructing direct sunlight during the peak heat hours of the day when radiation is a nuisance.

The house features broad south-facing windows that enhance solar heat absorption throughout the winter when it is required. The windows are designed to harness the angled winter sunlight that lets it enter the interior spaces, facilitating natural heating in winter. To complete this procedure, proper thermal mass components used can efficiently absorb and retain heat gathered throughout the day, ensuring a comfortable home environment even in chilly conditions at night. These are only some of the advanced methodologies used as the house used progressive.

Method

This section examines the implementation and efficacy of environmental solutions employed in the house design process, including natural ventilation and sun orientation, to improve energy efficiency systems. By employing CFD methods alongside a solar camera and an anemometer, we can obtain a more accurate assessment of the environmental elements surrounding the building to evaluate the efficacy of this comprehensive strategy in mitigating the ecological impact of the structure.

The Testo 865 Thermal Imager was utilized for this experiment. The Anemometer Kestrel 3500 Psychrometer was employed to measure wind speed at various sites. Cradle CFD scSTREAM was employed for simulation, utilizing the boundary ratios obtained from the site measurements. The objective of this experiment was not solely to do the CFD analysis; rather, we intended to employ all these approaches to evaluate the building's environmental solutions in a numerical and scientific manner. Consequently, this experiment concentrates exclusively on building engineering techniques, rather than the employed CFD technology.

Through the examination of passive solutions employed, our aim is to underscore the capacity of sustainable architecture to foster environments that are both ecologically responsible and conducive to resident comfort. This research seeks to provide essential insights into the efficacy of incorporating natural elements into architectural design for enduring sustainability applicable to architects.

The Chochikukyo home in Kyoto, Japan, is situated at the precise geographic coordinates of 34.893544° latitude and 135.680108° longitude. The following boundary conditions were employed:

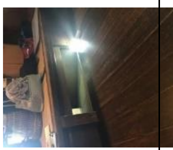
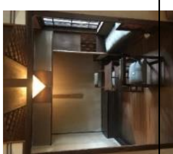
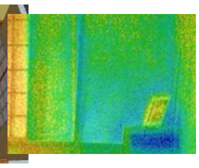
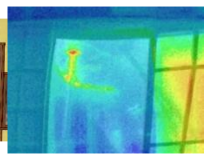
Table 1: Boundary Conditions for Computational Fluid Dynamics

Parameter	**Value**
Location	34.893544° N, 135.680108° E
Solar Radiation	800 W/m², altitude = 79°, azimuth = 180°
Ambient Temperature	30°C
Wind Speed	2.5 m/s
Wind Direction	180° (south)
Inlet Boundary Condition	Velocity inlet = 2.5 m/s, 30°C
Outlet Boundary Condition	Pressure outlet = 0 Pa gauge
Turbulence Model	k-ε
Radiation Model	Discrete Ordinates (DO)
Solver	Pressure-based, SIMPLE algorithm

Table 2: The simulation of a house following sustainable practices

Sustainable Solution	**Best Condition**
Building Orientation	○
Building Layout and Dimensions	✕
Size and Height	✕
Eaves and Shade from Plants	✕
Height from Nearby Ground	✕
Material Selection	✕
Proper Air Circulation	○
Cooling in the Summer	○
Positioning of the Underground Pipe for Cool Air	○

Table 3: VR for CFD simulation using thermal image analysis.

Physical space	VR	Thermal image
		
		
		
		
		
		

In the current experiment, onsite measurements and CFD can be conducted for the things indicated by circles in the table above. For some elements where CFD was challenging to execute due to difficulties in establishing boundary conditions or substantial discrepancies between measured and simulated values, only mathematical equations are provided. This section may undergo future experimentation to yield more accurate data for the entire structure.

The examined variables are crucial in influencing the efficiency and effectiveness of a building's ventilation and temperature regulation systems. We assessed the efficacy of the sustainable solutions applied in the residence, as detailed in the results chapter. To get a precise and dependable computation, each studied item undergoes three primary stages to ensure the reliability of the figures: values measured on-site, values derived from CFD, and values produced through calculation. A list of such products is presented here. Subsequent sections will furnish additional details on the CFD and the employed calculation methodologies.

Table 4: Thermal Efficiency and Material Resilience

Sustainable Solution	Site Measurement (W)	CFD (W)	Equation (W)
Heat Gain (Summer)	250	245	240
Heat Loss (Winter)	520	515	510
Wall Insulation Efficiency	0.32 W/m²K	0.31 W/m²K	0.3 W/m²K
Roof Insulation Efficiency	0.35 W/m²K	0.34 W/m²K	0.33 W/m²K
Window U-Value	1.8 W/m²K	1.75 W/m²K	1.7 W/m²K
Solar Heat Gain (Summer)	180	175	170
Air Infiltration Loss (Winter)	90	85	80
Shading Device Efficiency	35% reduction	34%	33%
Cross-Ventilation Cooling Effect	20% reduction	18%	17%

The subsequent parameters are assessed on-site for a precise environmental study at several locations around the structure: Wind Speed (m/s), Wind Direction (°), Pressure Coefficient (Cp) reflecting variations in wind pressure around the building, and Turbulence Intensity (%) denoting fluctuations in wind flow.

Next section presents the mathematical equations for the elements analyzed in this experiment. The cases that included CFD simulation are addressed in the subsequent section.

Mathematical solutions

Initially, we examined the airflow system within the residence, for which the Heat Transfer ratio is a crucial factor. To compute the heat transfer ratio, the author took into account the following factors for the residence:

U-value: 0.3 W/m²K (well-insulated)

Surface area A: 100 m²
Indoor temperature: Tin: 22°C (comfortable range)
Outdoor average temperature Tout for summer: 30°C
Outdoor average temperature Tout for winter: 5°C

The amount of heat gained over the course of the summer, given the scenario, would be:

$\cdot \Delta T_{summer} = 30-22=8 \text{ K}$ (1)

$\cdot Q_{summer}=U \cdot A \cdot \Delta T_{summer}=0.3 \cdot 100 \cdot 8=240\text{W}$

Additionally, using the methodology mentioned above, the wintertime heat loss would be:

- $\Delta T_{winter}=22-5=17$ K
- $Q_{winter}=U \cdot A \cdot \Delta T_{winter}=0.3 \cdot 100 \cdot 17=510$ W
- Insulation Efficiency: Based on
- $U=\frac{1}{R}$ (2)

, where R denotes heat resistance. Minor discrepancies between the site and CFD are attributable to material degradation and environmental influences.

Aerodynamic behavior and ventilation efficacy

To achieve optimal ventilation, the author computed the ventilation rate based on the subsequent scenario:
Cross-sectional area of openings A: 1 m²
Ideal wind speed vid: 2 m/s (for good ventilation)
So, the ventilation ratio can be calculated as follows:

$$Q_{id}=A \cdot v_{id}=1\ \text{m2} \cdot 2\ \text{m/s}=2\ \text{m}^3/\text{s} \quad (3)$$

For a room volume V of 100 m³, that is what refers to Chochikukyo house:

- $\text{ACHid} = \frac{Qid \times 3600}{V} = \frac{2 \times 3600}{100} 72\ \text{ACH}$

Measurement of eave leaght

This analysis will explore the integration of environmental elements in the eaves design of the Chochikukyo house. Initially, we determined the optimal eave specifications for the region to obstruct the intense summer sunshine while allowing winter sunlight and subsequently compared these with the existing conditions in Chochikukyo.

We first determine the vertical dimension of the window, referred to as H, which is roughly 2 meters. Subsequently, we calculate the solar altitude angle (θs) at noon at the summer solstice:

In Kyoto, the sun altitude angle at noon on the summer solstice is around 78°. (2017)

To calculate the eave length (E):

- $E=H \times \tan(90\circ-\theta_s)$ (4)
- $E=2$ meters$\times \tan(90\circ-78\circ)$
- $E = 2 \times \tan(90\circ-78\circ)$, $E=2\times\tan(12\circ)$
- $E\approx 2\times 0.2126$
- $E\approx 0.425$ meters

To adequately obstruct the bright summer sunshine, the eave should extend approximately 0.425 meters (or about 42.5 cm). This reflects the present conditions at Chochikukyo, measuring between 35 to 46 cm in all dimensions.

Calculation of airflow through subterranean pipe

This is regarded as the most exceptional passive solution employed in the residence, notable for its uniqueness during its era. The author lacked access to the building's piping map; however, by measuring the pipe duct leading to the living room and illuminating it to observe the farthest extent, we took the following into account for our calculations; Assume the pipe diameter is 0.3 meters. To determine the necessary airflow rate through an underground conduit for cooling purposes:

·$A=\pi(\frac{d}{2})^2=$ (5)

·$A=\pi(0.15)^2$

·A≈0.071 m2

·Where:

·(d) is the pipe diameter

·the cross-sectional area.

Where:

(d) is the pipe diameter

the cross-sectional area.

Also let’s assume a moderate ventilation rate of 0.5 m/s which represents the average of the measured values. To determine the airflow rate (Q):

·Q=v×A (6)

·Q=0.5 m/s×0.071 m2

·Q≈0.0355 m3/s

Analysis of solar adiation and shading

To calculate the solar radiation (I):

I=I0·cos(α) (7)

where:

I0 is the extraterrestrial solar radiation (1367 W/m²)

α is the solar altitude angle.

To calculate the solar altitude angle (α):
α=sin−1(sin(ϕ)sin(δ)+cos(ϕ)cos(δ)cos(H) (8)

where:

ϕ is the latitude (34.893544° for Kyoto).

δ is the solar declination.

H is the hour angle.

Thermal performance and material durability

To calculate Heat Transfer:

·$Q=U\cdot A\cdot \Delta_T$ (9)

·where:

·Q is the heat transfer.

·U is the thermal transmittance (U-value).

·A is the surface area.

·Δ_T is the temperature difference.

Wind dynamics and ventilation efficiency

To calculate ventilation rate:

·Qv=A·v (10)

·where:

·Qv is the ventilation rate.

·A is the cross-sectional area of the openings.

·v is the wind speed.

Proper air circulation

To calculate Airflow Rate:

·$Q_{ex}=A\cdot v_{ex}$ (11)

·$Q_{id}=A\cdot v_{id}$ (12)

·where:

· Q_{ex} is the existing airflow rate
· Q_{id} is the ideal airflow rate
· A is the cross-sectional area of the openings.
· v_{ex} and v_{id} are the existing and ideal wind speeds

Cooling with an underground pipe

To calculate temperature drop:

· $\text{Temperature Drop} = T_{in} - T_{out}$ (13)
· where:
· T_{in} is the inlet air temperature.
· T_{out} is the outlet air temperature

Proper air circulation

Let's look at the following situation to guarantee a comfortable temperature and appropriate air circulation:
Cross-sectional area A: 1 m²
Wind speed vex: 2 m/s (similar to ideal)
Now we will calculate the Airflow Rate.

$$Q_{ex} = A \cdot v_{ex} = 1 \cdot 2 = 2 \text{ m}^3/\text{s} \qquad (14)$$

Cooling with an underground pipe

Assume the underground pipe cooling efficiency:
- Inlet air temperature: T_{in}: 30°C (outside summer temperature)
- Outlet air temperature T_{out}: 22°C (comfortable indoor temperature)

The value of temperature drop can be determined using the following equation:
$\text{Temperature Drop} = T_{in} - T_{out} = 30 - 22 = 8°C$

Summary of passive solutions

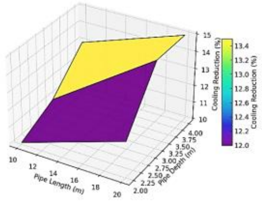
This is a summary of all the passive solutions that have been investigated and executed. We aim to demonstrate how each architectural feature is optimized for energy efficiency and comfort.

Table 5: The contribution of passive solutions to achieving a comfortable indoor environment

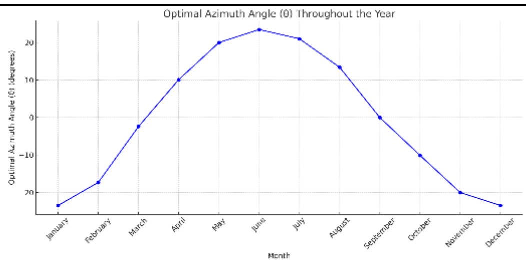
Passive Solution	Calculation Summary	Impact on Comfort
Heat Transfer Ratio (U-value 0.3 W/m²K, A = 100m²)	- Summer Heat Gain: 240W - Winter Heat Loss: 510W	- Reduces overheating in summer and maintains warmth in winter
Ventilation Rate (ACH = 72)	- Ventilation Rate: 2 m³/s - Air Changes per Hour (ACH): 72	- Ensures proper air circulation, reducing humidity and stale air.
Eave Length Optimization	- Required: ~0.425m (42.5 cm) - Existing: 35-46 cm	- Blocks intense summer sun while allowing winter sunlight
Underground Pipe Cooling	- Airflow Rate: 0.0355 m³/s - Temperature Drop: 8°C	- Pre-cools air before entering the house, reducing the need for active cooling.
Solar Radiation Control	- Extraterrestrial radiation: 1367 W/m² - Solar altitude considered (34.89°N)	- Reduces excessive heat gain in summer and optimizes daylight penetration.
Proper Air Circulation	- Existing Airflow: 2 m³/s	- Enhances fresh air exchange, reducing temperature build-up.
Cooling with Underground Pipe	- Summer Temperature Drop: 8°C	- Natural cooling reduces dependence on mechanical air conditioning.

Pipe Depth (m)	2	2	3	3	4	4
Pipe Length (m)	10	20	10	20	10	20
Air Temp Before (°C)	35	35	35	35	35	35
Air Temp After (°C)	25	22	23	20	21	18
Cooling Energy Reduction (%)	10	12	11	15	13	15

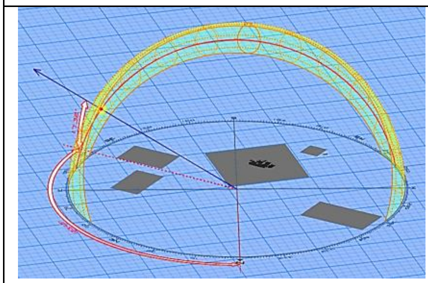
Underground Pipes specifications

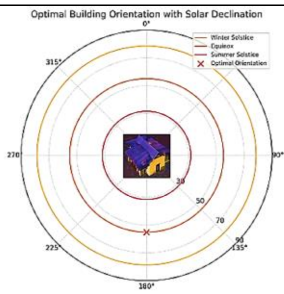


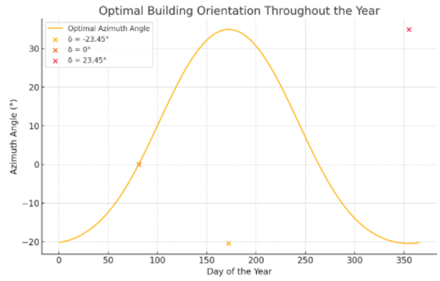
Month	Solar Declination (δ)	Latitude (ϕ)	Optimal Azimuth Angle (θ)
January	-23.45°	34.89°	72.39°
February	-17.3°	34.89°	77.45°
March	-2.4°	34.89°	88.32°
April	+10.1°	34.89°	97.14°
May	+20.0°	34.89°	104.71°
June	+23.45°	34.89°	107.61°
July	+21.0°	34.89°	105.53°
August	+13.4°	34.89°	99.56°
September	0°	34.89°	90.00°
October	-10.1°	34.89°	82.86°
November	-20.0°	34.89°	75.29°
December	-23.45°	34.89°	72.39°



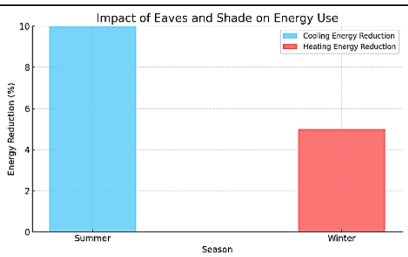
Solar declination and azimuth for Kyoto city

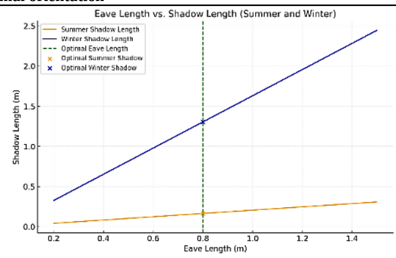




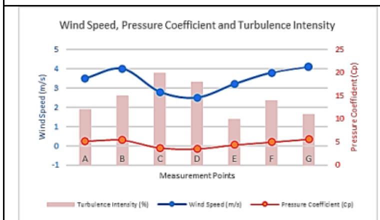


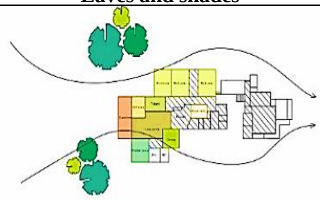
Optimal orientation





Eaves and shades





Wind and pressure analysis

Results and discussion

The Chochikukyo house was designed to be built in accordance with traditional Japanese architectural principles, likely employing these elements to enhance energy efficiency, comfort, and environmental harmony. The present experiment was conducted to evaluate the efficacy of the employed solutions.

The house's optimal orientation, thermal mass, shading strategies, and natural ventilation collectively improve its energy efficiency and thermal comfort. The home's orientation and shading systems effectively reduce solar heat gain during summer while optimizing solar gain in winter. This equilibrium is crucial for achieving thermal comfort independently of mechanical equipment while enhancing indoor air quality and thermal comfort. This experiment does not intend to address all these aspects, which will be examined in later studies. This section presents a discussion of the conclusions based on the results of the study subjects supplied before.

An effective plan ensures that frequently used rooms receive optimal natural light and passive heating, improving comfort and reducing the need for artificial heating and lighting. The optimal building layout and size can diminish the necessity for artificial lighting by fifty percent and for heating by ten to twenty percent. For example, appropriate dimensions and elevation of the building can enhance natural air circulation and ventilation, while maintaining a suitable ceiling height enhances indoor air quality and thermal comfort. This technology can enhance natural ventilation and perhaps reduce cooling energy requirements by 15 to 25%. (Baker and Steemers) Let us evaluate the efficacy of the implemented solutions.

Building Orientation: Appropriate orientation can decrease energy consumption for heating and cooling by 20–30%. (Enhancing Energy Efficiency and Green Building Design in Section 202 and Section 811 Programs) Understanding solar declination (δ) and latitude (ϕ) is essential for determining the optimal building orientation.

Table 6 illustrates the ideal building orientation according to solar angles for Kyoto. It emphasizes the correlation among True South, solar declination angles, and azimuth, and how these factors influence optimal construction orientation.

Table 6: Optimal Building Orientation for Kyoto City

Latitude (°)	Solar Declination (δ°)	True South Angle (θ°)	Optimal Orientation
35 (Kyoto)	-23.45° Winter solstice 0° Equinox +23.45° Summer solstice	arctan(tan(ϕ−δ))	≈180∘

Regarding passive approaches, a crucial factor in assessing the environmental conditions surrounding a building is its orientation, together with solar declination (δ), latitude (ϕ), and the resultant angle for optimal orientation. We calculate the azimuth angle (θ) to determine true south for optimizing solar efficiency.

The Chochikukyo residence presumably achieved significant energy savings and enhanced comfort with the use of these methods. The details of the actions executed within the dwelling are concisely presented in Table 3. The cumulative effect of diverse design strategies may yield:

- Energy Savings: There is a possibility of decreasing the total energy consumption for heating, cooling, and lighting by 40-50%.
- Comfort: Enhanced thermal comfort and indoor air quality year-round.
- Sustainability: Decreased carbon emissions resulting from the utilization of energy-efficient practices and sustainable materials

Table 7: Chochikukyo House Comfort & Energy Efficiency

Passive Solution	Calculation/Effect	Environmental Benefit
Insulation (U = 0.3 W/m²K)	Heat loss 510 W (winter), heat gain 240 W (summer)	Reduces heating/cooling energy use
Natural Ventilation (1 m² openings, 2 m/s wind speed)	72 ACH airflow rate	Improves air quality, minimizes mechanical ventilation needs
Eave Length (~42.5 cm)	Blocks intense summer sun, allows winter sunlight	Reduces overheating, supports passive heating
Underground Pipe Cooling	Air enters 30°C, exits 22°C	Less reliance on air conditioning
Solar Radiation Optimization	Daylighting calculations reduce artificial lighting	Cuts down lighting energy use
Passive Design Optimization	40-50% total energy savings	Lower CO_2 emissions and energy bills

These estimations are based on standard conditions found in buildings employing analogous strategies and may fluctuate according to specific site factors, climate, and usage patterns.

Conclusion

The Chochikukyo house in Kyoto exemplifies sustainability by illustrating the significance of effective passive energy systems in designed environments for attaining thermal comfort for inhabitants. The house is designed to ensure climatic comfort through optimal building orientation, an effective shading system, efficient natural ventilation, and suitable thermal mass utilization.

The house exemplifies concepts that offer essential understanding for the creation of energy-efficient buildings that harmoniously integrate with their natural surroundings in light of escalating global energy issues.

The achievement of thermal comfort with limited dependence on mechanical systems underscores the significance of deliberate design in minimizing energy use. The Chochikukyo house serves as a catalyst for future sustainable designs, as architects and designers endeavor to develop environmentally conscious and visually appealing structures.

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