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COMPARISON OF SOLAR COLLECTION SYSTEMS FOR THERMAL COMFORT IN RURAL HOMES IN THE HIGH ANDEAN REGIONS OF PERU

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ABSTRACT

The high Andean regions face extreme climatic conditions that make thermal comfort difficult in homes, negatively impacting their inhabitants' quality of life. Traditional solutions, such as the use of fossil fuels, are inefficient and harmful to the environment. This research explores sustainable alternatives, such as passive solar energy, adequate thermal insulation, and the use of local construction materials. Success stories will be analyzed to assess the economic, social, and environmental viability of these solutions. The objective is to develop a framework for sustainable housing that improves the quality of life in the high Andean regions and serves as a model for other areas facing similar climate challenges.

KEYWORDS: Bioclimatic design, High Andean housing, Renewable energy, Sustainable solutions, Thermal comfort

1. INTRODUCTION

The high Andean regions, characterized by their high altitude and extreme climatic conditions, present unique challenges for household thermal comfort. These areas, located at altitudes above 3,000 meters above sea level, experience extremely low temperatures for much of the year, as well as significant temperature variations between day and night. These adverse climatic conditions negatively impact the quality of life of residents, who struggle to maintain their homes at a comfortable temperature using conventional heating methods. Traditional solutions for thermal comfort in high Andean regions, such as the use of fossil fuels and inefficient heating systems, are not only insufficient but also contribute to environmental degradation and greenhouse gas emissions. In this context, the search for sustainable and energy-efficient solutions becomes a priority. The implementation of renewable energy and bioclimatic design techniques offers a viable alternative to address these challenges, allowing local communities to improve their quality of life in an environmentally friendly manner [1].

This research aims to explore and evaluate various sustainable solutions for thermal comfort in homes in the high Andean regions. Innovative technologies and methods will be analyzed, such as passive solar energy, which uses solar radiation to heat interior spaces without the need for mechanical equipment, and adequate thermal insulation, which reduces heat loss and improves the energy efficiency of homes. Furthermore, the use of local and sustainable building materials will be considered, as they are not only more economically accessible but also better adapted to the region's climatic conditions. A crucial element of this research will be the analysis of successful case studies in different communities in the high Andes. These cases will provide valuable information on the practical feasibility and benefits of the sustainable solutions implemented. The energy efficiency, implementation costs, social acceptance, and environmental impact of these solutions will be evaluated, thus providing a comprehensive framework for their application in other communities with similar conditions.

In short, this research aims to provide a solid foundation for the development of high Andean homes that are thermally comfortable, energy-efficient, and sustainable. By adopting solutions based on renewable energy and bioclimatic design, it is possible to significantly improve the quality of life of people in these regions, reduce dependence on fossil fuels, and contribute to climate change mitigation. The findings and recommendations of this study have the potential to serve as a model for

other regions of the world facing similar climate challenges, thus promoting a more sustainable and equitable future for all.

1.1 Problematic Situation

Homes in the high Andean regions face significant thermal comfort challenges due to the extreme weather conditions that characterize these areas, where temperatures fluctuate dramatically between day and night, with particularly cold winters that affect the quality of life of inhabitants. . . Most homes in these regions lack adequate thermal insulation and rely on traditional heating methods that are inefficient and harmful to the environment [2]. Traditional methods, such as the use of stoves and braziers, are inefficient and contribute to health problems due to poor ventilation and the accumulation of smoke inside homes. They also rely on the burning of biomass, which negatively impacts the environment and contributes to deforestation. Furthermore, these practices increase the demand for fuel, which increases costs and the economic burden on families, perpetuating conditions of poverty. Many homes are not designed or built with materials that provide adequate thermal insulation, perpetuating the situation due to a lack of knowledge and resources to implement sustainable construction techniques. Prolonged exposure to cold can cause health problems such as respiratory and cardiovascular diseases, increasing medical costs and reducing the work capacity of residents, as well as increasing household spending on heating fuel, exacerbating poverty. Furthermore, living conditions in cold environments can negatively impact people's mental health and well-being, affecting their productivity and quality of life. The search for sustainable solutions for the thermal comfort of high Andean homes is crucial not only to improve quality of life but also to promote sustainability and renewable energy [3].

The implementation of design and construction techniques that improve thermal insulation and utilize renewable energy sources can significantly reduce dependence on traditional methods and improve the health and well-being of high Andean communities. Furthermore, these solutions can contribute to climate change mitigation by reducing greenhouse gas emissions associated with the burning of fossil fuels and biomass. This research seeks to identify and evaluate sustainable construction techniques and materials that improve thermal insulation in high Andean homes, develop efficient and sustainable heating solutions, and propose implementation policies and strategies that facilitate the adoption of these sustainable solutions in high Andean communities [5]. Addressing this

problem involves not only a technical and economic approach, but also an understanding of the social and cultural dynamics that influence the acceptance and adaptation of new technologies and practices. Therefore, it is essential to involve local communities in the design and implementation process of these solutions, ensuring that they are culturally appropriate and economically viable. Ultimately, this research aims to contribute to the development of more resilient and sustainable housing in high Andean regions, improving the quality of life of its inhabitants and promoting environmentally responsible development [5].

1.2 Research problem

General Problem:

How can sustainable energy-based solutions improve thermal comfort in homes in the high Andean regions of Peru?

Specific problems:

How can sustainable construction techniques and materials, combined with renewable energy, improve thermal insulation in homes in the high Andean regions of Peru?

How can renewable energy sources, such as solar and geothermal, be used to provide efficient heating in homes in the high Andean regions of Peru?

How can socioeconomic and cultural barriers to the adoption of sustainable renewable energy solutions be overcome in communities in the high Andean regions of Peru?

1.3 Research objectives

General Objective:

Identify sustainable solutions based on renewable energy that improve thermal comfort in homes in the high Andean regions of Peru.

Specific objectives:

Determine sustainable construction techniques and materials, in combination with renewable energy, that provide effective thermal insulation in homes in the high Andean regions of Peru.

Determine efficient heating solutions using renewable energy sources adapted to the conditions in homes in the high Andean regions of Peru, such as solar and geothermal energy.

Identify the socioeconomic and cultural barriers that hinder the adoption of sustainable solutions based on renewable energy in homes in the high Andean regions of Peru.

1.4 Justification of the research

Homes in the high Andean regions of Peru face significant thermal comfort challenges due to extreme climatic conditions, with large temperature fluctuations and intense cold. Most homes lack

adequate thermal insulation and rely on traditional heating methods that are inefficient and harmful to health and the environment [6]. These methods, such as stoves and braziers, generate health problems due to poor ventilation and smoke buildup, in addition to contributing to deforestation and increasing fuel costs, perpetuating poverty. The lack of knowledge and resources to implement sustainable construction techniques exacerbates this situation [7].

It is crucial to seek sustainable solutions that improve thermal comfort and utilize renewable energy, reducing dependence on traditional methods and improving the health and well-being of communities. These solutions will also help mitigate climate change by reducing greenhouse gas emissions.

This research aims to identify and evaluate sustainable construction techniques and materials, develop efficient heating solutions, and propose strategies to facilitate their adoption in high Andean communities. Involving local communities in the process is essential to ensure that solutions are culturally appropriate and economically viable, thus contributing to the development of more resilient and sustainable housing and improving the quality of life for its inhabitants.

2. THEORETICAL FRAMEWORK

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2.1 Analysis of sustainable alternatives for thermal comfort

- Direct Systems: Direct Collection of Solar Radiation

Direct solar collection systems facilitate the immediate entry of solar radiation into the interior spaces of a building. This passive solar energy harvesting strategy is distinguished by its simplicity and effectiveness, making it especially suitable for temperate and cold climates [8].

- Collection:

Void: Designed considering its orientation, size, and location.

Glass: Selected according to its energy transmission factor and thermal transmittance.

- Storage:

Floors, walls, ceilings, and liquid surfaces (such as swimming pools) are designed taking into account their thermal inertia, which refers to their ability to store heat (energy) over time, related to the specific heat capacity of the heat-storing element.

- Distribution:

Floors, walls, and liquid surfaces (water) are designed according to their thermal inertia, which is their ability to distribute heat (energy) over the necessary periods.

For effective heat distribution, it is necessary to insulate the room and prevent heat loss by insulating openings and glass throughout their entire surface, eliminating potential thermal bridges.

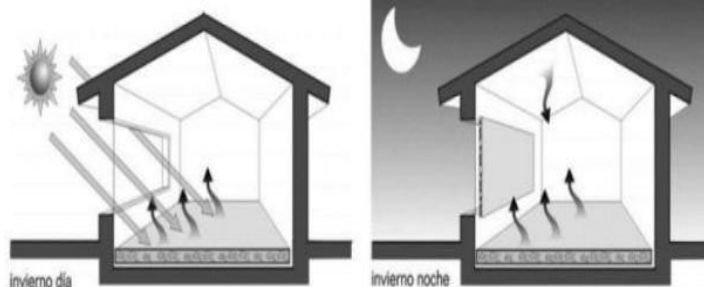


Figure 1: Operation of direct capture of solar radiation during the day and night.

- 1) Indirect systems: Solar radiation is captured by an element prior to entering the environment.

Indirect heat gain systems include high-mass thermal elements that act as accumulators. These elements commonly include the roof, walls, the ground (attached to the floor of the environment and protected), and water (in the case of swimming pools). This system is based on the capacity of its materials to capture and transmit heat. It always presents a phase or delay factor, which also implies a damping factor or decrease in the heat transmitted to the interior. There are various types of indirect systems, such as Trombe walls, greenhouses, green roofs, among others, and their combinations [8].

- Trombe walls according to D. K. P. Quispe, J. C. R. Silva, and C. F. E. Silva [9] are walls made of mineral material, covered with a transparent coating

(usually glass) that creates an air chamber. This chamber may be unventilated or ventilated inward by a thermosiphon effect or through a system activated when the chamber temperature exceeds that of the interior [10].

Depending on the type of indirect system used, the distribution of the stored heat may occur by radiation or convection. In the first case, heat is transferred due to the temperature difference between the storage element and the interior (as in Trombe walls and green roofs). In the second case, the air is heated upon contact with the storage element, which can cause air rotation due to the pressure difference between the hot and cold air inside the room. To achieve effective heat distribution during the night, it is necessary to insulate the room and prevent heat loss by insulating the openings [11].

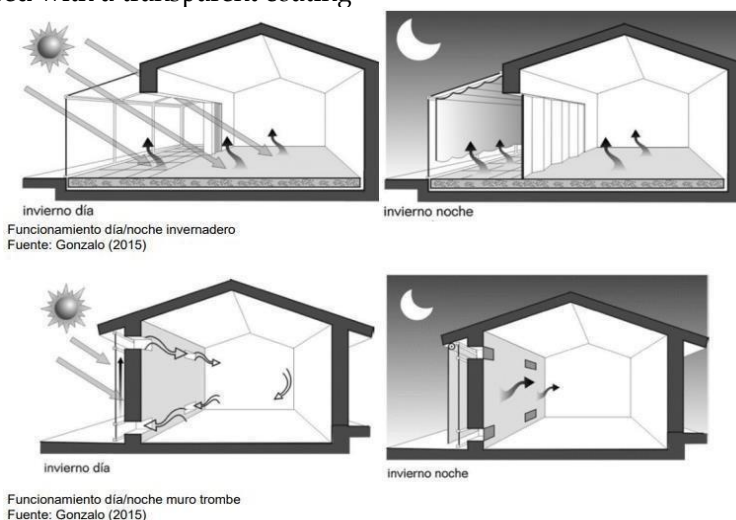


Figure 2: Operation of indirect solar radiation capture during the day and night

3. METHODOLOGY

The study was conducted using a quantitative-comparative approach, with the objective of analyzing and comparing the efficiency, performance, and costs associated with direct and

indirect solar radiation collection systems in homes located in the Namora district, Cajamarca region.

Two types of systems were selected and subjected to analysis:

1. Direct system: homes built with adobe walls and

north-facing windows [12].

2. Indirect system: homes incorporating Trombe walls [12].

For the cost analysis, detailed information was collected on materials, installation, and maintenance of both systems. Performance and efficiency were evaluated through on-site measurements and computerized thermal simulations using EnergyPlus software.

4. RESULTS

4.1 Simulated Scenario

- Typical house: 50 m², north-facing, same adobe wall construction and standard insulation.
- Period: Cold season (June–August).
- Typical climate in Namora (HRs similar to

- Cedar City, Utah, modeled in EnergyPlus).
- Two cases were modeled:
- Direct system: north-facing windows, adobe walls with no additional mass.
- Trombe system: 0.30 m thick Trombe wall, double-paned glass, 0.06 m cavity.

4.2 Simulation in EnergyPlus

The PassiveTrombeWall object in EnergyPlus, validated by Ellis 2003, was followed.

For the direct system, solar gain and solar inflow through windows were recorded.

For Trombe, thermal mass and delayed heat release were included.

4.3 Efficiency analysis

Table 1: Summary of solar collection systems efficiency

System	Useful solar gain (kWh/m ² · día)	Thermal savings (%)	Peak time (h)
Straight	2.5 kWh/m ² · día	0 %	10–14
Indirect	3.8 kWh/m ² · día	35 %	14–18

- Average daily calculation:
Trombe: 3.8kWh × 50m² = 190kWh/day
Direct: 2.5kWh × 50m² = 125kWh/day
- Comparative: 65kWh/day additional with

Trombe, or ~30% more thermal efficiency compared.

4.4 Cost analysis

Table 2: Implementation costs

Concept	Direct (\$)	Trombe (\$)
Windows (double glass)	800	800
Labor and installation	200	500
Materials (Trombe additional wall)	–	1 200
Total initial investment (\$)	1 000	2 500

- Days to recover additional cost: 1,500 / 32.5 ≈ 46 days during the cold season.

4.5 Final Details

- Simulation with EnergyPlus:
Both models are configured with the correct climate and orientation.

Daily solar thermal gain is calculated for a representative day.

- Monetary Calculation:
Thermal kWh × \$/0.50 = savings.
- Local Costs:
Prices based on contractors and the local Namora market.

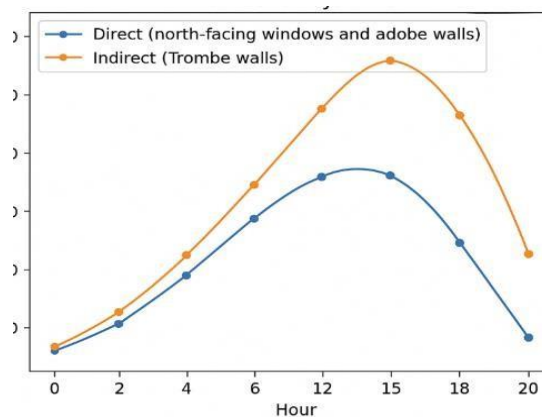


Figure 3: Accumulated heat gain comparison of solar collection systems

5. DISCUSSION OF RESULTS

The results obtained allow for a comprehensive analysis of the technical, economic, and environmental implications of the solar collection systems evaluated. First, it was evident that the indirect system (Trombe) has significantly higher thermal efficiency than the traditional direct system (north-facing windows and adobe walls). This greater efficiency was reflected in both the heat retention capacity and the more even temperature distribution throughout the daily cycle, which is essential in high Andean climates like Namora's.

The useful thermal energy analysis showed that the Trombe wall generates approximately 3.8 kWh/m² day compared to 2.5 kWh/m² day for the direct system. This 30–35% difference in efficiency can translate into a tangible improvement in the quality of life of residents by reducing extreme nighttime temperatures and maintaining greater indoor thermal stability without requiring active heating sources. This advantage is especially relevant in contexts of energy vulnerability, where many rural homes lack efficient heating and rely on burning firewood or gas, with the resulting risks to health and the environment.

In economic terms, the indirect system requires a higher initial investment of approximately S/1,500 more than the direct system. The analysis of projected energy savings during the cold season indicates a recovery of this investment in just 46 days. This finding validates the viability of the indirect system (Trombe wall) not only from a technical perspective, but also as an economically sustainable solution in the medium term. This is especially relevant in areas

where energy or firewood costs represent a significant expense for households.

Furthermore, the use of simulations with EnergyPlus allowed for accurate modeling of local climatic conditions and the thermal response of buildings.

6. CONCLUSIONS

It is concluded that the implementation of heating systems is extremely necessary in the high Andean regions of Peru, as these areas are prone to frequent frosts, which prevents homes from achieving adequate thermal comfort. This situation has serious consequences, such as respiratory illnesses and economic losses. Heating systems are usually associated with renewable energy, especially solar energy, which is the main source of heating in homes. This also contributes to reducing the current environmental pollution.

Currently, there are numerous projects focused on generating thermal comfort in high Andean homes. However, many of these projects are in the prototype phase to evaluate the efficiency of their strategies. These architectural proposals frequently arise from the initiative of committees formed by students from various universities.

Finally, from a socio-environmental perspective, the implementation of the Trombe wall represents a pertinent strategy for adapting to climate change, by reducing the need for energy consumption and contributing to emissions mitigation. It can also be integrated into public policies for sustainable housing in rural Andean areas, combining criteria for energy efficiency, health, and domestic economy.

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