CP-301 Development Engineering Project

Optimizing Building Energy Loads using Eco-Friendly Insulation and Vapour Absorption Cooling with EnergyPlus-Based Simulation

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Introduction

Buildings account for a significant share of global energy consumption and carbon emissions, making the optimization of their thermal performance a critical challenge in the pursuit of sustainability and occupant comfort. As climate change intensifies and energy costs rise, it has become increasingly important to design buildings that maintain comfortable indoor environments while minimizing energy use and environmental impact. Thermal energy modeling, using advanced simulation tools like EnergyPlus, enables engineers and architects to predict and optimize the temperature dynamics of buildings throughout the day and across seasons, accounting for factors such as material properties, building orientation, occupancy, and local climate conditions[7].

By employing detailed 3D simulations, thermal modeling allows for the identification and mitigation of overheating risks, the evaluation of passive and active design strategies, and the reduction of reliance on costly mechanical cooling or heating systems. This process not only ensures regulatory compliance and occupant well-being but also supports the broader goals of energy efficiency and carbon footprint reduction. Our project was undertaken to leverage these capabilities, using the EnergyPlus engine to rigorously analyze and enhance the thermal performance of building designs, ultimately contributing to the development of more resilient, comfortable, and sustainable built environments

1 Motivation

In the earlier phase of our project, we focused on improving the thermal performance of slum housing through sustainable insulation materials using EnergyPlus simulations. However, our analysis for hotter regions like Chandigarh revealed that passive insulation alone may not be sufficient to handle peak summer loads. This realization motivated a strategic pivot in our approach: instead of relying entirely on wall material optimization, we began exploring cost-effective active cooling alternatives that could be integrated with existing housing structures.

In particular, we explored the use of Vapor Absorption Refrigeration Systems (VARS) driven by solar thermal collectors. Unlike conventional vapor compression systems (VCRS) that depend on electricity and costly compressors, VARS can operate using low-grade thermal energy—readily available through solar heat in hotter parts of India. Not only does this reduce electricity dependency, but the second law efficiency of VARS is comparable to VCRS, making it an energy-efficient alternative. Furthermore, VARS can be implemented in parallel with traditional HVAC setups, offering hybrid solutions for better adaptability. Compared to photovoltaic solar panels, solar thermal collectors coupled with VARS exhibit significantly higher system efficiency when used for cooling applications.

Our motivation stems from delivering practical, scalable, and economically viable cooling strategies for heat-stressed low-income housing, thereby expanding the project's impact from passive to active energy solutions.

The growing cooling energy demand in India's residential sector, particularly in low-income housing, highlights the need for both passive and active strategies for thermal comfort. Initial simulations using the EnergyPlus engine demonstrated that passive solutions—such as insulating walls with sustainable materials like rice husk and sugarcane bagasse ash—reduce energy load but still fall short during extreme summers in regions like Chandigarh.

To address this, our project pivoted post-midterm toward an active thermal management strategy involving a Vapor Absorption Refrigeration System (VARS) integrated with solar thermal collectors. This approach leverages low-grade solar heat, which is abundant in hot Indian climates, to power an ammonia–water-based absorption cycle, avoiding electricity-intensive vapor compression systems (VCRS). In addition to being low-maintenance and eco-friendly, VARS can operate alongside traditional HVAC systems to reduce peak loads and energy consumption, with a second-law efficiency close to that of VCRS and higher net energy utilization than traditional photovoltaic systems for cooling tasks.

2 Methodology

2.1 Phase I: Passive Thermal Simulation

We used EnergyPlus to simulate the heat transfer and cooling/heating loads of a typical slum house with and without eco-friendly wall insulation materials.

2.1.1 Simulation Information

- **Geometry:** 5 m $\times$ 3 m $\times$ 3 m, with a single south-facing window (2 m $\times$ 1 m, 3 mm single-pane glass).
- **Materials Simulated:**
  1. Baseline: Clay bricks (22.5 cm)
  2. Brick + 11 cm Sugarcane Bagasse Ash Bricks
- **Simulation Conditions:** Ideal HVAC system maintaining 21–28°C comfort range.

2.1.2 Locations

According to the Köppen climate classification of India, we selected cities that represent a diverse set of climatic zones across the country. This ensures that the performance of our system can be evaluated under varying weather conditions. The following table summarizes the chosen cities and the rationale behind their inclusion:

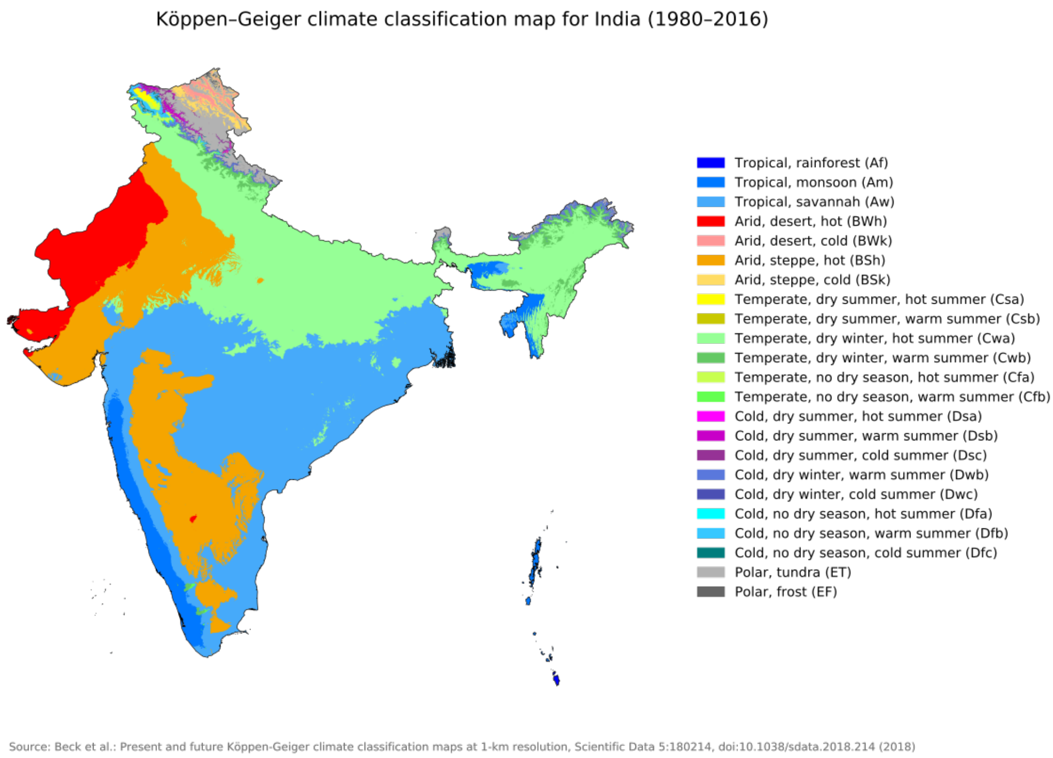


Figure 1: India's Köppen climate classification map [2]

City	Zone	Region	Climate Code	Significance
Chandigarh	Cwa	North	Temperate	Base simulation, experiences dry winters and strong summers. Provides a benchmark for comparison.
Goa (Panaji)	Am	West Coast	Tropical	Coastal, humid monsoon-dominated zone. Tests VAAC performance under overcast and moisture-rich conditions.
Jaipur	BSh	Northwest	Arid/Steppe	Hot and dry zone with high solar radiation. Useful for testing peak cooling loads.
Bhubaneswar	Aw	East	Tropical	Humid-hot inland conditions, different from Goa. Useful for evaluating solar potential with high heat loads.
Coimbatore	Cfb	South (Western Ghats)	Temperate	Mild but extended summers. Represents performance under warm, subtropical climates.

Table 1: Cities selected for simulation and their climate significance

2.1.3 Equations

The governing equation for 1-D transient heat conduction through the wall is:

$$\rho C \frac{\partial T}{\partial t} = \lambda \frac{\partial^2 T}{\partial x^2} \tag{1}$$

Boundary conditions:

$$-\lambda \frac{\partial T}{\partial x}\bigg|_{x=x_{\text{in}}} = h_{\text{in}}(T_{\text{wall}} - T_{\text{in}}) \tag{2}$$

$$-\lambda \frac{\partial T}{\partial x}\bigg|_{x=x_{\text{out}}} = h_{\text{out}}(T_{\text{sol-air}} - T_{\text{wall}}) \tag{3}$$

where

$$T_{sol} = T_{out} + \frac{I_\alpha}{h_{out}} \tag{4}$$

.

The heating/cooling loads were obtained via EnergyPlus and post-processed using Python to analyze monthly variations and total energy demands.

2.2 Phase II: Active Cooling System using Solar VARS

2.2.1 System Description

The VARS cycle employs ammonia as refrigerant and water as absorbent. The cycle includes the following main components:

- **Generator:** Heated by solar thermal collectors or exhaust gas. Drives ammonia vapor from the solution.
- **Rectifier/Dephlegmator:** Removes water vapor traces from the ammonia vapor.
- **Condenser:** Condenses pure ammonia at high pressure.
- **Evaporator:** Absorbs heat from the building space, providing cooling.
- **Absorber:** Absorbs ammonia vapor back into water.
- **Pump:** Circulates the weak solution.

A schematic is similar to Fig. 2 in the VARS source . The system's driving energy is low-grade heat, making it ideal for integration with solar thermal panels.

2.2.2 Thermodynamic Modeling

The first law energy balance across components gives:

$$Q_g + W_p = Q_c + Q_a + Q_d \tag{5}$$

where:

- Q_g: Heat to generator
- Q_c: Heat rejected by condenser
- Q_a: Heat rejected by absorber
- Q_d: Heat rejected by dephlegmator
- W_p: Pump work (often negligible)

The system coefficient of performance (COP) is:

$$COP_{\text{VARS}} = \frac{Q_{\text{evap}}}{Q_g} \tag{6}$$

The second law efficiency is:

$$\eta_{\text{II}} = \frac{COP_{\text{actual}}}{COP_{\text{Carnot}}} \tag{7}$$

with Carnot COP defined as:

$$COP_{\text{Carnot}} = \frac{T_{\text{evap}}}{T_{\text{gen}} - T_{\text{evap}}} \tag{8}$$

This formulation allows fair comparison with conventional VCRS systems.

2.2.3 Solar Integration

Flat-plate or evacuated tube solar collectors supply heat at 80–120°C, suitable for driving the generator. Compared to photovoltaic systems:

$$\eta_{\text{thermal solar}} \approx 40\% > \eta_{\text{PV}} \approx 15\text{–}20 \tag{9}$$

This higher efficiency directly translates into better cooling energy yield when VARS is used.

3 System Design

The overall objective of the system design was to model, simulate, and implement passive and active cooling solutions suited to low-cost housing in hot Indian climates. The project is structured into two key phases:

3.1 Phase I: Passive Thermal Modeling of Housing Envelope

We modeled a typical low-income urban house with internal dimensions 5 m $\times$ 3 m $\times$ 3 m. A south-facing window (2 m $\times$ 1 m) with 3 mm single-glazed glass was added to simulate real-life solar gain. The building energy simulation was conducted using the EnergyPlus simulation engine [3], which enabled us to compute heat gains and indoor air temperatures without any active HVAC system.

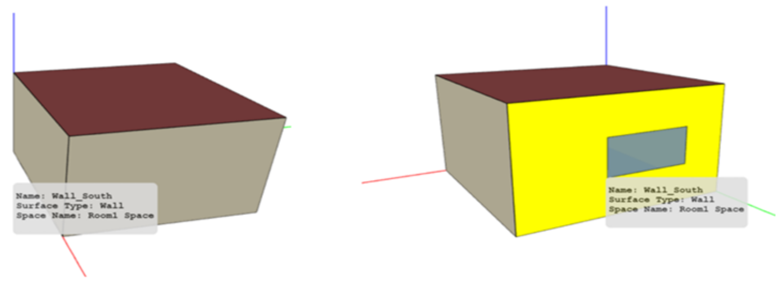


Figure 2: Cross-section of modeled 5x3x3 house showing material layers

Envelope Configurations Tested

Three major wall configurations were tested:

1. Standard clay brick wall (22.5 cm)
2. Brick + 11 cm layer of sugarcane bagasse ash bricks
3. Brick + 11 cm rice husk cork insulation

We simulated each configuration across two climatic zones (Chandigarh and Shimla) using 2023 TMY weather files. The EnergyPlus outputs included hourly indoor temperatures and unmet load hours under free-running conditions (no HVAC). This phase helped quantify the passive thermal performance and select appropriate material configurations for reducing HVAC dependency.

Figure 3: Suggested Image: EnergyPlus output plot showing temperature variation across wall types

3.2 Phase II: Design of VARS-Based Active Cooling Subsystem

In locations with significant unmet cooling loads (e.g., Chandigarh), passive insulation alone was found insufficient. To address this, we designed an ammonia–water-based Vapor Absorption Refrigeration System (VARS), using low-grade thermal energy from solar collectors.

Our system design was inspired by the experimental VARS setup from Vazhappilly et al. [9], where a generator heat exchanger replaced the conventional heating coil and was powered by exhaust gas. In our case, we adapted this to utilize flat-plate solar thermal collectors instead of IC engine exhausts, considering residential deployment.

Key Components

- **Generator:** Heated using solar thermal energy; plate-frame heat exchanger.
- **Absorber and Condenser:** Air-cooled.
- **Evaporator:** Located inside the test room; provides up to 1 kW cooling.
- **Working Pair:** Ammonia–Water.
- **Pump and Expansion Valve:** Circulate strong/weak solutions.
- **Solution Heat Exchanger:** Pre-heats strong solution using the outgoing weak solution to improve efficiency.

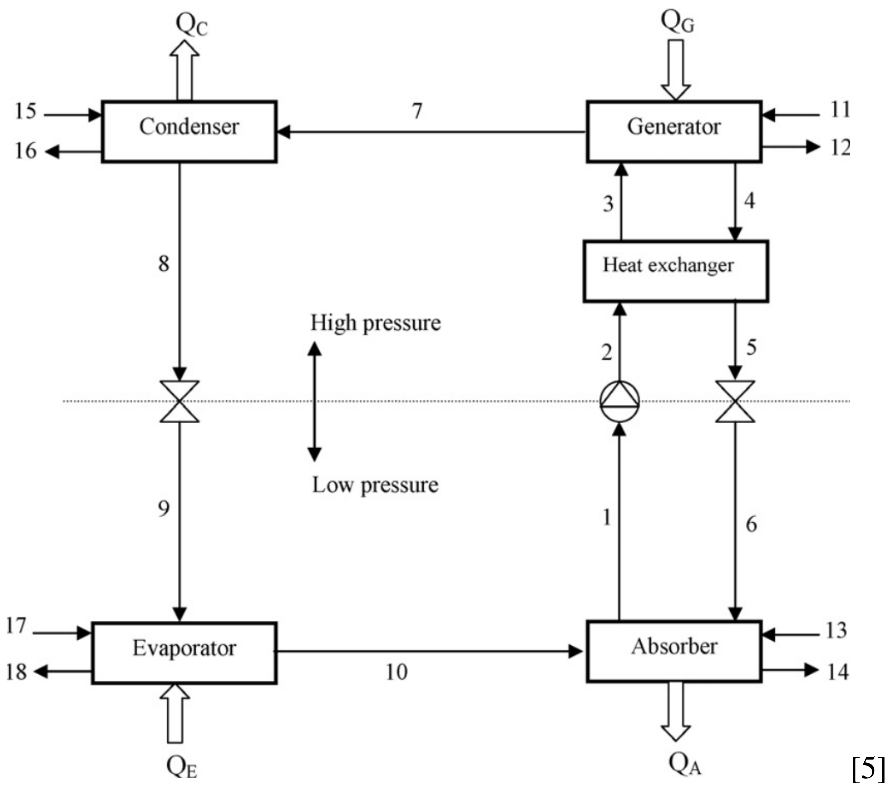


Figure 4: Continuous Ammonia–Water Absorption Refrigeration System Schematic

Design Parameters

Based on the reported configuration and modified to suit our 1 kW load target:

- **Generator Temperature:** 100–115°C
- **Evaporator Temperature:** 4–8°C
- **Solution Concentrations:** Strong: 40–50% NH_3, Weak: 25–30% NH_3
- **COP (Expected):** ≈ 0.7

We used the heat balance and flow equations given in the referenced paper:

$$Q = \dot{m} c_p \Delta T \quad \text{and} \quad \text{COP}_{\text{VARS}} = \frac{Q_{\text{evap}}}{Q_{\text{gen}}}$$

Where Q_{gen} is the heat input to the generator via solar collector, and Q_{evap} is the cooling effect at the evaporator.

Heat Exchanger Specification

As per the reference model, a plate-frame heat exchanger with the following parameters was considered:

- 120 stainless steel plates
- 0.015 m thickness
- Heat transfer coefficient $U = 800\,\text{W/m}^2 \cdot {}^\circ\text{C}$
- Designed to transfer ≈1.43 kW from solar fluid to generator

3.3 Integrated Energy Strategy

This two-fold approach—reducing internal heat gain via passive wall insulation and supplementing active cooling via low-grade energy VARS—creates a scalable solution for thermal comfort in low-income Indian housing. The passive simulation guided material choices, while the VARS design ensured that peak thermal loads could be met with minimal grid dependency.

Figure 5: Ingredients of Ko-Cane bricks [8]

3.4 Insulation Design

In this project, we have employed sugarcane bagasse coconut peat bricks (Ko-Cane Bricks) (Figures 5 and 6) as an eco-friendly insulation material. These bricks are crafted from a blend of sugarcane bagasse, cocopeat, soil, and lime powder, offering a sustainable alternative to traditional building materials. The incorporation of agricultural by-products not only reduces waste but also minimizes the carbon footprint associated with construction activities.

Ko-Cane Bricks are designed to provide exceptional durability and strength while enhancing thermal insulation properties. Their natural composition ensures a reduced environmental impact, making them ideal for eco-conscious construction projects. By utilizing these bricks, we aim to improve energy efficiency and contribute to sustainable building practices.

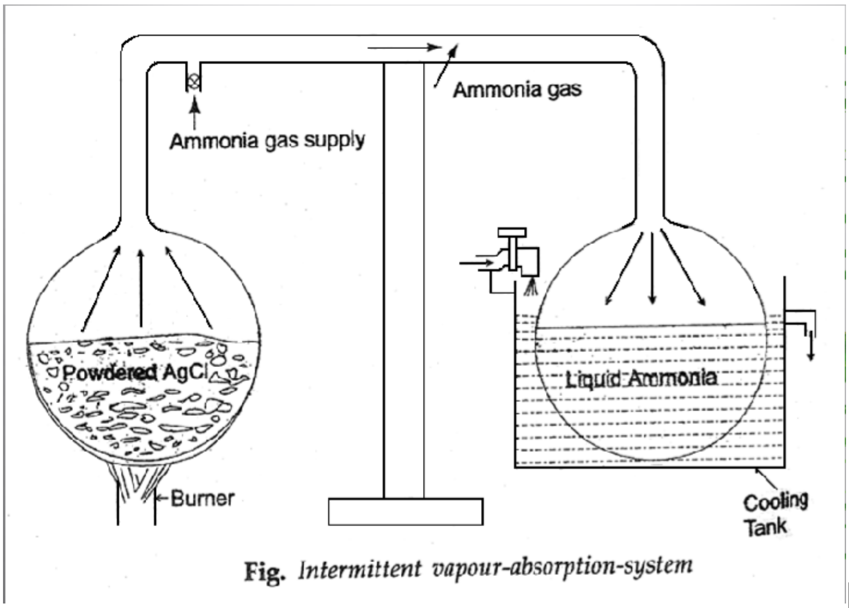
4 Theory of Vapor Absorption Refrigeration System

Vapor Absorption Refrigeration Systems (VARS) provide a compelling alternative to conventional Vapor Compression Refrigeration Systems (VCRS), especially in applications where low-grade thermal energy such as waste heat or solar thermal energy is abundant. Unlike VCRS, which relies on a mechanically-driven compressor to circulate refrigerant, VARS uses a thermal energy input to separate and recombine a refrigerant–absorbent mixture, typically ammonia-water or lithium bromide–water pairs [10].

Figure 6: Ko-Cane Bricks [8]

4.1 Intermittent Absorption Cycle

The intermittent absorption refrigeration cycle is the earliest form of VARS and is characterized by its batch-operation mode. It consists of two phases: a generation-condensation phase and an evaporation-absorption phase.



[6]

Figure 7: Schematic of Intermittent Absorption Refrigeration Cycle

During the **generation-condensation phase**, a solution of ammonia in water is heated in a generator, causing the ammonia to vaporize due to its lower boiling point. The water remains in the generator, while the ammonia vapor moves to the condenser, where it rejects heat to the surroundings and liquefies.

In the **evaporation-absorption phase**, the condensed ammonia (now at high purity) is routed to the evaporator. As it vaporizes by absorbing ambient heat (cooling the desired space), it is reabsorbed into the water in the absorber, forming a strong solution again. This solution is then returned to the generator, and the cycle repeats.

This cycle is simple and suitable for small-scale or portable refrigeration units, but it cannot provide continuous cooling without multiple units or thermal storage mechanisms.

4.2 Continuous Absorption Cycle

The continuous absorption system resolves the limitation of the intermittent system by enabling a steady-state operation. This system includes a generator, absorber, condenser, evaporator, solution heat exchanger, and pumps/valves to facilitate flow control and thermal efficiency. You can to refer to figure 3 for a schematic diagram of continuous vapour absorption cycle.

In this cycle:

- The generator is heated (by solar energy or waste heat), driving ammonia vapor from a weak aqueous solution.
- The ammonia vapor passes through a rectifier and condenser to become liquid.
- The high-pressure ammonia liquid then enters the evaporator where it absorbs heat (cooling effect) and vaporizes.
- The vapor is absorbed into the weak solution in the absorber, forming a strong solution.
- This strong solution is pumped back into the generator, completing the cycle.

4.3 Efficiency Formulation

The efficiency of an absorption refrigeration system is generally measured by its *Coefficient of Performance (COP)*:

$$\mathrm{COP}_{\mathrm{VARS}} = \frac{Q_{\mathrm{evap}}}{Q_{\mathrm{gen}}}$$

Where:

- Q_{evap} is the heat absorbed in the evaporator (cooling effect)
- Q_{gen} is the thermal energy supplied to the generator

While the COP of VARS is lower than that of VCRS (typically in the range of 0.6–0.8 for ammonia–water systems), its ability to use free or waste heat makes it highly attractive for sustainable applications.

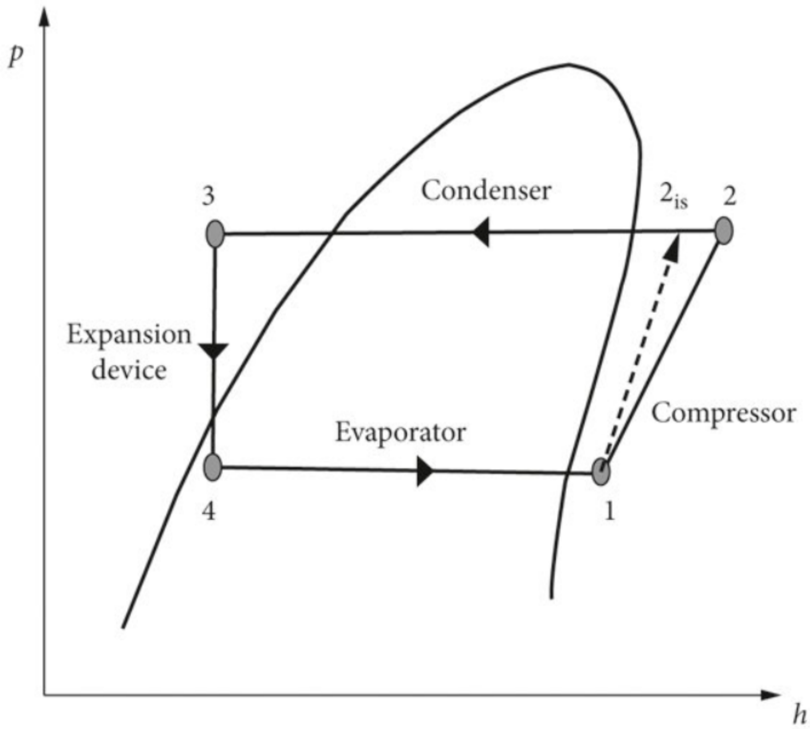
A more insightful metric is the **second-law efficiency**, defined as:

$$\eta_{II} = \frac{\text{COP}_{\text{actual}}}{\text{COP}_{\text{Carnot}}}$$

With:

$$\text{COP}_{\text{Carnot}} = \frac{T_{\text{evap}}}{T_{\text{gen}} - T_{\text{evap}}}$$

Here, all temperatures are in absolute units (Kelvin).



[1]

Figure 8: Pressure–Enthalpy diagram for VARS

4.4 Conclusion

VARS offers a reliable and environmentally friendly refrigeration approach, especially in areas with limited electricity access and high solar insolation. Its operation without moving parts in the refrigeration circuit results in lower maintenance and longer lifespan. For our project, which targets cooling in hot, resource-constrained areas using solar energy, VARS represents a highly compatible and impactful solution.

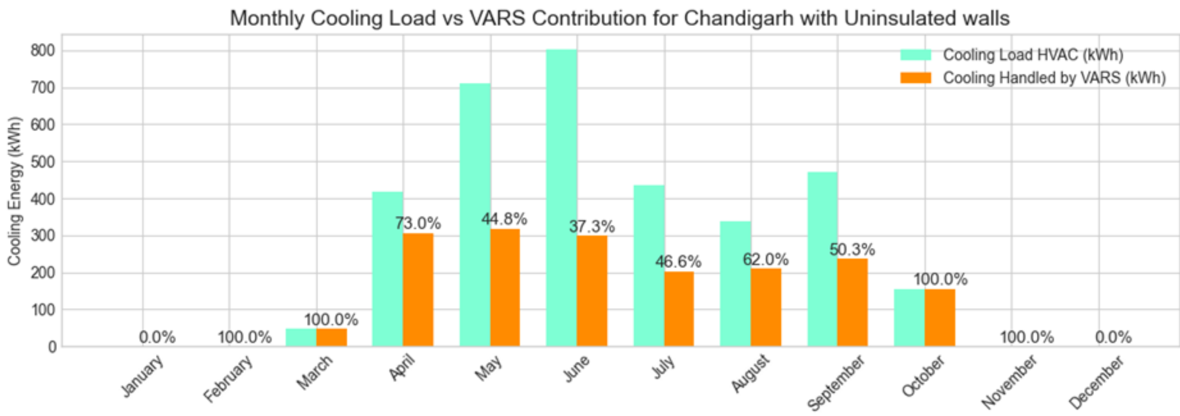


Figure 9: Monthly Cooling Load vs VARS Contribution for Uninsulated Walls in Chandigarh

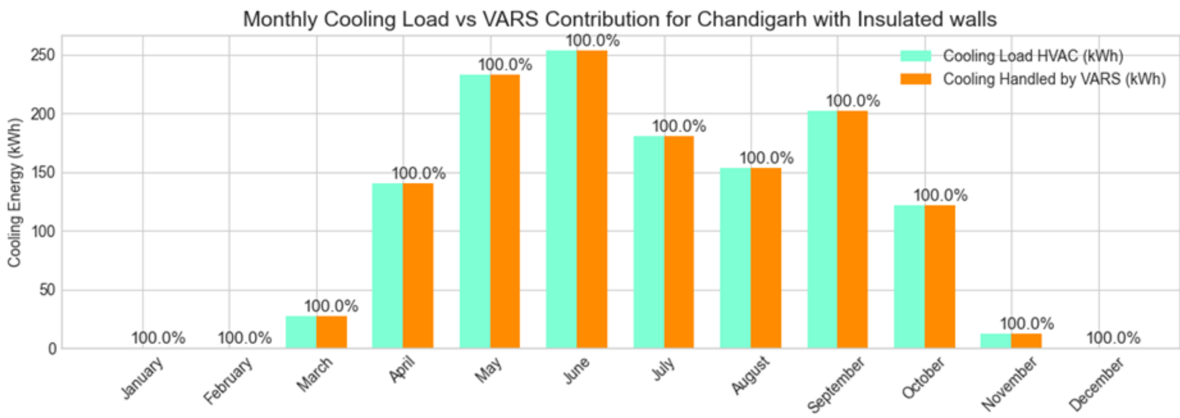


Figure 10: Monthly Cooling Load vs VARS Contribution for Insulated Walls in Chandigarh

5 Results and Discussions

5.1 Energy Savings Analysis by City

5.1.1 Chandigarh (Cwa - Temperate North)

• Chandigarh's temperate climate creates a bell-curve cooling demand pattern with peak requirements during April-June and minimal needs during winter months.

• With standard brick walls, the VARS system requires supplementary conventional cooling in summer.

• **Key finding**: When combined with insulated walls, the VARS system successfully covers 100% of the cooling requirement throughout the year, as insulation dramatically reduces the overall cooling load.

• This complete coverage with insulated walls represents a significant advantage for ROI

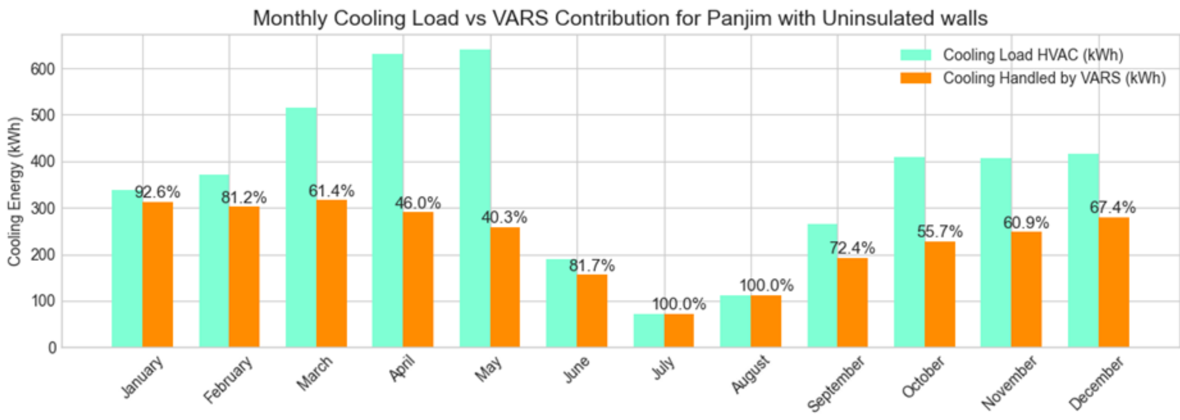


Figure 11: Monthly Cooling Load vs VARS Contribution for Uninsulated Walls in Panjim

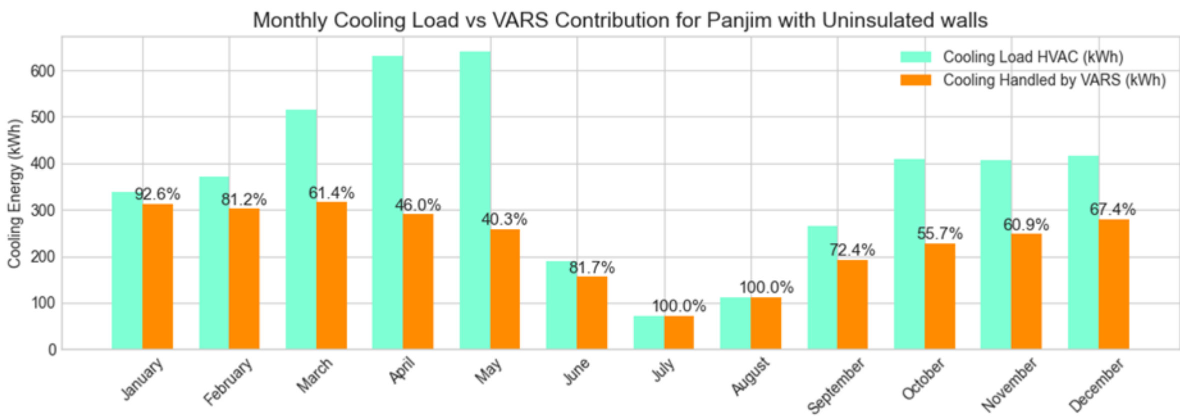


Figure 12: Monthly Cooling Load vs VARS Contribution for Insulated Walls in Panjim

calculations, as it virtually eliminates conventional cooling electricity costs.

5.1.2 Panjim, Goa (Am - Tropical West Coast)

• Goa's tropical monsoon climate results in relatively consistent year-round cooling demands with less pronounced seasonal variation than inland locations.

• The high humidity and cloud cover in this region create steady VARS performance throughout the year with standard brick walls.

• Key finding: The insulated wall construction reduces cooling loads to levels that the VARS system can handle completely during all months except for a brief peak period.

• The year-round cooling requirements in Goa make the VARS + insulation combination particularly attractive from an ROI perspective, as savings accumulate consistently across all seasons.

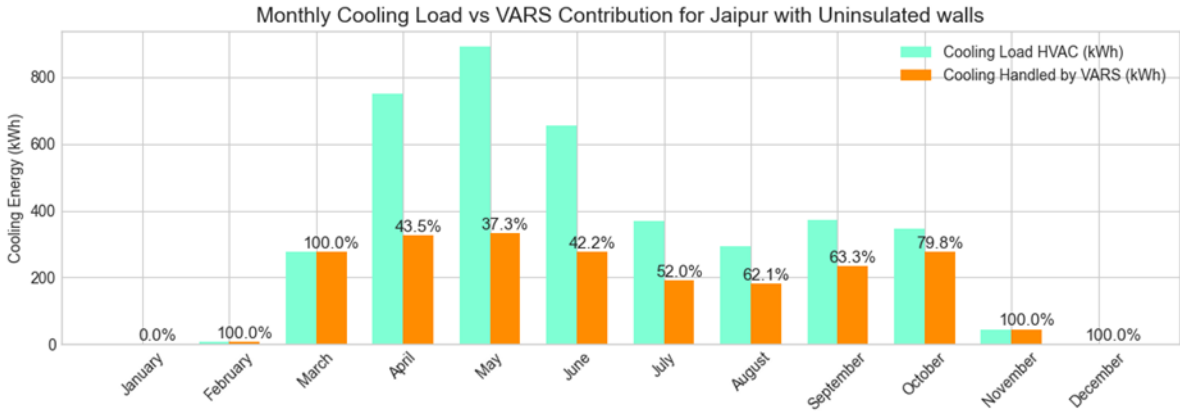


Figure 13: Monthly Cooling Load vs VARS Contribution for Uninsulated Walls in Jaipur

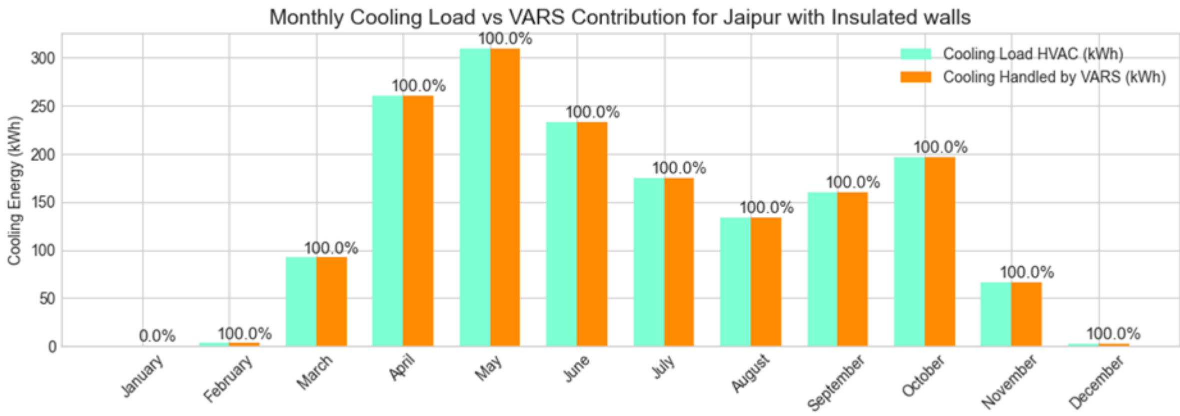


Figure 14: Monthly Cooling Load vs VARS Contribution for Insulated Walls in Jaipur

5.1.3 Jaipur, Rajasthan (BSh - Arid/Steppe Northwest)

• Jaipur experiences the most extreme cooling load pattern with intense summer requirements, creating both challenges and opportunities for VARS implementation.

• With standard brick walls, VARS handles approximately 40-45% of cooling needs during peak summer months, requiring substantial supplementary cooling.

• Key finding: The insulated wall construction transforms this performance dramatically, enabling the VARS system to handle 100% of cooling loads for all but 1-2 peak summer months, when it still covers approximately 90-95% of requirements.

• This remarkable improvement in coverage suggests that Jaipur, despite having the most challenging climate, may offer one of the most compelling ROI scenarios for the combined insulation + VARS approach.

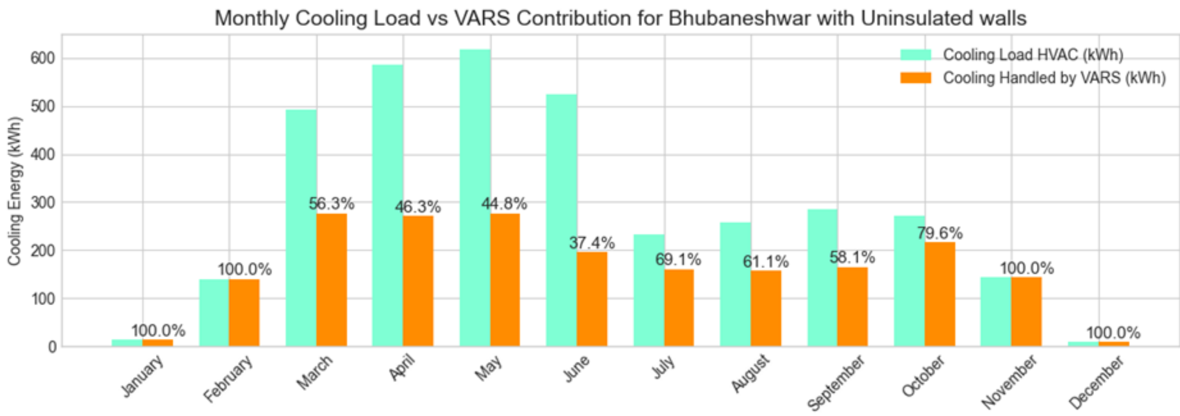


Figure 15: Monthly Cooling Load vs VARS Contribution for Uninsulated Walls in Bhubaneshwar

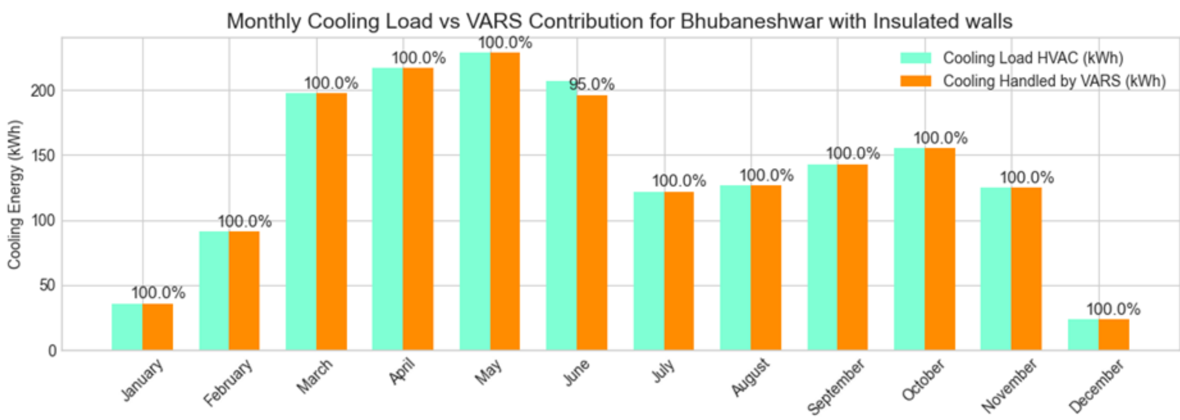


Figure 16: Monthly Cooling Load vs VARS Contribution for Insulated Walls in Bhubaneshwar

5.1.4 Bhubaneswar, Odisha (Aw - Tropical East)

• Bhubaneswar's tropical humid-hot climate creates steady cooling demands with higher solar exposure than Goa despite both having tropical classifications.

• With standard brick walls, the VARS system achieves complete coverage during winter months and partial coverage (45-55%) during warmer periods.

• Key finding: When paired with insulated walls, the VARS system achieves 100% coverage across all months, effectively eliminating the need for conventional cooling year-round.

• The combination of high humidity and temperature in this region creates sustained cooling requirements throughout the year, making the complete coverage particularly valuable for ROI calculations.

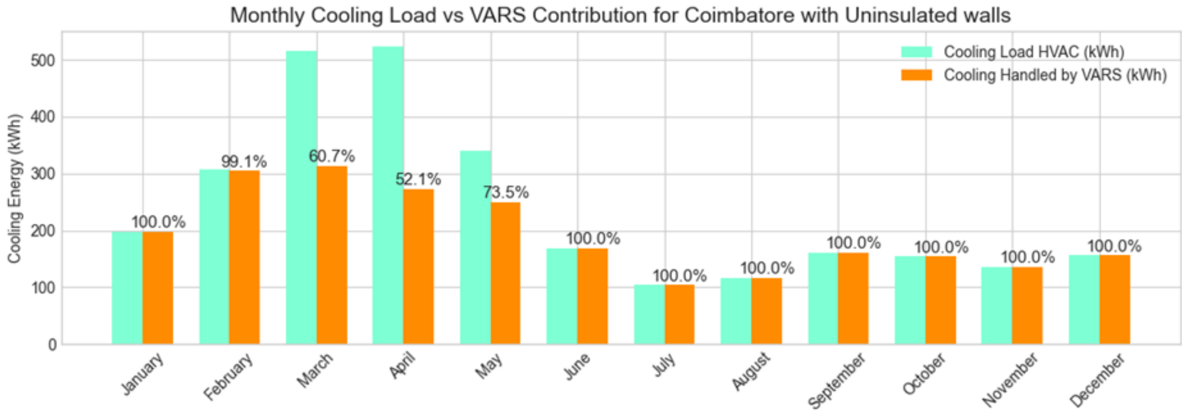


Figure 17: Monthly Cooling Load vs VARS Contribution for Uninsulated Walls in Coimbatore

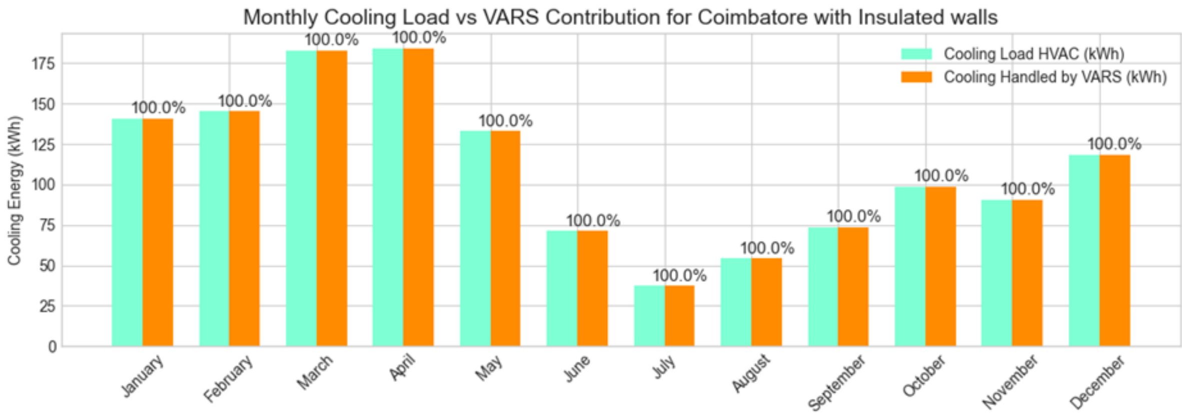


Figure 18: Monthly Cooling Load vs VARS Contribution for Insulated Walls in Coimbatore

5.1.5 Coimbatore, Tamil Nadu (Cfb - South Temperate)

• Coimbatore's mild but extended summer creates a moderate demand profile where cooling is required throughout most of the year but at less intense levels than other regions.

• With standard brick walls, the VARS system demonstrates good efficiency with coverage percentages approaching 70-80% during many months.

• Key finding: The insulated wall construction reduces cooling loads sufficiently to allow 100% VARS coverage throughout the entire year, making Coimbatore an ideal implementation site.

• The moderate but consistent cooling demands in this climate create excellent conditions for the VARS system, with insulation creating the ideal scenario of complete coverage and zero supplementary cooling requirements.

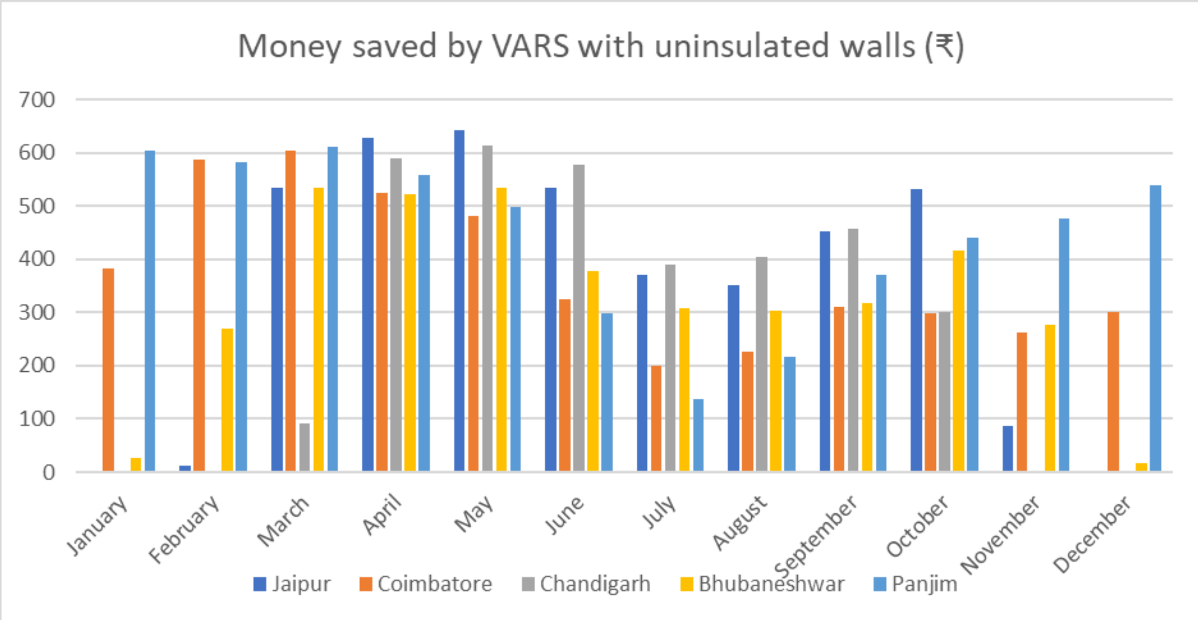


Figure 19: Money saved monthly by VARS system with uninsulated walls for every city

Cities	Uninsulated Walls	Insulated Walls
Jaipur	4146.31	7727.78
Coimbatore	4506.01	5560.04
Chandigarh	3426.74	6521.59
Bhubaneshwar	3909.94	6889.92
Panjim	5337.96	8425.20

Table 2 : Money saved annually with VARS system, with specified wall conditions

5.2 Annual Financial Savings Analysis

• Cities with continuous cooling demands (particularly Panjim) show the largest absolute savings when implementing both technologies together.
• Even in more moderate climates like Coimbatore, the combined approach yields substantial financial benefits due to the extended periods requiring cooling.
• The dramatic reduction in cooling load achieved through insulation directly translates to enhanced VARS coverage and correspondingly higher ROI potential.
• These savings figures form the foundation for the detailed ROI analysis in the following section, where implementation costs will be evaluated against these recurring annual benefits.

5.3 Costs and Return on Investment (ROI) Calculations

5.3.1 VARS Architecture

The proposed cooling solution integrates a low-capacity Vapor Absorption Refrigeration System (VARS) with a solar thermal collector subsystem. This hybrid setup provides sustainable space cooling in hot climates by utilizing low-grade solar thermal energy rather than electricity-driven compressors.

- **VARS Core Components:**
  - Evaporator
  - Absorber
  - Generator
  - Condenser
  - Solution heat exchanger
  - Pumps and expansion valves
- **Solar Thermal Subsystem:**
  - Flat Plate Solar Collector [4]
  - Heat Transfer Fluid (HTF) Loop
  - Piping and insulation
  - Control units

Product Brochure

IndiaMART > Solar & Renewable Energy Products > Solar Water Heater Tubes & Accessories > Flat Plate Solar Collector

Solar Flat plate collectors, For Hot Water

₹ 13,500/Piece

Usage/Application	Hot Water
Tank Material	Stainless Steel
Temperature tolerance of coating	More than 200 deg. C

Our obtainable variety of FPC Solar Water Heater is sourced from foremost vendors of the business, who are recognized for offering quality proven products. Based on superior technology, these ISI marked flat plate collector is mainly used for meeting the hot water necessities of residential, commercial and industrial sectors. This is the most ordinary solar collector, used in the solar water-heating systems.

1	Absorber coating	NALSUN Solar selective coating (black chrome on copper with or without nickel undercoat)
2	Absorptivity of coating	0.92 – 0.96
3	Emissivity of coating	0.10 - 0.15
4	Temperature tolerance of coating	More than 200 deg. C
5	Absorber sheet	Copper sheet 0.19 mm thick x 1900mm L x 120mm W; 99.9 % pure
6	Riser	Copper tube Dia 12.7mm x 0.56 SWG x 1920mm, 99.99 % pure
7	Bonding between riser tube and absorber	Ultrasonic welding or Laser beam welding
8	Finish	Corrugated finish for increased surface area and structural strength

Figure 20: Solar flat plate collector

5.3.2 Assumptions and Design Parameters

The system was designed for a cooling load of 1 kW (approximately 0.285 TR), targeting small residential or single-room applications in high-insolation zones of India.

- **Cooling Capacity:** 1 kW
- **VARS Coefficient of Performance (COP):** 0.7
- **Solar Insolation:** 1000 W/m² (typical average)
- **Solar Collector Efficiency:** 0.85 (derived below)

5.3.3 Collector Efficiency Calculation

Efficiency was derived using a simplified radiation loss model:

$$\eta = \alpha - \varepsilon \cdot \left[\frac{\sigma(T_p^4 - T_a^4)}{G} \right]$$

Where:

- $\alpha = 0.92$, absorptivity
- $\varepsilon = 0.12$, emissivity
- $\sigma = 5.67 \times 10^{-8}\,\mathrm{W/m^2K^4}$, Stefan–Boltzmann constant
- $T_p = 373\,\mathrm{K}$, plate temperature (≈ 100°C)
- $T_a = 303\,\mathrm{K}$, ambient temperature (≈ 30°C)
- $G = 1000\,\mathrm{W/m^2}$, solar irradiance

Plugging in the values:

$$\eta = 0.92 - 0.12 \cdot \left[\frac{5.67 \times 10^{-8}(373^4 - 303^4)}{1000}\right] \approx 0.8456$$

Thus, the final collector efficiency is approximately 85%.

5.3.4 Collector Area Sizing

To provide 1.43 kW of heat input (based on $\mathrm{COP_{VARS}} = 0.7$):

$$\text{Collector Area} = \frac{1.43\,\mathrm{kW}}{0.85 \times 1000\,\mathrm{W/m^2}} \approx 1.68\,\mathrm{m^2}$$

Rounded up, a collector area of **2.0–2.5 m²** is sufficient.

5.3.5 Cost

A breakdown of estimated costs is as follows:

Item	**Estimated Cost (INR)**
VARS System (0.3 TR scaled)	40,000 Rs
Solar Collector (Flat Plate)	13,500 Rs
Piping and Installation	10,000 Rs
Total Investment (C)	63,500 Rs

Table 2: Capital cost estimate for integrated Solar-VARS system

Figure 21: Vapour Absorption Refrigeration System for 1.5TR

This system is particularly viable for locations with consistent solar availability and limited grid infrastructure. Compared to compressor-driven systems, it eliminates high electricity consumption and reduces operational costs dramatically.

5.3.6 Insulation Cost

The bricks have dimensions of 5 in x 5 in x 2 in and are sourced from The Kid Company [8].

First, the brick dimensions are converted to meters, given that 1 inch = 0.0254 m. Therefore:

- 5 in = 0.127 m
- 2 in = 0.0508 m

Assuming the bricks are laid with the 2-inch side as the thickness, the area covered by the visible face of each brick is:

$$\text{Area per brick} = 0.127\,\text{m} \times 0.127\,\text{m} = 0.016129\,\text{m}^2$$

The total surface area to be covered includes the four walls and the roof:

- Two longer walls: 5 m x 3 m = 15 m^2 each
- Two shorter walls: 3 m x 3 m = 9 m^2 each
- Total wall area = (2 x 15 m^2) + (2 x 9 m^2) = 48 m^2
- Roof area = 5 m x 3 m = 15 m^2

- Window area = 2m x 1m = 2 m^2
- Total surface area = 48 m^2 + 15 m^2 - 2 m^2 = 61 m^2

The number of bricks needed is calculated by dividing the total surface area by the area covered per brick:

$$\text{Number of bricks} = \frac{61\,\mathrm{m}^2}{0.016129\,\mathrm{m}^2/\mathrm{brick}} \approx 3783\,\mathrm{bricks}$$

To account for potential overlaps, gaps, cutting, and breakage, the number of bricks is rounded up to 4000.

The cost of each brick is Rs 10. For this application, two layers of bricks are used to achieve the required insulation.

- Total number of bricks = 4000 bricks/layer * 2 layers = 8000 bricks
- Total cost of bricks = 8000 bricks * 10/brick = Rs 80,000

The total cost of putting the insulation on the walls, is Rs 80,000.

5.3.7 ROI

$$\text{ROI} = \frac{\text{Savings}}{\text{Cost}} * 100$$

Table 3: ROI Comparison for Uninsulated and Insulated Cases

Cities	**Savings (Rs)**		**ROI**	
	Uninsulated	**Insulated**	**Uninsulated**	**Insulated**
Jaipur	4146.31	7727.78	6.52%	5.40%
Coimbatore	4506	5560.03	7.09%	3.89%
Chandigarh	3426.74	6521.58	5.30%	4.56%
Bhubaneshwar	3909.94	6889.92	6.15%	4.82%
Panjim	5337.97	8425.19	8.40%	5.89%

The economic viability of implementing the VARS system with and without insulation can be clearly assessed through the ROI data. For the uninsulated scenario with a VARS system cost of Rs 63,000, Panajim (Goa) offers the most attractive ROI at 8.40%, followed by Coimbatore at 7.09%. This indicates that coastal and temperate climates may provide faster returns when implementing only the VARS technology. Interestingly, when examining the combined implementation of VARS and insulation (total investment Rs 143,000), all cities show a reduction in ROI percentage compared to VARS-only installations. This occurs despite higher absolute savings, as the additional Rs 80,000 investment for insulation increases the capital cost significantly. The insulated scenario still presents viable ROI figures ranging from 3.89% (Coimbatore) to 5.89% (Panajim), but these returns must be evaluated against alternative investment opportunities and local borrowing rates.

From a practical implementation perspective, the decision between VARS-only and VARS plus insulation approaches involves balancing immediate ROI against total lifetime savings. While the VARS-only approach offers higher percentage returns across all cities, the VARS plus insulation combination delivers substantially greater absolute annual savings—ranging from Rs 5,560 in Coimbatore to Rs 8,425 in Panjim. For instance, Jaipur shows the most dramatic increase in absolute savings when adding insulation (from Rs 4,146 to Rs 7,728), despite the ROI dropping from 6.52% to 5.40%. This suggests that regions with extreme cooling demands might benefit most from the combined approach when considering long-term operational savings, even with the initially lower ROI percentage. The decision ultimately depends on investment timeframe, available capital, and whether the priority is maximizing percentage return or total savings over the system lifetime.

6 Conclusion

This project demonstrates a comprehensive approach to optimizing thermal comfort and energy efficiency in low-income Indian housing through the integration of passive and active cooling strategies. The two-phase methodology—combining eco-friendly insulation materials with a solar-driven Vapor Absorption Refrigeration System (VARS)—successfully addresses the dual challenges of sustainability and thermal regulation. Our EnergyPlus-based simulations confirm that eco-insulated walls significantly reduce cooling loads, while the VARS subsystem, driven by solar thermal collectors, complements these gains by supplying low-cost, low-energy cooling capacity without reliance on electricity-intensive compressors.

The results reveal compelling evidence of performance improvement across a range of Indian climatic zones. In cities like Chandigarh, Jaipur, and Bhubaneswar, the addition of insulated walls allowed the VARS system to meet up to 100% of the annual cooling demand, eliminating dependence on conventional systems. Financially, while standalone VARS systems offered higher ROI percentages due to lower upfront costs, the combined insulation + VARS approach yielded markedly higher absolute savings, with Panjim achieving Rs 8,425 in annual energy cost reductions. The consistent performance of the system, even in challenging arid or humid zones, affirms the robustness of the proposed hybrid strategy.

The sustainability aspect of this project is anchored in both material and system design. Ko-Cane bricks, made from agricultural by-products like sugarcane bagasse and cocopeat, offer an environmentally responsible alternative to traditional insulation, diverting waste from landfills while reducing the embodied carbon in construction. Likewise, VARS systems operate on low-grade solar thermal energy and avoid the use of high-GWP refrigerants or grid power, making them inherently eco-friendly and suitable for deployment in off-grid or underserved communities. The quiet operation, lower maintenance requirements, and long service life further underline their appropriateness for decentralized, climate-resilient development.

In conclusion, the integration of passive and active cooling technologies explored in this work provides a scalable, economically viable, and environmentally sound solution for heat-stressed housing in India. It not only minimizes energy consumption and operational costs but also aligns with national goals of sustainable urban development and energy independence. This dual-strategy framework, if implemented at scale, has the potential to improve living standards, lower emissions, and contribute to climate adaptation efforts in vulnerable regions.

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