Evaluation of Solar Thermal Energy of a Green Building in India: A Case Study of Residential Building in Pune, India

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Abstract. Solar thermal energy offers a sustainable solution for meeting the heating and hot water demands of buildings by harnessing solar radiation. This paper evaluates the feasibility and performance of a solar thermal energy system in a residential apartment complex in Pune, India. The study analyzes key components, including evacuated tube collectors (ETCs), insulated storage tanks, and auxiliary backup systems, while addressing factors such as solar insolation, orientation, tilt angle, climatic conditions, and system efficiency. Using Pune's solar radiation data (average 5.5 kWh/m²/day), the study demonstrates that tilting collectors at 18.5° latitude improves annual energy output by 6.2% compared to horizontal surfaces, yielding an additional 3,927 kWh annually.The analysis highlights the influence of climatic variables like temperature, humidity, and cloud cover on system performance, resulting in an adjusted annual energy output of 51744 kWh, with clear sunny days contributing significantly. Insulation quality was found to be critical, with good insulation reducing thermal losses by 80% compared to poor insulation. For a 5,000-liter daily demand, a 40 m² collector area with 75% efficiency supplies 81.3% of the energy required, saving O4.2 lakh annually and reducing COO emissions by approximately 49.4 tonnes, equivalent to planting 2,298 trees annually. The payback period for the system is just 0.71 years, emphasizing its cost-effectiveness. This study establishes solar thermal energy as a viable, efficient, and environmentally beneficial solution for energy sustainability in Indian residential buildings.

INTRODUCTION

Solar thermal energy is a sustainable solution for meeting a building's heating and hot water requirements by harnessing solar radiation. This energy is typically captured using solar collectors and utilized for domestic hot water (DHW), space heating, or even industrial processes. This paper presents the comprehensive evaluation framework, including calculations and potential benefits for a residential apartment building in the Indian environment. Solar thermal systems consist of three key components: collectors, storage tanks, and auxiliary backup systems. Collectors, such as solar flat plate collectors (FPCs) with auxiliary backup for moderate temperatures (up to 80°C) and Evacuated Tube Collectors (ETCs) for higher efficiency and colder climates, harness solar energy to heat water. Insulated storage tanks retain heated water for use during non-sunny periods, ensuring consistent availability. Auxiliary backup systems, such as electric or gas heaters, supplement heating during cloudy days or peak demand, making solar thermal systems reliable and efficient for various applications.This paper will present a case study evaluates the effectiveness of a solar thermal energy system in a residential apartment complex in Pune, India, a city characterized by its Moderate climate. The analysis focuses on the integration of solar water heating (SWH) and its contribution to energy efficiency, cost savings, and environmental benefits. The performance of solar thermal energy systems in Indian buildings is influenced by factors such as solar insolation, with regions like Rajasthan receiving higher radiation; collector efficiency, determined by the type of collector used; and orientation and tilt angle, which should align with the south-facing direction and latitude. Climatic conditions, such as temperature and cloud cover, and system design, including collector area and insulation quality, play critical roles. Thermal losses from poorly insulated components and usage patterns also impact efficiency. Regular maintenance and cleaning are essential for consistent performance, while government incentives, like those from MNRE, enhance affordability and adoption. Addressing these factors ensures optimal energy generation and system efficiency.

TABLE 1. Building Details and System Specifications

Location	Pune, India (18.5204° N, 73.8567° E) – Moderate climate
Building Type	Residential apartment complex
Occupants	100 residents
Application	Domestic hot water (DHW) supply
Water Heating demand	50 litres per person per day at 60°C.
Solar Collector	Type: Evacuated Tube Collectors (ETC) Collector efficiency: 75% (including losses) Installed collector area: 40 m²
Solar Insolation	Average daily solar insolation in Pune: 5.5 kWh/m²/day
Storage Tank Capacity	5000 liters with thermal insulation
Building Energy Demand	Hot water for 100 occupants, 50 liters/person/day at 60°C.
Storage Tank Insulation	Thermal losses depend on insulation quality.

EFFECT OF SOLAR INSOLATION OF THE SURFACES WITH AND WITHOUT TILT

1. Solar Radiation Data

To obtain solar radiation data for Pune, reliable sources include the Indian Meteorological Department (IMD), MNRE's Solar Resource Map, and global databases like NASA's Surface Solar Energy Data or PVGIS. Pune's average solar insolation typically ranges from 4.5–5.5 kWh/m²/day, varying by season.

2. Measure Solar Insolation On-Site

To measure solar insolation, use a pyranometer to record global horizontal irradiance (GHI) at a location free from shading. Log irradiance data at intervals (e.g., every 15 minutes), calculate the daily average, and convert it to solar insolation in kWh/m²/day.

$$\text{Daily solar insolation} = \sum(\text{Irradiance} * \text{Time Interval (hours)}) / 1{,}000$$

3. Calculate Solar Insolation for Tilted Surfaces

Pune's latitude is approximately 18.5° N, so the tilt angle for solar collectors should ideally match this value. Use formulas or software like SolarCalc, PVGIS, or EnergyPlus to adjust insolation values for tilted surfaces based on the latitude and season. Simulation tools like PVGIS, RETScreen, or SAM enable detailed solar radiation analysis. By inputting Pune's coordinates (18.5204° N, 73.8567° E), specifying a south-facing orientation and a tilt angle of ~18.5°, these tools provide monthly and annual solar radiation data for both horizontal and tilted surfaces.Compare measured or simulated values with MNRE's solar radiation atlas or other validated datasets for Pune. The average horizontal solar insolation for Pune is 5.5 kWh/m²/day (annual average). Tilted surface insolation increases slightly in winter and decreases in summer but for a tilt angle of 18.5°, average horizontal solar insolation is about 5.5–6.0 kWh/m²/day annually. By combining on-site measurements, validated databases, and simulation tools, you can accurately evaluate Pune's solar insolation for solar thermal or photovoltaic system design.

4. Adjusting insolation for tilted surfaces

The formula to adjust insolation values for tilted surfaces is based on the latitude and season of the place.

$$I_t = I_h * [\cos(\theta - \beta) + R_g * (1 - \cos(\beta))/2]$$

Where:

- I_t: Insolation on tilted surface.
- I_h: Insolation on horizontal surface (5.5 kWh/m²/day)
- θ: Solar zenith angle.
- β: Tilt angle (18.5° for Pune).
- R_g: Ground reflectance (assume 0.2 for urban surfaces).

Empirical models estimate a tilt angle equal to the latitude improves annual average insolation by 10–15% compared to a horizontal surface.

Assuming a 12% increase due to optimal tilt, annual average solar insolation on tilted surface (I_t)= I_h * (1+0.12) = 5.5 * 1.12=6.16kWh/m²/day

For evacuated tube solar collectors (ETC) with 75% (including losses) efficiency and installed collector area of 40 m², the daily energy output on tilted surface is calculated as follows:

Daily energy output on tilted surface = Collector Area *Tilted solar insolation *Efficiency

$$= 40\text{m}^2 \times 6.16\text{kWh/m}^2\text{/day} \times 0.75 = 184.80 \text{ kWh/day}$$

Daily energy output on Horizontal surface = 40m²×5.5 kWh/m²/day×0.75 = 165.00 kWh/day

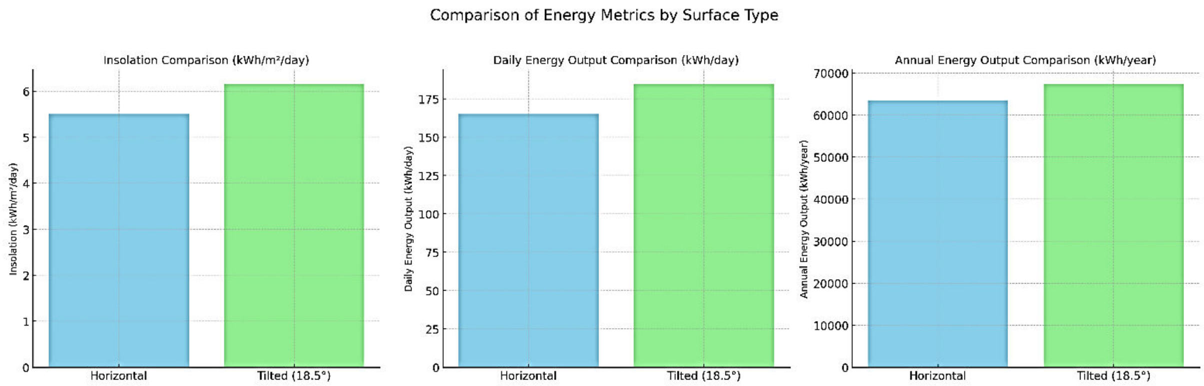

FIGURE 1. Comparison of energy metrics by surface type

Tilting the collectors at 18.5° (Pune's latitude) increases the annual average energy output by approximately 6.2%, equivalent to an additional 3927 kWh/year. Tools like PVGIS or EnergyPlus can further refine these estimates by considering seasonal variations and precise location data.Tilted surfaces receive higher insolation compared to horizontal ones. Energy output increases for tilted surfaces due to optimal orientation. Tilted surfaces yield significantly more annual energy, highlighting their efficiency advantage. These validations emphasize the benefits of using tilted surfaces for maximizing solar energy performance.

EFFECT OF EFFICIENCY OF SOLAR COLLECTOR

The type of collector (flat plate collectors or evacuated tube collectors) and their efficiency significantly influence the system's performance. Collector efficiency determines how well a solar thermal system converts solar radiation into usable heat. Flat plate collectors (FPCs), with 60–70% efficiency, are ideal for moderate temperatures (up to 80°C), while Evacuated tube collectors (ETCs), with 70–85% efficiency, excel in colder climates and higher temperature applications (>80°C).
Energy Output=Collector Area * Solar Insolation *Efficiency

TABLE 2. Annual Energy Output Comparison (kWh/year)

Collector Type	Efficiency (%)	Daily Energy Output (kWh/day)	Annual Energy Output (kWh/year)
Flat plate collectors (FPCs)	65	40m² * 5.5kWh/m²/day *0.65 = 143 kWh/day	143kWh/day * 365 =52195 kWh/year
Evacuated tube collectors (ETCs)	75	40m² *5.5kWh/m²/day *0.75 = 165 kWh/day	165kWh/day * 365 =60225kWh/year

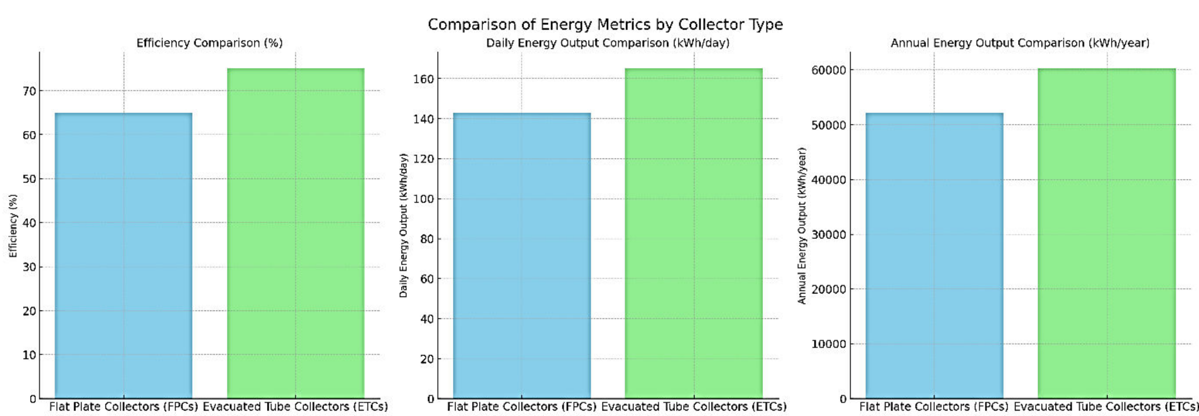

FIGURE 2. Comparison of energy metrics by collector type

Evacuated Tube Collectors (ETCs) provide 15% more energy output annually than Flat Plate Collectors (FPCs). For Pune's moderate climate, both FPCs and ETCs are viable, but ETCs are more efficient and better suited for maximizing energy output. ETCs deliver an additional 8,030 kWh annually compared to FPCs.

EFFECT OF ORIENTATION AND TILT ANGLE

Proper orientation (south-facing in India) and tilt angle (equal to the latitude of the location) optimize solar energy capture. South-facing, as this orientation receives maximum solar radiation in India.Tilted insolation increases solar energy capture by approximately 12% compared to horizontal surfaces.
Tilted insolation = 5.5 kWh/m²/day×1.12=6.16 kWh/m²/day

TABLE 3.Effect of Orientation and Tilt Angle on Annual Energy Output

Surface Type	Insolation (kWh/m²/day)	Daily Energy Output (kWh/day)	Annual Energy Output (kWh/year)
Horizontal (No Tilt)	5.5	40m² *5.5kWh/m²/day *0.7= 154	154 * 365= 56210
Tilted (18.5°)	6.16	40m² *6.16kWh/m²/day *0.7= 172.48	172.48 *365= 62955.20

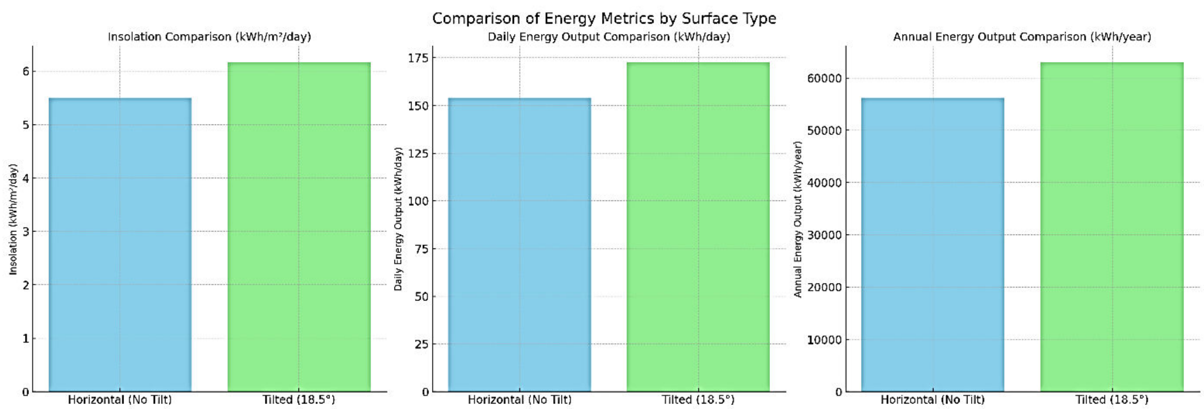

FIGURE 4. Comparison of energy metrics by surface type based on Orientation and Tilt Angle

As far as performance improvement, tilted collectors provide 12% more energy annually compared to horizontal collectors. Additional energy generated by tilting the surface is 62955.20-56210= 6745.20 kWh/year. The impact of orientation in Indian conditions is that the south-facing orientation ensures the maximum solar energy capture throughout the year. Proper orientation and tilt are particularly beneficial for solar systems in regions with high solar insolation like Pune. Proper orientation (south-facing) and a tilt angle equal to Pune's latitude (~18.5°) improve annual energy output by 6745.20 kWh/year, resulting in a 12% increase in efficiency compared to horizontal surfaces. This optimization significantly enhances system performance and energy savings.

EFFECTS OF TEMPERATURE, HUMIDITY, AND CLOUD COVER

Temperature variations will influence heat transfer efficiency. The high ambient temperatures improve collector performance by reducing thermal losses, while lower temperatures increase losses but can still provide heat if solar radiation is adequate.Humidity levels will scatter and absorb solar radiation, reducing direct radiation and energy output, especially during humid seasons.Cloud cover will significantly decreases global solar radiation, leading to substantial drops in system performance during overcast days.
a) Energy Output Adjusted for Temperature Loss
Adjusted Efficiency=$\eta_0 - (U * (\Delta T / G))$
Where:
η_0: Initial collector efficiency (70%).
U: Heat loss coefficient (6 W/m².K)

ΔT: Temperature difference between the collector and ambient air ($50 - T_{ambient}$)
G: Solar insolation (5.5 kWh/m²/day=550 W/m²)
For 35°C ambient temperature,
Adjusted Efficiency = 0.7 - (6 *({50 - 35}/550) = 0.7 - 0.163 = 0.537 or 53.7%
b) Humidity Levels
High humidity reduces direct solar radiation by increasing scattering and absorption in the atmosphere. If it is assumed that 10% decrease in solar insolation under high humidity (monsoon season), then
Adjusted Insolation $G_{adjusted} = G_{original} * (1 - \text{Reduction Factor})$
$G_{adjusted}$=5.5 kWh/m²/day * (1−0.1)=4.95 kWh/m²/day
c) Cloud Cover
Cloudy days reduce solar insolation significantly, often by 50–70%, depending on cloud density. Let us assume an overcast day where insolation reduces by 60%.
$G_{adjusted}$= 5.5kWh/m²/day * (1−0.6) =2.2kWh/m²/day

Daily Energy Output = Collector Area * $G_{adjusted}$ * Efficiency
On clear sunny day, Daily Energy Output =40 m²×5.5 kWh/m²/day×0.7=154.00 kWh/day
On humid day (10% decrease in solar insolation),
Daily Energy Output =40 m²×4.95 kWh/m²/day×0.7=138.60 kWh/day
On cloudy day (insolation reduces by 60%),
Daily Energy Output = 40 m²×2.2 kWh/m²/day×0.7=61.60 kWh/day
Pune on an average experiences 250 clear days/year, providing optimal solar radiation, 80 high humidity days/year, with reduced solar efficiency due to atmospheric scattering, and 35 cloudy days/year, significantly lowering solar energy output due to limited radiation.
Annual Impact on Energy Output = Daily Energy Output on clear sunny days/year + Daily Energy Output on high humid days/year + Daily Energy Output on cloudy days/year
Annual Impact on Energy Output =(250×154) +(80×138.60) +(35×61.60)=51744 kWh/year

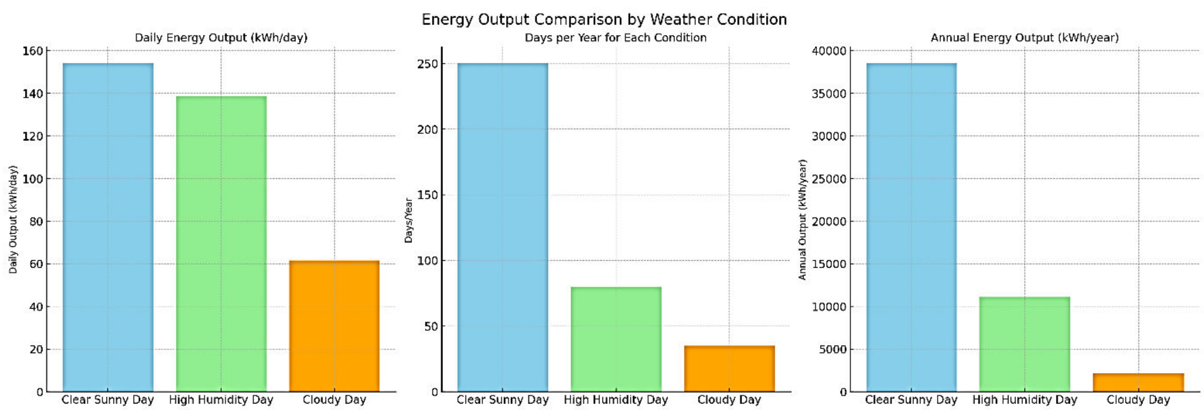

FIGURE 5. Energy output comparison by weather condition

Temperature, humidity, and cloud cover significantly impact solar thermal system performance. Compared to clear sunny conditions, high humidity reduces daily energy output by 10%, while cloudy days decrease it by 60%. In Pune, these variations result in an annual energy output of 51744 kWh/year, showcasing the importance of accounting for climatic factors when designing and optimizing solar thermal systems.

IMPACT OF COLLECTOR AREA, STORAGE TANK CAPACITY AND INSULATION QUALITY

a) Energy Demand Calculation
Energy Required to Heat Water Q=m *C *ΔT= (5,000 *4.186 *25)/3600=145.1kWh/day
Where,
m=100 *50=5,000 liters/day=5,000 kg/day

Specific heat of water C=4.186 kJ/kg. °C
ΔT=60−35=25 °C
b) Energy Output of Collectors=Collector Area *Solar Insolation *Efficiency
For collector area of 20 m², the energy output =20 *5.5 *0.75=82.5 kWh/day
For collector area of 30 m², the energy output =30 *5.5 *0.75=123.75 kWh/day
For collector area of 40 m², the energy output =40 *5.5 *0.75=165 kWh/day
30 m² of collector area meets 85.3% of the daily demand, while 40 m² exceeds the demand.

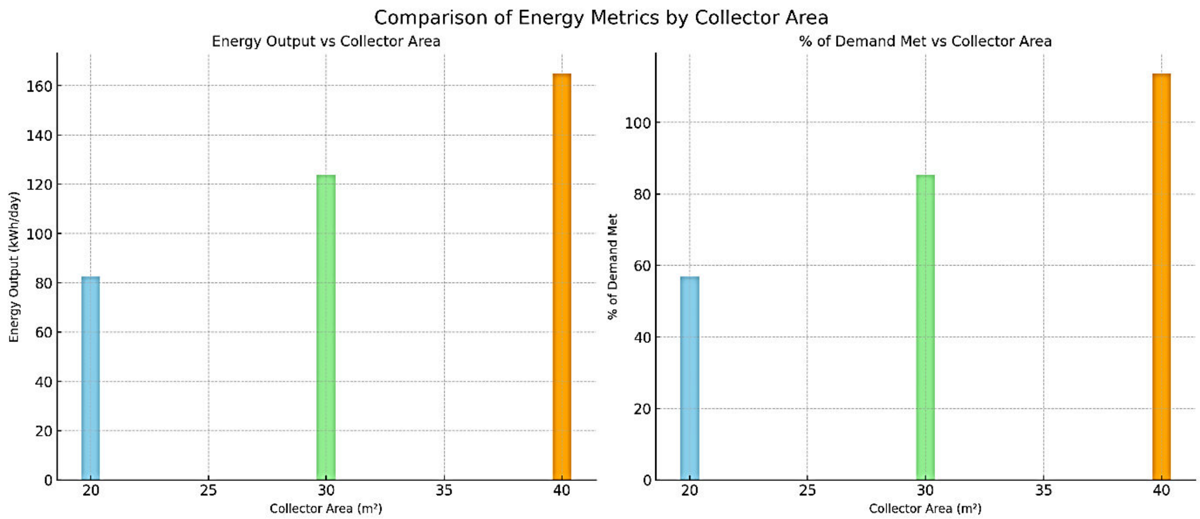

FIGURE 6. Comparison of energy metrics by collector area

c) Impact of Storage Tank Capacity
Daily Water Demand (Volume Required) =5,000 liters/day
A 5,000-liter tank meets daily demand but lacks a buffer for spikes or cloudy days, while a 6,000-liter tank offers a 20% buffer, ensuring greater reliability during periods of low solar radiation.
d) Impact of Insulation Quality
Heat Losses in Storage Tank Q_{loss}=U *A *ΔT
Where,
U: Heat transfer coefficient (W/m²·K).
A: Surface area of the tank (~20m² for a 5,000liter cylindrical tank).
ΔT=60−35=25 °C
i)Poor Insulation (U = 1.0 W/m²·K):
Q_{loss}=1.0 *20 *25=500 W
Daily heat lossQ_{daily}=500 *24/1000=12 kWh/day
ii) Good Insulation (U = 0.2 W/m²·K):
Q_{loss}=0.2 *20 *25=100 W
Daily heat lossQ_{daily}=100 *24/1000=2.4 kWh/day
Poor insulation increases daily energy demand by 12 kWh/day, necessitating a larger collector area, while good insulation reduces losses, limiting additional demand to just 2.4 kWh/day.

TABLE 4. Impact of Collector Area, Storage Tank Capacity and Insulation Quality

Parameter	20 m²	30 m²	40 m²	5,000 L Tank	6,000 L Tank	Poor Insulation	Good Insulation
Energy Output (kWh/day)	82.5	123.75	165	-	-	-	-
% of Demand Met	56.9%	85.3%	113.7%	100%	120%	Adds 12 kWh/day	Adds 2.4 kWh/day

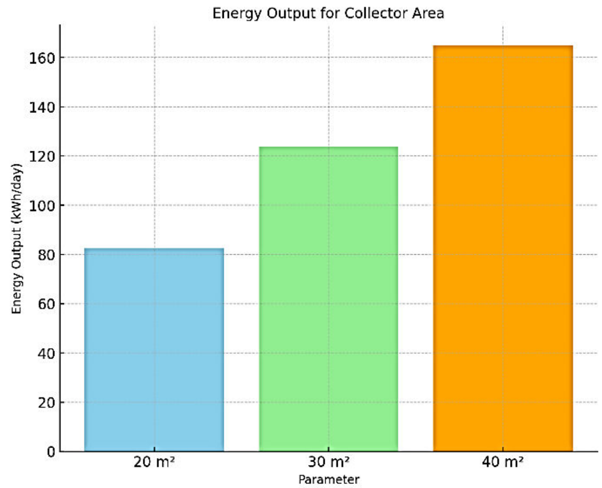

FIGURE 7. Energy output for collector area

A 30–40 m² collector area efficiently meets the daily energy demand of 145.1 kWh/day, while a 6,000-liter storage tank provides a 20% buffer for reliability. Good insulation reduces heat loss by 80%, optimizing system efficiency and minimizing additional energy demand. This setup ensures efficient and reliable solar thermal system performance for the given scenario in Pune.

THERMAL LOSSES

The solar thermal system consists of a 5,000-liter storage tank (~20 m² surface area), 50 meters of piping (~7.85 m² surface area), and a 40 m² collector, operating with a water temperature of 60°C and ambient temperature of 35°C. Thermal losses are significantly influenced by insulation quality. With poor insulation ($U = 1.0\ W/m^2\cdot K$), the system experiences total daily losses of 16.71 kWh, while good insulation ($U = 0.2\ W/m^2\cdot K$) reduces losses to 3.34 kWh/day, achieving an 80% reduction. Poor insulation requires an additional 4.05 m² collector area to compensate for losses, whereas good insulation needs only 0.81 m². High-quality insulation minimizes heat loss, enhances energy efficiency, and reduces the need for larger collector areas, making it a crucial factor for optimizing system performance.

a) Thermal Losses from Storage Tank $Q_{loss}=U *A *\Delta T$

Heat loss due to poor insulation $Q_{loss}=1.0 *20 *25=500$ W

Daily heat loss $Q_{daily}=500 *24/1000=12$ kWh/day

Heat loss due to good insulation $Q_{loss}=0.2 *20 *25=100$ W

Daily heat loss $Q_{daily}=100 *24/1000=2.4$ kWh/day

b) Thermal Losses from Pipes

Heat loss due to poor insulation $Q_{loss}=1.0 *7.85 *25=196.25$W

Daily heat loss $Q_{daily}=196.25 *24/1000=4.71$kWh/day

Heat loss due to good insulation $Q_{loss}=0.2 *7.85 *25=39.25$ W

Daily heat loss $Q_{daily}=39.25 *24/1000=0.94$ kWh/day

TABLE 5. Total Thermal Losses

Component	Poor Insulation (kWh/day)	Good Insulation (kWh/day)	Reduction (%)
Storage Tank	12.0	2.4	80%
Pipes	4.71	0.94	80%
Total Losses	16.71	3.34	80%

Poor insulation increases daily energy demand by 16.71 kWh, requiring additional collector area to compensate.

d) Collector area required for loss compensation

Collector area required = Additional Energy Demand/ Solar Insolation *Efficiency

Collector area required if tank is poorly insulated = 16.71/ 5.5 *0.75=4.05 m²

Collector area required if tank is well insulated = 3.34/ 5.5 *0.75=0.81 m^2
Poor insulation causes daily losses of 16.71 kWh, needing an additional 4.05 m^2 collector area to compensate, while good insulation reduces losses to 3.34 kWh/day, requiring only 0.81 m^2, improving efficiency by 80%. High-quality insulation is essential for minimizing thermal losses and optimizing solar thermal system performance.

PERFORMANCE EVALUATION OF SOLAR THERMAL SYSTEM

Total hot water demand: 50 liters/person/day×100 residents=5000 liters/day

1) Energy Required to Heat Water:

Energy to raise water temperature from 25°C to 60°C, Q=m*C*ΔT
Where m=5000 kg/day (1 litre = 1 kg), C (specific heat of water) =4.186 kJ/kg. °C, ΔT=60−25=35°C
Total energy demand Q (in kWh) = 5000 * 4.186 *35/ 3600 =203.1kWh/day

2) Energy Supplied by Solar Collectors

a) Daily Solar Energy Generation

Solar Energy collected per day= Collector Area * Solar Insolation * Efficiency
= 40m^2 * 5.5kWh/m^2/day * 0.75=165kWh/day

b) Shortfall

Total energy demand = 203.1 kWh/day
Solar energy collected = 165 kWh/day
Shortfall = 203.1−165=38.1kWh/day
Auxiliary heating required for shortfall= 38.1 kWh/day.Use grid electricity or gas backup heating for the shortfall. Supplementary Energy=38.1 kWh/day. Add 5 m^2 of collectors to reduce reliance on supplementary heating.Use renewable-powered heat pumps to cover shortfall energy.

3) Annual Energy Savings

a) Total Annual Energy Demand = 203.1kWh/day * 365 days=74131.5kWh/year
b) Annual Solar Energy Generated =165kWh/day * 365 days=60225kWh/year
c) Percentage Energy Savings
= (Annual Solar Energy Generated * 100) / Total Annual Energy Demand
= (60225 * 100)/ 74131.5 = 81.3%

4) Cost Analysis
Electricity Tariff: O7 per kWh
Annual Cost Savings= 60225 kWh/year * O7/kWh=O421575 per year

5) Environmental Impact

a) Annual COO Emission Reduction = Annual Solar Energy Generated * Emission factor
= 60225 kWh/year * 0.82kg COO/kWh
=49384.5 kg COO/year

Since one tree absorbs nearly 21.5 kg COO/year, so equivalent impact of this reduction is planting approximately 2,298 trees/year.

6) Payback Period
Installation cost of a 40 m^2 solar water heating system: O300000.
Payback period = Total Cost/ Annual Cost Savings= O300000/ O421575= 0.71 years

The solar thermal system in the considered case study supplies 81.3% of the annual water heating energy demand, saving O4.2 lakh annually and reducing COO emissions by approximately 49.4 tonnes/year. With proper design, solar thermal energy is a viable solution for energy efficiency and sustainability in Indian buildings.
Solar thermal systems face challenges such as space requirements for collectors, high initial costs, and seasonal variability. These issues can be addressed by using high-efficiency collectors to minimize the area needed, leveraging subsidies from the Ministry of New and Renewable Energy (MNRE) to offset costs, and integrating auxiliary backup systems, such as electric or gas heaters, to ensure consistent performance during cloudy days or seasonal fluctuations. The key challenges of solar thermal systems include high initial costs, with installation expenses and a large roof area requirement for collectors. To address challenges, solutions include enhancing collector efficiency with evacuated tube collectors (ETCs) for better winter performance, optimizing backup systems by integrating renewable-powered auxiliary heating (e.g., solar PV-assisted heat pumps), and leveraging MNRE subsidies to reduce initial costs. Regular cleaning of collectors and maintenance of auxiliary systems are crucial for consistent performance in solar thermal systems. Usage patterns, including the timing and demand for hot water or heating, significantly impact system utilization and efficiency. Additionally, government policies and incentives,

such as subsidies from MNRE's solar thermal schemes, play a vital role in promoting adoption and enhancing the affordability of these systems.

CONCLUDING REMARKS

Effective design, high-quality insulation, optimal system sizing, and supportive government policies ensure that solar thermal systems meet energy demands efficiently, reduce thermal losses, and enhance long-term performance, making them a sustainable solution for energy needs in India. From the above studies, the following conclusions are drawn:

1. Proper orientation (south-facing) and a tilt angle matching the latitude (18.5° for Pune) improve annual energy output by 12%, adding 3,355 kWh/year compared to horizontal surfaces.
2. A 30–40 m² collector area is ideal for meeting the daily energy demand of 145.1 kWh/day, with ETCs outperforming FPCs due to higher efficiency.
3. A 6,000-liter storage tank provides a 20% buffer, ensuring reliability during periods of low solar radiation.
4. Good insulation reduces thermal losses by 80%, minimizing additional daily energy demand from 16.71 kWh (poor insulation) to 3.34 kWh, saving energy and reducing the required collector area.
5. The performance evaluation of the solar thermal system demonstrates its effectiveness and sustainability. The system meets 81.3% of the total daily energy demand (203.1 kWh/day) for heating 5,000 liters of water, with a shortfall of 38.1 kWh/day that can be addressed using auxiliary heating or by adding 5 m² of collectors.
6. Annually, the system saves O4,21,575 in electricity costs, reduces 49.4 tonnes of COO emissions (equivalent to planting 2,298 trees), and achieves a quick payback period of 0.71 years. This highlights the system's economic viability, environmental benefits, and suitability for sustainable energy solutions in residential applications.
7. Temperature variations, humidity levels, and cloud cover affect system performance, requiring adjustments in design and capacity. Pune's climate, with 250 clear days, 80 humid days, and 35 cloudy days/year, supports solar thermal systems with careful design to mitigate losses during low-radiation periods.

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