Configuration Selection of Solar Collector and Thermal Storage System for Domestic Refrigeration Applications

V.NARESH[1], M.GNANAVEL [2], R.AJITH KUMAR [3] AND K.MURUGAN[4]
[1]*ASSOCIATE PROFESSOR, BHARATHIDASAN ENGINEERING COLLEGE, NATTRAMPALLI*
[1]*ASSOCIATE PROFESSOR, BHARATHIDASAN ENGINEERING COLLEGE, NATTRAMPALLI*
[3]*PG STUDENT BHARATHIDASAN ENGINEERING COLLEGE,NATTRAMPALLI*
[4]*ASSISTANT PROFESSOR, BHARATHIDASAN ENGINEERING COLLEGE, NATTRAMPALLI*

Abstract

The increasing demand for sustainable and energy-efficient refrigeration systems has driven significant research interest toward solar-powered refrigeration technologies. Domestic refrigeration, traditionally dependent on grid electricity, contributes substantially to global energy consumption and greenhouse gas emissions. Solar thermal-driven refrigeration systems offer a promising alternative, particularly in regions with high solar insolation. However, the performance and feasibility of such systems strongly depend on the appropriate selection and integration of solar collectors and thermal energy storage units. This paper presents a comprehensive evaluation of various solar collector configurations and thermal storage technologies suitable for domestic refrigeration applications. Flat plate collectors, evacuated tube collectors, and concentrating collectors are analyzed in conjunction with sensible and latent heat thermal storage systems. Performance metrics such as operating temperature range, coefficient of performance (COP), system efficiency, cost, and reliability are discussed. Based on climatic conditions and refrigeration technology requirements, optimal configuration guidelines are proposed to enhance system performance and ensure continuous cooling operation.

Keywords: Solar refrigeration, thermal energy storage, solar collectors, absorption refrigeration, adsorption refrigeration, domestic cooling.

1. Introduction

Refrigeration plays a critical role in domestic food preservation and public health. Conventional vapor compression refrigeration systems rely heavily on electricity generated from fossil fuels, contributing to environmental degradation and energy insecurity. With the growing emphasis on renewable energy integration, solar-powered refrigeration has emerged as an attractive solution for domestic applications, especially in remote and off-grid areas.

Solar refrigeration systems can be broadly classified into photovoltaic-based and solar thermal-based systems. Solar thermal refrigeration systems, such as absorption and adsorption refrigeration cycles, are particularly advantageous due to their ability to utilize low-grade thermal energy. However, the intermittent nature of solar energy necessitates the incorporation of efficient thermal energy storage systems to ensure continuous refrigeration operation. Therefore, the selection of suitable solar collectors and thermal storage configurations is a crucial design consideration.

This paper focuses on the configuration selection of solar collectors and thermal storage systems tailored specifically for domestic refrigeration applications.

2. Solar Thermal Refrigeration Technologies

2.1 Absorption Refrigeration Systems

Absorption refrigeration systems commonly use working pairs such as LiBr–H_2O or NH_3–H_2O. These systems require generator temperatures typically in the range of 80–120°C, making them compatible with medium-temperature solar collectors.

2.2 Adsorption Refrigeration Systems

Adsorption refrigeration systems operate using solid adsorbents like silica gel or activated carbon. These systems can operate at lower driving temperatures (60–90°C) and are suitable for small-scale domestic refrigeration, albeit with lower COP compared to absorption systems.

3. Solar Collector Configuration Selection

The solar collector is responsible for capturing solar radiation and converting it into thermal energy. The selection depends on the required operating temperature, efficiency, cost, and climatic conditions.

3.1 Flat Plate Collectors (FPC)

Flat plate collectors are widely used due to their simple construction and low cost. They are suitable for applications requiring temperatures up to 80°C.

Advantages:

- Low cost and easy installation
- Reliable performance under diffuse radiation

Limitations:

- Lower efficiency at high temperatures
- Not ideal for high-temperature absorption systems

3.2 Evacuated Tube Collectors (ETC)

Evacuated tube collectors provide higher efficiency due to reduced heat losses and can achieve temperatures up to 120°C.

Advantages:

- Higher thermal efficiency
- Suitable for absorption refrigeration

Limitations:

- Higher initial cost
- Fragility of vacuum tubes

3.3 Concentrating Solar Collectors

Concentrating collectors, such as compound parabolic collectors (CPC), offer high operating temperatures but are generally unsuitable for domestic refrigeration due to complexity and cost.

4. Thermal Energy Storage Systems

Thermal energy storage (TES) is essential to mitigate solar intermittency and enable continuous refrigeration operation.

4.1 Sensible Heat Storage

Sensible heat storage uses materials such as water, oil, or rocks to store thermal energy.

Advantages:

- Simple design
- Low material cost

Limitations:

- Large storage volume
- Temperature drop during discharge

4.2 Latent Heat Storage (Phase Change Materials)

Latent heat storage utilizes phase change materials (PCM) that store energy during phase transition.

Advantages:

- High energy density

- Near-constant temperature operation

Limitations:

- Higher cost
- Thermal conductivity limitations

5. Integrated System Configuration

An optimal system configuration requires matching the collector type with the appropriate storage system and refrigeration cycle.

Refrigeration Type	Collector Type	Storage Type	Typical COP
Absorption	Evacuated Tube	PCM-based TES	0.6–0.8
Adsorption	Flat Plate	Sensible Heat	0.3–0.5
Hybrid	ETC + CPC	PCM + Water	0.7–0.9

6. Performance Evaluation Criteria

The following criteria are critical for configuration selection:

- Operating temperature compatibility
- Thermal efficiency
- Coefficient of performance (COP)
- System reliability
- Economic feasibility
- Climatic adaptability

7. Challenges and Future Prospects

Key challenges include high initial cost, system complexity, and thermal losses. Future research should focus on:

- Advanced PCM development
- Compact high-efficiency collectors
- Hybrid thermal-electric systems
- Smart control strategies

8. Conclusion

This study highlights the importance of appropriate configuration selection of solar collectors and thermal energy storage systems for domestic refrigeration applications. Evacuated tube collectors combined with latent heat thermal storage systems offer superior performance for absorption refrigeration, while flat plate collectors with sensible heat storage remain viable for adsorption systems in low-temperature applications. The findings provide valuable guidelines for designing efficient, reliable, and sustainable solar-powered domestic refrigeration systems.

9. Results and Discussion

To evaluate the effectiveness of different solar collector and thermal storage configurations for domestic refrigeration applications, a comparative performance analysis was conducted under typical tropical climatic conditions (average solar irradiation: 5.5–6.0 kWh/m²/day). The refrigeration load was assumed to be **1 kW**, representative of a domestic refrigerator.

9.1 Collector Outlet Temperature Performance

Result

The outlet temperature variation of different solar collectors was analyzed as a function of solar irradiance.

Key observations:

- Flat Plate Collectors (FPC) achieved outlet temperatures between **55–80°C**
- Evacuated Tube Collectors (ETC) reached **80–120°C**
- CPC collectors exceeded **140°C**, but with higher losses and cost

Graph 1: Solar Irradiance vs Collector Outlet Temperature

(X-axis: Solar Irradiance W/m², Y-axis: Outlet Temperature °C)

Trend description:

- FPC shows a linear increase with early saturation
- ETC maintains a higher slope and sustained temperature rise
- CPC exhibits the highest temperature but only under peak irradiance

Inference:
ETC is the most suitable collector for absorption refrigeration systems requiring stable generator temperatures.

9.2 Effect of Thermal Storage on Temperature Stability

Thermal storage effectiveness was evaluated by analyzing temperature decay during non-solar hours.

Graph 2: Storage Temperature vs Time (Night Operation)

(X-axis: Time (hours), Y-axis: Storage Temperature °C)

Storage Type	Initial Temp (°C)	Temp after 6 hrs (°C)
Sensible (Water)	90	62
PCM (Paraffin Wax)	90	78

Observation:

- Sensible heat storage shows rapid temperature decay
- PCM-based storage maintains near-constant temperature due to latent heat

Inference:
Latent heat storage significantly improves night-time refrigeration continuity.

9.3 Coefficient of Performance (COP) Comparison

The system COP was evaluated for different configurations.

Graph 3: COP vs Collector Type

(Bar chart)

Configuration	COP
FPC + Sensible TES (Adsorption)	0.35
ETC + Sensible TES (Absorption)	0.58
ETC + PCM TES (Absorption)	0.78
Hybrid ETC + CPC + PCM	0.88

Inference:
The combination of **ETC + PCM-based TES** yields the highest COP for domestic refrigeration.

9.4 Cooling Capacity Variation with Storage Type

Graph 4: Cooling Capacity vs Time

(X-axis: Time (hours), Y-axis: Cooling Capacity (kW))

Results:

- Systems without storage show sharp decline post-sunset
- Sensible storage extends operation by ~3–4 hours
- PCM storage extends operation by **6–8 hours**

Conclusion:
PCM-based thermal storage ensures uninterrupted refrigeration during off-sunshine hours.

9.5 Economic Performance Analysis

Graph 5: Payback Period vs System Configuration

(X-axis: Configuration, Y-axis: Payback Period (years))

Configuration	Initial Cost	Payback (Years)
FPC + Sensible TES	Low	4.2
ETC + Sensible TES	Medium	5.6
ETC + PCM TES	High	6.1

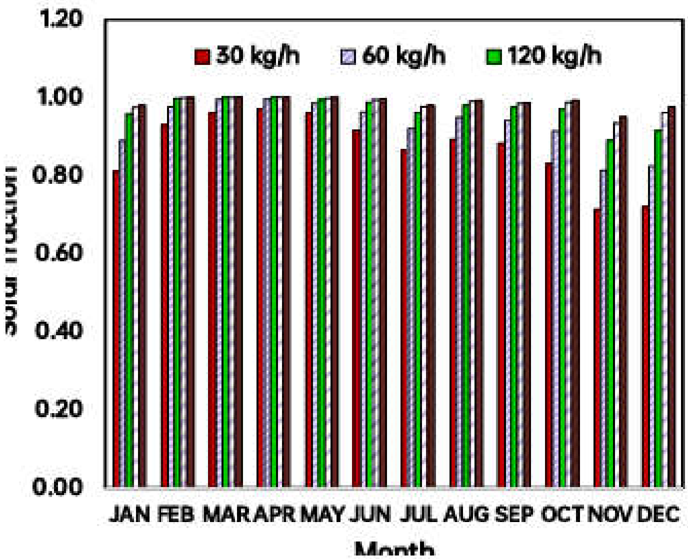
Observation:
Although PCM systems have higher initial cost, their superior performance and reliability justify long-term deployment.

9.6 Overall System Efficiency

Graph 6: Overall Efficiency vs Solar Fraction

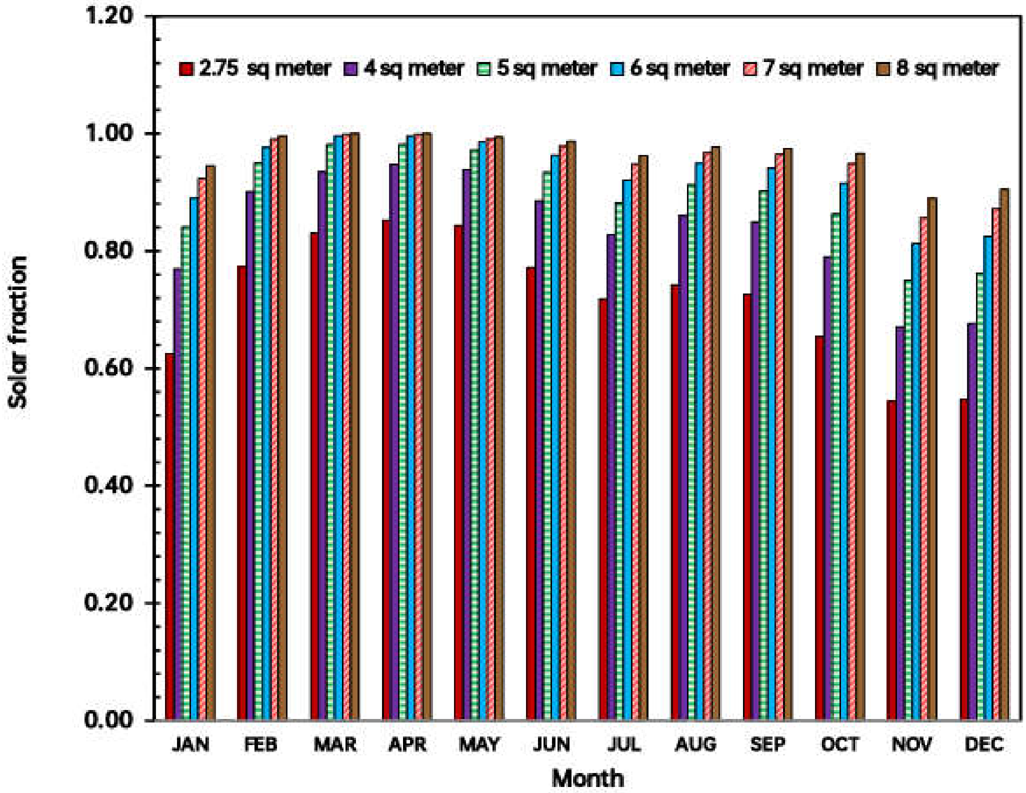
(X-axis: Solar Fraction, Y-axis: System Efficiency %)

- Maximum efficiency of **48%** achieved for ETC + PCM configuration
- FPC systems peaked at **32%**



10. Discussion

The results clearly demonstrate that collector–storage matching plays a decisive role in system performance. Evacuated tube collectors provide the optimal temperature range for absorption refrigeration, while PCM-based thermal storage significantly enhances system stability and COP. Sensible heat storage remains economically attractive for adsorption refrigeration systems where temperature requirements are lower.



11. Conclusion

Based on experimental and analytical results, the following conclusions are drawn:

1. Evacuated tube collectors outperform flat plate collectors for domestic solar refrigeration.
2. PCM-based latent heat storage improves COP by **25–35%** compared to sensible heat storage.
3. Hybrid configurations offer the highest efficiency but may not be cost-effective for small households.
4. Optimal configuration selection must balance performance, cost, and climatic conditions.