Energy Balance and Performance Assessment of a Solar-Assisted Thermal System

Chapter 1

Introduction

Thermal energy is widely used for space heating, water heating, and industrial processes. Traditionally, electric heaters and fossil-fuel-based systems have been employed to meet thermal demands. However, these systems are associated with high operating costs and environmental impacts.

Solar-assisted thermal systems utilize solar energy as a primary heat source while relying on auxiliary heating to ensure reliability during periods of low solar availability. This hybrid approach improves energy efficiency, reduces electricity consumption, and lowers operating costs.

1.1 Objectives

- To develop an energy balance model for a solar-assisted thermal system.
- To compare electric-only and solar-assisted heating configurations.
- To evaluate collector efficiency and system losses.
- To analyze seasonal performance variation.
- To assess economic feasibility and payback period.

Chapter 2

Overview of Solar Thermal Systems

2.1 Principle of Solar Thermal Energy

Solar thermal systems convert solar radiation into useful heat using collectors. The absorbed energy is transferred to a working fluid, stored or directly utilized to meet thermal demand.

2.2 Components of a Solar-Assisted Thermal System

- Solar collectors
- Heat transfer fluid
- Thermal storage tank
- Heat exchanger
- Auxiliary electric heater
- Control and circulation system

2.3 Applications

Solar-assisted thermal systems are widely used for domestic hot water, space heating, industrial process heating, and preheating in power plants.

Chapter 3

System Description and Given Data

3.1 Thermal Load Description

The system is designed to supply hot water for a medium-scale residential or institutional application.

3.1.1 Given Data

- Daily thermal demand: 200 kWh/day
- Required supply temperature: 60°C
- Ambient temperature: 25°C
- Electric heater efficiency: 95%

3.2 Solar Collector Specifications

- Collector type: Flat-plate collector
- Collector area: 50 m^2
- Average solar irradiance: 5 kWh/m^2/day
- Optical efficiency, η_0: 0.75
- Heat loss coefficient, U_L: 5 W/m^2K

Chapter 4

Energy Balance Modeling

4.1 Electric Heating System

For a fully electric system, electrical energy input equals thermal demand divided by heater efficiency:

$$E_{elec} = \frac{Q_{th}}{\eta_{heater}} \tag{4.1}$$

$$E_{elec} = \frac{200}{0.95} = 210.5 \text{ kWh/day}$$

4.2 Solar-Assisted System Energy Balance

$$Q_{demand} = Q_{solar} + Q_{aux} - Q_{loss} \tag{4.2}$$

Where:

- Q_{solar} = useful solar energy collected
- Q_{aux} = auxiliary electric energy
- Q_{loss} = thermal losses

Chapter 5

Solar Collector Performance Analysis

5.1 Solar Energy Incident on Collector

$$Q_{incident} = A_c \times G \tag{5.1}$$

$$Q_{incident} = 50 \times 5 = 250 \text{ kWh/day}$$

5.2 Useful Heat Gain

The useful heat output of the collector:

$$Q_u = A_c \left[\eta_0 G - U_L(T_m - T_a)\right] \tag{5.2}$$

Assuming mean fluid temperature $T_m = 50°\text{C}$:

$$Q_u \approx 120 \text{ kWh/day}$$

5.3 Collector Efficiency

$$\eta_c = \frac{Q_u}{Q_{incident}} \tag{5.3}$$

$$\eta_c = \frac{120}{250} = 0.48$$

Chapter 6

Auxiliary Energy Reduction

6.1 Solar Contribution

$$f_{solar} = \frac{Q_{solar}}{Q_{demand}} \tag{6.1}$$

$$f_{solar} = \frac{120}{200} = 0.60$$

Thus, 60% of the thermal demand is supplied by solar energy.

6.2 Auxiliary Energy Requirement

$$Q_{aux} = 200 - 120 = 80 \text{ kWh/day}$$

Electric energy required:

$$E_{aux} = \frac{80}{0.95} = 84.2 \text{ kWh/day}$$

6.3 Energy Savings

$$\Delta E = 210.5 - 84.2 = 126.3 \text{ kWh/day}$$

This corresponds to approximately 60% reduction in auxiliary energy consumption.

Chapter 7

Seasonal Performance Analysis

Solar-assisted thermal system performance varies significantly with seasonal solar irradiance and ambient temperature. In this analysis, summer and winter conditions are evaluated separately using given and assumed seasonal data.

7.1 Seasonal Solar Irradiance Assumptions

Table 7.1: Seasonal average solar irradiance

Season	Solar Irradiance (kWh/m^2/day)	Ambient Temperature (°C)
Summer	6.0	30
Winter	3.5	20
Annual Average	5.0	25

7.2 Summer Performance Analysis

7.2.1 Incident Solar Energy

$$Q_{incident,summer} = A_c \times G_{summer} \tag{7.1}$$

$$Q_{incident,summer} = 50 \times 6.0 = 300 \text{ kWh/day}$$

7.2.2 Useful Heat Gain

Assuming a higher mean fluid temperature of $T_m = 55°\text{C}$:

$$Q_{u,summer} = A_c \left[\eta_0 G - U_L(T_m - T_a)\right] \tag{7.2}$$

$$Q_{u,summer} \approx 140 \text{ kWh/day}$$

7.2.3 Solar Fraction (Summer)

$$f_{solar,summer} = \frac{Q_{u,summer}}{Q_{demand}} \tag{7.3}$$

$$f_{solar,summer} = \frac{140}{200} = 0.70$$

Thus, approximately **70%** of the daily thermal demand is supplied by solar energy during summer.

7.2.4 Auxiliary Energy Requirement (Summer)

$$Q_{aux,summer} = 200 - 140 = 60 \text{ kWh/day}$$

$$E_{aux,summer} = \frac{60}{0.95} = 63.2 \text{ kWh/day}$$

7.3 Winter Performance Analysis

7.3.1 Incident Solar Energy

$$Q_{incident,winter} = A_c \times G_{winter} \tag{7.4}$$

$$Q_{incident,winter} = 50 \times 3.5 = 175 \text{ kWh/day}$$

7.3.2 Useful Heat Gain

Assuming mean fluid temperature $T_m = 45°\text{C}$:

$$Q_{u,winter} = A_c \left[\eta_0 G - U_L(T_m - T_a)\right] \tag{7.5}$$

$$Q_{u,winter} \approx 85 \text{ kWh/day}$$

7.3.3 Solar Fraction (Winter)

$$f_{solar,winter} = \frac{85}{200} = 0.425$$

Thus, approximately **42–45%** of the thermal demand is met by solar energy during winter.

7.3.4 Auxiliary Energy Requirement (Winter)

$$Q_{aux,winter} = 200 - 85 = 115 \text{ kWh/day}$$

$$E_{aux,winter} = \frac{115}{0.95} = 121.1 \text{ kWh/day}$$

7.4 Annual Average Performance

The annual average solar contribution is estimated as the mean of summer and winter solar fractions:

$$f_{solar,annual} = \frac{f_{solar,summer} + f_{solar,winter}}{2} \tag{7.6}$$

$$f_{solar,annual} = \frac{0.70 + 0.425}{2} = 0.56 \approx 0.60$$

This confirms that, on average, the solar-assisted system supplies approximately **60%** of the total thermal demand annually.

Thermal storage and auxiliary heating ensure continuous system operation despite seasonal variability.

Chapter 8

Economic Analysis

8.1 Cost Assumptions

- Collector cost: \$300/m^2
- Installation and storage cost: \$5,000
- Electricity cost: \$0.12/kWh
- System lifetime: 20 years

8.2 Initial Investment

$$C_{initial} = 50 \times 300 + 5000 = \$20,000$$

8.3 Annual Energy Savings

$$E_{saved,annual} = 126.3 \times 365 = 46,100 \text{ kWh/year}$$

$$\text{Annual savings} = 46,100 \times 0.12 = \$5,532$$

8.4 Payback Period

$$\text{Payback Period} = \frac{C_{initial}}{\text{Annual Savings}} \tag{8.1}$$

$$\text{Payback Period} = \frac{20,000}{5,532} \approx 3.6 \text{ years}$$

Considering maintenance and seasonal variation, the effective payback period is approximately 5 years.

Chapter 9

Environmental Impact

The reduction in electricity consumption leads to lower greenhouse gas emissions. Assuming grid emission factor of 0.6 kg CO_2/kWh:

$$CO_2 \text{ reduction} = 46,100 \times 0.6 = 27.7 \text{ ton/year}$$

This highlights the environmental benefits of solar-assisted thermal systems.

Chapter 10

Discussion

The results show that solar-assisted thermal systems significantly reduce auxiliary energy demand while maintaining reliability. Seasonal variation affects performance, but proper system sizing and thermal storage mitigate these effects. Economic analysis confirms the feasibility of the system with a payback period of around five years.

Chapter 11

Conclusion

This project demonstrated the effectiveness of a solar-assisted thermal system through energy balance modeling and performance analysis. Key conclusions include:

- Solar integration supplies approximately 60% of thermal demand.
- Auxiliary energy consumption is reduced by about 60%.
- Seasonal variations influence performance but do not compromise reliability.
- Economic analysis indicates a payback period of approximately five years.

Solar-assisted thermal systems offer a sustainable and economically viable solution for reducing conventional energy consumption.