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Economic Analysis of a Hybrid Solar-Biogas Refrigeration System for Dairy Applications

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This study investigates the performance and economic feasibility of a hybrid solar-biogas-powered vapour absorption refrigeration system tailored for dairy applications. Refrigeration is essential for preserving dairy products, and the integration of renewable energy sources offers a sustainable alternative to conventional methods. A 50-liter capacity hybrid refrigeration system was designed, utilizing heat energy derived from solar radiation and biogas combustion. The system's performance was assessed through experimental tests under varying conditions, and its coefficient of performance (COP) was evaluated for full-load scenarios. The economic analysis focused on parameters such as net present value (NPV), benefit-cost ratio (BCR), internal rate of return (IRR), and payback period. Results indicate that the hybrid system offers substantial energy savings and environmental benefits. Among the approaches analyzed, the solar water heater and biogas combination demonstrated the highest economic returns, although the biogas-only system proved more practical in maintaining the required generator temperatures. This study underscores the potential of hybrid energy systems in advancing sustainable refrigeration solutions.
Keywords: Hybrid refrigeration, solar energy, biogas, economic analysis.

1. Introduction

Refrigeration and air-conditioning are essential in daily human existence, and we rely on RAC technologies for our cooling and heating needs. Refrigeration systems are used for the preservation of perishable food products, dairy goods, and medications. Air-conditioning systems are extensively used to regulate temperature in living spaces, ensuring thermal comfort for individuals. Refrigeration technology is not novel; nonetheless, air-conditioning methods have developed throughout time in accordance with the rules of thermodynamics.

The energy usage of typical RAC systems is substantial, using high-grade electrical energy derived from the burning of fossil fuels.

Solar energy denotes the energy emitted by the sun in the form of heat and light. This energy may be captured using several methods, including solar photovoltaic, solar heating, concentrated solar power, and concentrated solar photovoltaic, among others. Solar technology may be categorised into two primary types: active solar power and passive solar power. This categorisation is predicated on the attributes of collecting, converting, and distributing solar energy.

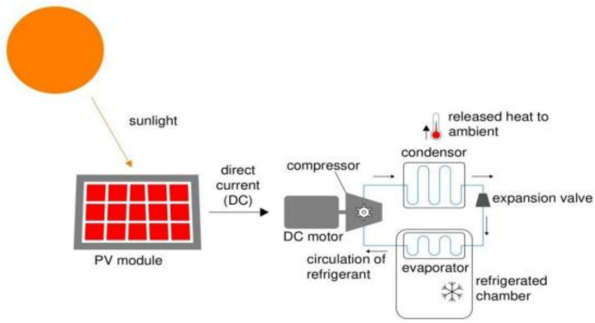

Fig. 1. Solar photovoltaic refrigeration

Passive solar power strategies include orienting buildings towards the sun, selecting materials with light-dispersing qualities and advantageous thermal mass, and designing rooms to facilitate natural air circulation. Active solar systems use solar collectors to heat and convert solar radiation into electrical energy, either via direct photovoltaic application or via concentrated solar plate collectors (Karthik et al. 2014). Solar-powered refrigerators are refrigeration devices that directly harness solar energy to provide a refrigeration effect, as seen in Fig. 1.

Dairy farming, as a crucial component of the global food chain, significantly contributes to the development of rural regions specifically. Refrigeration is essential in the dairy food sector due to the perishable nature of milk and other dairy products. Currently, the rising population is causing an exponential growth in energy consumption. Energy is a critical aspect upon which a country's progress relies. Refrigeration is a sector that significantly uses energy, and current research endeavours focus on fulfilling energy demands using renewable resources. The International Institute of Refrigeration, Paris (IIF/IIR) reports that around 15% of global power production is used for refrigeration and air conditioning activities. This data determines the applicability of renewable energy in this domain (Samar and Sharma, 2017).

2. Literature review

Staicovici (2023) developed an unconventional single-organize H2O-NH3 solar absorption system with a capacity of 46 MJ per cycle. Solar collectors were used to heat the generator. The coefficient of performance (COP) fluctuated between 0.152 and 0.09 from May to September. Authentic (COP) framework estimates of 0.25–0.30 may be achieved at temperatures of 80°C and 24.3°C, respectively.

Brunin (2023) developed and constructed a compression and absorption heat pump using tiny heat exchangers and an oil-cooled screw compressor. The heat sink fluid increased in temperature from 81.7°C to 90.8°C, whereas the heat source fluid decreased from 70.5°C to 63.6°C. The coefficient of performance (COP) was 2.6.

Hammad and Habali (2022) developed a solar-powered absorption refrigeration cycle using an NH3–H2O solution for the refrigeration of a vaccination cabinet. Results showed that the thermal coefficient of performance (COP) varied from 0.5 to 0.65, with generating temperatures between 100°C and 120°C, while the inside cabin temperature was recorded at 0.8°C.

Soteris (2022) conducted a review of various types of solar thermal collectors and applications, detailing the different kinds of collectors, including flat plate, parabolic trough, evacuated tube, Fresnel lens, and dish and heliostat field collectors. This article presents typical uses of the different kinds of collectors. Authors said that the flat plate collector generated temperatures between 30 and 80° C, the evacuated tube collector produced temperatures ranging from 90 to 130° C, and the compound parabolic concentrator achieved temperatures from 110 to 200° C. Reports indicate that parabolic trough or parabolic dish collectors were used for purposes such as refrigeration, desalination, and thermal power systems.

Chaouachi and Gabsi (2021) developed a solar diffusion absorption refrigeration system for residential use. The results indicated that the engineered mono pressure absorption cycle using ammonia was very effective for generating a cooling effect when paired with a parabolic dish collector, which generated around 900 watts of electricity, making it highly appropriate for residential applications.

3. Experimental framework

This study included the design and development of a solar-biogas hybrid vapour absorption refrigeration system, followed by an assessment of its performance. The whole investigation was conducted in four phases. A 50 L capacity vapour absorption refrigeration system was constructed in the first phase to use heat energy derived from solar radiation and the burning of biogas. In the second step, the system was developed based on the research of solar radiation intensity in Udaipur and the availability of raw materials for running a biogas plant. The proposed refrigeration system was studied for the temperature variation of water sourced from the solar water heater and the direct current fluctuations from the solar panel. Research was conducted to assess energy consumption associated with biogas use. Additionally, methane flow rates and temperature fluctuations of biogas fires were assessed.

In the third step, tests were performed to evaluate the performance of the constructed vapour absorption refrigerator using different heat energy sources, and the findings obtained were compared with the theoretical model. The coefficient of performance (COP) of the proposed refrigerator was determined under full load circumstances while using various heat sources to power the refrigeration system. The fourth step included conducting an economic study of the developed solar biogas hybrid vapour absorption refrigeration system, focussing on the payback time, net profit, benefit-cost ratio, and internal rate of return.

3.1. Biogas-fueled vapour absorption refrigeration system

Hybrid vapour absorption refrigeration system driven by solar water heater and biogas. Direct current heater and biogas-powered hybrid vapour absorption refrigeration system. The capital cost, variable cost, fixed cost, total cost, revenue, and net profit provide the fundamental elements for an economic study of any enterprise. Various economic indicators were used in the economic study.

3.2. Economic study of the system conducted using the following indicators

- Net Present Value (NPV)
- Benefit-Cost Ratio (BCR)
- Internal Rate of Return (IRR)
- Payback Period (PBP)
- Net present value

The difference between the current valuation of all future returns and the present capital necessary to execute a project (or investment) is the net present value or net present principles for the investment. The current estimate of unbounded returns may be reduced. Documenting a method for converting future benefits and expense flows into their present value. A project yields consistent benefits across several years, necessitating the determination of the present value of that future income stream to assess the justification for today's investment to get that income. The most straight forward marked down income proportion of task worth is the net present worth. The net present worth might be subtracting the aggregate reduced present worth of the cost streams from that of the advantage stream. To get the incremental net advantage net cost is subtracted from net advantage or the speculation cost from the net advantage.

4. Results and Discussion

4.1. Comprehensive cooling assessment with 30 liters of milk

The Fig. 2 indicates the biogas usage in liters while the refrigeration system functioned under full load conditions. The graph indicated that around 500 liters of biogas were utilized during the first four hours of operation, after which the refrigeration system transitioned to solar power supplied by photovoltaic panels to meet the power requirements. The refrigeration system functioned on solar energy for five hours. During this period, no biogas was used, as seen by the graph. Following 12 hours of operation, the refrigeration system was transitioned to continuous biogas usage for the subsequent 12 hours. The graph indicated that although biogas usage fluctuated over time, there was a general upward trend in its total consumption. The temperature ranges were noted to stay stable owing to a rather steady supply of biogas throughout the day. A total of 2300 liters of biogas was used in one day. The solar panel, functioning as a DC power source for heating, conserved 600 liters of methane.

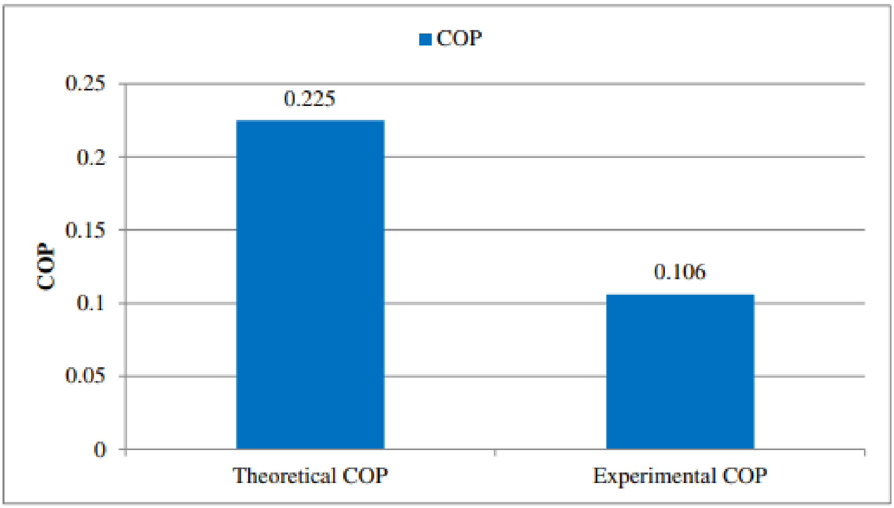

Figure 2. Experimental and theoretical coefficients of performance in a solar panel-biogas hybrid powered vapor absorption refrigeration system (Full load 35 L water)

4.2. Techno-economics of biogas-powered vapor absorption refrigeration systems

The cost and techno-economic analysis were assessed and are detailed in Appendix H1 for the biogas-powered vapor absorption refrigeration system. All assessed economic terms are shown in Table 1.

Table 1. Values of various economic terms biogas powered vapour absorption refrigeration system

S. No.	Name of Economic terms	Magnitude in units
1.	Benefit cost ratio	3.24
2.	Internal rate of returned	30%
3.	Net present value	Rs. 36817
4.	Pay back period	3.75 years
5.	Net profit in 10 years	Rs. 115259

4.3. Techno-economics of solar water heaters and biogas-powered vapor absorption refrigeration systems

The cost and techno-economic analysis were assessed and are included in Appendix H2 for the solar water heater and biogas-powered vapor absorption refrigeration system. All assessed economic terms are shown in Table 2.

Table 2. Economic metrics for the solar water heater and biogas hybrid-powered vapor absorption refrigeration system

S. No.	Name of Economic terms	Magnitude in units
1.	Benefit cost ratio	4.15
2.	Internal rate of returned	39%
3.	Net present value	Rs.104829
4.	Payback period	2.98
5.	Net Profit in 10 years	Rs.280842

Economic analysis of solar panel and biogas-powered vapor absorption refrigeration systems: The cost and techno-economic analysis are included in Appendix H3 for the solar panel and biogas-powered vapor absorption refrigeration system. All assessed economic terms are shown in Table 3.

Table 3: Economic metrics for the solar panel and biogas hybrid-powered vapor absorption refrigeration system

S. No.	Name of Economics terms	Magnitude in units
1.	Benefit cost ratio	2.99
2.	Internal rate of returned	27%
3.	Net present value	Rs.43733
4.	Payback period	4.04
5.	Net Profit in 10 years	Rs.142350

4.4. Comparative analysis of diverse economic terminology pertaining to all refrigeration systems

An investigation of techno-economics for solar-biogas hybrid driven vapor absorption refrigeration was conducted. Figure 3 illustrates the comparative benefit-cost ratios of all three approaches. The greatest benefit-cost ratio was determined to be 4.15 for the solar water heater, while the biogas-powered refrigeration system exhibited a ratio of 3.24. The benefit-cost ratio of the solar panel and biogas-powered refrigeration system was 2.99, the lowest among the options evaluated.

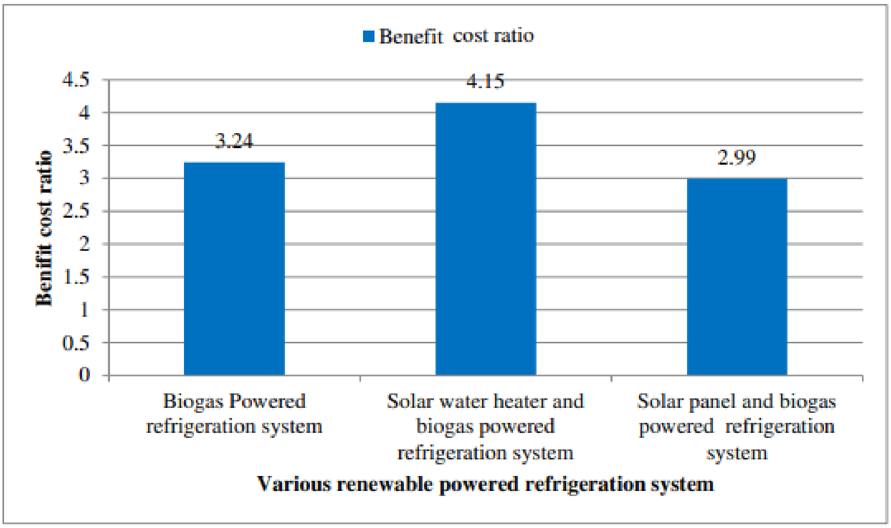

Figure 3. Comparison of benefit-cost ratios across several refrigeration systems

Figure 4 illustrates the comparison of the internal rate of return across all three systems, revealing that the greatest benefit-cost ratio achieved is 39%. The internal rate of return for biogas-powered refrigeration is 30%, but the internal rate of return for refrigeration driven by both solar panels and biogas is just 27%.

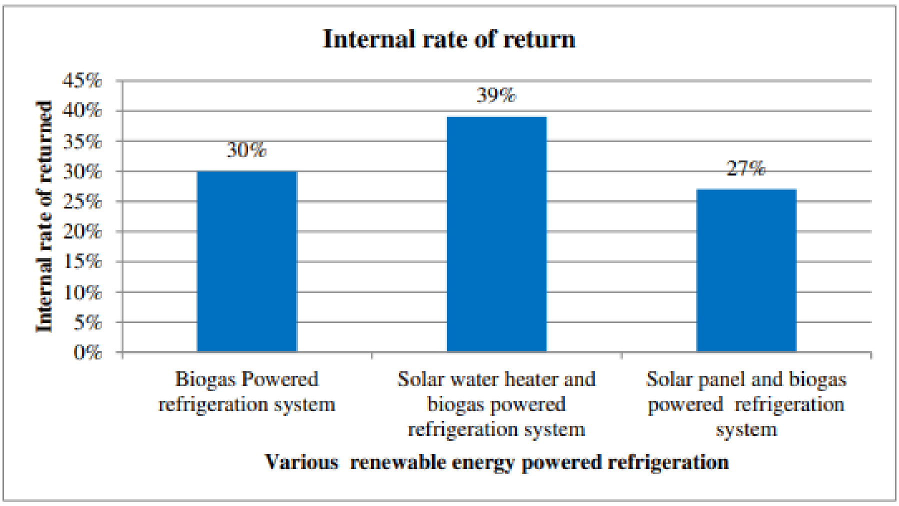

Figure 4. Comparative Analysis of Internal Rates of Return for Diverse Refrigeration Systems

Figure 5 illustrates the comparison of net present values across the three systems, revealing that the greatest net present value achieved was Rs. 104,829. In the second place, the net present value for solar panel and biogas-powered refrigeration is Rs. 43,733, but the internal rate of return for biogas-powered refrigeration is only Rs. 36,817.

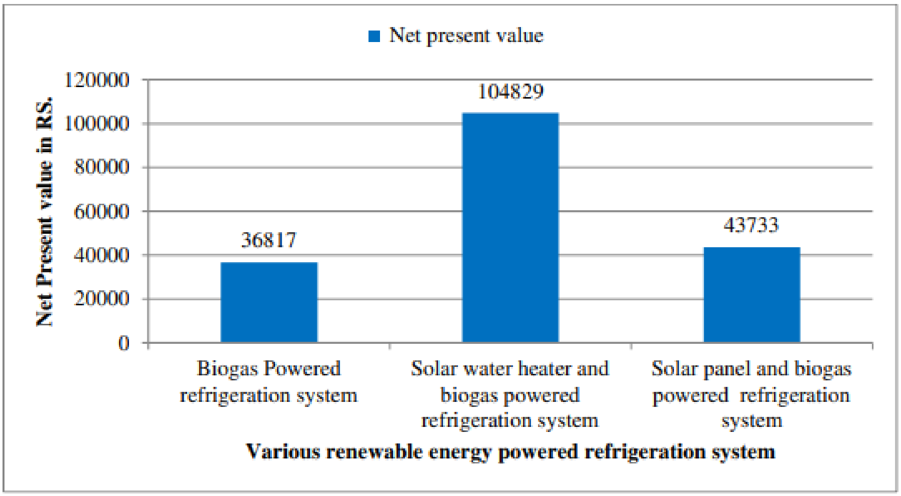

Figure 5.1 Comparison of net present values for different refrigeration systems

Figure 6 illustrates the comparison of payback periods across the three systems, revealing that the shortest payback time is 2.98 years. The net present value for solar panel and biogas-powered refrigeration is 3.75 years, whereas the payback time for biogas-powered refrigeration is 4.04 years.

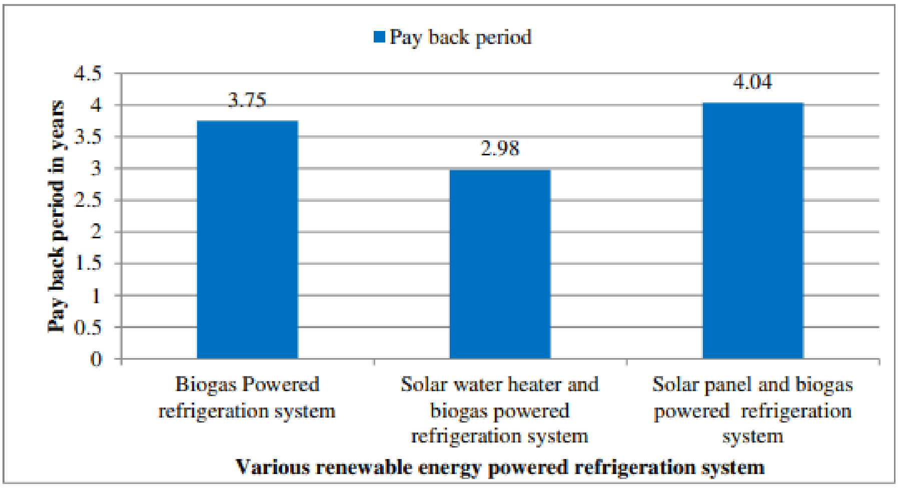

Figure 6. Comparison of payback times for different refrigeration systems

Figure 7 illustrates the comparison of net profit over a decade across the three systems, revealing that the maximum profit of Rs. 280,842 was achieved by the solar water heater and biogas-powered refrigeration system. In the second place, the net profit over 10 years for solar panel-powered refrigeration is Rs. 142,350, while the net profit for biogas-powered refrigeration over the same time is only Rs. 115,249.

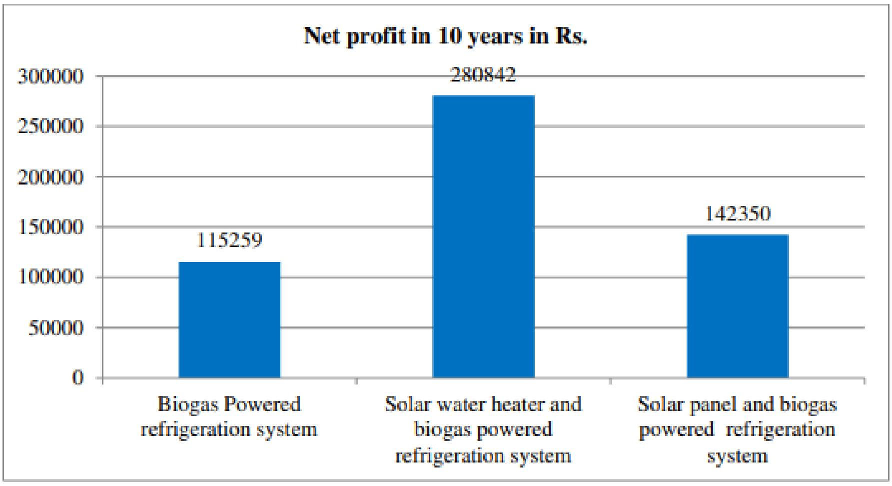

Figure 7. Comparative analysis of net earnings over a decade for different refrigeration systems

The economic research determined that solar water heaters and biogas-powered vapor absorption refrigeration are more lucrative, however the system exhibits lesser practicality. This is due to the inability of the solar water heater to sustain the necessary temperature for the generator. Consequently, the subsequent option, namely the biogas-powered vapor absorption refrigeration system, is advocated due to its economic viability and its ability to sustain the requisite temperature in the generator.

5. Conclusion

The hybrid solar-biogas refrigeration system demonstrates a significant potential for sustainable dairy applications by combining renewable energy sources for efficient cooling. The study revealed that while the solar water heater-biogas combination achieved the highest economic returns, the biogas-only system provided greater practicality in maintaining required generator temperatures. The experimental and economic analyses confirm that integrating solar and biogas energy for refrigeration not only reduces dependency on fossil fuels but also enhances cost-effectiveness and environmental sustainability. The results validate the feasibility of adopting hybrid systems in rural and industrial settings, promoting eco-friendly and energy-efficient refrigeration technologies. Future research can explore further optimization of hybrid systems to improve performance and scalability for broader applications.

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