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PERFORMANCE ANALYSIS OF A NOVEL PORTABLE SOLAR HYBRID VC REFRIGERATION SYSTEM

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Abstract- Humans have always been concerned about the environment and energy conservation. The novel design of a portable solar hybrid vapor compression refrigerator has been proposed in this study. This hybrid energy-operated DC refrigerator was tested with four load conditions on sunny days. The I-V curve of the PV panel, refrigerator chamber temperature and meteorological data were recorded. The solar panel generated an average of 785 Wh of solar energy in one sunny day. The refrigerator was consumed 98 Wh energy at the no-load condition in a single day. The refrigerator chamber was filled with 30% (70 L), 60% (140 L), and 90% (210 L) load that consumed 154 Wh, 316 Wh, and 492 Wh energy, respectively to reach 0 ^{o}C. Daytime energy consumption of refrigerator was higher as compared to night time. The lead-acid battery's energy storage capacity was 1260 Wh. The battery was able to run the refrigerator for 2.5 days with 90% load condition without solar energy. The refrigeration system's average COP was 1.2. Experimental results demonstrated that solar energy production was higher as compared to refrigerator energy consumption. The proposed unique technology demonstrates the feasibility of the hybridization of renewable energy and grid utility in a cost-effective and environmentally friendly way. This solar-assisted system can be used to store lifesaving medicines and vaccines in disaster-prone areas.
Keywords: Mobile solar refrigeration, energy-saving, performance, economic analysis.

1. INTRODUCTION

The availability of utilizable sources of energy is essential to every country's technical development and economic prosperity. In recent decades, fossil fuels have been considered and utilized as the primary source of energy. The energy production industry is highly dependent on fossil fuels such as coal, oil, and gas, which are producing large amounts of pollution. However, the adverse environmental effects of burning fossil fuels have forced energy experts to consider renewable energy sources seriously. Solar energy has tremendous potential and inherent availability [1].
Solar energy is an abundant energy resource in Asian countries. Solar energy has a significant positive impact on the world's environment, economics, and politics. Solar refrigeration is a significant application of renewable energy conversion technologies. This type refrigeration system has been gaining popularity around the world since the beginning of the last decade. It is beneficial because cooling demand is higher at times of the day when the availability of solar radiation is maximum [2]. The refrigeration and cooling demand are higher in the summer season.
The market for refrigeration and cooling systems is growing continually. The energy demand for refrigeration systems is rising throughout the world, especially in hotter regions. These systems consume about 30% of total global energy. Conventional cooling systems are less energy efficient. Therefore, Conventional cooling systems are more responsible for the negative influence on the ecosystem [3]. Refrigeration and cooling devices are consuming 15% of the total world electricity.
Energy demand is rising in tandem with the economy, population, and per capita energy consumption. Fossil fuels supply a larger amount of the world's energy, which is a significant contributor to global warming. Energy-optimized refrigeration and cooling systems are an urgent need worldwide [4].
One of the most pressing issues facing humanity is feeding the world's fast-growing population. Food preservation is essential for solving world hunger problems. Globally about 37% of vaccines and 40% of perishable foodstuffs require refrigeration systems for storage. The vaccination, medications, and perishable foodstuffs are storing at a lower temperature (0-8 ^{o}C). Currently, more than one-third of all food produced in the world is wasted, due to the lack of appropriate technologies, very limited access to energy, especially electricity, and affordability. Global losses for fruits and vegetables are estimated to be 45%, 35% for seafood and fish, 30% for cereals, and 20% for dairy products and meat.
The electricity cuts frequently in rural areas of developing countries in summer peak hours. Therefore, perishable food, vaccines, and medicine storage have always been big issues due to a lack of appropriate, reliable, and cost-effective technologies. Solar hybrid refrigeration (SHR) technology is expected to provide a more reliable, safer, and cleaner form of refrigeration for perishable foods and improve the cold chain for vaccines [5-7]. The usage of this technology in the cold chain saves grid energy. It also reduces the dependency on grid electricity. This type of technology helps to reduce greenhouse gases emission and global warming [8-15]. The primary aim of this paper is to analyze the performance of a solar-assisted hybrid refrigeration system.

2. REVIEW ON SHR SYSTEM

Earlier reviews on SHR system are briefed in table 2.1.

Table- 2.1 Review on SHR System Performance

Year & reference	Type of compressor & working refrigerant	Method & experimental parameters
2009 [16]	AC compressor (110 W); R134a refrigerant.	• Solar operated domestic refrigerator (SDR); • The solar intensity with time, solar photovoltaic panel (SPV) current, and voltage; • Freezer temperature and ambient temperature; • COP of the refrigerator with time.
	Short description: The COP of the refrigerator was decreased with sunrise; the maximum COP was recorded 2.1 at 7 am.	
2011 [17]	12V DC compressor; R134a refrigerant.	• Multi-purpose PV-refrigerator system; • Solar radiation and PV power; • Refrigerator-cabin temperature and the ambient temperature.
	Short description: The photovoltaic panel produced 425.9 Wh/day of energy; the refrigerator reached -10.6 °C temperature; the refrigerator's energy consumption was 347.7 Wh/day for the 15 L load condition.	
2012 [18]	12V DC compressor; R134a refrigerant.	• PV powered VCR system; • Speed of compressor; • Temperature variation time.
	Short description: The cooling rate was increasing from 0.231 to 0.8 ^{o}C/min when the DC compressor's speed was increased from 2000 to 3600 rpm.	
2016 [19]	VSDC compressor; R134a refrigerant.	• AC and DC compressor operated with solar energy; • Inside chamber temperatures; • AC and DC refrigerator energy consumption; • Speed of compressor; • Solar energy generation in peak hours; • Pull down-time.
	Short description: The Solar operated DC refrigerator system installation cost was 18% less than the AC refrigerator; the AC refrigerator consumed high power compared to the DC refrigerator.	
2017 [20]	12V DC-VCR compressor; R134a refrigerant.	• Battery and hybrid mode of energy supply; • The current and voltage of solar panel; • Current and voltage consumed by refrigerator; • Solar radiation and battery voltage; • The DC refrigerator chamber inside temperature.
	Short description: The refrigerator consumed 15-41% more power in loaded condition than the no-load condition.	
2018 [21]	12V DC compressor; R134a refrigerant.	• Solar-powered DC refrigerator; • The current and voltage of solar panel; • Current, voltage consumed by refrigerator; • Battery voltage.
	Short description: The refrigerator's power consumption ranged from 30.84 to 68.16 W.	
2019 [22]	VSDC compressor; R134a refrigerant.	• Directly coupled vapor compression (DCVC) solar refrigeration system; • Compressor speed range 1800–4200 rpm; • Current and voltage generated by the PV panel.
	Short description: The COP of the refrigerator was higher (2.25) at lower compressor speed and recorded the lowest (1.85) at higher compressor speed.	
2020 [23]	DC compressor; R134a refrigerant.	• Variable speed photovoltaic direct-current (DC) refrigerator; • Radiation intensity; • Compressor speed; • PV power; • The refrigerator's internal temperature and the outside ambient temperature.
	Short description: Compared with the fixed speed mode, the variable speed mode's cooling capacity	

	increased by 32.76%, and the average PV utilization efficiency increased by 45.69%.	
2021 [24]	VSDC compressor; R134a refrigerant.	• PV driven cold chain; • PV power; • Current and voltage generated by the PV panel.
	Short description: The daily average refrigeration COP ranged from 2.75 to 3.02, while the daily average system COP ranged from 2.27 to 2.46, with the highest daily cumulative ice mass reaching 178.45 kg. For the system driven by the PV array, the most daily ice mass was 144.10 kg obtained with the PV capacity of 5.4 kW and the highest cumulative solar insolation of 20.41 MJ/m2, and the daily refrigeration and system COP were 1.33 and 0.19, respectively.	
2021 [25]	Variable speed compressor.	• Solar operated-variable speed direct current (VSDC) system; • Speed of the compressor; • Refrigerating unit temperatures and pressures.
	Short description: The highest system COP reached 0.289 when the cumulative daily total radiation was 18.2 MJ/m^2 in Kunming, China.	

Some studies have already been done on direct sun-driven cooling systems, but very limited work is done on SHR system. Previous research had several shortcomings in terms of energy savings, economic analyses, and pollutants. Therefore, the present work focuses on a SHR system.

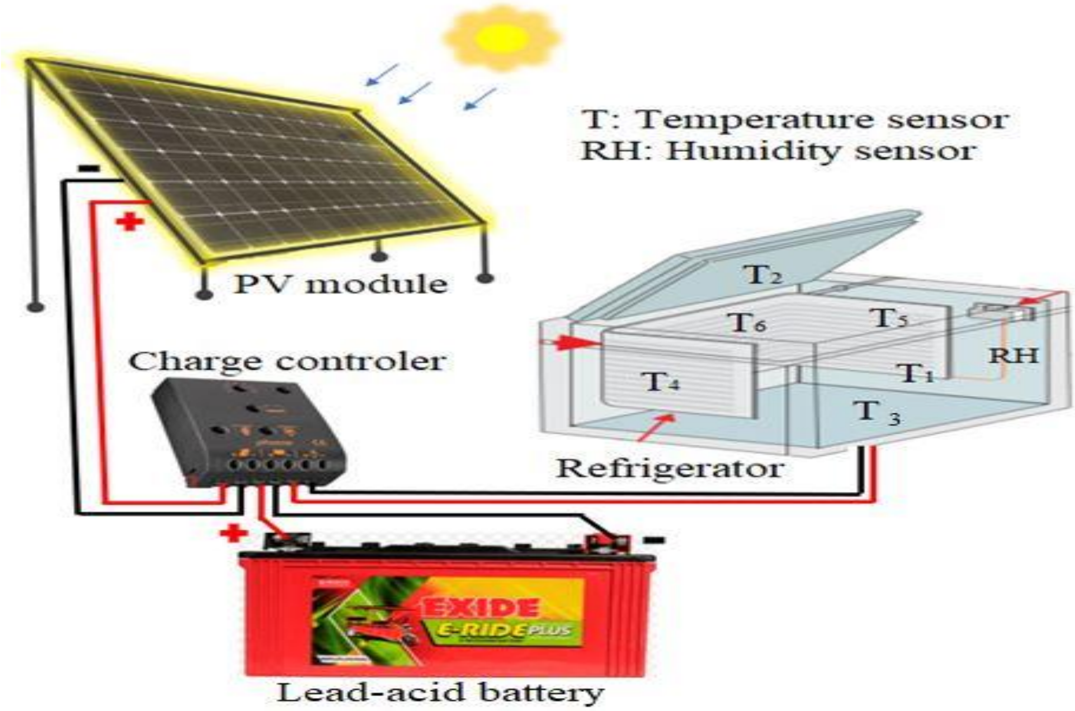

Fig. 3.1 Schematic diagram for SHR system

3. EXPERIMENTAL SETUP DESCRIPTION

Schematic of the solar hybrid refrigerator system is presented in figure 3.1. It is fabricated with four components: a cooling unit (refrigerator), an energy production unit (photovoltaic panel), an energy control unit, and an energy storage unit (lead-acid battery). This system works with an input voltage of 12 V direct current. R134a refrigerant was used in the DC refrigerator. Solar-generated energy and grid electricity are stored in the lead-acid battery. The refrigerating system is operated with the battery stored energy. This system's battery is charged using two different types of energy: first, solar energy, and second, by grid power. The SMPS charger (5A) is utilized to charge the battery with grid electricity. Polycrystalline PV panel was selected due to high efficiency. Solar energy is the primary energy resource for this system in the daytime, although it used battery stored energy when solar energy is insufficient. The charge controller regulates the fluctuation in solar output power. The solar panel is mounted on the upper side of the steel frame at a tilt angle of 27.62^o to receive the greatest amount of solar radiation annually. The steel structure is constructed in such a way that it can carry the weight of the system. The components detailed specifications for this system are given in table. The photographic view of this system is shown in figure 3.2. Two digital energy meters measure the electricity generated by the solar panel and the power consumed by the refrigerator.

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Fig. 3.2 Photographic view of SHR system

Table 3.1 Specifications of SHR system components

PV module	
Parameter name	Specification
Capacity (W_P)	150 W
Module volt (V)	12
Width (W)	666 mm
Height (H)	1483 mm
Thickness (T)	35 mm
Tolerance	+/- 5%
Module weight	11 kg
Cell in series	(9×4) 36
V_{oc}	21.5 V
I_{sc}	8.75 A
$P_{Max.}$	150 W
V_{pm}	18 V
I_{pm}	8.33
FF	>0.70
Efficency (η_{pv})	>15.0 %
Solar charge controller (MPPT)	
System voltage	24/48 auto recognition
Max charge/ load current	45A
Efficiency	90%
DC refrigerator	
Dimensions of outer cabinet	1145 mm×850 mm ×690 mm
Inner dimensions	900 mm×673 mm ×440 mm
Operating voltage	12V
Temperature range	-16 to +6 ^oC
Ambient temperature range	10 to 45 ^oC
Refrigerant used	R-134a (eco-friendly)
Door type	Top opening
weight	58 Kg
capacity	240 L
Insulation	Polyurethane (12 cm thick)
Compresser type	DC compresser
Lead-acid batterie	
Rated output	105 Ah, 12V
Depth of discharge	80% (First 1600 cycles)
Overall efficiency	65%

4. PROCEDURE FOR PERFORMING EXPERIMENTS

All of the experiments are carried out in an open environment on sunny days. These experiments were carried out in the Mechanical Engineering Department at the National Institute of Technology Jalandhar. These tests were performed between 5-29 September, 2019. The following experimental conditions were maintained:

- All experiments are performed in the same location.
- The thermostat knob was fixed at the 7th position during all refrigerator experiments.
- Before starting each refrigerator experiment, the door of the DC refrigerator is left open for 4 hours to maintain thermal equilibrium with ambient air.
- The door of the DC refrigerator was kept closed throughout the experiment.
- The first experiment was conducted in the refrigerator with no load, then tested with 30%, 60%, and 90% load conditions.

Six thermocouples are installed on the inner wall of the refrigerator to detect temperature. Another temperature-humidity metre is used to record data about the ambient air. Data from the solar and refrigerator tests are recorded every 30 minutes and every 15 minutes, respectively. The monthly average solar radiation in Jalandhar city is shown in fig. 4.1. The pyranometer is used to measure solar irradiation. The temperature on the surface of the PV panel is measured using a digital non-contact infrared thermometer (temperature gun).

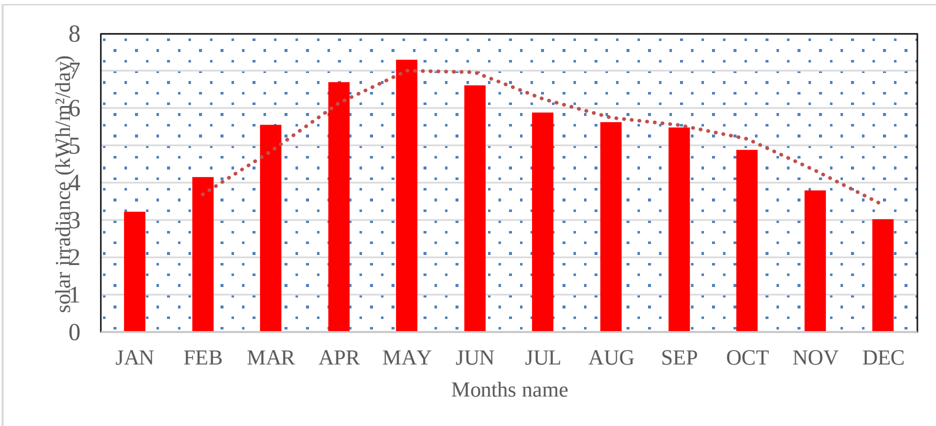


Fig. 4.1 The monthly average solar radiation in Jalandhar city [26]

The variation of meteorological parameters and performance of PV panel in experimental day is shown in figure 4.2. Equations 1 and 2 are used to calculate the power and energy consumed by a refrigerator.

$$Power = Current \times Volatage \quad (1)$$

$$E_{daily} = \int_{0}^{24hrs} p.dt = \sum_{t=0}^{24hrs} p\Delta t \quad (2)$$

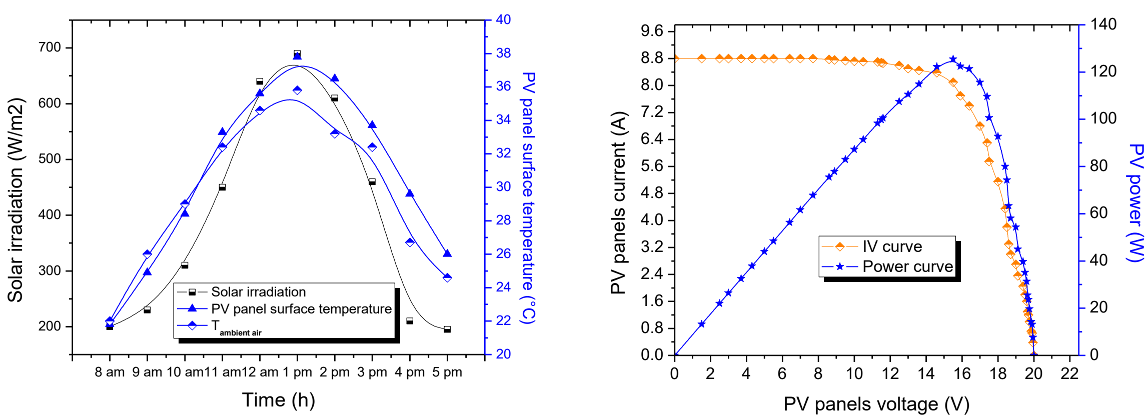


Fig. 4.2 Meteorological parameters variation and performance of PV panel in experimental day

5. RESULTS AND DISCUSSION

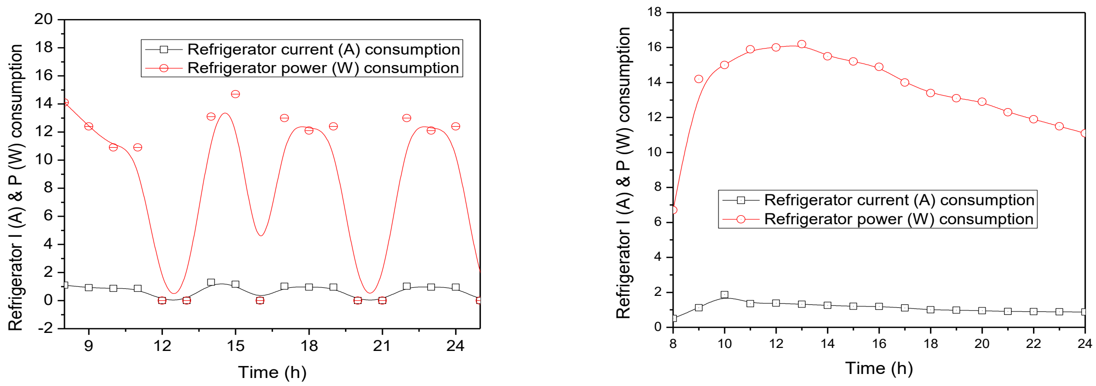
Experiments are conducted to analyze the performance of the SHR system on sunny days. These tests were carried out in two stages. The performance of the PV panel is tested in the first stage. The refrigeration of this system is tested in the second stage by changing the load situation.

5.1 The PV Panel Test

The experiment is carried out on a sunny day between 9:00 a.m. and 5:00 p.m. The PV panel's output current, voltage, and power are all measured. The output energy of the PV panel was 785 Wh, with output power ranging from 80 to 120 watts.

5.2 Experiments on the DC Refrigerator

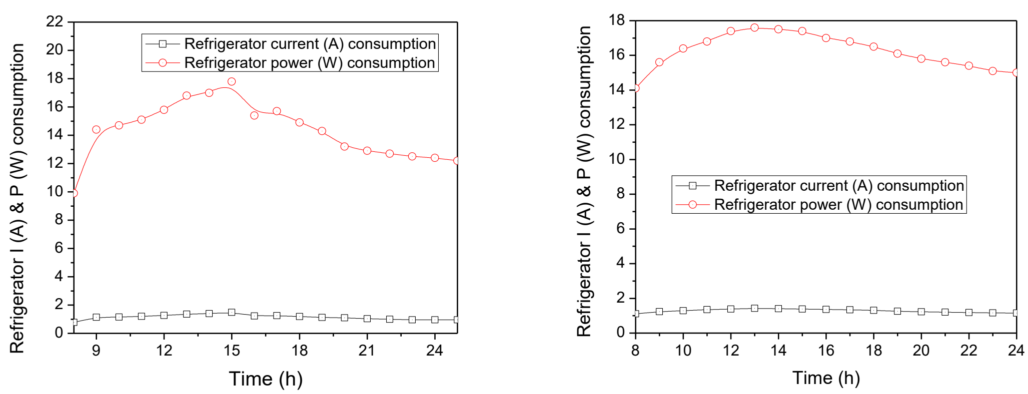
All experiments are performed under different loading conditions: (1) with no-load (2) with 30% (70 L) load (3) with 60% (140 L) (4) with 90% (210 L) load. The current and power consumed by the refrigerator under various loading situations are shown in figures 5.1 (a & b) and 5.2 (a & b). The results show that the refrigerator consumed more power when it was operated at 90% load capacity. The maximum amount of power consumption for no-load, 30%, 60% load, and 90% was measured 14.6 W, 16.5 W, 17.2 W, and 17.8 W respectively. The current consumption is also recorded higher at 90% load situation.



(a) **(b)**

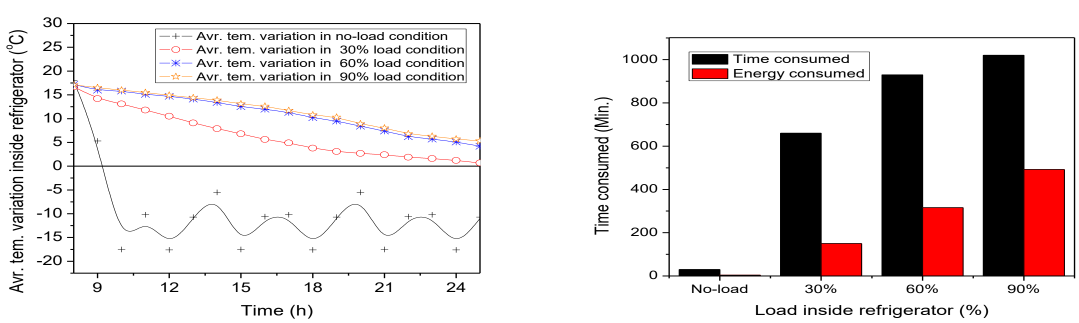
Fig. 5.1 Current and power consumed by refrigerator (a) at no-load and (b) 30% condition

Fig. 5.3 (a) shows the inside temperature variation of the refrigerated chamber. The lower temperature -17 ^{o}C was recorded inside the refrigerator at no-load condition. The refrigerator required more time to reach 0 ^{o}C when the loading quantity is raised. Figure 5.3 (b) shows the energy consumption of the refrigerator. The refrigerator's energy consumption increases when the proportion of load is raised.



(a) **(b)**

Fig. 5.2 Current and power consumed by refrigerator (a) at 60% and (b) 90% load condition



(a) **(b)**

Fig. 5.3 Refrigerator (a) chamber inside temperature variation (b) energy consumption

5.3 Payback Period of SAR System

The payback period of the SHR system = Total cost of this system / Total money earns by this system per year.
Total cost of this system in INR = 55000 (refrigerator cost) + 4500 (solar penal) + 2000 (charge controller) + 5500 (battery cost) = **67,000 INR.**
Considered 50 INR cooling cost for the different commodities in one day and ten months cooling is required in a year.
Case earns by this system per year = 50 INR (one-day cooling cost) × 30 (days in a month) × 10 (cooling required in months in a year) = 15000 INR
Average energy saved by this system per year = 0.787 (Panel generated energy in one day) × 30 (days in a month) × 8 (available solar energy months) = 189 KWh
Energy saved by this system in a year = 189 KWh × 8 INR (per unit cost) = 1512 INR
Total money earns by this system per year = Case earns per year + average energy saved per year = 15000 + 1512 = **16512 INR**
The payback period of SHR system = **67,000 / 16512 = 4 years**

CONCLUSION

The performance and energy consumption of a portable solar hybrid vapor compression refrigerator system was studied under different load conditions. This technology utilized two types of energy sources to run the DC compressor of the refrigerator. The battery was charged using both grid and solar energy. This system's battery was charged using solar energy during the day and grid electricity at night. The following are the most important findings from the experiments:

- Experimental results showed that the SHR system fits to achieve and maintained the lower desire temperature inside the refrigerator chamber at any time.
- The lead-acid battery capacity was 105 Ah (1260 Wh), which was enough to run the refrigerator for 2.5 days at 90% load without the use of solar energy.
- On a sunny day, the solar panel yielded an average of 65.4 Ah (785 Wh) of solar energy, which was sufficient to charge the battery during the day.
- The battery charged fully in 1.5 days using solar energy.
- The average COP of the refrigeration system was 1.2.
- The temperature variations in different parts of the refrigerated chamber were studied. In a no-load condition, the refrigerated chamber's lower average temperature of -12 ^{o}C was maintained by consuming 98 Wh of energy in one day.
- For a 30% load condition, the refrigerator's compressor was reached 0 ^{o}C in 660 minutes by consuming 154 Wh of energy.
- For 60% load condition, the refrigerator's compressor was reached 0 ^{o}C in 930 minutes by consuming 316 Wh energy.
- For 90% load condition, the compressor of the refrigerator was reached at 0 ^{o}C in 1020 minutes by consuming 492Wh energy.
- The Payback period of this system was 4 years.
- The running and maintenance costs of this portable refrigeration system were affordable, making it ideal for storing life-saving medications.

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