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Research Article

Design and Performance of Solar PV Integrated Domestic Vapor Absorption Refrigeration System

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The arrival of new technologies has increased the energy demand day by day and does not seem to slow down at any time soon. High energy demand is adding risk on energy depletion and cause of various environmental issues. Air conditioner, chiller, and refrigerator occupy a considerable amount of the world's total energy usage and have also proved to be a massive contributor to various environmental impacts. This technology might sound like a luxury on the surface, but they are in high demand to achieve food security. They can also help lifesaving vaccines to reach even the isolated parts of the world. Even though solar thermal refrigeration is a popular field, this paper solely concentrates on PV integrated refrigeration. In this paper, a renewable integration technology where a solar photovoltaic system is used to supply the electrical energy required to drive an absorption cycle is studied and compared with the commercial AC absorption refrigeration system. The Coefficient of Performance (COP) of the AC and DC system was 0.18 and 0.14. The simple payback of the system is 10.2 years.

1. Introduction

From the start of the day until the end of it, several types of technologies are making our life simple. Energy consumption is directly proportional to economic growth and population. In developed countries, 10-20% of total energy consumption is from HVAC [1]. In developing countries, the increase in consumption is due to economic growth, population, and urbanization [2]. Electricity has become a necessity for development, and hence, rural electrification has become a dream for many developing countries.

While discussing the advantages of energy, it has also become a necessity to discuss the disadvantages. Fossil fuels occupy a significant share in satisfying global electricity needs. As it requires millions of years for fossil fuels to form, they will be depleted sooner or later. They are also the reason for the world's biggest environmental problems. As the growth continues, energy demand would also be increasing, which in turn would increase carbon emission [3]. Even a small change in fossil fuel usage patterns would help protect energy reserves and achieve environmental sustainability [4]. Being stuck on only the impacts caused by the technologies does not add any advantage to society. The only way to move forward is by finding an alternative, which is renewable technologies that could overcome these issues.

Rural electrification is one of the solutions to remove poverty in developing countries. Villages located in rough areas like forests, deserts, and hilly regions are away from the existing grid location. To bring electricity to such places would be decentralized generation by renewable energy. This would also reduce transmission and distribution losses. Solar PV is the first choice for the Indian context among renewable technologies. A PV system was designed for a rural domestic load and proved to be a promising technology in rural development [5]. The government of India aims to achieve 175 GW of energy usage by 2022. As India is a tropical country, solar PV can provide a high yield. The lifetime of solar PV would be 25 to 30 years, making it worth investing [6].

The economic feasibility of the off-grid system for Nigeria was done and found to be an economically viable option [7]. Carbon emission per unit power production is very low compared with the coal power plant [8].

Several factors affect the performance of PV. One such factor is heating, which would affect the efficiency of the panel. This could be overcome by a heat recovery system by a continuous water cooling method. Optimizing the solar PV land utilization and growing vegetation was studied [9]. The vegetation growth would also improve panel efficiency and also reduce the payback period [10]. The author has discussed another solar PV optimization technique to enhance efficiency, and the waste heat from this process is utilized to improve the quality of drinking rural drinking water [11]. The shadowing effect and monsoon could also affect system performance [12]. A detailed design of the off-grid and the on-grid system was carried out. The economic analysis of both systems was also carried out. Though the off-grid system requires additional components, i.e., the battery, it is more economical than the on-grid system [13].

Cooling technology in the form of a hand fan or wind has been in practice even from ancient times. Even the method of ice cultivation was practiced by elites in European countries [14]. But, over a period of time, this technology has transcended from luxury to a common commodity. Cooling technology has seen a surge in growth because of its need in various fields like lifestyle, food, agriculture, processing, and pharma. Both the technology and market value of this technology is growing steadily. Being one of the most significant contributors to global energy consumption, it has a huge energy-saving potential by moving towards renewable technology. Solar energy could help achieve that dream. Even the gaps in the cold supply chain that could act as a barrier for the vaccines to reach the rural areas with no grid facility can be filled with the help of solar refrigeration [15].

Realizing the need for renewable integration, many authors have designed many solar integrated refrigeration methods. A DC-operated household refrigerator powered by solar PV was studied and found to have low exergetic efficiency due to low energy conversion efficiency [16]. A solar PV-operated stand-alone system was studied for various compression air conditioning systems [17]. A compression air conditioning system driven by solar PV was studied. The system required to operate the system includes a PV panel, charge controller, and a battery [18].

Even though absorption technology has lower COP than commercial refrigeration technology, it is more durable with a longer lifetime of 20-30 years [19]. Vapor absorption refrigeration (VAR) is proven to be an environmentally friendly replacement for commercial refrigeration. It also has better power quality in comparison with a commercial refrigerator. It can effortlessly reach 8-16°C, helping tropical agricultural product storage and achieving food security by reducing food wastage [20].

For the theoretical calculation of the COP, it is necessary to know the heat supplied and effective cooling. The experimental work was done, and it was compared with the theoretical data. The result shows that on a clear day, one pound of ice can be produced for every three to four square feet of collector area [21]. The COP of VAR can be improved from 0.39 to 0.65 by adding a heat exchanger [22].

With the high flexibility with source energy, a single-stage absorption chiller with $LiBr/H_2O$ would make decentralized storage of fruits and vegetables in the farm itself possible by integrating renewable energy. This would be more advantageous, especially during summer, when energy is abundant, and the need for cooling was also plentiful [23]. A solar flat plate collector refrigerator with a hot water storage tank was studied. It has recorded evaporator temperature as low as 6°C [24].

The author has studied a 10-ton single-stage $LiBr/H_2O$ system driven by an evacuated tube collector in the system. A 72 m^2 solar collector area was mounted on the rooftop of the building. In case, hot water temperature falls below 70°C, backup heating using LPG would start working. To provide continuous cooling, hot water and cold water storage tank were also included. Even though the system's cost is currently high, with steady growth, this CFC free technique could reduce price in the future. Even the VAR system's operational cost looks very attractive compared to the Vapor Compression Refrigeration (VCR) system. The system's yearly average solar fraction was 81%, and the LPG fired unit has supplied only the remaining 19% [25]. In the heat storage system, it requires an additional collector to supply the required heat energy for the storage tank [26]. This will increase the investment cost.

In a concentrated parabolic collector-driven system, the COP value was found to be 0.08, and the author has highly suggested it for no electricity areas [27]. An author has even suggested the usage of engine exhaust as the heat source to drive the system [28].

For continuous operation of the refrigeration cycle, a solar thermal integrated system would require either an auxiliary heater or a thermal storage buffer. The storage buffer can be either a heat storage tank or a cold storage tank, or both. The buffer storage tank also has thermal loss due to temperature difference with the environment. Based on the type of water heater and system design, several studies were done for a solar thermal integrated VAR system. In the case of vapor absorption technology, many studies were focused more on utilizing solar thermal energy. On the other hand, there is a lack of studies based on the solar PV integrated VAR system. So, this paper deals with solar PV-powered vapor absorption refrigeration technology.

2. System Description of Conventional and Solar-Assisted VAR

Figures 1 and 2 show the block diagram and components of the basic single-stage absorption refrigeration system, respectively. The selected system has H_2O-NH_3 as a working fluid. H_2O-NH_3 does not cause any environmental damage like other commercial refrigerants and does not have a crystallization problem below 0°C like Libr-H_2O [29]. In the generator, working fluid must be heated to be separated into refrigerant and absorbent. The heat required to achieve

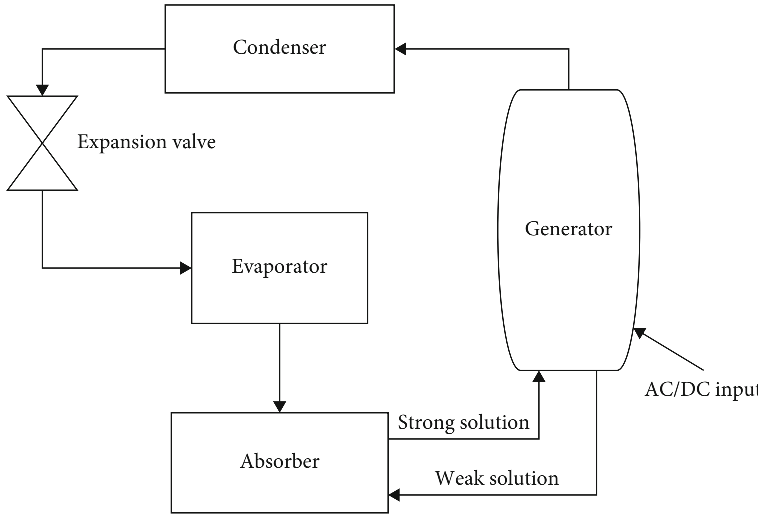

Figure 1: Block diagram of conventional VAR.

Figure 2: Components of the VAR system.

the desired temperature is supplied by a heater. The generator is the only component that requires a power supply to drive the entire system. A 220 V~240 V, 0.3 A heater was used in the AC system, and a 12 V, 5 A heater was used in the DC system. Once the refrigerant is separated from the strong solution, it will move to the condenser while the weak solution returns to the absorber. In the condenser, heat is rejected to the external environment to produce a low-temperature solution. A finned type condenser was used to increase the surface of exposure to disperse the heat quickly. After undergoing condensation and expansion, the refrigerant would be in a low-temperature low-pressure state, making it easy to absorb the heat from the selected environment, i.e., evaporator. The water in the absorber would absorb ammonia leaving the evaporator to continue the cycle.

The block diagram of the solar PV integrated DC system is shown in Figure 3. The only electrical load in the system is a heater. The heater is a resistive load that can operate in both AC and DC without any design changes. A solar PV panel would supply the electrical energy required by the system. For a country like India, solar energy is available throughout the year, so no other auxiliary energy is required. Solar energy is not available for 24 hours, but refrigeration is needed to provide continuous cooling without rest, especially for food storage. So, to run the system continuously, a battery bank is needed to drive the system even during the night time.

The circuit diagram of the PV integrated VAR system is shown in Figure 4. The charge controller acts as a control unit. Due to passing clouds, the solar intensity would vary every second. In that case, to maintain the charging and power supply, a charge controller is used. Energy generated from PV is passed through the charge controller, and a 12 V, 8 Amps regulated output can be achieved. The output from the charge controller is used to supply power to the refrigeration unit and charge the battery at the same time. During no sunshine time, the charge controller allows the power to flow from the battery to the refrigeration unit. A charge controller would also help to prevent overcharging of the battery, thus increasing the battery lifetime.

3. Objective

The main objective of this work is to integrate solar PV with the VAR system. Other objectives include calculating and comparison of the COP of conventional VAR and PV integrated VAR cycle, comparing the relationship between the generator and evaporator temperature, and calculating the payback of the system.

4. Experimental Methodology

The following conditions were considered:

(i) The specification of the AC system and a DC system taken for the study is shown in Table 1. The power

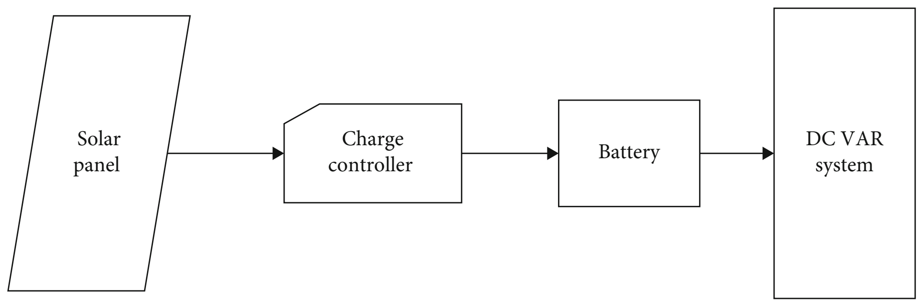

Figure 3: Block diagram of solar PV-powered system.

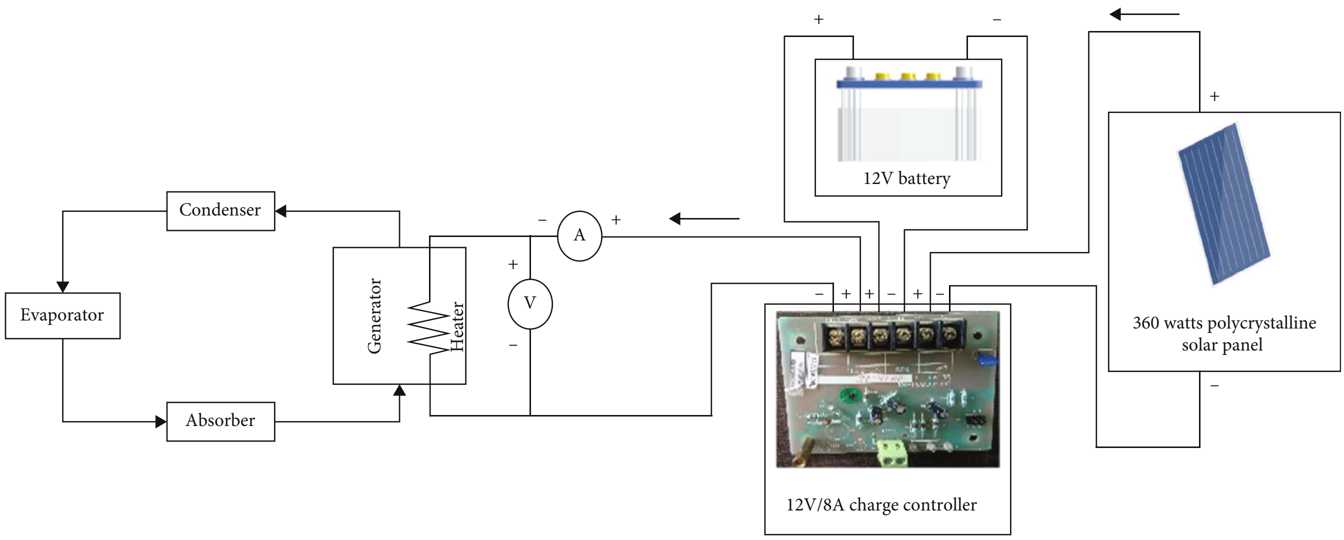

Figure 4: Circuit diagram of the proposed VAR system.

Table 1: Specification of the refrigeration system.

Name	AC VAR	DC VAR	Unit
Voltage	220–240	12	V
Current	0.3	5	A
Capacity	40	40	L
Condenser type	Finned type	Finned type	-
Dimension ($l * b * h$)	402 * 465 * 560	402 * 465 * 560	mm
Insulation	Styrofoam	Styrofoam	-
Working Fluid	H_2O-NH_3	H_2O-NH_3	-
Temperature	2-10	2-10	°C
Gross Weight	20	22	kg

Table 2: Specification of the instruments used.

Instrument	Function	Specification
K-type thermocouple	Measure the temperature of evaporator and generator temperature	-200 to 600°C
Fluke meter-I410	Used to measure the voltage and current	1 mV/Amp, 600 V, 400 Amp DC
Chino data logger-KR 2000	Store the measured data	1 mV/Amp, 1-400 Amp, 12 terminals, sampling -0.1 s/6 points, temperature drift - ±0.01% of full scale/°C

plug is replaced by a crocodile clamp in the DC system for easy integration into the solar PV system

(ii) The study was conducted under a loaded condition. A two-liter of water is used as a load in both AC and solar PV integrated DC refrigeration system

(iii) Temperature, voltage, and current with respect to time were the parameter to be measured. The K-type thermocouple was used to measure the temperature. A fluke meter was used to measure the voltage and current. With the help of the chino data logger, all the measured data were monitored and recorded for every one-minute duration for higher accuracy. Specification of the instruments used is given in Table 2

(iv) System performance like COP, simple payback, energy usage, and energy conservation was calculated using the following equations:

$$\begin{aligned}&\text{Annual power consumption by AC system}\\&\quad= \text{watts} * \text{hours of operation} * 365,\end{aligned} \tag{1}$$

$$\text{Annual energy saving by DC system} = \text{watts} * \text{hours of operation} * 365 \tag{2}$$

Payback is calculated by the simple payback method.

$$\text{Simple payback} = \frac{\text{Cash outflow}}{\text{Cash inflow}}, \tag{3}$$

where cash outflow includes the investment cost and the cash inflow is the total amount of annual energy-saving cost after subtracting the maintenance cost.

The Coefficient of Performance (COP) is defined as the ratio of heat extracted from the evaporator to the work done.

$$\text{COP} = \frac{m * C_p * dT}{V * I}, \tag{4}$$

where m is the mass of load in kg/s, C_p is specific heat capacity in kJ/kg/°C, dT is a temperature difference between initial temperature and final temperature in °C, V is the voltage in volt, and I is the current in Amps. $V * I$ should be in kW.

5. System Design

Maximum solar radiation should be required for both driving the system and charging the battery. For the solar PV-driven system to run for 24 hours, PV requires to generate 1440 Wh a day. This energy need has to be satisfied by utilizing only five-hour peak radiation available during the day. While calculating the panel size, the efficiency of the panel must also be considered.

$$\begin{aligned}\text{Panel wattage} &= \frac{\text{Total energy}}{\text{Average radiation time} * \text{pannel efficiency}}\\&= \frac{1440}{5 * 0.8} = 360\ \text{w}.\end{aligned} \tag{5}$$

A single 360-watt panel can be selected as there are 360 w panels available in the market. A 360-watt polycrystalline solar panel is selected from all the above considerations for driving the system and charging the battery to provide backup simultaneously. The study location is in the northern hemisphere at 10.2785°N, 77.9244°E. So, the solar panel was mounted facing south with a tilt angle of 25° with respect to the flat ground surface. Unlike other off-grid systems, it does not require any inverter because the load is a DC system. The output from the panel is passed through the 12 V, 8 A solar charge controller. This will help regulate the unpredictable energy from the solar PV to charge the battery. Charging duration and battery efficiency are required to calculate the battery size.

$$\begin{aligned}\text{Ah required} &= \frac{\text{panel wattage} * \text{charging hours} * \text{battery efficiency} * 1.5}{\text{Battery voltage}}\\&= \frac{360 * 5 * 0.8 * 1.5}{12} = 180\ \text{Ah}.\end{aligned} \tag{6}$$

A battery does not discharge 100%, so energy extraction is increased by 1.5 times. A 12 V 180 Ah battery is used to act as a backup during no sunshine hours.

6. Experimental Setup

A 40-liter 65 W AC system is shown in Figure 5. The K-type thermocouple is positioned to measure the temperature of the cooling chamber, and the chino data logger was used to monitor and measure data.

A 40-liter 60 W DC system was taken for the study. The experimental setup is given in Figure 6. The temperature of the cooling chamber and generator was measured simultaneously. The consumption side voltage and current were measured and logged.

7. Results and Discussion

Figures 7 and 8 show the graph between temperature and power supply in the AC and DC machine, respectively. In the AC system, the temperature is dropped from 33°C to 8.9°C in five hours. The DC system's five-hour temperature drop has reached 10°C, which is enough to store tropical fruits and vegetables. When the atmospheric temperature is reduced during winter, up to 8°C can be achieved easily. In both the system, once the desired temperature is reached, not much temperature change is noticed. There is also not much difference in the operation pattern of both the systems. This allows the possibility for the AC system to be replaced by the solar PV-powered DC system. Considering the role of refrigeration technology in achieving food security, the

Figure 5: Experimental setup of AC VAR.

Figure 6: Experimental setup of solar PV-powered VAR.

solar-powered vapor absorption system is much needed in the food supply chain, especially in rural agricultural areas where electricity is still inaccessible.

The refrigerator is required to operate 365 days a year. A 65-watt system would utilize 569.4 kWh energy per year. According to CO_2 Baseline Database for the Indian Power Sector [30], the average CO_2 emission factor per kWh of energy generation is 0.82.

$$\text{Yearly } CO_2 \text{ emission} = 569.4 * 0.82 = 466.9\,\text{kg},$$
$$CO_2 \text{ emission for 30 years} = 466.9 * 30 = 14\,\text{tons}. \tag{7}$$

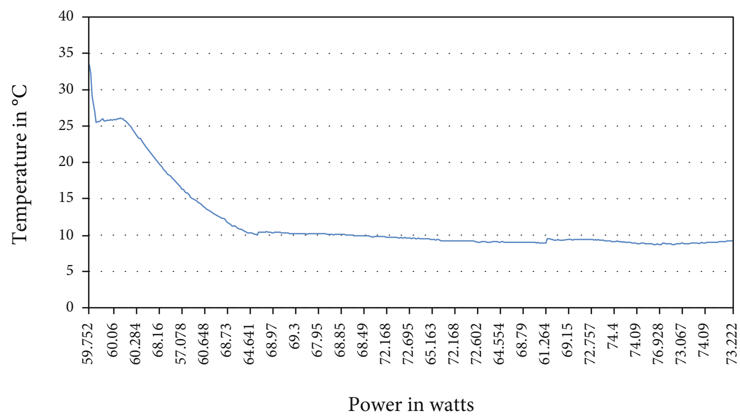

Figure 7: Performance graph of the AC system.

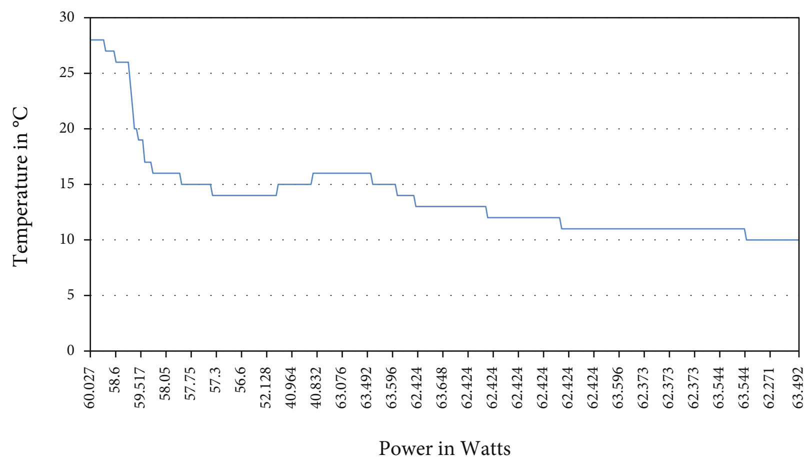

Figure 8: Performance graph of the DC system.

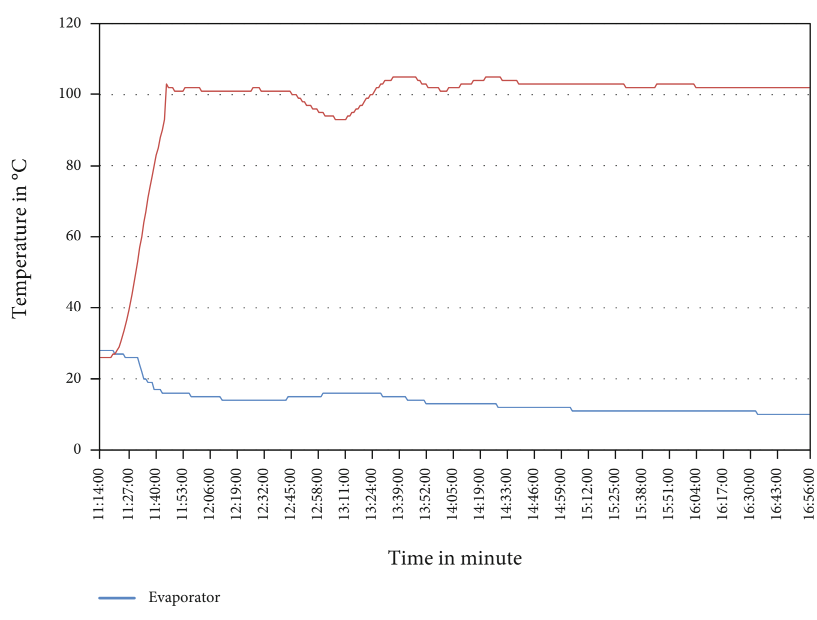

Figure 9: Comparison of generator temperature and evaporator temperature.

In a year alone, the AC system will contribute to 466.9 kg of CO_2. Throughout its entire lifetime, this system will release 14 tons of CO_2.

Figure 9 compares the evaporator temperature and generator temperature of the DC system with respect to time. Once the system is turned on, the generator temperature is slowly increasing. As the generator temperature increases, evaporator temperature reduces. When the generator temperature crosses the 60°C mark, the evaporator temperature started reducing. It took 15 minutes for the refrigerator to begin cooling. Once the generator temperature reaches an optimum temperature, the lowest evaporator temperature of 10°C is achieved and maintained continuously.

8. System Performance Calculation

Without the battery, by utilizing only the five hours of maximum sunshine radiation, in a single day, 0.3 kWh energy and ₹190 can be saved. But the refrigerator has to operate for 24 hours throughout the year.

Annual power consumption by the AC system is calculated using equation (1).

$$\begin{aligned} &= 65 * 24 * 365, \\ &= 569.4\,\text{kWh}. \end{aligned} \tag{8}$$

Annual energy saving by the DC system is calculated using equation (2).

$$\begin{aligned} &= 60 * 24 * 365, \\ &= 525.6\,\text{kWh}. \end{aligned} \tag{9}$$

Annual power consumption by the AC system is 569.4 kWh. In a PV-powered DC system, the entire power requirement is satisfied by the solar panel itself, and hence, the 525.6 kWh energy is saved by this system.

The additional components required for the solar-powered system would add to the additional investment cost. Simple payback is calculated using formula (3).

The value of each piece of equipment is given in Table 3.

A total of ₹35,500 investment cost is required for implementing the solar operated system. This system does not require any maintenance except for periodic cleaning of the solar panel. So, it does not require any maintenance cost. Solar integration has saved a total of 525.6 kWh of energy every year. For the Indian tariff rate, the yearly cost saving would amount to ₹3,469. Total cash outflow is equal to ₹35,500, and annual cash inflow is ₹3,466.

$$\text{Simple payback} = \frac{35{,}500}{3{,}466} = 10.2\ \text{years}. \tag{10}$$

The solar operated system's payback will be 10.2 years, which is not bad for a solar application.

The COP of both the systems was calculated using equation (4).

Table 3: Investment cost of the DC system.

Component	Cost in rupee (₹)
Absorption system	6000
Solar panel	11,000
Battery	17,000
Charge controller	500
Balance of system (include mounting and wire)	1,000

The COP of AC and DC systems is calculated for cooling 2 liters of water over a five-hour duration. The specific heat capacity of water is 4.186 kJ/kg/°C.

In the AC system for a five-hour duration, dT is 24.5°C, and the COP is

$$\text{COP} = \frac{(2/5 * 3600) * 4.186 * 24.5}{0.65} = 0.18. \tag{11}$$

In the DC system for a five-hour duration, dT is 10°C and the COP is

$$\text{COP} = \frac{(2/5 * 3600) * 4.186 * 10}{0.60} = 0.14. \tag{12}$$

The COP of the AC system is 0.18, while for the DC system, the COP is 0.14. There is only a small difference, so performance-wise will not affect the output.

9. Conclusion

Technology should grow and must be utilized without affecting the environment. Move towards renewable energy would not only meet energy demand but also help many satisfy their electricity dreams. In this paper, 60 w DC-operated VAR driven by a 360 w was studied, and the results have shown the possibility of reaching that dream.

(1) The annual CO_2 emission of the selected system is 466.9 kg, and this system alone contributes to 14 tons of CO_2 for its entire lifetime. The solar integrated system would help eliminate this 14 t CO_2. This is the saving from one system alone. Considering CO_2 emission control is one of the most significant issues to be tackled, the result is very encouraging to move towards the PV integrated system

(2) Refrigeration being one of the most significant contributors to power consumption in the world, solar PV integrated refrigeration would be a big stepping stone to reaching a sustainable future. A 525.6 kWh energy saving was achieved in the PV integrated DC system

(3) Even the 10.2-year payback is pretty good for a system that operates for 30 years

(4) A solar PV operated DC absorption system has a COP of 0.14. Currently, the COP of VAR is lower

than the VCR systems, which is still a disadvantage of the VAR system yet to overcome

In the future, studies related to the control system design to improve solar output can be done. The system's performance can be enhanced by giving design modification to the refrigeration system by adding additional heat exchangers or incorporating a cooling tower. An utterly renewable energy-driven absorption cycle could help this technology reach any corner of the world as far as there is enough solar energy available. This PV integrated system will allow utilizing all the technology services without compromising the environment and future energy needs.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no competing interests.

Acknowledgments

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