Journal of Renewable Energy and Smart Grid Technology, Vol. 17, No. 2, July-December 2022

A solar-powered vapor compression refrigeration system for vaccine storage

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Received: 28 October 2022, Revised: 6 December 2022, Accepted: 15 December 2022

Abstract

Herein, a solar-powered vapor compression refrigeration system for vaccine storage was proposed. The system comprises a 535-W photovoltaic module, a 60-A charge controller, a 200-Ah lead–acid battery, a 3,000-W inverter, and a 75-W commercial vapor compression refrigerator. The refrigerator is directly connected to the inverter. The experiments were conducted at Silpakorn University (13.82°N, 100.04°E), Nakhon Pathom, Thailand. It was found that the load temperature can be reduced from the ambient temperature of 26°C–28°C to 0°C within 18 h for small load (3.75-15.00L). Technically, the system performs well and can be used for vaccine storage. Also, the ARX modeling approach can be used to predict the load temperature with acceptable accuracy. From the economic analysis, the payback period of the system is 11.34 years.

Keywords:

Solar-powered Vapor Compression Refrigeration System; Solar Cooling; Vaccine Storage; ARX Modeling, Economic Evaluation

1. Introduction

Vaccines are important in preventing several diseases. Generally, vaccines must be stored in the cold chamber of a refrigeration system. A commercial refrigerator usually needs electricity from a grid to run it. However, the grids in the rural areas of developing countries are very limited. Most developing counties have abundant solar radiation, which can be converted to electricity by a photovoltaic (PV) module. Therefore, several researchers have attempted to use PV modules to supply electricity to vapor compression refrigerators for vaccine storage.

Uddin et al. [1] reported the energy analysis of a solar-driven refrigerator using environment-friendly refrigerants. They found that the R152a refrigerant could provide lower utilized electricity costs than conventional refrigerants. Kalbande et al. [2] investigated the feasibility of a solar refrigeration system and found that the system has a high potential for vaccine storage. Besides, the average PV conversion efficiency was 12.05%. Babalola et al. [3] proposed a solar-powered refrigerator for rural off-grid areas in Nigeria. They found that a 75-W refrigerator with a 100-W solar module, a 20-A charge controller, a 100-Ah deep cycle battery, and a 100-W inverter could be used reasonably for a health center in this country. Dhondge and Kalbande [4] evaluated the performance of a solar PV-powered vapor compression refrigeration system in a rural area of India. They found that the nanorefrigerant (R-134a + Al_2O_3) performed better than other refrigerants. Amratwar and Hambire [5] reviewed the development and application of solar PV-powered refrigeration systems for vaccine preservation.

Generally, the performance of a solar-powered refrigeration system depends on the location under investigation. To the best of our knowledge, the performance characteristics of solar-powered vapor compression refrigeration systems using inverters for vaccine storage have never been investigated in a Thai environment. Therefore, this study aims to investigate the performance of a solar-powered refrigeration system in a Thai environment. Also, the modeling and economic evaluation of this system were conducted.

2. Materials and methods

2.1. Materials

The material mainly used herein is a solar-powered vapor compression refrigeration system. The system comprises a 535-W PV module, a 60-A charge controller, a 200-Ah lead–acid battery, a 3,000-W inverter, and a 75-W commercial vapor compression refrigerator. The connection of the components of the system is shown in Fig. 1.

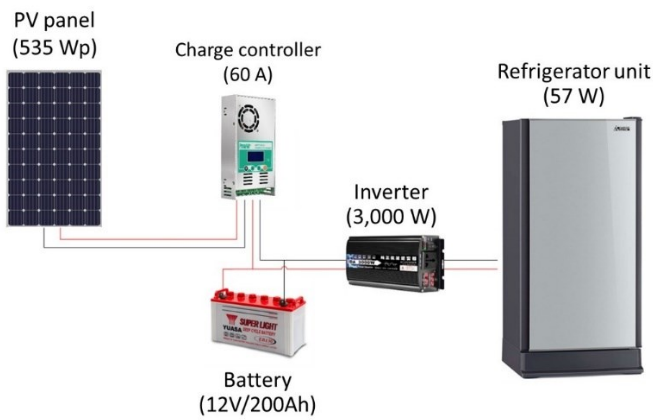

Fig. 1 The connection of the components of the system proposed in this study.

From Fig. 1, the PV module is connected to the charge controller and the charge controller is connected to the battery. The PV module supplies the electricity to the battery under the control of the charge controller. The battery is connected to the inverter and this inverter is connected directly to the refrigeration unit. The electricity from the battery is supplied to the refrigerator unit through the inverter. The PV module was placed on the rooftop of a hut, and the rest of the system was placed inside the hut (Fig. 2).

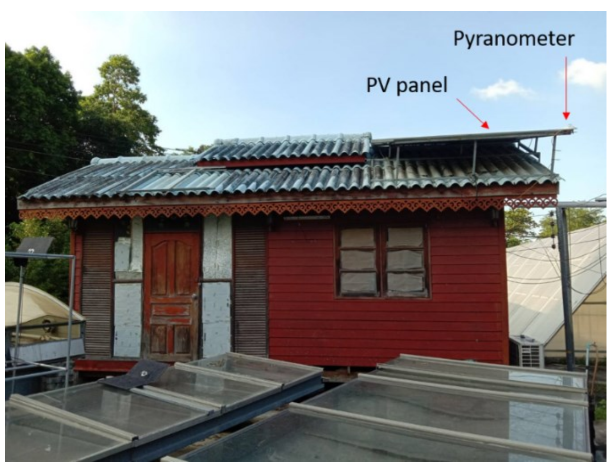

Fig. 2 The hut for system installation.

The hut is located in the experimental field (13.82°N, 100.04°E) of the Department of Physics, Faculty of Science, Silpakorn University in Nakhon Pathom, Thailand. The system was experimented with using water in plastic bottles as loads. The data from experiments were used to demonstrate the performance of the system, and they were also employed to model the system using the ARX technique.

2.2. Methods

To accomplish the objective of this study including the modeling of the economic evaluation, the following methods were employed.

2.2.1. Performance determination method

To investigate the performance of the system, this system was used to cool loads of 3.75, 7.50, 11.25, 15.00, 18.75, 22.50, 26.25, 30.00, 33.75, and 37.50 L of water, as most vaccines are liquid. We assume that the water behaves thermally as a vaccine. The parameters affecting the performance of the system are monitored and recorded. A pyranometer (Kipp&Zonen, model CMP6) was installed on the plane of the PV module to measure the global solar radiation incident on the PV module. The ambient air temperature, the temperature of the air inside the hut, and the temperature of the water in the refrigerator are measured using K-type thermocouples. The output readings of these instruments were recorded every 1 min in a data logger (Yokogawa, model DC100). Each experiment started at 6 a.m. and continued until the final load temperature was reached. These data were averaged over 10 min and the average value was used in the analysis. For each load, only one experiment was conducted. This is because only the load was changed. The rest of the system is the same for every experiment.

As PV module has a high enfluence on the system's performence, the PV module used in this study is based on the single crystalline silicon solar cell with the efficiency of 20.75%. It is the highest efficiency PV module available in Thai markets.

2.2.2. System modeling

As the cooling processes occurring in the system is quite complicated, a machine learning approach was selected, and the technique called Auto-Regressive with eXogeneous variables (ARX) technique [6] was used to model the system. The experimental results for loads of 3.75, 11.25, 18.75, 26.25, and 37.50 L of water were used to model the system, whereas the experimental results for loads of 7.50, 15.00, 22.50, 30.00, and 33.75 L of water were employed to validate the model.

Herein, the cooling water temperature inside the cooling chamber of the refrigeration unit is the output variable (y(t)), which depends on the previous time series data and exogenous variable. The input is the time series of the solar radiation (u_1), outdoor temperature (u_2), indoor temperature (u_3), and load (u_4), and it can be generally written as:

$$A(z)y(t) = B(z)u(t) + e(t), \tag{1}$$

where A(z) is the coefficient of y(t), B(z) is the coefficient of u(t), e(t) is the model error, and z is the delay operator.

2.2.3. Economic evaluation

Although an energy system performs technically well, it is attractive to use when the economics of the system must also be attractive. Herein, a payback period of the refrigeration system is evaluated based on the economic parameters in Thailand (Tables 1 and 2). The method used is the cash flow technique without considering the time value of money [7].

Table 1 Economic data for economic analysis.

Economic parameter	Size	Quantity	Cost (Baht)*
Refrigerator	140 L	1	4,500
PV module	535 W	1	6,000
Solar charge controller	60 A	1	3,500
Inverter	3,000 W	1	3,590
Battery	12 V (200 Ah)	1	5,800
Other equipment (circuit breakers and wires)			300
Total cost	-	-	23,690

*37 baht = 1 USD

Table 2 Economic analysis conditions.

Conditions	Value
Battery lifetime (Batteries are changed every 5 years)	5 (years)
Annual distilled water cost for battery	78 (baht)
Annual energy saving	714.29 (kWh)
Electricity cost	4.2 (baht/kWh)
Project life	25 (years)

3. Results and discussions

3.1. Results and discussion on system performance

Ten experiments were conducted, and the results are shown in Fig. 3. For all days of the experiments, solar radiation is highly fluctuated due to clouds. During the experiments, the maximum solar radiation occurred at noon time with the value of about 300-1,200 W/m^2, depending on sky conditions. From Fig. 3, it can be seen that the indoor temperature varies directly with the outdoor temperature because the outdoor temperature influences the indoor temperature. Also, it can be seen that the outdoor temperature varies directly with solar radiation because solar radiation has a direct effect on the air temperature. Solar radiation heats the outdoor air. High solar radiation stimulates the solar cell module to produce more electricity, but the high air temperature reduces the efficiency of the solar cell. In this work, solar radiation does not affect directly the power of the refrigeration system as the system was powered by the battery with constant output. The variation of all temperatures of the load is illustrated in Fig. 4.

The graphs in Fig. 4 can be separated into two groups. The first group is for the small loads (3.75 L, 7.50 L, 11.25 L, and 15.00L). The second group is for the big loads (18.75 L, 22.50 L, 26.25 L, 30.00 L, 33.75 L, and 37.50 L). The rapidity of the decrease of load temperature depends on both the mass of the load and the ambient temperature. The load temperature depends on the mass of the load in such a way that the more massive load takes more time to reach the minimum temperature and vice versa. For the ambient temperature, a higher ambient temperature takes more time to reduce the temperature of the load to the minimum temperature due to more heat flow from ambient air to the refrigerator unit and vice versa. The gap between the two groups may cause by solar radiation. For the first group, the system receives only 1 day of solar radiation. For the second group, the system receives 2 days of solar radiation. For the case of the load of 15 L, the load temperature decreases more rapidly than the case of the more massive load because for the load of 15 L, only one day is required to reduce the load temperature to the minimum and the more massive loads takes two days and on the second day the system receives heat from the ambient air, slowing down the decrease of the load temperature.

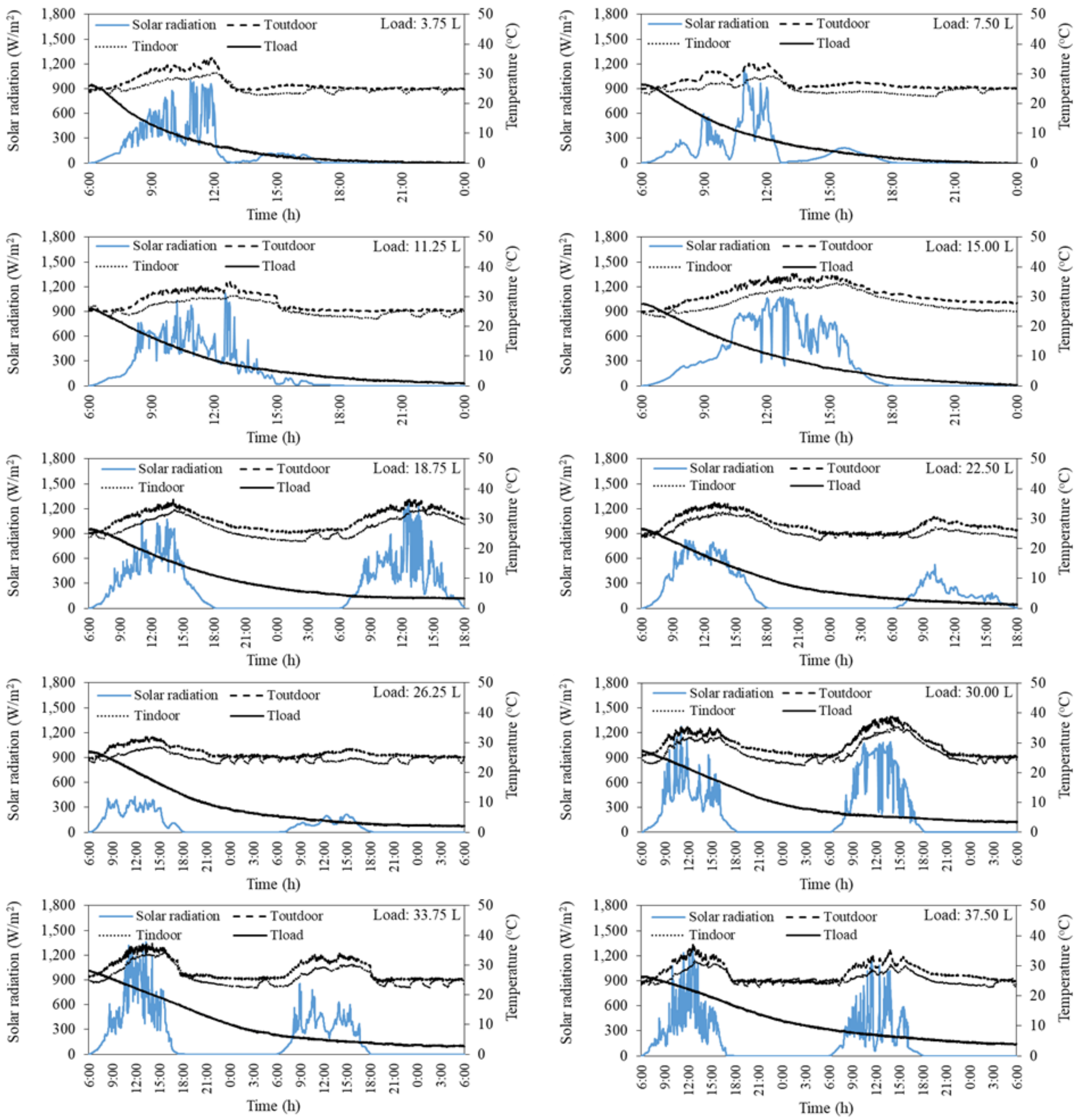

Fig. 3 Results of the experiments showing time variations of solar radiation and outdoor, indoor, and load temperatures.

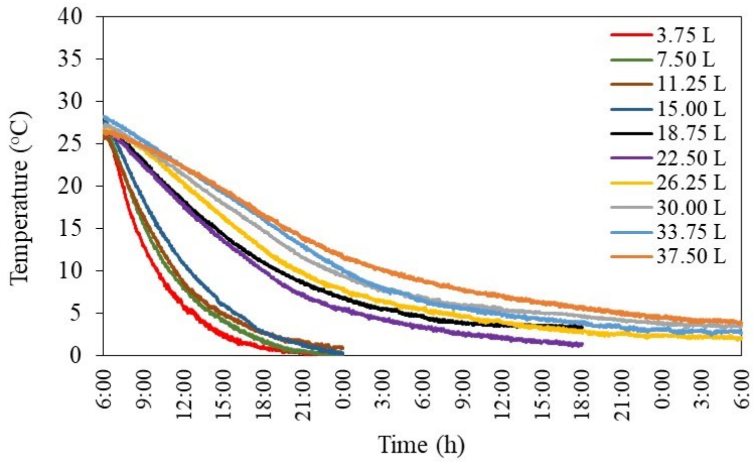

Fig. 4 Time variation of load temperature for all loads subjected to these experiments.

In Fig. 4, it is also noticed that the load temperature for 22.50 L decreased more rapidly than that of 18.75 L. This may be due to the fact that the decrease in the load temperature does not depend only on the mass of the load but also on the ambient temperature. From the experimental result in Fig. 3, it is clearly seen that the outdoor temperature for the experiment with the load of 22.50 L is lower than that of the experiment for the load of 18.75 L, especially on the second day of the experiment. In this case, the influence of the ambient temperature is more than that of the mass of the load. Therefore, the load temperature for the experiment of 22.50 L decreases more rapidly than that of 18.75 L.

From the experiment for the small loads (3.75 L, 7.50 L, 11.25 L, and 15.00 L), the decrease of the load temperature to the final temperature of 0°C or 3°C are within 18 h and for the big loads (18.75 L, 22.50 L, 26.25 L, 30.00 L, 33.75 L, and 37.50 L), the load temperature are reduced to the minimum of 2-5°C within 2 days.

3.2. Modeling results and discussion

After modeling, the following equations were obtained:

$$A(z) = 1 - 1.906z^{-1} + 0.3077z^{-2} + 0.7986z^{-3} + 0.1051z^{-4} - 0.3057z^{-5}, \tag{2}$$

$$\left.\begin{aligned} B1(z) = {} & 0.00001423z^{-1} + 0.0000117z^{-2} - 0.0001808z^{-3} - 0.0001141z^{-4} + \\ & 0.0005972z^{-5} - 0.00004012z^{-6} - 0.0004617z^{-7} + 0.0001733z^{-8} \end{aligned}\right\},$$

(3)

$$\left.\begin{aligned} B2(z) = {} & 0.03332z^{-3} + 0.008169z^{-4} - 0.1824z^{-5} + 0.1241z^{-6} + 0.09797z^{-7} - \\ & 0.06137z^{-8} - 0.03788z^{-9} + 0.01805z^{-10} \end{aligned}\right\}, \tag{4}$$

$$\left.\begin{aligned} B3(z) = {} & 0.09484z^{-4} - 0.2698z^{-5} + 0.2356z^{-6} - 0.04577z^{-7} - 0.03444z^{-8} + \\ & 0.04078z^{-9} - 0.02278z^{-10} + 0.001708z^{-11} \end{aligned}\right\}, \tag{5}$$

$$B4(z) = -0.00001169z^{-1}, \tag{6}$$

where B1(z) is the solar radiation coefficient, B2(z) is the outdoor temperature coefficient, B3(z) is the indoor temperature coefficient, and B4(z) is the load coefficient.

The percentage of the root mean square difference (RMSD) relative to the mean measured value, the percentage of the mean bias difference relative to the mean measured value (MBD), and the coefficient of determination (R^2) were used to indicate the performance of the model. The results are presented in Table 3.

Table 3 Variation results (RMSD is the root mean square difference, MBD is the mean bias difference, and R^2 is the coefficient of determination).

Load (L)	RMSD (%)	MBD (%)	R^2
7.50	7.13	−0.02	0.9957
15.00	7.08	1.55	0.9944
22.50	5.79	0.08	0.9956
30.00	7.01	−0.09	0.9902
33.75	8.50	−0.07	0.9879
Combined data	7.41	0.12	0.9918

From Table 3, the RMSD and MBD for various loads range from 5.79%–8.50% and −0.09%–1.55%, respectively, whereas the lowest R^2 value is 0.9879. Additionally, the RMSD, MBD, and R^2 for the combined data are 7.41%, 0.12%, and 0.9918, respectively. The RMSD and MBD are relatively low and have acceptable errors [8]. Therefore, the model performs well in predicting the load temperature.

3.3. Economic analysis results and discussion

According to Tables 1 and 2, the cash flow for evaluating the payback period of the system is shown in Fig. 5. The payback period is 11.34 years, and it is shorter than the life span of the system. This implies that the system is attractive for investment.

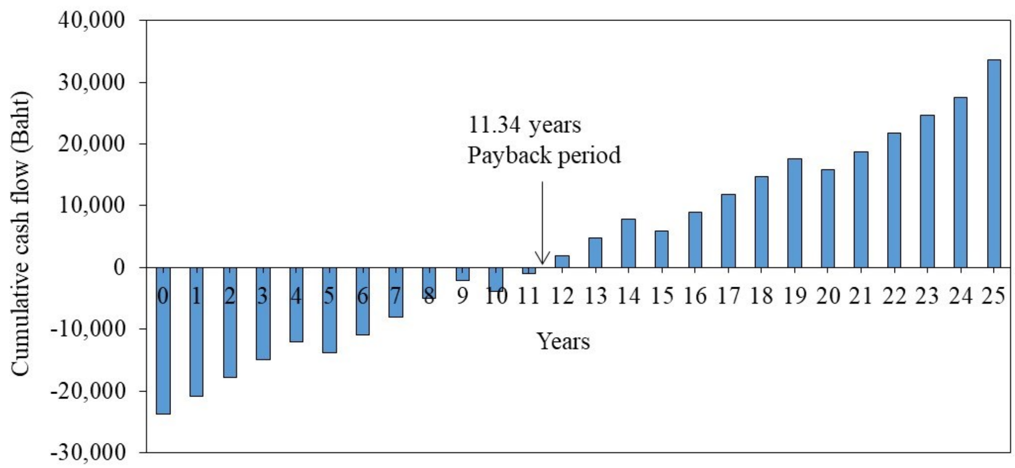

Fig. 5 Illustration of cash flow and payback period of the system.

4. Conclusion

A solar-powered vapor compression refrigeration system was proposed. The system was tested, and the results revealed its excellent performance. Technically, the system can store many types of vaccines, requiring a system temperature of 0°C–8°C [9]. For the modeling, the ARX approach gave satisfactory accuracy in predicting the load temperature. Economically, the system has a payback period of 11.34 years, which is shorter than the lifespan of the system. Therefore, the system is attractive for investment.

Acknowledgments

Mr. Sattra Sirikaew, the first author of this paper, has received a scholarship entitled Science Achievement Scholarship of Thailand (SAST) from the Ministry of Higher Education, Science, Research, and Innovation. We would like to thank the Ministry for this scholarship.

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