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Modification of a 220-V vapor compression refrigeration system to a 12-V photovoltaic solar-powered refrigeration system for cooling beverages: Modification process, performance, modeling, and economic evaluation

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ABSTRACT

This paper presented the modification of a conventional 220-V vapor compression refrigeration system to a 12-V photovoltaic (PV) solar-powered refrigeration system for cooling beverages in Thailand. The modified system mainly comprised a vapor compression refrigeration unit with the same cooling volume as that of the conventional system. The modification included the change of a 220-V AC compressor to a 12-V DC compressor, the change of 220-V AC fans to 12-V DC fans, and the addition of two 535-W PV modules, four batteries, and a charge controller to the system. Twenty experiments were conducted to evaluate the performance of the conventional and the modified systems. The comparison of load temperature of both systems revealed that the conventional system reached the set temperature more rapidly than the modified system. The load temperature of the modified system can be reduced from about 30°C to 10-12 °C within 12 h for most cases. Experimental data were also used to model the modified system. The model predicted well the load temperature with the discrepancy, in terms of root mean square difference of 3.1%. The modified system has the payback period of 11.21 years.

Keywords: modified refrigeration system; vapor compression refrigeration system; ARX modeling

1. INTRODUCTION

Cold beverages are popular in Thailand because the ambient temperature of this country is 20-38°C year-round (Climatological Center, 2010). A Thai vendor usually utilizes a locally made cooling chamber to produce a cold beverage. Internationally, the common temperature used in cooling chamber for cold beverage is +8°C to +14°C (James et al., 2017) and in Thailand the upper limit may be a bit greater than 14°C (may be 15°C) due to high ambient temperature. This chamber employs a conventional cooling system using 220-V AC from an electricity grid to run the compressor and fans of the system. This system consumes a considerable amount of electricity (Energy Policy and Planning Office, 2022), thus inducing electricity supply problems.

Thailand is located in a tropical zone with abundant solar radiation (Janjai et al., 2005). The use of photovoltaic (PV) modules to supply electricity to the system is an interesting solution to the problem of high electricity consumption for the cooling system. Solar cooling systems can be broadly divided into two types. The first type is an absorption system and the second type is a vapor compression system (Karellas et al., 2019). The first type is appropriated for a big application and the second type is good for a small application or domestic utilization. The current study focused on the second type because refrigerators are domestically used for cooling beverages, which is popular in all regions of Thailand.

Due to the problem of access to electricity grid in developing countries, PV modules were used to supply electricity to the vapor compression refrigeration system. PV module available in markets could be broadly divided into 3 types namely, single crystalline silicon solar cell modules, polycrystalline silicon solar cell modules and amorphous silicon solar cell modules. All three types of these solar cell modules were used in the refrigeration systems. The choice of the type depends on the budget available and efficiency required for the system. The pioneering work in using PV module to supply electricity to a cooling system dated back to the year 1980s (McCarney et al., 2013). Since then, a number of works on the vapor compression refrigeration system have been conducted in several countries.

Mehmet (2011) proposed a solar refrigerator, which could reduce the load temperature to -10.6°C, and concluded that the refrigerator can be used in a place without a local grid. Ekren et al. (2011) introduced a solar refrigerator powered by a solar PV panel without any inverter. They found that a small household refrigerator with DC compressor can be operated by using PV power without any inverter, which helps to reduce the initial cost. Sharma et al. (2016) conducted a comparative investigation of the performance of solar PV-operated vapor compression refrigeration systems with that of absorption refrigeration systems and found that the vapor refrigerator consumes less power than that of the absorption system. Hammad and Tarawneh (2018) developed a 60-W solar DC refrigerator and PV panels to power the refrigerator. They reported that the refrigerator powered by the PV panels works as designed. Salilih et al. (2020) studied the effect of operating parameters on the performance of directly coupled variable speed solar refrigeration system and found that the refrigerant mass flow rate and cooling capacity have significant sensitivity to variation in saturation temperature of condenser. Sabry and Ker (2021) developed strategies in decreasing the energy consumptions of a refrigerator with in PV system including battery storage. The saving can be obtained from the use of new inverter technology and smoother power pattern. Amratwar and Hambire (2021) reviewed the research work on the development and application of solar PV-powered refrigeration systems.

As the modeling approach is a powerful tool for developing solar technology, a lot of works on modeling of the vapor compression refrigeration system have been carried out (Salilih and Birhane, 2019).

Mba et al. (2012) developed a computer model for a PV power refrigeration system. The model is written in MATLAB software and can be used to simulate the performance of this system, which may be installed in different environments. Gupta et al. (2014) established a conventional model of a PV-operated domestic refrigeration system, and this model has been employed to optimize the system components. Su et al. (2020) developed a dynamic model for simulating the variable speed PV refrigeration system. They found that the model can be used to simulate the performance of the system and based on the simulation of this system, the cooling capacity of the variable speed PV refrigeration system increases by 45.69%, as compared to that of the fixed speed refrigeration. A considerable amount of work has been conducted in this direction (Amratwar and Hambire, 2020). Recently, Ikram et al. (2021) presented the conceptual study of a solar PV refrigeration system for a cold storage facility based on the conventional vapor compression system for banana fruit in Pakistan and they found that several components of the existing system were oversized and they optimized them by using the PV*SOL software. In addition, Gardenghi et al. (2021) presented transient mathematical model for simulating a vapor compression refrigeration system. They found a good agreement between the simulation results and the experimental data and they also analyzed the influence of refrigerant charge and ambient temperature.

The performance of a PV refrigeration system generally depends on the surrounding environment. To the best of the authors' knowledge, research works on the modification of a big refrigeration system in Thailand are unavailable. Therefore, this study aimed to modify the 220-V AC refrigeration system to a 12-V DC PV-powered refrigeration system, to investigate the performance of the modified refrigeration system, and to perform a modeling and economic evaluation of this system.

2. MATERIALS AND METHODS

2.1 Materials

The main material used in this study was a conventional vapor compression refrigeration system, which was purchased from a local electrical equipment shop in Nakhon Pathom, Thailand. The system has the cooling volume of 789 L and it requires electricity power of 550 W from 220 V electricity grid. The system was placed in a hut located in an experimental field of the Department of Physics, Faculty of Science, Silpakorn University (13.82°N, 100.04°E), Nakhon Pathom, Thailand (Figure 1).

This system is the most widely used in refrigeration applications in Thailand, especially for cooling beverages. Moreover, the system is commonly referred to as vapor compression refrigeration due to the mechanical compression used in such systems.

2.2. Modification process

The modification process included the following: changing a motor to run the compressor from a 220-V AC motor to a 12-V DC motor, and installing two PV modules (535 W each, single crystalline silicon type), four batteries (200 Ah each) and a charge controller. In the conventional system, an AC fan was used to spread cool air from the evaporator to the load in the cooling chamber and to distribute the heat from the condenser to the environment. Therefore, the AC fans were changed to DC fans.

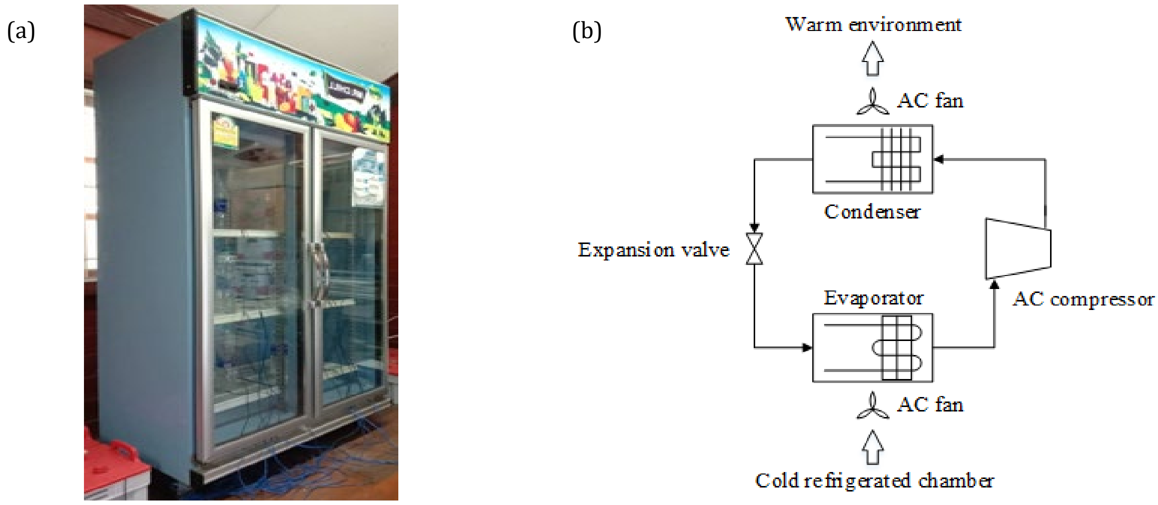

Figure 1. (a) Pictorial view of a conventional vapor compression refrigeration system used for cooling beverages in Thailand and (b) diagram of the system

2.3 Performance evaluation

The modified system was constructed and installed in the same hut as that used to place the conventional system and the PV modules were installed on the roof of the hut (Figure 2). The evaluation of the system performance was completed in 10 experiments. Water contained in plastic bottles was used for cooling loads. The experiments for the loads of 18, 36, 54, 72, 90, 108, 126, 144, 162, and 180 L were conducted. The parameters affecting the thermal performance of the system, including solar radiation, outdoor temperature, indoor temperature, and load, were measured. The solar radiation incident on the PV modules was also measured by a pyranometer (Kipp&Zonen, model CMP6). All temperatures were measured by thermocouples (type K). The output signals from these sensors were recorded using a multichannel data logger (Yokogawa, model DC100) every 1 min. For each measurement, data logger measured it for the time duration of 1 s. The output signals were averaged over 10 min and the average value were used in the analysis.

As before the modification, the system was experimented to cool the load of 18, 36, 54, 72, 90, 108, 126, 144, 162, and 180 L, the results of the experiments were compared to those of the modified system.

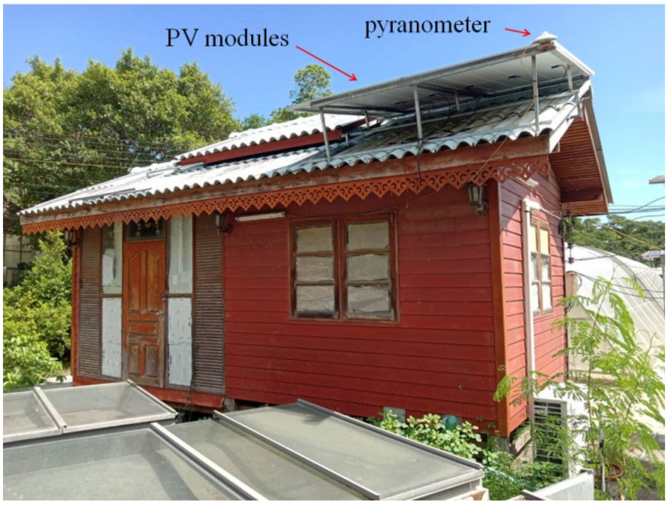

Figure 2. The hut for placing the modified refrigeration system

2.4 Modeling

Modeling is a powerful tool for the development of a solar system (Duffie and Beckman, 2013). Therefore, a system model can be used to investigate the influence of system parameters on its performance without performing experiments. The technique called “auto-regressive with exogenous variable (ARX)” is selected in the current study due to its simplicity and its capability to provide reasonable accuracy (Ljung, 1999).

According to the ARX technique, let y(t) be the output of the system at time t, u(t) be the input of the system at time t, and A(z) and B(z) be the coefficients of the output and input, respectively. Thus, the relationship between the output and input is written as follows:

$$A(z)y(t) = B(z)u(t) + e(t), \qquad (1)$$

where z is a delay operator and e(t) is a model error.

The expression for A(z) and B(z) can be obtained from MATLAB software by using the measurement data from the experiments with loads of 18, 54, 90, 126, and 180 L.

After the orders of the model were determined and the structure of the ARX model was defined, the errors between the measured values ($y_m(t)$) and the simulated data ($y_s(t)$) were calculated to obtain e(t) using the Levenberg–Marquardt algorithm (Blaifi et al., 2019).

2.5 Economic evaluation

The modified system uses electricity from the PV modules, however, several parts of the system must be changed, which may be costly. A payback period of the modified system was calculated to justify the change economically. The payback period was calculated in this study by using the conventional payback method due to its simplicity and popularity (Nabnean et al., 2016). The data used in the calculation are shown in Tables 1 and 2.

3. RESULTS AND DISCUSSION

3.1 Modified system and its performance

The conventional cooling system was modified. The modified system comprising the refrigeration unit, PV modules, batteries, and a charge controller was obtained after the modification. The diagram of the solar-powered vapor compression refrigeration system is shown in Figure 3. This system operated as follows. Electricity from the PV modules was charged in the batteries. The charge of electricity was controlled by the charge controller. This electricity would then be used directly to supply the refrigerator unit. The batteries could run the refrigerator for two days without solar radiation.

Ten experiments with the modified system were conducted and the results are shown in Figure 4.

Figure 4 shows that the temperature of the load could be reduced from about 30°C to 10-12°C within 12 h for most cases. From Figure 4, it is observed that indoor temperature varied with outdoor temperature because the indoor temperature was mainly influenced by the outdoor temperature and the outdoor temperature varied directly with solar radiation because solar radiation had direct influence on the air temperature. Solar radiation plays an importance role on the performance of the system, both a positive way and a negative way. For the positive way, more solar radiation, make the solar cell modules produce more electrical energy. For the negative way, more solar radiation make high ambient temperature, which reduce the efficiency of the modules. In our case, the positive way is more than the negative way because most of the days during the experiment (Figure. 4), the solar radiation were quite high, with the peak at noon time about 900 - 1100 W/m^2 and the temperature of the ambient air varied between 35-40°C, which is lower than the nominal operating cell temperature (NOCT). The NOCT of our solar cell is 45±2°C. As temperature of the cooling system could be reduced to 10-12°C, which is in the range of common temperature of the cool chamber of a cooling system. Therefore, the modified system could be used to cool beverages in Thailand.

Comparison of the performance of the conventional system and that of the modified system are shown in Figure 5. From Figure 5, it is observed that the load temperature of the conventional system reached the set temperature (15°C) more rapidly than the modified system. This may be due to the fact that the modified system used too low capacity of the DC motor. However, the conventional system used electricity from the electricity grid while the modified system used electricity from the solar cell modules, which produced electricity from renewable energy source (solar radiation).

Table 1. Economic data used for economic analysis

Economic parameter	Size	Quantity	Total cost (baht)*
AC refrigerator	630 mm × 1,100 mm × 2,000 mm	1	22,000
DC compressor	650 BTU	1	7,000
PV module	535 W	2	12,000
Charge controller	60 A	1	3,500
Battery	12V (200 Ah)	4	23,200
Other equipment (wires, circuit breakers)			2,200
Grand total cost			69,900

* 37 baht = 1 USD

Table 2. Economic analysis condition

Condition	Value
Battery lifetime (The batteries were changed every five years)	5 (years)
Annual distilled water cost for battery	320 (baht)
Annual energy saving	2255.7 (kWh)
Electricity cost	4.2 (baht/kWh)
Project life	25 (years)

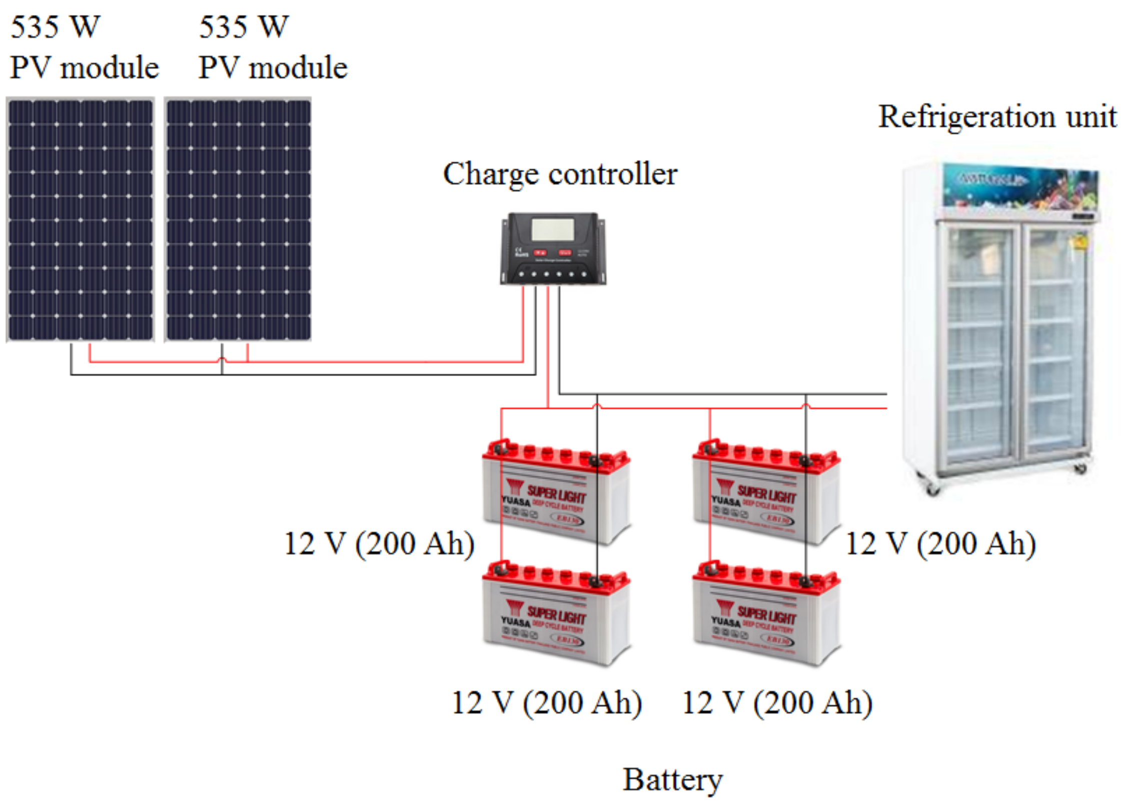

Figure 3. Schematic of the modified refrigeration system

3.2 Modeling of the modified system

The ARX model was simulated to predict the water temperature inside the cooling chamber. The input data of the ARX model were a time series of solar radiation, ambient or outdoor temperature, indoor temperature, and volume of the water (loads), and the simulated temperature of the water inside the cooling chamber was the output. The following equations were obtained on the basis of experiments with the loads of 18, 54, 90, 126, and 180 L.

$$\mathrm{A(z)} = 1 - 1.178z^{-1} - 0.5989zz^{-2} + 0.7767z^{-3}, \tag{2}$$

$$\mathrm{B1(z)} = 0.00001943 - 0.00006777z^{-1} + 0.0000524z^{-2}, \tag{3}$$

$$\mathrm{B2(z)} = 0.06171z^{-3} - 0.135z^{-4} + 0.07348z^{-5}, \tag{4}$$

$$\mathrm{B3(z)} = 0.07626z^{-3} - 0.113z^{-4} + 0.01322z^{-5} + 0.02873z^{-6} - 0.005412z^{-7}, \tag{5}$$

$$\mathrm{B4(z)} = 0.000007916z^{-1}, \tag{6}$$

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

The simulated water temperature inside the vapor compression solar refrigeration system was compared with the experimental data to validate the ARX model for the cooling effect simulation of the vapor compression solar refrigeration system. Figure 6 shows a typical comparison between the ARX simulated cooling temperatures and the experimental data using loads of 36, 72, 108, 144, and 162 L. The root mean square difference (RMSD), mean bias difference (MBD), and coefficient of determination (R^2) were evaluated (Trivedi and Bobbio, 2017). The RMSD was 3.10%, the MBD was -0.17%, and the R^2 was 0.99, based on the combined data of the experiments for the validation of the model. Thus, these evaluated results demonstrated that the ARX model performed well in predicting the load temperature. The RMSD of 3.10% was within the acceptable limits (O'Callaghan, 1971).

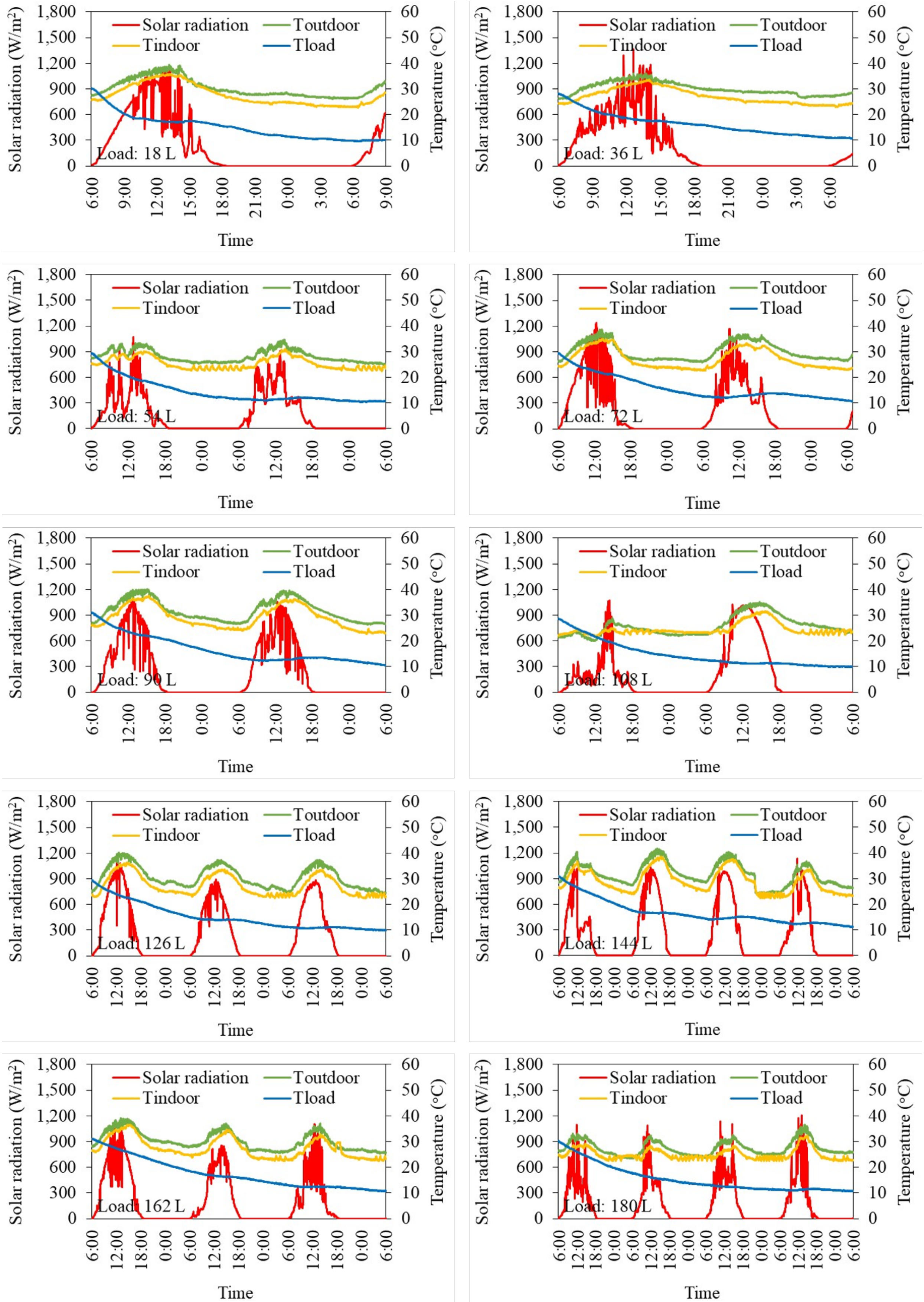

Figure 4. Time variation of solar radiation, outdoor temperature ($T_{outdoor}$), indoor temperature (T_{indoor}), and load temperature (T_{load}) of the modified system

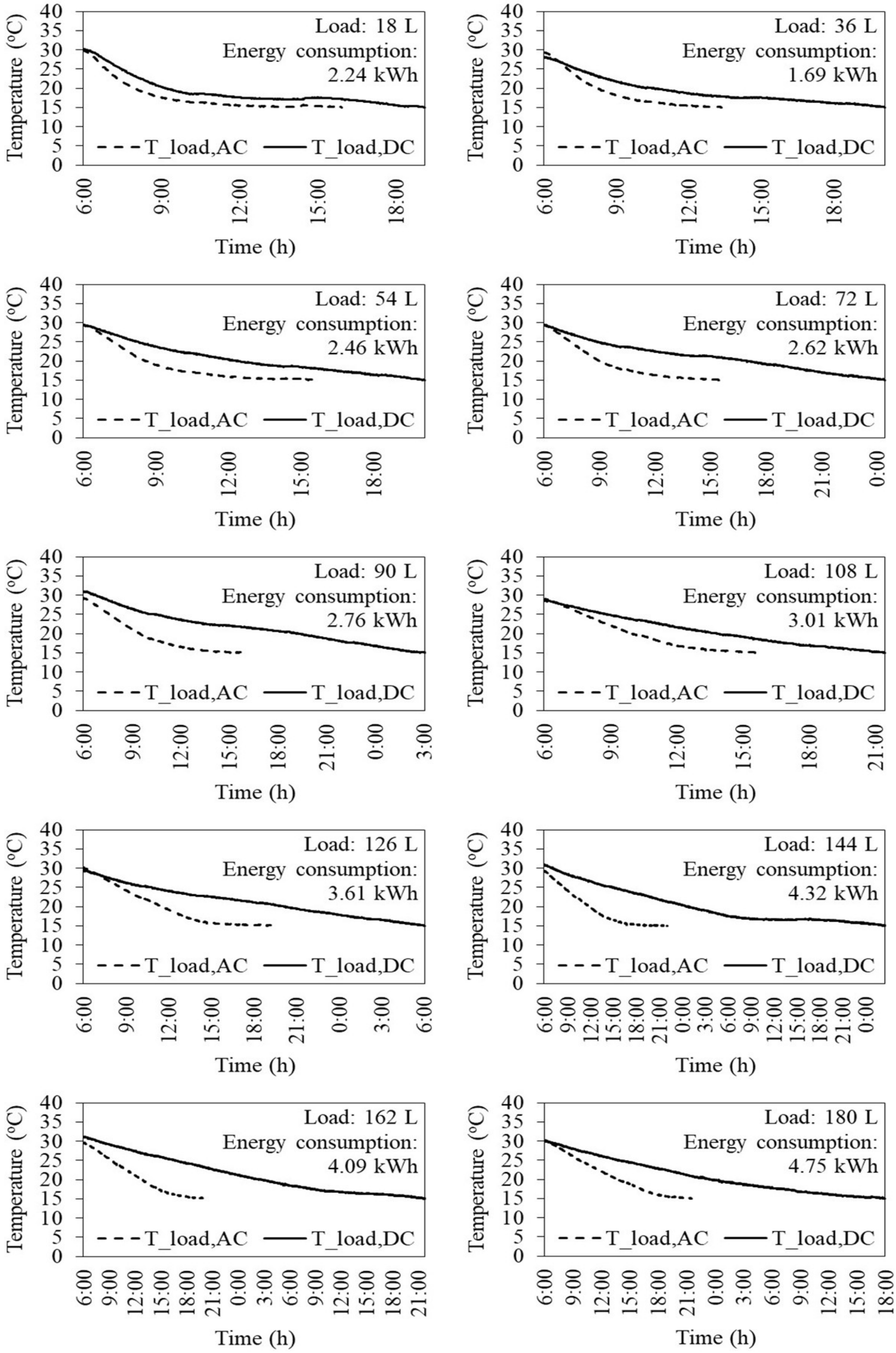

Figure 5. Comparison of the load temperature of the conventional system ($T_{\_load,AC}$) and that of the modified system ($T_{\_load,DC}$)

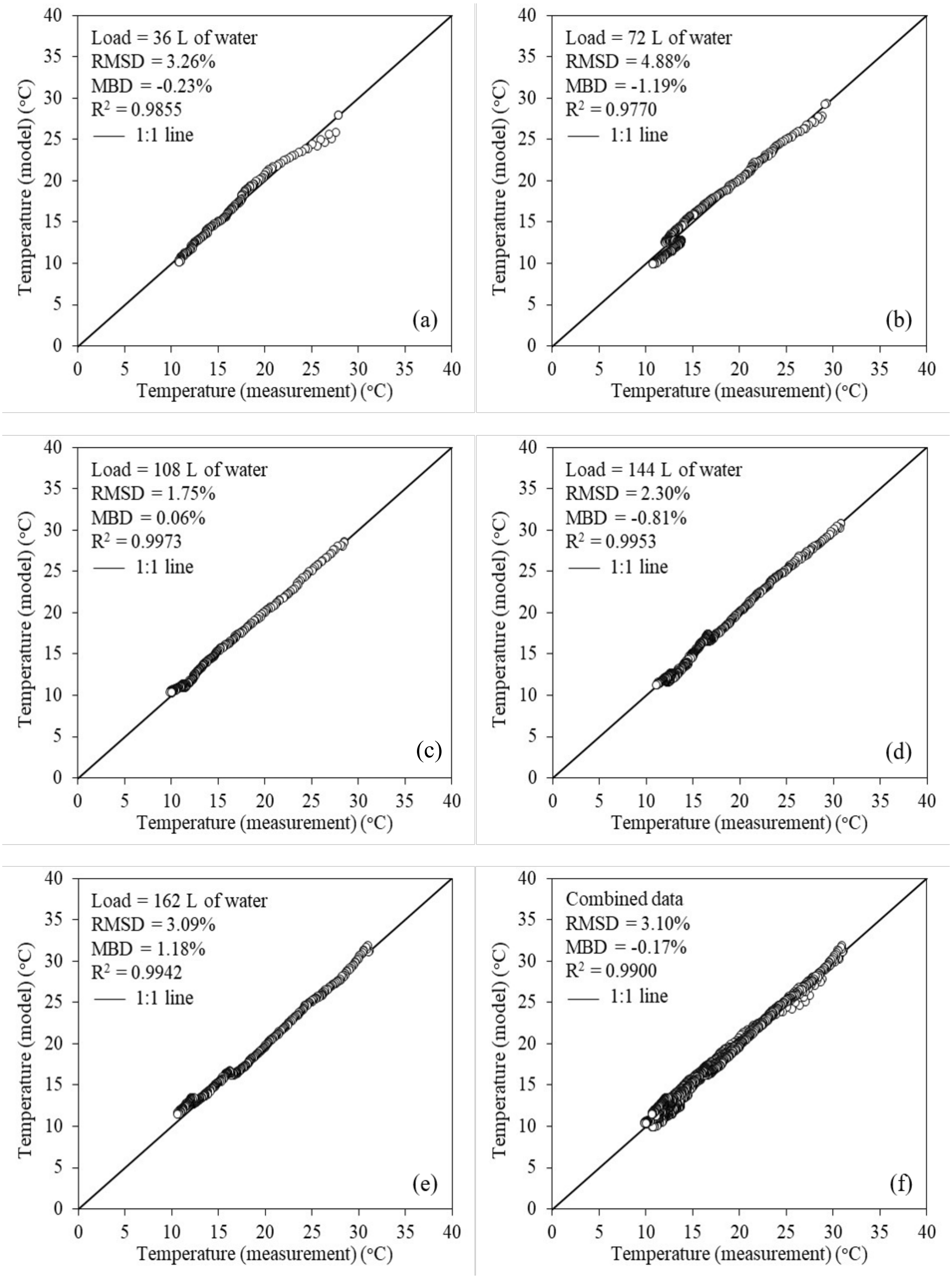

Figure 6. Comparison of temperatures from the ARX model with the measured values for (a) 36 L, (b) 72 L, (c) 108 L, (d) 144 L, (e) 162 L of water, and (f) the combined data

3.2 Economic evaluation

The cumulative cash flows over the project life are shown in Figure 7, based on the economic parameters in Thailand as presented in Table 1. This figure revealed that the payback period was 11.21 years. Although the payback period of the modified system was quite long, the modified system had advantages that it helped to reduce greenhouse gases and it also reduced the dependence on fossil energy source of the country.

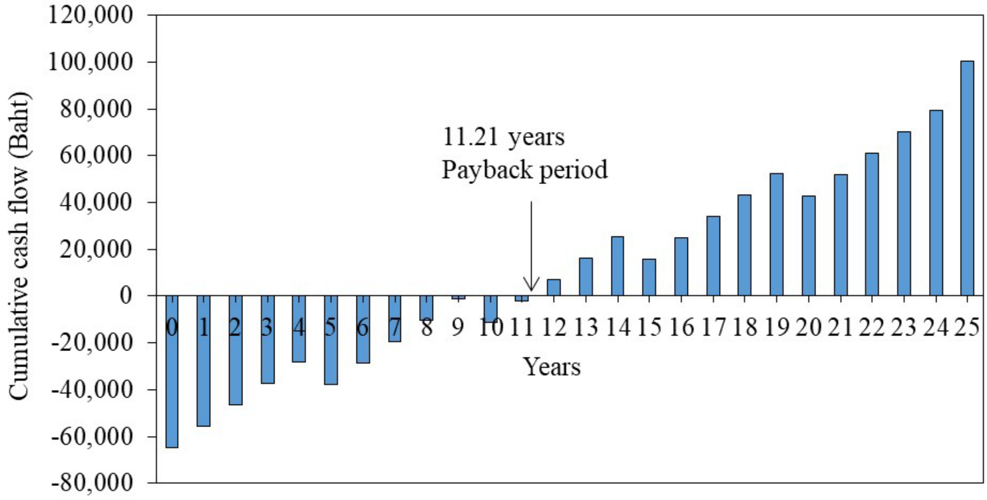

Figure 7. Illustration of the cash flow and the payback period of the modified system

4. CONCLUSION

A 220-V vapor compression refrigeration system for cooling beverages in Thailand was modified to a 12-V PV solar-powered refrigeration system. The 10 experiments with different loads revealed that the modified system can reduce the load temperature to the final temperature of 10-12°C within 12 h for most cases depending on the load. The modified system performed well. This system was modeled using the ARX approach. The results showed that the model effectively predicted the load temperatures. Finally, the modified system has a payback period of 11.21 years. Although, the payback period of the modified system is quite long, this system offers some advantages in terms of the reduction of the release of greenhouse gases and the dependence of the system on the conventional energy source.

Due to the fact that the load temperature of the modified system are reached less rapidly than that of the conventional system and the load temperature could be reduced to 10-12°C, which may be caused by too low capacity of the DC motor, this work should be carried out in the future.

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