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Dekui Yin

Review of Systems Integrating Solar PV and Phase Change Thermal Storage

Dekui Yin, Martin Belusko, David Whaley and Frank Bruno

University of South Australia, Mawson Lakes Boulevard, Mawson Lakes SA 5095, Australia
E-mail: Frank.Bruno@UniSA.Edu.Au

Abstract

Over recent years the cost of solar photovoltaic (PV) power systems has reduced significantly. However, one of the drawbacks of this technology is that electric power is not always generated when required. Whilst electricity storage with batteries can be used to overcome this shortcoming, they are not economical in many cases. Being up to ten times cheaper than battery storage, energy-dense phase change material energy storage offers an economic solution when the final use of electricity is for heating and cooling.

This paper reviews systems that integrate solar PV and phase change thermal energy storage, combined with and without batteries. Systems that are both commercially available and have been researched are reviewed.

1. Introduction

Solar photovoltaic (PV) power system applications are increasing due to both technical and economic factors. However, one of the drawbacks of this technology is that electric power is not always generated when required, due to lack of solar resources at night time and during cloudy periods. Systems have been developed that integrate solar PV with refrigeration which use batteries to solve this problem, however this energy storage technology is not economical in most cases. In recent years, the application of phase change materials (PCMs) for thermal energy storage has been widely studied due to its high storage density and low cost. Being less expensive than battery storage, applying PCM storage could represent a more economical solution for solar PV driven refrigeration. This concept involves converting solar energy into electrical energy, which is then used to drive a compressor of a refrigeration system to freeze a PCM, which is then used to provide cooling to meet the thermal load. A PV system combined with a conventional refrigeration system has the advantage of being relatively straight forward to integrate and offers a high overall efficiency (Kim and Ferreira, 2008). Examples of applications of PV refrigeration systems include the pharmaceutic, medical and food industries, and for cooling crops and transporting vaccines. They can also be used in remote areas to replace off-grid diesel powered generators for cold storage applications.

This paper briefly describes the principle of a PV refrigeration system integrated with PCM for energy storage, operating with or without batteries. Previous work and research in this field is summarised.

2. System Description

Figure 1 presents the basic configuration of a solar PV refrigeration system combined with phase change thermal storage.

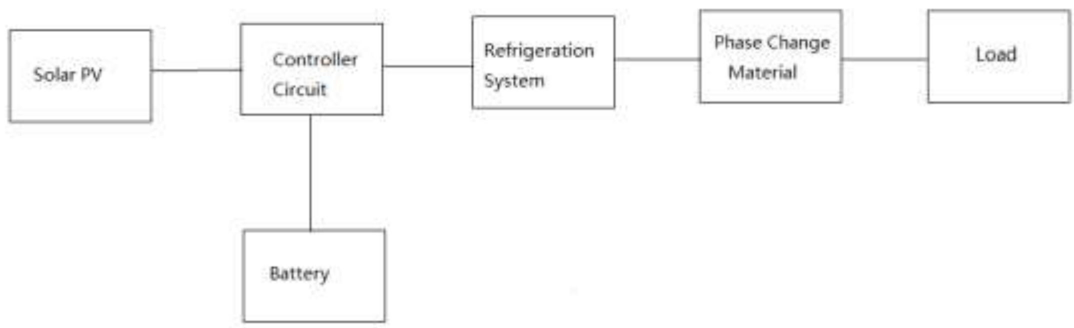

Figure 1: Basic configuration of a solar PV refrigeration with PCM as thermal storage

Solar PV refrigeration systems coupled with phase change thermal storage can be divided into six parts:

1. Solar PV panels: convert solar energy to electrical energy for battery or refrigeration system.

2. Controller circuit: maximum power point tracker for PV panels, manages energy flow between the refrigeration system, battery and solar PV, control for compressor motor start.

3. Battery: If the thermal store is full, additional electrical energy can be stored from the PV in the daytime and the energy stored can be discharged at night or during cloudy weather.

4. Refrigeration system: AC or DC compressor, condenser and evaporator. An inverter is needed if the compressor operates from an AC supply.

5. Phase change material: store the thermal energy needed to provide cooling.

6. Load: cooling demand.

A solar PV refrigeration system converts solar energy to electrical energy for both charging the battery and running the compressor during the day. In contrast, at night or during cloudy periods, the battery discharges the surplus energy stored during the daytime to the refrigeration system to facilitate continuous operation. The refrigeration system compressor transfers the electrical energy to mechanical energy which is then used to cool the PCM. Cooling can be taken from the PCM store as required. Optimal control of the system will depend on maximizing the available solar PV electricity.

Since the cost of batteries in the PV system represents almost 20-40% of the total cost (Shehata, 2014), several researchers have focused on PV systems without a battery when the system does not need continuous power. This system is known as a PV direct-driven, battery-free solar refrigeration system. It uses thermal storage and a direct connection between the vapor compressor and PV panels. Solar PV refrigeration systems integrated with thermal storage, with and without batteries, is discussed in this literature review.

3. Literature Review

3.1 Solar PV refrigeration system with battery

As mentioned previously, a solar PV refrigeration system can use a battery to store the surplus energy generated during the day and discharge this stored energy during the night or cloudy times to maintain continuous cooling throughout the year. Both AC or DC compressors can be used to fulfill the cooling task. When using an AC compressor for the refrigeration system, a DC to AC inverter is needed to invert the DC output power from the solar panels to AC input power for the compressor.

In 2014, Shehata presented an off-grid PV driven cooling system using PCM as thermal storage (Shehata, 2014). The system provides cooling for post-harvest crops in Egypt. The system consist of a 290 W_P PV array, a valve-regulated lead acid (VRLA) battery with maximum depth of discharge of 80% and 600 discharge and recharge cycles, a variable speed DC compressor refrigeration system, a 310 kg ice thermal storage unit and a solar controller to track maximum power from solar panels and to manage the surplus energy into the battery. The electrical energy generated from solar panels is directed by a controller which operates the compressor with high priority. The average annual coefficient of performance (COP) of the chiller was expected to be 3.5. The 310 kg of ice has a maximum storage cooling capacity of 32.36 kWh. The system is unable to operate for only 26 hours per year, and has provided an annual cooling load of 9998 kWh. Assuming an inflation rate of 2.5%, interest rate of 10% and system lifetime of 20 years, the cost of this system is cheaper than the cost of the conventional diesel-driven systems.

Also, in 2015, El-Bahloul et al. carried out an experimental investigation on the performance and sizing of a solar-driven DC motor refrigeration system which was used to deliver crops at high quality in hot arid remote areas in Egypt (El-Bahloul et al., 2015). The system consists of three main components: a 130 W_P multi-crystalline PV module, a battery as a buffer to provide regular 12V DC and a 50 litre portable refrigerator with/without PCM thermal energy storage. In order to evaluate the solar refrigerator sizing and performance, a theoretical model was built. The PCM used in the system was Rubbermaid reusable Blue Ice and it was installed around the evaporator inner surface. The performance and results were discussed in two situations: without PCM at full load or no load indoor condition, and with PCM at full load or no load indoor or outdoor condition. The refrigerator temperature was set at 5° C at no load tests and -10° C at full load tests. Results indicated that the COP is higher when the refrigerator operates without PCM. However, when solar energy is not available, the system operating without PCM begins to lose its thermal energy faster than that of the system operated with PCM. Compared with the performance between the refrigerator at indoor or outdoor conditions, when the system operates with PCM at full load, the COP of the refrigerator at the outdoor condition is lower than the refrigerator at the indoor condition. From the outdoor PCM full load tests, a COP of 1.22 was achieved and the storage temperature reached 5° C on the third day and 0° C on the sixth day. The results indicated that the built-up system can fulfill the cooling demand for refrigeration or post-harvest crops transportation activities in remote hot arid areas.

3.2 Solar PV refrigeration system without battery

In 2000, Cherif and Dhouib discussed the performances, simulation responses and the dynamic behaviour of a battery-free solar PV refrigeration system using latent storage (Cherif and Dhouib, 2000). The schematic diagram of the battery-free storage system is shown in Figure 2.

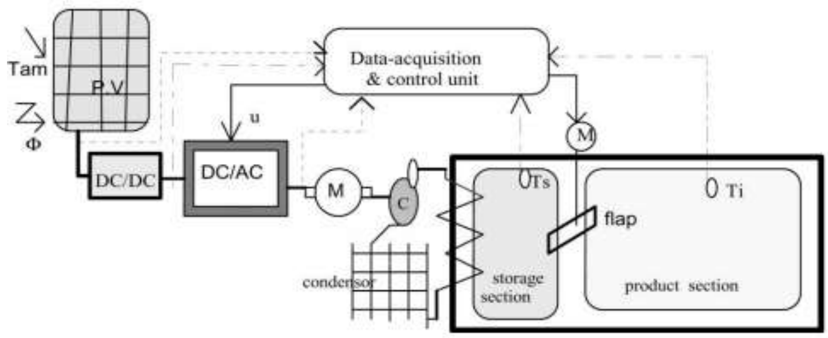

Figure 2 Schematic diagram of battery-free PV refrigeration system (Cherif and Dhouib, 2000)

The system consists of an electronic unit which includes PV panels, DC/DC and DC/AC converters, a thermal section which contains a refrigerator and cooling sections and a control/data acquisition chain to control and manage the PV system. Two sections are separated by a controlled flap in the refrigerator. One section contains the latent storage (50kg ice) and the other is used for product conservation (150 kg vaccines). The compressor of the system works continuously during the daytime with sufficient solar radiation to load the storage section and to keep the product at the desired temperature. The latent storage will perform as the cold source during the night or cloudy days. The simulation results for the PV system performance and its dynamic behaviour is obtained by using a physical model. The results indicate that the system achieves an adequate efficiency and reliability for good climatic conditions. However, the system efficiency and performance decreases with solar radiation disturbances since the system operates without an energy storage or buffer device (battery) and has no backup power.

Ewert et al. discussed field test results of a PV direct-drive, battery-free solar refrigerator in 2002 (Ewert et al., 2002). The researchers built several units which had been sent to different locations, including New Mexico, Alabama and Houston, for field testing. These units have a 105 litre capacity and use 80 to 180 W_p solar panels with ice thermal storage. Peak power-point tracking and elimination of batteries are accomplished by integrating a PCM into a well-insulated refrigerator cabinet and by developing a microprocessor-based control system that allows direct connection of a PV panel to a variable-speed DC compressor. It also mentioned that a fixed-speed compressor can only use about 50% of solar resource while a variable-speed compressor uses 75% of the available solar resource on good weather conditions, because of the limitation of working hours for a fixed-speed compressor. In order to supply the power surge needed when starting the compressor, *starting* capacitors are required for the system. The field tests results showed that all the units performed well. The system lost temperature control in cloudy periods, which could be overcome by adding additional solar panels or phase change material. The battery-free system is more competitive in sunnier climates, because the thermal storage capacity is easier to increase with high level solar irradiance.

Another similar case was developed by Pedersen et al. (2004). The system was designed to fulfill the World Health Organization (WHO) requirements for vaccine coolers. The vaccine should be kept at 0 to 8°C for four days without auxiliary power. Therefore, the ice storage capacity and size can be calculated. Since the compressor is running whenever the solar PV can deliver sufficient power, an electric heater was used to control the temperature and to prevent freezing which would compromise the vaccines. The system was powered by 3×60 W_p solar panels and was running by a Danfoss BD35F DC variable speed compressor. The field tests results indicated the system can fulfill the WHO requirements and the system was ready for the market.

Axaopoulos and Theodoridis designed and experimentally tested a PV ice maker system without a storage battery in 2009 (Axaopoulos and Theodoridis, 2009). The system included a 440 W_p PV array and a 175 L ice storage tank. Unlike the previous systems, the newly developed system has four DC variable-speed compressors (Danfoss BD35-Solar). Three advantages of using multiple compressors, over a single-compressor system, were mentioned in the research. They were:

- a wider control range,
- the start-up power is lower, due to the lower static friction.
- a multiple compressor system has higher level of fault tolerance.

In order to provide easy start-up, maximum power point tracking for the solar panels and to manage power for the four compressors, a novel controller was used in the system to allow effective performance. The experimental results showed that the proposed system requires 150 W_p/m^2 solar irradiance to start the compressors while a single compressor system needs 400W_p/m^2. The 440 W_p solar PV system can produce up to 17kg of ice at about 7.3kWh/m^2 and 4.5kg of ice at only 3kWh/m^2.

4. Conclusion

Systems that integrate solar PV and phase change thermal storage have been reviewed. Both AC and DC compressors can be utilized in solar PV refrigeration system. However, AC compressor systems need a DC/AC inverter, which reduces the overall efficiency of the system. Previous research of solar PV refrigeration systems with or without a battery has been reviewed. The solar PV refrigeration system with a battery can work continuously during non-sunny periods but increases the cost of the system. The PCM selected in most previous research for small refrigeration systems is ice. Overall, solar PV refrigeration system combined with phase change thermal storage is suitable in areas with high level of solar irradiance and it has been used in the pharmaceutic, medical and food industries.

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