ISSN: 2350-0328

International Journal of Advanced Research in Science, Engineering and Technology

Vol. 10, Issue 5, May 2023

Energy performance evaluation of autonomous solar powered refrigerator

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ABSTRACT. The energetic performance of autonomous solar powered refrigerator is analyzed. In this refrigerator, the solar energy is converted into electrical energy by a photovoltaic (PV) array, then the generated electrical energy is used to power a vapor – compression system which produces cooling energy at its evaporator. The evaporator is sunk to the water so that produced cooling energy is used to formation water ice, thus accumulates cooling energy in the form of ice. While, compressor is working during the daylight hours, cooling energy is produced. During the night, the cooling energy comes from latent heat of fusion of ice which is collected in day time. The results of experiments showed that not only the solar energy has influence on the energetic performance of solar refrigerator but ambient temperature is also crucial factor in this case.

KEYWORDS. Solar energy, latent heat, water ice, solar refrigerator, PV array.

I. INTRODUCTION

The time mismatch between the availability of solar irradiance and the energy demand, dictates the storage of the solar energy for later use. In general, solar energy can be converted to electricity via PV panels and/or to heat via solar thermal collectors. One of the most common methods of storing the electricity from PV panels is the utilization of accumulation batteries, which convert the electricity to chemical energy[1]–[3]. Stored chemical energy in batteries has to be converted again to another form of energy and after that can be used depending on demand, regardless whether there is solar irradiance available or not. However, storing solar energy directly in the form of end use, not as chemical energy in battery, makes it possible to exclude accumulation battery from above mentioned method. Authors studied the energy performance of a solar powered refrigerator which stores solar energy in the form of thermal energy in ice. Latent heat of fusion of ice is used to store cooling energy and ice becomes accumulator of thermal energy. The main objectives of this work is to study the possibility of providing cooling facility in places where there is no access to electricity or the power grid is unreliable and to evaluate the energetic performance of solar powered refrigerator.

In [4]–[7] the possibility of exploiting PV powered refrigerators in remote locations having no access to electricity to keep perishable foods, drugs and other goods for longer periods of time was studied. In other study [8], it was found that the performance of solar refrigerators is sufficient for vaccine storage even in at very hot climate, given appropriate equipment selection and proper installation. Vapor compression refrigeration is the most commonly used technology for cooling worldwide and it is estimated to increase by three times by 2050 [9]. Therefore, using solar energy to produce cooling by running the vapor compression cooling system is a sustainable approach towards meeting the cooling demand in the future and many researchers have worked in this area [10]–[13]. Research has demonstrated that solar energy has great potential to contribute on the large energy demand for cooling and heating in the residential sectors. In the works of [4], [14] solar electric cooling and heating was found to be more economical compared to other solar energy technologies.

Techno – economical characteristics were studied of two systems, conventional alternating current compressor and direct current (DC) compressor refrigerators both powered by solar PV [15]. Alternative current (AC) refrigerator connected to the PV through DC – AC converter while other, DC refrigerator connected directly to PV. Also, when solar irradiance is available, batteries are charged from PV to power both refrigerators in night time. AC and DC refrigerators could maintain almost the same evaporator temperature -10 C and cooling cabinet temperature +2 ℃. However, it was found that AC refrigerator consumes relatively more power with power surges compared to DC. Small solar portable refrigerator was fabricated [16] which consists of PV panel, uninterruptible power supply unit (UPS) and vapor compression system with DC compressor. This refrigerator performed highest 5.89 coefficient of performance (COP) in winter and 4.53 in summer, with the temperature inside the refrigerator to be 6 ℃. Another experimentation was conducted for cooling 14 L milk in solar PV powered refrigerator [17]. This refrigerator powered by 500 W PV array and equipped 150 Ah battery. The results showed that the 14 L of milk cooled down from 25 ℃ to 5 ℃ within 240 minutes.

ISSN: 2350-0328
International Journal of Advanced Research in Science, Engineering and Technology
Vol. 10, Issue 5, May 2023

By the recommendation of World Health Organization, all vaccines, except OPV and freeze – dried vaccines, should be stored at between +2 ℃ and +8 ℃ at all levels of cold chain [18]. In many cases, the national electricity gird is not available, these places are mostly villages and remote locations.
Uzbekistan has a large solar energy potential [19]–[21] that could be effectively used, especially in the places where national electricity grid is not available or in villages and remote locations. Mostly based on agriculture industry, villages and remote locations mainly produce milk and its other stock-farming products. In Uzbekistan, according to the sanitary norms, milk and products made from milk should be maintained at temperature below +8 ℃. For this reason, experimented refrigerator with ice storage is considered suitable to be exploited, regarding the capability to maintain the temperature of refrigerator below +8 ℃. The main difference of proposing solar refrigerator from other known solar refrigerators is energy is conserved directly in the form of ice, not in accumulator batteries.

II. EXPERIMENTS

The autonomous solar powered refrigerator consists of four main parts: PV array, controlling block, vapor–compression system, storage tank. The layout of the system is schematically presented in Fig.1.
PV array has 4 parallel connected monocrystalline PV panels with the nominal power of 110 Wp. Generated electrical energy in PV array is distributed to the four vapor–compression systems via controlling block which implements specific control algorithm. The storage tank has box-in-box geometric shape which exterior wall of outer box is thermally insulated. The gap between the two boxes is filled with water to be used as a thermal reservoir and inner box is used as a cooling cabin.

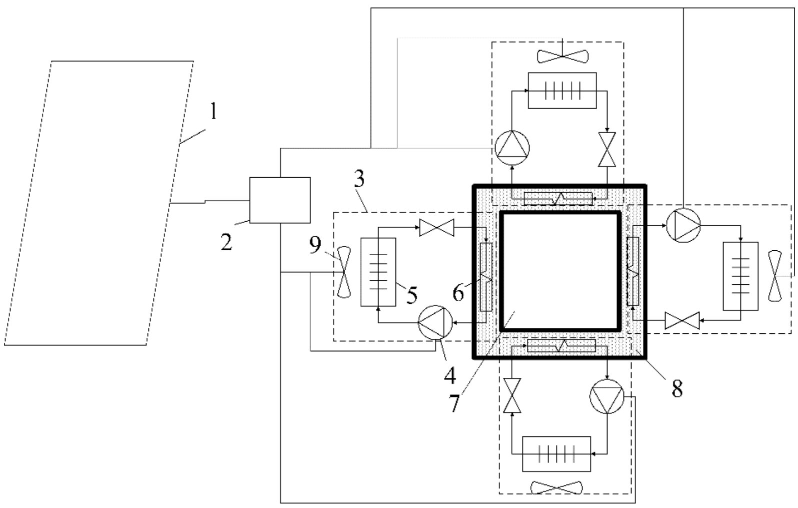

Fig.1. Schematic view of the solar powered refrigerator.
1 – PV array, 2 – controlling block, 3 – vapor-compression circuit, 4 – compressor, 5 – condenser, 6 – evaporator, 7 – cooling cabin, 8 – water, 9 – condenser cooler.

The evaporator of the vapor–compression system is located in the gap between two boxes inside the water. Freon flowing through the evaporator at liquid phase absorbs heat energy from ambient i.e., from the water where the evaporator is sunk, result in it is evaporated and obtained steam phase. Freon in the form of steam enters a compressor as a low-pressure steam where it is compressed, causing it to become superheated. After the compressor high – pressure and superheated vapor heat transfer agent enters a condenser where it releases heat energy to the ambient air consequently turning into liquid phase. Condensed heat transfer agent with high pressure and temperature flows through expansion valve where its pressure and temperature drop significantly before entering to the evaporator again. Produced cooling energy in the evaporator is used to transform water to ice so that cooling energy is accumulated to be consumed later when compressor is not operating.
When solar energy is available, electrical energy generated in PV is used to power the compressors, which in turn vapor-compression system is operated and produced cooling energy. As known, cooling energy is directly released at the evaporator, all produced cooling energy is used to generate water ice at water freezing temperature. Due to cooling cabin

ISSN: 2350-0328
International Journal of Advanced Research in Science, Engineering and Technology
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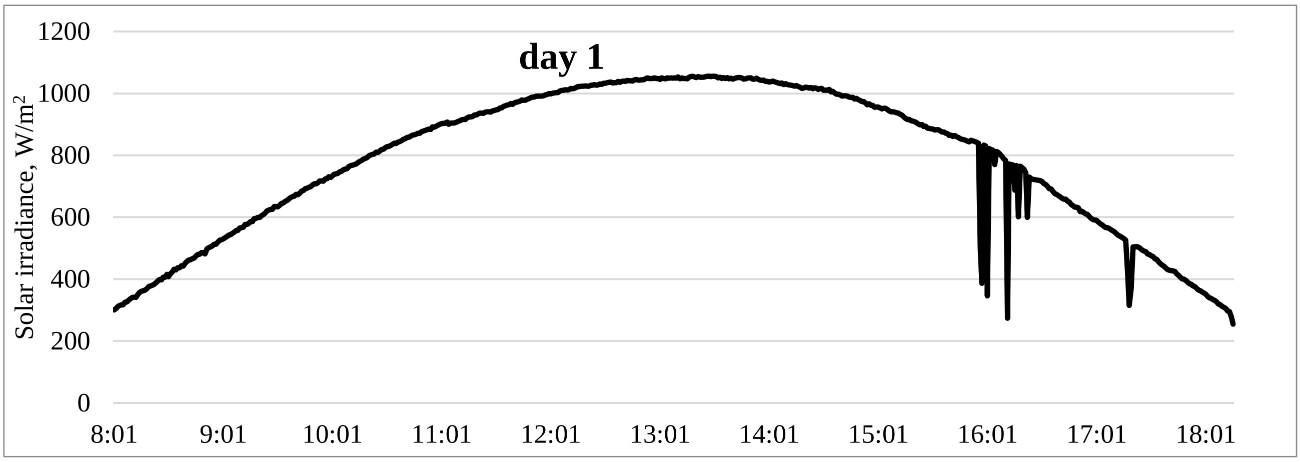
being surrounded by the water-ice mixture which is used to be thermal reservoir, air temperature inside the cooling cabin would be just higher than water freezing point.
When solar energy is not available, PV array is not able to generate electrical energy, consequently compressors also are not powered and cooling energy is not released at evaporators. Lower temperature inside the cooling cabin is kept by the heat of fusion of ice i.e., while earlier generated ice is melting, it absorbs heat energy from surround causing cooling cabin temperature is lower.

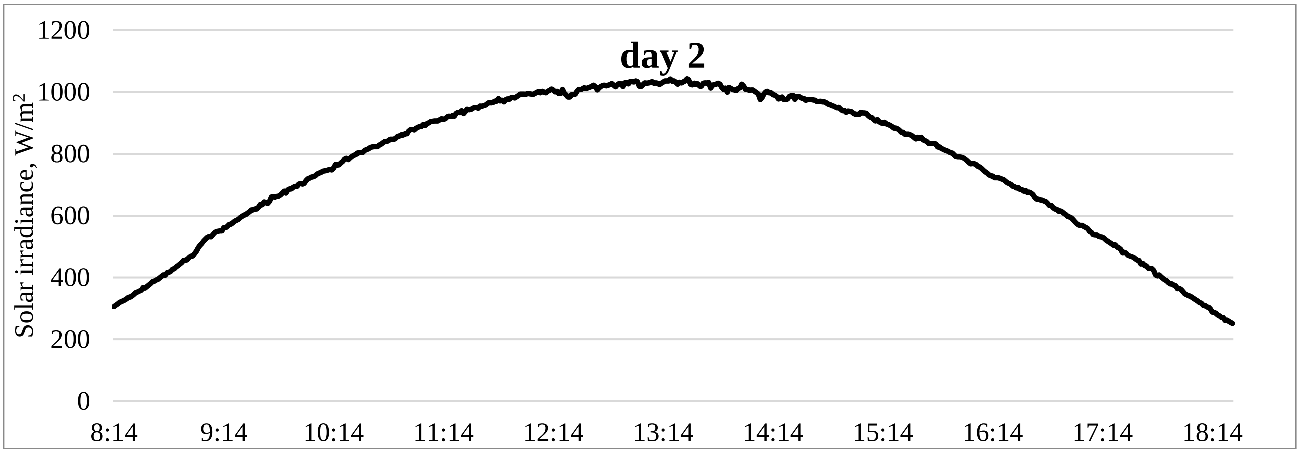
III. INSTRUMENTATION

Experiments are conducted exploiting KIPP&ZONEN CM11 pyranometer to measure solar irradiance on the PV array surface, KIMO TM200U four channel digital thermometer to measure ambient temperature and cooling cabin temperature, PT100 temperature sensors to measure PV panel temperature at different points. All measured values are obtained automatically every two minutes and stored in a logger.

IV. RESULTS

Experiments are conducted in different weather conditions with different day profile so that energetic performance of solar powered refrigerator is evaluated for different conditions. There are four experiment days to be analyzed in this scientific work. Day 1 has clear sky with slightly cloudy afternoon and mean ambient temperature is 32 ℃, day 2 has very clear sky with average mean ambient temperature 33 ℃, while day 3 sky is partly clouded and mean ambient temperature is 36 ℃, the last day 4 has totally clouded sky and mean ambient temperature is 28 ℃. The pattern of solar irradiance incident on a PV array surface is illustrated in Fig.2.





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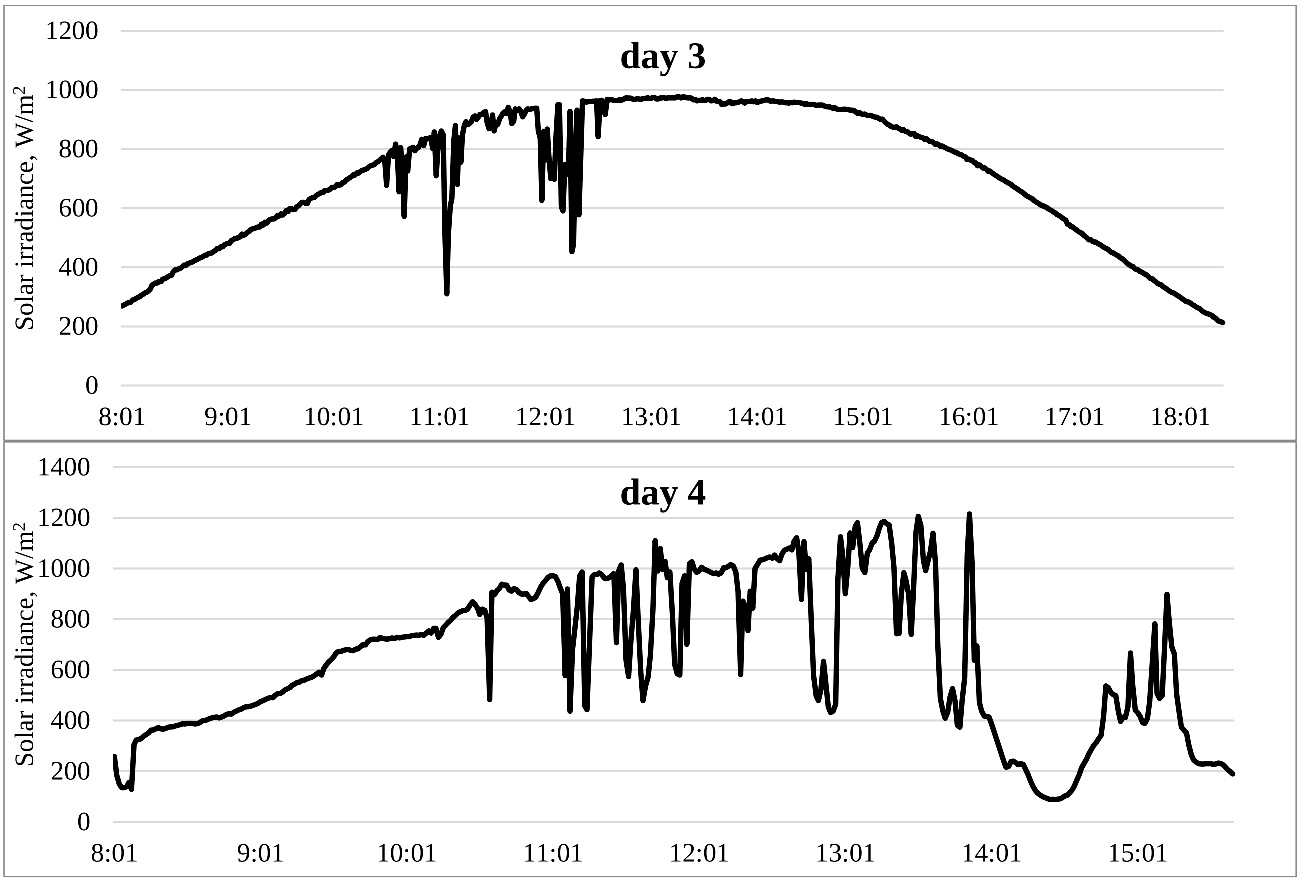

Fig.2. The solar irradiance during the four characteristic days

Daily culminative solar energy on the PV array surface, generated electrical energy generated in PV array and produced useful cooling energy for a day, also, mean ambient temperature are shown in Fig.3.

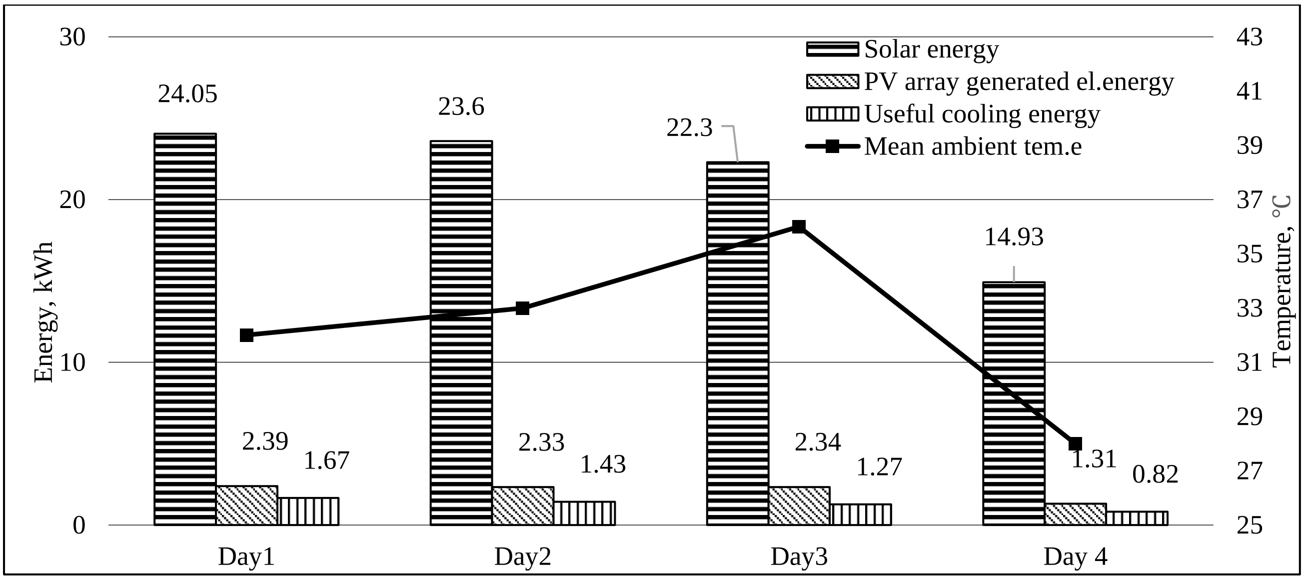

Fig.3. Amount of converted energy from one form to another

Solar energy on the surface of the PV array and generated electrical energy is determined by measurement using special measurement tools, while amount of useful cooling energy is determined multiplying produced ice mass, measured at the end of experiment day, inside of storage tank by its specific heat of fusion. This means, useful cooling energy is the remaining part of the total produced energy by vapor compression system after heat losses in storage tank and which is spent only to form water ice.

V. DISCUSSION

It can be seen from the Fig.2 that day 1 - 3 have relatively clear sky, solar irradiance changed smoothly, but the value of solar irradiance on the surface of PV array has sharp fluctuations in day 4, which evidence from cloudy sky.
Amount of energy that participates in each energy conversion process of the solar refrigerator unit is shown in Fig.3. Day 1, daily total solar energy on the surface of the PV array is equals to 24.05 kWh absorbing which 2.39 kWh electrical energy is generated, in other words, 9.9 percent of primary energy is converted to electrical energy. Similarly for days 2, 3 and 4 the PV efficiency was found to be 9.87 %, 10.5 % and 8.8 % respectively. Generated electrical energy is used to power the compressors so that vapor-compression system is operated and cooling energy is produced. Here, energy efficiency is considered as the part of total received energy that transformed to useful energy and numerical value is found by dividing useful energy to total and presented in percentage.
The amount of generated electrical energy for day 1 is 2.39 kWh, consuming this electrical energy, vapor-compression system produced 1.67 kWh useful cooling energy and average daily energetic efficiency of vapor-compression system constitutes 69.8 %. Daily energy efficiency of vapor-compression system for day 2, 3 and 4 equals to 61.5, 54.2 and 62.2 % respectively.
Also, it must be noted that ambient temperature influences the energy performance of the solar powered refrigerator. Day 1 and day 3, almost the same amount of electrical energy is consumed by compressors, 2.39 kWh and 2.34 kWh, however the amount produced useful cooling energy differs greatly from each other for these days. The reason, energy efficiency of vapor-compression system is sensitive to ambient temperature where it is operating, this means, the lower ambient temperature the higher energetic efficiency. Because lower ambient temperature encourages condenser to reject heat from freon more intensively with relatively greater heat transfer coefficient, while higher ambient temperature prevents to heat transferring from freon to ambient air.

VI. CONCLUSION

Above-described solar powered refrigerator has two step of energy conversion: solar energy to electrical energy at PV array and electrical energy to cooling energy at vapor-compression system. The experimental results showed that the first stage of energy conversion has average 10 % energy efficiency, 0.1 part of solar energy is converted to electrical energy, while second stage of energy conversion has average 62 % energetic efficiency, that 0.62 part of electrical energy converted to ice.
Furthermore, it is found that ambient temperature also crucial factor for the operation of the solar powered refrigerator. Almost the same amount of electrical energy is consumed by compressors in day 1 and day 3, at ambient temperature difference 4 ℃. However, energy efficiency of vapor-compression system operated at lower ambient temperature 31 % (1.67 kWh against 1.27 kWh) greater than that of vapor-compression system operated at higher ambient temperature.

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