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Full Length Research Paper

Experimental study of a multi-purpose PV-refrigerator system

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Refrigerators used in daily life are one of the indispensable tools. Uninterrupted power should be supplied to refrigerators in order to maintain cooling service. Photovoltaic (PV) systems provide an independent, reliable electrical power source at the point of use, making it particularly suited to remote locations. For this reason, nowadays, the use of PV solar energy in refrigeration has been increasing in rural regions. But, the design conditions and operating performance of a PV-refrigeration system are significantly affected by local climatic conditions. In this study, a PV-powered multi-purpose refrigerator system has been established to investigate experimentally its daily and seasonal operating performance. Operational parameters affecting system capacity and performance were determined under a semi-arid climate condition of Şanliurfa province in Turkey's GAP Region. The region's critical need for refrigeration comes also from, that it is one of the sunniest rural regions of the world. Detailed results obtained during daily experimental measurements are presented here. The results in overall reveal that, PV-refrigerator system can be reliably used at where the local grid is not continuously available whereas refrigeration need is critical.

Key words: Solar energy, photovoltaic (PV), stand-alone, refrigeration, GAP region.

INTRODUCTION

Solar energy that is virtually an inexhaustible natural source produces little or no greenhouse gases. It is known as a clean and environmental friendly energy source. Solar energy applications in different fields have been increasing gradually. One of the most important of these applications is refrigerators used in daily life. It is difficult to use refrigerator due to increase in the air temperature in summer and long-term power outages; goods stored in refrigerator such as meat, dairy products, medicine and vaccines are mostly spoilage. Especially residential areas away from electricity grid in rural areas, similar problems can be experienced frequently. Therefore, security of electricity supply is of great importance in electricity generation. For this purpose, energy demand of refrigerator can be supplied by solar energy. Solar energy can be captured in two forms, either as heat (thermal) or as electrical energy (photovoltaic). There are a lot of solar refrigerator systems. Classification of solar refrigeration systems is presented in Figure 1 (Kim and Ferreira, 2008; Papadopoulos et al., 2003; Ewert et al., 1998). As can be seen in the figure, a lot of technologies are available to deliver refrigeration from solar energy. Scientists and research centers focusing on these technologies have made a lot of work on the subject. Kim and Ferreira (2008) presented an overview of the state of the art of the different solar refrigeration technologies including solar electric, thermo-mechanical, sorption and also some newly emerging technologies.

They compared the potential of these different technologies in delivering competitive sustainable solutions. Papadopoulos et al. (2003) focused on the state of the art of thermal solar systems use and on the possibilities of combining those with state of the art technologies in sorption refrigeration, in order to cover the cooling demand of residential and commercial buildings. Most review articles were limited to solar thermal refrigeration technologies (Dai et al., 2003;

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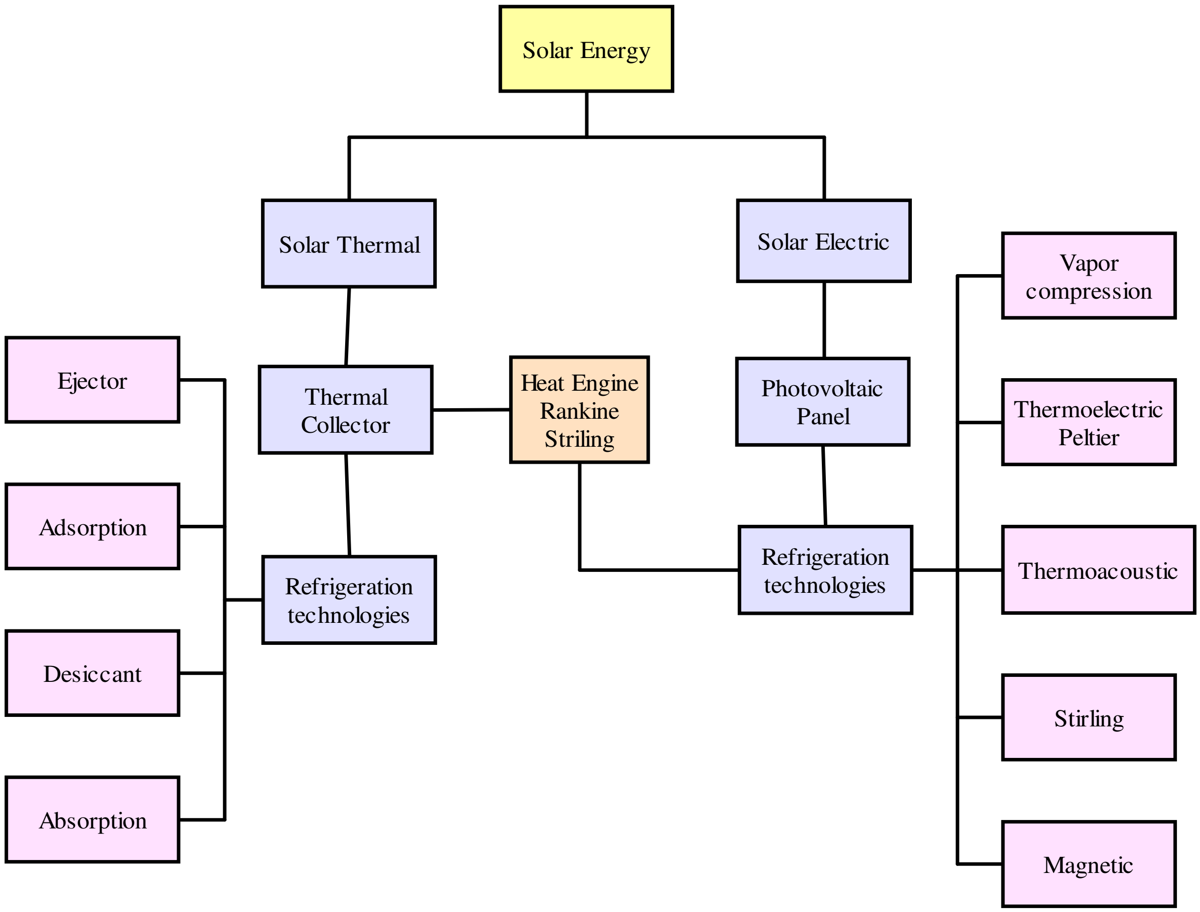

Figure 1. Classification of solar refrigeration systems (Kim and Ferreira, 2008; Papadopoulos et al., 2003; Ewert et al., 1998).

Abdul-Wahab et al., 2009; Kaplanis and Papanastasiou, 2006; Dieng and Wang, 2001; Fan, 2007). Thermo electric method is one of the investigated methods among solar cooling technologies (Anyanwu, 2003, 2004). Sözen and Özalp (2005) investigated the usage possibility of solar-driven ejector-absorption cooling systems in Turkey. They reported that it is sufficient to have a collector surface-area of 4 m^2 with high-performance refrigeration all over Turkey. Desideri et al. (2009) analyzed the technical and economic feasibility of solar absorption cooling systems, designed for two different application fields: 1) industrial refrigeration and 2) air conditioning. They described different technical installations for solar cooling, their way of operation, advantages and limits. Most of the studies performed in solar technology field are based on the vapor compression cycle. Kaplanis and Papanatasiou (2006) described the design and development stages to convert a conventional refrigerator to a solar powered one. Axaopoulos and Theodoridis (2009) experimentally investigated a solar photovoltaic powered ice-maker which operates without the use of batteries. It was reported that their study results have shown very good ice-making capability and reliable operation, as well as a great improvement in the startup characteristics of the compressors, which remain operational even during days with low solar irradiation and operate with improved utilization of the available photovoltaic power. Ewert et al. (1998) experimentally investigated three different refrigeration technologies (thermoelectric, stirling, and vapor compression). They reported that proper sizing of solar-refrigerator components and system integration are essential for good design options.

The most preferred solar system in the refrigerator is photovoltaic system applications (Kim and Ferreira, 2008; Papadopoulos et al., 2003; Ewert et al., 1998). Photovoltaic (PV) is a technology that converts sunlight directly into electricity. With the global demand to reduce carbon dioxide emissions, PV technology is gaining popularity as a mainstream form of electricity generation. Today, decrease in the cost of PV panels with the increasing PV panel demand, and in parallel to this situation, increase in duration of use (lifetime) of PV panels, use of these systems has been increasing. However, solar energy are geographically distributed and highly dependent on the location, changing weather and climate conditions, which makes their direct control extremely challenging and requires storage units as an additional concern (Mazhari et al., 2011). Therefore, autonomy of systems that is worked with solar energy is very important parameter. For example, autonomy is described as the time in days that a PV-refrigerator can maintain the load within the acceptable temperature range under low solar radiation conditions (e.g. rain). According to the solar refrigerator performance specification published by World Health Organization (WHO), all solar direct drive refrigerators must pre-qualify with at least a minimum autonomy of 3 days at the specified solar radiation reference period and temperature. Cold autonomy depends on several factors such as, the capacity of the accumulator, the ambient temperature, insulation and air tightness (Toure and Fassinou, 1999). Autonomy of the PV-refrigerator can be increased by different methods; increasing the electrochemical (battery) capacity, making a cold storage in the refrigerator (without battery storage) and using auxiliary energy source (such as, PV-wind, PV-diesel). The first method is an expensive method that is not a good solution (Martinez and Medina, 2010). The scientists are intensively studied about the other two methods (El-Hefnawi, 1998; Toure and Fassinou, 1999; Axaopoulos and Theodoridis, 2009; Nfah and Ngundamb, 2009; Martinez and Medina, 2010; Mazhari et al., 2011). The main purpose of these researches has been directed to develop solar powered refrigerators.

Recently, the refrigerator applications powered by photovoltaic system are seen in various sectors. According to WHO, the technology of photovoltaic refrigerators is mature and fully commercialized with more than 5,000 now in use worldwide, the majority of them in African countries. Especially in less developed countries, the PV-refrigerator systems supported by WHO are used intensively (Yeşilata and Işiker, 2006). A solar powered refrigerator (SolarChill) has been developed in an international project involving Greenpeace International, GTZ Proklima, United Nations Children's Fund (UNICEF), United Nations Environment Programme (UNEP), WHO, industrial partners (Vestfrost, Vibocold, Danfoss, Gaia Solar) and Danish Technological Institute (DTI). The main objective of the SolarChill Project is to help deliver vaccines and refrigeration to the rural poor. The refrigerator is able to operate directly on solar PV panels, without battery or additional electronics, and is therefore suitable for locations where little maintenance and reliable operation is mandatory (Pedersen et al., 2004). The SolarChill Vaccine Cooler and Refrigerator Project was the winner of the prestigious 2006 UK Cooling Industry Award in the Environmental Pioneer Refrigeration category at the October 4, 2006 Cooling Industry Award Ceremonies in London, England.

On March 18, 2010, the WHO prequalified its first solar direct-drive vaccine refrigerator. Ten years in the making, the SolarChill vaccine cooler operates with a compressor powered directly from sunlight. Instead of storing electrical energy in a battery, the refrigerator stores thermal energy in ice and a thermostat maintains the temperature between the required 2 to 8°C for vaccine storage. In low-sun situations or when power is completely disrupted, the insulated "ice battery" maintains acceptable temperatures for up to 5 days. An intelligent fan enhances the convection circulation of the cold air and is operated by a small rechargeable battery, which is recharged by solar power (Mate and McCarney, 2010). There is a widespread consensus that, PV-refrigerator systems are economic and reliable solution for rural regions, regardless of the level of national development (Yesilata and Işiker, 2006). In other sectors except for health sector, PV-refrigerator systems are also preferred for seasonal and occasional use in the cottage, villas and resorts place. Design conditions and operating performance of PV-refrigeration system are significantly affected by local atmospheric conditions (Mazhari et al., 2011). The detailed analysis of local weather data is required to assess the various aspects of PV-refrigerator; such as design capacity, operating performance, operating cost, etc.

In this study, a multi-purpose refrigerator system powered by photovoltaic panel has been tested at Harran University, located in the Southeastern (GAP region) of Turkey. The PV-refrigerator system is independent of the local electricity grid. Daily and seasonal operating performance of PV-refrigerator was investigated experimentally. During the daily operation of the refrigerator system, the parameters which affect the system capacity and performance were determined experimentally. The results obtained from experimental study were presented and evaluated.

EXPERIMENTAL SETUP AND MEASUREMENT TECHNIQUE

Schematic of the PV-refrigerator system is presented in Figure 2 (a). It is composed of four parts; i) the cooling unit (refrigerator), ii) the energy production unit (PV panels), iii) the energy control unit, and iv) the energy storage unit (the battery bank). The PV-refrigerator system, thanks to the latest A^{++} energy efficiency class, together with optimal electronic control and a rotational speed control of the compressor, it is possible to ensure that the energy is used extremely efficiently. This leads to significant cost reductions. It can be used as either a refrigerator or a freezer. The total cost of the PV refrigerator system is likely to cost around $2500 and will cost more to install than conventional refrigerator. A true comparison of a solar refrigerator cannot be made with a conventional one, since its common use is where the electricity is not continuous and reliable. Therefore, it should be compared with kerosene and bottled gas fuelled refrigerators. Even in this case, reasonable cost comparisons can only be made through a life-cycle cost analysis since PV-refrigerator has great potential for lower operating costs, although its initial cost is higher. PV-refrigerator

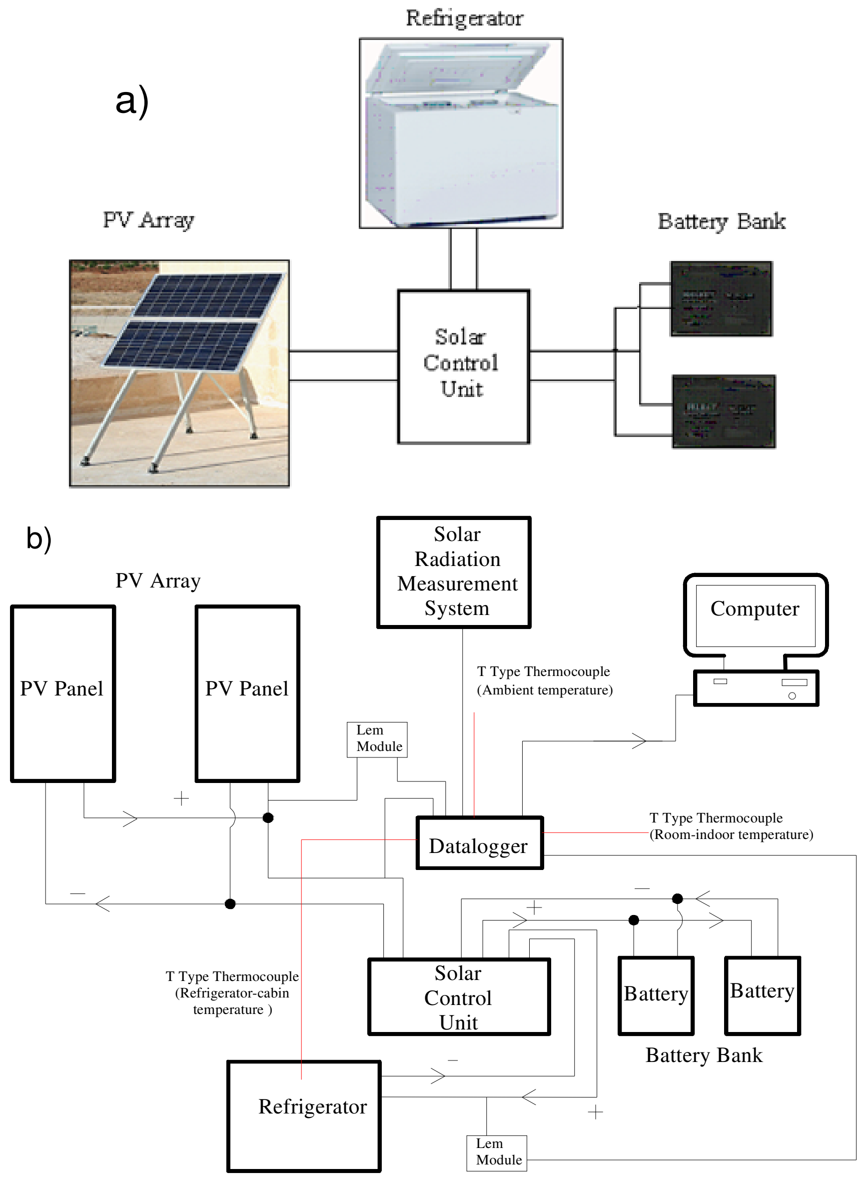

Figure 2. (a) Schematic of the PV-refrigerator system, (b) Experimental measurement loop.

system works with an input voltage of either 12 or 24 V and direct current (DC). R134a refrigerant was used in the refrigerator (Solar refrigerator catalogue). Energy demand of PV-refrigerator system was provided by two units photovoltaic panels (DC 12V-80W) connected in parallel. PV-refrigerator system is worked with 12 V during the experimental period. Photovoltaic panels were selected by polycrystalline type due to high efficiency. Panel specifications for standard test conditions are given in Table 1 (Photovoltaic module catalogue). Panel standard test conditions are: Irradiance of 1000 W/m^2, air mass of 1.5 (AM) and module temperature of 25℃. Solar control unit regulates the DC output of the PV panel, and supplies energy to the battery bank. It prevents battery over-charge and full discharge. Battery bank consists of two units 100 Ah -12 V dry-type batteries connected in parallel. Therefore, the battery bank supplies 12 volt energy to the solar refrigerator.

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In stand-alone PV-refrigeration systems, the selection and proper installation of appropriately-sized components directly affects system reliability, lifetime, and initial cost. Using for example more batteries and increasing PV array size may extend the life and reliability of a PV system designed for a specific application but will increase the initial cost. On the other hand, the size of the solar array and the battery storage capacity will vary depending on site location. By considering these facts, selections of system components, including total rated power of PV panel, were made here as directed in the 'Handbook of Recommended Design Practices'. The designs presented in the 'Handbook of Recommended Design Practices' represent real applications and illustrate some of the trade-offs necessary in system design and component selection. Therefore, directive remarks given there were applied in selection of the components. The types and number of

Table 1. Panel specifications (photovoltaic module catalogue).

Cell type	Polycrystalline silicon,125.5 mm^2
No. of cells and connections	36 in series
Dimensions	1200 x 530 x 35 mm
Weight	8.5 kg
Nominal power	80 W
Module efficiency	12.6%
Maximum power voltage	17.1 V
Maximum power current	4.67 A
Maximum system voltage	DC 540 V
Series fuse rating	10 A
Open circuit voltage (V_{oc})	21.3 V
Short circuit current (I_{sc})	5.31 A
Operating temperature	-40 to +90°C
Storage temperature	-40 to +90°C

Table 2. The average variation of some climatic data measured long period for Şanliurfa (DMİ, EIE).

Months	Monthly average temperature (°C)	Monthly total solar energy (kWh/m^2month)	Sunshine duration (h/month)
January	5.7	58.50	140.7
February	6.9	74.10	170.1
March	11.0	122.70	210.3
April	16.2	151.80	245.1
May	22.3	184.80	300.0
June	28.3	204.60	370.2
July	32.0	196.50	373.5
August	31.2	177.90	351.0
September	26.8	150.00	302.1
October	20.2	37.90	232.5
November	12.5	73.20	178.8
December	7.4	54.00	134.7
Annual total	-	1562 kWh/m^2year	3009 h/year
Daily average	-	4.34 kWh/m^2day	8.36 h/day

PV panels were then decided upon their availabilities from the local market.

Figure 2b shows the experimental measurement loop. The datalogger used in the measurement system is a 32-channel; 8-channel was used in measurements, 4 of them for measuring the current and voltages values and the others for measuring the temperature values. The inside temperature of refrigerator, indoor and outdoor air temperatures were measured using T type thermocouples. The current and voltage values at the output of the PV panels and refrigerator were measured using lem module to determine the energy produced by the PV panels and the energy consumed by refrigerator. Data were recorded to datalogger for 1 min intervals. Besides, solar radiation values were measured with the solar radiation measurement system with solar tracker, which can measure global, direct beam and diffuse radiation with high resolution. The total uncertainty in power measurements was found to be 0.044%, which was calculated from the formula given in Holman (2000). In calculations, uncertainties in voltage and current measurements, corresponding to respectively 0.426 V and 0.106 A at peak power, were used.

Experimental study was carried out at Harran University located in Şanliurfa province in Turkey's GAP region. The name of the GAP region was taken from the Southeastern Anatolia Project (GAP), the biggest project of Turkey. GAP is one of the biggest ones of the development projects in implementation in the world, which is addressed with an integrated and sustainable development concept which is cited as a model by these properties in human oriented and international platforms (GAP). Located in Southeastern Anatolia between Anatolian and Arabian peninsulas, the province of Şanliurfa extends over a land of 18,584 km^2. Its population is 1,613,737 according to 2009 census (TÜİK). Şanliurfa has semi-arid climate. The monthly variation of average temperature measured in long period for Şanliurfa is given in Table 2 (DMİ). Şanliurfa's solar energy potential is also presented in Table 2 (EIE). Şanliurfa is a leader in solar energy potential in Turkey and is one of the numbered regions in the world.

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Table 3. The yearly, monthly and daily average values of Turkey's solar potential (EIE).

Months	Monthly total solar energy (kWh/m^2month)	Sunshine duration (h/month)
January	51.75	103.0
February	63.27	115.0
March	96.65	165.0
April	122.23	197.0
May	153.86	273.0
June	168.75	325.0
July	175.38	365.0
August	158.40	343.0
September	123.28	280.0
October	89.90	214.0
November	60.82	157.0
December	46.87	103.0
Annual total	1311 kWh/m^2year	2640 h/year
Daily average	3.6 kWh/m^2day	7.2 h/day

Table 4. The regional distribution of solar energy potential of Turkey (EIE).

Region	Total solar radiation (kWh/m^2year)	Sunshine duration (h/year)
Southeastern Anatolia	1460	2993
Mediterranean	1390	2956
East Anatolia	1365	2664
Central Anatolia	1314	2628
Aegean	1304	2738
Marmara	1168	2409
Black Sea	1120	1971

Turkey is located in a relatively advantageous geographical position. The solar energy potential evaluations were made by Electrical Power Resources Survey and Development Administration (EIE), based on the data measured by the Turkish State Meteorological Services (DMİ). Turkey's solar energy potential is given in Table 3 (EIE). Solar energy potential according to geographical regions of Turkey is given in Table 4 (EIE). As shown from tables, the total yearly radiation period and the yearly average solar-radiation are 2640 h (7.2 h/day) and 1311 kWh/m^2year (3.6 kWh/m^2day), respectively (EIE).

RESULTS AND DISCUSSION

In this study, experimental study for operation state of the refrigerator under different load and without load was performed in 2009 to determine the daily and long-term behaviors of the PV-refrigerator systems during some typical days in summer and winter. In all the experiments, the inside temperature of refrigerator was set to -10°C. Detailed results obtained during experimental measurements are presented subsequently.

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No-load operation state of the refrigerator

The instantaneous values of some operating parameters of PV-refrigerator system were obtained for a typical hot day in May 2009. Experimental study was started at local time of 8:00 AM for no-load stored in refrigerator. Figure 3 (a) shows the instantaneous distribution of solar radiation components of global, diffuse, and direct. It is seen that global and direct beam radiations have high potential due to clear sunny day. Maximum values of solar global and direct beam radiations were observed at 12:50 to be 967 and 943 W/m^2, respectively. Sunshine duration is 14.33 h. Besides, instantaneous values of the solar radiation components were also compared with PV-power generation. Average efficiency of PV array is calculated to be about 12 to 14%. Figure 3 (b) shows the instantaneous distributions of the inside temperature of refrigerator, room-indoor and ambient (outdoor). As can be seen in figure, while average indoor and outdoor temperatures are 26.3 and 24.9°C, respectively, low

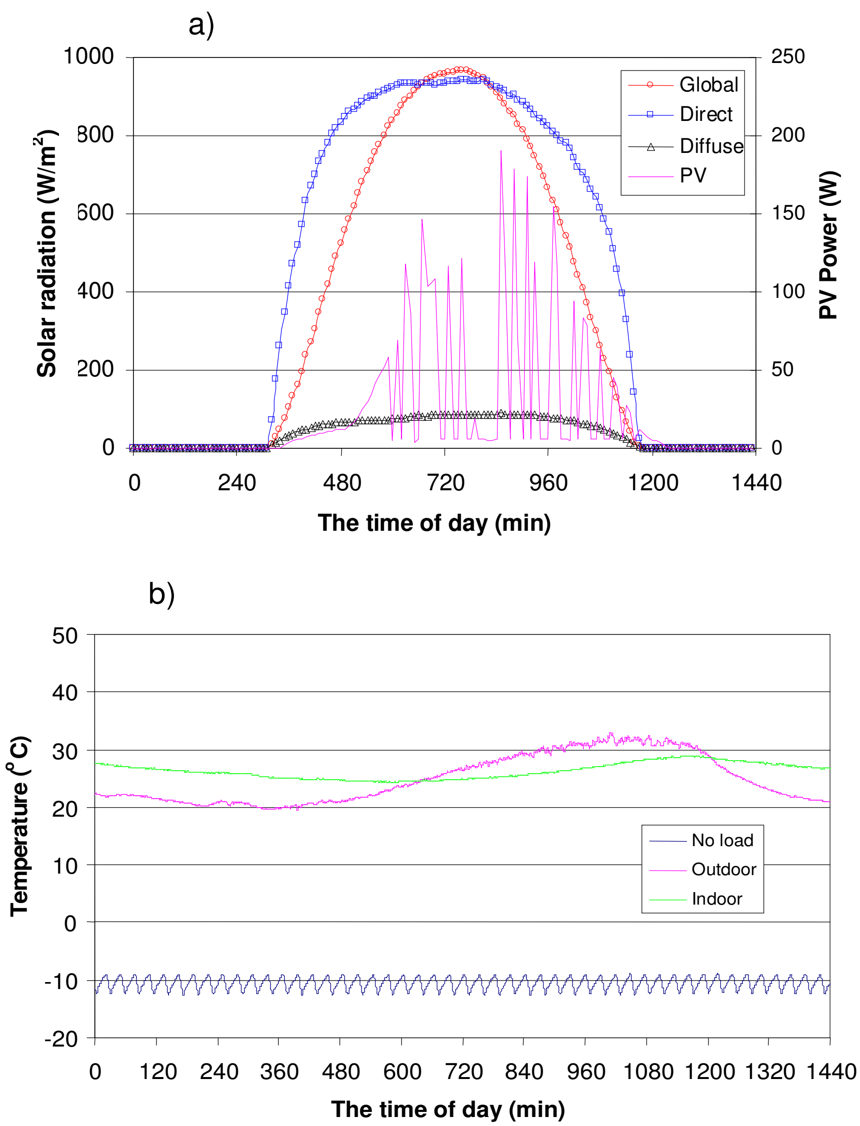

Figure 3. Instantaneous values of the some operating parameters for a typical hot day in May 2009, where t = 0 corresponds to local time of 8:00 AM; (a) solar radiation components of global, diffuse and direct, and PV-power, b) temperatures of refrigerator-cabin, room-interior and the ambient.

temperature of -10.6°C can be reached in refrigerator and the battery-use remain low.

Power distributions of solar refrigerator and PV panel for a typical hot day in May 2009 were presented graphically in Figure 4a. As shown in Figure 4, PV-refrigerator works with power of about 50 W. When the sun is available, the refrigerator is operated with some part of the energy produced by the PV panel. The remaining parts of the energy are stored in the battery bank. Thus, after sunset, operation of the refrigerator is provided with energy from battery bank. Energy produced by PV panel is variable throughout the day and the maximum energy was observed at noon as 180 W. Nominal power of PV panel is 80 W for standard test conditions. Generally, power production of PV panel is lees than the nominal power. However, power production of PV panel is affected by many parameters; such as air temperature, air mass, humidity, solar radiation etc. At some discrete times of the daily operations, it is also possible to measure higher peak-powers, due to more favorable parametric values than those given at standard conditions (Dunlop, 2009).

Power balance of battery bank for the daily period is shown in Figure 4 (b). As shown in the figure, if the power is positive, the battery bank is charging with the energy produced by PV panels. If the power is negative,

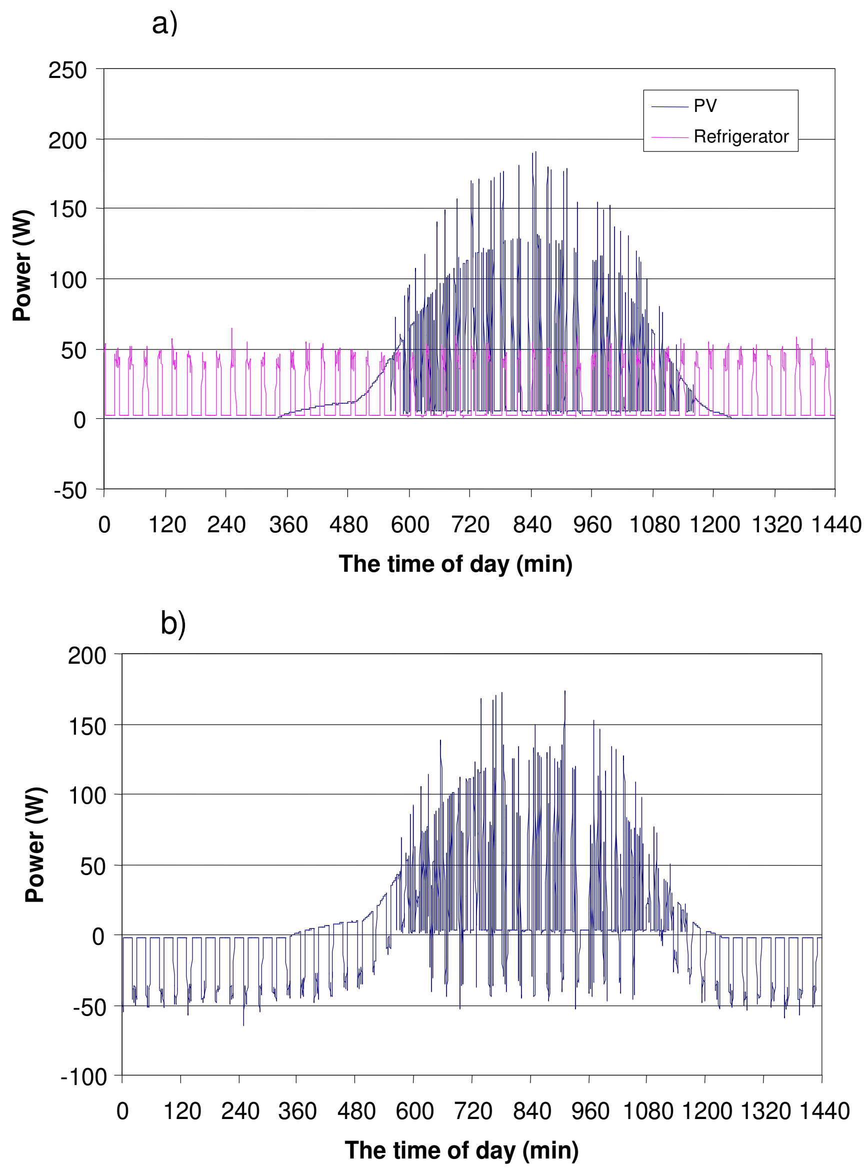

Figure 4. Instantaneous power values of the components for a typical hot day in May 2009, where t = 0 corresponds to local time of 8:00 AM; (a) PV and refrigerator, (b) battery-bank.

requirement energy of the refrigerator are supplied from the battery bank. Refrigerator is shut off with automatic control circuit when the inside temperature of refrigerator was equal to the set temperature point (-10°C). Thus, energy consumption of refrigerator was decreased significantly. For a typical hot day in May 2009, the amount of electric energy produced by photovoltaic panel is 425.9 Wh/day. 347.7 Wh/day of this energy is consumed by the refrigerator, and the remaining part (78.2 Wh/day) is stored in the battery bank. Energy consumption rate of refrigerator is compatible with the catalog values.

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An experimental study was also carried out in order to observe the long-term (during 23 days) behaviors of the PV-refrigerator parameters during winter days in December 2009. Experimental study was started at local time of 8:00 AM for no-load stored in refrigerator. Figure 5a presents the instantaneous distributions of power of refrigerator and PV panel. As can be shown in figure, refrigerator during the 23-day long period has continued to operate without interruption and paying a fee. When solar radiation is insufficient, PV-refrigerator system is supplied by battery bank. Figure 5b shows the instantaneous distributions of the temperatures of inside

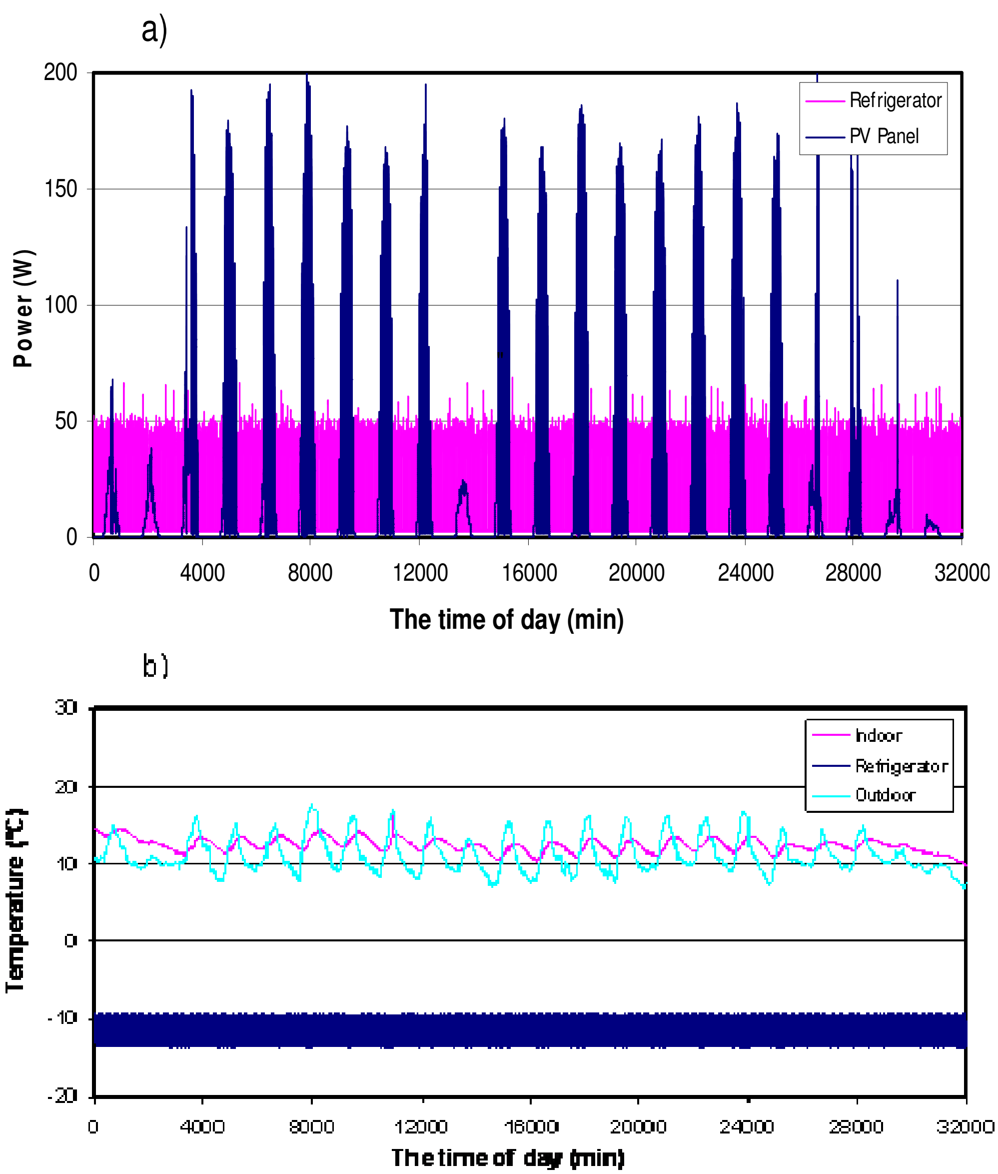

Figure 5. Long-term (during 23 days) behavior of the PV-refrigerator parameters during winter days in December 2009, where t = 0 corresponds to local time of 8:00 AM; (a) Corresponding powers of refrigerator and PV panel, (b) Corresponding temperatures of refrigerator-cabin, room-interior and the ambient.

refrigerator, indoor and outdoor. The average temperatures of refrigerator, indoor and outdoor are -11.1, 12.3 and 11.2°C, respectively.

Operation state of the refrigerator under different load

Here, the relative effect of cooling load on instantaneous operating parameters of the PV-refrigerator under systematically increased cooling load condition for a typical hot day in May 2009 was investigated in detail. The results obtained were compared with the results obtained from PV-refrigerator under no-extra-cooling load condition. Experimental study was started at local time of 8:00 AM. Loads put into the refrigerator are 5, 10 and 15 L water tanks, respectively. Typical behaviors of instantaneous operating parameters of the PV-refrigerator under no-extra-cooling load condition for a typical hot day in May 2009 are presented in Figure 6. As shown in Figure 6a, for a daily period, the distribution of inside temperature of refrigerator is between -8.9 and

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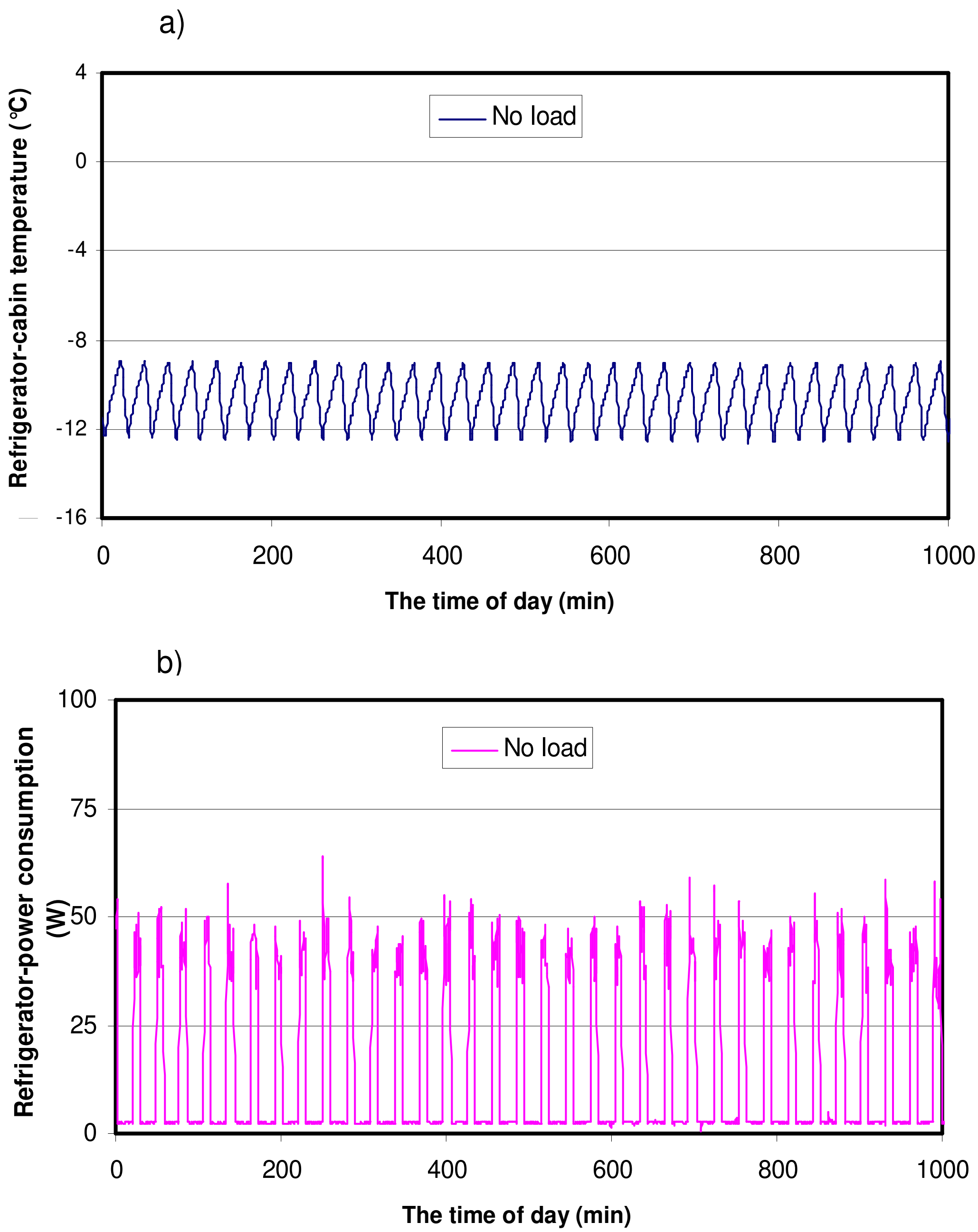

Figure 6. Typical behavior of instantaneous operating parameters of the PV-refrigerator under no-extra-cooling load condition for a typical hot day in May 2009, where t = 0 corresponds to local time of 8:00 AM; (a) refrigerator-cabin temperature, (b) refrigerator-power consumption.

-12.6°C to reach set temperature point (-10°C). PV-refrigerator works with power of about 50 W for a daily period (Figure 6b).

Typical behaviors of instantaneous operating parameters of the PV-refrigerator under systematically increased cooling load condition for a typical hot day in May 2009 are presented in Figure 7. As can be seen in Figure 7a, a certain period of time will have to pass in order to reach the inside temperature of the refrigerator under different loads to set point temperature. This period varies depending on the load. This time periods for 5, 10 and 15 L loads are performed to be approximately 150, 350 and 550 min, respectively. Energy consumption rate of refrigerator are increased with the amount of the load put into the refrigerator (Figure 7b). The highest amount of energy consumption of refrigerator is observed

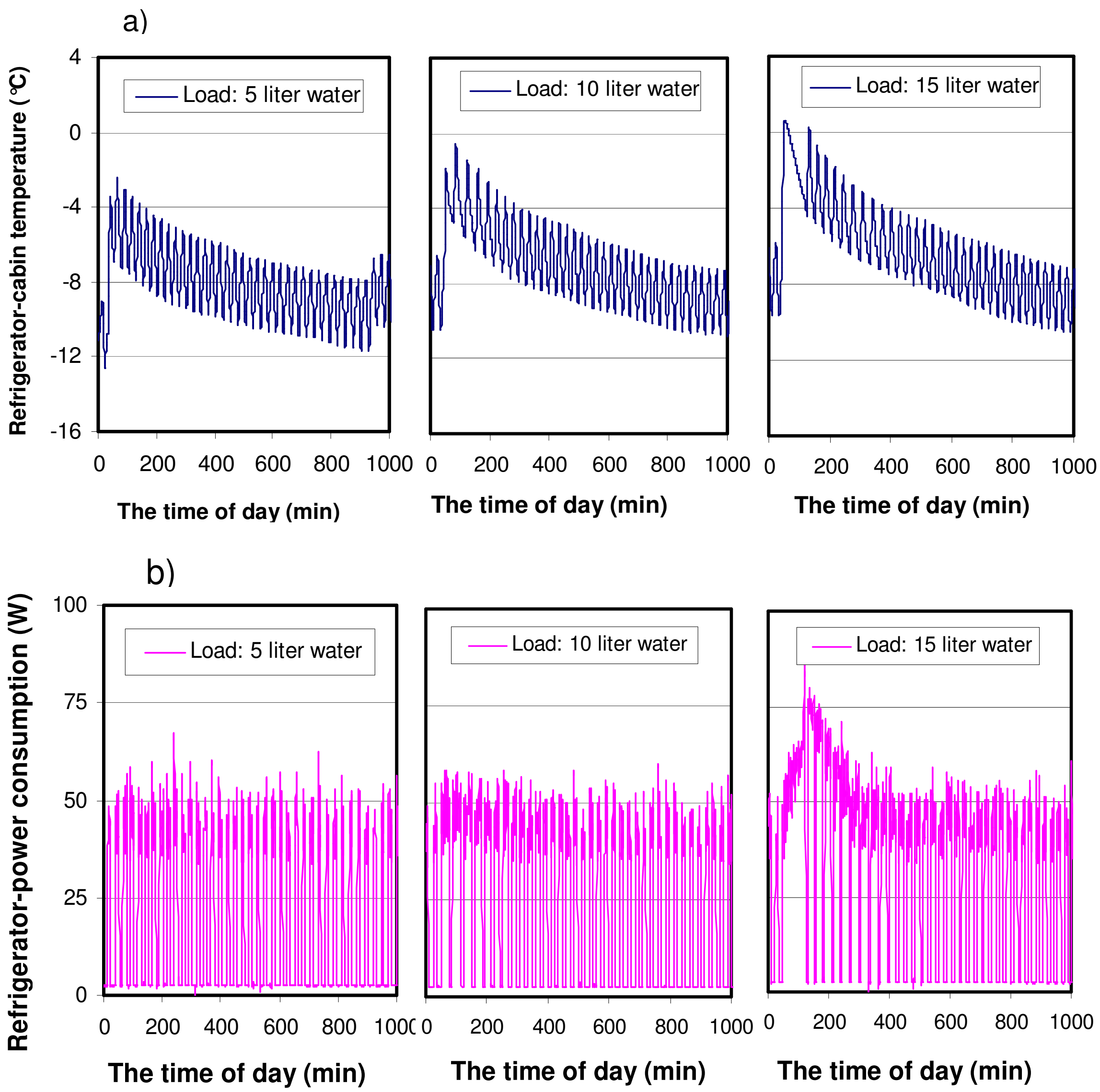

Figure 7. Relative effect of cooling load on instantaneous operating parameters of the PV-refrigerator under systematically increased cooling load condition for a typical hot day in May 2009, where t = 0 corresponds to local time of 8:00 AM; (a) refrigerator-cabin temperature, (b) refrigerator-power consumption.

to be 75 W for 15 L load. Then, the rate of consumption energy has become a regular (50 W).

Conclusion

In this study, a PV-powered multi-purpose refrigerator system has been established to investigate experimentally its daily and seasonal operating performance. The PV-refrigerator system is independent of the local electricity network. Operation of this system under Şanliurfa climatic conditions is continuously observed. During the daily operation of the refrigerator system, the parameters affecting the system capacity and performance were determined experimentally. The following findings were obtained from experimental study:

1. Low temperature of -10.6°C can be reached in the refrigerator while average indoor and outdoor temperatures are 26.3 and 24.9°C, respectively.
2. During the daily period, the highest energy amount produced by PV panels is recorded between 11:00 and 14:00.
3. Under Şanliurfa local conditions for a typical hot day in May 2009, energy consumption amount of refrigerator was determined to be 347.7 Wh/day. The amount of

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energy stored in the battery bank is 78.2 Wh/day while the amount of electric energy produced by photovoltaic panel is 425.9 Wh/day.

4. Energy balance of the refrigerator and PV system has been provided. The operating costs of this system were reduced due to operating lower power.

5. The energy required for refrigerator is provided by photovoltaic power, clean energy source. There is no negative impact of the electrical energy generation by PV panel on the environment.

It can be seen from results of this study that, the use of PV-refrigerator system is suitable for applications in different sector fields, required the low and medium cooling capacity. Such small-scale stand-alone system can suitably be used in many rural regions where electricity is unreliable or non-existent but refrigeration is continuously critical.

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