Solar Powered Refrigeration: Technical Challenges and Uses - A Review.

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ABSTRACT

Refrigeration is available in the industrialized countries through the availability of electricity but is not readily available in the major part of the world. An alternative solution for this problem is solar energy, available in most areas and it represents a good source of thermal energy; the combination of solar energy with absorption, adsorption, desiccant, and others technologies less studied for refrigeration are being investigated and improved around the world. This work reviewed various methods of solar refrigeration such as Photovoltaic Operated Refrigeration Cycle, Solar Mechanical Refrigeration, Absorption Refrigeration, and the Solar Thermal Method. This work also treated technical problems in solar refrigeration and the uses of solar refrigeration.

(Keywords: solar refrigeration, absorption, electricity, cooling, photovoltaic technology)

INTRODUCTION

Energy supplies for refrigeration and air-conditioning systems constitutes a significant role in the world [1]. The International Institute of Refrigeration (IIR) has estimated that approximately 15% of all electricity produced worldwide is used for refrigeration and air-conditioning processes of various kinds (Lucas, 1988) [2].

According to the statistics survey by JARN1 and JRAIA2, the demand for air conditioners worldwide has the fundamental tendency of steady increase (IIR, 2006) [3]. The global growth rate is about 17%. The cooling load is generally high when solar radiation is high. Together with existing technologies, solar energy can be converted to both electricity and heat; either of which can be used to power refrigeration systems [1]. The idea is not new, a solar-driven refrigerator was first recorded in Paris in 1872 by Albel Pifre (Thévenot, 1979) [4]. A solar boiler was used to supply heat to a crude absorption machine, producing a small amount of ice.

Solar powered refrigeration systems have been installed worldwide in many countries e.g. Australia, Spain, and the USA. Most are thermally driven absorption systems, designed for air-conditioning purposes [1]. Being provided with a good electricity grid worldwide, people are, however, more likely to choose a vapor compression air-conditioning system.

Before the energy crisis in the 1970s, research and development on solar thermal driven refrigeration systems was notably reduced. Subsequently, electricity-driven vapor compression systems have played a significant role on the market. At that time, photovoltaic (PV) technology was expensive, had low efficiency and was not as widely available as today [1].

Due to energy shortages in some regions, especially after the energy crisis of the 1970's, solar energy as a renewable energy source has once again become a popular energy source. Research and development in the solar energy field has grown rapidly, along with research in solar cooling.

With the invention of the DC-motor, photovoltaic technology was first used for pumping water [1]. Later the pump motor was modified to drive the vapor compression system. PV-driven water pumps and refrigerators have since become a relatively large business. Subsequently, researchers have integrated so-called Peltier coolers with PV-panels as simple, yet inefficient solar coolers. These systems are used in the cold chain projects of the World Health Organization (WHO). WHO initiated the development of solar refrigeration by photovoltaic panels in 1979, following the world conference on environment in Rio de Janeiro.

The first specification of a solar refrigerator for medical use was published by the 'Expanded Programme of Immunization' (EPI). WHO and the United Nations International Children's Emergency Fund (UNICEF) adopted a certifying procedure to ensure that refrigerators from different companies had the same standard. In 1993, WHO reported that solar-driven refrigerators could improve the storage and transportation of vaccines in the EPI, which was better than the kerosene refrigerator (kerosene-driven diffusion absorption refrigerator, Electrolux type), and vaccines could consequently be distributed more efficiently.

In 1996, WHO concluded that solar-refrigerators had significant benefits fulfilling immunization activities. Furthermore, the photovoltaic power system could be coordinated with other applications in a medical center. However, WHO decided on refraining from an implementation program that focused exclusively on solar vaccine refrigerators, contending that it could not compete with gas-powered units in terms of investment and recurring costs (WHO, 1996) [5].

The number of solar refrigerators has been increasing annually. Fléchon, Lazzarin, et al. (1999) reported that a180 kilowatt peak (kWp) of solar driven refrigeration capacity had been installed by 1985, 740 kWp by 1993, and 1600 kWp by 1997. Almost half of the systems are installed and operating in Africa for vaccine storage. There are a few commercial systems currently available, e.g. a vapor-compression/PV and an absorption/ thermal collector. Solar air-conditioning systems have also been regularly in operation. Commercial absorption cooling machines (e.g. Yazaki (Japanese)) are available. According to Hans-Martin Henning (Fraunhofer Institute Ise, Germany), about 70 solar air-conditioning systems driven by the solar energy are in operation in Europe, with a total cooling capacity of 6.3 MW, corresponding to 17 500 m2 of installed solar thermal collector area (Meyer, 2005) [6].

REFRIGERATION METHOD AND TECHNOLOGIES IN REFRIGERATION

Photovoltaic Operated Refrigeration Cycle

Photovoltaics (PV) involve the direct conversion of solar radiation to direct current (DC) electricity using semiconducting materials [7]. In concept, the operation of a PV-powered solar refrigeration cycle is simple. Solar photovoltaic panels produce DC electrical power that can be used to operate a DC motor, which is coupled to the compressor of a vapor compression refrigeration system [7]. The major considerations in designing a PV-refrigeration cycle involve appropriately matching the electrical characteristics of the motor driving the compressor with the available current and voltage being produced by the PV array. Manufacturers of Solar Arrays generally state that a properly installed system will provide power for the solar refrigerator for over 20 years with no fuel costs and little maintenance [8]. The rate of electrical power capable of being generated by a PV system is typically provided by manufacturers of PV modules for standard rating conditions, i.e., incident solar radiation of 1,000 W/m^2 (10 800 W/ft^2) and a module temperature of 25°C (77°F). Unfortunately, PV modules will operate over a wide range of conditions that are rarely as favorable as the rating condition.

Battery-based solar systems require a high initial capital investment [8]. In addition, the power produced by a PV array is as variable as the solar resource from which it is derived. The performance of a PV module, expressed in terms of its current voltage and power-voltage characteristics, principally depends on the solar radiation and module temperature. Figure 2 shows a work done by Klien and Douglas 2005 indicating current (solid lines) and power (dotted lines) vs. voltage for a 1.32 m^2 (14 ft^2) single crystalline PV module at the reference condition and four operating conditions.

At any level of solar radiation and module temperature, a single operating voltage will result in maximum electrical power production from the module. Most of solar energy is harnessed by photovoltaic cells. This array of cells are massive in size and cost of manufacturing is also high [9]. The module represented in Figure 1 was done by Klien and Douglas (2005), shows the voltage that yields maximum power ranges between 30 and 35 volts for this PV array.

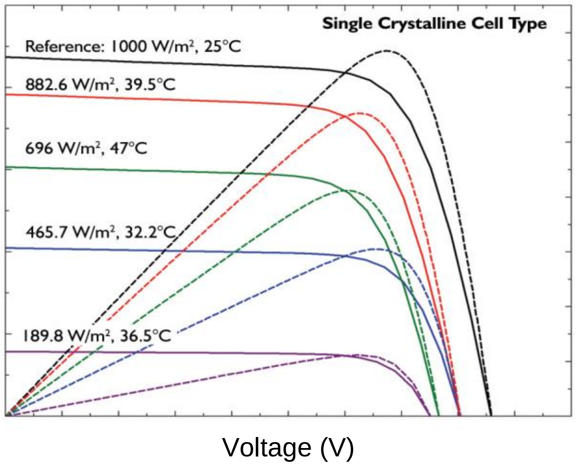


Figure 1: Current (solid lines) and Power (dotted lines) vs. Voltage for a Single Crystalline PV Module at Different Operating Conditions [7].

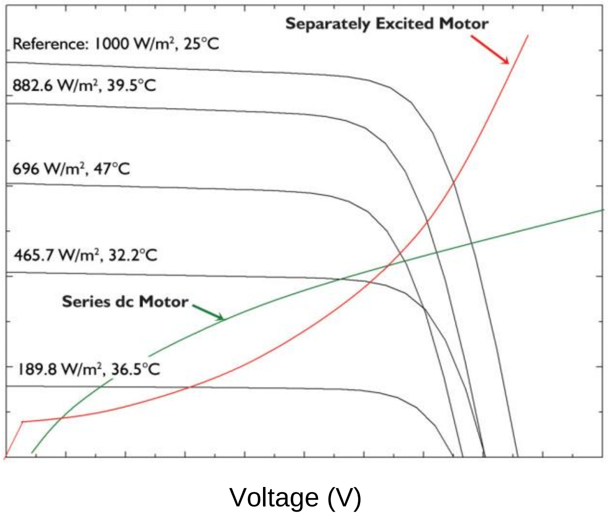


Figure 2: Current-Voltage Characteristics for a PV Module and two DC Motor Types [7].

The efficiency of the solar panels, defined as the ratio of the electrical power produced to the incident radiation, is between 8% to 10% at maximum power conditions for the PV array represented in Figure 1. If the PV refrigeration system is to operate at high efficiency, it is essential that the voltage imposed on the PV array be close to the voltage that provides maximum power. This requirement can be met in several ways. First, a maximum power tracker can be used which, in effect, continuously transforms the voltage required by the load to the maximum power voltage. If the system includes a battery, the battery voltage will control the operating voltage of the PV module [7]. PV panels can then be chosen so that their maximum power voltage is close to the voltage for the battery system. The battery also provides electrical storage so that the system can operate at times when solar radiation is unavailable. However, the addition of a battery increases the weight of the system and reduces its steady-state efficiency. Electrical storage may not be needed in a solar refrigeration system as thermal storage, e.g., ice or other low temperature phase storage medium, may be more efficient and less expensive.

A final option for systems that do not use a maximum power tracker or a battery is to select an electric motor having current-voltage characteristics closely matched to the maximum power output of the module. Figure 2 superimposes the current-voltage characteristics of a series dc motor and separately excited motor on the photovoltaic module [7]. In this case, the separately excited motor would provide more efficient operation because it more closely matches the maximum power curve for the photovoltaic module. However, neither motor type represented in Figure 2 is well-matched to the characteristics of the PV module over the entire range of incident solar radiation. Studies of solar-powered motors have shown that permanent magnet or separately excited dc motors are always a better choice than series excited dc motors in direct-coupled systems that are not equipped with a maximum power tracker.

Solar Mechanical Refrigeration

Solar mechanical refrigeration uses a conventional vapor compression system driven by mechanical power that is produced with a solar-driven heat power cycle [7]. The heat power cycle usually considered for this application is a Rankine cycle in which a fluid is vaporized at an elevated pressure by heat exchange with a fluid heated by solar collectors. A storage tank can be included to provide some high temperature thermal storage. Klien and Douglas (2005) showed in their work that the vapor flows through a turbine or piston expander to produce mechanical power, as shown in Figure 3.

The fluid exiting the expander is condensed and pumped back to the boiler pressure where it is again vaporized [7]. The efficiency of the Rankine cycle increases with increasing temperature of the vaporized fluid entering the expander, as shown in Figure 3 (bold line). The Rankine cycle efficiency in Figure 4 was estimated for a high-temperature organic fluid assuming that saturated vapor is provided to a 70% efficient expander and condensation occurs at 35°C (95°F) [7]. The efficiency of a solar collector, however, decreases with increasing temperature of the delivered energy. High temperatures can be obtained from concentrating solar collectors that track the sun's position in one or two dimensions. Tracking systems add cost, weight and complexity to the system. If tracking is to be avoided, evacuated tubular, compound parabolic or advanced multi-cover flat plate collectors can be used to produce fluid temperatures ranging between 100°C – 200°C (212°F – 392°F) [7].

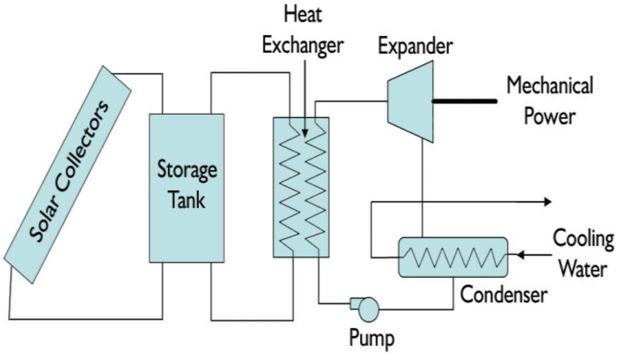
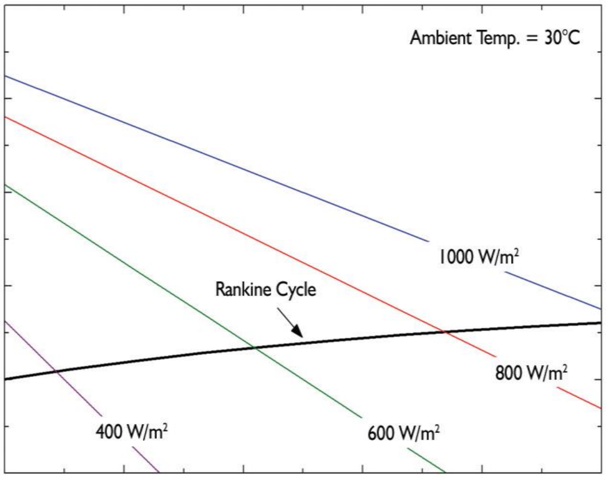


Figure 3: Solar Driven Mechanical Power Cycle [7].



Temperature (°C)

Figure 4: Approximate Efficiencies for a Rankine Cycle (bold line) and Evacuated Solar Collectors (fine lines) at 30°C (86°F) Ambient and Differing Solar Radiation Values [7].

The efficiency of solar collectors depends on both solar radiation and the difference in temperature between the entering fluid and ambient. Figure 4 done by Klien and Douglas (2005) also shows approximate solar collector efficiencies as a function of fluid delivery temperature for a range of solar radiation values. The overall efficiency of solar mechanical refrigeration, defined as the ratio of mechanical energy produced to the incident solar radiation, is the product of the efficiencies of the solar collector and the power cycle. Because of the competing effects with temperature, there is an optimum efficiency at any solar radiation. However, the optimum efficiency would be a maximum of 4.5% for the conditions assumed in Figure 4.

This efficiency is significantly lower than that which can be achieved with non-concentrating PV modules. Solar mechanical systems are competitive only at higher temperatures for which tracking solar collectors are required. Because of its economy-of-scale, this option would only be applicable for large refrigeration systems (e.g., 1,000 tons or 3,517 kWT).

Absorption Refrigeration

Absorption refrigeration is the least intuitive of the solar refrigeration alternatives. Unlike the PV and solar mechanical refrigeration options, the absorption refrigeration system is considered a "heat-driven" system that requires minimal mechanical power for the compression process [7].

It replaces the energy-intensive compression in a vapor compression system with a heat activated "thermal compression system." A work done by Klien and Douglas (2005) shows a schematic of a single-stage absorption system using ammonia as the refrigerant and ammonia-water as the absorbent is shown in Figure 5. Absorption cooling systems that use lithium bromide-water absorption-refrigerant working fluids cannot be used at temperatures below 0°C (32°F) [7].

The condenser, throttle, and evaporator operate in the exactly the same manner as for the vapor compression system. In place of the compressor, however, the absorption system uses a series of three heat exchangers (absorber, regenerating intermediate heat exchanger and a generator) and a small solution pump.

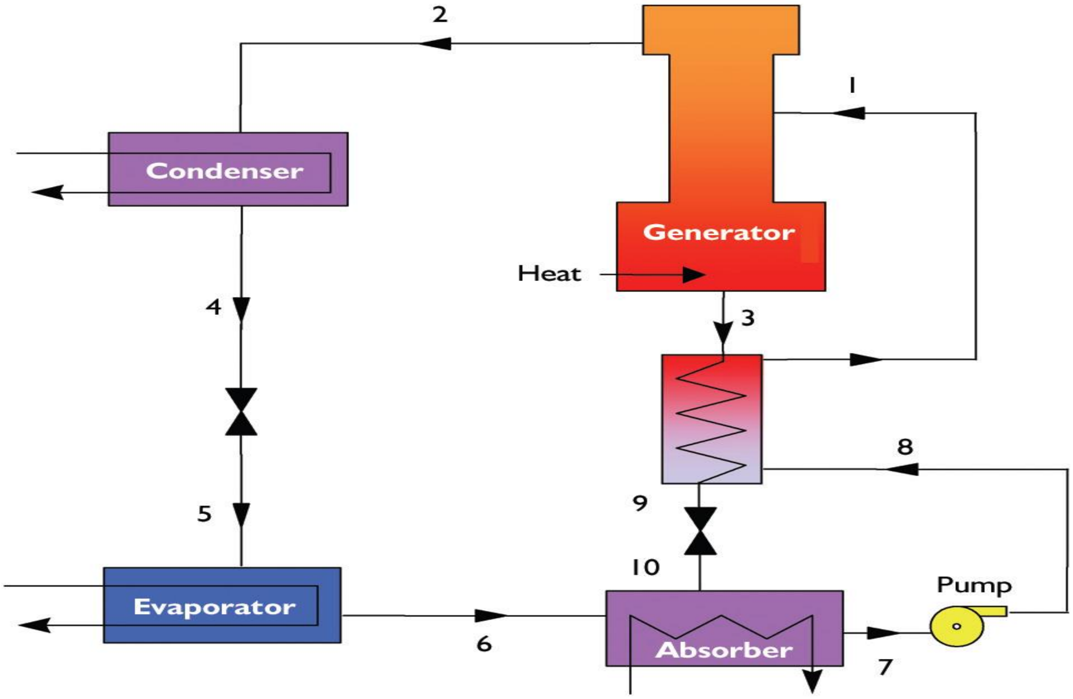


Figure 5: Ammonia-Water Absorption Refrigeration System [7].

Ammonia vapor exiting the evaporator (State 6) is absorbed in A liquid solution of water-ammonia in the absorber. The absorption of ammonia vapor into the water-ammonia solution is analogous to a condensation process. The process is exothermic and so cooling water is required to carry away the heat of absorption. The principle governing this phase of the operation is that a vapor is more readily absorbed into a liquid solution as the temperature of the liquid solution is reduced.

The ammonia-rich liquid solution leaving the absorber (State 7) is pumped to a higher pressure, passed through a heat exchanger and delivered to the generator (State 1). However, the power requirement for the pump is much smaller than that for the compressor since v, the specific volume of the liquid solution, is much smaller than the specific volume of a refrigerant vapor. It is, in fact, possible to design an absorption system that does not require any mechanical power input relying instead on gravity. However, grid-connected systems usually rely on the use of a small pump. In the generator, the liquid solution is heated, which promotes desorption of the refrigerant (ammonia) from the solution.

Unfortunately, some water also is desorbed with the ammonia, and it must be separated from the ammonia using the rectifier. Without the use of a rectifier, water exits at State 2 with the ammonia and travels to the evaporator, where it increases the temperature at which refrigeration can be provided.

This solution temperature needed to drive the desorption process with ammonia-water is in the range between 120°C to 130°C (248°F to 266°F). Temperatures in this range can be obtained using low cost non-tracking solar collectors. At these temperatures, evacuated tubular collectors may be more suitable than flat-plate collectors as their efficiency is less sensitive to operating temperature.

The overall efficiency of a solar refrigeration system is the product of the solar collection efficiency and the coefficient of performance of the absorption system.

The COP for a single-stage ammonia-water system depends on the evaporator and condenser temperatures. The COP for providing refrigeration at –10°C (14°F) with a 35°C (95°F) condensing temperature is approximately 0.50 [7]. Advanced absorption cycle configurations have been developed that could achieve higher COP values. The absorption cycle will operate with lower temperatures of thermal energy supplied from the solar collectors with little penalty to the COP, although the capacity will be significantly reduced.

A number of barriers have prevented more widespread use of solar refrigeration systems. First, solar refrigeration systems necessarily are more complicated, costly, and bulky than conventional vapor compression systems because of the necessity to locally generate the power needed to operate the refrigeration cycle. Second, the ability of a solar refrigeration system to function is driven by the availability of solar radiation. Because this energy resource is variable, some form of redundancy or energy storage (electrical or thermal) is required for most applications, which further adds to the system size and cost.

The advantage of solar refrigeration systems is that they displace some or all of the conventional fuel use. The operating costs of a solar refrigeration system should be lower than that of conventional systems, but at current and projected fuel costs, this operating cost savings would not likely compensate for their additional capital costs, even in a long life-cycle analysis. The major advantage of solar refrigeration is that it can be designed to operate independent of a utility grid.

Applications exist in which this capability is essential, such as storing medicines in remote areas. Of the three solar refrigeration concepts presented here, the photovoltaic system is most appropriate for small capacity portable systems located in areas not near conventional energy sources (electricity or gas). Absorption and solar mechanical systems are necessarily larger and bulkier and require extensive plumbing as well as electrical connections.

In situations where the cost of thermal energy is high, absorption systems may be viable for larger stationary refrigeration systems. The solar mechanical refrigeration systems would require tracking solar collectors to produce high temperatures at which the heat power cycle efficiency becomes competitive. If the capital cost and efficiency of tracking solar collectors can be significantly reduced, this refrigeration system option could be effective in larger scale refrigeration applications.

Solar Thermal Method

The main advantage of using the Solar Thermal Method is that they can utilize more of the incoming sunlight than photovoltaic systems [10]. In a conventional PV collector, 65% of the incident solar radiation is lost as heat whereas in solar collectors, over 95% of the incoming solar radiation is absorbed. But all of this is absorbed energy is not converted to useful energy due to inefficiencies and losses. Collection efficiencies for commercial solar thermal collectors are generally more than double that of crystalline photovoltaic solar collectors.

A typical solar thermal refrigeration system consists of four basic components - a solar collector array, a thermal storage tank, a thermal refrigeration unit, and a heat exchange system to transfer energy between components and the refrigerated space [10]. Selection of the solar array depends upon the temperature needed for refrigeration system. Generally, for temperature range 60-100°C, flat plate collectors, evacuated tube collectors and concentrating collectors of low concentration can be used. Concentrating collectors are avoided for residential purposes due to high cost of solar trackers. Selection of the thermal storage tank depends upon the type of storage medium and the temperatures desired. Water is mainly selected for its low environmental impact and high specific heat.

Desiccant

A desiccant system is usually an open cycle where two wheels turn in tandem – a desiccant wheel containing a material which can effectively absorb water, and a thermal wheel which heats and cools inward and outward flows. Warm, humid, outside air enters the desiccant wheel where it is dried by the desiccant material. Next, it goes to the thermal wheel which pre-cools this dry, warm air. Next, the air is cooled further by being re-humidified. When leaving, cool, conditioned air is humidified to saturation and is used to cool off the thermal wheel. After the thermal wheel, the now warm humid air is heated further by solar heat in the regenerator. Lastly, this hot air passes through the desiccant wheel so that it can dry the desiccant material on its way out of the cycle.

Pre-packaged desiccant is most commonly used to remove excessive humidity that would normally degrade or even destroy products sensitive to moisture. Some commonly used desiccants are silica gel, activated charcoal, calcium sulfate, calcium chloride, montmorillonite clay, and molecular sieves.

Adsorption

In this cycle, solar heat is directed to a sealed container containing solid adsorbent saturated with refrigerant. Once this reaches the proper temperature/pressure the refrigerant desorbs and leaves this container as pressurized vapor. That is, the vapor has been compressed with thermal energy. This vapor then travels to a condenser where it turns to liquid by rejecting heat to the surroundings. Expanded, low-pressure liquid refrigerant then flows over the evaporator which pulls heat from the conditioned space to boil off the refrigerant. The refrigerant vapor can then be adsorbed again by the cool adsorbent material easily at night. Although there are similarities between absorption and adsorption refrigeration, the latter is based on the interaction between gases and solids. The adsorption chamber of the chiller is filled with a solid material (for example zeolite, silica gel, alumina, active carbon and certain types of metal salts), which in its neutral state has adsorbed the refrigerant.

Advantages of Solar Powered Refrigeration

A solar-powered refrigerator is a refrigerator which runs on electricity provided by solar energy [10]. Solar-powered refrigerator are able to keep perishable goods such as meat and dairy cool in hot climates and are used to keep much needed vaccines at their appropriate temperature to avoid spoilage. Solar-powered refrigerators may be most commonly used in the developing world to help mitigate poverty and climate change [10]. In developed countries, plug-in refrigerators with backup generators store vaccines safely, but in developing countries, where electricity supplies can be unreliable, alternative refrigeration technologies are required.

Solar fridges were introduced in the developing world to cut down on the use of kerosene or gas-powered absorption refrigerated coolers which are the most common alternatives. They are used for both vaccine storage and household applications in areas without reliable electrical supply because they have poor or no grid electricity at all. They burn a liter of kerosene per day therefore requiring a constant supply of fuel which is costly, smelly, and responsible for the production of large amounts of carbon dioxide. They can also be difficult to adjust which can result in the freezing of medicine. The use of Kerosene as a fuel is now widely discouraged for three reasons: Recurrent cost of fuel, difficulty of maintaining accurate temperature and risk of causing fires.
Solar refrigeration has the potential to improve the quality of life for people who live in areas where electricity supply is inadequate and important role in industrial and commercial sector for cooling and heating applications [9]. The use of refrigeration is to keep food fresh, has become a part of our daily life in this society.

Challenges of Solar Refrigeration

The main technical problem of solar refrigeration is that the system is highly dependent upon environmental factors such as cooling water temperature, air temperature, solar radiation, wind speed and others [11]. On the other hand, its energetic conversion efficiency is low, and from an economic point of view, solar cooling and refrigeration are not competitive with the conventional systems.

CONCLUSION

Energy is the soul of the modern world. The economic growth and technological advancement of every country depends on it and the amount of available energy reflects that country's quality of life. Three vital factors—economy, population, and per capita energy consumption—have caused the increase in demand for energy during the last few decades, making reliable energy one of the massive challenges for the 21st century.

Solar refrigeration depends on solar energy from the sun. This work reviewed various methods by which solar energy can be utilized for refrigeration purposes. They are as follows- Solar Electric Method, Solar Mechanical Method and Solar Thermal Method. The work also treated uses of solar refrigeration and the technical challenges encountered with these technologies.

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