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Development and performance evaluation of solar powered ice-cream cart

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Abstract
Ice-cream is a widely consumed food across the globe especially during the summer season. The global ice-cream market, according to various reports, is expanding and is expected to touch greater heights with time. Due to high temperatures and inefficiency of conventional ice-cream storage units, the street vendors face challenge of storing ice-cream especially during peak summer times due to load shedding issues. To address the issue a solar powered ice-cream cart was designed, developed and evaluated for its performance and economic feasibility. The system was developed using off-the-shelf components *viz*, a chest freezer, a solar photovoltaic (SPV) array, a solar conditioner, a battery bank, and a hand-driven cart. The cost of the system was 96,000/- INR which was found to be reasonable keeping in view the benefits obtained from it. The system was tested at no load, 25% load, 50% load and full load conditions and the results obtained approved its feasibility. The minimum temperature of more than 22 °C was observed and the system provided a backup period of 16 hours. The instant COP of the system was found to be greater than 1 despite fluctuations in load and solar intensity. The total daily load of the system was calculated to be 1.92 kWh. The net present worth analysis, considering a system lifespan of 20 years, yielded a value of Rs. 24,530, the payback period for the invested capital was found to be 0.56 years, the benefit-cost ratio was calculated to be 1.7, supporting the system's economic viability. Additionally, the internal rate of return (IRR) over the system's 20-year lifespan was determined to be 35.8%. In terms of environmental impact, the system was shown to mitigate approximately 0.506 tons of CO_2 emissions per year, assuming an operational period of 330 days annually.

Keywords: Battery, ice cream, payback period, mitigate

Introduction

Solar energy refers to the energy produced from nuclear fusion reactions that occur in the sun's core, resulting in the emission of electromagnetic radiation such as visible light, ultraviolet light, and infrared radiation, which can be captured and converted into usable energy via a variety of technological processes [1]. It is one of the most reliable renewable energy sources that has the immense potential to transform our planet's energy landscape. It is a clean, plentiful, sustainable energy source that can lessen our reliance on fossil fuels while mitigating the effects of climate change as well as other ecological issues. International Energy Agency, in one of its reports even declared solar energy as the cheapest source of electricity and expects it to dominate global electricity market in coming decades [2]. Solar energy has become an increasingly popular source of renewable energy in recent years, with global installed solar capacity reaching over 600 GW in 2019 [3].

With ever improving living standards, the use of modern gadgets and appliances is increasing which in turn leads to rapid increase in energy demands. Refrigeration plays a key role since it facilitates the preservation and storage of food, medication, and other perishable commodities, all of which are necessary for a healthy and modern existence [4]. Refrigeration basically is the process where heat is removed from a space so as to cool it down and hence improve shelf life of the commodities stored there. To run the refrigerators various energy sources like gas, electricity, solar energy, etc. are used. Solar refrigeration is an innovative solution that aims to meet the increasing demand for sustainable cooling technologies. It utilizes solar energy as the main source of power for cooling, hence has the potential to significantly reduce carbon emissions by reducing dependence on fossil fuels, boosting CO_2 mitigation and therefore making it an attractive option for addressing climate change. Solar cooling is more appealing since cooling demand is often highest at periods of maximum solar radiation availability, and cooling is significantly more needed in hotter regions than in colder climates [5-6]. Along with being eco-friendly, reliable, sustainable and renewable way of cooling, solar refrigeration comes with additional benefit of being location independent which makes its implementation favorable in locations with limited or no grid electrical supply such as remote or far flung areas [7].

In this paper a solar operated refrigerator for ice-cream storage is discussed. Ice cream is a widely consumed dessert worldwide. Its consumption varies significantly with location and season and is mostly consumed during the peak summer times. A report by Research and Markets mentioned that the global ice cream market was valued at $70.8 billion in 2020 and is projected to reach $91.2 billion by 2026. In food industry, ice cream storage is seen as a challenging job since it needs to be stored at temperatures below freezing for its texture and quality maintenance. According to the United States Food and Drug Administration (FDA), ice cream should be stored at a temperature of -18 °C (0°F) or lower to prevent bacterial growth and maintain its quality. Any temperature fluctuations during storage can cause recrystallization of ice crystals, leading to a grainy texture and reduced shelf life [8-9]. Ice cream storage becomes more challenging for street vendors during summer times due to frequent power cuts and inefficient storage units (carts/portable refrigerators) used by them. The designed system aims at providing a reasonable solution to the problems faced by the street vendors. By virtue of solar energy, a considerable amount of ice cream is expected to be saved which otherwise could go waste due to inefficiency of conventional ice cream carts and frequent power cuts during peak summertime. The application can be further extended to pharmaceuticals as well as use in the food industry for other purposes. This in turn will lead to prevention of food wastage, hence reducing chances of food insecurity, energy wastage and aiding in overall economic development by providing support and job opportunities in the food industry. In health care, the solar refrigeration can be put to use in vaccine storage and making them available for populations of remote locations, e.g., tribals. By reducing dependence on conventional energy sources, this concept paves way to CO_2 mitigation, hence contributing to environmental conservation.

Material and Methods

The solar photovoltaic based refrigeration system was designed, fabricated and evaluated for its performance and working capacity at Department of Renewable Energy Engineering, College of Technology and Engineering, MPUAT, Udaipur. The system was developed by using off-the-shelf components *viz* solar modules, solar conditioner, freezer and a battery bank and all the components were mounted on a hand driven four wheeled cart. The specifications of the various components were calculated using following design criteria:

Cooling load in watts;

$$Q = \frac{mC_{p\Delta T}}{3600}$$

Where m is the mas of material to be cooled,

Cp is the specific heat of the load material, ΔT is the temperature difference.

Total load;

Total load (Wh/day) = DC load + AC load

Array load;

$$\text{Array load} = \frac{\text{Detailed Energy Consumption}}{\text{Battery efficiency x Charge regulatore efficiency}}$$

Array size;

$$\text{Array size} = \frac{\text{Array load}}{\text{Insolation x Mismatch factor (0.85)}}$$

Battery capacity

$$\text{Battery capacity} = \frac{\text{Total daily load (Wh/day)xStorage period in days}}{\text{Battery voltage x Battery efficiency x DoD}}$$

Tilt angle;

Tilt angle = Latitude + 15°

After doing the necessary assumptions and calculations, the CAD diagram of the system was drawn (Fig. 1).

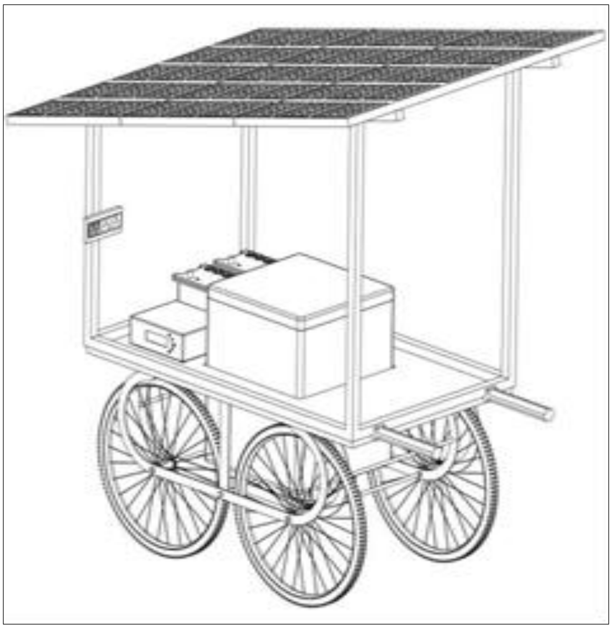

Fig 1: CAD diagram of the system

Instrumentation

For the measurements of various parameters, different instruments *viz*. lux meter, thermometer and multi meter (Clamp meter) were used for measuring solar intensity, temperature and current and voltage across the terminals respectively.

Testing methodology

The system was tested for no load, 25%, 50% and full load conditions at different times of the year (in different seasons). The process began by charging the system fully once and letting it discharge on its own. Then the no load condition testing was done, and the system was allowed to stand in the sun so as to test it in the conditions where it is expected to be used. The parameters *viz* solar intensity (Power), temperature and voltage were measured using lux meter, thermometer and multi meter respectively. Then 20 liters of water (25% load capacity) was filled in the freezer, and it was let to freeze. Once frozen, the system and allowed to stand so that the water could freeze and the time for which water remained frozen was noted down. The same procedure was repeated for 40 liters and 80 liters of water i.e., 50% and 100% load capacity respectively. Before each performance test, the batteries were fully charged, and smooth operations of the various components and instruments were ensured. In between the consecutive tests, system was allowed to rest so as to let it attain ambient temperature.

Calculation of Coefficient of performance (COP)
When assessing the effectiveness of a refrigerator, particularly one that uses the vapour absorption cycle, the coefficient of performance (COP) is a crucial thermodynamic measure. The ratio of the required energy input to produce the desired cooling effect is known as the COP in the realm of thermodynamics. It serves as an indicator of how effectively a refrigerator can transfer heat from a cold reservoir to a hot reservoir. Mathematically,

$$COP = \frac{\text{Refrigeration capacity}}{\text{Energy supplied to compressor}} = \frac{Qin}{P}$$

Or

$$COP = \frac{Qc}{W}$$

$$COP = \frac{\textit{Ambient temperature}}{(\text{Ambient temperature} - \text{Temperature inside the refrigerator})} = \frac{T_H}{(T_H - T_C)}$$

Where W stands for the energy input or work required to power the absorption cycle and Qc stands for the cooling effect, or the quantity of heat evacuated from the cold reservoir.

Assessment of the economic feasibility of the developed system
Techno-economic feasibility of the system was evaluated by calculating Net present worth, Benefit cost ratio, Internal rate of return and Payback period of the designed and developed system10.

Result and conclusion
After making the necessary assumptions and doing the calculations, specifications of various components were known. The details and specifications of various components are as follows:

Freezer: A top lid opening type chest freezer was used. The specifications of the component are stated in Table 1.

Table 1: Specifications of the freezer.

Parameter	Specifications
Type, make and model	Chest freezer, Cold wave, CWCF125
Climate type	T(5)
Anti-electric shock	Class I
Rated voltage	230V
Current	0.75A
Power	80W
Rated frequency	50Hz
Charging of refrigerant	R600a/40g
Insulation blowing gas	Cyclopentane
Gross/Net volume	93/86L
Dimensions (cm)	54 x 54 x 76
Body color	Milky white

The type of freezer used in the system is the chest freezer. While front-opening freezers have advantages such as quick access and view of stored items, chest freezers are often recommended for ice cream storage due to improved temperature control, effective cooling, and bigger storage space. When opposed to front-opening freezers, chest freezers have higher temperature stability. They have a design that keeps the cold air within the freezer even when the top is opened. This makes it suitable for use by street vendors as they tend to open the freezer frequently. This aids in the preservation of ice cream's flavour and texture by maintaining a consistent and stable temperature
The refrigerant i.e., the cooling agent used is R600a due to its low global warming potential and eco-friendly nature. The reason for this is the current theory of stratospheric ozone layer depletion by certain chlorofluorocarbons which has stimulated extensive study and development of novel stratospherically safe fluids for a variety of applications and R600a is one such fluid (Refrigerant) [5].

SPV array: An array of three SPV panels with rated power of 165W each were connected in parallel, generating a voltage of 19.47V and a power output of 495W, optimum for the smooth functioning of the freezer, meanwhile charging the batteries. The specifications of the modules are stated in Table 2.

Table 2: Specifications of the module

Parameter	Specifications
Make and model	UTL Solar, UTL 165W
Rated power (Pmax)	165W
Rated voltage	19.47V
Rated current	8.48A
Application class rating	Class A
Safety class rating	Class II
Maximum system voltage	1000V
Module dimensions (L x W x H)	1490mm x 670mm X 35mm

Solar conditioner: A solar conditioner with rated voltage of 675VA was used which performs the function of charge controller and inverter combined. The specifications of the unit are stated in Table 3.

Table 3: Specifications of the solar conditioner

Parameter	Specifications
Make and model	UTL Solar Heliac, SA675
Capacity	675VA
DC voltage	12VDC

Battery bank: since solar energy is time and weather specific, so a battery bank was provided to ensure input supply to the freezer during non-sunshine hours. The specifications of the batteries are stated in Table 4.

Table 4: Specifications of the battery bank

Parameter	Specifications
DC voltage	12VDC
Make and model	Select Acumen, SNS-100
Voltage	12V

Cart: All the above-mentioned components were mounted upon a hand driven cart with a platform covered with GI sheet and panels mounted above at an angle of 40°. The dimensions and other specifications are stated in Table 5 and the schematic view of the entire system is shown in Fig. 1.

Table 5: Specifications of the cart

Parameter	Specifications
Type	4-wheeled, hand driven
Dimensions (L x W x H)	154 cm x 95 cm x 200 cm
Tilt angle	40°

The total cost for the system was calculated to be around INR 95,000/- which is affordable, despite being more as compared to the conventional ice cream carts due to zero electricity bill.

From the data collected and the calculations done, it was interpreted that the system showed positive results in Udaipur (27° 42' N, 75° 33'E) during different times of the year. Significant and optimum temperature drop, and maintenance was observed which proved the system feasibility for use during peak summer times for apt storage of ice-cream and hence prevent melting and wastage of ice-cream due to regular power cuts. The minimum temperature recorded went beyond -22 °C and the average temperature maintained was -18 °C, which is optimum for ice cream storage. Once fully charged, the backup period recorded was 16 hours. The instant COP recorded was always greater than 1, despite variations in the solar intensity. The developed system exhibited several positive economic indicators. Its net present worth over a 20-year lifespan amounted to Rs. 24,530, indicating its financial value. The system's economic viability was further supported by calculations showing that the initial investment could be recovered in just 0.56 years of operation. Additionally, the benefit-cost ratio was calculated to be 1.7, highlighting the favorable economic outlook. The system's internal rate of return (IRR) stood at an impressive 35.8% over its 20-year lifespan. Furthermore, the system contributed to environmental sustainability by mitigating approximately 0.506 tons of CO_2 per year, assuming it operated for 330 days annually. With its wide range of potential applications, such as in the health sector, post-harvest handling and processing of various foods, seasonal tourism, defense, and geographical expeditions, the developed system held promise for various industries and sectors.

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