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The solar powered refrigerator and heat pump for urban street vendors.

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Abstract

This article proposes an integrated solar PV refrigerator and heat pump (ISPVRHP) for Sub-Saharan African food vendors; the warm chamber would keep prepared food warm until the food is sold, while the cold chamber would minimise food spoilage. The ISPVRHP proposed in this article can cool water or other beverages and be capable of utilising the heat rejected to the atmosphere by the condenser for warming food. The ISPVRHP was modelled using ANSYS software, and the results were validated experimentally. The results show that both systems work well at peak hours, especially under more intense sun rays. The study found that the variation of incident solar radiation and ambient temperature has significant effects on the performance of the ISPVRHP; the wind speed, however, has only a minor impact on the total heat load of the system. In addition, the systems (cooling and heating) reached the desired temperatures and maintained them for long periods. The capacity of the refrigeration system can be increased by increasing the component sizes, including the PV system size. The ISPVRHP performance dropped substantially when the doors remained open for extended periods due to loss of energy through mass transfer.

Keywords: photovoltaic system; refrigeration cycle; solar heat pumping; solar powered refrigeration; vapour compression refrigeration

1. INTRODUCTION

The demand for energy and related services to satisfy human social and economic development, welfare and health is increasing. As a result, there is a need for efficient energy conversion systems because energy resources are finite. Additionally, rapid urbanisation has increased the demand for electrical machines that preserve form. Urban population prefer cooked food that is warm, adding further energy needs.
This research responds to the need for a suitable food storage system for street vendors in Sub-Saharan Africa. In most cases, The vendors opt for buckets of ice to keep the beverages at low temperatures. The design is unique, low cost and provides a turn-key solution to street vendors and the food storage industry.

1.1 BACKGROUND

According to the Food and Agriculture Organization (FAO), sub-Saharan Africa (SSA) incurs postharvest losses (PHL) of about 37% of total food production, equivalent to 4 billion United States dollars [1]. One reason for the high PHL is that most smallholder farmers in rural SSA have minimal electricity grid access, limiting their food production storage options. The problem of food loss is not limited to smallholder farmers; prepared food vendors in SSA also experience high food loss and spoilage. The PHL problem is exacerbated by extreme heat caused by climate change, poor food handling practices and cold storage infrastructure. In addition, limited non-grid-dependent storage technologies are

available to the SSA smallholder farmers. Renewable energy technologies such as solar-driven evaporative cooling and photovoltaic-driven systems could be used as innovative refrigeration systems [2]. They would also help mitigate climate change and provide a sustainable way to meet the energy demand [1].
A significant portion of the SSA urban population procures prepared food from street vendors, at least during the day, driven by convenience and cost considerations. However, several researchers have raised food safety reservations, primarily related to food handling and storage.
The storage part of the PHL problem could be addressed by providing affordable storage solutions for street vendors. This paper reports on the design and experimental results of a solar photovoltaic refrigerator and heat-pump system to introduce a hybrid system that can satisfy both food refrigeration and warming needs of SSA street vendors. Two 90 W solar photovoltaic (PV) panels powered the integrated solar PV refrigerator and heat pump (ISPVRHP). The PV panels run a 149 – 186 W 12 Volt DC compressor that drove a refrigerant 134a in a vapour compression refrigeration system. The ISPVRHP had a combined capacity of 50L and could achieve 5°C – 10°C in the cold chamber and between 40°C – 50°C in the warm chamber. Photovoltaic (PV) systems provide an independent, reliable electrical power source at the point of use, particularly suited to remote locations. An uninterrupted power could be added to the system to maintain the system services

2. LITERATURE REVIEW

Most previous studies on solar refrigeration projects focused on solar thermal energy from concentrating or flat plate solar collectors; the heat would power an adsorption refrigerator, depending on the collector outlet temperature, cold store and ambient temperatures. The main advantage of this design principle is the relatively low cost of solar collectors compared to photovoltaics. Still, it suffers from a poor COP of the cooling circuit and therefore requires a large solar collector surface [3-5].

Some studies focused on solar refrigeration in rural areas with inadequate electricity supply [6-9]. For example, one study developed a solar refrigeration system for rural villages in Palestine. These villages have poor and inadequate energy sources, leading to a continuing low quality of life. The study developed a solar system with a DC to AC inverter that could power an AC refrigerator while minimising noise emanating from the compressor. The study used a conventional refrigerator that works on the vapour compression system. Although this design was developed for domestic use, it could also be used by small businesses within the community.

A Malaysian study found that micro compartments decrease the time needed to reach set-point temperature [9]. The study focused on an R134a refrigeration system with 150 × 150 × 250 mm macro compartments. The main objective of this study was to analyse and design an optimum cooling system for a macro compartment. The compartments were purposely designed to fit a bottle or drink can. They found that a cold drink would be cooled to the desired drinking temperature of about eight degrees centigrade within one minute. The study achieved this rapid cooling by optimising the heat exchangers that formed the evaporator and condenser. In addition, they optimised the compressor displacement and the expansion valve resistance. This approach is suited to the warm weather in countries such as Malaysia, where the demand for ice-cold drinks is high.

A Saudi Arabian study considered the incorporation of a DC compressor into an R134a refrigeration system [10]. They used a 75 W, 12V/24 V DC compressor powered by a150 V monocrystalline PV panels via a charge controller. They tested the system under load and

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no-load conditions. With no load, the compressors consumed 25 Ah to 87.96 Ah per day, depending on the thermostat setting. With the refrigerator load with water bottles, the compressor consumption increased to a maximum of 109.95 Ah. The most significant finding from the study related to the period that a 150 Ah battery was found to sustain refrigeration without power from the PV panels. They found that the battery would run the refrigerator for about 36 hours.

There has been a substantial amount of work in literature on solar PV-powered heat pumps for crop drying and air conditioning. In contrast, few studies have focused on low-temperature applications that would be relevant to this study. Ismail et al. [11] reviewed studies on low-temperature heating (below 80°C) applications of solar PV heat pumps and found that solar thermal collectors are preferred in this temperature range, primarily because of the cost-effectiveness compared with solar PV heat pumps. This study investigates this gap considering that there is waste heat rejected from the condensers of refrigerators. Thus, the study aimed to develop a dual system of solar PV-driven refrigeration and a heat pump with the heat pump utilising waste heat from the refrigerator. This goal is significant because energy recovery from the refrigerator increases the efficiency of the dual system.

3 METHODOLOGY

3.1 DESIGN PROCESS

The study opted for an ISPVRHP based on an R134a vapour compression refrigeration system (VCRS). A VCRS has four major components: an evaporator, compressor, condenser, and expansion valve. The ISPVRHP uses R-134a as the refrigerant and is concerned with analysing the heat load in both cooling and heating; therefore, a Mollier diagram is necessary to develop the refrigeration system. Property data of R-134a were taken from thermodynamic property tables.

Below are preliminary assumptions made for the system:

- Evaporator temperature: -2°C
- Cooling product: 500 ml Coca-Cola water bottle
- Condenser temperature: 50°C
- Heating product: Potatoes fries & sausages
- Refrigerant: R134a
- Volume: 50 litres

The primary task was to select a suitable compressor for the VCRS. To do this, the authors computed the heat loads in refrigerating and warming compartments. These two compartments represent a refrigeration system and a heat pump and share the same compressor. Table 1 presents a summary of the heat loads. It was determined that a compressor of a capacity higher than 148W was required to meet these loads. Therefore, the authors chose a 12V DC compressor with a cooling capacity ranging from 149W and 186W (selected from the available market catalogue). It was expected that the system would have a refrigeration coefficient of performance (COP_R) of about 3.32 and a heat pump coefficient of performance (COP_{HP}) of 4.32.

Table 1. Identification of heat loads in both compartments

Parameters	**Heating**	**Cooling**
Leakage load	224 kJ	879.7 kJ
Product load	159.6 kJ	2302.3 kJ
Infiltration load	10.5 kJ	31.5 kJ
Miscellaneous load	14.4 kJ	14.4 kJ
Total heat load	433.5 kJ	3550.7 kJ
Refrigeration capacity	377.4 W	493 W
Condensing capacity	484 W	639 W
Compressor	114 W	148 W
Mass flow rate	0.003 Kg/s	0.0039 Kg/s

The heat loads and the system performance were simulated using MATLAB and ANSYS, respectively. The simulations aimed to confirm the rejected heat from the condenser while the refrigeration runs on a vapour compression cycle. The heat collection in the isolated space will have the maximum temperature in the system, while the cooled side will have the minimum system temperature. Therefore, with the computer simulation, the temperature variance confirmed whether it was adequate for heating and cooling with time variations.

Figure 1 shows the arrangement of the evaporator and condenser in the two compartments. The condenser lies at the bottom of the heating compartment. The evaporator was placed at the top of the cooling space. This arrangement is informed by the physical phenomenon that hot air rises and cool air descends.

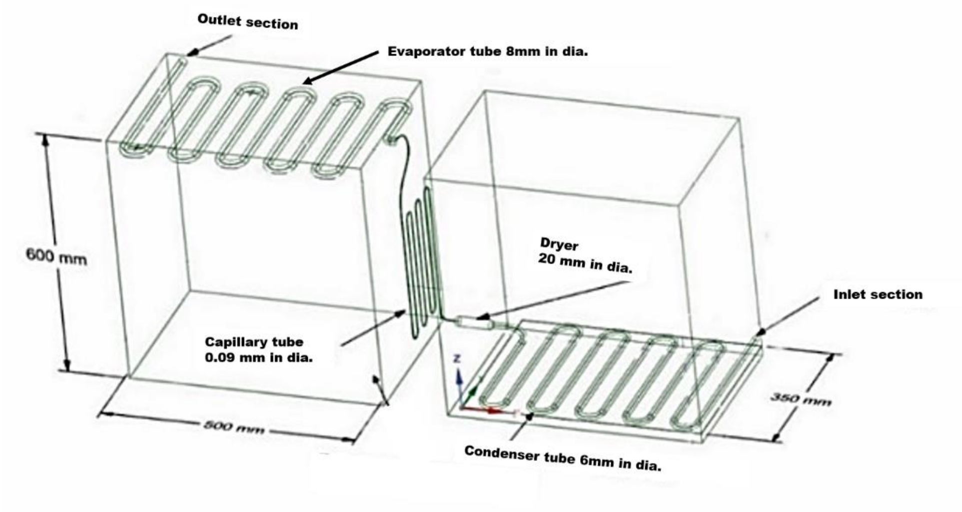

Figure 1. The layout of the evaporator and condenser

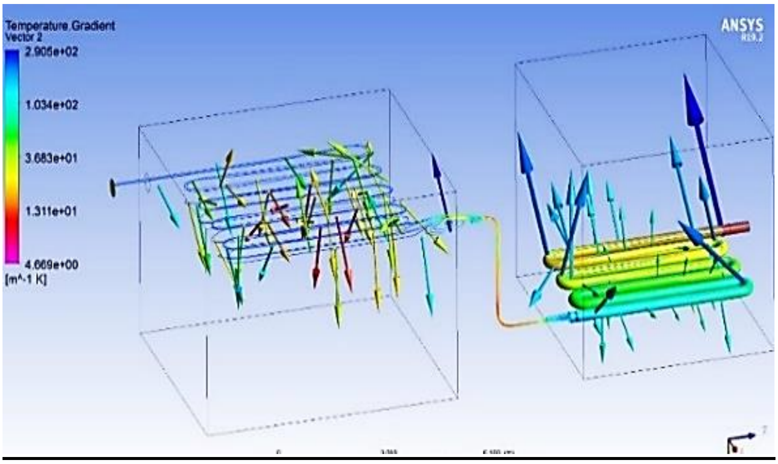

Figure 2. The ISPVRHP simulated air distribution

4 CONSTRUCTION

The adopted design principle for this work entails selecting appropriate components based on their operational characteristics and utilising suitable materials for construction and perfect finishing. Table 2 presents the topology and size of each component.

Table 2. Component selection for the ISPVRHP

Components	**Specifications/Dimensions**	**Quantity**
90 W Photovoltaic panel	Monocrystalline silicon panel 1200 × 544 × 25 mm	2
Compartment	50 litres	2
DC Battery	12V	1

Charge controller	10A	1
DC Compressor	12V	1

Two small household refrigerators were used as cooling and heating compartments to reduce costs. The 90W solar panel was used because a pair of identical panels were already available on-site. Therefore, all other aspects of the design were based on the size and specifications of the photovoltaic panel. Since the heating unit depends on the condenser's performance, the condenser has a practical design, and the heating container has been adapted to meet the design criteria. All individual parts were assembled and formed a single unit.

Figure 3. The components of the ISPVRHP

Figure 4. The ISPVRHP assembled for testing

5. EXPERIMENTAL WORK

5.1 ZONE CONDITIONS

The experimental testing of the ISPVRHP was done in Bellville, Cape Town, South Africa (Latitude and Longitude: 33.9249° S, 18.4241° E) for seven days in the summer between December 2020 and January 2021. The table below shows the weather overview in Bellville during the testing period.

Table 3. Weather overview (extracted from the Campbell data logger)

Months	Avg. temp	Avg. humidity	Avg. daily sunshine	Max. wind Speed	Avg. pressure
December	21°C	72%	10 h	6.25 m/s	1013.7 mbar
January	23°C	73%	11 h	7.08 m/s	1012.5 mbar
Avg. wind speed during experimental days					2.55 m/s
Avg. ambient temperature during experimental days					26.7°C

5.2 TOOLS AND EQUIPMENT

- 90Wp monocrystalline silicon PV panel
- Kipp & Zonen CMP6 and Kipp & Zonen SP-LITE silicon pyranometers
- 03101 R.M Young anemometer
- Campbell Scientific Weather Station
- SetSolar 12V, 102Ah battery
- 10A, 12V solar charge controller
- Thermometer
- K-type thermocouples
- Etekcity MSR-C600 digital clamp meter & multimeter

5.3 EXPERIMENTAL SETUP AND PROCEDURE

The cooling and heating performances were evaluated starting with empty spaces and then tested with compartments loaded with water bottles in the refrigerated compartment and potatoes and sausages in the heated compartment. The data recorded during the testing period included ambient temperature, wind speed and solar intensity for clear sunny days. The PV solar panels and the prototype sets were placed outdoors with the PV panels oriented north and at a slope of 30°C from the horizontal. Two thermocouples were placed inside the compartments to measure temperature variation. They were connected to temperature controllers with digital displays. Solar radiation was measured using a pyranometer that was part of a weather station. Figure 5 shows the pyranometer with a shading ring used to measure diffuse radiation. Another pyranometer measured the total solar radiation (diffuse and beam). An anemometer was used to measure air velocity. All sensors were connected to a data logger that recorded the variation of the measurements and stored the values as a CSV text file that was readable in MS Excel. Electrical energy recovery was monitored by recording voltages and currents generated by the PV every 15 minutes.

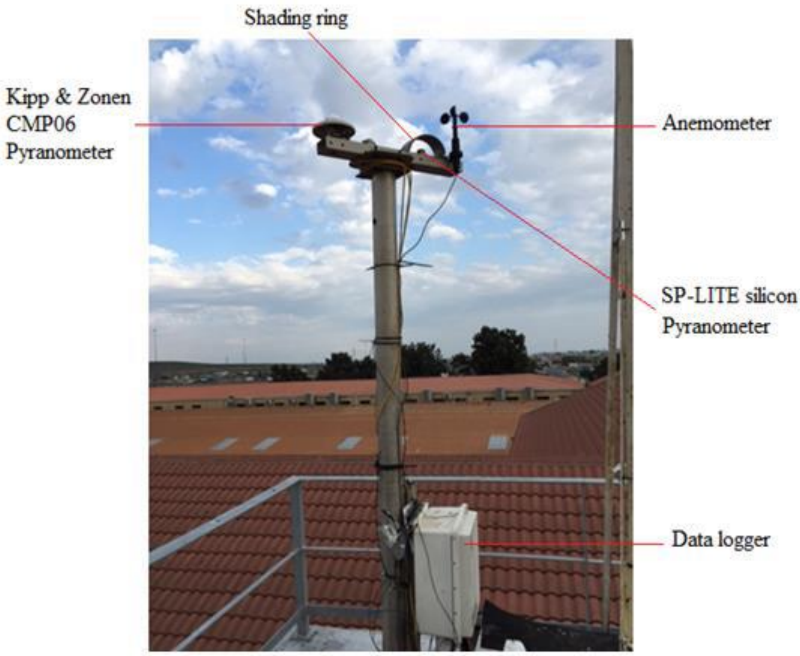

Figure 5. Bellville campus scientific weather station

The collected data were analysed for temperature variation in the refrigerated and heated compartments, the COP_R and COP_{HP} of the system. These parameters were analysed for loaded and unloaded compartments. In addition, the influence of PV panel tilt angle on the temperatures of the compartments and system performance was investigated.

6 RESULTS AND DISCUSSION

This section presents system performance results between December 2020 and January 2021. Meteorological parameters impacted the overall performance of the PV panels. The PV panels performed better on a sunny day as clouds and rain rendered the system ineffective. The section also presents a comparative analysis of the system performance of loaded and unloaded compartments. System performance measures included the duration set points for the refrigerated and heated compartments. The system ran for three days on empty and four days on loaded compartments. A comparison of PV panel performance for tilt and horizontal orientation was also made.

6.1 TEMPERATURES

Figures 6 and 7 show the temperature patterns for empty and loaded compartments for cooling and warming compartments. The patterns indicate that maximum temperatures occur between noon and 2 pm in refrigerator and heat pump compartments. The warming compartment reached a maximum temperature of 55°C with the system operating as a heat pump. The refrigerated compartment reached a low temperature of 2°C, which was quite good for keeping drinks as cold as possible throughout the day due to good radiation occurring around 11:00 am. However, it was observed that once the door was left open for more than 15 minutes, a drop in temperature was evident at 15:00 on the graph while running the heat-pump system. But the weather was good enough for the operation of the PV panels, and the results obtained were satisfactory.

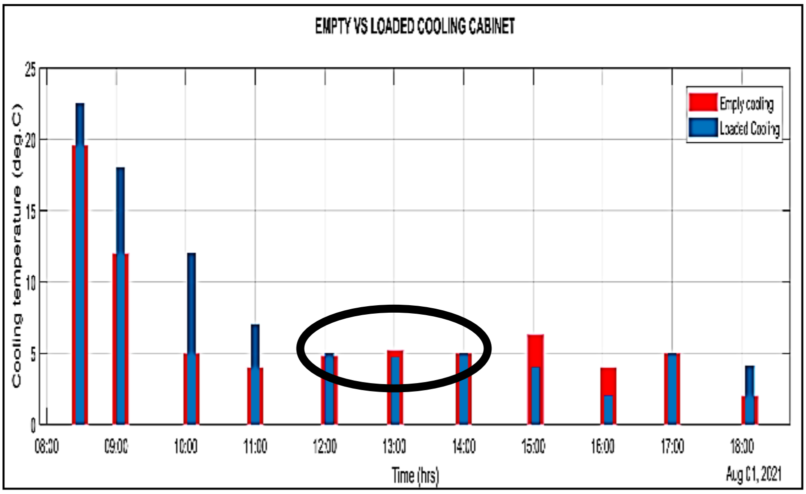

Figure 6. Temperature comparison on empty and loaded cooling system

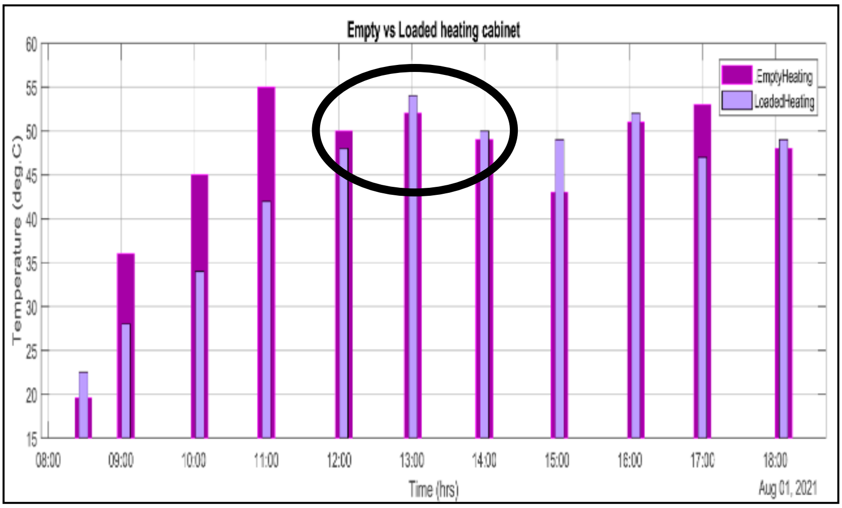

Figure 7. Temperature comparison on empty and loaded heating system

6.2 SOLAR RADIATION

Figure 8 presents the solar radiation received by the PV panels when inclined at an angle of 30° and horizontal. The finding that PV panel perform better at an inclination of 30°is consistent with the results of other studies [12-19]. There were variations in the intensity of solar radiation falling on the panels based on time, season, and location.
Figure 8 shows how the tilt angle influences the amount of solar radiation on the PV panel. It was observed that the 30° tilted PV panel received higher irradiance, which caused both systems to reach their design temperatures right before noon; therefore, it proved best suited for the entire system's performance. These values were validated for Cape Town and should not be used to estimate the best slope for a different location.

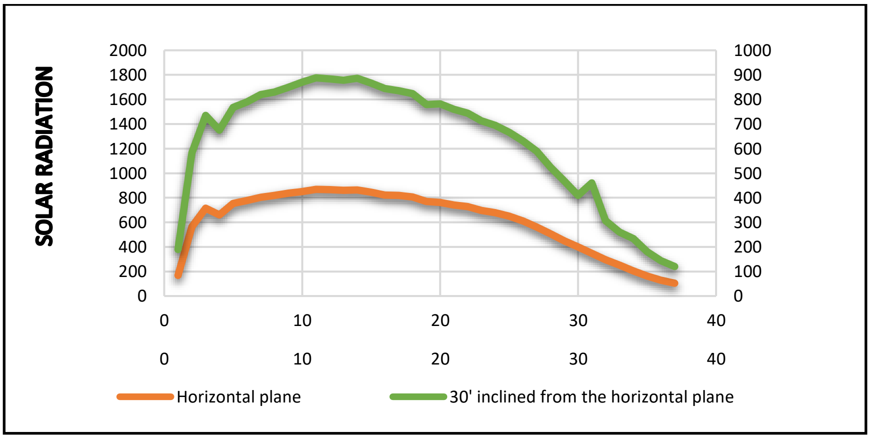

Figure 8. Horizontal PV panels vs 30° tilted PV panels

6.3 POWER CONSUMPTION AND COPS

The experiment also revealed that the total loads of the model with empty compartments were reasonably stable because only heat leakage contributed to the load. When the compartments were loaded, the temperature fluctuated during the first four hours before becoming stable. The difference in food temperature caused this variation. It was observed that the heat loads increased with the increase in ambient temperature, but the variation in wind speed had no significant impact on the total heat load. On the other hand, power consumption was affected by the number of products and the time the door was left open. At some point, the power consumption decreased to zero when the compressor was at rest.

The ISPVRHP demonstrated good overall efficiency under normal conditions; higher COP means higher efficiency and less power consumption. The average COP for the hot and cold compartments were 2.91 and 3.8, respectively. Several reasons for the lower efficiency of the heating system, in this case, are mechanical and fluid friction and heat loss to the surroundings. Other factors that may affect the efficiency are system controls and the efficiency of peripheral equipment like fans. Figure 9 shows some irregularities in the solar radiation trend due to the presence of a cloud in the path of the sunlight. Again, the increasing or decreasing trend of solar radiation is almost symmetrical, explaining why the system performance was at its best and the COP remained constant during those periods.

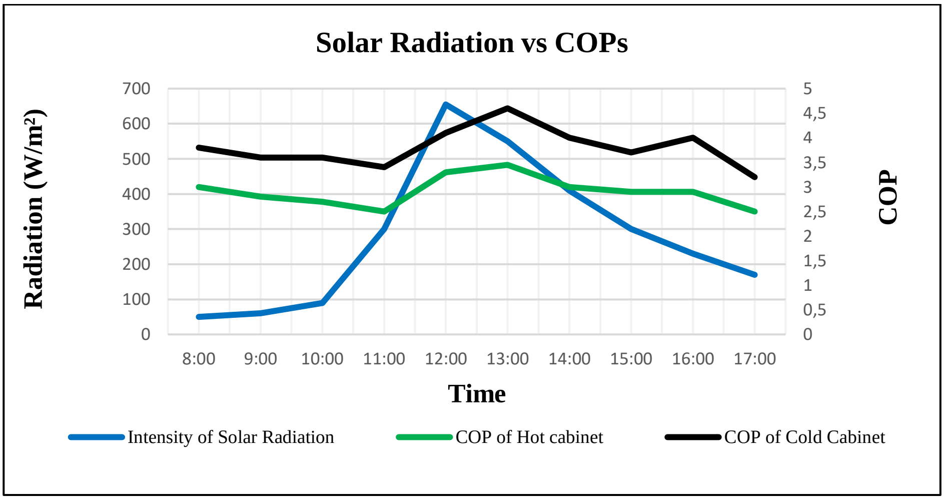

Figure 9. Effect of solar radiation on the COP of both systems

7 CONCLUSION

The study demonstrated that a VCRS could provide a dual function of cooling and heating, opening the possibility of street vendors using such an ISPVRHP to cool beverages and keep cooked food warm. This dual function is vital in remote areas where an ISPVRHP would increase the profitability of street vending by reducing the need for a separate refrigerator and food warmer.
Results have led to the following conclusions:

- The variation of incident solar radiation and ambient temperature significantly affects the performance of the ISPVRHP. The wind speed has only a minor impact on the total heat load of the system.
- The systems (cooling and heating) could reach ideal temperatures and maintain these temperatures for longer. When fully loaded, the refrigerator took time to bring the drinks to be cold due to the size of the evaporator. But on hot days, the performance of both systems was quite efficient.
- Several degrees, 25°, 30° and 34°, prove to be the ideal tilt angle since they give maximum solar radiance on the panel in Cape Town. For other geographical locations, the system might work efficiently at different slopes.

There is a need for further work on preventing rapid energy loss caused by the opening of the doors, as this is inevitable for ISPVRHP used by street vendors. Also, improving the heating system could make the entire device perform better.

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