EXPERIMENTAL STUDIES ON SOLAR PHOTOVOLTAIC REFRIGERATION SYSTEM.

BY

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A Thesis Presented to the
DEANSHIP OF GRADUATE STUDIES

KING FAHD UNIVERSITY OF PETROLEUM & MINERALS

DHAHRAN, SAUDI ARABIA

In Partial Fulfillment of the
Requirements for the Degree of

MASTER OF SCIENCE

In

MECHANICAL ENGINEERING

September, 2013

KING FAHD UNIVERSITY OF PETROLEUM & MINERALS

DHAHRAN- 31261, SAUDI ARABIA

DEANSHIP OF GRADUATE STUDIES

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Dedication

To my mum and dad.

ACKNOWLEDGMENTS

I give gratitude to Almighty God for sparing my life and making this thesis research a reality. All these would not have been possible without the support of my Advisor, Prof. Maged El-Shaarawi, and members of my thesis committee Prof. Amro Al-Qutub and Prof. Syed Said. Their advice and constructive criticism really helped me to executive this task successfully. The financial support provided by the center of research excellence on renewable energy, was instrumental for the actualization of this work and highly appreciated. Also, the knowledge acquired from all my professors in KFUPM during my master's program has been beneficial towards the completion of this work and I pray that God continues to enrich them in wisdom. Finally the morale support and prayers showered on me by my loving parents, siblings, and friends are greatly appreciated.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

PV	photovoltaic panel
AC	Alternating current
DC	Direct current
WHO	World health organization
A_e	effective area (m^2)
P	power (W)
V	voltage (V)
I	current (I)
I_T	total solar irradiance (W/m^2)
I_{PV}	solar irradiance received (W/m^2)
m	mass
L	latent heat of fusion of water (J/kg)
c	specific heat capacity (J/kgK)
t	time of the experiment
W	energy input
H_{SOL}	total energy received on the PV panel
H_{PV}	total energy produced by the PV panel
Q_{ref}	refrigeration effect
EMF	electromotive force
PWM	pulse width modulation
FS	full scale

COP	Coefficient of Performance

Subscript

orient	orientation
SOL	solar
comp	compressor
ref	refrigeration
w	water
max	maximum
mp	maximum power
sc	short circuit
oc	open circuit

ABSTRACT

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Thesis Title : [Experimental Studies on Solar Photovoltaic Refrigeration System]

Major Field : [Mechanical Engineering]

Date of Degree : [May 2013]

This thesis presents the outcome of the performance test and economic analysis of a simple photovoltaic powered vapor compression refrigeration system conducted in the eastern province of Saudi Arabia. The system has a 66W DC refrigerator, 100W PV mono-crystalline module and a 100Ah battery bank. Two different approaches are adopted for ice production (bulk mass loading pattern and distributed loading pattern). For the bulk mass loading pattern, a bulk mass of 0.6kg of ice was produced after 6hrs and 50mins with a refrigeration *COP* of 0.20. While for the distributed loading pattern, the thermal loads were distributed in the refrigerator compartment using ice trays of 300ml each for a total mass of 2.1kg. The performance was greatly enhanced and a refrigeration *COP* of 0.60 was obtained as the system operates continuously without any interruption or fault for the entire time of the experiment and ice was completely formed after 6hrs and 40mins. The performance enhancement is due to larger area to volume ratio of the distributed mass loading pattern when compared to the bulk pattern. As a result the heat transfer rate is higher in the distributed pattern compared to bulk pattern. At the maximum solar radiation, best PV efficiency was calculated to be 15.5% and best solar panel orientation was calculated to be 99%. It was however observed from the cost analysis that the system would not be economical without government subsidy on the system components or alleviating the current subsidy on the price of electricity in Saudi Arabia.

ملخص الرسالة

الاسم الكامل: عبدالحفيظ أديبي

عنوان الرسالة: دراسات عملية على نظام تبريدي شمسي

التخصص: الهندسة الميكانيكية

تاريخ الدرجة العلمية: 12 مايو 2013

تقدم هذه الرسالة, والتي أجريت في المنطقة الشرقية من المملكة العربية السعودية, نتائج اختبار الأداء والتحليل الاقتصادي لنظام تبريدي بسيط يعمل بالطاقة الشمسية ويدار من خلال دورة الانضغاط التقليدية. النظام لديه ثلاجة بقوة كهربائية تقدر بـ 66 واط. يتم اكتساب الطاقة من الشمس بلوحة شمسية أحادية البلورات بقوة كهربائية تصل إلى 100 واط, وبطارية تعمل بقوة 100 AH. يتم اعتماد نهجين مختلفين لإنتاج الثلج (نمط التحميل الشامل ونمط التحميل الموزع). في نمط التحميل الشامل، تم إنتاج 0.6 كجم من الثلج بعد 6 ساعات و50 دقيقة بمعامل أداء يقدر بـ 0.20. أما بالنسبة لنمط التحميل الموزع،فقد تم توزيع الأحمال الحرارية في مقصورة الثلاجة باستخدام حاوي للجليد يقدر حجم كل منها بـ 300 مل لمجموع كتلة 2.1 كجم. هذا النمط عزز بشكل كبير أداء نظام التبريد وتم الحصول على معامل أداء يقدر بـ 0.60. كما عمل النظام باستمرار دون أي انقطاع أو خطأ لكامل وقت التجربة وتم تشكيل الجليد بشكل كامل بعد 6 ساعات و40 دقيقة. ويرجع معامل الأداء الأعلى إلى القيمة الأعلى لنسبة المساحة إلى نسبة الحجم للكتلة الثلجية في نمط التحميل الموزع بالمقارنة مع نمط التحميل الشامل. ونتيجةً لذلك فإن معدل نقل الحرارة أعلى في نمط التحميل الموزع مقارنة مع نمط التحميل الشامل. في أقصى معدلات الإشعاع الشمسي، تم احتساب أفضل كفاءة كهروضوئية بـ 15.5٪ و تم احتساب أفضل توجيه للوحة الطاقة الشمسية لتكون 99٪. لكن لوحظ من تحليل التكاليف أن النظام لن يكون اقتصادياً دون الدعم الحكومي لمكونات النظام. أو بإلغاء الدعم المالي على سعر الكهرباء بالمملكة العربية السعودية.

CHAPTER 1

INTRODUCTION

The abundant solar energy, vast land area and natural resources make the Kingdom of Saudi Arabia of a great potential for developing and deploying solar energy systems. The kingdom has an annual solar irradiation of about 2200kWh/m^2 **(Alawaji 2001)** which is about twice the amount received in Europe and has a vast land area of 2,250,000km^2 and a desert climate. As a result of the climate conditions, extreme hot weathers are usually experienced and maximum ambient air temperature are reported just after the maximum solar irradiation **(Sahin et al., 1999)** thereby increasing the demand for refrigeration of food products, vaccines and drinking water.

1.1. Solar Refrigeration Options

Solar refrigeration, though less intuitive has gained attention in both academic and industrial research. Several technologies developed to harvest the energy from the sun for refrigeration purposes are generally categorized into solar electric, thermo-mechanical and sorption refrigeration technologies.

1.1.1 Solar electric refrigerators

The solar electric refrigerators comprises of photovoltaic powered vapor compression refrigerators, thermoelectric refrigerator, electrically driven Stirling refrigerator and magnetic cooling. The vapor compression and magnetic system are the most attractive solar electric refrigeration technologies **(Kim and Ferreira 2008)**. Also, **Klein & Reindl (2005)** concluded that the photovoltaic vapor compression refrigeration system is the most viable technology when compared with the thermo-mechanical and the sorption based systems. The photovoltaic vapor compression refrigeration system is a vapor compression refrigerator powered with photovoltaic converters.

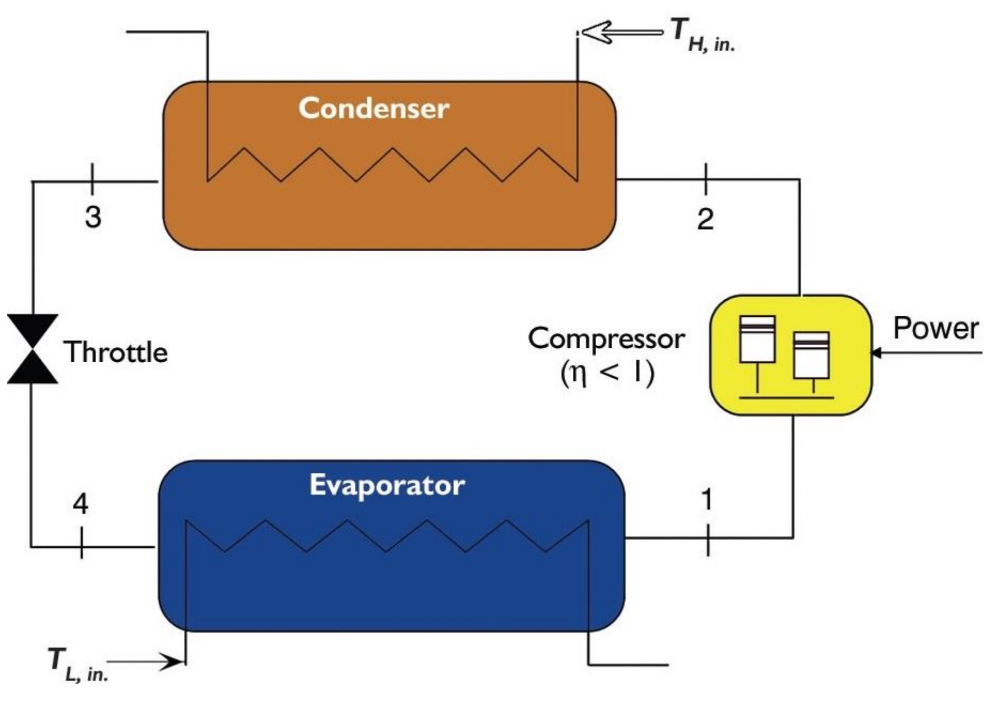


Figure 1 Schematic of a vapor compression refrigeration system. Klein & Reindl, (2005)

The photovoltaic converters are made up of semiconductor materials which convert parts of the solar energy into electrical energy. An ideal vapor compression system is a four-process cycle as presented in Figure 1 and Figure 2. The refrigerant is compressed at constant entropy to the condenser pressure and enters the condenser superheated. Then it leaves after been condensed to an expansion valve or a capillary tube which throttles the refrigerant into the evaporator where the heat is removed from the cooling cabin or compartment. While the vapor compression technology might be matured, a solar driven vapor compression refrigerator is faced with several challenges one of such is the intermittent nature of the sun necessitating the need for energy storage either through electrical or thermal energy storage media.

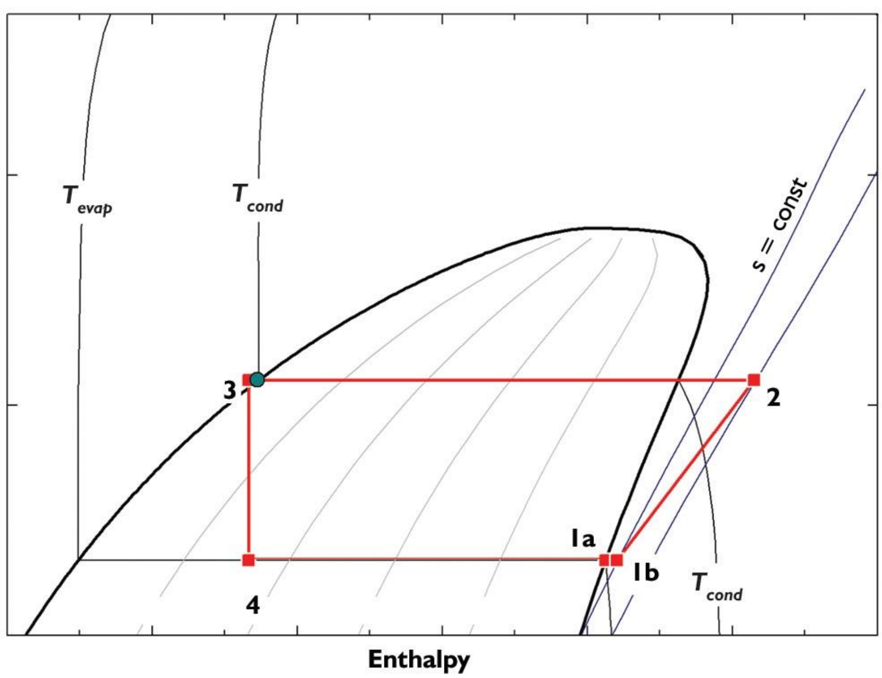


Figure 2 Pressure-enthalpy diagram for a vapor compression system. Klein & Reindl, (2005)

1.1.2 Thermo-mechanical refrigerators

A thermo-mechanical refrigeration system uses the heat supplied from a solar energy system to power a heat engine typically Rankine engine which then drives the compressor of a vapor compression refrigeration system. Heat is usually collected by a flat plate or an evacuated tube solar collector using an organic fluid as the working fluid which then flows through a heat exchange unit that converts the high pressure fluid to vapor which produces mechanical energy that drives the compression system of the vapor compression unit. The vaporized fluid is then passed through a condenser that cools and condenses the fluid after which a pump returns the fluid back to the heat exchange unit thereby completing the cycle. A typical thermo-mechanical refrigeration system is shown in Figure 3.

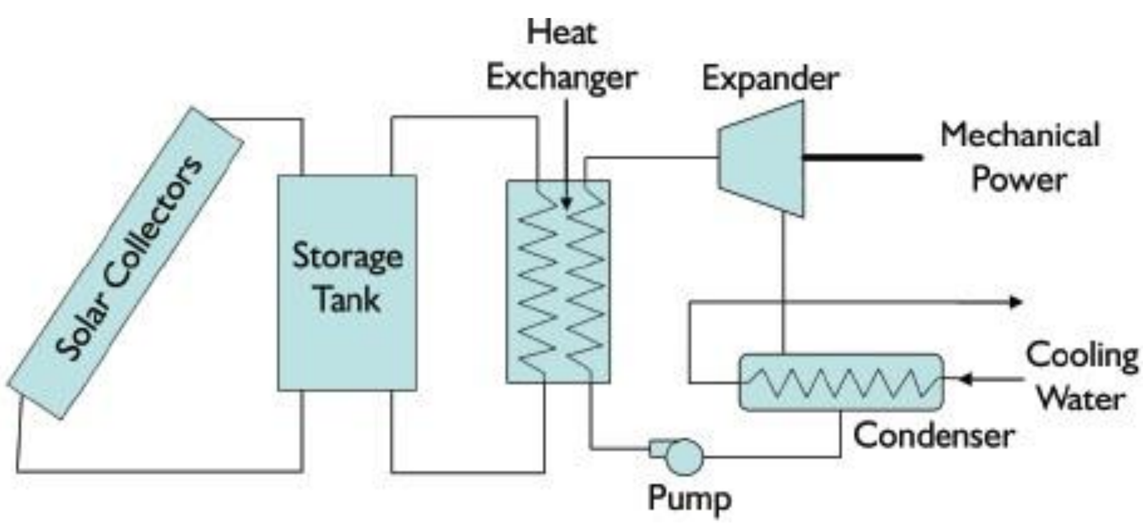


Figure 3 Thermo-mechanical solar refrigeration system. Klein & Reindl, (2005)

1.1.3 Sorption refrigerators

This system is completely heat driven, utilizing the affinity between a pair of substances to produce refrigeration effect and they are generally categorized as absorption, adsorption and desiccant systems. One of the substance pair called the sorbent, absorbs and desorbs the other one called the sorbate thereby creating a cooling effect in the process.

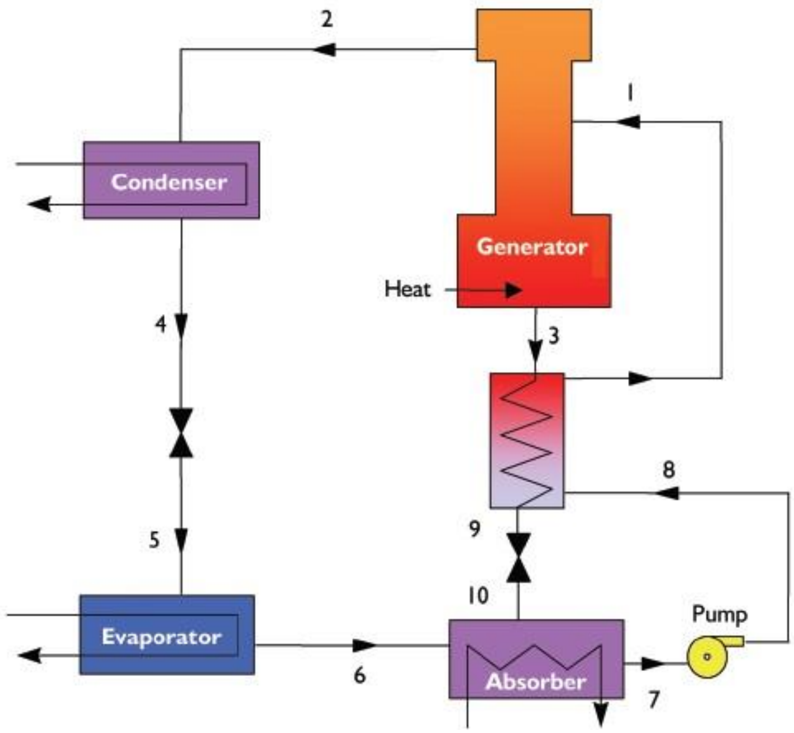
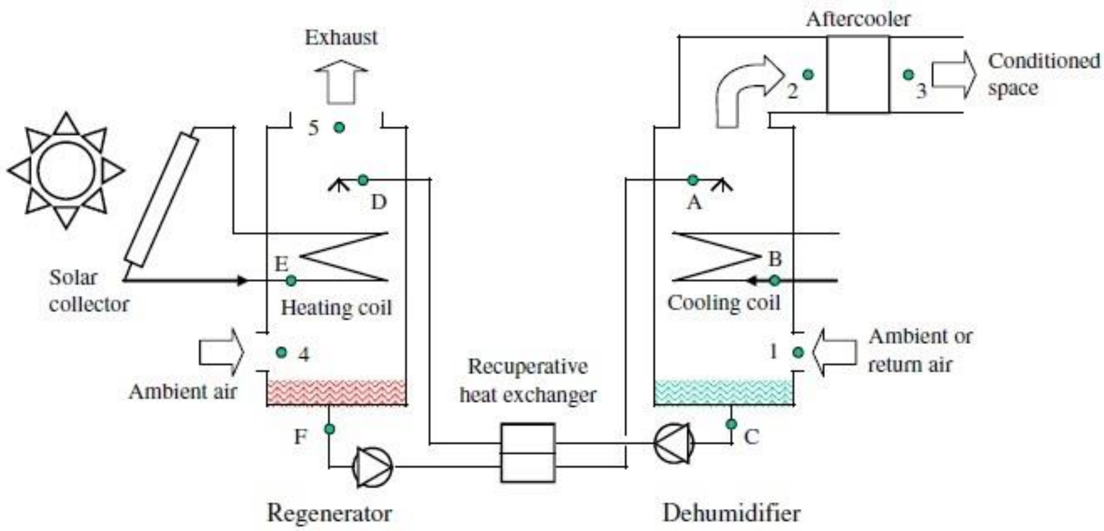


Figure 4 Schematic diagram of solar ammonia absorption refrigeration system. Klein & Reindl, (2005)

The system generally consists of an absorber where the absorption takes places, a generator which receives heat from a solar collector and desorbs the sorbent from the sorbate thereby regenerating the refrigerant which is then passed into a condenser. The fluid leaving the condensers is cooled down and throttled into the evaporator where refrigeration takes place.



/Figure 5 Schematic diagram of liquid desiccant cooling system. (Kim and Ferreira 2008)

In absorption systems the sorbent, is either in liquid or solid forms and they absorb the molecules of the sorbate into its inside and changes chemically and or physically during the process. While in the adsorption systems, the sorbent is in solid form and it attracts the molecules of the sorbate to its surface (called adsorption process) without undergoing any significant change in its form. Also a desiccant system uses a solid or liquid desiccant to absorb moisture from humid air. A typical absorption system is shown in Figure 4 while typical desiccants systems are shown in Figure 5 and Figure 6.

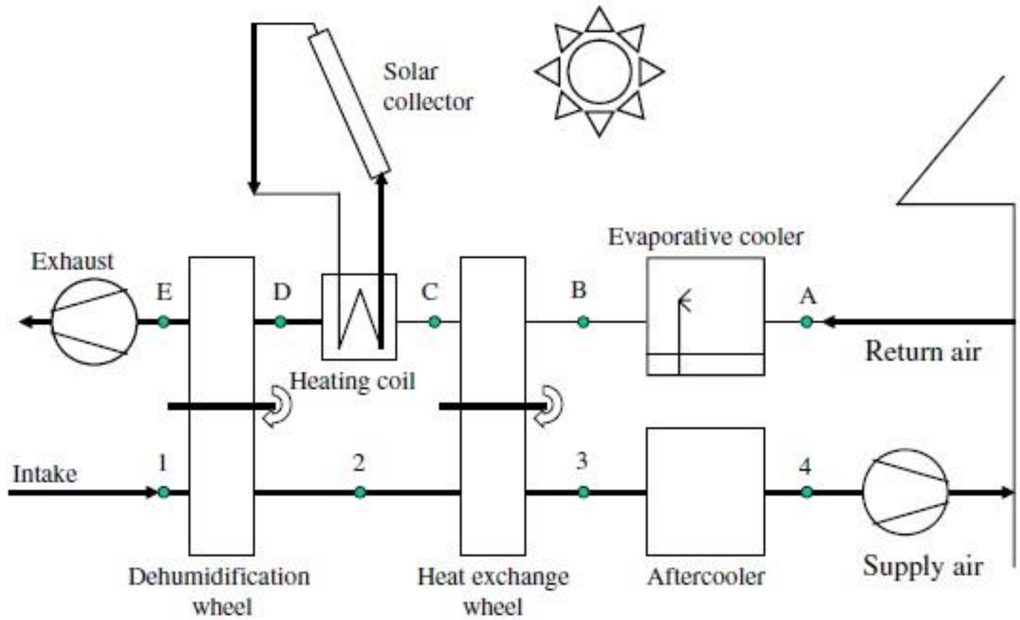


Figure 6 Schematic diagram of solid desiccant cooling system. (Kim and Ferreira 2008)

1.2 Scope of Study

Photovoltaic based vapor compression refrigerators are simple systems consisting of a photovoltaic generator/module which generates the electrical energy that drives the vapor compression thermodynamic cycle. It usually incorporate an energy storage medium mostly in the form of battery or latent energy storage that operates the system in the absence or insufficient solar energy. Though the vapor compression system might be matured, the adoption of a solar photovoltaic driven one has been affected by several challenges. One of such is the deposition of dust on the photovoltaic panels. For a dust deposition density of 22gm^{-2} a 26% reduction in efficiency of a photovoltaic cell was observed **(Lu et al., 2011)**. Another challenge is the intermittent nature of the sun which has necessitated energy storage and management.

In this study a technical and economic analysis is conducted on a solar photovoltaic vapor compression refrigeration system. Experiments are conducted in the premises of King Fahd University of Petroleum & Minerals, Dhahran. Dhahran is an area situated on the north eastern part of the kingdom near the coast of the Arabian Gulf on the latitude 26^{O}N and longitude 50^{O}E. The area is a desert region characterized with low precipitation rate, high ambient temperature and frequent sand storm. Monthly averaged daily ambient air temperature for Dhahran during the period from October 2005 till January 2013 is given in Figure 7.

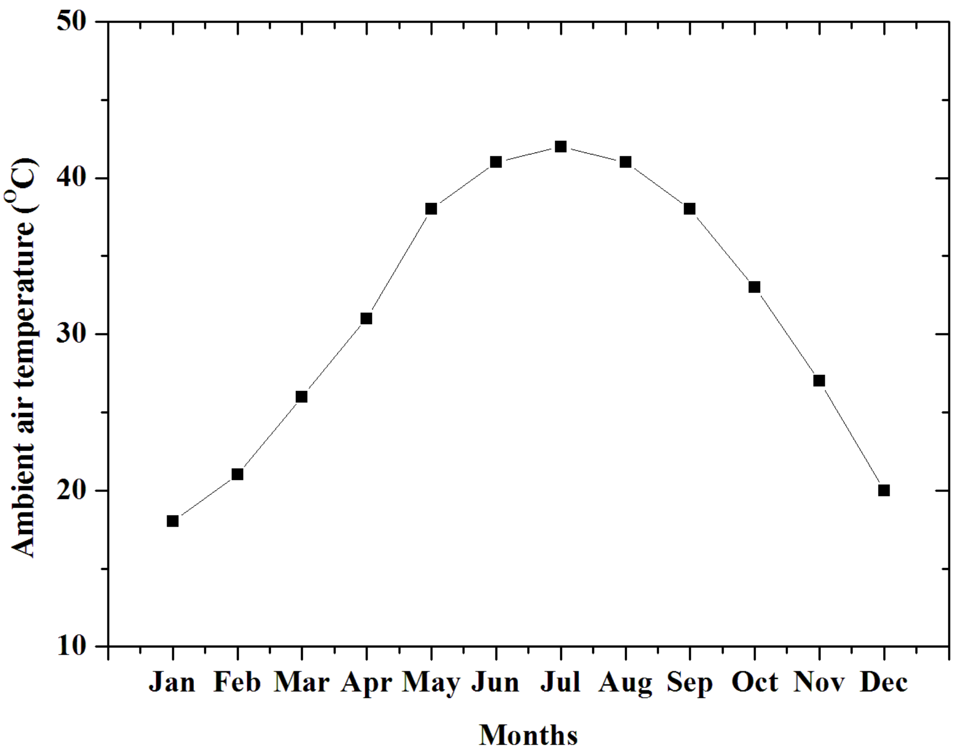


Figure 7 Monthly averaged daily ambient air temperature from 10/2005 – 1/2013 in Dhahran. (Weather Statistics Dhahran).

CHAPTER 2

LITERATURE REVIEW

Several studies and development have taken place in the past few decades towards the adoption of solar PV refrigeration for homes, vaccine preservation and industrial purposes. The main problem mitigating the adoption of solar cooling systems especially in rural communities is the high initial cost and lower system efficiency compared to convention systems **Enibe (1997)**. Most PV refrigeration vapor compression systems developed are either electrical energy storage or thermal energy storage based.

2.1 Electrical Energy Storage Based Systems

Large number of the solar PV refrigeration systems reported in the literature uses electrical energy storage. These systems commonly use a battery bank consisting of one or more batteries connected in series or parallel to meet the energy needs of the refrigerator during low or no solar radiation.

Kilfoyle et al. (1990) narrated the lessons learnt from testing three photovoltaic vaccine refrigerators in Florida and compared the performance with a kerosene powered adsorption refrigerator. The three photovoltaic based systems have the following descriptions. System 1 has a refrigerator of Marvel 4STD model of 127L, powered by Solarvolt 6-MSVM4011 40W PV panel with incorporated Exide 4 × GC-IV 6v-220Ah battery and a prototype 12V charge controller. System 2 has a refrigerator of Sunfrost

RFV- 4 model of 84L, powered by Arco 3-M55 53W PV panel with incorporated NIFE Sunica 3 × SUN 31-3 4v-338Ah battery. System 3 has a refrigerator of Polar Prod RR-2 model of 127L, powered by Solarex 5-SX147 47W PV panel with incorporated IBE 2 × Power-Plus 6v-368Ah battery and Polar Prod PCC 12V charge controller. The kerosene power adsorption system is SIBIR S2325/PEV1ST of 232L. In the PV systems the performances of the arrays were stable and the refrigerator performance is reliable but it is affected by decline in battery capacity. However the kerosene based adsorption system is less expensive and freezes the ice rapidly albeit requires a regular supply of fuel which causes air pollution.

In the work of **Omer (1991)** the performance of a photovoltaic solar refrigerator system under the climatic condition of Sudan was conducted. The system consists of a refrigerator cabinet with 180L capacity and 24V DC compressor using R12 as refrigerant, six PV modules of 40W each, two 12V-105Ah batteries and a charge controller. The COP of the refrigerator was found to be 77% at low cooling and 64% at maximum cooling levels.

Kattakayam (1997) developed and tested a PV-AC refrigeration system with both battery and kerosene generator back up for rural agricultural purpose in India. The system consists of a 165L refrigerator running on 50Hz main supply with voltage range 170-270V, thermostat, eight PV panels having peak power of 35W, four 6V/180Ah lead acid battery, inverter and a 1kVA back-up generator. The inverter was designed to take into account the compressor stop, start and run characteristics in order to reduce the overall power consumption and a 25-30% energy savings was recorded without negatively affecting the temperature profile in the refrigerator.

Bahaj (2000) investigated the performance of a trailer photovoltaic refrigerator system in the UK. The system has 4.4kW PV array, charge controller, battery bank, inverter and refrigerator unit designed to operate on 3^{o}C and 7^{o}C temperature set points. It was observed that the average energy consumption during a 2hrs delivery time at an ambient temperature of 12^{o}C was 3.2Wh/delivery. Also the thermal load was observed to increase as a result of the incident solar radiation on the surface of the trailer when stationary and reduces when the trailer was moving.

Nagaraju et al. (2001) investigated the performance of a photovoltaic powered cold room designed to store 10tons of fish at -15^{o}C. The system has a 4kW photovoltaic panel, 96V-180Ah battery bank, vapor compression system with R12 refrigerant, electronic control unit and an insulated cold room of 21m^{3}. It was observed that the system can operate a maximum heat load of 2350W in order to maintain cold room temperature below freezing temperature of the fish. In the performance test conducted on the system components, it was observed that their output has degenerated after a 5year period.

Bahaj & James (2002) conducted an economic analysis of a solar-trailer refrigeration system in London, UK in comparison with a diesel powered alternative. The solar-trailer designed for delivering chilled product at +3^{o}C or +7^{o}C consists of a 4.4kW PV module installed 35m^{2} trailer roof with 28kWh lead acid battery with two inverters which supplies ac power to a refrigerator unit and the economic analysis indicate an 18years payback period for the system.

Kaplanis & Papanastasiou (2006) studied the performance of a modified conventional refrigerator converted to a PV powered one under Greece climatic condition. The FV100 refrigerator model used was modified into DC compressor with variable speed running from 2000 to 3500rpm with extra insulation added to reduce heat loss which cuts-down energy consumption to 1.53kWh for refrigeration purpose of 15hrs operation and 1.7kWh for conservation purpose of 24hrs operation. The battery used was 12V-190Ah lead acid battery. It was also observed that the power consumption increases with the rpm value and evaporation temperature.

Eltawil & Samuel (2007) developed and tested a PV powered refrigeration system for potato storage in rural India. The system consists of 14 modules PV panels; 24Volts lead acid battery bank, inverter and refrigerated space with cold storage capabilities. The total energy consumption under full load and the average daily solar panel output were 4.115kWh and 5.65kWh, respectively. The average coefficient of performance obtained for the system when loaded and with air circulation in under sunny days was 3.25.

Modi (2009) investigated the performance and cost effectiveness of a domestic refrigeration system powered by PV panels under climatic condition of Jaipur city in India. The refrigeration system consists of a 165L refrigerator with 110W compressor running on 50Hz electricity, a thermostat which switches off the compressor at -4^{o}C, four 35W PV panels inclined at 45^{o} to the horizontal facing due south, two 12V-135Ah batteries and a charge controller. Performance tests carried out are observation of normal operation of the refrigerator at 42^{o}C ambient temperature, pull down and steady-state tests at ideal ambient conditions during which the battery was used to power the refrigerator, warm-up test was also performed on the refrigerator. The refrigerator is kept in a room in all cases and no loads are kept inside. In the normal running test, the refrigeration temperature was observed to reduce continuously without cutting off as a result of the high room temperature. During the pull down test the compressor performed at its normal on-off cycle due to better room temperature and a maximum COP of 2.102 was recorded. The warm up test indicates that the freezer temperature drops from -4^{o}C to 28^{o}C within one hour due to poor insulation. Finally the financial analysis of the system indicates that it is not economically viable without government subsidy on components cost.

Aktacir (2011) tested a DC refrigerator in order to determine its daily and seasonal performance in the Sanliurfa region of Turkey. The system consists of two 12V-80W solar panels connected in parallel with two 12V-100Ah dry type batteries connected in parallel. Experimental conditions are no load conditions and 5, 10, 15L water tank loaded inside the cabin while refrigeration temperature is set to -10^{o}C. Results indicate that the highest amount of energy produced by PV panels is recorded between 11:00 and 14:00, for a typical hot day in May 2009 and energy consumed by the refrigerator and battery bank is 347.7Wh/day and 78.2Wh/day while energy produced by PV panel is 425.9Wh/day. It was also observed that by increasing the load, the time to attain the set temperature also increases likewise the energy consumption rate which was recorded as 75W for 15L load.

Ekren (2011) conducted an investigation to evaluate the performance of a refrigeration system by performing both energy and exergy analysis. The system consists of a DC refrigerator with an internal volume of 50L, 76W cooling capacity running R134a refrigerant and an 80Ah lead acid battery backup. Power is supplied from an 80W solar panel inclined 45^{o} to the horizontal. The energetic COP'S obtained were 0.670, 0.571, and 0.477 for no load; nominal and over load condition respectively. Similarly, the exegetic COP'S obtained were 0.048, 0.063, and 0.040 for no load, nominal and over load conditions. For over load case, the overall energy efficiency of the system was 51.4%.

Fatehmulla et al. (2011) investigated the performance of a low power PV refrigeration system. The system has a 37.9W DC chiller, charge controller, 12V/75Ah battery power with two photovoltaic panels connected in series. The efficiency of the solar array is calculated to be 9.63% at peak time and it was observed that the specific gravity of the battery electrolyte is proportional to its voltage. The refrigeration temperature dropped from 32^{o}C to 6^{o}C after a 6hours period and the cost analysis conducted indicates that the system has a payback period of about 7years.

Laidi et al. (2012) investigated the performance of a photovoltaic based refrigeration system in winter and summer days in both the Mediterranean and arid areas of Algeria. The system consists of a 1.5m^3 locally fabricated refrigerator container with 380W ac compressor powered by a PV array consisting of seven 24V-150W polycrystalline panel connected in parallel and two 24V-550Ah connected in parallel. It was observed from the experience obtained in the two locations that refrigerator operated with temperature range of 4-8^{o}C. It was also observed that the highest energy produced was between 11:00 and 14:00 while the energy consumed during a typical hot day in May 2011 was observed to be 4464Wh/day.

Sobamowo et al. (2012) developed and analyzed the performance and long term cost of a PV powered refrigeration system installed with a sun tracking device in Lagos, Nigeria. The system consists of a DC refrigerator with a variable speed compressor, 12V/20A charge controller, 12V/200Ah deep cycle battery and two 8.5A solar panel. It was observed that by varying the compressor speed between 2500 and 3500rpm the cooling rate increases correspondingly. Also, the cooling of the system at 3500rpm compressor speed was similar to that obtained when the system was driven by AC power obtained from the national grid. The payback period of the system was estimated to be 17years.

Nawaz et al. (2012) conducted an investigation in India on the technical and economic feasibilities of a solar PV powered vapor compression refrigeration system having a refrigerator with 90-110W AC compressor, three 70W PV module. It was observed that the system payback time will be after 6years.

Henriques et al. (2012) described the implementation of a mobile vaccine refrigeration system in eastern Kenya. The system described has three deep cycle battery, low cost DC refrigerator unit which was designed to operate with a mobile and photovoltaic system installed on the rear end of a vehicle and on the vaccination sites. It was observed that the system performed with low operating temperature of -5^{o}C for ambient temperature ranging between 27^{o}C and 35^{o}C. Also it was observed that the battery voltage dropped by 0.5volts after operating 20hrs which includes 9hrs of darkness for the stationary system while the battery voltage drop of 0.4V was recorded on the vehicle after operating for 1hr.

Zang et al. (2012) described the design and testing of a photovoltaic powered refrigeration system with both battery storage and electric grid supply during unfavorable days. The test results obtained indicate that the system could run normally and satisfies the requirement in beverage preservations.

2.2 Thermal Energy Storage Based Systems

Some systems reported in the literature are battery free and excess energy in form of thermal energy are stored for use in the night and periods of unfavorable weather conditions. Some of the thermal energy storage media available are ice thermal storage and phase change material storage medium. The latent heat of fusion is used to sustain the cooling needs of these systems and insulation is of high importance.

Adnene & Ahmed (1996) simulated the operation of a latent storage based system and the results obtained were used in the optimization of the system. It was observed from the results obtained that thermal loss which is a function of the insulation thickness, contribute to over 50% of the power consumption and also increases the total life cost of the system. The optimal insulating thickness size of latent storage based photovoltaic system is computed to be 8.5cm. It was also observed that for load power greater than 1000W, the latent storage system is better than the battery based system.

Toure & Fassinou, (1999) investigated the performance of a solar photovoltaic refrigerator with three compartments for vaccine storage, personal use of medical staff and water freezing. The system has a PV generator of 350W, a TOTAL RCD 72-12V regular, battery bank of 150Ah-12V, operating 12V motor-compressor connected to a condenser with circulating INDEL 'B' refrigerant. In the period when the compressor was off, the cold storage helps to maintain temperature of the compartments for three days which satisfies the autonomy requirement of WHO. A thermal loss of 11W and an exergy efficiency of 17% were calculated for the system.

Khelfaoui & Belhamel (2000) simulated the operation of a photovoltaic driven vapor compression system with cold storage using SIMULINK for the desert area of Algeria. It was observed that the power consumption and the performance of the compressor are greatly affected by the ambient temperature.

Ewert et al. (2001) conducted series of tests on a direct drive system using a phase change material as storage medium. The system has a 105L capacity with 80-180Watts PV panel tested in areas of USA, South Africa and Mexico. The availability of the refrigerator defined as the percentage time in which the cabin air temperature was below 10^oC was reported to be over 90% in USA during the summer period and higher than other regions where test was conducted.

Pedersen et al. (2001) developed and tested a solar refrigeration system operating directly on PV panels with ice pack storage as back up in Denmark. The system consists of a refrigerator cabinet with 100mm polyurethane insulation and 12V-3x60W PV module. It was discovered that the cooling capacity in ice storage is similar to lead battery based on volume and weight. Specific cooling capacity in ice storage is 60% higher to lead battery on the bases of weight and 13% smaller on the basis of volume. The result from the field test also indicates that the desired temperature range was maintained throughout.

Adnene & Ahmed (2002) simulated the operation and performance of latent storage based refrigeration plant using varying climate conditions and intermittent door opening/load disturbance. It was discovered from the simulation results that the solar radiation variation greatly affect the efficiency of a latent storage plant.

Axaopoulos & Theodoridis (2009) developed and tested a battery free photovoltaic refrigeration system in Greece. The system consists of a 440W photovoltaic panel, refrigerator unit with four small DC (Danfoss BD35F-Solar) compressors, ice tank storage and a specially designed charge controller which controls startup of the compressors, load management-maximum power tracking and multiple compressor operations. It was observed that the first compressor begins operation when the solar irradiance was just 150W/m^2 and a compressor-PV panel efficiency of 9.2% was obtained which is almost the same as the PV panel efficiency. The daily ice production capacity was observed to be 4.5kg at 3kWh/m^2 and 17kg at 7.3kWh/m^2.

Driemeier & Zilles (2010) developed and experimented an autonomous battery free ice machine with variable speed drive in Brazil. The system has 1040W PV module covering 9m^2 area which supplies power to a variable speed drive that runs an induction motor connected to a reciprocating compressor. It was observed that the system has a daily ice production capacity of 27kg of ice for a solar irradiance ≥5.5kW/m^2 for a cost of $0.3/kg of ice which is about six times more expensive than a similar grid connected system.

Zhongbao et al. (2012) compared the performance of a solar photovoltaic DC refrigerator system using phase change material(PCM) as energy storage medium, one with battery storage medium and a grid connected system. It was observed that the system with a PCM storage medium has an advantage of start-stop frequency of the compressor and a heat insulation time over the other two systems.

CHAPTER 3

EXPERIMENTAL SET-UP AND ANALYSIS

3.1 Systems Description

The Solar PV refrigeration system studied in this investigation is shown in Figure 8. It consists of a refrigerator, charge controller, battery bank, electrical cables and the photovoltaic converter/panel. The refrigerator is powered from the electrical energy produced by the PV panel during the day while the battery supplies energy to the compressor in the absence of or insufficient solar radiation. The system components are described in Figure 8.

3.1.1 Refrigerator unit

The refrigerator is a Bauxie BD/C-80AC/DC model having QDZH25G DC compressor model of 66W running R134a refrigerant with a capacity of 80L. The refrigerator cabin is made of stainless steel, with size of $26.38 \times 19.29 \times 22.64$ inch and insulated with polyurethane of 65mm thickness.

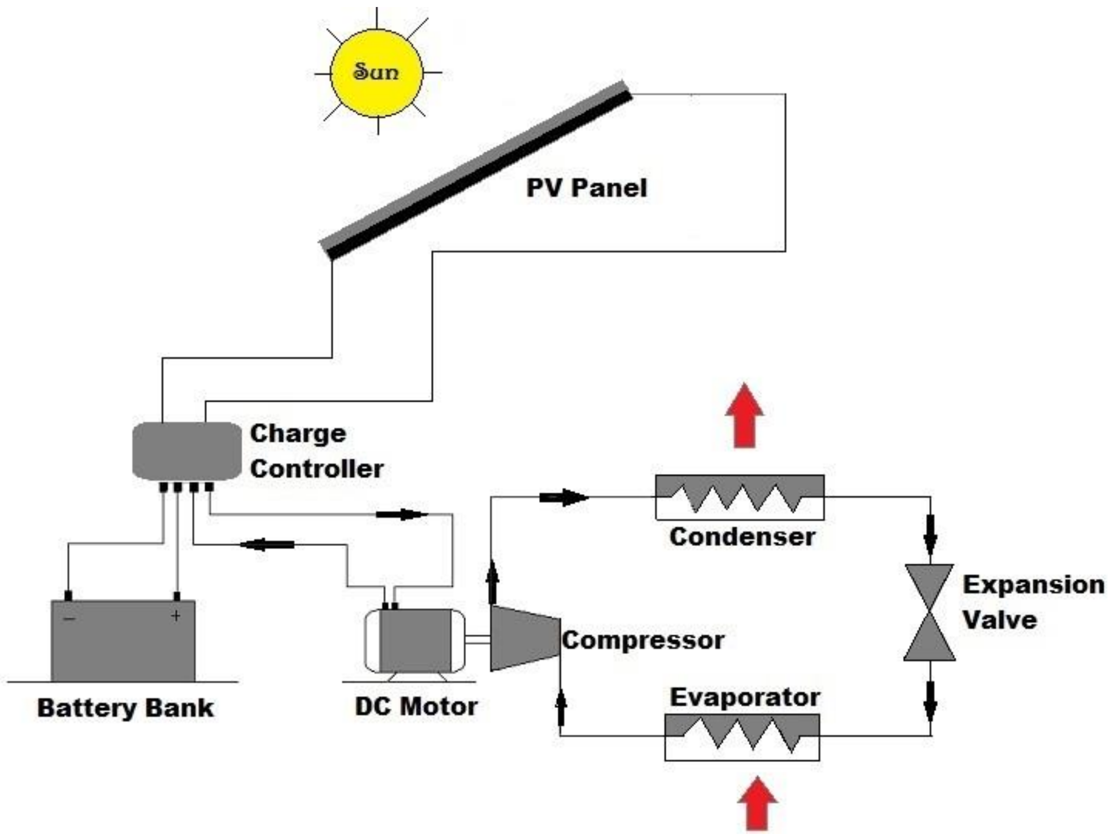


Figure 8 Schematic view of the solar photovoltaic refrigeration system.

3.1.2 Charge controller

The charge controller is a phocos CML 10 type with pulse width modulation (PWM) technology having automatic 12/24 volts detection, and a maximum module/load current of 10A. The charge controller regulates the charging and discharging of the battery by ensuring the battery is not overcharged or over-discharged.

Figure 9 Indoor view of set up

3.1.3 Photovoltaic converter

Photovoltaic panel adopted for this experiment is a NSS-12100M mono-crystalline silicon based model having $P_{\max}$ of 100W, V_{mp} of 19V, I_{mp} of 5.26A, V_{oc} of 22.8V, I_{sc} of 5.68A and an effective area of 0.52m^2.

3.1.4 Battery Bank

The battery bank consists of two 12V/50Ah lead acid battery connected in parallel to make a 100Ah battery bank. Battery bank stores energy and supplies the load in the absence of or insufficient solar radiation.

Figure 10 Outdoor View of Set Up

3.2 Measurement techniques

The experiment entails logging the temperature, current, voltage and solar irradiance data. The devices used to achieve this are multi-logger thermometer, thermocouples, DC digital ammeter, digital multi-meters and pyranometer.

3.2.1 Digital Multi-Meter(DMM)

The digital multi-meter used is a UT58D model. It is used to measure the current produced by the PV panel and voltage drop across the PV panel, compressor and the battery bank. The best accuracy for DC voltage 200mV/20V/200V/1000V is

$(\pm 0.5\% rdg + 1)$ while DC current 2mA/200mA/20A has accuracy of $(\pm 0.8\% rdg + 1)$.

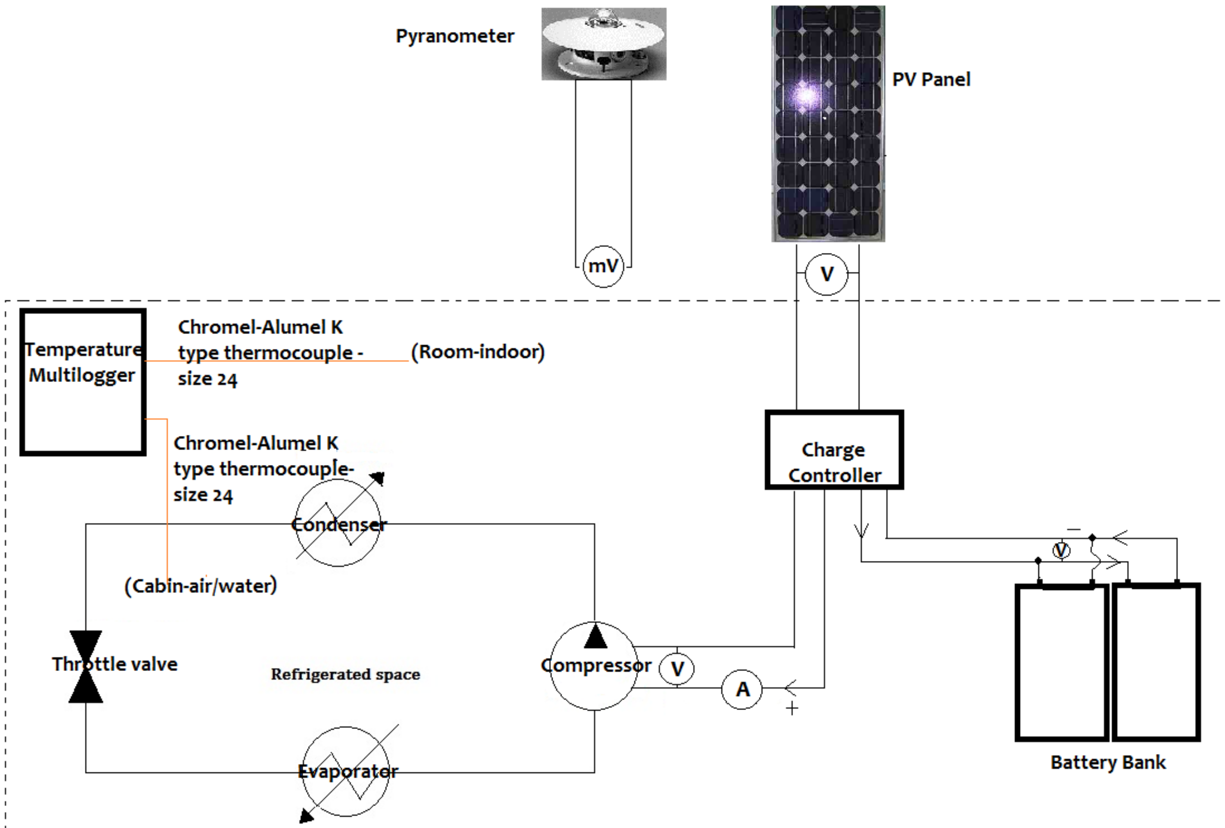


Figure 11 Experimental measurement loop

3.2.2 DC Digital Ammeter

The current supplied to the compressor is measured with a 30A digital ammeter with an accuracy of 0.2% of the Full Scale (0.2% of 30).

3.2.3 Pyranometer

The pyranometer is an eppley precision spectral pyranometer used to measure solar radiation. The device has the following specifications; Sensitivity: approximately $9\mu V/Wm^{-2}$; Temperature dependence: $\pm 1\%$ over ambient temperature range -20 to $40^{o}C$; Linearity: $\pm 0.5\%$ from 0 to $2800Wm^{-2}$.

3.2.4 Multi-logger Thermometer

The thermometer is a HH506RA omega digital thermometer logger with selector switch with an accuracy of $(\pm 0.05\% rdg + 0.3^{\circ}C)$ for K-type thermocouples.

3.3 Experimental Procedures

The photovoltaic panel is fixed outdoor on a metallic frame as presented in Figure 10 facing due south at fixed angle of 26^{O} corresponding to the latitude of Dhahran while the refrigerator, charge controller and the battery bank are kept indoor. The photovoltaic panel is operated at both clean and dusty conditions. Two loading patterns are adopted: bulk mass and distributed mass loading. For the bulk mass pattern, the water to be refrigerated is put in a single container while ice trays of 300ml each were used to achieve a distributed loading pattern and the loads are properly spaced in the refrigerator cabin to enhance the cooling rate of the water.

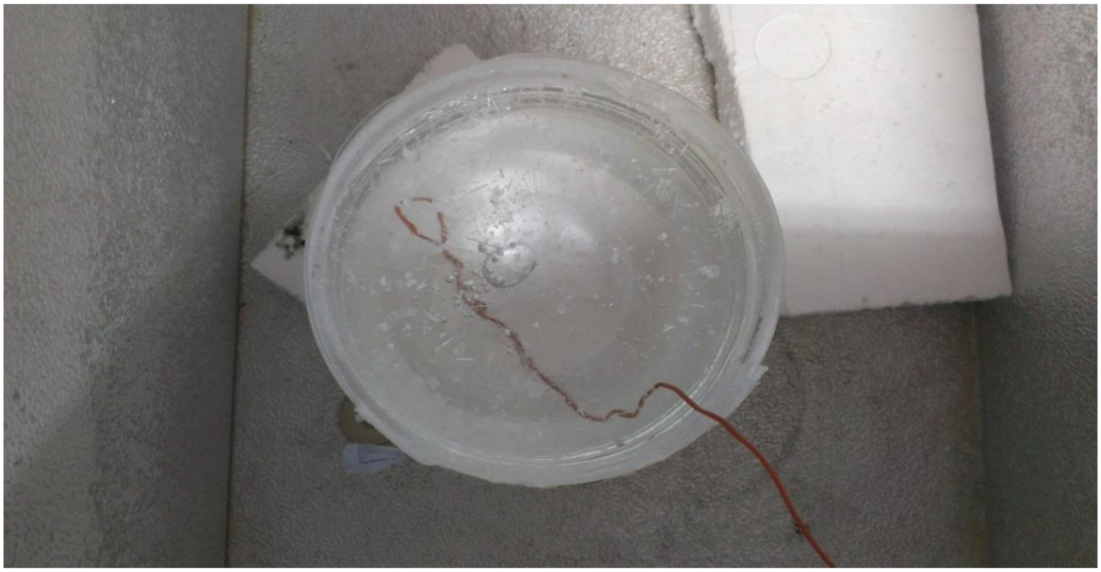


Figure 12 Bulk mass loading pattern

For the distributed loading pattern, the arrangements were made up of three layers consisting of two trays each with the seventh tray placed on the rightmost side as shown in Figure 13. The trays have been labeled from the bottom -up. On the bottom (1^{st} layer), the left tray is B, while the right tray is tray C. On the middle (2^{nd} layer), the left tray is D while the right tray is tray E. On the top (3^{rd} layer), the left tray is F while the bottom right tray is G. And seventh tray placed on the rightmost side of the cabin is tray is H.

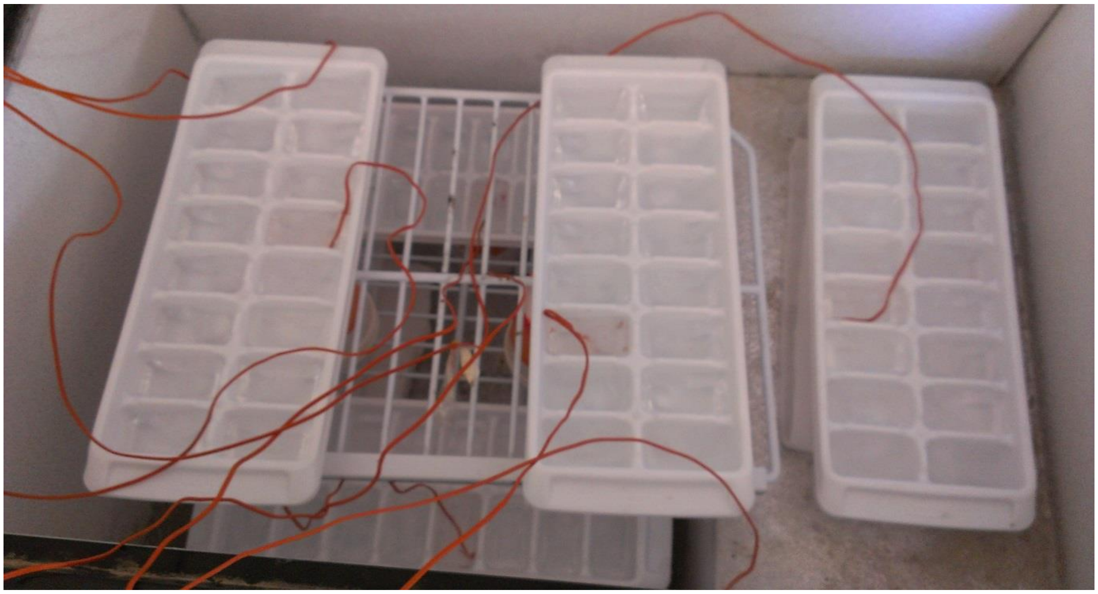


Figure 13 Distributed mass loading pattern

For both patterns, the containers are placed on a thermal insulator to ensure that heat transfer occurring during the cooling process is mainly convective. The K-type thermocouples connected to the thermometer logger are used to measure the temperature of the water, refrigerator cabin-air and the room. The total solar irradiance is measured by pointing the pyranometer directly at the sun, such that its surface is perpendicular to the sun rays, while the received solar irradiance is measured by placing the pyranometer on the same plane as the PV panel. The power produced by the PV panel and consumed by the compressor are obtained from the current and voltage measured from the amp and volt meters. All the experimental variables have been taken at a 10minute interval.

3.4 Systems Analysis

3.4.1 Basic Equations

The analyses carried out on the overall system are the solar panel orientation efficiency, solar panel efficiency, refrigeration efficiency and the cost analysis.

The PV orientation efficiency (η_{orient}) is defined as the percent of the available total solar irradiance that is received by the system.

$$\eta_{orient} = \frac{I_{PV}}{I_T} \times 100\% \qquad (1)$$

Where: I_{PV} *is received solar irradiance on a unit area of PV panel in* W/m^2.

I_T *is the total available solar irradiance in* W/m^2.

The received solar power (P_{SOL}) is the product of the solar irradiance received and the effective area of the PV panel.

$$P_{SOL} = I_{PV} \times A_e \qquad (2)$$

Where: A_e *is the effective area of the PV panel in* m^2.

The power produced by the PV panel (P_{PV}) is the product of the current measured and the voltage drop across the panel.

$$P_{PV} = (I \times V)_{PV} \qquad (3)$$

The solar panel efficiency (η_{PV}) is defined as the ratio between the electrical power produced by the PV panel and the amount of solar power received by the PV panel.

$$\eta_{PV} = \frac{P_{PV}}{P_{SOL}} \times 100\% \tag{4}$$

The total energy received on the PV panel (H_{SOL}) during a period t is defined as the integral of the solar power over the time t.

$$H_{SOL} = \int_0^t P_{SOL} dt \tag{5}$$

The total energy produced by the PV panel (H_{PV}) is defined as the integral of the PV power over the time t.

$$H_{PV} = \int_0^t P_{PV} dt \tag{6}$$

Power consumed by the refrigerator (P_{ref}) is the product of the current supplied to the compressor and the voltage drop across it.

$$P_{ref} = (I \times V)_{ref} \tag{7}$$

The total energy consumed by the refrigerator compressor (W_{ref}) is the integral of the power consumed by the compressor over the entire time t.

$$W_{ref} = \int_0^t P_{ref}\,dt \tag{8}$$

The refrigeration effect (Q_{ref}) is the total amount of energy removed from the water during the refrigeration process.

$$Q_{ref} = \int_0^t (mc)_w \frac{dT}{dt}\,dt + (mL)_w \tag{9}$$

Where: m is mass of the water kept in the refrigerator.

c is the specific heat capacity of water.

T is the temperature of water.

t is the time duration of the experiment.

L is the latent heat of fusion of ice.

In the above equation, the cooling of the air inside the fridge has been neglected since it is small and tests are usually conducted after the air inside the fridge has been cooled.

The refrigeration power $(\dot{Q}_{ref})$is the average rate at which the energy was removed from the water.

$$\dot{Q}_{ref} = \frac{Q_{ref}}{t} \tag{10}$$

The refrigeration coefficient of performance $\left(COP_{ref}\right)$ is the measure of the percent of the energy input to the refrigerator that has been utilized for the refrigeration process.

$$COP_{ref} = \frac{Q_{ref}}{W_{ref}} \qquad (11)$$

3.4.2 Uncertainty Analysis

The error propagation(uncertainty) in the experiment from the measured variables such as current, voltage, temperature into the calculated variables such as the refrigeration power, compressor power consumption and the coefficient of performance is estimated as follows.

The uncertainty in the refrigeration effect $\delta_{Q_{ref}}$ and power $\delta_{\dot{Q}ref}$ are obtained as follows.

$$\mathrm{Q_{ref,i}} = mc_p\left(T_1 - T_2\right) \qquad (12)$$

$\mathrm{Q_{ref,i}}$ *is the refrigeration effect at each time interval*

T_1 *is the initial temperature at each time interval*

T_2 *is the final temperature at each time interval*

$$c_p = \frac{\left(c_{p2} + c_{p1}\right)}{2} \qquad (13)$$

c_{p2} *is the specific heat capacity at temperature* T_2

c_{p1} *is the specific heat capacity at temperature* T_1

c_p *is the average specific heat capacity over the entire time interval.*

$$Q_{ref} = \sum_{j=1}^{\mathrm{M}} \sum_{i=1}^{N} Q_{ref,i} \tag{14}$$

M *is the number of water containers.*

N *is the number of intervals of the experiment*

Q_{ref} *is the total refrigeration effect*

$$\delta_{Q_{ref,i}} = \sqrt{\left(\left(\frac{\partial Q_{ref}}{\partial T_1} \delta_{T_1} \right)^2 + \left(\frac{\partial Q_{ref}}{\partial T_2} \delta_{T_2} \right)^2 \right)} \tag{15}$$

δ_{T_1} *is the error in the measurement of temperature* T_1

δ_{T_2} *is the error in the measurement of temperature* T_2

$\delta_{Q_{ref,i}}$ *is the error in the calculated refrigeration effect at each time interval and for mass of the water.*

$$\delta_{Q_{ref}} = \sum_{j=1}^{\mathrm{M}} \sum_{i=1}^{N} \delta_{Q_{ref,i}} \tag{16}$$

$\delta_{Q_{ref}}$ *is the total error in the calculated refrigeration effect.*

$$Q_{ref,un} = Q_{ref} \pm \delta_{Q_{ref}} \qquad (17)$$

$Q_{ref,un}$ *is the total refrigeration effect produced with the uncertainty*

$$\delta_{\dot{Q}_{ref}} = \frac{\delta_{Q_{ref}}}{t} \qquad (18)$$

$\delta_{\dot{Q}_{ref}}$ *is the total error in the refrigeration power*

t *is the total time in seconds*

$$\dot{Q}_{ref,un} = \dot{Q}_{ref} \pm \delta_{\dot{Q}_{ref}} \qquad (19)$$

$\dot{Q}_{ref,un}$ *is the refrigeration power with the uncertainty*

The uncertainty in the coefficient of performance and the refrigerator power is defined as follows.

$$P_{ref} = IV \qquad (20)$$

I *is the current flowing into the refrigerator*

V *is the current flowing into the refrigerator*

P_{ref} *is the power consumed by the refrigerator*

$$\delta_{P_{ref}} = \sqrt{\left(\left(\frac{\partial P_{ref}}{\partial I}\delta_I\right)^2 + \left(\frac{\partial P_{ref}}{\partial V}\delta_V\right)^2\right)} \qquad (21)$$

δ_I *is the error in reading the current value*

δ_V *is the error in the voltage readings*

$\delta_{P_{ref}}$ *is the error in the refrigerator power at each time interval*

$$W_{ref} = \left(\frac{P_{ref,1} + P_{ref,2}}{2} \right) \times \Delta t \quad (22)$$

$P_{ref,1}$ *is the initial power at each time interval*

$P_{ref,2}$ *is the final power at each time interval*

W_{ref} *is the energy consumed by the refrigerator at each time interval*

$$\delta_{W_{ref,i}} = \sqrt{\left(\left(\frac{\partial W_{ref,1}}{\partial P_{ref,1}} \delta_{P_{ref,1}} \right)^2 + \left(\frac{\partial W_{ref,2}}{\partial P_{ref,2}} \delta_{P_{ref,2}} \right)^2 \right)} \quad (23)$$

$\delta_{P_{ref,1}}$ *is the initial error in power for each time interval*

$\delta_{P_{ref,2}}$ *is the final error in power for each time interval*

$\delta_{W_{ref,i}}$ *is the error in energy consumed by the refrigerator for each time interval*

$$\delta_{W_{ref}} = \sum_{i=1}^{N} \delta_{W_{ref,i}} \quad (24)$$

$\delta_{W_{ref}}$ *is the total error in energy consumed by the refrigerator.*

$$W_{ref,un} = W_{ref} \pm \delta_{W_{ref}} \quad (25)$$

$W_{ref,un}$ *is the error in the energy consumed by the refrigerator with the uncertainty value.*

$$COP_{ref} = \frac{Q_{ref}}{W_{ref}} \qquad (26)$$

$$\delta_{COP_{ref}} = \sqrt{\left(\left(\frac{\partial COP_{ref}}{\partial Q_{ref}}\delta_{Q_{ref}}\right)^2 + \left(\frac{\partial COP_{ref}}{\partial W_{ref}}\delta_{W_{ref}}\right)^2\right)} \quad (27)$$

$\delta_{COP_{ref}}$ *is the error in the coefficient of performance*

$$COP_{ref,un} = COP_{ref} \pm \delta_{COP_{ref}} \ (28)$$

$COP_{ref,un}$ *is the coefficient of performance with the uncertainty value.*

CHAPTER 4

EXPERIMENTAL RESULTS

4.1 Solar Radiation

The received solar irradiance for selected days between September 2012 and March 2013 are presented in Figure 14. The maximum irradiance value recorded for each of the days is also presented in the vertical bars in Figure 15.

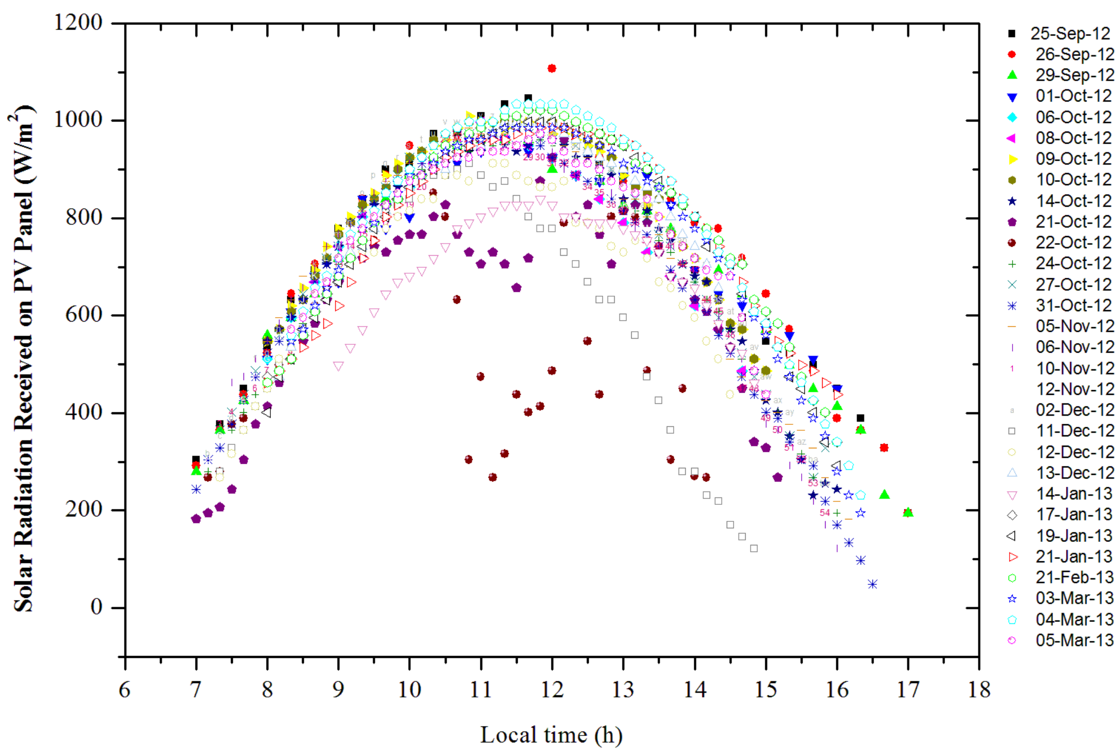


Figure 14 Solar radiation received on PV panel measured for selected days between September 2012 and March 2013.

For days with clear sky the solar irradiance variation forms a well-defined parabolic profile, while the presence of cloud introduces some scattering in the profiles. Typically the maximum irradiance values are recorded at noon time for days with clear sky. The maximum irradiance for the entire period was 1107W/m^2 corresponding to the amount measured at 12noon on 26th of September 2012.

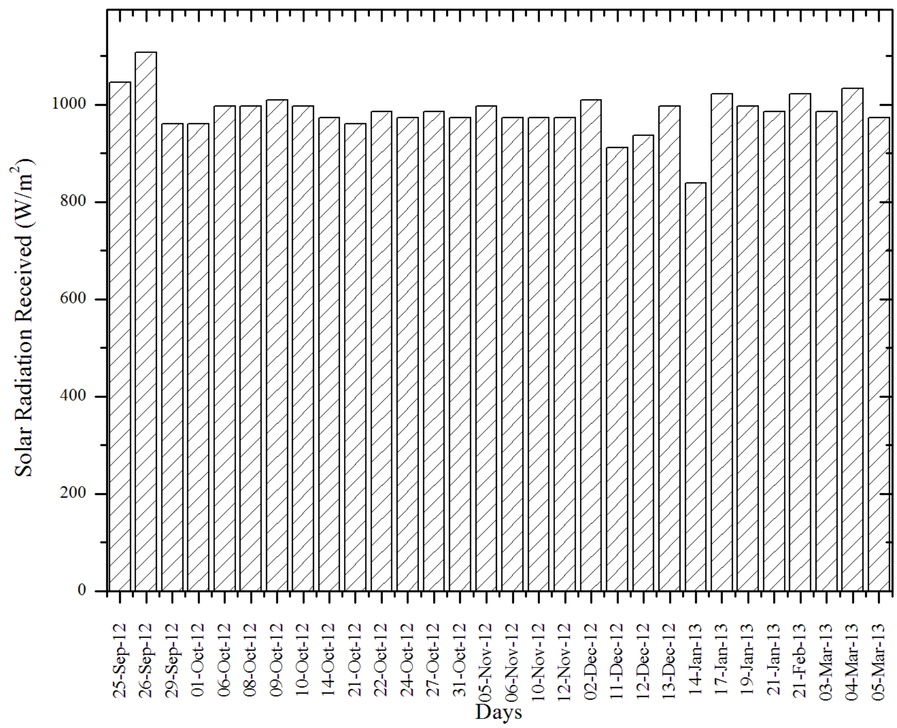


Figure 15 Maximum received solar irradiance measured.

Both the total solar irradiance measured I_T , the amount received on the PV panel I_{PV} over entire time and the corresponding panel orientation efficiencies are presented in Figures 16 through 29.

Table 1 Peak irradiance, orientation efficiency and the corresponding local time

Date	Local Time	Max I_T	Max I_{PV}	Max η_{orient}
17/01/13	11:50am	1058W/m^2	1022W/m^2	98%
19/01/13	11:30am-1:00pm	1034W/m^2	998 W/m^2	96%
21/01/13	11:40am-11:50pm	1022W/m^2	985 W/m^2	97%
21/02/13	11:20am-11:50pm	1058W/m^2	1022W/m^2	98%
03/03/13	11:30am-12:50pm	998W/m^2	985 W/m^2	99%
04/03/13	11:40am-12:30pm	1046W/m^2	1034 W/m^2	99%
05/03/13	12:00pm	985W/m^2	973W/m^2	99%

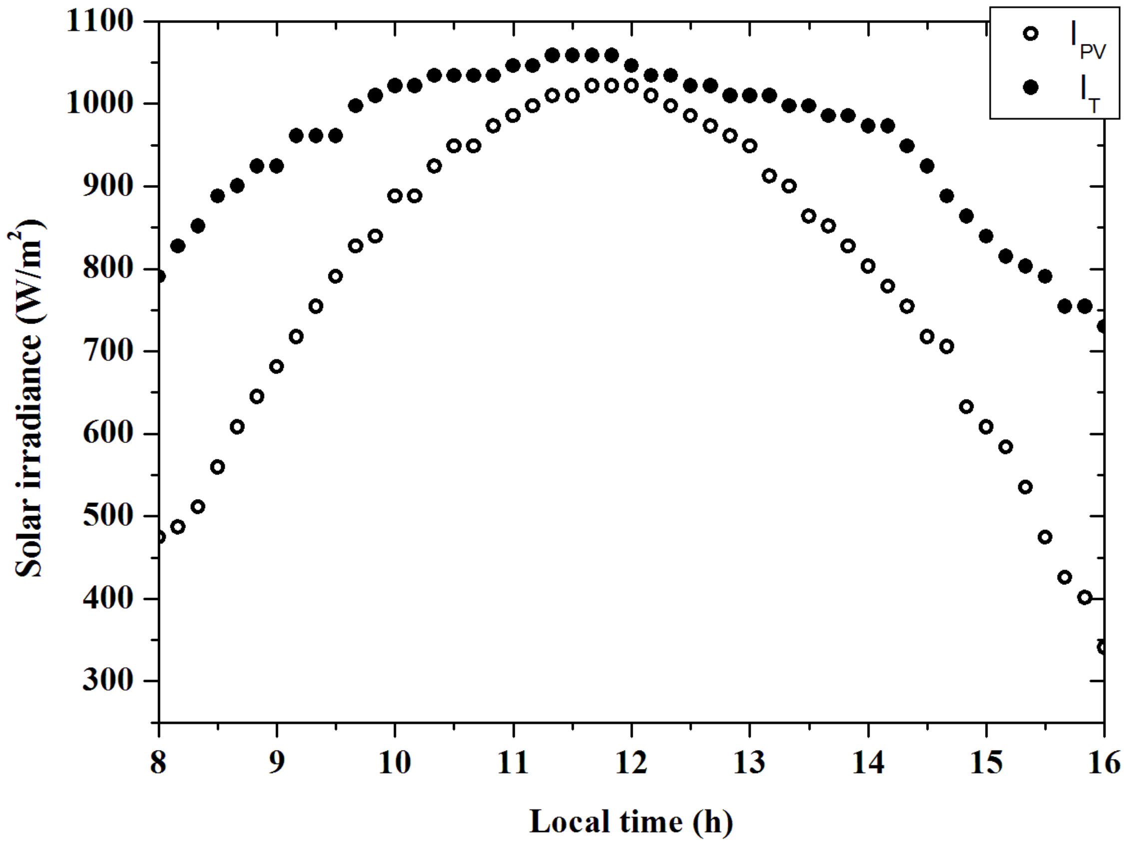


Figure 16 Variation of the total and received solar irradiance over time on the 17th of January 2013.

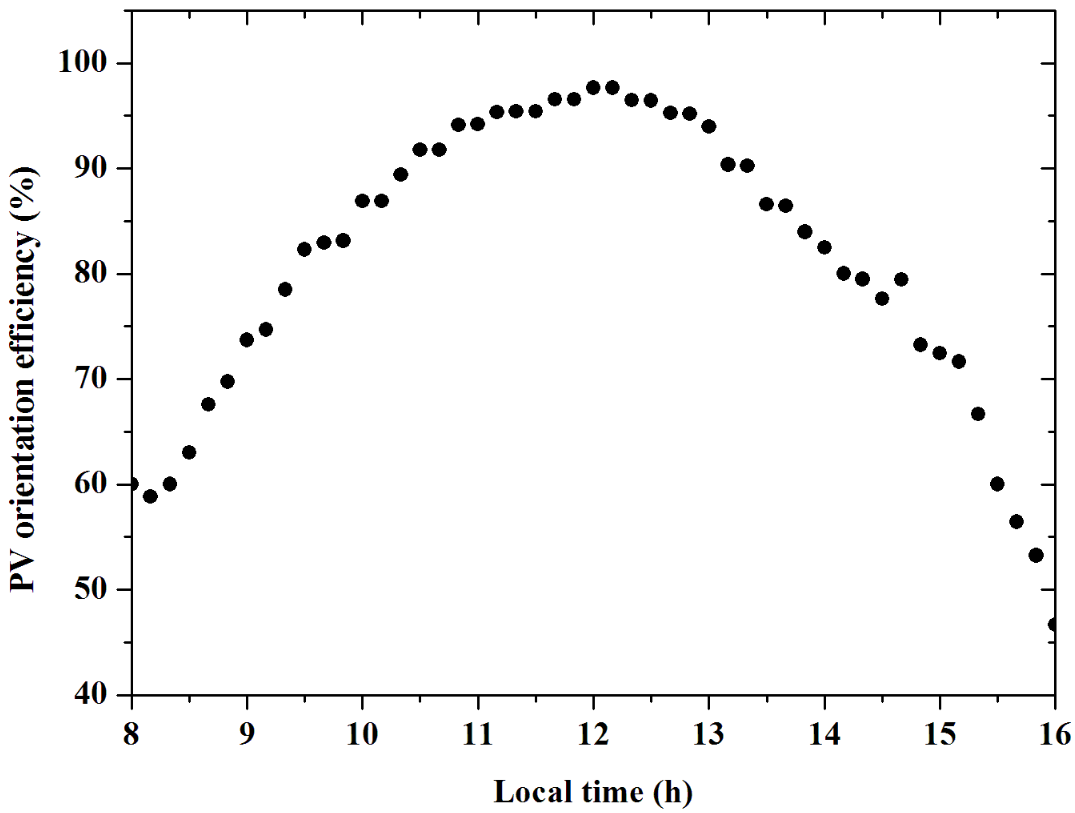


Figure 17 Variation of the panel orientation efficiency over time on the 17th of January 2013.

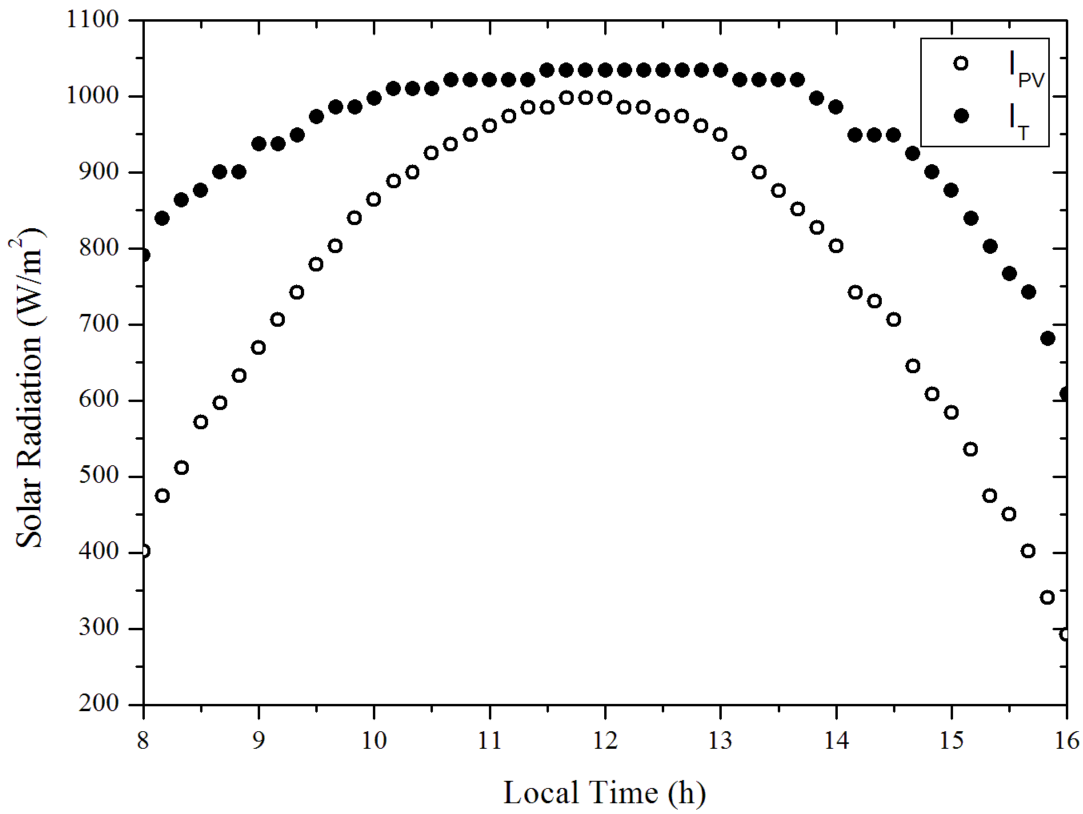


Figure 18 Variation of the total and received solar irradiance over time on the 19th of January 2013.

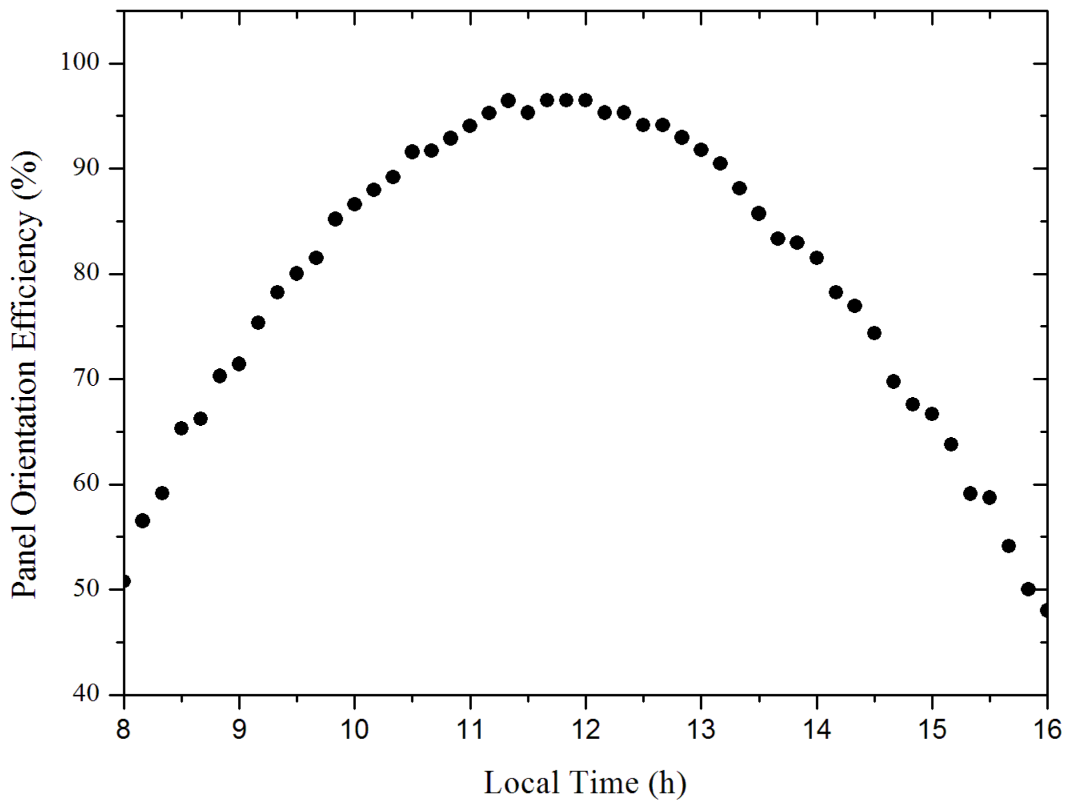


Figure 19 Variation of the panel orientation efficiency over time on the 19th of January 2013.

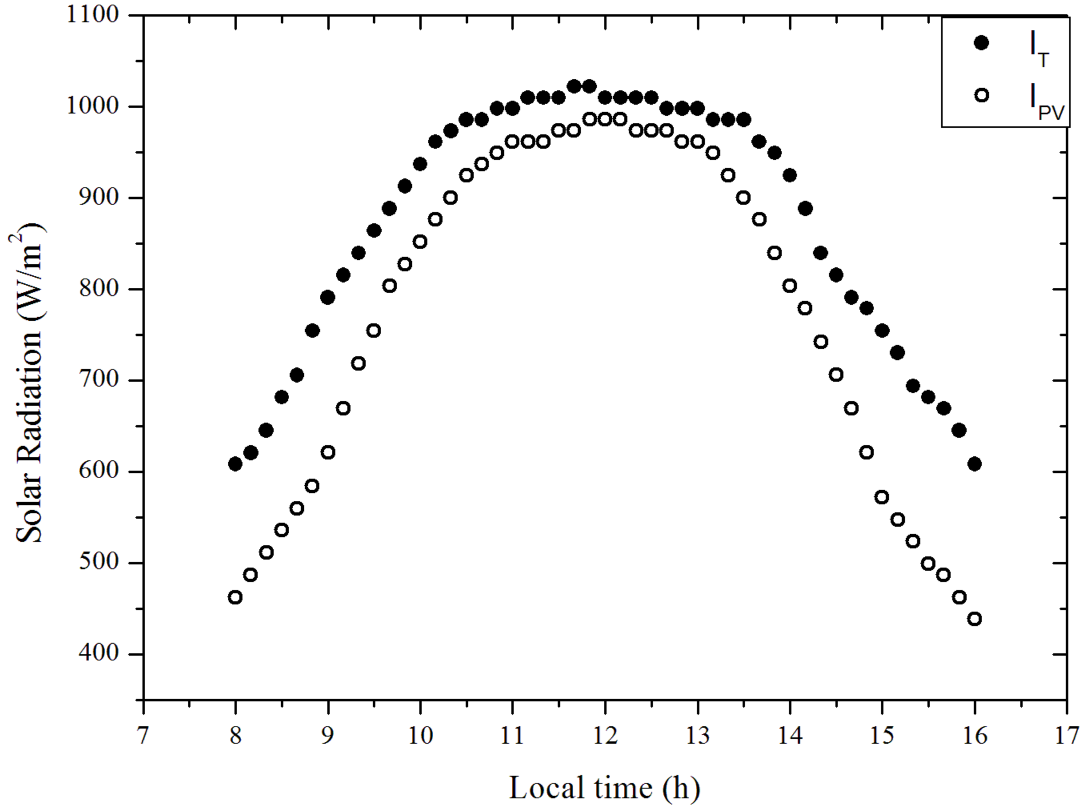


Figure 20 Variation of the total and received solar irradiance over time on the 21th of January 2013.

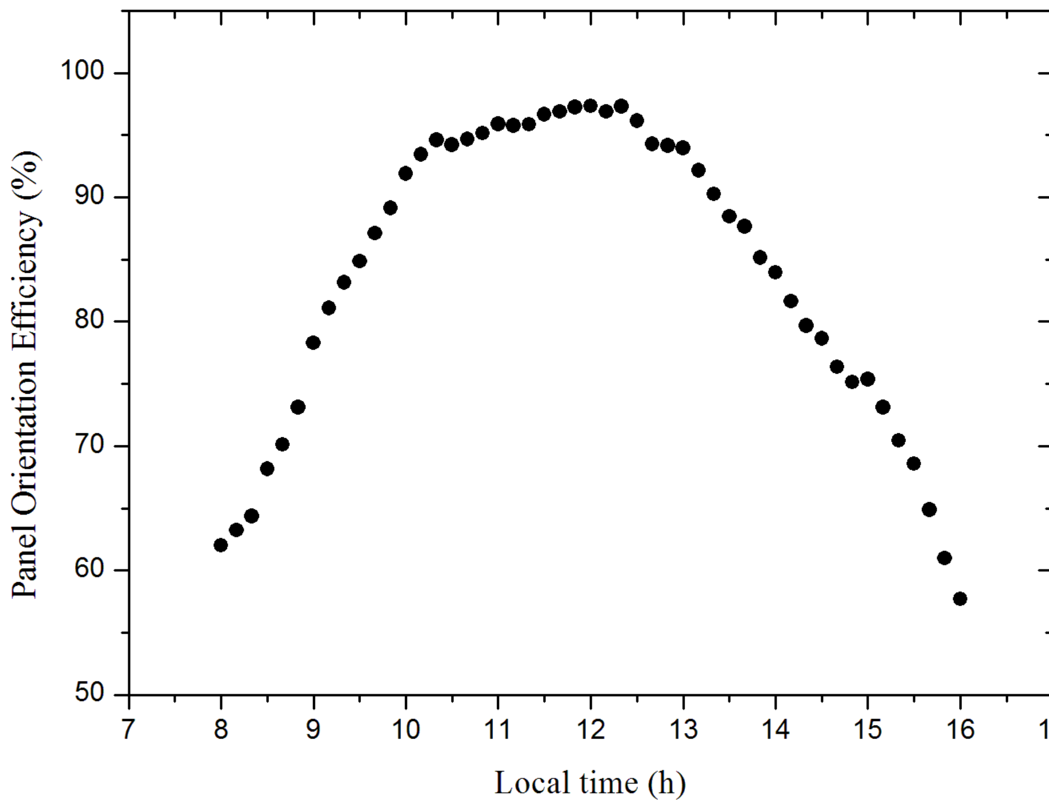


Figure 21 Variation of the panel orientation efficiency over time on the 21th of January 2013.

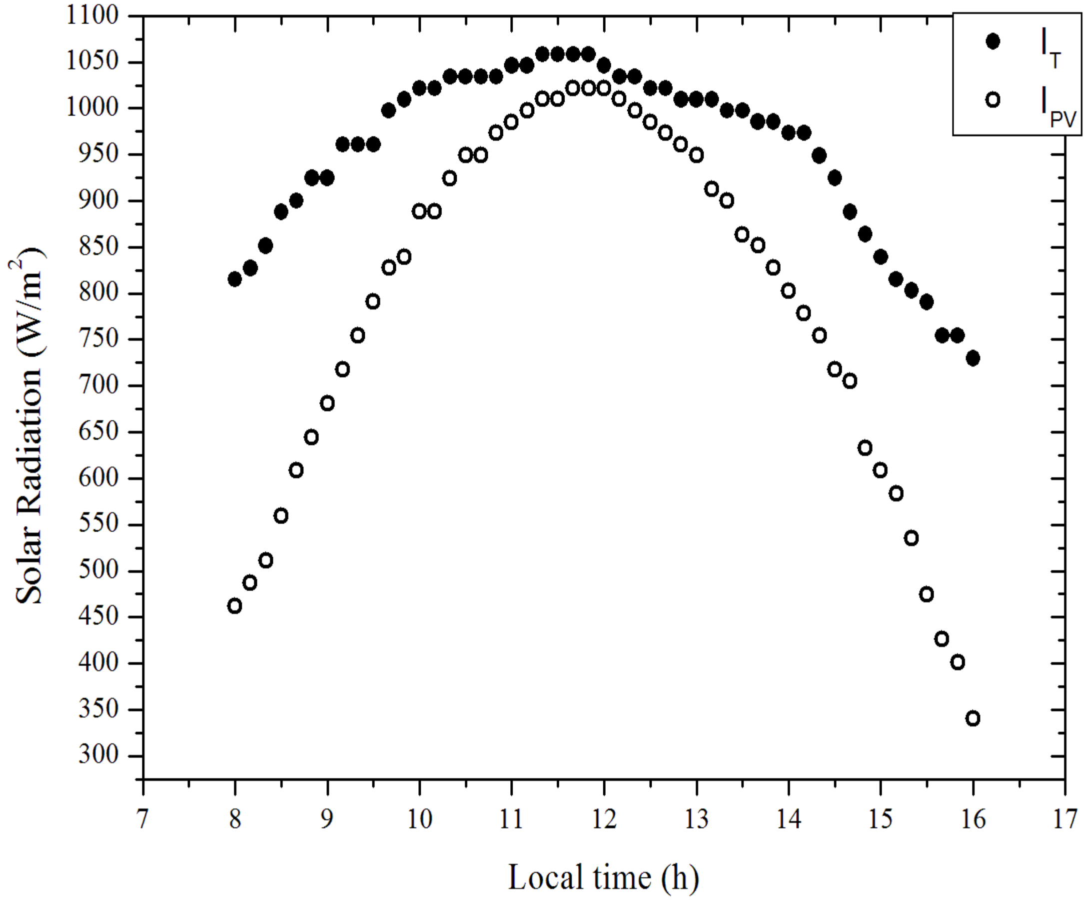


Figure 22 Variation of the total and received solar irradiance over time on the 21th of February 2013.

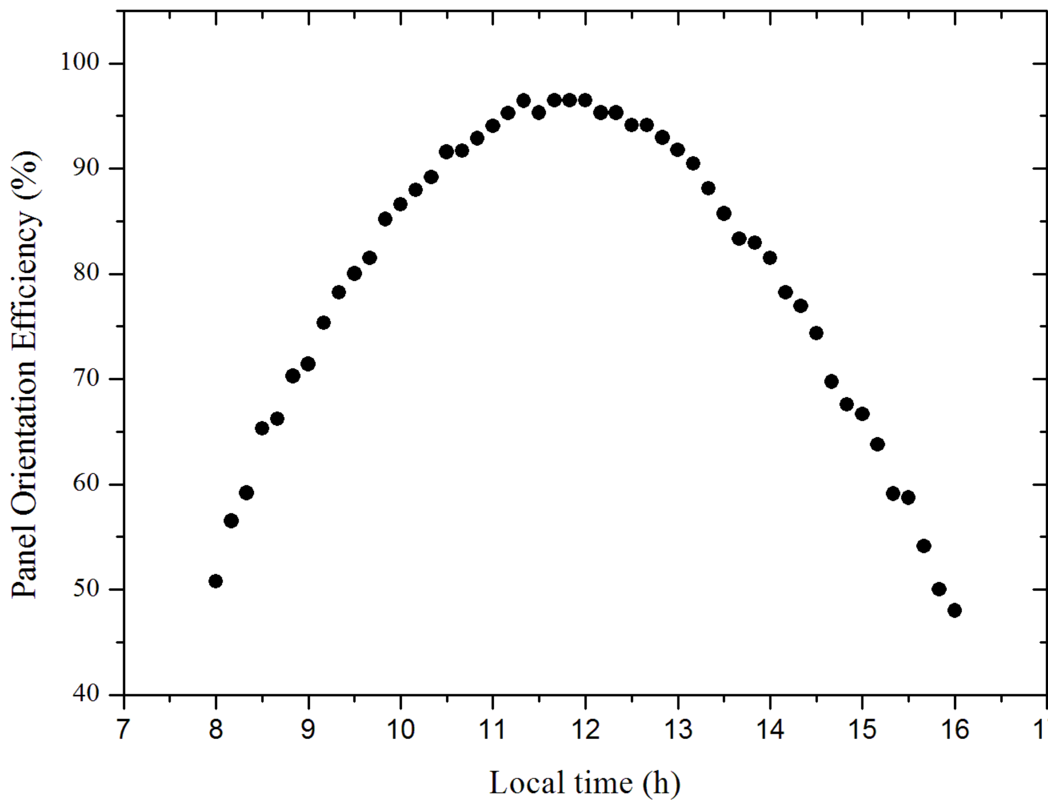


Figure 23 Variation of the panel orientation efficiency over time on the 21th of February 2013.

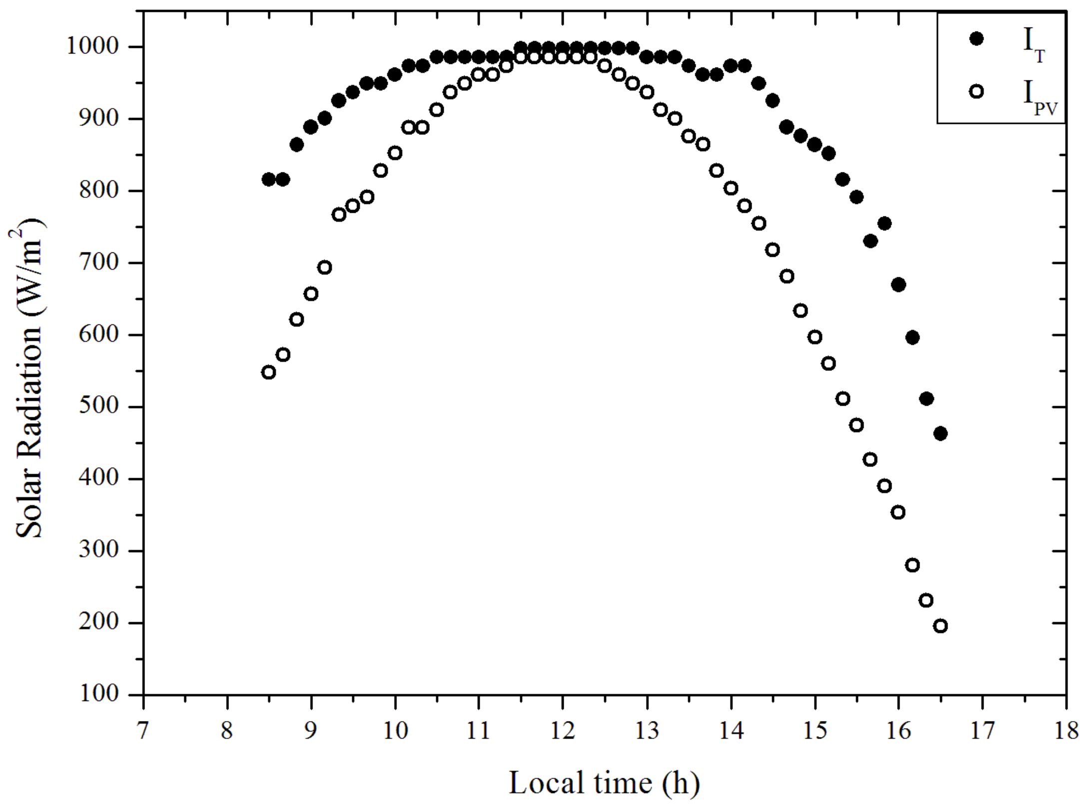


Figure 24 Variation of the total and received solar irradiance over time on the 3rd of March 2013.

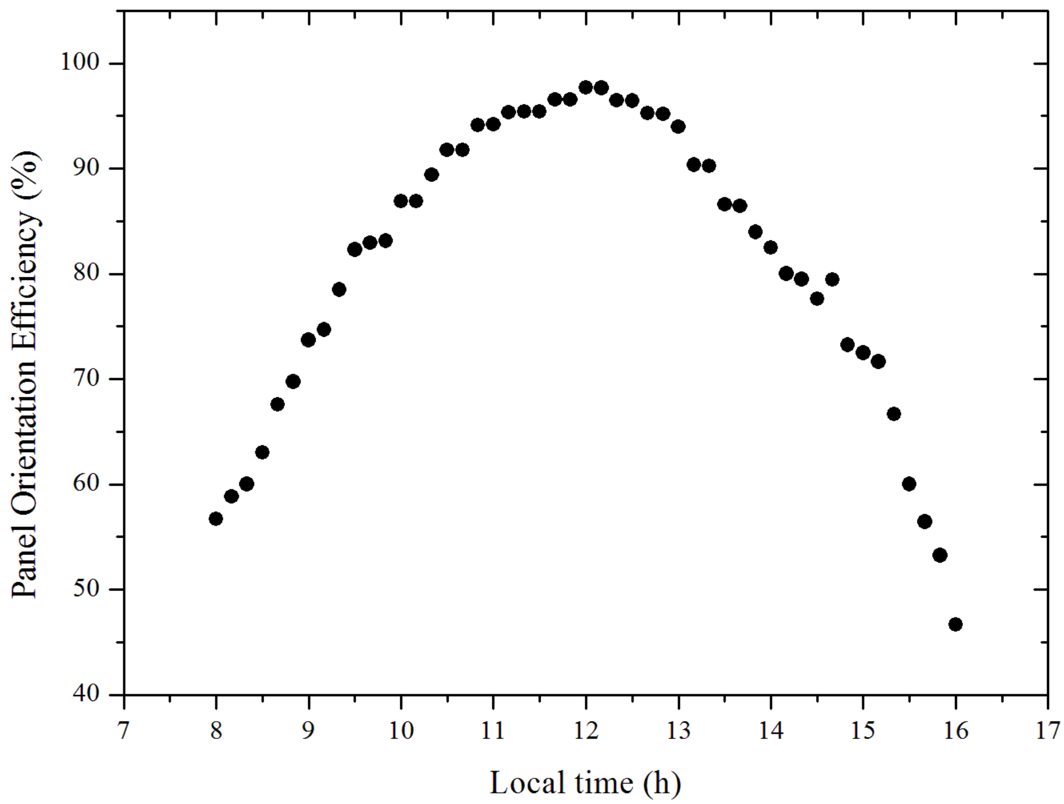


Figure 25 Variation of the panel orientation efficiency over time on the 3rd of March 2013.

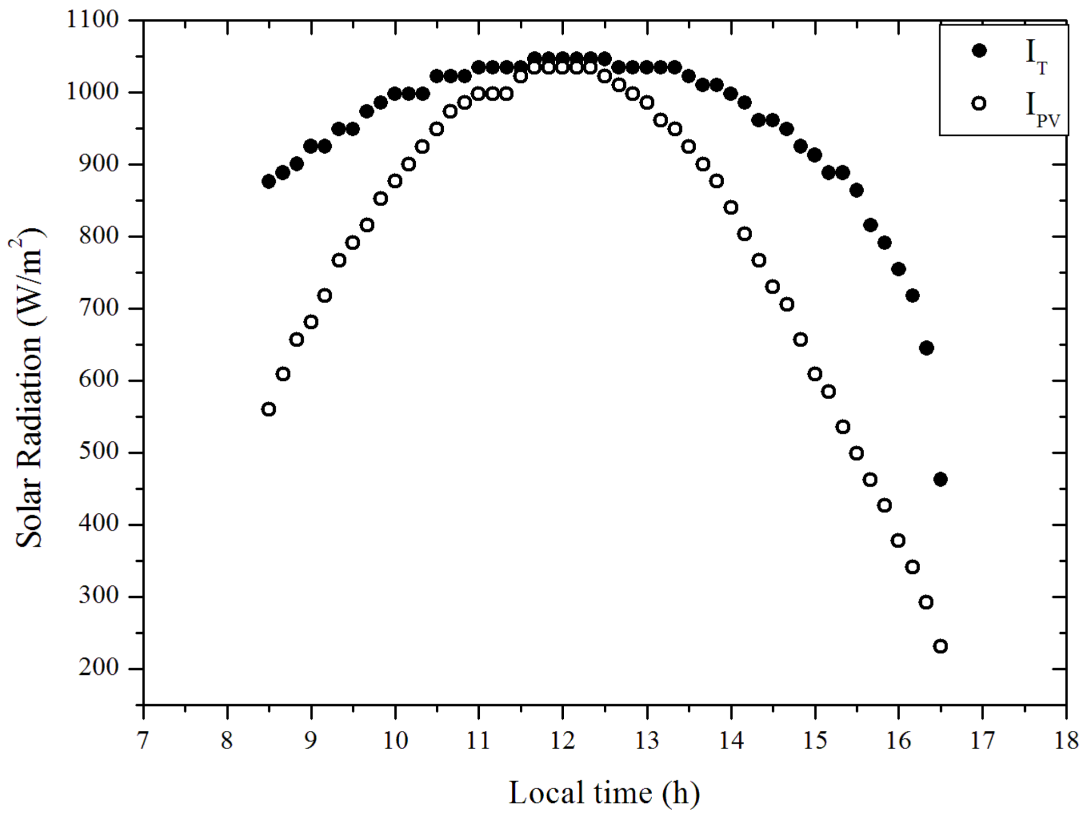


Figure 26 Variation of the total and received solar irradiance over time on the 4th of March 2013.

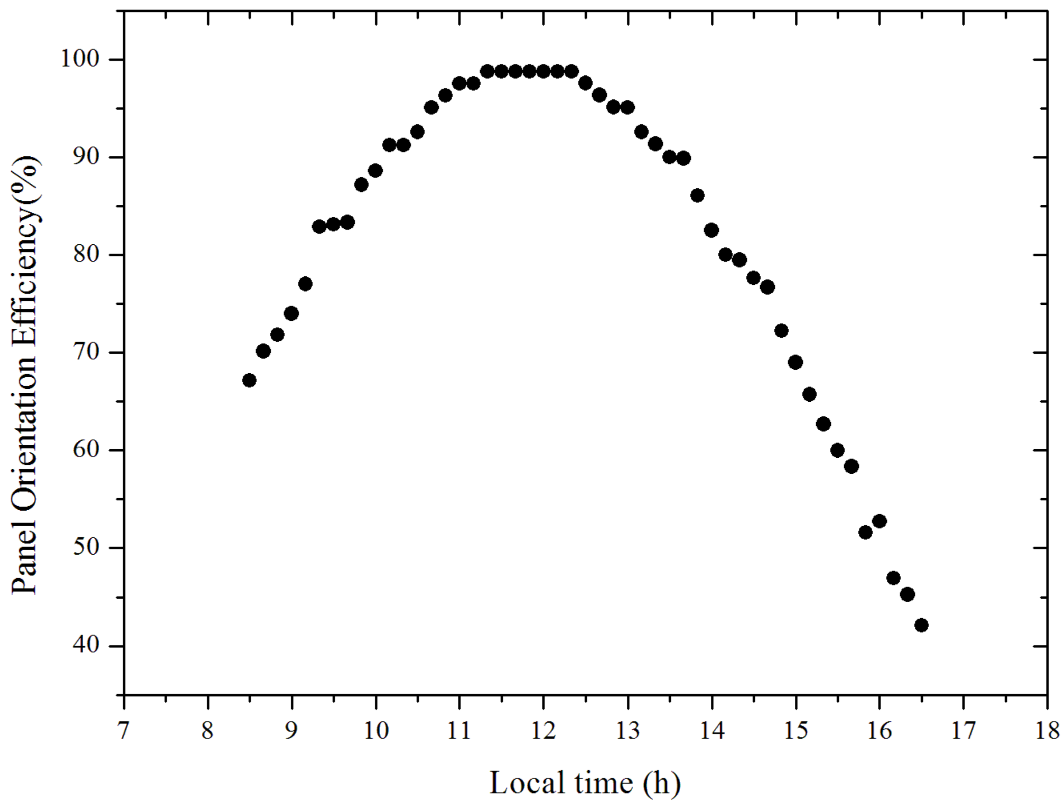


Figure 27 Variation of the panel orientation efficiency over time on the 4th of March 2013.

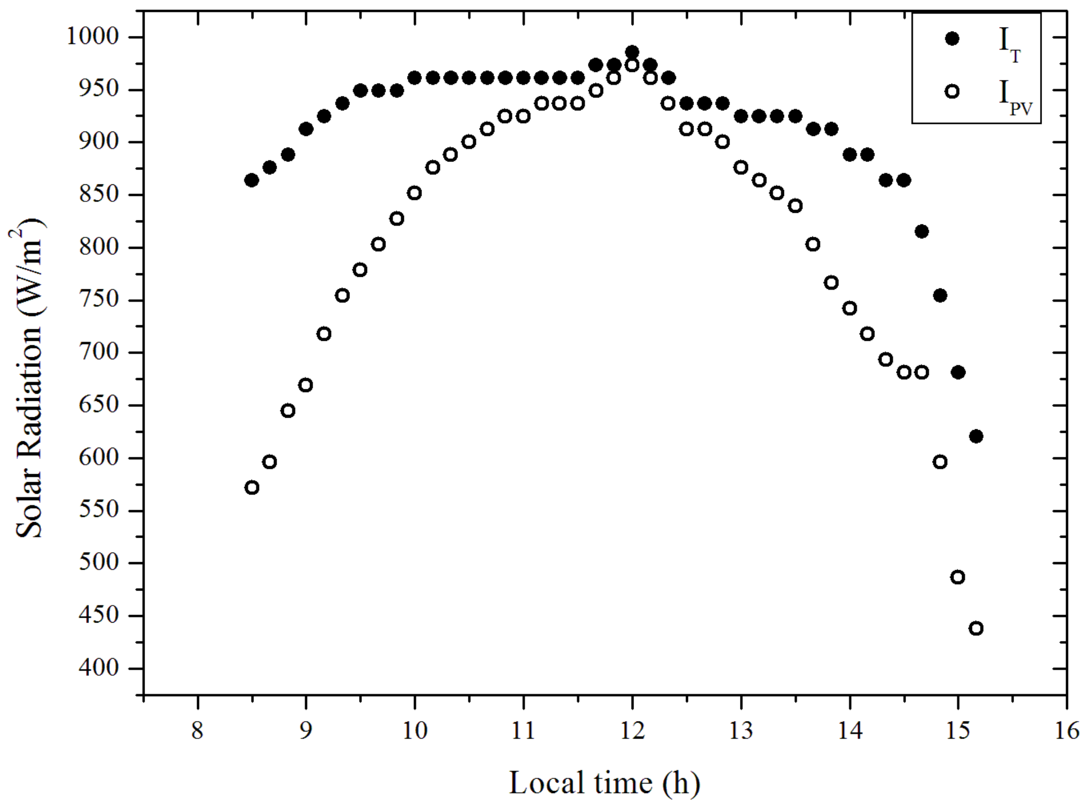


Figure 28 Variation of the total and received solar irradiance over time on the 5th of March 2013.

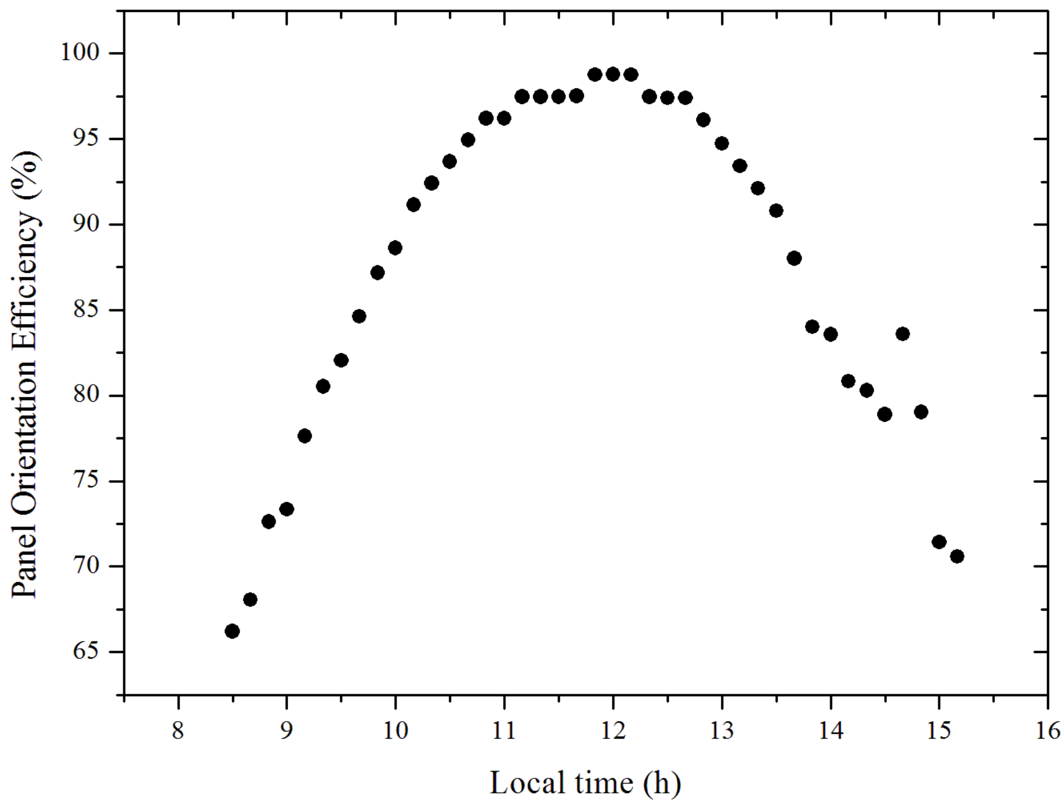


Figure 29 Variation of the panel orientation efficiency over time on the 5th of March 2013.

4.2 PV Performance

The solar panel efficiency describes the amount of the received solar energy that is converted into electrical energy. It can be observed from the Figures 30 through 33 below that the efficiency is dependent on the panel orientation efficiency, especially for days with clear sky. It is also dependent on the dust accumulation on its surface.

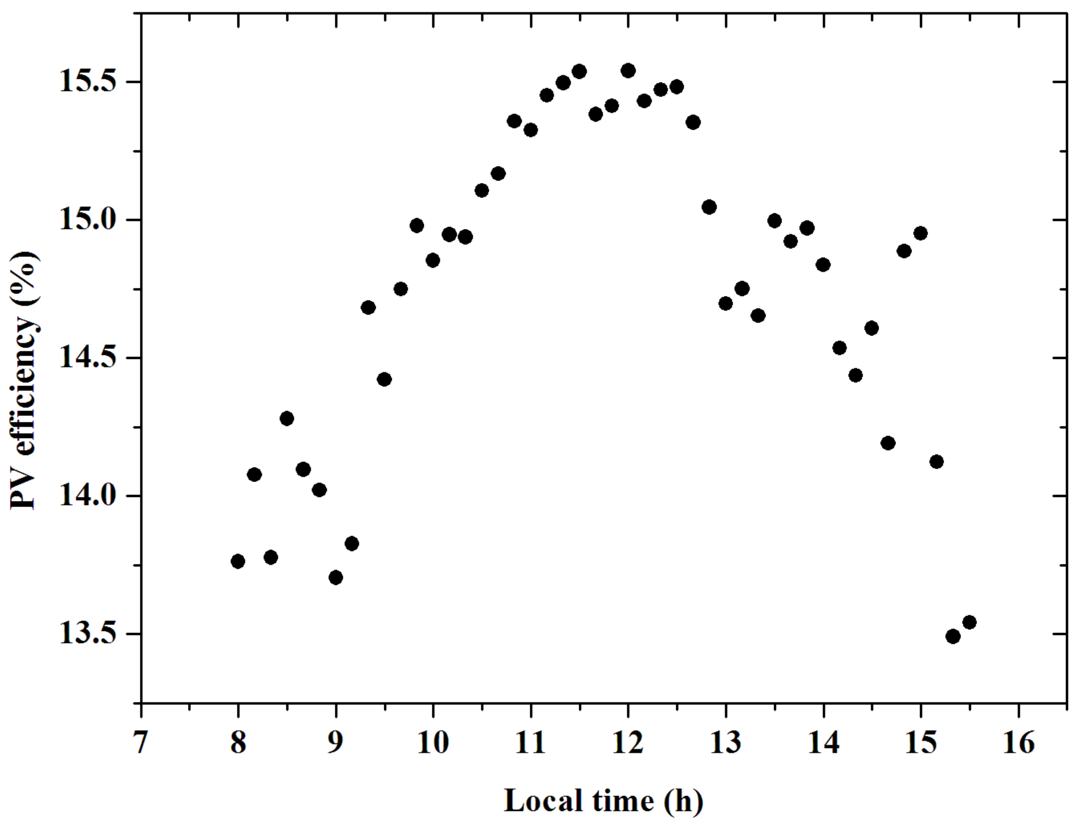


Figure 30 Variation of the PV efficiency over time on 17th January, 2013.

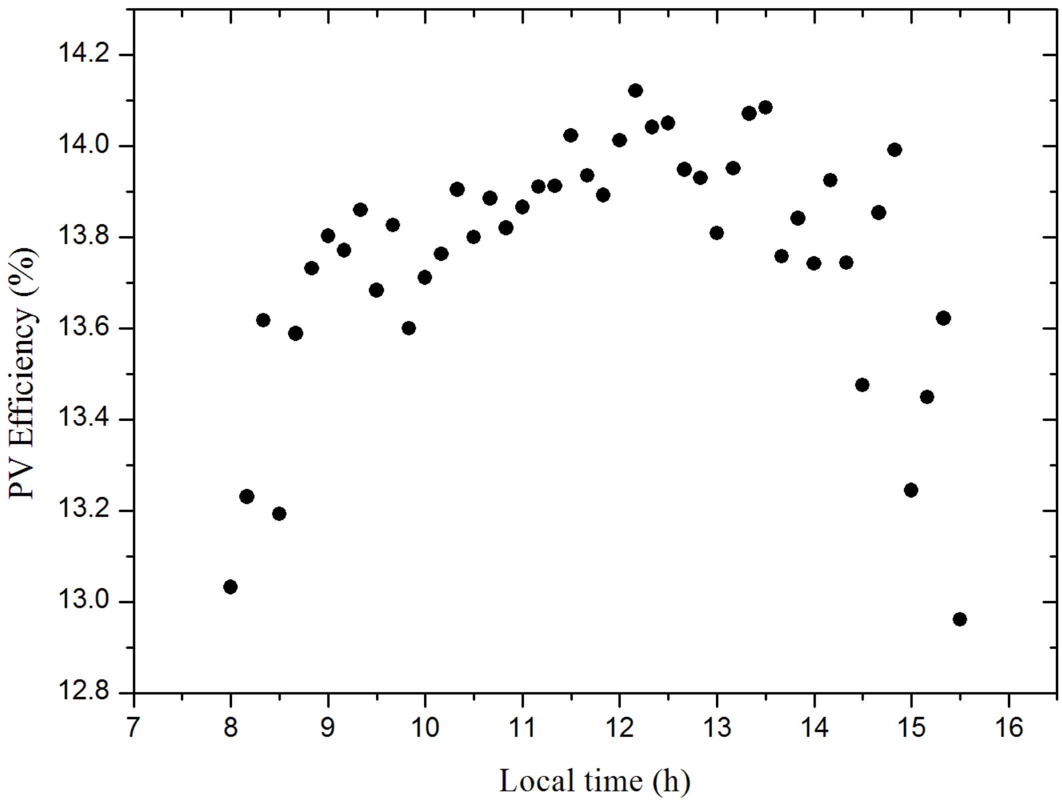


Figure 31 Variation of the PV efficiency over time on 19th January, 2013.

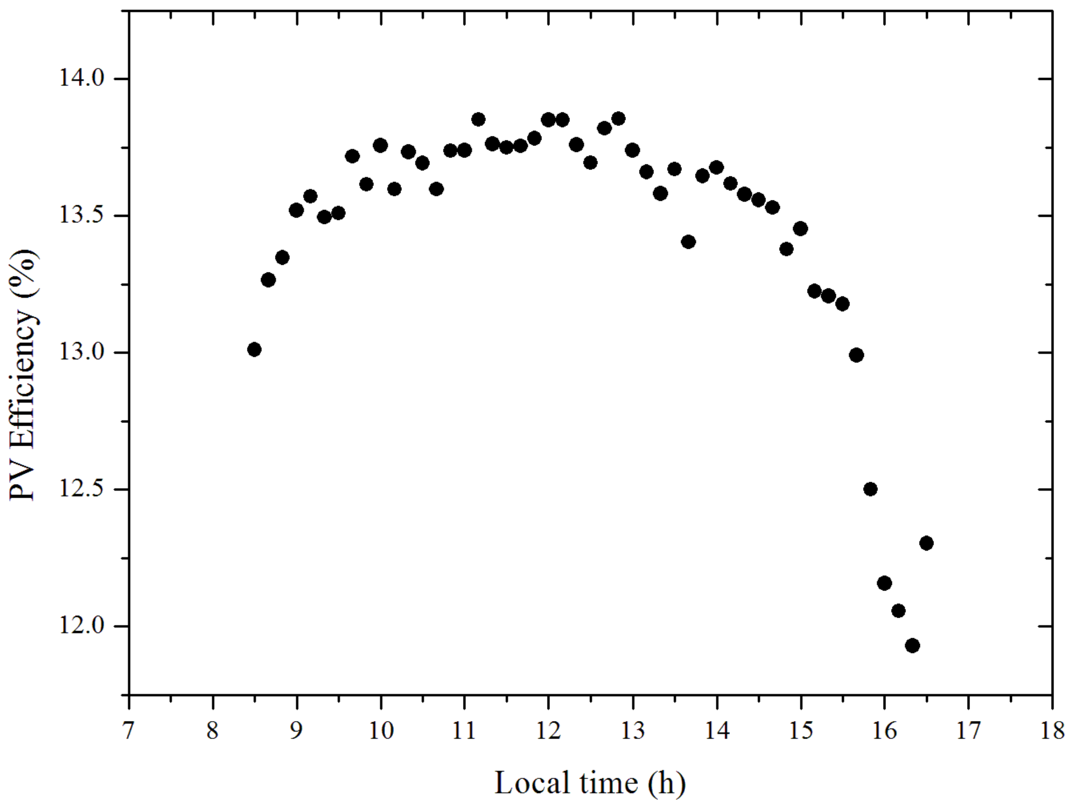


Figure 32 Variation of the PV efficiency over time on 4th March, 2013.

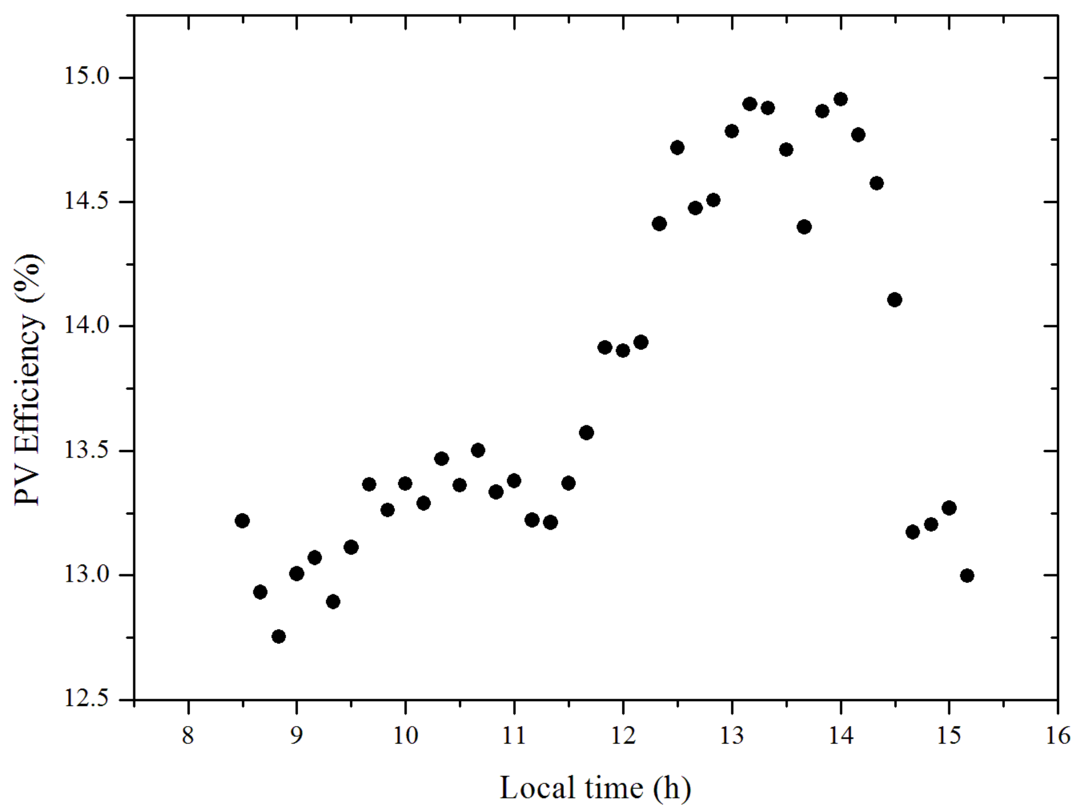


Figure 33 Variation of the PV efficiency over time on 5th March, 2013.

4.3 Energy Analysis

The electrical power profile for both the PV and the compressor is presented in Figures 34-39. It can be observed from the figures that at start up, the compressor power consumption vary and it then becomes almost steady after a short time. The integral of the power profile over time gives the total energy. During the morning operation hours, the refrigerator draws energy from the battery to compensate for the low solar energy available and then this energy is restored in the noon time when excess solar energy is being generated.

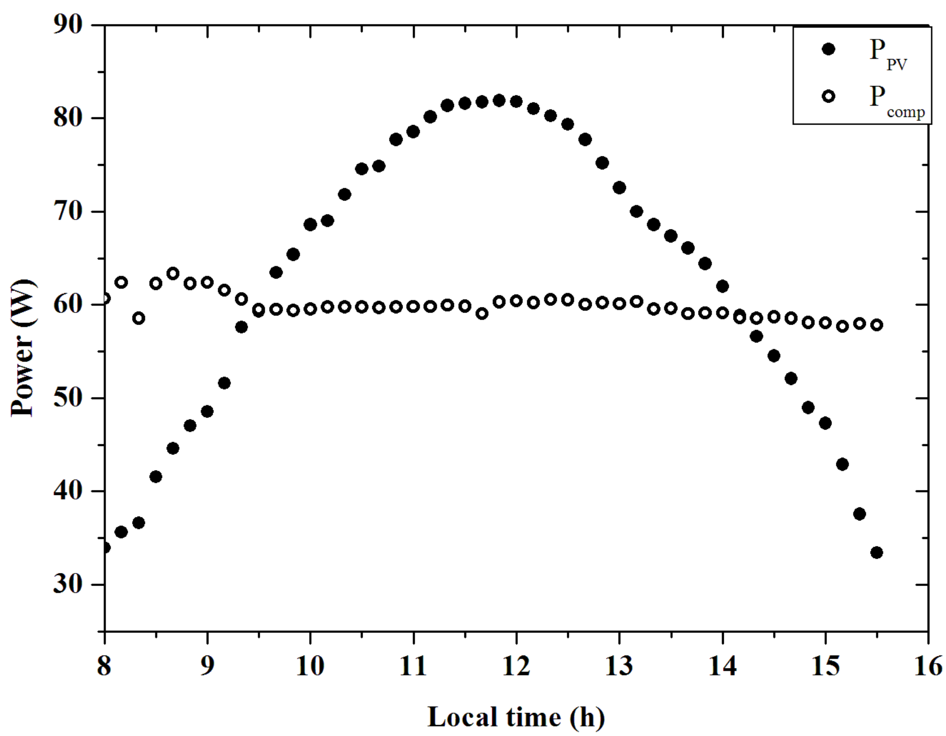


Figure 34 Variation of the output PV power and the compressor input power over time on 17th January, 2013.

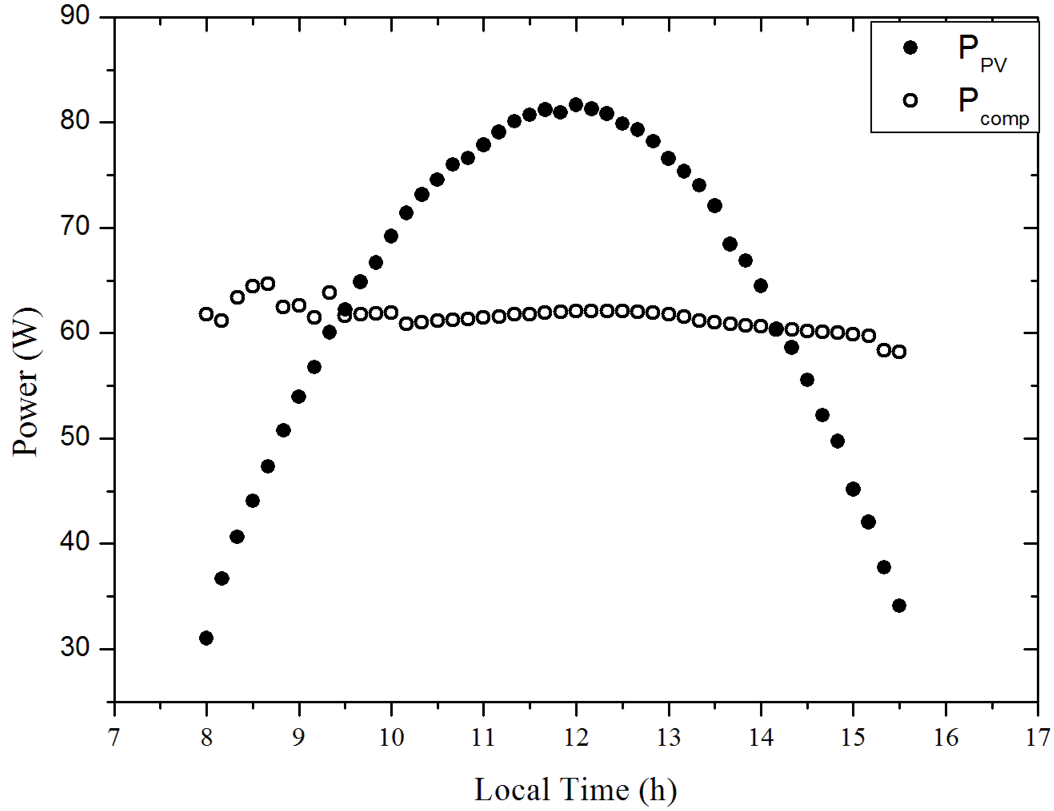


Figure 35 Variation of the output PV power and the compressor input power over time on 19th January, 2013.

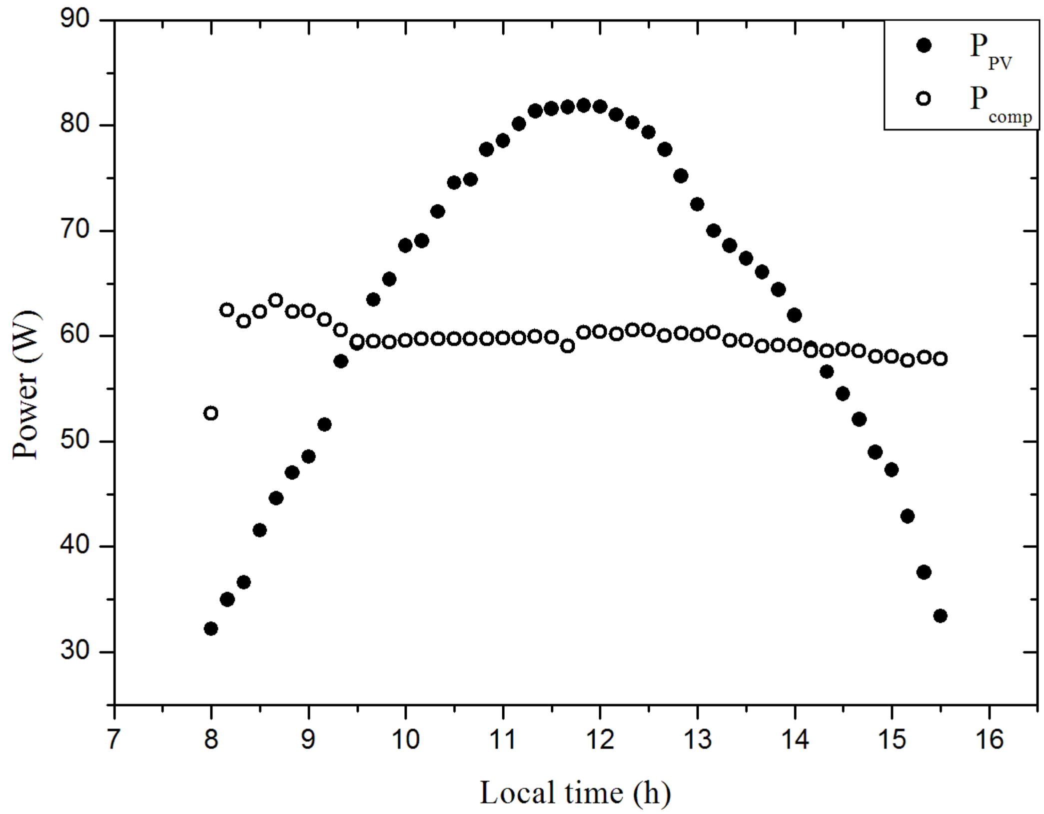


Figure 36 Variation of the output PV power and the compressor input power over time on 21th February, 2013.

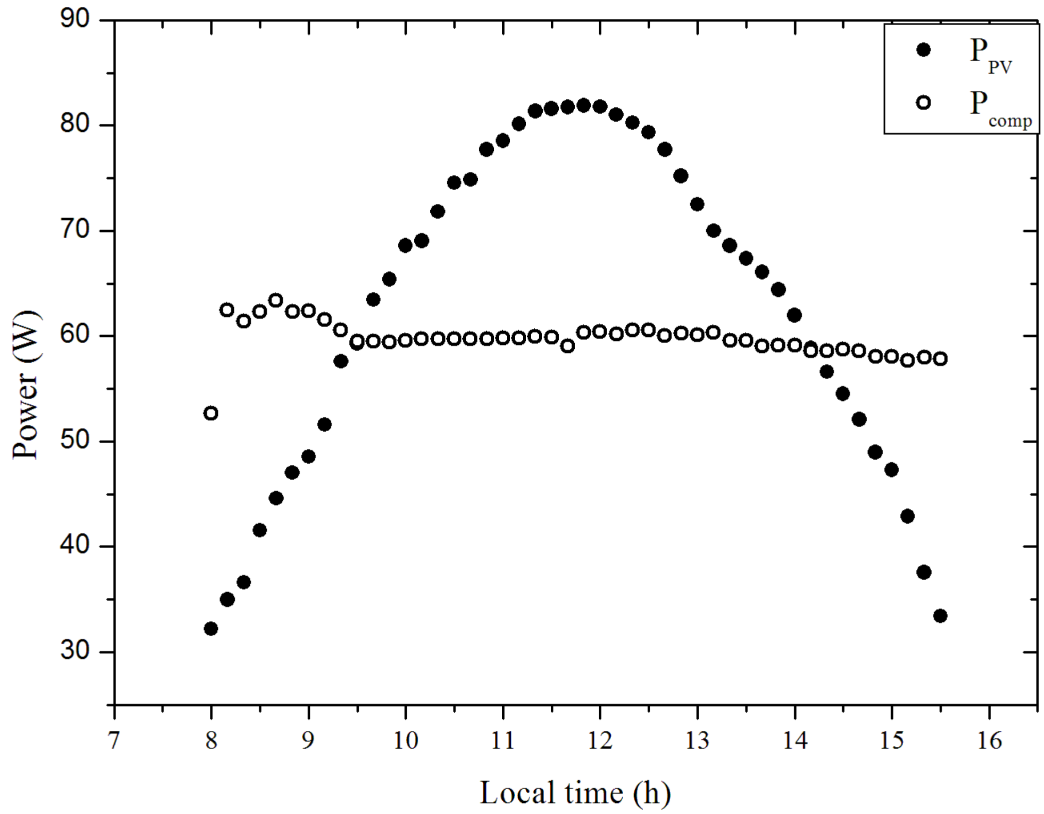


Figure 37 Variation of the output PV power and the compressor input power over time on 3rd March, 2013.

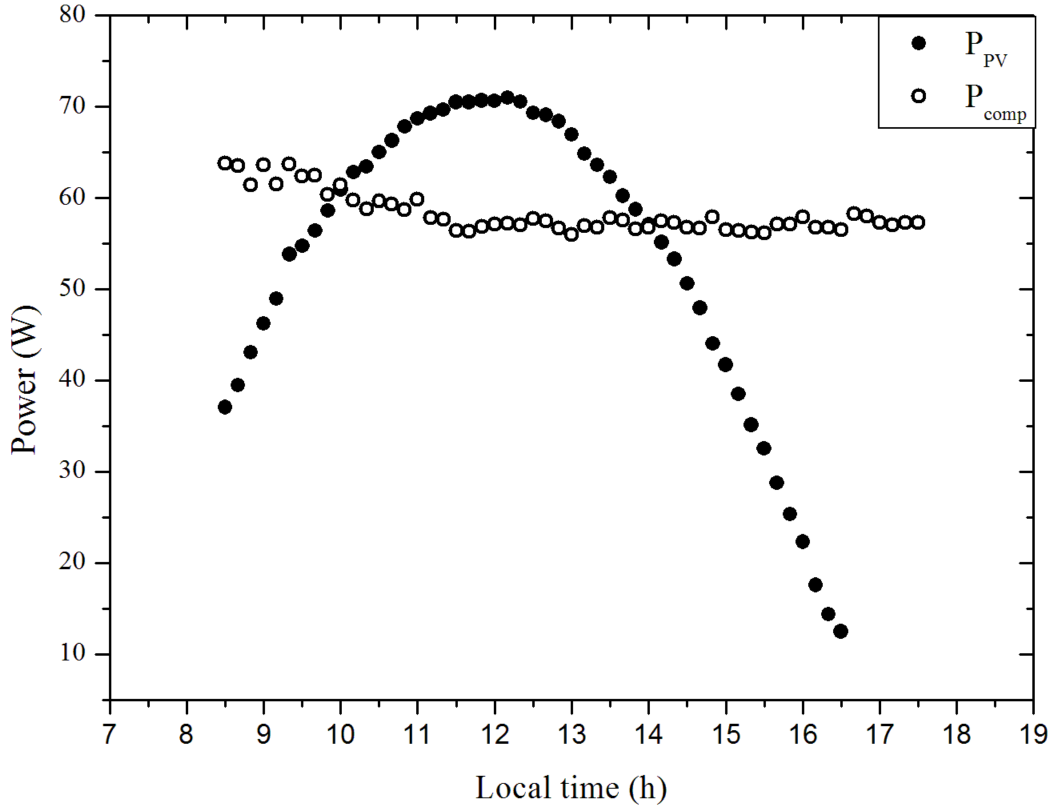


Figure 32 Variation of the output PV power and the compressor input power over time on 4th March, 2013.

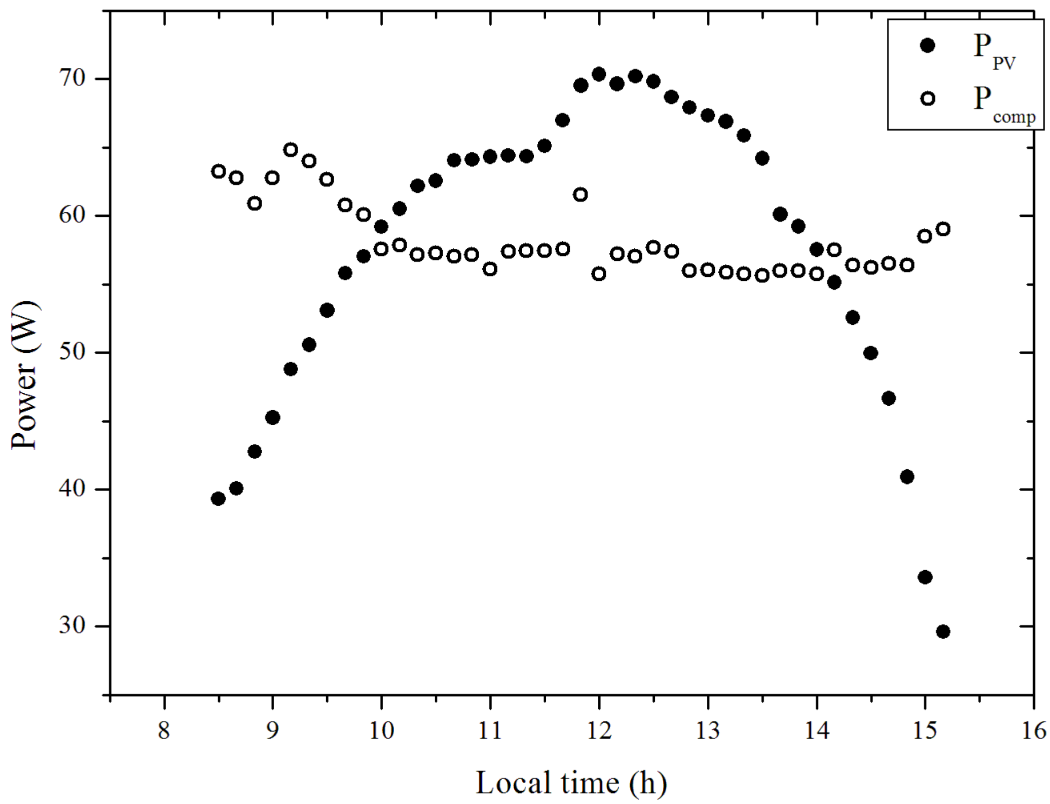


Figure 33 Variation of the output PV power and the compressor input power over time on 5th March, 2013.

4.4 Battery Performance

The battery performance is determined from the *EMF* measured at each time interval as shown in Figures 40-42. The system was operated to ensure that the voltage at the end of the experiment equals the voltage at the beginning. The *PWM* based charge controller helps to keep the battery from been over charged and over discharged. During the morning periods while the sun radiation is insufficient to drive the compressor and gradually increasing, the charge controller draws current from the battery while also supplying periodic equalization charges to the battery to increase its *EMF* as observed in the figures. At peak solar radiation period, the battery *EMF* reaches the maximum and begins to drop as the sun declines.

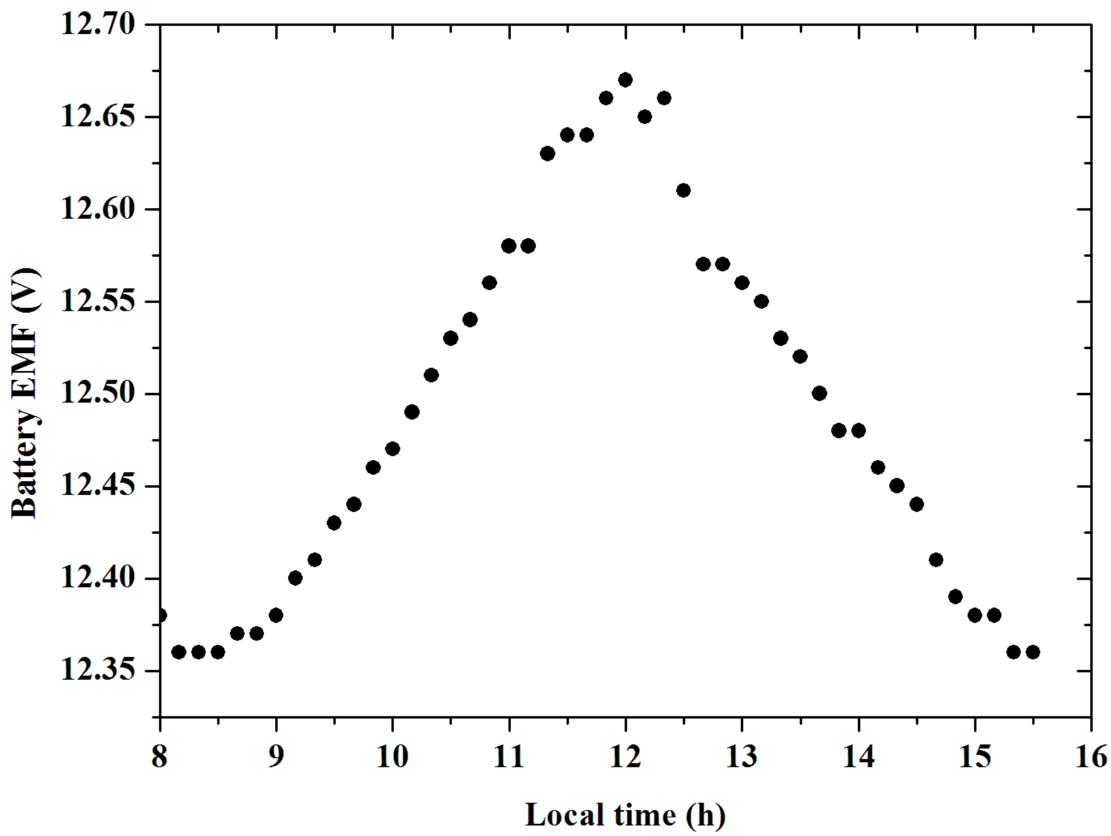


Figure 40 Variation of the battery EMF over time on 17th January 2013.

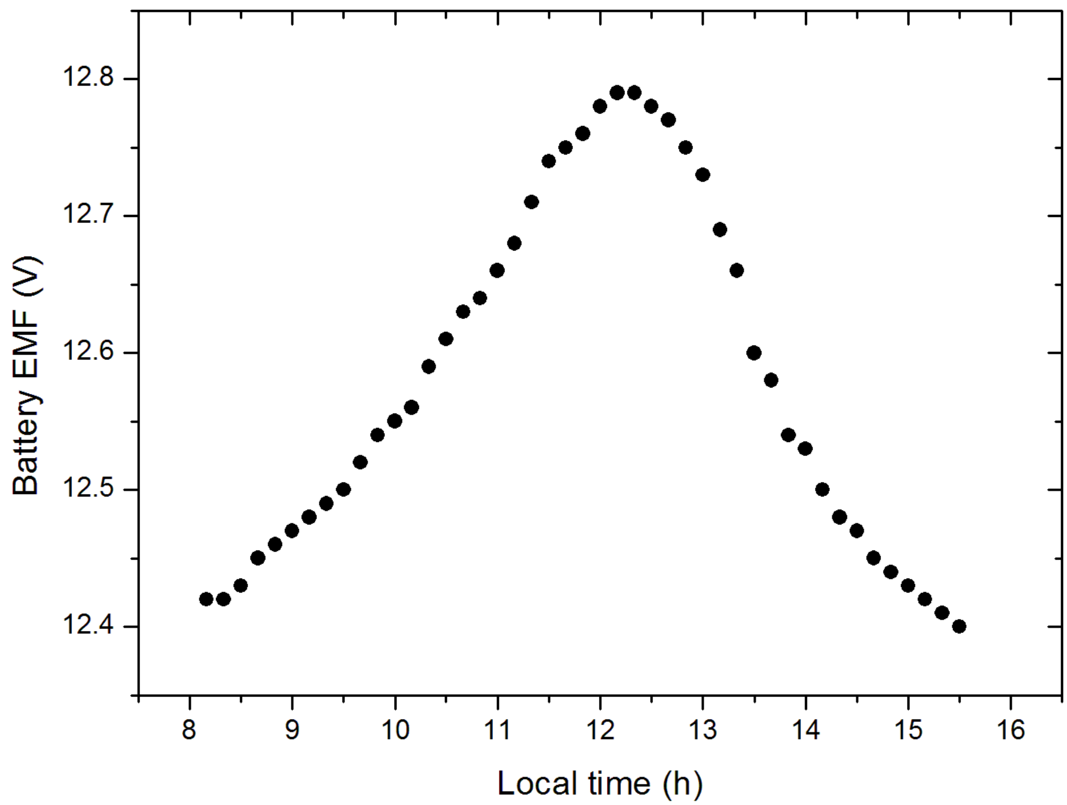


Figure 41 Variation of the battery EMF over time on 19th January 2013.

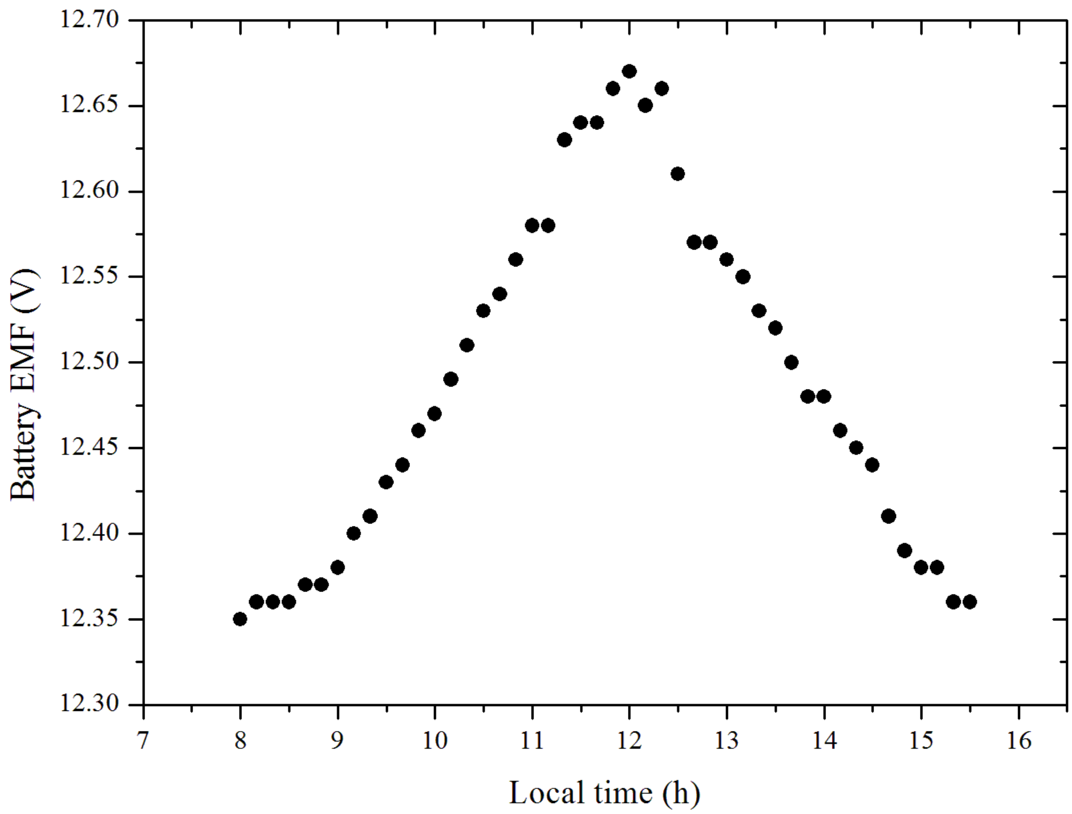


Figure 42 Variation of the battery EMF over time on 21th February 2013.

4.5 Refrigeration Performance

The water, cabin and room air temperature are presented in Figures 43 through 51. The refrigeration effect produced by the system, refrigeration power, coefficient of performance with the corresponding uncertainties are calculated from equations 9 through 11 from the initial time till when the water temperature had fallen below 0°C. And the refrigeration performance for the both bulk mass and distributed mass loading pattern is compared.

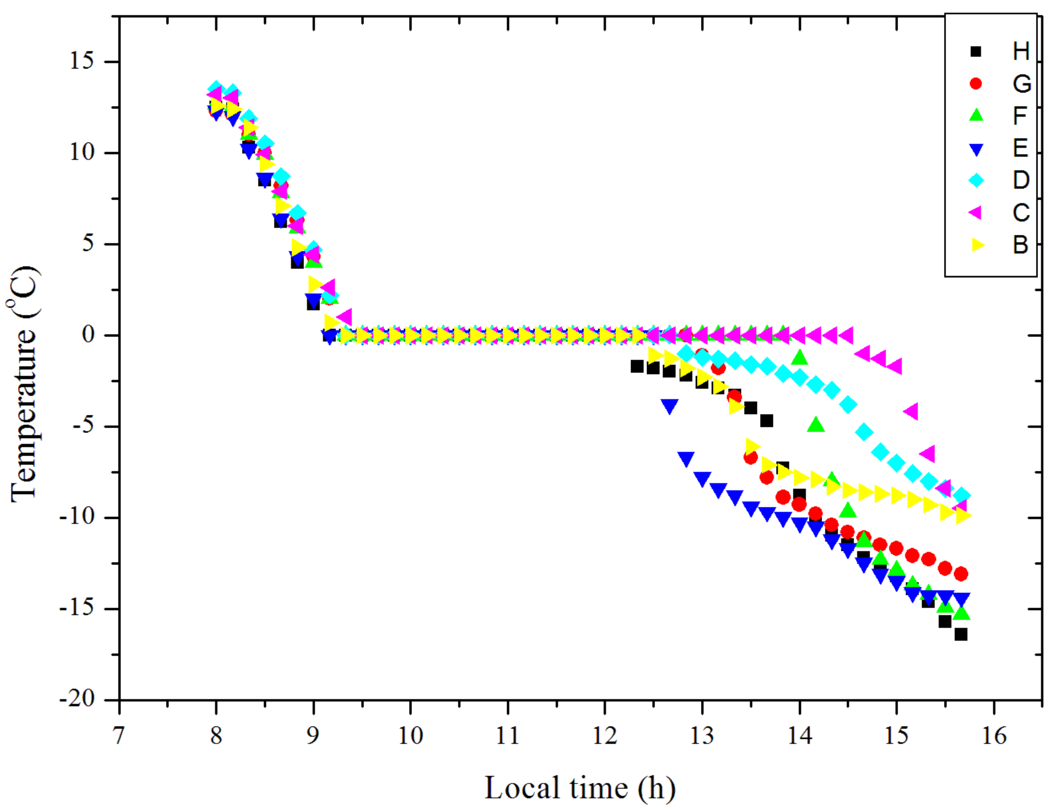


Figure 43 Variation of the water temperature over time on the 17th of January, 2013.

In the experiments conducted on the 17th, 19th and 21st of February, the distributed water loading pattern was adopted while those on the 3rd, 4th and 5th of March have bulk mass loads. It is observed that for the distributed loading patterns, the temperature variations of each of the 7 trays of water are independent of their positions in the refrigerator cabin.

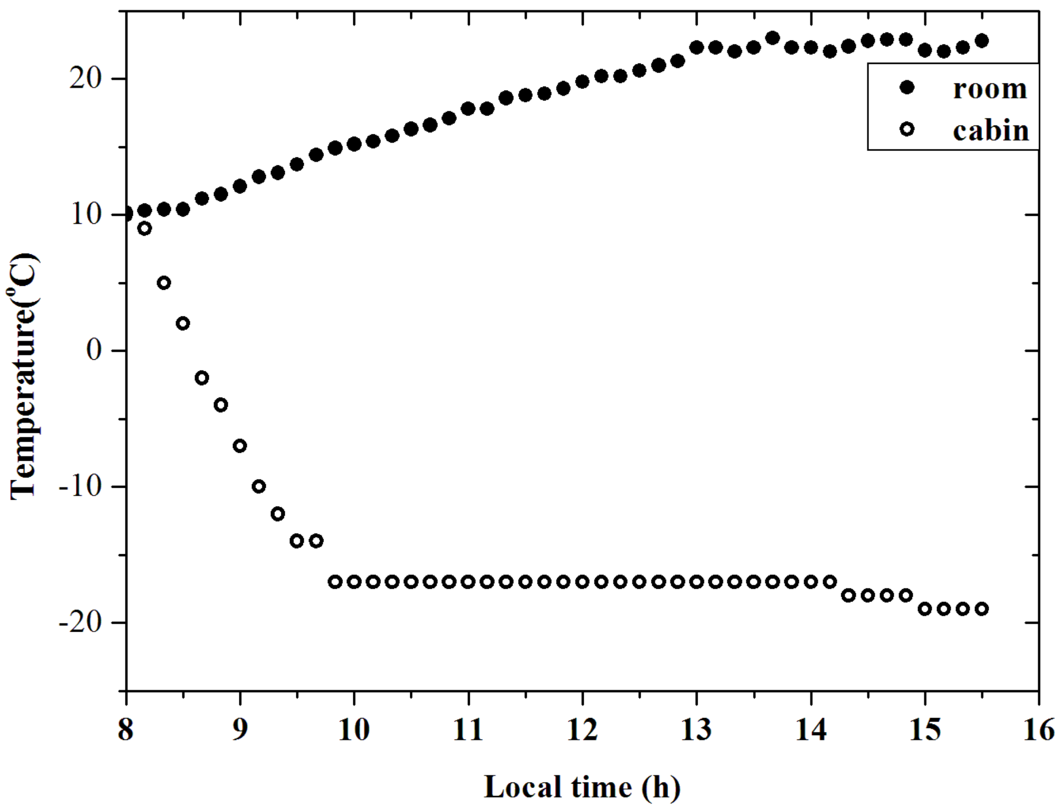


Figure 44 Variation of the room and cabin temperature over time on 17th January 2013.

On the 17th of January, 2.1kg of water is distributed in the cabin. As shown in Figure 44, the measured cabin air temperature varies between 10°C to -17°C and the room air temperature varies between 10.2°C to 22°C while the average room temperature is 18°C. The time taken for the water to reach sub-zero temperatures was 6hours and 40minutes. The refrigeration effect Q_{ref}, refrigeration power $\dot{Q}_{ref}$, refrigeration *COP* calculated is (863043±136101) J, (32±5) W and (0.60±0.094) respectively.

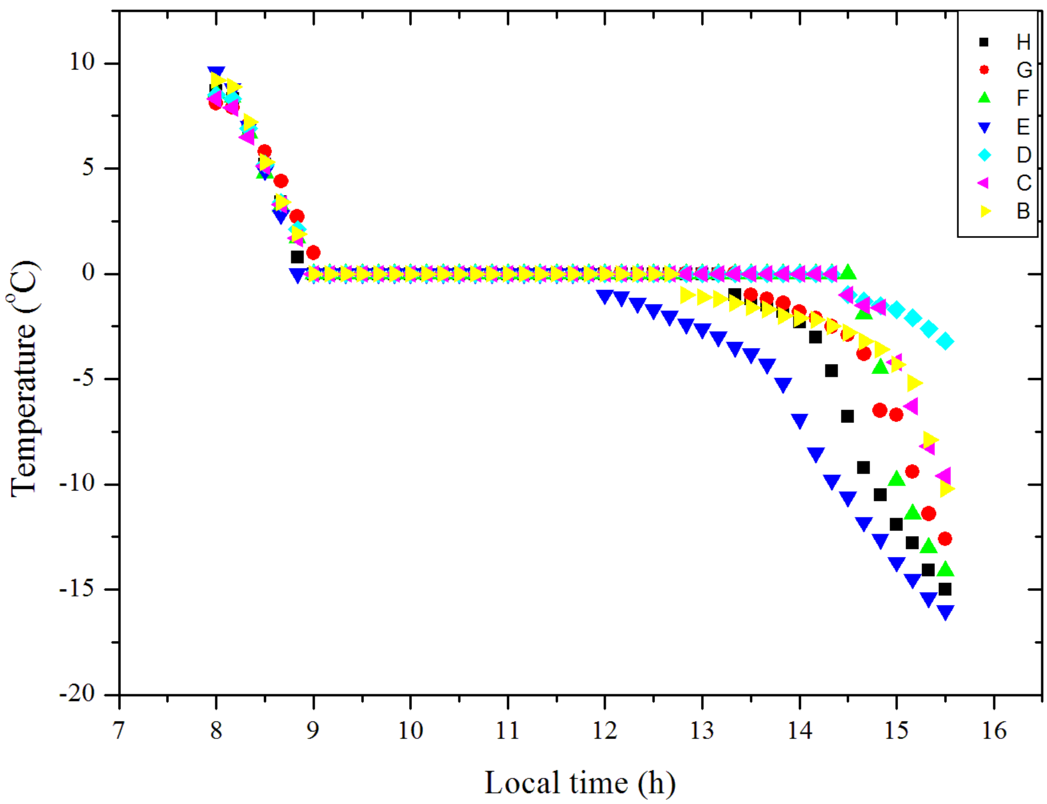


Figure 45 Variation of the water temperature over time on the 19th of January, 2013.

For 19th of January, 2.1kg of water is evenly distributed in the cabin. The cabin air temperature measured falls from 7°C to -19°C and the room air temperature varies between 13.1°C to 23.8°C with an average of 21°C. The time taken for all the water to reach sub-zero temperatures was 6hours and 40minutes. The refrigeration effect Q_{ref}, refrigeration power $\dot{Q}_{ref}$, refrigeration COP calculated is (863043±136101) J, (30±5) W and (0.54±0.093) respectively.

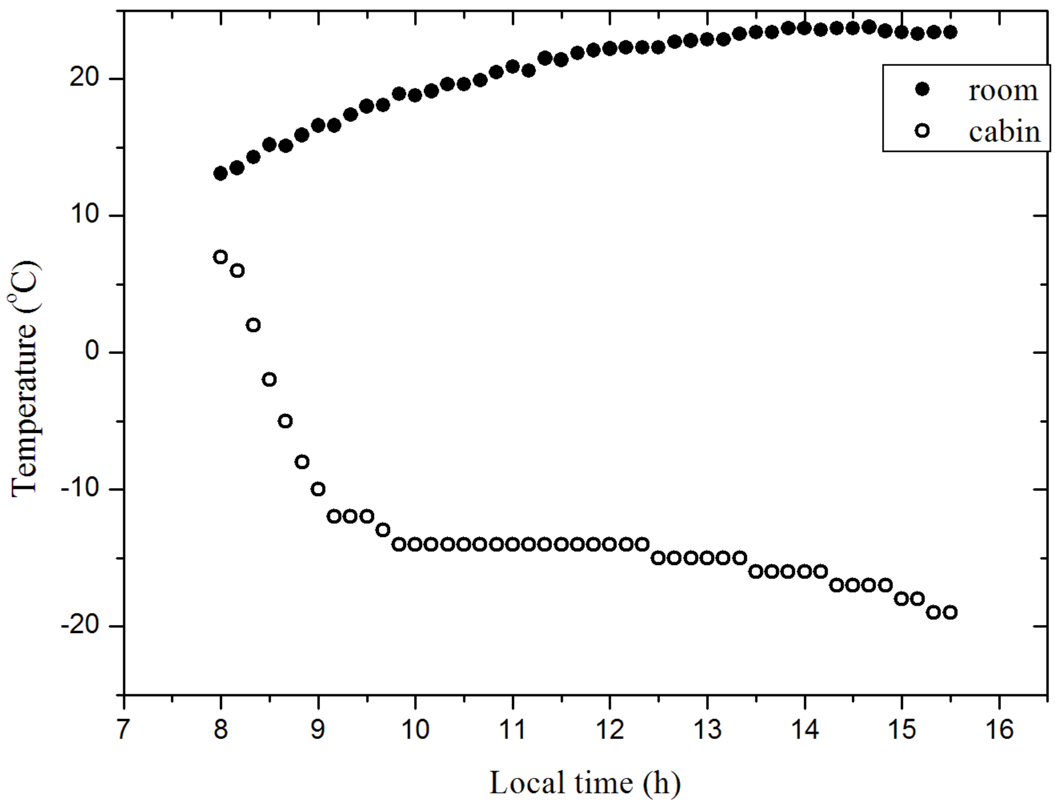


Figure 46 Variation of the room and cabin temperature over time on 19th January 2013.

A 2.1kg of water is also even distributed in the cabin on the 21st of February. The cabin air temperature measured falls from 18°C to -19°C and the room air temperature varies between 18°C to 22.8°C while the average room temperature is 21°C. The time taken for all the water to reach sub-zero temperatures was 7hours and 10minutes. The refrigeration effect $Q_{ref,un}$, refrigeration power $\dot{Q}_{ref,un}$, refrigeration coefficient of performance $COP_{ref,um}$ calculated are (927796± 14381) J, (34.4±5.1) W and (0.60±0.089) respectively.

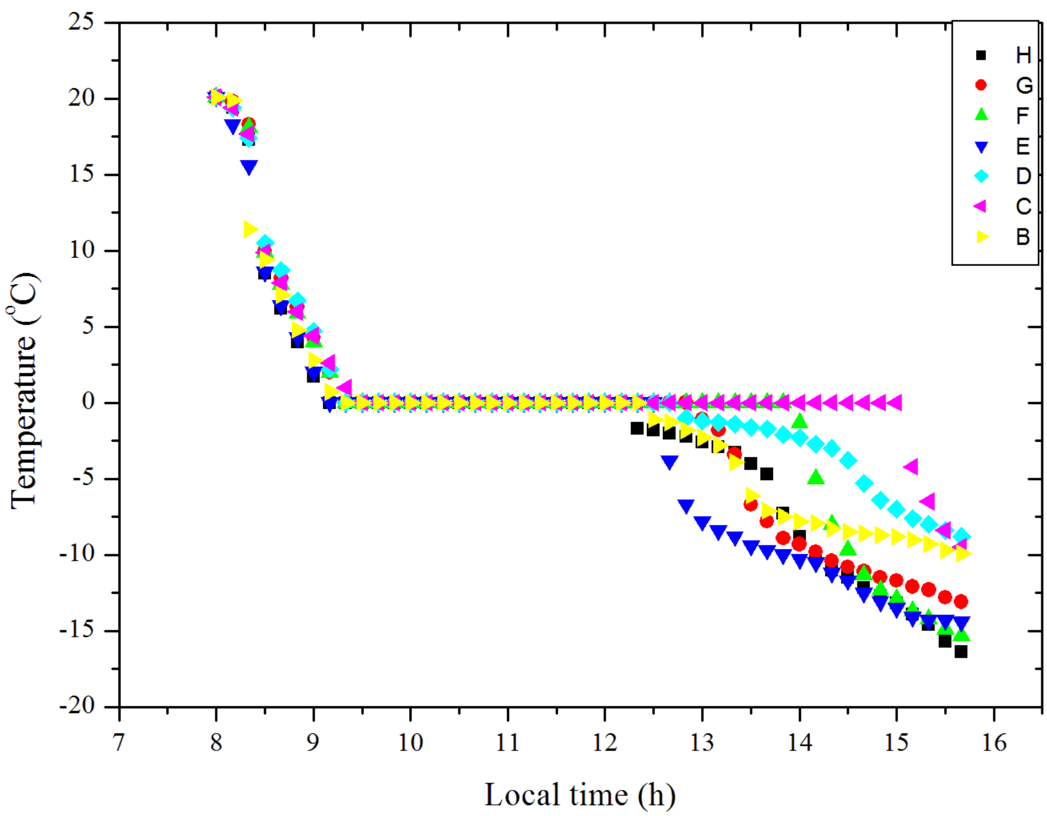


Figure 47 Variation of the water temperature over time on the 21th of February, 2013.

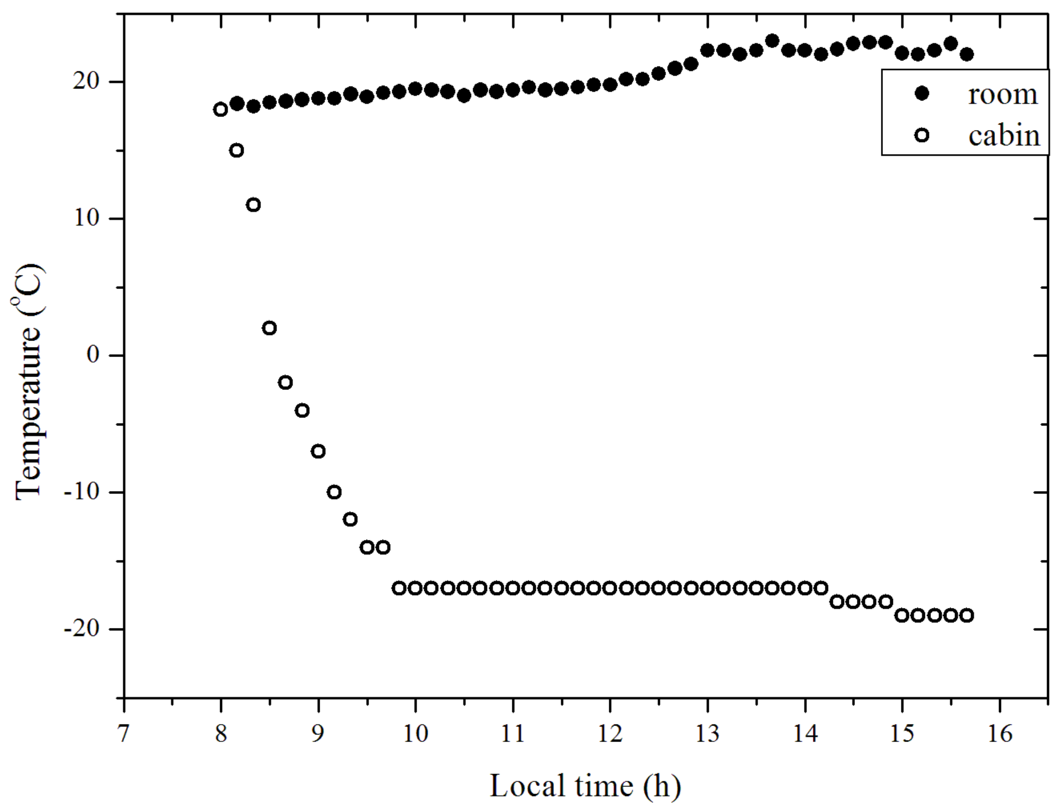


Figure 48 Variation of the room and cabin temperature over time on 21th January 2013.

For bulk loading pattern adopted on the 3rd, 4th and 5th of March 2013, the refrigeration performance is observed to be much less than the distributed loading pattern. On the 3rd of March, a fixed mass of water of 2.1kg was kept in the cabin, but the water never dropped below 0^oC within the time frame of the experiment as presented in Figure 49.

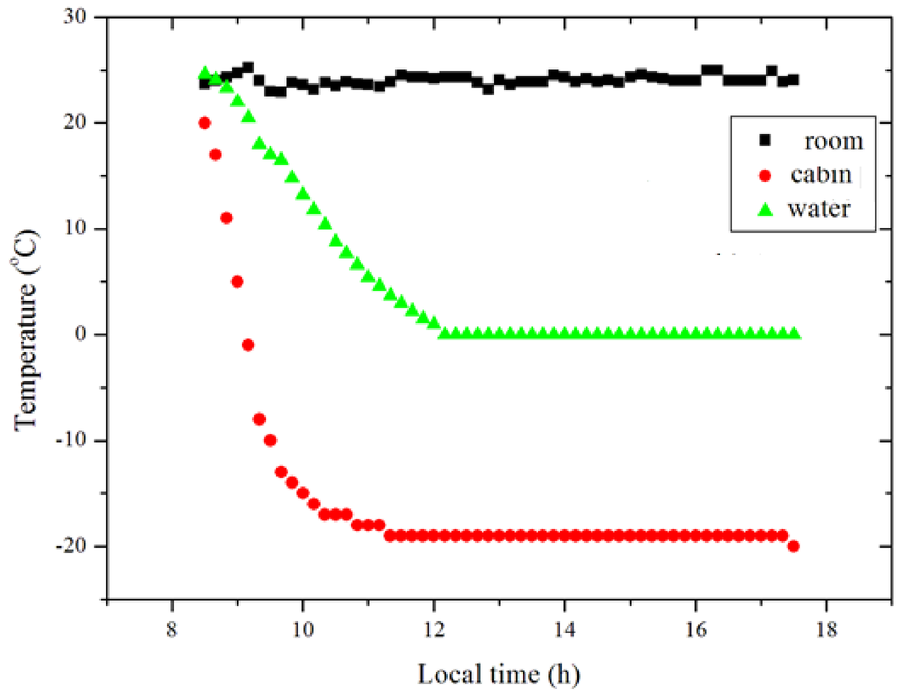


Figure 49 Variation of the water temperature, room and cabin air temperature over time on 3rd of March 2013.

Similarly for the experiment carried out on the 4th of March, a fixed mass of water of 1.2kg was kept in the cabin and ice formation was not fully achieved during the experimental time as indicated in Figure 50.

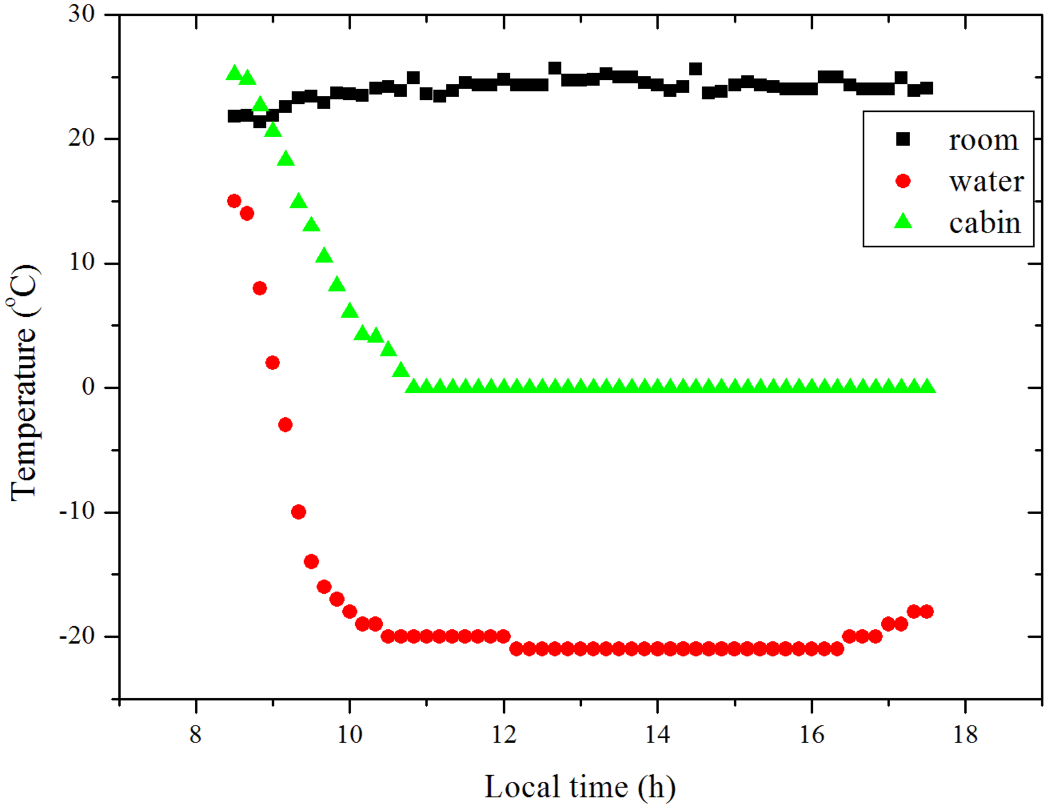


Figure 50 Variation of the water temperature, room and cabin air temperature over time on 4th of March 2013.

On the 5th of March, a fixed mass of 0.6kg of water is kept in the cabin, the cabin air temperature drops from 19^{o}C to -22^{o}C and ice was formed after about 6hrs and 50mins. The refrigeration *COP* is 0.20 and the average power consumed is 58W.

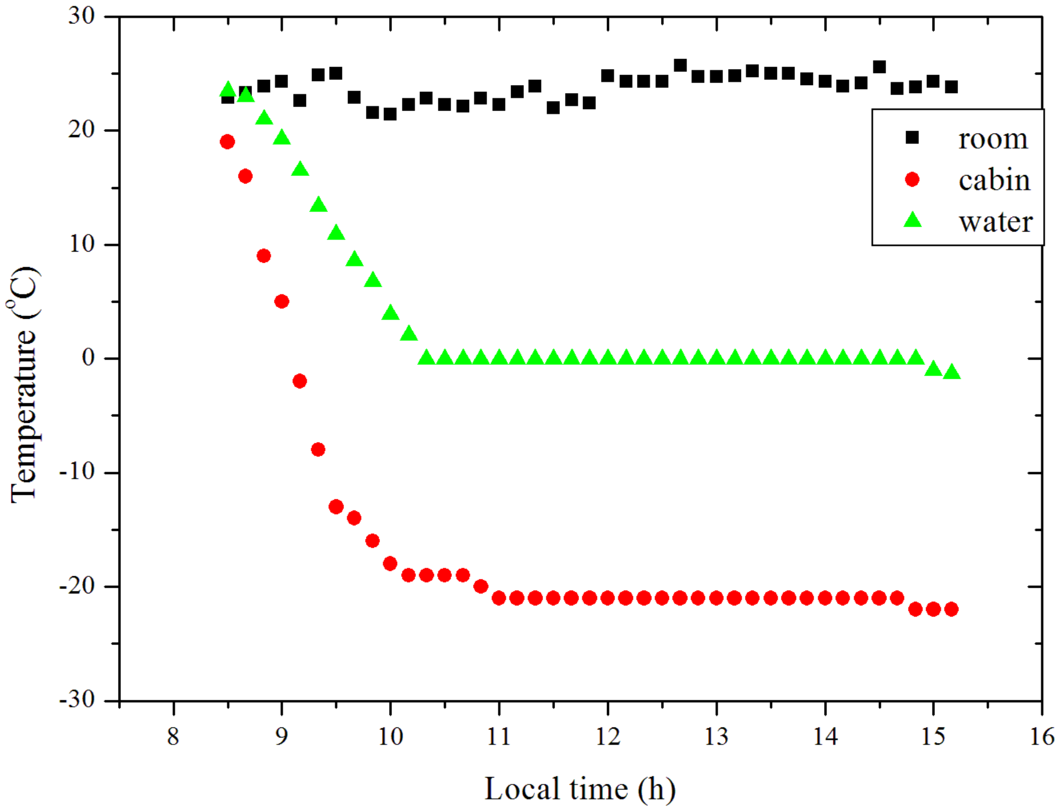


Figure 51 Variation of the temperature over time on the 5th of March, 2013.

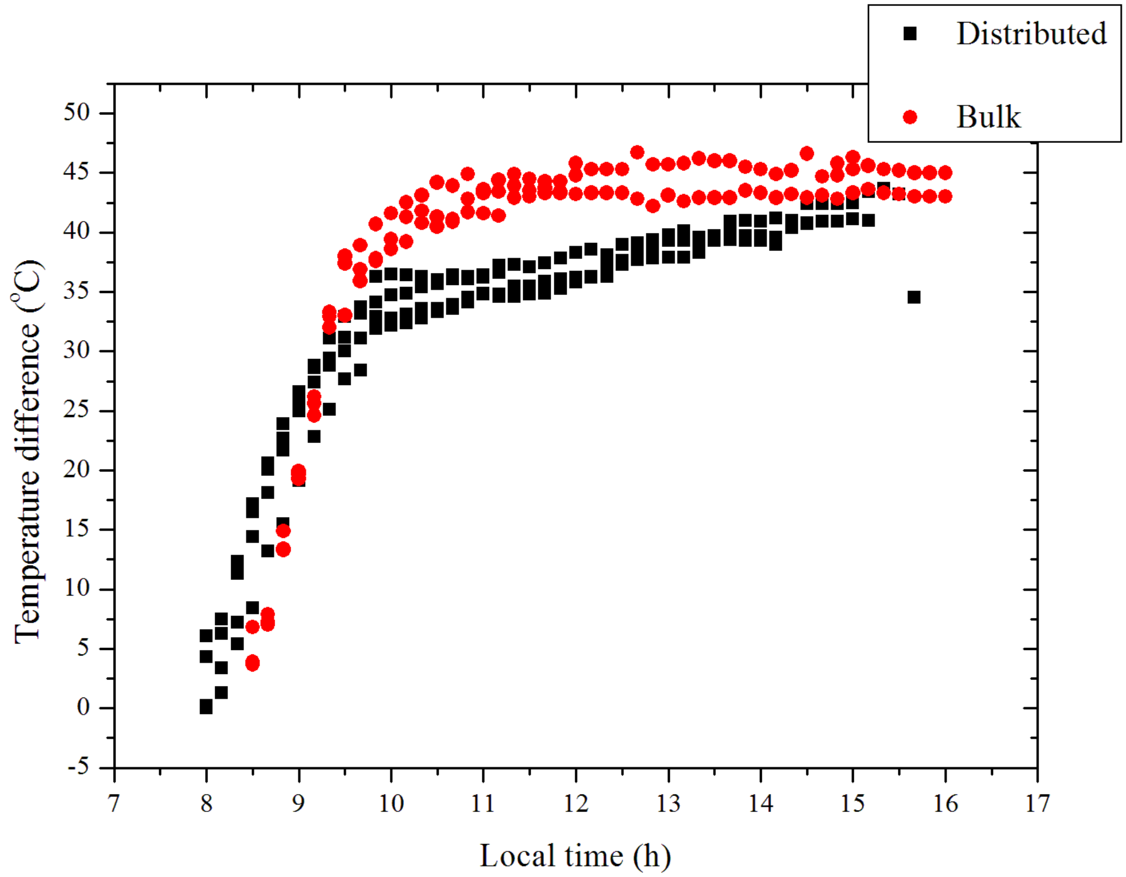


Figure 52 Temperature difference between the room and the cabin air for both distributed and bulk loading pattern.

The temperature difference variation between the room and cabin air for both the distributed and the bulk loading pattern is plotted in Figure 52. From Figure 52, variation of the temperature difference between the room and cabin air indicates that the distributed loading pattern allows less heat gain into the refrigerator cabin compared to the bulk loading pattern and this account for the low efficiency calculated for the bulk loading pattern.

The performance enhancement in the distributed loading pattern is also due to larger area to volume ratio of the distributed mass loading pattern when compared to the bulk pattern. As a result, the heat transfer rate is higher in the distributed pattern when compared to the bulk loading pattern.

CHAPTER 5

ECONOMIC ANALYSIS

5.1. Cost Analysis

The total cost of the PV refrigeration system is SR4285 as presented in table 2. The payback period is the total time after which total cost of the PV based system equals to the long term cost of a grid connected system. The long term cost of a grid connected system is the initial cost of the refrigerator and the cumulative cost of electric energy provided by the grid company until it is equivalent to the PV based one. Also, the point at which the contributions from the sales of the ice produced equals to the total fixed cost of the PV refrigeration system is the 'Break-even point'.

Table 2 System Cost

Quantity	Items	Unit Price(SR)	Total Price(SR)
1	Refrigerator	2035	2035
1	Charge controller	850	850
1	PV panel	1000	1000
2	Battery	200	200
7	1.5mm cable	5	35
10	4mm cable	6	60
7	Ice tray	15	105
Total Cost		**SR4285**	

Table 3 Electricity Consumption Tariff in Saudi Arabia(SECO 2013)

<table>
<tr><th>Consumption Categories kWh</th><th>Residential (SR)</th><th>Commercial (SR)</th><th>Governmental (SR)</th><th>Private educational establishments (SR)</th><th>Private health establishments (SR)</th><th>Agricultural (SR)</th><th>Charities (SR)</th></tr>
<tr><td>1-1000</td><td>0.05</td><td rowspan="4">0.12</td><td rowspan="11">0.26</td><td rowspan="11">0.12</td><td rowspan="11">0.12</td><td>0.05</td><td>0.05</td></tr>
<tr><td>1001-2000</td><td>0.05</td><td>0.05</td><td>0.05</td></tr>
<tr><td>2001-3000</td><td>0.10</td><td>0.10</td><td>0.10</td></tr>
<tr><td>3001-4000</td><td>0.10</td><td>0.10</td><td>0.10</td></tr>
<tr><td>4001-5000</td><td>0.12</td><td rowspan="4">0.20</td><td>0.10</td><td>0.10</td></tr>
<tr><td>5001-6000</td><td>0.12</td><td>0.12</td><td>0.12</td></tr>
<tr><td>6001-7000</td><td>0.15</td><td>0.12</td><td>0.12</td></tr>
<tr><td>7001-8000</td><td>0.20</td><td>0.12</td><td>0.12</td></tr>
<tr><td>8001-9000</td><td>0.22</td><td rowspan="3">0.26</td><td>0.12</td><td>0.12</td></tr>
<tr><td>9001-10000</td><td>0.24</td><td>0.12</td><td>0.12</td></tr>
<tr><td>More than 10000</td><td>0.26</td><td>0.12</td><td>0.12</td></tr>
</table>

5.2. Payback Period

The annual total AC energy consumed by the grid connected 80W refrigeration system operating for 24hrs daily and 365days per year is 700.8kWh and the total cost of operating the grid connected refrigerator was calculated to determine the payback period of the system for the different tariff types offered by the Saudi Electricity Company in table 3.

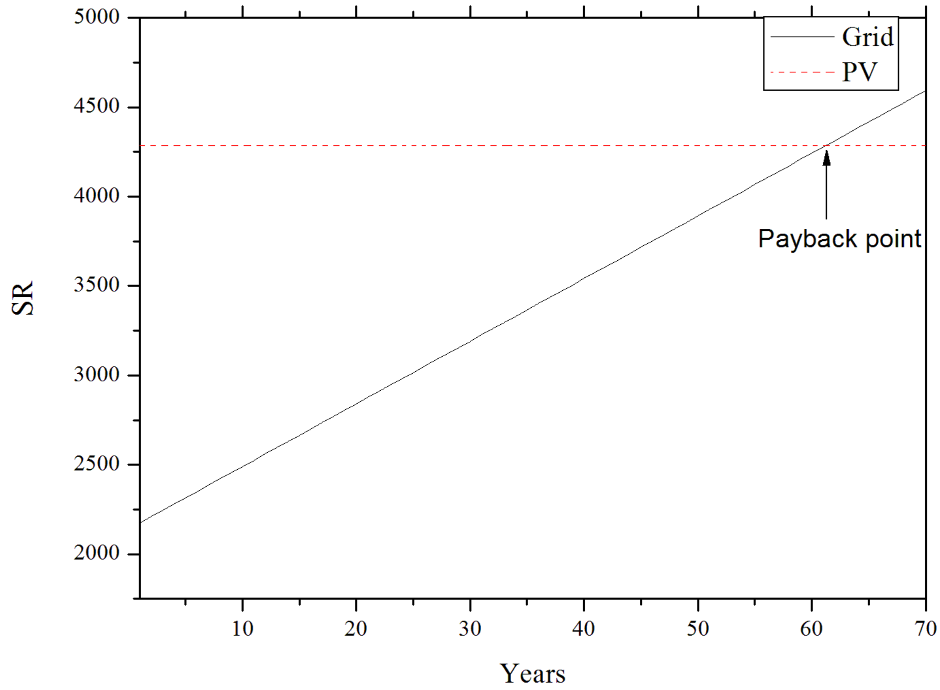


Figure 53 Payback period considering a 0.05SR/kWh tariff rate.

Table 4 Grid Based Total Cost and Payback Time

	Tariff Rate (SR/kWh)	Annual Electricity Cost(SR)	Payback Period (years).
1	0.05	35.04	61
2	0.1	70.08	31
3	0.12	84.096	26
4	0.2	140.16	16
5	0.26	182.208	12

5.3. Break-Even Point

There are several ice factories in the Kingdom of Saudi Arabia producing ice specifically for cooling purposes. Al Arji Ice Factory located in Qatif, Dammam sells 1kg of ice for SR0.19. Since the system will produce a minimum of 2.1kg of ice daily and assuming that sales are made daily, then the 2.1kg of ice would be sold for SR0.40 which amounts to SR145 annual sales .

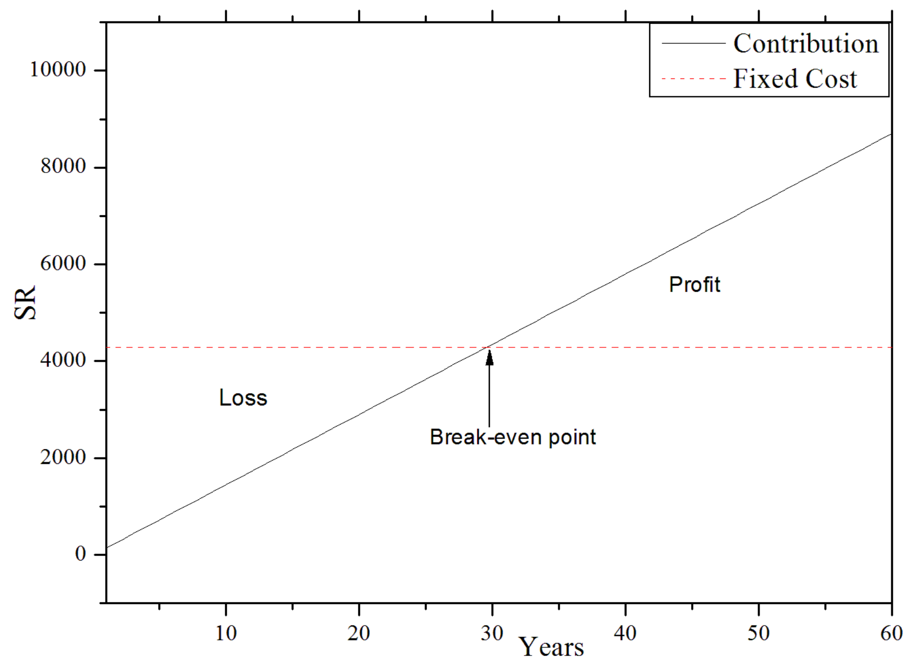


Figure 54 Break-even point for the PV refrigeration system.

CHAPTER 6

CONCLUSIONS

A technical and economic analysis on a solar photovoltaic vapor compression refrigeration system has been conducted in Saudi Arabia. The refrigerator was operated continuously with the goal of converting water to ice with power supplied from the photovoltaic panel. The best refrigeration COP was calculated to be 60% when the internal load was distributed inside the refrigerator and a low refrigeration efficiency of 0.2 was obtained for bulk loading pattern. The best panel orientation efficiencies vary 96% and 99% while the best photovoltaic performance efficiencies vary between 14.5% and 15.5% at peak periods.

The refrigeration performance for the two loading patterns considered indicates that the distributed loading pattern is more efficient than the bulk loading pattern.

Because the photovoltaic performance efficiency is calculated from a fixed effective area, optimizing the panel orientation will increase the effective surface area of solar radiation incidence while also increasing the PV orientation efficiency and the panel performance efficiency. The battery voltage at the beginning was restored at the end the experiment and the energy balance indicates that the solar energy is sufficient to power the system even during winter days with clear sky.

Finally the economic analysis was conducted for electricity energy tariff rates of 0.05, 0.10, 0.12, 0.20 and 0.26 riyal per kWh. The payback period obtained for the system indicates that it will take a minimum of 12years to get returns on the initial investment when the system is adopted in government services where tariff rates is highest and increases in other application areas such as commercial, residential and agricultural purposes. In other words, the system would not be viable without government subsidy on component cost except for off-grid applications and for desert camping activities in the kingdom.

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PUBLICATIONS

Adebiyi, A., El-Shaarawi, M.A.I., Al-Qutub, A., Said, S.A.M., "**Technical And Economic Investigation Of Solar Photovoltaic (SPV) Refrigeration System In Eastern Province Of Saudi Arabia**," International Journal of Air-Conditioning and Refrigeration, DOI: 10.1142/S2010132513500223 - *Accepted: 25 August 2013*.

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