Experimental Investigation on Solar Photovoltaic Driven Cool Thermal Storage System for the Development of Sustainable Micro Grid in Building Sectors

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Abstract **- In most of the developed nation, the increase in percentage share of renewable power in the total power generation causes major concerns over the integration of these renewable power with the grid resulting grid instability. Energy storage is a new frontier technology which is considered as the ultimate solution in developing smart micro grid with distributed renewable energy (RE) generation. Most of the hot countries like India spend nearly 24% of the electricity generated on air conditioning and food preservation. Under such scenario, among the various types of storage systems, the cool thermal storage plays a vital role to promote renewable power in an economical way. Considering the importance in the present increasing RE scenario, in the present work, an experimental investigation was performed on a cool water storage integrated with a chiller system driven by solar PV unit which has major advantages in central air conditioning system for demand management strategies and to solve the Grid instability. The results revealed that with the installation of 100 W chiller operated by a 200 Wp solar PV panel it is possible to generate 25 liters of cool brine at – 6°C from 35°C along with the storage of 0.405 kWh and 0.1 kWh of electrical energy in the battery respectively during the months of May and September. In the month of January the temperature was brought down only to a temperature of 1.3°C along with 0.234 kWh of energy stored in the battery. These results will be very useful for the design and development renewable based micro grid for cooling and other applications which are electrically driven in various building sectors.**

Keywords**:** ***DC Compressor, Micro grid, Energy Efficient Building, Solar PV, Cool storage***

1. INTRODUCTION

In the recent years, progress on solar-powered air conditioning has increased and at present air conditioning system is almost a must in every building if there is a requirement for good indoor comfort inside the building. Dauta et al [1] reported that the demand of air conditioning is increasing continuously due to climate change and global warming. If the conventional air conditioning based from fossil fuels, is continued the greenhouse gas emission would continuously worsen global warming; in turn the demand of air conditioning will also increase. In subtropical cities, air conditioning is a standard requirement in all buildings. However, air conditioning would normally consume half of building electricity consumption. In recent years the use of thermal energy storage has become a topic with a lot of interest within the research community, but also within architects and engineers. It is well known that there is a need to develop technologies to achieve thermal comfort in buildings lowering the cooling and heating demand. The development of renewable energy is on the rise worldwide because of the growing demand on energy, high oil prices, and concerns of environmental impacts.

In order to obtain a feasibility of the air conditioning system using solar, a lot research and testing have been initiated to learn and discover the design and operation of the air conditioning and solar system. Sahoo and Rout [2] reported that with the increase in gas and electricity tariffs, solar energy becomes attractive once the system has been installed. As one of the sources of renewable energy, solar energy is likely the most suitable system for installation in sub-tropical countries. The most common globally, preferred type of thermally driven technology for air-conditioning is absorption cooling. The system, which has simpler capacity control, mechanism, easier implementation, high reliability, silent operation, long life and low maintenance cost was a genuine candidate for efficient and economic use of solar energy for cooling applications. Utilizing solar energy to run the air conditioning system is a practical technique to replace conventional electricity.

Chidambaram et al [3] stated that the power shortage and unstable power supply remain serious problems. Further, they have discussed that the conventional cooling technologies that utilize harmful refrigerants consume more energy and cause peak loads leading to negative environmental impacts.. Also authors highlighted that the thermal storage systems are essential to overcome the disadvantage of the intermittent nature of solar energy and the mismatch in cooling demand. Foster et al [4] experimentally investigated the PV direct drive solar farm milk chillers (FMC) in Kenya with zero failures in the first 2.5 years of operation. The solar FMC technology was introduced to cool about 25 to 40 liters of milk overnight to 4°C. No overnight chilled milk was rejected by milk buyers in the 2-year study (traders and dairy cooperatives) and farmer incomes were significantly increased by over 30%. El-Bahloul et al [5] studied and investigated the performance of 15 ft^3 transportable solar driven DC refrigeration system to be utilized for post-harvest handling of crops at Alexandria, Egypt. The said system comprises, two compartments with different working temperatures of 5 and 0°C to store different types of fruits and vegetables. They have determined cooling loads for the two cold storages are 5.44 and 6.21 kW, respectively. Modi et al [6] studied the performance of domestic refrigerator powered by PV generator and stated that the refrigerator which was designed to operate using R-600a Butane refrigerant of 160 W rating capacity can work smoothly and continually by using a PV generator module of 140 Wp.

Axaopoulos and Theodoridis [7] ensured the successful operation of the refrigeration compressors by the PV panels by using a novel concept dedicated controller, which provides easy start up, power management and maximum power tracking for all the compressors of the system. Ekren et al [8] performed an experimental analysis of a direct current type refrigeration compressor implemented in a 79 litre refrigerator. The authors also investigated the energy usage reduction and operational improvement potential of the direct current compressor via variable speed operation. Further they have performed the experiments at variable speed operation and four different constant speed operation modes of the compressor. Chedop et al [9] presented an assessment of a solar electric-vapor compression refrigeration (SE-

VCR) system in a dry tropical area. They have performed a specific case of the city of Maroua, located in the climatic region of Cameroon. The authors performed an overall evaluation of the hourly cooling loads and the performance of the system by means of energy balance method. The results showed that, for an evaporating temperature of 0°C, the effective power of the compressor in the range of 5.33 kW and 6 kW, the capacity of the condenser in the range of 24 and 28 kW, and the coefficient of performance in the range of 3.28 to 3.74 while the efficiency of the installation is in the range of 17% and 35%. Blas et al [10] centred on the analysis of a direct current permanent magnet motor integrated in a refrigeration facility for milk cooling. They have also estimated the motor parameters by analysis of motor losses, data coming from simple no-load, load and locked-rotor laboratory tests.

The present work focuses to develop and test a prototype DC air conditioning system operated with solar PV system integrated with cool thermal storage for buildings deployed with central air conditioning units. The major advantages of the CTES system used in the solar-based VCR system are: (a) the cool storage system allows 50% reduction in the capacity of the chiller normally used in the central air-conditioning system that particularly reduces the demand cost for the building owner (b) reduces the burden on the power utilities towards the grid management. (c) A high-efficiency direct current motor can be used to run the compressor.

2. EXPERIMENTAL SETUP

A lab scale solar PV operated DC driven chiller unit was developed in the Solar Laboratory of Institute for Energy Studies, Anna University, Chennai, whose latitude and longitude are 13.0827° N, 80.2707° E respectively. The system consists of a 200 W_p PV module, 12 V, 20 Ah Lithium ion battery, a chiller unit with a cooling capacity of 100 W and a cool thermal storage tank of 0.025 m^3. The layout of the experimental setup is shown in Fig.1.

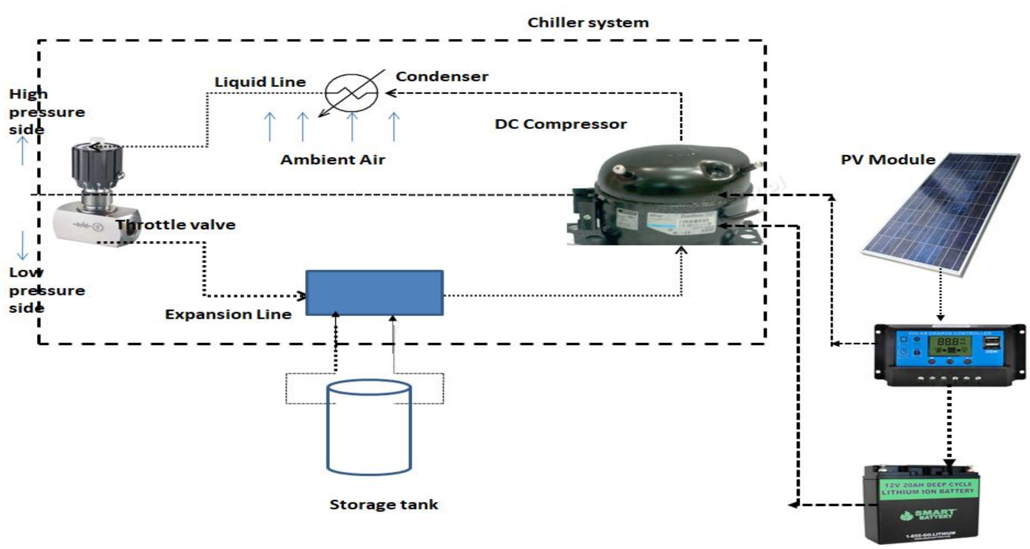

Fig.1 Basic Schematic of Experimental Setup

The detailed specification of the PV module used in the system is given in Table 1. Further, Lithium-ion battery of 12 V, 20 Ah is connected to the PV panel through a charge controller of rating 24 V, 30 A and to the chiller system which is used as a backup to store the excess energy when the intensity of sunlight is high and to provide the required energy for the operation of the compressor in the chiller system when the intensity of the sunlight is not sufficient to drive the compressor.

Table 1 Specification of 200 W_p PV module

Parameter	Values
Wattage (Wp)	200
Voltage at Max Power, Vmp (V)	20
Current at Max Power, Imp (A)	11.12
Open Circuit Voltage, Voc (V)	22
Short Circuit Current, Isc (A)	12.12
Number of Cells	36
Space requirement	14 Sq ft
Panel technology	Poly crystalline
Efficiency	15%
Standard	IEC
Life time	25 years

A DC compressor, evaporator, condenser and the expansion devices are the major components in the chiller unit. A Danfoss BD 35F, 12 V DC compressor particularly designed for the purpose of direct solar application, due to its "soft start" machinery with a minimum starting current of around 4 A to initially start the compressor is the uniqueness in the present setup. A highly efficient variable speed DC brushless motor drives the compressor and it is driven by the PV module directly (or) through discharging the energy from the battery. The rated speed of the motor is 2000 RPM with the maximum of 3500 RPM. The electronic control unit is adjusting the compressor and the motor speed. One advantage of this compressor is the ability to connect it directly to a PV or other source of DC energy supply without an inverter. The compressor is charged with the refrigerant "R134a". The evaporator of the chiller unit has its cooling coil immersed in the brine kept in a stainless steel tank insulated with polyurethane material.

In the evaporator the refrigerant is vaporized at a low pressure and temperature, by absorbing the heat from the brine. From the evaporator, the vapour is drawn by the compressor to a higher condenser pressure level. The superheated vapour enters the air-cooled condenser, where it condenses into the liquid phase while releasing heat to the ambient. Then the liquid refrigerant passes through an expansion valve and returned to the evaporator. In order to bring the chilled water temperature to -6°C, the evaporator temperature was set to -5°C. For the Chennai location the ambient temperature has an average value of almost 30°C and reaching 40°C in late summer. The cool thermal storage unit is used to store the cool energy and to deliver during the cooling demand in the non-sun shine hours. The value of the parameters of the storage unit integrated with the chiller system are shown in Table 2.

The radiation intensity was measured using the pyranometer (Delta Make LP PYRA 02) with a sensitivity of 10 μV/(W/m^2). Three RTDs (PT 100 – class A) with an accuracy of ± 0.1°C were used to measure the temperature of the brine in the storage tank and the ambient temperature. A DC ammeter, Voltmeter and digital DC energy meter were used to measure the generation side and load side electrical parameters. The accuracy of voltmeter and ammeter are ± 0.02 V and ± 0.023 A respectively.

Table 2 Major parameters of the storage unit integrated with chiller system

Parameter	Value
Chiller capacity	100 W
Evaporator set temperature	-6°C
Evaporator cum storage tank capacity	25 liters
Storage material	Brine (80% Water + 20% mono ethylene glycol)
Storage tank insulation material	Polyurethane foam

Several experimental trials were performed to generate data in order to evaluate the performance of the system. All the trials experiments were conducted between 8 am and 4 pm. Initially the power is drawn from the battery to start the compressor. An on/off control unit is arranged so as to operate the compressor with the priority from solar PV panel directly. During the operation, the ammeter, voltmeter and energy meter readings were continuously monitored on the source and load side. The radiation intensity was continuously monitored through the pyranometer mounted near the solar PV panel that monitors the radiation intensity throughout the day. During this experiment initially the temperature of the brine in the evaporator was around 35°C and the temperature of the brine was decreased continuously with respect to time during the experiment. The temperature of the brine was monitored until the temperature reaches 6°C.

3. Experimental Procedure

In order to evaluate the optimal quantity of refrigerant to be charged in the developed solar powered DC compressor based chiller unit, experiments were performed with various masses of 20g, 25g, 30g, 35g, 40g & 45g of refrigerant R134a charged in the constructed system under other similar operating conditions. During all these experiments, initially the temperature of the brine in the chiller unit was maintained at 35°C and the system is allowed to operate between 11 am to 3 pm. During this time interval the solar radiation received by the solar module and the module power and voltage characteristics were observed to determine the module efficiency. The cooling capacity was evaluated based on the final temperature attained by the brine. The performance of the system under various mass of refrigerant were evaluated.

After evaluating the optimal quantity of charging in the chiller unit, the experiments were performed for the entire day during three different months of January, May & September for the year 2018. These months were selected because the radiation intensity level were highly different. During these experiments, if the solar energy generated by the PV unit is sufficient to run the DC compressor the energy generated will be utilized to produce cool energy in the chiller unit and if the power generated is not sufficient to drive the compressor the generated electricity will be utilized to charge the battery. Further, if the brine in the chiller unit attains –6°C during a day then the additional energy generated also will be utilized to charge the battery. Several experiments were performed to ensure the repeatability of the results.

4. Results and Discussion

Fig. 2 shows the variation of the ambient temperature and the solar intensity measured for a typical day in the months of January, May &

September, 2018 on which the other experimental results obtained from the chiller unit are reported. During the month of May the ambient temperature at 6:30 am is around 28.5°C and it reaches a maximum of 37.5°C at 2 pm, whereas the maximum temperature during the typical day in the months of September and January are only 27°C & 23°C respectively. The peak solar intensity in the month of May is 795 W/m^2 whereas it is 750 W/m^2 & 625 W/m^2 during the months of September and January respectively. Fig. 3 shows the power and voltage characteristics of the PV module used in the present experiment set up. In the month of January the P_{max} occurs at a voltage of 16 V and it delivers a maximum power of 130.6 W. In the month of September the maximum power delivered is 173.1 W at 17 V and during the month of May the maximum power delivered is 185.6 W at 19 V.

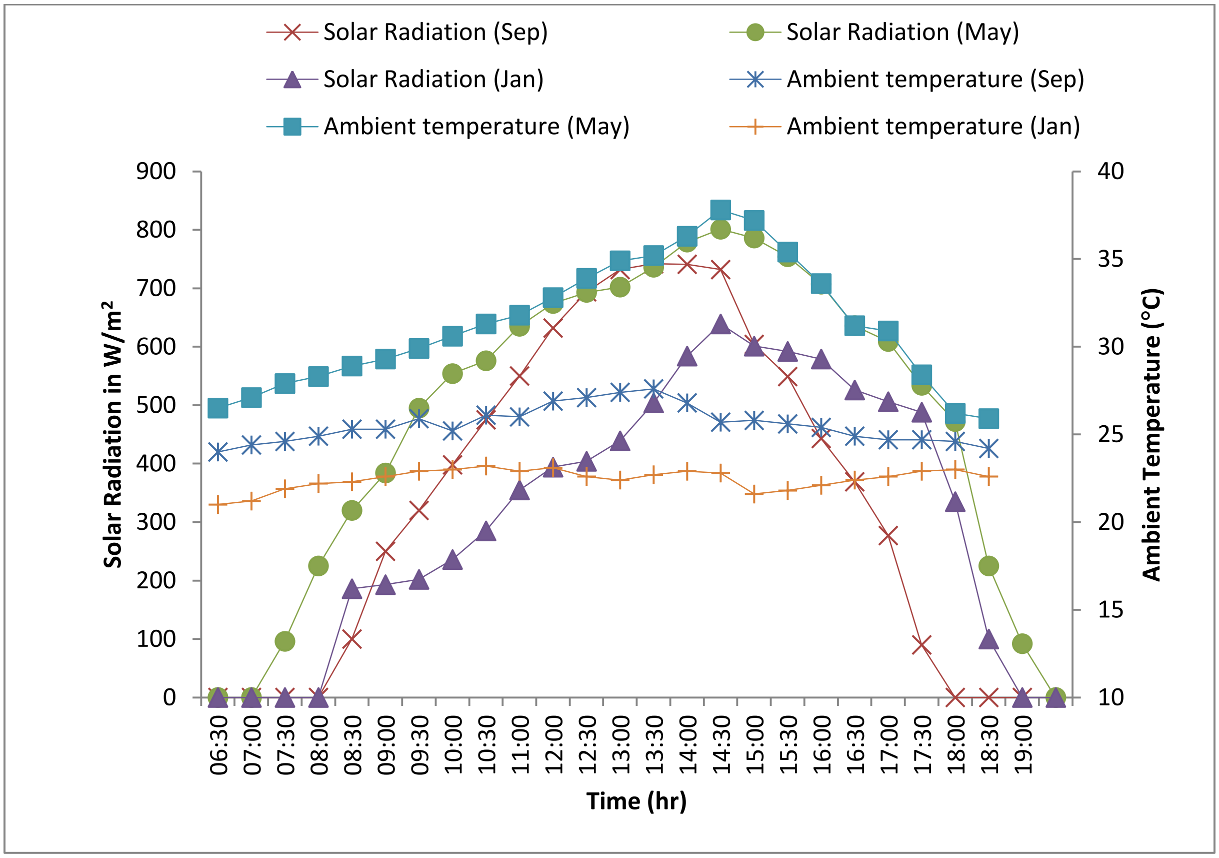

Fig. 2 Variation in Solar intensity and the ambient temperature with respect to time

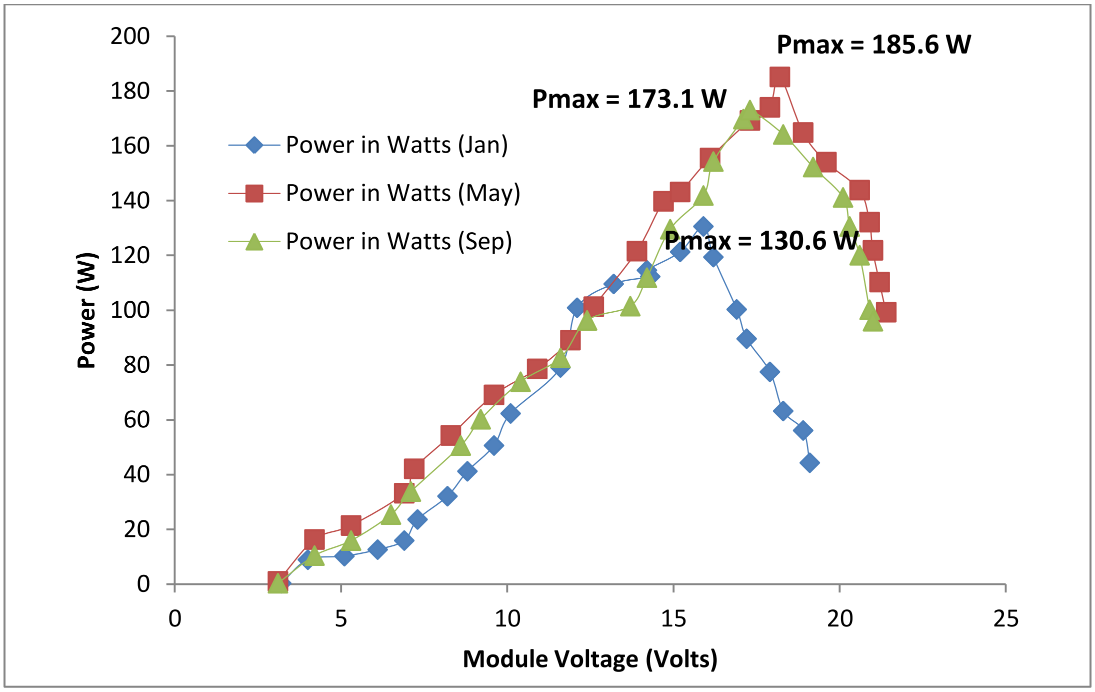

Fig. 3 Power and Voltage Characteristics of PV module

Fig. 4 shows the performance of the solar powered DC chiller unit representing the cooling capacity and the COP along with the power utilized under different mass of the refrigerant charged in the compressor. It is seen from the figure 4 that the average cooling capacity is only 60 W when the mass of the refrigerant is 20 g. Further, it is seen that the cooling capacity increases upto 75 W, when the mass of the refrigerant is increased upto 35 g and increasing the mass of the charge beyond this value does not contribute for further increase in cooling capacity. On the other hand there is a small increase in the average power consumption when the mass of the charge increases from 20 g to 45 g. Though this increase in power requirement is marginal on seeing the COP of the system, the maximum COP is seen when the mass of the refrigerant charged is 30 g. Hence, it is construed to perform the further experiments by charging the system with 30 g of refrigerant.

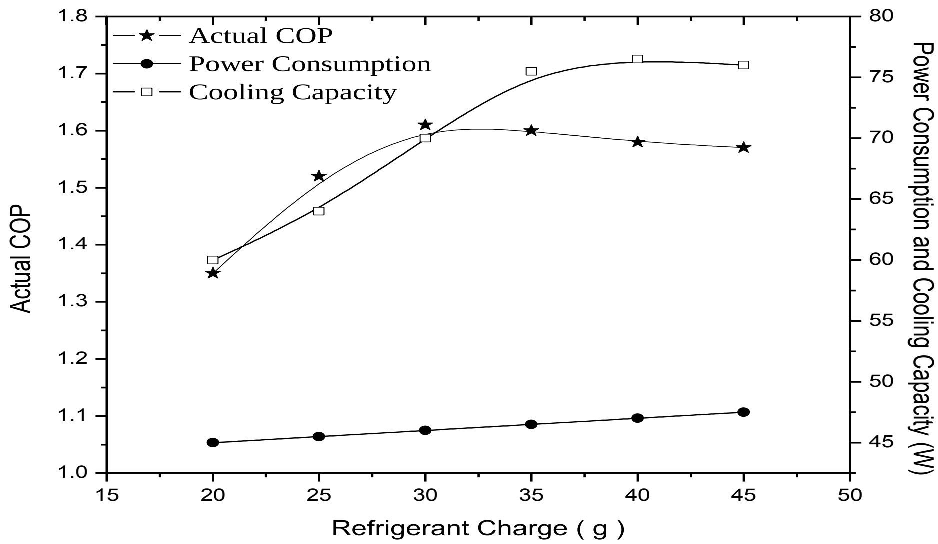

Fig. 4. Performance of the chiller under various mass of the refrigerant charged

Figure 5 shows the temperature variation of the brine in the cool storage tank. Initially the temperature of the brine in the cool storage tank was maintained at 35 °C in all the experiments. Though the experiments were commenced at 8 am, the compressor of the chiller unit was started, when sufficient power was generated from the PV panel to run the compressor. It is seen that during the month of January only after 4 hr the chiller unit was started and the temperature of the brine starts decreasing only after 4 hr from the start of the experiment. Hence, within a day the temperature could not be reduced to -6°C. The final temperature of the brine in the cool storage unit has only reached 1.3°C around 5 pm. In the month of May the brine in the evaporator tank reached -6°C before 3 pm and in the month of September the -6°C was attained by the brine around 4 pm. During these months if the compressor are not in operation the energy generated from the solar PV panel are used to store the energy in the Li-ion battery.

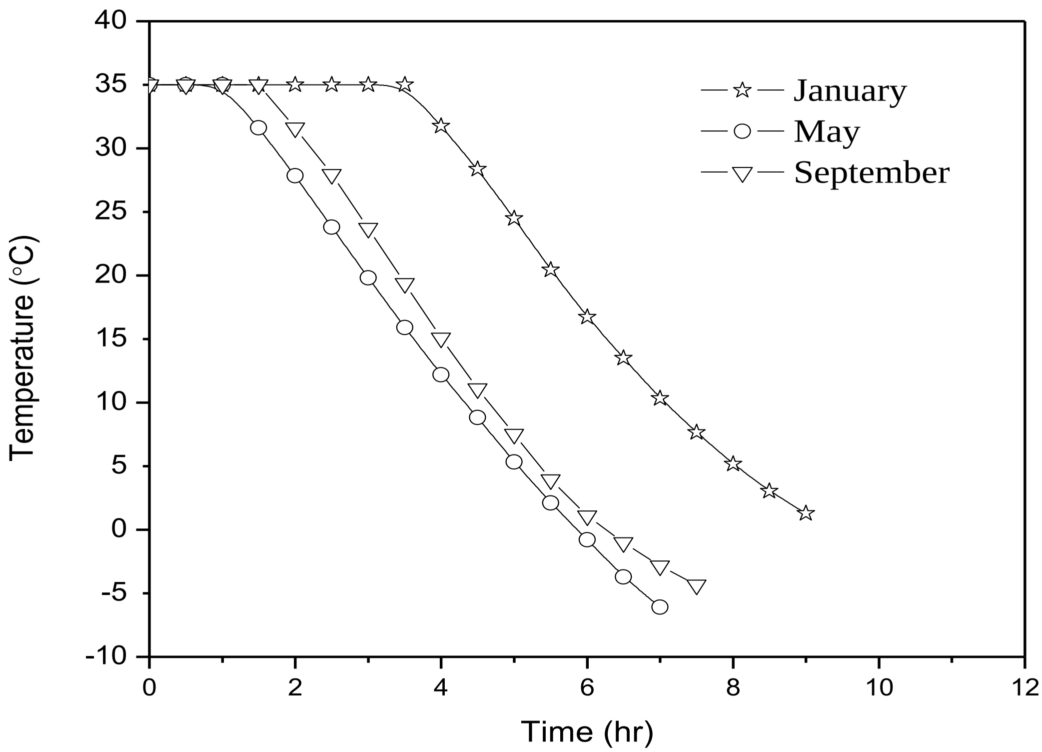

Fig. 5. Temperature variation of the brine in the evaporator during the charging process

The energy utilized to run the compressor for the purpose of cooling and the energy supplied to the battery for charging from the solar PV module are presented in fig. 6. It is seen from the figure that 0.54 kWh of energy is used to run the compressor and nearly 0.23 kWh of energy is used to charge the battery during the month of January. In the month of May, 0.792 kWh of energy generated from PV module is used to run the compressor and nearly 0.405 kWh energy generated is used to charge the battery. In the month of September, 0.738 kWh of energy is utilized to run the compressor and only a very small portion of 0.1 kWh of energy is stored in the battery.

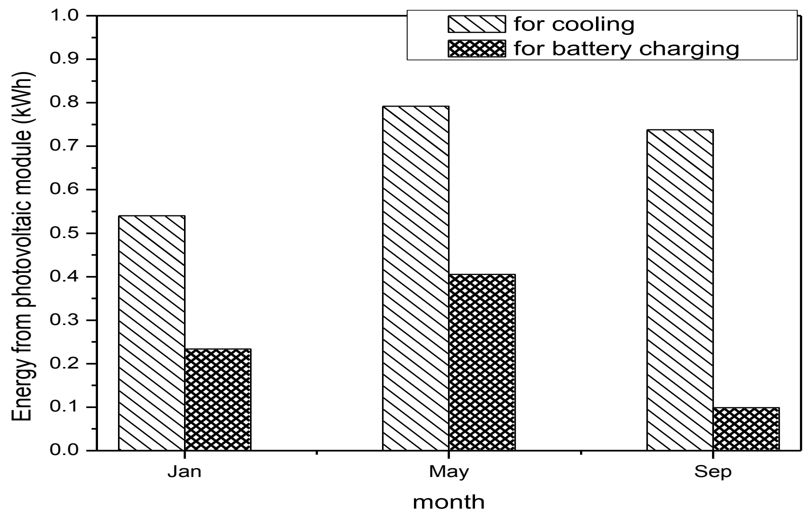

Fig. 6. Energy from PV module used for cooling and battery charging

The total energy generated from the solar PV module during the month of January, May & September are 0.774 kWh, 1,197 kWh & 0.837 kWh respectively. It could be seen that during the month of May & September the contribution by the solar PV module towards the cool energy generated is higher compared to the month of January. Normally during the month of December, the cool energy required for air conditioning also will be lesser and since the duration of the day lighting is lesser the electrical energy for lighting requirement will be more. Hence with the proper selection of the size of the system components such as solar PV module, chiller and the battery storage, it is possible to design a micro grid for various types of buildings.

5. CONCLUSIONS

In the present work a solar operated DC driven cool storage based chiller unit integrated with battery storage unit was constructed and its performance were analyzed. It is concluded that 25 liter of brine could be brought down to -6°C from 35°C using 100 W DC operated chiller and 200 W_p solar PV panel during the month of May & September. In the month of January since the operational duration of the compressor is less the brine was brought down only to a temperature of 1.3°C. In addition to the cool energy generated, 0.234 kWh, 0.405 kWh & 0.1 kWh of electrical energy generated was also charged in the battery during the months of January, May & September respectively. The demonstration of the present set up with the experimental results will be very useful for the solar, air conditioning and building engineers to extend their services for the design and development of RE based micro grid in the building sector.

ABBREVIATIONS

CTES	:	Cool Thermal Energy Storage
DC	:	Direct Current
ES	:	Energy Storage
FMC	:	farm milk chillers
HVAC	:	Heating Ventilation and Air Conditioning
W	:	watt
kW	:	Kilowatt
hr	:	hour
Li-ion	:	Lithium-ion
PV	:	Photovoltaic
RE	:	Renewable Energy
TES	:	Thermal Energy Storage
V	:	Volt
VCR	:	Vapor Compression Refrigeration

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